LIQUID CRYSTAL BASED TUNABLE BANDPASS AND BANDSTOP FILTERS
FOR MILLIMETER WAVE SIGNAL PROCESSING APPLICATIONS

by

EVANGELOS C. ECONOMOU

B.S., University of Colorado, Colorado Springs, 2009

A dissertation submitted to the Graduate Faculty of the
University of Colorado Colorado Springs
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy
Department of Physics and Energy Science
2017
This dissertation for the Doctor of Philosophy degree by

Evangelos C. Economou

has been approved for the

Department of Physics and Energy Science

by

Zbigniew J. Celinski, Chair

Anatoliy Glushchenko

Karen Livesey

Robert Camley

T.S. Kalkur

Date  December 12, 2017
Economou, Evangelos C. (Ph.D. Applied Science – Physics)  
Liquid Crystal Based Tunable Bandpass and Bandstop Filters for Millimeter Wave Signal Processing Applications  
Dissertation directed by Professor Zbigniew J. Celinski  

ABSTRACT  
This work reports on the development and characterization of electrically tunable millimeter wave signal processing devices based on liquid crystal materials. More specifically, the devices include on-wafer bandpass and bandstop inverted-microstrip filters embedded in liquid crystal cells. The liquid crystals studied are proprietary and primarily include the nematic LC1917 and LC2020. Photolithography, thin film deposition, and standard liquid crystal cell assembly techniques are used to manufacture the filter devices. The filter devices utilize an inverted microstrip to coplanar waveguide transition to allow for injection of the microwave and bias signals with a Vector Network Analyzer and AC bias test setup. S-parameter measurements with respect to frequency are collected and compared with simulated results on filters modeled with computational electromagnetics software employing the Finite Integration Technique.

The bandpass filters developed are comprised of half-wavelength long open stubs and quarter-wavelength connecting lines. The length of each stub determines the passband frequency of the filter. Filters with central passband frequencies of 30, 50, and 85 GHz are manufactured and tested. The filters show good passband transmission and reflection characteristics for a proof-of-concept device. Namely, the passband insertion loss of the 50 GHz filter is -3.76 dB, while return loss ranges from -9 to -25 dB. The
passband central frequency is tunable by 10% when a 14 volt peak-to-peak AC bias is applied across the 38 µm thick liquid crystal layer (electric field of 0.19 V/µm).

The bandstop filters are of the spurline configuration and have quarter-wavelength long, resonant elements embedded in the inverted microstrip. Filters with notch frequencies centered at 50 and 85 GHz are designed, measured, and compared with simulations. The stopband frequencies are tunable by 3% with the above-mentioned electric field. The minimum stopband insertion loss of both filters achieves lower than -50 dB, while the stopband return loss varies from -4 to -12 dB.

The concept of merging liquid crystals with signal processing technologies appears to be a very promising path the radio-frequency industry could take. Liquid crystals can be designed to have low absorption in the microwave frequency range (by selecting the right molecular constituents), large dielectric anisotropy (and therefore tunability), and are easy to integrate into inverted microstrip devices. Devices based on these materials are inexpensive, small, and consume very little power during operation. In addition, liquid crystal display manufacturing is a mature industry whose technological processes can be employed immediately for microwave applications. This concept may also be utilized for many other on-wafer transmission structures, besides filters, and for much higher frequencies (100 – 1000 GHz) since the liquid crystal dielectric constant typically lacks inherent resonances in this frequency range. The filter devices presented in this study, although intended for microwave signal processing applications, also furnish an effective methodology for characterizing the dielectric properties of liquid crystal materials (and fluids or solids in general) up to the THz frequency range.
DEDICATION

To Mom, Dad, Sofia, and Dimitrios. Mom and Dad, you have made all things possible, encouraged me to go to college, and supported me a great deal. Thank you for all of your help and patience with me during my endeavors. Thanks Dimitrios, for helping me see the world a little differently—something I needed during grad school. Thanks Sofia, for being a great sister and for being my “homework buddy.”

To James, who was helpful in class and integral in my decision to choose UCCS for graduate school when I was unsure of my next steps.

To Colyn, and to Heidi, for letting me live with you during a huge chunk of my degree. Thanks for your company and your friendship, and hearing me out every night after toiling long hours in the lab.

To Kassy, who I was very fortunate to have met during graduate school. I would not have made it without your help. Thank you for all of your support and advice while I worked towards the end of my dissertation.
ACKNOWLEDGEMENTS

There are many individuals who have been helpful during my time in graduate school that I would like to acknowledge. First, I thank my advisor and mentor, Dr. Zbigniew Celinski, who has supported me and challenged me continuously at every step of my studies and my research.

I also thank my Ph.D. advisory committee, Dr. Zbigniew Celinski, Dr. Anatoliy Glushchenko, Dr. Karen Livesey, Dr. Robert Camley, and Dr. TS Kalkur. Thank you for your support; I appreciate all of the help you have given me.

Special thanks also to Dr. Kathrin Spendier. I greatly enjoyed working with you on the project in BioFrontiers and really appreciate your support and mentorship.

There are also many great colleagues that were helpful during my research. In particular, this group includes Dr. Ian Harward, who I consulted at just about every aspect of my research; Olha Melnyk, Dr. Dario Bueno-Baques, Dr. Yurii Garbovskiy, and Dr. Akihiro Mochizuki, for liquid crystal expertise; Natalie Bledowski, thin film deposition; Jason E. Nobles, AC bias scheme and general discussion; Dr. James (Jim) Lovejoy, liquid crystal microwave devices; Dr. Vira Kravets and Dr. Olena Zribi, dynamic light scattering; Dr. Ke Jiang, Kyle Culhane, Simon Marinelli and Meghan C. Smith, magnetic nanodrug fabrication and characterization; Christopher Reinecke, Jason Hill, Stephen Lewis, Benard Kinyanjui, and Thomas Moore, LC cell assembly and/or planetary ball milling; Joshua Baptist, Daming Chen, Kevin Smiley, Nicholas Christian, Sara Goldman, and Dr. Janusz Hankiewicz, for general help.
Finally, I would like to thank Dr. Marek Grabowski, Dr. Robert Camley, Dr. Zbigniew Celinski, Thomas Stringer, and Dr. Tom Christensen for teaching my graduate classes.
# TABLE OF CONTENTS

## CHAPTER

### I. BACKGROUND ........................................................................................................ 1

  - Introduction ........................................................................................................ 1
  - Liquid Crystals .................................................................................................. 4
  - Liquid Crystal Microwave Devices .................................................................. 8

    - Dielectric Characterization in Microwave Frequencies ................. 10
    - Motivation for Liquid Crystal Based Filters in the Industry .......... 11
    - Prior Research on Liquid Crystal Microwave Devices .................. 13

      - Liquid Crystal Phase Shifters ............................................................ 13
      - Liquid Crystal Bandpass Filters ...................................................... 14
      - Liquid Crystal Bandstop Filters ..................................................... 15

    - Current Research: Liquid Crystal Based Filters .............................. 16

      - Device Requirements ........................................................................... 16

    - General Engineering and Design Process ....................................... 17

      - General Fabrication Process ........................................................... 18

### II. DEVICE DESIGN, FABRICATION AND CHARACTERIZATION .......... 21

  - Overview ....................................................................................................... 21

    - Open Stub Filter Design ........................................................................ 21

      - Metrology of Liquid Crystal Materials in GHz Frequencies ....... 23
Determination of Stub Dimensions ................................................................. 28
  Stub Lengths ......................................................................................... 28
  Stub Widths ......................................................................................... 28
Structure Thickness and the Skin Depth Equation ................................. 30
Inverted Microstrip and Coplanar Waveguide Design ............................ 31
Design of Spurline Filter Devices ............................................................. 34
  Double Spurlines Versus Single Spurlines ............................................. 35
  Determination of Spur Lengths and End Fringing Capacitance .......... 36
Liquid Crystal Materials: 1917 and 2020 ................................................. 38
  Chemical Constituents ......................................................................... 38
  Phase Transitions ............................................................................... 41
  Switching Time ................................................................................... 42
Microwave Device Fabrication ................................................................. 42
  Photolithography .................................................................................. 42
  Photomask Design ............................................................................. 43
  Thin Film Deposition ......................................................................... 47
  Liquid Crystal Cell Assembly .............................................................. 47
Experimental Configuration ..................................................................... 50
Computational Electromagnetics Techniques .......................................... 52
III. RESULTS AND DISCUSSION ............................................................... 54
  Overview ............................................................................................. 54
  Open Stub Filters ................................................................................ 54
    Analysis of Insertion Loss Due to CPW and Liquid Crystal .......... 54
B. A Brief History of Liquid Crystals ................................................................. 87
C. Complete Tunable Filter Fabrication Process ............................................... 89
REFERENCES ........................................................................................................... 95
# LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1.</td>
<td>Bandpass (open stub) filter performance expectations</td>
<td>16</td>
</tr>
<tr>
<td>1.2.</td>
<td>Bandstop (spurline) filter performance expectations</td>
<td>17</td>
</tr>
<tr>
<td>2.1.</td>
<td>Open stub filter parameters (actual device)</td>
<td>30</td>
</tr>
<tr>
<td>2.2.</td>
<td>Spurline filter parameters (actual device)</td>
<td>38</td>
</tr>
<tr>
<td>2.3.</td>
<td>A selection of rigid cores for high birefringence liquid crystal molecules</td>
<td>40</td>
</tr>
<tr>
<td>2.4.</td>
<td>The structures found on each cell design of the photomasks, reading from the</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>top left to the bottom right</td>
<td></td>
</tr>
<tr>
<td>2.5.</td>
<td>Vector Network Analyzer (VNA) Set-up</td>
<td>51</td>
</tr>
<tr>
<td>4.1.</td>
<td>A compilation of peer-reviewed studies on liquid crystal bandpass filters</td>
<td>77</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1.</td>
<td>Illustration of the solid, liquid crystal, and liquid phases of the thermotropic, nematic liquid crystal………………………………………..4</td>
</tr>
<tr>
<td>1.2.</td>
<td>AutoCAD illustration of the cross-section of a LC cell when LC molecules are a) aligned with the polyimide, and b) fully biased with an electric field. Drawing not to scale…………………..6</td>
</tr>
<tr>
<td>1.3.</td>
<td>Perspective view of an inverted microstrip structure containing liquid crystal, prepared in CST Microwave Studio………………………………………………………………………………………………9</td>
</tr>
<tr>
<td>1.4.</td>
<td>Engineering and design process of filter devices………………………18</td>
</tr>
<tr>
<td>1.5.</td>
<td>Device manufacturing process…………………………………….19</td>
</tr>
<tr>
<td>2.1.</td>
<td>AutoCAD rendering showing the top view of a LC cell with microstrip filters. The bottom substrate (in orange) supports the microstrip and CPW. The top substrate (blue, dashed outline) supports the ground plane. A 38 μm thick LC layer rests between the two substrates. The bottom of the figure shows details of the CPW to microstrip transition used to inject the microwave and bias signals. All units are in microns………………………………………………………22</td>
</tr>
<tr>
<td>2.2.</td>
<td>The measured frequency dependence of S-parameters on a biased three-stub, 30 GHz filter structure filled with LC2020 at room temperature………………………………………………………………………………………………24</td>
</tr>
<tr>
<td>2.3.</td>
<td>The frequency of resonances as a function of LC2020 permittivity predicted by CST modeling of a three-stub filter………………………………………………………………………………………………25</td>
</tr>
<tr>
<td>2.4.</td>
<td>The measured frequency response dependence of S-parameters on a biased three-stub, 50 GHz filter structure filled with LC2020 at room temperature………………………………………………………………………………………………26</td>
</tr>
</tbody>
</table>
| 2.5.   | The measured frequency response dependence of S-parameters on a three-stub, “60 GHz” filter structure filled with cured NOA68T Norland Optics glue at room temperature…………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………
2.7. Close-up perspective view of the CPW-microstrip transition in CST Microwave Studio........................................................................................................32

2.8. AutoCAD drawing showing the details of quarter-wavelength, double-spurline elements designed for notch frequencies of (a) 50 GHz and (b) 85 GHz. All units are in microns..........................34

2.9. CST simulation of the reflection, $S_{11}$ (dashed curves), and transmission, $S_{21}$ (solid curves), versus frequency of a 50 GHz spurline filters. The red curves represent the double spurline filter, while the black curves represent the single spurline filter..................................................................................................................36

2.10. AutoCAD rendering of a) the LC cell supporting the double-spurline filters and b) a zoom-in of the CPW-microstrip transition at each port of the filter device. The microstrip filters and CPW, supported on the bottom substrate, are in orange. An outline of the top ground plane is represented by the blue, dashed lines. All units are in microns........................................................................................................................................37

2.11. ACD/ChemSketch drawing of a functional group bonded with isothiocyanate, a termination molecule found on most of the rigid cores in LC1917 and LC2020..................................................................................39

2.12. MJB4 Mask Aligner from SUSS MicroTec for exposure step in photolithography..........................................................................................................43

2.13. AutoCAD rendering of the photomask for top substrates (ground planes): “April Filters New Transition – 1TopGND.”..........45


2.15. Magnetron sputtering system for thin-film deposition over photoresist patterns..........................................................................................................................47

2.16. Rubbing machine, for aligning polyimide films.................................47

2.17. Front and back of a LC cell with 3-stub, 30 GHz open stub filters.................................................................................................................................48

2.18. Front and back of a LC cell with 30, 50, and 85 GHz spurline filters.................................................................................................................................48
2.19. Front and back of a partially-filled LC cell with a 50 GHz, open stub filter (left), 85 GHz filter (middle), and microstrip line (right). ..............................................................49

2.20. Front and back of a LC cell with 5-stub, 30 GHz open stub filters. .................................................................49

2.21. VNA test setup used to perform S-parameter versus frequency measurements up to 110 GHz of the device-under-test (DUT)..................50

2.22. GSG probes landed on the CPW of a LC cell.........................51

2.23. AC bias test set-up for applying a 1 kHz square wave signal to the LC cells (photograph courtesy of Jason E. Nobles).................52

3.1. \( S_{21} \) versus frequency of 2.25 µm thick copper-based CPW structures on Borofloat 33 .........................................................54

3.2. The change in insertion loss, \( \Delta S_{21} \), versus frequency when a drop of LC is deposited on top of a CPW.................................55

3.3. 3-stub, 30 GHz bandpass filter. (a) Central frequency vs voltage. Inset shows \( S_{21} \) vs frequency at various voltages. (b) \( S_{11}, S_{22}, \) and \( S_{21} \) vs frequency at 30 Vpp. (c) CST simulation \( S_{21}, S_{11}, \) and \( S_{22} \) vs frequency.......................................................57

3.4. 3-stub, 50 GHz bandpass filter. (a) Central frequency vs voltage. Inset shows \( S_{21} \) vs frequency at various voltages. (b) \( S_{11}, S_{22}, \) and \( S_{21} \) vs frequency at 30 Vpp. (c) CST simulation of \( S_{21}, S_{11}, \) and \( S_{22} \) vs frequency......................................................60

3.5. 3-stub, 85 GHz bandpass filter. (a) Central frequency vs voltage. Inset shows \( S_{21} \) vs frequency at various voltages. (b) \( S_{11}, S_{22}, \) and \( S_{21} \) vs frequency at 30 Vpp. (c) CST simulation of \( S_{21}, S_{11}, \) and \( S_{22} \) vs frequency......................................................61

3.6. \( S_{21} \) versus frequency of simulated filters with 3 (black curve), 5 (red curve), and 7 (blue curve) stubs........................................63

3.7. \( S_{22} \) (black), \( S_{11} \) (red), and \( S_{21} \) (blue) versus frequency of a fully-biased, 30 GHz five-stub filter...................................................65

3.8. CST simulation of the transmission, \( S_{21}, \) versus frequency of a 3-stub filter with various stub widths (in microns) ......................66
3.9. Prediction from CST simulation of the 3 dB bandwidth of a 3-stub filter as a function of stub width…………………………………………………….66

3.10. CST simulation of $S_{21}$ versus frequency of a 30 GHz, three-stub filter with various center stub widths. The outer stub widths were fixed at 275 $\mu$m…………………………………………………….67

3.11. CST simulation of $S_{11}$, $S_{22}$, and $S_{21}$ versus frequency of a 30 GHz, three-stub filter with center stub width of 350 $\mu$m and outer stub widths of 275 $\mu$m…………………………………………………….68

3.12. Tunable double-spurline filter with 50 GHz center notch frequency: a) notch frequency versus applied voltage; the inset shows $S_{21}$ versus frequency at various AC voltages applied across the LC layer, and b) transmission, $S_{21}$, and reflection parameters, $S_{11}$ and $S_{22}$, versus frequency when 4 $V_{pp}$ is applied across the LC layer…………………………………………………….69

3.13. CST simulation of the transmission, $S_{21}$, and reflection, $S_{11}$, parameters of a modeled 50 GHz double-spurline filter at the center value of LC permittivity…………………………………………………….71

3.14. CST simulation of the S-parameters versus frequency of a tuned 50 GHz, double spurline filter. The minimum, center, and maximum LC permittivities are represented by the red, blue, and black curves, respectively. The transmission, $S_{21}$, is represented by the solid curves and the reflection, $S_{11}$, is represented by the dashed curves…………………………………………………….72

3.15. Tunable double-spurline filter with 85 GHz center notch frequency: a) notch frequency versus applied voltage; the inset shows $S_{21}$ versus frequency at various AC voltages applied across the LC and b) a graph showing the transmission, $S_{21}$, and reflection parameters, $S_{11}$ and $S_{22}$, versus frequency when 4 $V_{pp}$ is applied across the LC cell……………………………..73

3.16. A simulation of the transmission, $S_{21}$, and reflection, $S_{11}$, parameters of a modeled 85 GHz double-spurline filter at the center value of LC permittivity…………………………………………………….75

4.1. Filter with DFLC, 1909c: $S_{21}$ versus frequency at various AC bias frequencies (ranging from 1 to 20 kHz) with fixed voltage of 36 $V_{pp}$………………………………………………………………………..81

4.2. Filter with DFLC, 1909c: $S_{21}$ versus frequency at various AC bias voltages (1 kHz)…………………………………………………………………………………………………………………..82
4.3. MOKE system at UCCS ................................................................. 85
## LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>B33</td>
<td>Borofloat 33</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>CPW</td>
<td>Coplanar Waveguide</td>
</tr>
<tr>
<td>CST</td>
<td>Computer Simulation Technology (software from Dassault Systèmes)</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DF LC</td>
<td>Dual Frequency Liquid Crystal</td>
</tr>
<tr>
<td>DIW</td>
<td>Deionized Water</td>
</tr>
<tr>
<td>DUT</td>
<td>Device Under Test</td>
</tr>
<tr>
<td>EO</td>
<td>Electro-optic</td>
</tr>
<tr>
<td>FDTD</td>
<td>Finite Difference Time Domain</td>
</tr>
<tr>
<td>FIT</td>
<td>Finite Integration Technique</td>
</tr>
<tr>
<td>FMR</td>
<td>Ferromagnetic Resonance</td>
</tr>
<tr>
<td>FOM</td>
<td>Figure of Merit</td>
</tr>
<tr>
<td>IPA</td>
<td>Isopropyl Alcohol</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>ITO</td>
<td>Indium Tin Oxide</td>
</tr>
<tr>
<td>LC</td>
<td>Liquid Crystal</td>
</tr>
<tr>
<td>LCD</td>
<td>Liquid Crystal Display</td>
</tr>
<tr>
<td>MEMS</td>
<td>Micro Electro-Mechanical Systems</td>
</tr>
<tr>
<td>mm-waves</td>
<td>Millimeter waves</td>
</tr>
<tr>
<td>MO</td>
<td>Magneto-optic</td>
</tr>
<tr>
<td>MOKE</td>
<td>Magneto-optic Kerr Effect</td>
</tr>
<tr>
<td>MUT</td>
<td>Military University of Technology, Warsaw, Poland</td>
</tr>
<tr>
<td>P2P</td>
<td>Point-to-point</td>
</tr>
<tr>
<td>PBA</td>
<td>Perfect Boundary Approximation</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>PVD</td>
<td>Plasma Vapor Deposition</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RPM</td>
<td>Rotations per Minute</td>
</tr>
<tr>
<td>TST</td>
<td>Thin Sheet Technique</td>
</tr>
<tr>
<td>UAV</td>
<td>Unmanned Aerial Vehicle</td>
</tr>
<tr>
<td>UCCS</td>
<td>University of Colorado at Colorado Springs, USA</td>
</tr>
<tr>
<td>UV</td>
<td>Ultra Violet</td>
</tr>
<tr>
<td>VNA</td>
<td>Vector Network Analyzer</td>
</tr>
<tr>
<td>V&lt;sub&gt;pp&lt;/sub&gt;</td>
<td>Volts (Peak to Peak)</td>
</tr>
<tr>
<td>w/w</td>
<td>Weight-by-weight volume</td>
</tr>
</tbody>
</table>
CHAPTER I – BACKGROUND

Introduction

There has been an increasingly strong demand for microwave and millimeter wave signal processing devices operating in the frequency range from 1 to 300 GHz. Such devices have wide-ranging applications in wireless networking, satellite and terrestrial communications, wireless security systems, navigation, radar, medical diagnostics and treatment, environmental remote sensing, and basic research tools. This trend has grown for many reasons. Microwaves and millimeter waves can allow, for example, far more bandwidth (i.e. increased data rates), enhanced line-of-sight propagation for radar and point-to-point (P2P) communication links, reduced size and weight of the technology, and lower costs. Also, various molecular, atomic, and nuclear resonances occur at microwave frequencies, necessitating the use of microwave technology for basic research. In microwave or millimeter wave systems, waveguides and planar transmission line structures such as slot-lines or microstrips are typically used. Of the many planar structures employed in microwave networks, tunable distributed-element filters embedded into transmission lines are of particular interest.

There are many types of filters, but two of the major types are bandpass and bandstop filters. A bandpass filter is a two-port device that provides transmission of electromagnetic waves in a small range of frequencies known as the passband, while attenuating all other frequencies. Bandstop filters, also known as notch filters, accomplish the opposite by rejecting a small domain of frequencies in the stopband and accepting frequencies outside of it. Filters are an integral component of communications
and phased array radar systems;\textsuperscript{9} they are found in wireless transceiver architectures\textsuperscript{10} for picking out the frequency range of interest while eliminating noise. They are also commonly used in diplexers and multiplexers to separate frequencies and are also components in impedance-matching networks.\textsuperscript{2} A theory of filters was first established by W. P. Mason, R. A. Sykes, S. Darlington, R. M. Fano, A. W. Lawson, and P. I. Richards in the early 1900’s before World War II, and was later modernized in the 1950’s by G. L. Matthaei, L. Young, E. M. T. Jones, and S. B. Cohn, and others at the Stanford Research Institute.\textsuperscript{1} Its history is best consulted in other literature.\textsuperscript{1,11}

To add more functionality to the filter devices, various methods and materials are utilized to enable tuning of the passband or stopband frequencies. Typically, microelectromechanical systems (MEMS), PIN and varactor diodes, or ferroelectrics, ferrites, ferromagnetic films, garnets, spinels, and metamaterials are traditionally employed for this purpose.\textsuperscript{4,12,13,14,15,16,17,18,19,20,21,22,23,24} However, some of these materials or methods have various disadvantages including high power consumption, size, cost, low reliability, or limited operational frequency. One of the recent developments that addresses these problems is liquid crystal (LC) based microwave technology, which made its debut mainly in the form of electrically tunable phase shifters.\textsuperscript{25,26,27,28,29,30,31,32,33}

This forms the ultimate idea of the presented work, namely, the merging of LC materials with microwave and millimeter wave signal processing technologies. More specifically, the concept of applying an AC bias across LC materials to electrically tune the resonant frequencies of inverted microstrip bandpass and bandstop filters is investigated. The frequency range studied is from 1 to 110 GHz. The theory, design, experimental results of actual devices, and simulations will be presented. The scope of
this concept, however, is not just limited to filters, nor the frequency range studied. LCs may be integrated with other planar transmission structures or general devices including phase shifters, capacitors, antennas, beam steering reflect arrays, phased arrays, and other fundamental components. Furthermore, frequencies of up to 1 THz may be used due to the non-dispersive dielectric properties of the LC up to this frequency region. Therefore, a plethora of LC based microwave devices could potentially be developed for the microwave, millimeter wave, and radio frequency (RF) signal processing industry.

Finally, the LC based filters developed in this study are not only useful for the signal processing industry. They also prove to be useful for studying the dielectric properties of LCs, and fluids and solids in general, in a wide frequency range from 1 to 1000 GHz. Therefore, these filter devices may be beneficial to both the research and industrial communities. In this chapter, the reader will first be introduced to the physics and the benefits of LCs and their union with microwave signal processing technology. This will lead, naturally, into the characterization of LC materials in GHz frequencies, and how the filters developed in this study can be used to determine the high-frequency dielectric constant of any material embedded in the filter structures. Prior research performed on LC based planar transmission structures, as well as current research in the field (see Appendix A for a list of the publications associated with this dissertation) will then be discussed. Chapter II is devoted to the complete design, layout, fabrication, experimental characterization, and computational electromagnetic analysis of the bandpass and bandstop filters. In Chapter III the experimental and simulated results of the LC based bandpass and bandstop filter devices will be given. Last, the work will be
summarized in Chapter IV and suggestions for future research directions will be expounded upon.

**Liquid Crystals**

Liquid crystals (LCs)\textsuperscript{44,45,46,47} are exotic materials composed of anisotropic molecules which, under the right conditions, have a phase resembling both that of a conventional liquid and crystalline solid. They are used primarily in visible-light applications, most notably liquid crystal displays (LCDs)\textsuperscript{48,49} which are built into our televisions, laptops, smartphones, electronic tablets, and watches. Other LC applications include cholesteric and CO\textsubscript{2} lasers, metamaterials, tunable spatial modulators for laser beam steering and holography, lenses, photonic fiber, and much more.\textsuperscript{50,51,52,53,54,55,56,57,58,59} LCs also find non-optical applications spanning the fields of medicine, biology, nanotechnology, and material science.\textsuperscript{60,61,62} A brief history of LCs is provided in Appendix B.

LCs may be divided into two classes, namely, thermotropic and lyotropic LCs. For a thermotropic LC, relevant to this presented work, the LC phase exists in a specific temperature range where all of the LC phase transitions occur. Figure 1.1 illustrates the progression of phases in a liquid crystal material as temperature is increased. At low temperatures, LC materials behave like a typical solid. In the LC

![Figure 1.1. Illustration of the solid, liquid crystal, and liquid phases of the thermotropic, nematic liquid crystal.](image-url)
phase, however, the molecules making up the LC are able to flow around—similar to that of a conventional liquid. The temperature is high enough that the intermolecular forces between the molecules are not strong enough to keep the molecules close together as in a solid. Hence, the LC is able to take the shape of its container like a liquid can. Unlike a conventional liquid, however, the molecules have a preferred direction. Instead of pointing in completely random directions, the molecules tend to align themselves more or less in the same direction. This is reminiscent of the behavior of molecules in a crystalline solid. If the temperature is raised high enough, the LC eventually undergoes a phase transition to the isotropic, liquid state. In this case, the adjacent molecules are oriented in random directions and the LC behaves like a liquid.

Many types of LCs exist with wide ranging molecular shapes, sizes, and organization, and there are many types of LC phase transitions as well. The LCs are all composed of anisotropic molecules (e.g., rod-shaped, disk-like, and bent-core). One of the most common phases in thermotropic LCs is the nematic phase. An LC in the nematic phase has calamitic, or rod-shaped, molecules that align with one another, forming a long-range directional order that may be described with the nematic director $\mathbf{n}$. Nematic LCs have a uniaxial symmetry, so that in a homogeneous LC medium, the LC appears to be the same when a rotation is performed around the director. Like other LCs, they tend to align themselves with electric and magnetic fields, acoustic fields, temperature, surfaces, and impurities because of their shape anisotropy and dielectric properties. The orientation of the molecules is important, as it affects the dielectric constant of the LC as seen by an electromagnetic wave used to probe the material. Typically, one controls the
dielectric constant of a thin film of LC by applying a voltage across it, to reorient the molecules.

A simple way to do this is to “sandwich” the LC between two pieces of glass coated either with Indium Tin Oxide (ITO) or copper (Cu) (see Figure 1.2). Such a configuration is referred to as a “liquid crystal cell.” On each glass there is a layer of polyimide used to align the LC molecules. The polyimide is rubbed mechanically in one, uniform direction with a velvet cloth. This establishes grooves in the polyimide which aligns and anchors the LC molecules along the direction of rubbing. This is known as planar alignment and is illustrated in Figure 1.2(a)). The two substrates are put together in an anti-parallel fashion with a specified gap between them, and a capillary tube is used to insert the LC between the two substrates. The layer of LC immediately adjacent to the polyimide experiences an anchoring force which tends to extend self-alignment to the molecules. In this state, the LC relative permittivity, sensed by an electromagnetic wave used to probe the LC, is $\varepsilon_{\parallel}$. When a voltage is applied across the LC, the molecules start

![Figure 1.2. AutoCAD illustration of the cross-section of a LC cell when LC molecules are a) aligned with the polyimide, and b) fully biased with an electric field. Drawing not to scale.](image)
to follow the electric field. At full saturation, which typically requires an electric field on the order of 1 V/μm, the molecules are fully aligned with the field; this state is known as homeotropic alignment (see Figure 1.2(b)). Here, the LC has a relative permittivity of $\varepsilon_\perp$, as sensed by the electromagnetic waves. The difference between these relative permittivity values is known as the dielectric anisotropy, $\Delta \varepsilon$, and may be either positive or negative. If $\Delta \varepsilon$ is positive, then minimum relative permittivity occurs when the LC molecules are in the planar alignment.

This technique of containing the LC and controlling it with a voltage can be used to study the electric field induced birefringence, $\Delta n$, and the switching time, $\tau$, of the LC material, among many other properties.

When an electromagnetic wave passes through a LC layer biased with an electric field, the wave undergoes an electric field induced optical phase shift, $\delta$, described by the equation,

$$\delta = \left(\frac{2\pi}{\lambda}\right) (\Delta n) h,$$

(1.1)

where $\lambda$ is the wavelength of the electromagnetic wave, and $h$ is the height of the LC layer. LCs with higher $\Delta n$ are desirable because of the increased optical phase shift and the ability to use a thinner LC layer. A thinner LC layer helps with conservation of LC material and also improves the switching time, $\tau$, of the LC devices, which is the time it takes to rotate the nematic director (direction of average molecular orientation) of the LC molecules from the planar to homeotropic alignment, and then back to planar alignment. When a high enough voltage is suddenly applied across the LC layer, the LC molecules rotate from the planar to homeotropic alignment over a time interval $\tau_{ON}$.

$$\tau_{ON} = \frac{\gamma h^2}{\epsilon_0 |\Delta \varepsilon| (\gamma^2 - \pi^2 K_{ll})},$$

(1.2)
where \( \gamma \) is the rotational viscosity, \( h \) is the LC cell gap (LC height), \( \varepsilon_0 \) is the permittivity of free space, \( U \) is the driving voltage, and \( K_{ii} \) are the elastic constants.\(^{44,45,46,47,48}\) The time \( \tau_{ON} \) is shorter if the LC material has lower rotational viscosity or a higher elastic constant. To reduce the time \( \tau_{ON} \), the driving voltage, \( U \), can be increased or a LC with lower Freedericksz transition voltage, \( U_{th} \), can be used.\(^{44,45,46,47,48}\) This transition may be explained briefly: the LC molecules do not begin to change orientation until the field reaches a threshold value, \( U_{th} \), which is dependent on the elastic constant \( K_{ii} \) and effective dielectric anisotropy, \( \Delta\varepsilon \), of the LC:

\[
U_{th} \sim \sqrt{\frac{K_{ii}}{\Delta\varepsilon}}, \tag{1.3}
\]

When the power is turned off and the LC layer is no longer biased with an electric field, the LC director returns to the planar orientation. This reorientation is typically a much longer process than \( \tau_{ON} \), by as much as an order of magnitude and is usually the hindering factor in the switching time of the LC. The time, \( \tau_{OFF} \), that it takes for this relaxation to occur is,\(^{44,45,46,47,48}\)

\[
\tau_{OFF} = \frac{\gamma h^2}{\pi^2 K_{ii}}, \tag{1.4}
\]

and so the total switching time, \( \tau_{switch} \), is

\[
\tau_{switch} = \tau_{ON} + \tau_{OFF}. \tag{1.5}
\]

Clearly, the time of relaxation is solely dependent on the visco-elastic properties of the LC as well as the thickness of the cell height, since no voltage is used to drive it.

**Liquid Crystal Microwave Devices**

It turns out that the technique of containing a LC between two substrates and applying an electric field across it can also be used with planar microwave devices. This
may be done by forming an inverted microstrip structure, in which the LC is confined between a ground plane and a substrate supporting the microstrip (see Figure 1.3). By applying an AC bias voltage across the LC layer, the nematic director can be rotated from the planar alignment to the homeotropic alignment parallel with the electric field, as explained above. Electromagnetic waves propagating through the LC medium (along the microstrip) sense a different orientation of the molecules as a voltage is applied. This changes the propagating signal’s wavelength. By applying a voltage across the LC, the wavelength of the propagating wave may be shortened relative to the physical length of the microstrip structure. Such behavior can be utilized to tune the resonant frequency of filters, which will be explained in more detail in Chapter II. Obviously, one can not design such a filter without first knowing the dielectric properties of the LC in GHz frequencies, which in itself represents a challenge. There is a need for the development of a quick and easy method to measure the dielectric constant of LC materials in GHz.

Figure 1.3. Perspective view of an inverted microstrip structure containing liquid crystal, prepared in CST Microwave Studio.
frequencies. Conveniently, the LC based filter devices made in this study provided an
effective technique for achieving this goal.

**Dielectric Characterization in Microwave Frequencies**

Measurement of the frequency-dependent dielectric properties of LCs is well-
established for the visible range or for frequencies below 1 MHz.\(^6^3\) In contrast, there is
no standard method for this measurement in the 1 – 1000 GHz range. There are a number
of fundamental issues associated with this frequency range. First, bulk-like
measurements (cavity based) at lower frequencies require large amounts of material (1
cm\(^3\)) which is not appropriate for large-scale testing of rare materials.\(^6^4,6^5\) In the 250 GHz
– 1 THz range one can use infrared spectroscopy schemes, but this still requires up to 200
mm\(^3\) of material.\(^6^6\) Various resonator methods (e.g. open type and circular disk type)
work at GHz frequencies but are primarily intended for low-loss sheets, printed circuit
board (PCB), ceramics, and powders, while only providing information at one frequency
data point.\(^6^7,6^8\) One study that characterized LCs at microwave frequencies was carried
out by O. H. Karabey.\(^6^9\) Again, a cavity perturbation method\(^7^0\) was used to determine the
relative permittivity and electrical loss tangent of the LC. The measurement, however,
was limited to 30 GHz.

While in the presented work our attention is concentrated on the development of
millimeter wave bandpass filters, it will also be described how the developed structures
can be employed to determine the dielectric properties of LCs in GHz frequencies. The
new metrology involves using resonance structures embedded in microstrip waveguides
that together with a vector network analyzer (VNA) allows, in principle, characterization
of LC materials up to 750 GHz. Furthermore, the ultra-small waveguides significantly concentrate the energy of the input wave, creating oscillating electric fields with amplitude on the order of 1 V/μm. This allows one to probe both the linear and nonlinear dielectric coefficients at these frequencies, something that has never been done for this frequency range. Therefore these structures may be used to explore new physics and as a result, high power applications of these materials could emerge. Finally, nearly all LC materials used in this study were developed keeping in mind applications in visible or near-infrared (IR) frequencies. This means that LC material properties are not optimized for GHz frequencies. Currently, one simply selects a LC material from existing ones and tries to utilize its properties in a completely different spectrum of electromagnetic frequencies for which the material was developed. Due to the small size of our structures, the estimated volume of LC material used is only 1-2 mm³, which is less material than what is used in existing methods by a factor of 100. This is important because preparing small amounts of many new LCs (containing up to 20 different chemical compounds) is feasible and cost-effective. Thus, this new evaluation method, which makes it possible to rapidly determine LC properties, will allow chemists to choose the optimal path of synthesis for new materials with the goal to optimize performance for applications in GHz frequencies.

Motivation for Liquid Crystal Based Filters in the Industry

From the point-of-view of the signal processing industry, the presented filter devices based on LCs have various advantages over other reconfigurable filters. Compared with filters based on garnets, spinels, or ferrites, which utilize a magnetic field
for tunability, the LC filter devices are very light-weight and power efficient as an
electric field is used for tuning (typically less than 1 mW of power is required). The
ferroelectrics (e.g. barium strontium titanate) based filters may also be light-weight and
power efficient, but their operational frequency is limited typically to 40 GHz.
Mechanical methods for tuning (e.g., MEMS) are promising because of their low power
consumption and wide frequency range of operation, but are sometimes subject to
problems like sticking. LC filters on the other hand, may be tuned with either an electric
or magnetic field. They have low inherent losses, large dielectric anisotropy (and
therefore tunability), low power consumption, and small size. LCs also take the shape of
their container and are therefore easy to integrate in many designs. Furthermore, the
manufacturing processes created for the LCD industry make it possible to rapidly deploy
LC-based microwave technology. This makes LCs an even greater candidate to be used
as a dielectric for tuning the resonant frequencies in filters.

Although LCs are typically designed for visible-light applications, an
understanding of the correlation between their molecular structure and behavior in the
near infrared, far infrared, and millimeter wave frequency range is beginning to develop.
Upon synthesizing the materials, their figure of merit parameter relating modulation
(related to optical anisotropy) with the absorption and dichroism can be determined to
further optimize the molecular structure of the LCs for microwave and millimeter wave
applications. Fortunately, the existing molecular structure of the LCs reported in this
study makes the LCs largely suitable for these applications.

There are many examples of the types of applications that can emerge from this
new technology. Imagine during wartime, for instance, an enemy using a signal to jam a
system of antennas (based on LC) at a specific frequency. Then a voltage can be applied across the LC to tune its relative permittivity, thereby changing the center frequency of the antennas to be used. The same concept would also be helpful in the more common case where unintentional interference disrupts a communications or radar system. Other applications include collision-avoidance radar systems for automobiles or unmanned aerial vehicles (UAV), or all-weather landing radar systems on aircraft. Environmental conditions (e.g. outside temperature) could de-tune the antenna systems being used in these technologies; by applying a voltage across the LC, the system can be returned to the desired frequency. LCs could one day become an integral component in filter devices, and other microwave signal processing technologies, to the same degree that they are used in optical technologies today.

Prior Research on Liquid Crystal Microwave Devices

LC based microwave devices are reported in peer-reviewed literature from the early 1990’s. Examples of devices built include phase shifters (delay lines), various types of bandpass and bandstop filters (open stub, spurline, coupled line, coupled ring), patch antennas, linear phased arrays, and others. A brief description of the prior research completed on some LC based microwave devices is provided in the following sections.

Liquid Crystal Phase Shifters. Phase shifters are one of the first microwave structures based on LCs, making their appearance in the early 1990’s. One of the earliest examples includes a phase shifter developed in 1993 by Dolfi et al., which consisted of a 4 cm long microstrip line deposited on alumina substrate and
overlayed with the K15 LC (Merck). With a field of 0.13 V/μm applied across the LC, they obtained a phase shift of 20° at 10.5 GHz. In the same year another group, Lim et al.,\textsuperscript{29} integrated the LC BDH-E7 in a 2.5 cm long, modified 30 GHz WR28 rectangular waveguide acting as a phase shifter. A center plane electrode inside the waveguide was used to apply a modulating electric field across the LC. Two permanent magnets with magnetic field of 5 kG were also placed across the waveguide with the magnetic field transverse to the phase shifter, to control relaxation of the LC molecules. 200 V was needed to achieve a phase shift of 125°.

Phase shifters at UCCS have also been developed. Garbovskiy et al.,\textsuperscript{31} for example, made an 8 mm long LC based phase shifter based on the LC, W1825. The phase shifter had an inverted microstrip geometry. The phase shift achieved, with a DC voltage of 10 V, was 0-300°/cm at 110 GHz (true time delay of 2.5 ps/cm at all frequencies). Since the LC is essentially non-dispersive in the microwave frequency regime, it was argued that a phase shift of 600°/cm at 220 GHz could theoretically be achieved. Many LC phase shifters, in addition to the ones reported above, have been produced since and motivated researchers to look into the possibility of developing other planar microwave structures, including filters.

**Liquid Crystal Bandpass Filters.** Tunable LC-based bandpass filters are relatively new and have been developed by other research teams during the last decade (since 2006).\textsuperscript{25,74,75,76,77,78} Bernigaud et al.\textsuperscript{74} have developed a half-wavelength, open-circuited stub resonator using Merck K15 LC. Its central passband frequency was near 10 GHz and was tuned by 100 MHz with a DC voltage. In addition, they developed a dual-behavior resonator filter (a filter with two parallel, open-circuited stubs of different lengths) based
on Merck BL037 LC with central frequency of 5 GHz. It was capable of tuning by 300 MHz and its $S_{21}$ transmission ranged from -4 to -6 dB in the passband region. Structures developed by Torrecilla et al.$^{76}$ achieved 7.3% tuning of a 5 GHz central passband frequency using the Merck MDA-98-1602 LC and a microstrip square patch resonator with a central square notch. $S_{21}$ transmission in the passband was approximately -7 dB. Goelden et al.$^{77}$ designed a 3-pole filter at 20 GHz with 10% tuning capability and passband insertion loss of -9 to -11 dB. Finally, 3-stub filters based on LC W1825 with passband frequencies of 80 and $>$110GHz have been developed by Lovejoy.$^{25}$ These filters were tunable by 12% and had a passband insertion loss of -8 dB.

**Liquid Crystal Bandstop Filters.** LC-based notch filters have been reported in the literature only in the last few years (early 2010’s).$^{79,80,81,82}$ Torrecilla et al.,$^{79}$ for example, developed a spiral spurline microstrip filter combined with the nematic LC 1631E,$^{83,84}$ in which the central notch frequency could be tuned from 3.75 to 3.40 GHz using 12 V AC bias. The insertion loss, $S_{21}$, ranged from -16 to -20 dB in the stopband throughout its tuning range. Cai et al.$^{80}$ engineered a wideband microstrip bandstop filter employing a double-stub bending structure. 20 V AC bias was used to tune the central frequency from 4.135 to 3.845 GHz. Its rejection level had approximately -40 dB insertion loss. Skulski and Szymańska$^{81}$ developed an inverted microstrip bandstop filter with a branching structure based on the liquid crystal W1825.$^{83,84}$ The filter response showed an insertion loss level of -60 dB. The stopband was tuned from roughly 2.5 to 2.2 GHz. Finally, Urruchi et al.$^{82}$ developed a standard spurline in inverted microstrip geometry with a central stopband frequency which could be tuned from 4.85 to 4.45 GHz using 15 V AC bias. Its minimum stopband insertion loss ranged from -23 to -25 dB.
Current Research: Liquid Crystal Based Filters

Device Requirements. The results from the latest studies mentioned above motivated us to design LC based bandpass and bandstop filters at GHz frequencies with: 1) improved return and insertion loss, 2) higher resonant frequencies, 3) greater tuning capacity (specifically with AC biasing), 4) alternative microstrip geometries, and 5) better control of the bandwidth. The LC-based bandpass filters described in the section on prior research had relatively poor transmission in the passband region. The best result found was -4 to -6 dB by Bernigaud et al. The highest central passband frequency reported in peer-reviewed literature was 20 GHz by Goelden et al. Therefore, we aimed to demonstrate proof-of-concept bandpass filters with higher passband frequencies and better passband transmission. Table 1.1 shows the performance criteria we had in mind when developing the bandpass filter devices.

Table 1.1: Bandpass (open stub) filter performance expectations

| Central passband frequency, \( f_1 \) | 30, 50, and 85 GHz |
| Q-factor (based on -3 dB passband width) | 6 |
| Passband insertion loss, \( S_{21} \) | -3 dB |
| Passband return loss, \( S_{11} \) | -10 dB |
| Tuning capacity (with respect to \( f_1 \)) | 12% |

As for the prior research on LC-based bandstop filters, most of the filters operated under 5 GHz and had good tunability and stopband insertion loss. However, to our knowledge, there are no reports of LC-based notch filters in the peer-reviewed literature at higher frequencies. Since typical LCs have a low electrical loss tangent and lack inherent resonances up to THz frequencies, they could be useful in microwave devices at much higher frequencies. Furthermore, the above mentioned studies do not report on the
measured return loss in the S-parameter characterization of the filters, which is helpful for understanding the impedance match of the filter device. Therefore, we set out to design bandstop filter structures with certain device requirements in mind, which are outlined in Table 1.2.

**Table 1.2:** Bandstop (spurline) filter performance expectations

<table>
<thead>
<tr>
<th>Specification</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central stopband frequency, $f_0$</td>
<td>30, 50, and 85 GHz</td>
</tr>
<tr>
<td>Q-factor (based on -3 dB passband width)</td>
<td>4</td>
</tr>
<tr>
<td>Stopband insertion loss, $S_{21}$</td>
<td>-60 dB</td>
</tr>
<tr>
<td>Stopband return loss, $S_{11}$</td>
<td>-10 dB</td>
</tr>
<tr>
<td>Tuning capacity (with respect to $f_0$)</td>
<td>6%</td>
</tr>
</tbody>
</table>

**General Engineering and Design Process.** The entire experimental process behind the research in this presented work can be organized into device design, fabrication, characterization, and analysis. These steps are explained in great detail in Chapter II and III. However, the “big-picture” process of designing and manufacturing the filter devices will be presented here. Figure 1.4 shows the process used to engineer and design the filter structures. First, the filter performance requirements (outlined above) and materials must be determined before designing the filter structures. Then, the physical dimensions of the filter structures can be approximated with the performance requirements and material parameters in mind. Given these dimensions, a 3D model of the filter structure is created and simulated with computational electromagnetics software; in this study, CST Microwave Studio is used. Since the filter dimensions initially obtained may not yield the desired performance results in the simulations, post-processing is performed in CST to further optimize the filter performance. This involves tweaking the filter and microstrip dimensions to obtain the desired resonance frequencies, passband width,
passband and stopband transmission and reflection characteristics, as well as impedance match to the industry standard of 50 Ω. Once the dimensions of the filter structures are completely optimized, a 2D model of the filter structure is produced in AutoCAD to prepare for the first steps in the fabrication process. Production of the photomask on a 5” by 5” glass was outsourced to a local company that furnishes 1 µm feature resolution.

**Figure 1.4.** Engineering and design process of filter devices.

**General Fabrication Process.** Once a model of the filter is successfully created and optimized with CST Microwave Studio, the device fabrication process, shown in Figure 1.5, can begin. The first major steps in this process, once the materials and photomasks are obtained, is photolithography and thin film deposition. Similar to using a stencil to produce images on a surface, with photolithography a photomask is used to project ultraviolet (UV) radiation on a light-sensitive chemical photoresist which is spin-coated onto glass. The photomask consists of a patterned Cu thin film on glass that will
eventually be reproduced. In the case for negative photolithography, the UV radiation changes the chemical structure of the photoresist so that it is insoluble when it’s exposed to a chemical developer at the end of the photolithography process. The unexposed regions, however, are soluble; once the sample is fully developed, the structures are left behind in the photoresist. Thin film deposition is then carried out to deposit a thin film of copper (using stainless steel as an adhesion layer) onto the photoresist pattern. A chemical lift-off treatment is then performed to remove the photoresist and residual copper, leaving behind the metallic structures. After this, the structures are inspected under a microscope to check for quality. If residual copper strands or “hangers” are present on the structures, then they are rubbed off with a plastic foam swab. Finally, the glass substrates with patterned copper are put together using liquid crystal cell assembly methods. These device fabrication steps, including the engineering, design, and characterization techniques, will described in greater detail in Chapter II.

Figure 1.5. Device manufacturing process.
The quality of these devices and their performance depend a great deal on the material parameters, especially the relative permittivity of the materials being used at microwave frequencies. Consequently, engineering these devices became an iterative process. The relative permittivity values of LC1917 and LC2020 were initially unknown. Once the filter structures were made, the resonance frequencies of the bandpass filters allowed us to more accurately determine the LC permittivity, as described earlier in this chapter. With more accurate values of the permittivity, the devices were redesigned and rebuilt to obtain better results.
Overview

In the sections ahead, I report on the development of the tunable open stub and double spurline filter devices based on the LC1917 and LC2020, with resonant frequencies centered at 30, 50, and 85 GHz. I will first go in depth into the physics and engineering design of the filter devices developed in this study. This includes not only the design of the exact filter structures, but of the coplanar waveguide (CPW) and microstrip structures that feed into the filters. Since the design requires knowledge of the relative permittivity values of the materials used to construct the LC devices, I will go in depth into the technique used to characterize LCs in the GHz frequency regime. I will then go into a description of the manufacturing processes used to assemble the filter devices. Finally, I will discuss the vector network analyzer (VNA) and AC bias test setup used to characterize the performance of the devices.

Open Stub Filter Design

The LC based devices typically require two physical surfaces (substrates) between which a LC material is confined. Figure 2.1 shows the basic AutoCAD layout of a LC cell containing the microstrip filters (designed for $f_1 = 30$ GHz). Shown at the top of the drawing is the LC cell consisting of two substrates: microstrip filters and CPW structures deposited on the bottom glass (in orange) and the top ground plane (outlined by blue, dashed lines). A LC material is confined between the top and bottom substrates. I discuss below how to design and construct the LC based bandpass filter in this geometry.
An extensive design theory of bandpass filters may be found in the literature.\(^1,2,3,5,90,91,92,93,94,95,96,97,98,99\) The stub filters in this study utilize a cascade of open-circuited, half-wavelength stubs bridged by quarter-wavelength connecting lines (see Figure 2.1). In the passband, electromagnetic waves propagating through the filter undergo constructive interference due to the \(\lambda/2\) stubs. Starting with the basic equation for constructive interference, the length of an individual stub for a desired passband frequency is determined by

\[
L_{\text{stub}} = \frac{c}{2f_1\sqrt{\varepsilon_{\text{eff}}}},
\]

where \(L_{\text{stub}}\) is the physical length of a stub, \(c\) is the speed of light in vacuum, \(f_1\) is the midband frequency of the filter’s passband, and \(\varepsilon_{\text{eff}}\) is the effective permittivity of the microstrip line with dielectric overlay. The length of a connecting line is \(L_{\text{cl}} = L_{\text{stub}}/2\).
In addition to the primary passband frequency, there are secondary passband resonances at integer multiples of $f_1$ (e.g. $f_2 = 2f_1$, $f_3 = 3f_1$, etc.). Stopbands are also naturally located at the frequencies $f_1/2$ and $3f_1/2$ and can be adjusted by enforcing a varying admittance throughout the length of each stub.²

For the given physical length of the stub (see Equation (2.1)), it is clear that the passband frequency, $f_1$, may be tuned by varying $\epsilon_{eff}$ of the microstrip. This is accomplished by applying an electric field across the LC layer, thereby increasing the LC relative permittivity, $\epsilon_{LC}$. This increasing effective permittivity leads to shortening of the signal wavelength relative to the stub’s physical length and, consequently, to a decrease in the passband frequency. Clearly, in order to design such a filter, a method must be employed to determine the dielectric constant of the LC in GHz frequencies. This will be described in the next section.

**Metrology of Liquid Crystal Materials in GHz Frequencies**

As mentioned in Chapter I, LC materials are typically designed and fabricated for the optical or near infrared frequency spectrum of electromagnetic radiation. However, recently these materials have started to attract attention for applications in GHz frequencies, making it necessary to understand their properties in this spectrum range. Below we outline the procedure that allowed us to determine the relative permittivity values of the LC materials as a function of the frequency in designed filter structures. While we present results obtained at room temperature, we note that these measurements can be carried out at different temperatures (for example -55 to 125°C) by utilizing a temperature stage.
Figure 2.2 illustrates how 30 GHz filter structures can be used to determine the dielectric properties of LC materials. It depicts the frequency dependence of S-parameters, $S_{11}$ (reflection) and $S_{21}$ (transmission). The clearly visible resonances are the first three harmonics associated with a given geometrical length of the open stub. The 4\textsuperscript{th} resonance is just outside of the VNA measuring range (0.05-110 GHz). Using a different VNA set-up that allows measurements in a frequency range above 110 GHz would reveal higher harmonics. The resonance frequencies (see Eq. (2.1)) are only determined by the value of effective permittivity that combines the properties of both substrate and LC materials. To determine relative permittivity of the LC materials one needs to first know the properties of the substrates as a function of frequency. This can be accomplished by building a filter structure that uses air (instead of LC materials) as a dielectric medium through which electromagnetic waves propagate. In such cases one can determine dispersion relations of the substrate material (in our case, Borofloat 33 glass) because the effective permittivity of the microstrip can be approximated using an analytical formula\textsuperscript{100} derived for microstrip lines with multi-layered dielectrics under assumption of quasi-TEM mode propagation or by modeling using, for example, CST software.\textsuperscript{101} The determined value
of $\varepsilon_{\text{eff}}$ depends on the known relative permittivity of air (1.000569 up to 30 GHz\textsuperscript{102} – for all practical reasons can be set to 1) as well as the glass relative permittivity. Knowing the permittivity of the substrate as a function of frequency allows one to measure the relative permittivity of LC materials or other materials repeating the above described procedure.

We illustrate below how to determine the values of $\varepsilon_\parallel$ and $\varepsilon_\perp$ of the LC materials. First a filter structure with known dimensions was built and the S-parameters were measured as a function of frequency (to be discussed later). The observed resonances of both the unbiased and fully saturated LC were then compared with simulations performed on a modeled filter for various values of the LC relative permittivity. Figure 2.3 shows how a change in LC relative permittivity affects the frequency of the first resonance as predicted by CST modeling. This approach allowed us to determine the relative permittivity of LC materials from the measured resonances. Repeating this procedure for higher harmonics allows one to measure a dispersion relation of the measured materials. Building structures with lower fundamental frequency $f_1$ would provide more experimental data points than the three observed resonances in the currently built
structure. On the other extreme, structures with a higher fundamental frequency \( f_1 \) would yield resonances that are more spread out. As seen in Figure 2.4, a filter whose primary passband is located at 50 GHz also has a secondary resonance at 100 GHz. However, this starts to fall out of the range of our VNA.

In GHz frequencies, \( \varepsilon_\perp \) and \( \varepsilon_\parallel \) of both LCs studied (LC1917 and LC2020\textsuperscript{84,103,104}) were found to be 2.76 and 3.70, respectively (\( \Delta \varepsilon = 0.940 \)). We have confirmed that the LCs are approximately non-dispersive by experimentally observing that the second and third passbands are at nearly integral multiples of the fundamental frequency, \( f_1 \). As mentioned above, this technique can be used also to measure properties of solids. For example, for our work we have determined the relative permittivity of the solid layer of Norland Optics glue (NOA68T) that enabled us to design the transition from CPW to microstrip geometry as discussed later in this chapter. Figure 2.5 shows the S-parameters versus frequency of a three-stub filter structure filled with the NOA68T photopolymer, at room temperature. The filter structure developed for this experiment was designed to have a central passband frequency of 60 GHz and was intended for LCs with a relative permittivity range of 4.5 to 6; its geometry was based on

![Figure 2.4. The measured frequency response dependence of S-parameters on a biased three-stub, 50 GHz filter structure filled with LC2020 at room temperature.](image)
the designs from Lovejoy.\textsuperscript{25} The glue was inserted by capillary tube into the filter device (on a hot plate, to lessen the viscosity) and then cured with UV irradiation. When measured with the VNA test set-up, the primary resonance was found to be at 76.2 GHz instead of 60 GHz. Compared with CST simulations of Lovejoy’s filter structures at various relative permittivity values,\textsuperscript{25} the relative permittivity of the NOA68T glue was found to be equal to 3 (conveniently close to the center permittivity of LC2020). Finally, it should be noted that the filter device made for this experiment had a poor impedance match (-21 dB insertion loss in the passband). However, this has no effect on the location of the resonances, which depend solely on the relative permittivity of the glue.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2_5.png}
\caption{The measured frequency response dependence of S-parameters on a three-stub, “60 GHz” filter structure filled with cured NOA68T Norland Optics glue at room temperature.}
\end{figure}
Determination of Stub Dimensions

**Stub Lengths:** All LC devices were designed using the mean permittivity value, defined as

\[ \epsilon_c = \frac{\epsilon_\parallel + \epsilon_\perp}{2}, \]

of the LC in order to minimize impedance mismatching as the LC is tuned from its unbiased state to its fully saturated state. The effective permittivity of the microstrip, determined from the relative permittivity value of Borofloat 33 and \( \epsilon_c \) of the LC material, was 3.66. This value was used to determine the stub lengths of the 30, 50, and 85 GHz filters employing Equation (2.1); the stub length needed to achieve a passband at 30 GHz is 2633 μm (see Figure 2.1). The filters with passband frequencies of 50 and 85 GHz (not shown) have stub lengths of 1568 and 922 μm, respectively.

**Stub Widths:** Initially the stub widths used in this study were chosen based on prior work performed on LC-based open stub filters. In the prior study, standard filter synthesis equations were implemented in a MATLAB code to obtain the impedances of the individual stubs and connecting lines. Then a CST model of the filter was created and the stub widths were varied to obtain the desired stub impedances, while maintaining 50 ohms impedance in the overall structure. After optimization, the widths of the center and outer stubs of the filters were 194.8 and 275.1 μm, respectively.

However, later work was performed in this study to obtain a simpler method for approximating the stub widths. With this method, the stub widths in the bandpass filters were approximated by equating the capacitance of a parallel-plate capacitor with that of a low-pass, prototype Butterworth filter. An individual, rectangular stub branching from the microstrip line resembles that of a parallel-plate capacitor with capacitance,
\[ C_{stub} = \frac{\varepsilon_0 \varepsilon_{eff} LW}{d}, \]  
where \( \varepsilon_0 \) is the permittivity of free space, \( \varepsilon_{eff} \) is the effective permittivity of a microstrip structure with dielectric overlay, \( L \) is the length of the stub, \( W \) is the stub width, and \( d \) is the thickness of LC between the stub and the ground plane.

The capacitance of a reactive component, \( k \), in a cascaded \( n^{th} \)-order low-pass Butterworth filter is derived by Lee\textsuperscript{5} as,

\[ C_k = \frac{b_k}{\omega_p R}, \]  
where \( R \) is the impedance of the stub and \( \omega_p \) is the low-frequency passband edge of the filter. The quantity \( b_k \) may be expressed as

\[ b_k = 2 \left( 10^{\frac{|S_{21}|}{10}} - 1 \right)^{\frac{1}{2n}} \sin \left[ \frac{(2k-1)\pi}{2n} \right], \]  
where \( S_{21} \) is the specified insertion loss in the passband, \( n \) is the number of independent energy storage reactive elements (stubs), and \( k \) ranges from 1 to \( n \).

By equating the Equations (2.3) and (2.4), one may obtain the outer stub width (first and third stub) in a three-stub LC filter device with low-frequency passband edge of 27.3 GHz. The calculated outer stub width is 260 \( \mu \)m, which is very close to the stub width obtained with the alternative approach.\textsuperscript{25} This provides a starting point for choosing the stub width in a filter. CST simulations can then be performed on a modeled filter to further optimize the stub width to obtain the desired passband characteristics.

From the above Equation (2.4), it is clear that characteristics of the passband are closely related to the capacitance, and therefore width, of the open stub. In Chapter III, results of CST simulations will show how passband width is correlated with the width of the stubs in a filter. There is a great deal of flexibility as to what stub widths may be
selected during the filter design. The stub and connecting line dimensions for the physical 30, 50, and 85 GHz bandpass filters made in this study are summarized in Table 2.1.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Parameter</th>
<th>Length (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Filters</td>
<td>Outer Stub Width</td>
<td>275.1</td>
</tr>
<tr>
<td></td>
<td>Center Stub Width</td>
<td>194.8</td>
</tr>
<tr>
<td></td>
<td>Connecting Line Width</td>
<td>59.7</td>
</tr>
<tr>
<td>30 GHz Filter</td>
<td>Stub Length (All Stubs)</td>
<td>2633.4</td>
</tr>
<tr>
<td></td>
<td>Connecting Line Length</td>
<td>1316.7</td>
</tr>
<tr>
<td>50 GHz Filter</td>
<td>Stub Length (All Stubs)</td>
<td>1567.7</td>
</tr>
<tr>
<td></td>
<td>Connecting Line Length</td>
<td>783.8</td>
</tr>
<tr>
<td>85 GHz Filter</td>
<td>Stub Length (All Stubs)</td>
<td>922.2</td>
</tr>
<tr>
<td></td>
<td>Connecting Line Length</td>
<td>461.1</td>
</tr>
</tbody>
</table>

**Table 2.1:** Open stub filter parameters (actual device)

**Structure Thickness and the Skin Depth Equation**

As a rule of thumb, the thickness of planar transmission structures is typically chosen to be at least five times the skin depth of the material used. The skin depth is defined as,

\[
\delta = \frac{\rho}{\sqrt{\pi f \mu_0 \mu_r}},
\]  

(2.6)

where \( \rho \) is the bulk resistivity of the propagation medium, \( f \) is the frequency of the propagating signal, \( \mu_0 \) is the permeability of free space, and \( \mu_r \) is the relative permeability of the medium. Also, the surface resistivity of the planar transmission structures is defined as,

\[
R_s = \sqrt{\pi f \mu_0 \mu_r \rho},
\]  

(2.7)

Copper was chosen for the planar transmission structures in this project, so as to minimize conductive loss. Its ideal bulk resistivity is \( 1.673 \times 10^{-8} \) Ωm, resulting in a
skin depth of 376 nm (using Equation (2.6) at 30 GHz). However, a simple four-point resistivity measurement performed on a thin film of copper grown with the magnetron sputtering system under 0.5 μTorr revealed the resistivity to be $2.135 \times 10^{-8}$ Ωm. The surface resistivity was 0.05 Ω/square. The lowest passband frequency that the filters are designed for is 30 GHz. Substituting these values into Equation (2.6), it is seen that the skin depth is 425 nm. Therefore, the copper films were grown to at least 2.25 μm to guarantee good signal transmission while conserving on materials during the sputtering process.

As seen in Equation (2.6), the skin depth of the conductor is thinner for higher frequencies. This decreases the microstrip’s effective cross section, leading to increased resistance and reduced transmission of the electromagnetic waves propagating through the structure. This skin depth is where the majority of the charges reside (63% of the current density is located within one skin depth). The skin effect is due to opposing eddy currents induced by the changing magnetic field in the electromagnetic wave. The eddy currents cancel the flow of current in the center of the microstrip, reinforcing it into the skin.

**Inverted Microstrip and Coplanar Waveguide Design**

A coplanar waveguide (CPW) to inverted microstrip transition was utilized at the input and output of the filters to effectively inject the microwave and bias signals into the filter structure (see Figure 2.6). CST simulations were performed to determine the width of a microstrip line necessary to maintain a characteristic impedance of 50 Ω for the center value of LC permittivity, $\varepsilon_c$. 50 Ω was chosen since it is the industry standard. A
large microstrip width and, consequently, a large LC thickness, was chosen to reduce eddy current\textsuperscript{105,106,107} losses in the metallization as much as possible. At the same time, the LC can not be too thick or the LC molecules will lose alignment with the polyimide. Therefore, we chose a 40 \textmu m thick LC cell. The optimal microstrip width, for the 40 \textmu m thick LC layer, was 63.5 \textmu m for obtaining 50 \Omega impedance in the structure. The trace width of the CPW was kept the same at 63.5 \textmu m, and CST simulations were performed to determine the optimal CPW gap width (between signal line to ground). Since glue was needed to seal the LC cells, CPW had to be modeled for both glue and air as the top layers. In the CPW/air region, the gap width was 11.4 \textmu m and gradually tapered to 19.6 \textmu m in the CPW/glue region.

\textbf{Figure 2.6.} Top view in AutoCAD of the CPW-microstrip transition.
The CPW-microstrip transition region is based on the geometry presented by Chen, et al., but further adapted for our work using different material parameters. Figure 2.7 shows a perspective view of the transition built in CST Microwave Studio. It is designed to sustain the characteristic impedance over a wide bandwidth in the transition from CPW to microstrip. The top and bottom-layer ground planes have cut-outs (in the shape of an exponential curve) which are designed to smooth out the electric field distribution of the electromagnetic wave propagating along the planar structures. Such design transitions are necessary to optimize the power transfer of the signals through the filter structure; compared with a more abrupt CPW-microstrip transition, the transmission is improved by 2-3 dB.
Design of Spurline Filter Devices

Bandstop filters are described extensively in the literature. Of the many types of bandstop filters, the spurline filter is one of the most simple in design, known for its moderate bandwidth, highly compact design, and low radiation. The spurline consists of an L-shaped cut-out in a standard microstrip signal line, leaving behind an open-circuit line edge-coupled to the main microstrip feed (as seen in Figure 2.8). In the stopband, electromagnetic waves propagating through the filter destructively interfere, since the open-circuit line is a quarter-wavelength long. Given a desired central notch frequency, the spur length, \( a \), may be calculated as:

\[
a = \frac{c}{4f_0\sqrt{\varepsilon_{eff}}} - l_{eg},
\]

Figure 2.8. AutoCAD drawing showing the details of quarter-wavelength, double-spurline elements designed for notch frequencies of (a) 50 GHz and (b) 85 GHz. All units are in microns.
where \( c \) is the speed of light in vacuum, \( f_0 \) is the desired central notch frequency of the propagating electromagnetic wave, \( \varepsilon_{\text{eff}} \) is the effective dielectric constant of the microstrip with LC overlay, and \( l_{eg} \) is the gap end-effect correction term. The correction term is due to an end fringing capacitance on the resonant element of the filter, and may be approximated as

\[
l_{eg} \approx \frac{cz_0C_f}{\sqrt{\varepsilon_{\text{eff}}}},
\]

where \( Z_0 \) is the characteristic impedance of the microstrip and \( C_f \) is the end fringing capacitance. The spur length determined from Equation (2.8) not only leads to the desired notch resonance, but also yields notch resonances at odd multiples of the fundamental frequency (namely, \( 3f_0, 5f_0, \) etc.). Passband resonances are also located at even multiples of the fundamental frequency, but are very broad in nature.

**Double Spurlines Versus Single Spurlines**

In this study, double spurlines were chosen over single spurlines to improve the attenuation of the electromagnetic waves in the stopband region. Figure 2.9 shows, by CST simulations, the reflection parameter, \( S_{11} \) (dashed curves), and transmission, \( S_{21} \) (solid curves), as a function of frequency of a double spurline filter (red curves) versus a single spurline filter (black curves). The notch frequency is approximately 50 GHz for both filters. As can be seen, the double spurline filter shows greater attenuation in the stopband region than the single spurline filter. At the notch frequency, the stopband transmission achieves -60 dB for the double spurline filter, whereas the single spurline filter reaches approximately -25 dB. Therefore, double spurline filters were preferred for LC cell manufacturing.
Determination of Spur Lengths and End Fringing Capacitance

Using Equation (2.8), the spur lengths for the 50 and 85 GHz filters were approximated by initially neglecting the gap end-effect extension. Models of the double-spurline filters were then created in CST Microwave Studio. Double-spurlines, spaced apart slightly less than a quarter-wavelength from each other, were chosen over single-spurlines to improve the notch filter performance. The gap between the coupled lines in the spurline filters was 14 μm (for both the 50 and 85 GHz filters). The CST time domain solver with Finite Integration Technique allowed us to simulate the S-parameters of the filter structure. Afterwards, post-processing was carried out in CST to fine-tune the spur lengths necessary to obtain the desired central notch frequencies (thereby accounting for the gap end-effect extension). The discrepancy between the initial calculations of spur length with the post-processed length revealed the upper limit of the gap end effect extension to be 54.4 and 46.2 μm for the 50 and 85 GHz filters, respectively. Using Equation (2.9), we determined that the end fringing capacitance is approximately 6-7 fF.

Figure 2.9. CST simulation of the reflection, $S_{11}$ (dashed curves), and transmission, $S_{21}$ (solid curves), versus frequency of a 50 GHz spurline filters. The red curves represent the double spurline filter, while the black curves represent the single spurline filter.
Once the filter dimensions were optimized, a photomask model was created in AutoCAD to prepare for manufacturing. A rendering of the two quarter-wavelength, double-spurline filters is presented in Figure 2.8. The optimal spur length of the 50 GHz spurline filter (see Figure 2.8(a)) was 724.4 µm. The spur length of the 85 GHz filter was 410.4 µm (see Figure 2.8(b)).

The final integration of the spurline microstrip filters into a LC cell is shown in Figure 2.10. The design of the CPW-microstrip transition and general LC cell assembly is the same as the design-work presented earlier for the bandpass filters. The spurline filter parameters are summarized in Table 2.2.
Table 2.2: Spurline filter parameters (actual device)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Parameter</th>
<th>Length (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Filters</td>
<td>Gap Between Coupled Lines</td>
<td>14</td>
</tr>
<tr>
<td>30 GHz Filter (not made)</td>
<td>Spur Length</td>
<td>1202.3</td>
</tr>
<tr>
<td></td>
<td>Gap Between Spurs</td>
<td>1140.3</td>
</tr>
<tr>
<td>50 GHz Filter</td>
<td>Spur Length</td>
<td>724.4</td>
</tr>
<tr>
<td></td>
<td>Gap Between Spurs</td>
<td>692.3</td>
</tr>
<tr>
<td>85 GHz Filter</td>
<td>Spur Length</td>
<td>410.4</td>
</tr>
<tr>
<td></td>
<td>Gap Between Spurs</td>
<td>397.9</td>
</tr>
</tbody>
</table>

Liquid Crystal Materials: 1917 and 2020

Chemical Constituents

The nematic LCs that were used in this study, as mentioned previously, are LC1917 and LC2020. These LCs are modifications of LC W1825\cite{83,84,115} developed a few years ago at the Military University of Technology (MUT), Institute of Chemistry, in Warsaw, Poland. Like many other LCs, they consist of as many as 20 different chemical compounds forming their “ingredients,” which in themselves, mostly consist of hydrocarbons such as benzene rings. With the application for the LC in mind, the individual ingredients are chosen to obtain the desired properties of the LC, such as the nematic-isotropic transition temperature, positive or negative dielectric anisotropy ($\Delta\varepsilon$), elastic constants ($k_{ii}$), resistivity, and chemical and photochemical stability, for example.\cite{84} Both the LC1917 and LC2020 are composed of isothiocyanato-terminated structures. These structures include laterally fluoro-substituted alkyl-oligophenyls (biphenyls, terphenyls), alkyl-tolanes (phenyl-tolanes, biphenyl-tolanes) and alkylcyclohexyl-tolanes.\cite{83,84,103} Detailed information about these individual ingredients and their synthesis can be obtained from the literature on organic chemistry combined
with literature dedicated to the chemistry of LCs. However, a brief description will be given below.

The isothiocyanates referred to above (see Figure 2.11) attach themselves to the ends of functional groups (groups with Hydrogen or Carbon atoms) such as the tolanes and oligophenyls; they are very prevalent in the ingredients of the LC mixtures in this study. By themselves, they consist of cyanides double-bonded with sulfur (NCS) and are classified as weak electrophiles (reagents attracted to electron pairs). They are susceptible to hydrolysis, which is one of the reasons why LCs should be stored in dry environments to extend their shelf life, and why LC devices should be sealed after manufacturing. The primary reason for using isothiocyanates as the terminations (instead of the chemicals F, Cl, CN, CF$_3$, or OCF$_3$, as in other LCs), is because of the higher dielectric anisotropy, higher birefringence, higher nematic-isotropic transition temperature, higher elastic constant, and lower rotational viscosity seen in the overall LC mixture.

The functional groups that bond with the isothiocyanates are the tolanes and oligophenyls mentioned above (see Table 2.3), and they consist of what are called conjugated systems. Conjugated systems have alternating single and double bonds between Carbon atoms (e.g. benzene rings). The double bonds are p-orbitals, which constructively overlap with one another by just the right amount (and are therefore referred to as conjugated) forming a pi-bond. If the double bonds are any further apart
(a.k.a. isolated systems) they are less stable. If they are closer together (a.k.a. cumulated systems) they would be even less stable. In contrast, conjugated systems are very stable. In addition, the electrons from the double bonds in these conjugated systems are delocalized around the entire molecule and are therefore not confined to a single atom.

Table 2.3: A selection of rigid cores for high birefringence liquid crystal molecules.\textsuperscript{84}

<table>
<thead>
<tr>
<th>General Formula</th>
<th>Rigid Core</th>
<th>$\Delta n$ (optical)</th>
<th>Description</th>
<th>Input to $\Delta n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>Biphenyl</td>
<td>$\leq 0.18$</td>
<td>Two benzene rings joined directly</td>
<td>0.09</td>
</tr>
<tr>
<td>-</td>
<td>Terphenyl</td>
<td>$\leq 0.27$</td>
<td>Three benzene rings joined directly</td>
<td>0.09</td>
</tr>
<tr>
<td>-</td>
<td>Tolane</td>
<td>$\leq 0.25$</td>
<td>Two benzene rings triple bonded</td>
<td>0.07</td>
</tr>
<tr>
<td>-</td>
<td>Phenyl Tolane</td>
<td>$\leq 0.34$</td>
<td>Three benzene rings triple and single bonded</td>
<td>0.07</td>
</tr>
</tbody>
</table>

The conjugated ingredients of the LC mixture are highly polarizable and consist of rigid core molecules and chains (consisting of two, three, or four rings), forming the “backbone” of the LC. These long, conjugated systems have large dielectric anisotropy and, consequently, large birefringence. The tolanes and phenyl-tolanes in particular have triple bonds separating the benzene rings (ethynyl bridge). Such a chemical make-up makes these particular LCs excellent as low-absorption materials at microwave frequencies.\textsuperscript{31} Furthermore, the tolanes may be functionalized with polar terminal or lateral substitutes, offering versatility in designing LCs with large birefringence.\textsuperscript{83,117} The
biphenyls and terphenyls consist of benzene rings which are joined directly by single bonds. These, too, contribute to the large birefringence of the LC materials.

In summary, the “big-picture” view of the LC chemical make-up is that the LC consists of many conjugated ingredients (e.g., the tolanes and oligophenyls) which give the LC its structure and high birefringence. Each of these ingredients are selected carefully to tailor the properties of the LC, and those individual ingredients may be modified themselves with polar terminal or lateral substitutes to tailor the birefringence. The birefringence, $\Delta n$, of the LC 1917 and 2020, at 589 nm wavelength, is 0.42 and 0.45, respectively; the $\Delta n$ of the LC2020 is slightly higher because of the conjugated ingredients selected for its mixture.\textsuperscript{118,119}

**Phase Transitions**

The temperature at which these LCs crystallize is typically lower than 0°C. The clearing temperature, corresponding to the nematic-isotropic transition, for LC1917 is higher than LC2020, at 134.1°C and 103.0°C, respectively.\textsuperscript{118,119} Because the LC phase of these LCs exists in a wide temperature range, these materials are highly dependable in environments with varying temperature. Since LC materials could foreseeably be used in many outdoor applications, this is very important. For example, automotive collision-avoidance radar is just one application in which the ambient temperature could affect the performance of such systems.
Switching Time

The time “on” of LC1917 and LC2020, defined as the time that it takes an electric field to reorient the LC molecules from planar to homeotropic alignment, is in the range of 2-5 ms (data not shown). The time “off” of the LCs, defined as the time it takes for the LC molecules to relax back to planar alignment, however, is approximately 10 seconds for a 40 µm thick LC layer. Therefore, the time off is the limiting factor in the total switching time of the LC based devices. If necessary, the time off can be reduced by incorporating in-plane switching to reorient the LC molecules, or by using a smaller LC thickness. Since the time off is proportional to the square of the LC layer thickness, using a thinner LC layer can reduce the reorientation time substantially. Also, using a different class of LC materials such as dual frequency or smectic C* (described in Chapter IV) would reduce the switching time considerably, to a few milliseconds.

Microwave Device Fabrication

Photolithography

Using photolithography,120 the metallic structures were defined on a glass substrate, and copper was deposited by magnetron sputtering, a plasma vapor deposition (PVD) process. Before photolithography, the 1.1 mm thick borosilicate glass (Borofloat 33) was cleaned with acetone, isopropyl alcohol (IPA), and de-ionized water (DIW) to remove contaminants. Residual solvents were removed by baking. A thin film of negative photoresist (AZ nLOF 2035) was spin-coated onto the glass at 2700 RPM for 36 seconds with a 500 RPM/s initial ramp rate, followed by a 110°C pre-bake for 60 seconds. Using an MJB4 mask aligner from SUSS MicroTec (see Figure 2.12), the
metallization pattern was created on glass by exposing a photomask to ultraviolet light for eight seconds, followed by a 110°C post-bake for 60 seconds. Finally, the pattern was developed in AZ 300 MIF developer.

**Photomask Design**

The photomasks (see Figure 2.13 and Figure 2.14) were developed using AutoCAD. Figure 2.13 shows the photomask design of ten different ground structures of the LC cells, while Figure 2.14 shows the photomask design of the inverted microstrip filter structures that correspond to those grounds. The structures on the very far right of each photomask are coplanar waveguides test structures designed specifically for Borofloat 33 glass, which are intended for calibration as well as the LC drop test (to be described in Chapter III). Table 2.4 provides information about the structures found in each cell design of the photomask, starting from the top-left of each photomask and listing down to the bottom-right.
Table 2.4: The structures found on each cell design of the photomasks, reading from the top left to the bottom right.

<table>
<thead>
<tr>
<th>Cell Design</th>
<th>Structures</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Top left)</td>
<td>6 mm, 3-stub bandpass filters (30 GHz)</td>
</tr>
<tr>
<td>2</td>
<td>8 mm, 3-stub bandpass filters (30 GHz), varied microstrip widths</td>
</tr>
<tr>
<td>3</td>
<td>10 mm, 5-stub bandpass filters (30 GHz)</td>
</tr>
<tr>
<td>4</td>
<td>8 mm, 3-stub bandpass filters (30 GHz), varied connecting line specs</td>
</tr>
<tr>
<td>5</td>
<td>5 mm, 3-stub bandpass filters (50 and 85 GHz) and phase shifter</td>
</tr>
<tr>
<td>6</td>
<td>6 mm, 3-stub bandpass filter and phase shifter</td>
</tr>
<tr>
<td>7</td>
<td>8 mm, single/double spur filters (50 and 85 GHz) and phase shifter</td>
</tr>
<tr>
<td>8</td>
<td>10 mm, 5-stub bandpass filters (30 GHz) and phase shifter</td>
</tr>
<tr>
<td>9</td>
<td>8 mm, single/double spur filters (30 and 50 GHz) and phase shifter</td>
</tr>
<tr>
<td>10 (Bottom right)</td>
<td>5 mm, double spur filters (30, 50, and 85 GHz)</td>
</tr>
</tbody>
</table>
Figure 2.13. AutoCAD rendering of the photomask for top substrates (ground planes): “April Filters New Transition – 1TopGND.”
Figure 2.14. AutoCAD rendering of the photomask for bottom substrates (filters): “April Filters New Transition – Main Structures.”
Thin Film Deposition

Using magnetron sputtering,\textsuperscript{121,122} (see Figure 2.15) a 6-7 nm stainless steel 316 (Plasmaterials, Inc.) adhesion layer followed by 2.25 μm copper layer was sputtered onto the substrate. The sputtering was carried out under a base pressure of roughly $10^{-7}$ Torr while 3 mTorr Argon pressure was maintained during deposition. The deposition rate used was approximately 17 nm/minute. After deposition, the substrate was placed in resist stripper for lift-off leaving behind the desired copper pattern. The copper ground planes, which serve as the backing of the LC cells, were also prepared using the above mentioned photolithography and sputtering processes.

Liquid Crystal Cell Assembly

The ground plane and substrate with filters were put together using LC cell assembly techniques\textsuperscript{48,49} modified for our purpose. To prepare an alignment layer, a polyimide
(1:4 solution of RN1744 polyimide:#21 solvent) was spin-coated onto both substrates at 2000 RPM for 30 seconds and baked at 100° C under vacuum for 75 minutes. Vacuum and low temperature was necessary to hinder chemical interaction of the solvent with the copper. After cool-down, the polymer was rubbed mechanically with a rubbing machine (see Figure 2.16) equipped with a velvet cloth drum to create an alignment layer that establishes the unbiased orientation direction of the LC molecules. Thin, conducting tape was situated between every CPW-microstrip transition in order to bridge the CPW grounds with the top ground plane at the end.
of the assembly process. Solid glass microspacers were suspended in IPA and spin-coated at 1400 RPM for 20 seconds onto one of the substrates. The rubbed substrates were then aligned, glued together (with NOA68T photopolymer, Norland Products, Inc.), and irradiated with ultraviolet light for two minutes. The conducting tape was then soldered to the CPW grounds. Finally, a capillary tube was used to fill the cells with the LC under vacuum. Photographs of the complete LC filter devices are shown in Figure 2.17 – Figure 2.20 (courtesy of Dr. Janusz Hankiewicz). For more in-depth procedures on manufacturing LC devices,

![Figure 2.19](image1.png) 1 cm

**Figure 2.19.** Front and back of a partially-filled LC cell with a 50 GHz, open stub filter (left), 85 GHz filter (middle), and microstrip line (right).

![Figure 2.20](image2.png) 1 cm

**Figure 2.20.** Front and back of a LC cell with 5-stub, 30 GHz open stub filters.
please reference Appendix C.

Experimental Configuration

![VNA test setup](image)

**Figure 2.21.** VNA test setup used to perform S-parameter versus frequency measurements up to 110 GHz of the device-under-test (DUT).

Scattering parameter (S-parameter) measurements were carried out with a two-port vector network analyzer (VNA) combined with a millimeter head controller and combiner assembly (Agilent Technologies) allowing for characterization up to 110 GHz. Figure 2.21 shows a photograph of the VNA set-up, while Table 2.5 lists the equipment used in the VNA set-up. Ground-signal-ground (GSG) probes were used to inject microwave and AC bias signals through the two CPW ports on the LC devices (see Figure 2.22). The signal-to-ground spacing of the probes is 150 µm, while the center tip’s contact width is 25 µm. AC biasing of the LC devices was performed with a set-up (see
Figure 2.23) developed in-house that allows application of variable frequency biasing signals to a VNA.\textsuperscript{123} This is necessary, because otherwise with a DC bias, device performance can be severely impacted due to electrode ionic impurity build-up combined with ion generation in the LC.\textsuperscript{124,125,126,127}

Table 2.5: Vector Network Analyzer (VNA) Set-up

<table>
<thead>
<tr>
<th><strong>Vector Network Analyzer (VNA) Set-up</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Agilent Technologies E8361A Vector Network Analyzer</td>
</tr>
<tr>
<td>• N5260A Millimeter Head Controller</td>
</tr>
<tr>
<td>• Right/Left Combiner Assembly (mo. 60012/3)</td>
</tr>
<tr>
<td>• Three-prong GGB Industries Picoprobes (Mo. 110H-GSG-150-P)</td>
</tr>
<tr>
<td>• LabVIEW controlled function generator combined with AC bias test setup</td>
</tr>
</tbody>
</table>

The bias signal from this setup was applied directly through the force-to-ground bias tee on one of the combiner assemblies. The applied bias signal was in the form of a 1 kHz square wave with amplitude ranging from 0 to 30 V peak-to-peak ($V_{pp}$). LabVIEW was used to control the VNA and AC bias set-up while performing data acquisition. The S-parameters versus frequency was collected at various voltages applied across the LC layer. After measurements were performed, the raw data was calibrated using on-wafer, multiline thru/reflect/line (TRL) calibration with NIST MultiCal software and an on-wafer calibration kit.\textsuperscript{128} General information about vector network analysis, calibration,
and measurements, as well as details concerning NIST multiline TRL calibration may be found in the literature.\textsuperscript{129,130,131}

**Figure 2.23.** AC bias test set-up for applying a 1 kHz square wave signal to the LC cells (photograph courtesy of Jason E. Nobles).

### Computational Electromagnetics Techniques

The inverted microstrip filter devices were modeled in CST Microwave Studio,\textsuperscript{101} a software package for performing full wave 3D electromagnetic simulations on high frequency components such as antennas, filters, and planar and multi-layer structures, to name a few. Unless otherwise stated in this report, the Transient Time Domain Solver\textsuperscript{132} of CST Microwave Studio was primarily used to perform S-parameter versus frequency simulations on the filter devices. This solver computes the evolution of electromagnetic fields as a function of time at discrete position and time steps, using a hexahedral-shaped grid (mesh). It is based on the Finite Integration Technique (FIT),\textsuperscript{133,134,135} a numerical
simulation method for solving Maxwell’s equations\textsuperscript{105,106,107} in integral form. The FIT in the Time Domain Solver is also complemented with numerical techniques such as the Perfect Boundary Approximation (PBA)\textsuperscript{136} and Thin Sheet Technique (TST)\textsuperscript{137} to improve the speed and accuracy of simulations performed on highly curved structures (e.g., cavities and boundaries) and very thin metallic sheets, respectively. This reduces the need to define a high-resolution computational mesh near fine structures.

Typically a 3D model is designed in the program by first defining the geometrical parameters and materials of the model’s constituents, as well as the material background properties (e.g. air) and boundary conditions. Parameters in the model can be assigned variables so that the designer can change the parameters as needed. A hexahedral mesh is then defined at various portions of the model to tell CST where its calculations must be refined. Waveguide ports must also be defined at the input and output of the modeled device to tell the program where electromagnetic energy will be stimulated and absorbed.

Various methods were employed to improve the quality and speed of the simulations performed on the filter devices. To prevent artificial resonances from appearing in the S-parameter results, it was necessary to use open boundaries in the model while ensuring electric shielding at the waveguide ports. A more detailed description concerning this step can be consulted.\textsuperscript{138} To improve the speed of the simulations, a symmetry plane was created running through the microstrip of the filter, in which the tangential component of magnetic field was set to zero (based on the electric and magnetic field configuration of a microstrip structure). This reduced the calculation time of the simulations by a factor of two. Also, in the Time Domain Solver Parameters, S-Parameter symmetry is also set, so that the input and output return loss are the same.
CHAPTER III – RESULTS AND DISCUSSION

Overview

In this chapter the experimental results of both open stub and spurline filters with resonance frequencies of 30, 50, and 85 GHz will be presented and discussed. Results from CST simulations will also be presented for comparison.

Open Stub Filters

Analysis of Insertion Loss Due to CPW and Liquid Crystal

Ideally, the passband insertion loss of the filters should be 0 dB, with a return loss of at least -15 dB. However, some insertion loss in the passband is expected due to attenuation of the signal propagating through the glass and LC media as well as eddy current losses in the metallic signal lines. To understand the contribution to loss coming from the CPW on glass, S-parameter measurements were performed on CPW structures with different trace lengths.

Figure 3.1 shows a graph of insertion loss, $S_{21}$, as a function of frequency for CPWs with

![Figure 3.1. $S_{21}$ versus frequency of 2.25 μm thick copper-based CPW structures on Borofloat 33.](image)
lengths of 0.3 cm (black curve), 0.6 cm (red curve) and 1 cm (blue curve). The insertion loss of each CPW was linear in the frequency range from 0 to 95 GHz. As expected, the insertion loss magnitude increases proportionately with the CPW length as well as the frequency of the propagating signal. At 30 GHz, a 1 cm long CPW results in -1.8 dB of insertion loss. From these experimental results, we may extrapolate the amount of insertion loss to be expected from the CPW in each filter device. All LC cells presented in this study have a total of 4 mm CPW (2 mm at each port). Therefore, the CPW insertion loss expected at 30, 50, and 85 GHz is -0.53, -0.93, and -1.5 dB, respectively.

In the inverted microstrip region of the cell, the LC also contributes to the insertion loss; however, the LC absorption is very small. To estimate the amount of loss coming from the LC material, a drop of LC2020 was dispersed onto CPW and S-parameter measurements were taken. The results were then compared with measurements performed on the CPW without LC. As mentioned above, the LC2020 and LC1917 belong to the same family of LCs and therefore share many of the same chemical constituents. Figure 3.2 shows the change in insertion loss, $\Delta S_{21}$, versus frequency when a drop of LC is deposited on top of a CPW.
At 30 GHz, the 0.6 cm CPW exhibits 0.2 dB additional insertion loss when LC is placed on it. At the same frequency, a 1 cm CPW shows approximately 0.55 dB additional insertion loss from the LC. Comparing these $S_{21}$ measurements (with and without LC material on top of the CPW) with $S_{11}$ (not shown) leads to the conclusion that the absorption in LC is indeed small. Using a simple calculation, we can approximate the loss tangent $\delta$.

The power of the waves propagating through the structure decay exponentially with distance as

$$P_f = P_0 e^{-\delta k z},$$  \hspace{1cm} (3.1)

where $P_f$ is the power of the transmitted electromagnetic wave which has propagated through the LC along the CPW (obtained from the measured transmission parameter, $S_{21}$), $P_0$ is the power of the incident electromagnetic wave (-6 dBm from the VNA), $k$ is the wavenumber ($2\pi/\lambda$), and $z$ is the length of the structure. The difference between the loss tangent of the CPW with LC and that of the plain CPW with air gives the loss tangent of the LC alone, such that,

$$\delta_{LC} = -\frac{c}{2\pi f z} \left[ \ln \left( \frac{P_f}{P_0} \right) \left( \frac{1}{\sqrt{\varepsilon_{eff}}} \right)_{CPW+LC} - \left( \frac{1}{\sqrt{\varepsilon_{eff}}} \right)_{CPW+AIR} \right],$$  \hspace{1cm} (3.2)

where $c$ is the speed of light in vacuum, $f$ is the frequency of the electromagnetic wave, and $\varepsilon_{eff}$ is the effective permittivity. The first term in the parentheses corresponds to the case for power transmitted through LC along the CPW, whereas the second term is for power transmitted through air along the CPW; therefore the effective permittivity in either case is different. The reflected power (obtained from $S_{11}$) in both cases is negligible (<0.5% of incident power) and is not taken into account. The accuracy of $\delta_{LC}$
depends on knowledge of the substrate permittivity at 30 GHz, which is unknown. There is also uncertainty in the effective permittivity of the CPW in air. Instead, we approximate $\delta_{LC}$ knowing that roughly 6% of the incident power was absorbed by the LC. This gives a loss tangent of approximately 0.005, typical of most LCs.

**S-Parameter Characterization of a 30 GHz Bandpass Filter**

As mentioned in Chapter II, filters with passband frequencies of 30, 50, and 85 GHz were manufactured and on-wafer characterization was carried out using the VNA. The filter structures were filled with LC1917 to form a 38 $\mu$m thick LC layer. For a 30 GHz bandpass filter with three stubs, the central frequency as a function of applied voltage is shown in Figure 3.3(a) while the inset shows the changes of $S_{21}$ versus frequency biased at various AC voltages. The passband central frequency was tuned from 32.3 to 29.2 GHz by varying

**Figure 3.3.** 3-stub, 30 GHz bandpass filter. (a) Central frequency vs voltage. Inset shows $S_{21}$ vs frequency at various voltages. (b) $S_{11}$, $S_{22}$, and $S_{21}$ vs frequency at 30 V$_{pp}$. (c) CST simulation $S_{21}$, $S_{11}$, and $S_{22}$ vs frequency.
the applied AC bias signal from 0 to 30 V_{pp} across the LC layer. This corresponds to 10.3% tuning referenced to the design frequency of 30 GHz. Note that the onset of tuning occurs at 2 V_{pp}, which corresponds to the Fréedericksz transition. Such behavior was observed for all built filters because the thickness of LC layer is the same for all structures. The Fréedericksz transition is associated with the value of electric field needed to start rotation of the LC molecules from the anchoring position. The majority of the tuning occurred between 2 and 14 V_{pp}. The passband width, defined as the frequency range over which the insertion loss is smaller than 50% of maximum power in the passband region, is 5 GHz. We note that the width of the passband region can be controlled by the width of the stubs. The Q-factor of this filter, defined by the equation,

\[ Q = \frac{\sqrt{f_l f_r}}{f_r - f_l}, \quad (3.3) \]

where \( f_l \) and \( f_r \) are the left and right -3 dB passband edge frequencies, respectively, is equal to 6. All of the filters reported in this study had approximately the same Q-factor of 6.

Figure 3.3(b) shows a graph of the reflection parameters \( S_{11} \) and \( S_{22} \) as well as \( S_{21} \) versus frequency when the filter was biased with 30 V_{pp}. The transmission parameter in the pass region is not flat. Visible ripples in the transmission indicate the presence of multiple reflections from CPW to microstrip transitions or glue regions, indicating the entire measured structure is not perfectly matched to 50 \( \Omega \). In the passband region, the insertion loss reaches -4.9 dB. The passband return loss ranges from -5 to -20 dB. The reflection parameters also overlap each other, indicating good alignment of the top ground plane with the bottom substrate supporting the signal line elements. Since the LC cell has 4 mm of excess CPW and 2.62 mm of excess microstrip/LC outside the filter
structure, -1.3 dB of the insertion losses can be accounted for in the passband region of the filter.

The experimental results show reasonable agreement with simulations. A model of a 30 GHz filter with the same dimensions as the measured filter was created in CST Microwave Studio. The model excluded the CPW and CPW-microstrip transitions on the input and output of the filter. Figure 3.3(c) shows a CST simulation of $S_{21}$ and $S_{11}$ versus frequency of the filter with $\varepsilon_\parallel = 3.7$, corresponding to the LC molecules fully aligned with the electric field. There is a clearly defined peak in $S_{21}$ at 30 GHz, with poles located at around 15 and 45 GHz. The passband width is roughly 5 GHz. Because the simulation neglects the CPW and transition region, the passband insertion loss is at -1.5 dB. Two resonances appear in the passband of the reflection parameters, resembling the experimental results.

As a final note concerning the physical 30 GHz filter devices, we would like to mention that the filters demonstrate good power-handling. By introducing a 30 dB amplifier between the filter device and the first port of the VNA in the set-up described in Chapter II, signals with power from 0.1 to 240 mW between 20-45 GHz were injected into the filter. The output power of the signal leaving the filter was linearly proportional to the input power. The LC media did not show any undesired, non-linear behavior while encountering an increase in signal power. The same behavior is also expected for the higher-frequency filters described in the sections following. Similar power handling was observed for phase shifter structures filled with LC1825 up to 1 W of RF power in past research.\textsuperscript{31} Finally, as far as total device power consumption is concerned, no more than 0.5 mW of power is needed to bias the LC based filter devices.
S-Parameter Characterization of a 50 GHz Bandpass Filter

Figure 3.4(a) shows the passband central frequency as a function of applied voltage while the inset shows the transmission $S_{21}$ versus frequency at various applied voltages for a 50 GHz filter. The passband central frequency was tuned from 52.7 to 47.6 GHz (10.3% tuning) by applying a 1 kHz, 0-30 V$_{pp}$ AC bias signal across the LC layer. The passband width is approximately 9 GHz. The inset shows that with increasing voltage, the transmission slowly gets better indicating an improving match of the whole system to 50 Ω impedance.

Figure 3.4(b) shows a graph of $S_{11}$, $S_{22}$, and $S_{21}$ versus frequency at 30 V$_{pp}$. The transmission parameter $S_{21}$ achieves -3.76 dB in the passband (the best value out of the three filters measured). The 50 GHz filter had 4 mm of excess CPW and 2.69 mm excess microstrip/LC, thus -1.8 dB of insertion loss may be accounted for. The
passband return loss ranges from -10 to -25 dB. The reflection parameters $S_{11}$ and $S_{22}$ also have a better overlap than observed for the 30 GHz filter, indicating very good alignment. The experimental results show good agreement with CST simulations. Figure 3.4(c) shows the simulation results for a 50 GHz filter. The passband insertion loss achieves -1.92 dB in the passband and peaks at 50 GHz, with poles around 25 and 75 GHz. Its passband width is approximately 9 GHz. We note that there is also a double resonance seen in the passband return loss, indicating a non-ideal impedance match. However, insertion losses measured and predicted by CST simulations for this filter nearly match (-1.96 versus -1.92 dB). The passband region can be improved by further optimizing the filter dimensions.

S-Parameter Characterization of an 85 GHz Bandpass Filter

Figure 3.5(a) shows the passband central frequency as a function of applied
voltage while the inset shows the transmission $S_{21}$ versus frequency at various applied voltages for a 3-stub, 85 GHz bandpass filter. This filter was embedded in the same LC cell which contained the 50 GHz filter. The center passband frequency is tuned from 89.5 to 80.7 GHz (10.4% tuning) when a 1 kHz, 30 V$_{pp}$ bias signal is applied. The passband width is 14 GHz. In Figure 3.5(b), a graph of measured $S_{11}$, $S_{22}$, and $S_{21}$ parameters versus frequency at 30 V$_{pp}$ bias is shown. Insertion loss reaches -7.63 dB in the passband region. With 4 mm excess CPW and 3.33 mm excess microstrip/LC, -2.3 dB insertion loss is accounted for. The passband return loss ranges from -10 to -27 dB. Finally, a simulation of $S_{21}$ and $S_{11}$ versus frequency was performed on a filter with similar dimensions (see Figure 3.5(c)). The passband insertion loss reaches a value of -3.35 dB and is centered at 85 GHz, with passband width of 14 GHz. Poles are located near 60 and 105 GHz. The passband return loss reaches -25 dB. The measured performance of the 85 GHz filter is in reasonable agreement with CST simulations, as one can see comparing Fig. 3.5(b) and Fig. 3.5(c).

**Simulations of Filters with Three, Five, and Seven Stubs**

In the previous sections, we presented results of CST simulations of three open stub filters and compared them with experimental data. While the performance of these filters was close to the simulated results, we investigated the possibility of further performance improvements of filters shown in Figure 2.1. We determined that a larger number of stubs can be implemented to improve the performance of the filters. Simulations indicate that with increasing number of stubs the insertion loss magnitude in the passband region slightly increases, from 1.3 dB for three stubs to 2.8 dB
with seven stubs, but with significant increase in the roll-off. In units of decibels per octave, this is defined as,

\[
Roll\ of\ f = \frac{S_{21}(f_2) - S_{21}(f_1)}{\log_2 \left(\frac{f_2}{f_1}\right)}
\]  

(3.4)

where \(f_1\) and \(f_2\) are the minimum and maximum frequencies between the attenuation poles and passband edges where the response is approximately linear. The quantities, \(S_{21}(f_2)\) and \(S_{21}(f_1)\), are defined as the insertion loss defined at the frequencies, \(f_2\) and \(f_1\), respectively. Figure 3.6, for example, shows simulations of \(S_{21}\) versus frequency comparing three (black curve), five (red curve), and seven (blue curve) stub filters with a central frequency of 30 GHz. The filter with three stubs has a roll-off of 8.3 dB/GHz (149 dB/octave) for frequencies below the band-pass region. When the number of stubs is increased to five, the roll-off increases to 16.7 dB/GHz (300 dB/octave). The seven-stub filter gives the best roll-off at 26.6 dB/GHz (480 dB/octave). These results clearly indicate that the larger number of stubs significantly increases the filter performance. Other variations of the filter are also possible, including open stub filters with a suppressed second harmonic.\textsuperscript{90} We note that all these possible changes to filter construction (e.g., number of stubs) can be easily implemented in these LC based microwave structures.
Comparing the CST simulation results with measured experimental structures indicates a very good agreement for roll-off values. We measured, for the three-stub 30 GHz filter, 180 and 140 dB/octave roll-off for frequencies below and above the passband region, respectively. Certain asymmetry is also visible in all CST simulated structures. For a 30 GHz filter, CST simulations predict 149 and 133 dB/octave roll-off for frequencies below and above the passband, respectively. The fact that the measured values of roll-off are better in the physical structure is attributed to the visible ripples in transmission as discussed previously (concerning the 30 GHz filters) that enhance roll-off values. For the three-stub 50 GHz filter, the measured values of roll-off are 241 and 105 dB/octave for frequencies below and above the passband, respectively; for simulations these are 168 and 155 dB/octave, respectively. For the 50 GHz filter, the ripples in transmission skew the values of roll-off enhancing it for frequencies below the passband region and decreasing it for higher frequencies. Similar behavior was observed for the three-stub 85 GHz filter, where values of roll-off are 197 (168) and 93 (143) dB/octave below and above the measured (simulated) passband region, respectively.

An effort was made to produce a five-stub filter in the lab to verify the sharper roll-off seen in simulation results. However, the filter produced had an abrupt CPW-microstrip transition on both ends and so the passband insertion loss (-8.3 dB) is not ideal. Nevertheless, the experimental results successfully demonstrate the sharper roll-off to be expected when additional stubs are included in a stub filter. Figure 3.7 shows the S-parameter versus frequency results of a fully biased (30 V_{pp}), five-stub filter with central passband frequency of 30 GHz. S_{22}, S_{11}, and S_{21} are represented by the black, red, and blue curves, respectively. The passband has a sharper roll-off than what is seen in the
three-stub filter presented in Figure 3.3. Its low-frequency and high-frequency roll-off is 287 and 264 dB/octave, respectively. This is close to the roll-off of 300 dB/octave seen in the simulations for a 5-stub filter. Filters with a high number of stubs, then, are a promising route for improving the transmission characteristics.

Simulations of the Bandwidth Dependence on Stub Width

Three Stubs with the Same Width: CST Simulations were performed on an open stub filter to understand the correlation between stub width and the passband width of the filter. In Equation (2.4) of Chapter II, it is clear that the low-frequency passband edge is inversely proportional to the capacitance of a given reactive element in the filter. Therefore one should expect that if the stub width is increased, then the capacitance of the stub will also increase, leading to a decrease in the low-frequency passband edge. Intuitively this makes sense, because an increase in energy storage at the stub will result in less total power transmitted through the entire filter structure and therefore a smaller passband.

Figure 3.7. $S_{22}$ (black), $S_{11}$ (red), and $S_{21}$ (blue) versus frequency of a fully-biased, 30 GHz five-stub filter.
Such behavior can be seen in Figure 3.8, which shows the simulated transmission parameter $S_{21}$ versus frequency of a 3-stub filter with various stub widths. In the modeled filter, all three stubs had the same width during each simulation. As the width of the stubs was increased, the passband width of the filter became narrower. Figure 3.9 shows the 3 dB bandwidth of the same filter as a function of the stub width. When the filter had 25 μm wide stubs, the passband width was 9 GHz with -2 dB passband insertion loss. Stubs that were 275 μm wide had a passband width of 5 GHz. This is in strong agreement with the actual, manufactured filters, which had a 5 GHz passband width. Their outer stubs were 275 μm wide, but with center stub width of 194.8 μm.
μm wide stubs led to a narrower passband width of 3 GHz, but with passband insertion loss of -4.3 dB. These results reveal a design trade-off. Namely, open stub filters with narrower passbands have more transmission loss than filters with wider passbands.

Three-Stub Filters with Various Center Stub Widths: Figure 3.10 shows the simulated transmission $S_{21}$ versus frequency of a 30 GHz, three-stub filter with changing center stub widths. The outer stub widths are fixed at 275 μm. The center stub width was varied from 5 to 500 μm. As the center stub width is increased, the passband width decreases. When the center stub width is 5 μm, the passband width is 8.3 GHz. At 200 μm, very close to the width used in the actual filters presented earlier in this chapter, the bandwidth is 5.4 GHz. At 500 μm, the passband width is narrower at 3.7 GHz.

Simulations were also performed to determine which configuration of stub widths produced the best impedance match. The majority of the configurations showed an additional, unwanted resonance in the reflection parameter, $S_{11}$, similar to the simulated and experimental results for the filter presented earlier (see Figure 3.3). However, the simulated filter with center stub width of 350 μm had good reflection curves. Figure 3.11
shows the CST simulation results for $S_{11}$, $S_{22}$, and $S_{21}$ as a function of frequency for a filter with center stub width of 350 μm and outer stub widths of 275 μm. The reflection curves are far more symmetrical than what is seen in other stub width configurations, with peak return loss ranging from -22 to -30 dB. The unwanted resonance is evident only in $S_{11}$ and is very miniscule.

**Spurline Filters**

**Losses due to Liquid Crystal, Glass, and Metallization**

As described in the above section on open stub filters, experiments were performed to determine the amount of insertion loss due to the glass and LC media as well as eddy current losses in the metallization. The information gleaned from these experiments likewise applies to the spurline filters to be described in the sections ahead.

From Figures 3.1 and 3.2, we deduce that at least 2.3 and 3.3 dB of insertion loss, at 50 and 85 GHz, respectively, can be expected in the spurline filter device. This is due to the 4 mm of CPW on the filter device (2 mm on each side) and 5 mm of inverted microstrip covered by LC that the spurline filters are embedded into.
50 GHz Double-Spurline Filter Characterization

The 50 and 85 GHz double-spurline filter structures were both integrated into the same physical LC cell filled with LC1917. S-parameter measurements were performed on each filter over a frequency range from 1 to 110 GHz. Figure 3.12(a) shows the notch frequency of the 50 GHz filter versus voltage applied across the LC layer. Initially, the notch frequency of the filter is 51.1 GHz, corresponding to the case where the LC molecules are in alignment with the rubbed polyimide above the filter structure. A minimum voltage of approximately 2 V$_{pp}$ is needed to initiate the tuning of the notch frequency. This effect is associated with the Fréedericksz transition, and as explained previously it is the minimum voltage required to begin rotation of the LC molecules from their anchoring position. From 2 to 30 V$_{pp}$, the tuning

Figure 3.12. Tunable double-spurline filter with 50 GHz center notch frequency: a) notch frequency versus applied voltage; the inset shows S$_{21}$ versus frequency at various AC voltages applied across the LC layer, and b) transmission, S$_{21}$, and reflection parameters, S$_{11}$ and S$_{22}$, versus frequency when 4 V$_{pp}$ is applied across the LC layer.
is continuous. At 30 V_{pp}, the notch frequency is 49.7 GHz. The majority of the tuning occurs between 2 and 14 V_{pp}.

The inset in Figure 3.12(a) shows the transmission parameter, S_{21}, as a function of frequency for various applied voltages. When the device is unbiased, the insertion loss achieves a minimum of -50 dB in the stopband. As voltage is increased to 30 V_{pp}, the notch frequency decreases while the minimum insertion loss increases to -35 dB in the stopband. Outside the stopband at lower frequencies, the insertion loss is -3 dB, indicating good passband transmission for this proof-of-concept device.

Figure 3.12(b) shows a comparison of the transmission parameter, S_{21}, with reflection parameters, S_{11} and S_{22}, versus frequency when the filter is biased with 4 V_{pp} (corresponding roughly to the center value of LC permittivity, \( \epsilon_r \)). The reflection curves were smoothed by the Savitzky-Golay method.\(^{140}\) The reflection parameters nearly overlap each other, indicating good alignment of the top ground plane of the filter device with the bottom substrate supporting the filters. In the stopband, the reflection parameters vary from -3.5 to -11 dB, while the transmission reaches -41 dB. Visible oscillations in S_{11}, S_{22}, and S_{21} indicate that the device is not perfectly matched to 50 \( \Omega \) impedance. The notch frequency is roughly 50.5 GHz. The -3 dB passband width of the stopband filter is 12.2 GHz, giving a Q-factor of 4.1. Knowing the -3 dB level of the passband and details of the center notch, we were able to determine the roll-off of the stopband frequency response. The low frequency response of the stopband of the filter structure in Figure 3.12(b) had a roll-off of 147 dB/octave. The high frequency roll-off (199 dB/octave) was slightly higher that that determined for lower frequencies.
On the low-frequency side of the notch filter response in Figure 3.12(b), there is -3.9 dB insertion loss at 40 GHz. Since there is 4 mm CPW and 5 mm of microstrip making up part of the filter structure, we use Figure 3.12 to determine that at least -2.1 dB insertion loss comes from the LC, glass, and metallization. The remaining loss is likely from the two CPW-microstrip transitions.

A simulation performed on a modeled filter with the same dimensions and material parameters as the physical filter is shown in Figure 3.13. The CPW and CPW-microstrip transitions are not included in the filter model. The reflection parameter, $S_{11}$, and transmission, $S_{21}$, are plotted as a function of frequency for a biased filter with center LC permittivity ($\epsilon_r = 3.23$). $S_{22}$ (not shown) is identical to $S_{11}$. The center notch frequency of 50.3 GHz closely agrees with the experimental value of 50.5 GHz. The transmission reaches -64 dB in the stopband, while return loss varies from -1.3 to -5 dB. The -3 dB passband width of the simulated filter is slightly wider than the experimental value, at 17 GHz, with a Q-factor of 3.0. The simulated filter structure exhibits higher attenuation at the notch frequency, thus its roll-off is larger than the experimental value;
the low-frequency roll-off is 234 dB/octave and the high-frequency roll-off is 240 dB/octave. However, we note that both the experimental and simulated values are high.

One final remark should be made concerning the tuning of the spurline filters. The experimental results for the 50 GHz, double spurline filter show that the stopband was tuned by 3-6% as a voltage of 0.18 V/µm was applied across the LC cell. This same result was also found in the 85 GHz, double spurline filter (discussed in the next section). This result is in stark contrast with the level of tuning seen in the bandpass filters (roughly 10-12%), despite the fact that the spurline filters were made in tandem with the bandpass filters with the same manufacturing protocols. Additional work was done to guarantee that this was not a manufacturing fluke. Therefore, a simulation was performed in CST to determine the level of tuning to be expected in a 50 GHz, double spurline filter as the LC relative permittivity is tuned from 2.76 to 3.7. Figure 3.14 shows the transmission coefficient, $S_{21}$ (solid curves), and reflection coefficient, $S_{11}$ (dashed curves), as a function of frequency when the LC relative permittivity is tuned. The minimum, center, and maximum values of LC permittivity are represented by the red, blue, and black curves.
curves, respectively. Sweeping through the entire LC relative permittivity range, the central stopband frequency is tuned from 51.89 to 48.73 GHz. The notch frequency is tuned by only 6%, referenced to the design frequency of 50 GHz. The lower tuning capability of the spurline filters is likely due to the low volume of LC material near the spur elements when compared to the entire structure.

85 GHz Double-Spurline Filter Characterization

Figure 3.15(a) depicts dependence of the notch frequency of the 85 GHz double-spurline filter with applied AC bias voltage. The notch frequency is tuned from 86.5 to 83.9 GHz with a voltage of 30 V\textsubscript{pp}. Again, the majority of the tuning occurs between 2 to 14 V\textsubscript{pp}. An interesting feature that should be noted is that the notch frequency does not become

![Graph showing the transmission, S\textsubscript{21}, and reflection parameters, S\textsubscript{11} and S\textsubscript{22}, versus frequency when 4 V\textsubscript{pp} is applied across the LC cell.]

Figure 3.15. Tunable double-spurline filter with 85 GHz center notch frequency: a) notch frequency versus applied voltage; the inset shows S\textsubscript{21} versus frequency at various AC voltages applied across the LC and b) a graph showing the transmission, S\textsubscript{21}, and reflection parameters, S\textsubscript{11} and S\textsubscript{22}, versus frequency when 4 V\textsubscript{pp} is applied across the LC cell.
completely saturated. This suggests that higher voltage could be used to achieve more tuning; however, this was outside the limits of the VNA/AC-bias setup.

The inset of Figure 3.15(a) shows the measured transmission as a function of frequency at various voltages applied across LC layer. Similar to the 50 GHz filter, as a voltage is applied across the device, the center notch frequency and the low and high frequency stopband edges are effectively shifted to lower frequencies. As the cell is biased, the minimum transmission, $S_{21}$, decreases from -31 to -46 dB in the stopband. Curiously, when 14 V$_{pp}$ is applied, the insertion loss achieves -55 dB, suggesting that there is a better impedance match at this particular voltage. However, as in the case of the 50 GHz filter, there are small oscillations visible in $S_{21}$ indicating that the structure as a whole is not perfectly matched to 50 Ω.

Figure 3.15(b) shows the transmission, $S_{21}$, and reflection parameters, $S_{11}$ and $S_{22}$, with respect to frequency for the filter when biased with 4 V$_{pp}$. Here, the center notch frequency is located at 85.6 GHz with a minimum insertion loss of -35 dB. In the stopband, the reflection parameters vary from -4 to -12 dB. The -3 dB passband width is 28.3 GHz, giving a Q-factor of 3.0. Similar to the 50 GHz filter, the high frequency roll-off is slightly larger than the low-frequency roll-off, at 118 and 102 dB/octave, respectively.

Figure 3.16 shows results of a CST simulation performed on an exact model of this filter with center value of LC permittivity. The S-parameters, $S_{11}$ and $S_{21}$, are plotted as a function of frequency. The center notch frequency is at 85.8 GHz. Again, this is very close to the experimental value. The stopband insertion loss reaches a minimum value of -42 dB while the stopband return loss ranges from -1.7 to -5.4 dB. The -3 dB passband
width of the simulated filter is 29.9 GHz, which is also in very good agreement with the measured width, giving a Q-factor of 2.9. The low and high-frequency roll-off values for the simulated filter are 162 and 142 dB/octave, respectively. In contrast to the measured values, the low-frequency roll-off is slightly larger than the high-frequency roll-off. The fact that the simulated roll-off is larger than the experimental roll-off is attributed to the higher attenuation at the notch frequency in the simulated frequency response. Finally, the experimental roll-off of the 85 GHz filter is smaller than that of the 50 GHz filter by 41 dB/octave on the low-frequency end and 81 dB/octave on the high-frequency end.

Figure 3.16. A simulation of the transmission, $S_{21}$, and reflection, $S_{11}$, parameters of a modeled 85 GHz double-spurline filter at the center value of LC permittivity.
CHAPTER IV - CONCLUSIONS AND FUTURE DIRECTION

Summary of LC Based Bandpass and Bandstop Filters

**Bandpass Filters**

LC cells containing three-stub tunable bandpass filters in inverted microstrip geometry were designed, manufactured, and tested. The cells utilized a broadband CPW to microstrip transition for injection of the microwave and bias signals into the filter. Filters with various stub dimensions were designed to have center passband frequencies at 30, 50, and 85 GHz. The passband frequencies were tunable by at least 10% using a 1 kHz, 14 V\text{pp} AC bias signal. The electric field applied across the LC was less than 0.19 V/\mu m. The smallest insertion loss, measured in the 50 GHz filter, was -3.76 dB which could be further reduced. The Q-factor for all filters was around 6. The return loss of all three devices ranged from -10 to -25 dB, indicating a good impedance match for a proof-of-concept device. Furthermore, experimental results were in good agreement with the results from CST simulations performed on filters with identical dimensions. Losses due to the LC media were significantly smaller than 1 dB/cm in the 1-110 GHz frequency range for the structures with dimensions presented in this paper.

Table 4.1 shows the results of frequency range, tuning capability, and passband insertion loss of these filters compared with filters reported by other teams in the peer-reviewed literature. The majority of the LC-based filters made by other teams have a central passband frequency of 5 GHz, since there are many applications that have a high demand for this frequency range. However, the filters presented in this study and those developed by J. Lovejoy demonstrate the feasibility of these structures in the 30-110 GHz
frequency range. The passband insertion loss of these filters is also at a reasonable level for a proof-of-concept study. We would like to note that the results presented in this table are one-time measurements performed on single devices; therefore, one can not necessarily say that a given filter device outperforms the other. Table 4.1 simply shows a compilation of studies to reveal what has been done before. In larger studies, or in a large-scale manufacturing facility, the LC devices would be manufactured in larger quantities. In this case, manufacturing would be optimized to yield better-performing devices, while under-performing devices would be discarded. Measurements performed on multiple devices (and averaged) would then give a more accurate representation of the performance.

**Table 4.1**: A compilation of peer-reviewed studies on liquid crystal bandpass filters.

<table>
<thead>
<tr>
<th>Author</th>
<th>Central Frequency (GHz)</th>
<th>Tuning (%)</th>
<th>Passband Insertion Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li, <em>et al.</em></td>
<td>4.2</td>
<td>12</td>
<td>-2.5 to -5</td>
</tr>
<tr>
<td>Bernigaud, <em>et al.</em></td>
<td>5.0</td>
<td>6.0</td>
<td>-4</td>
</tr>
<tr>
<td>Missaoui and Kaddour</td>
<td>5.0</td>
<td>0 (measured)</td>
<td>-5</td>
</tr>
<tr>
<td>Torrecilla, <em>et al.</em></td>
<td>5.0</td>
<td>7.3</td>
<td>-7</td>
</tr>
<tr>
<td>Guo, <em>et al.</em></td>
<td>5.0</td>
<td>0 (measured)</td>
<td>-2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 (simulated)</td>
<td></td>
</tr>
<tr>
<td>Liu, <em>et al.</em></td>
<td>6.5</td>
<td>8.0</td>
<td>-2.5 to -5</td>
</tr>
<tr>
<td>Bernigaud, <em>et al.</em></td>
<td>10</td>
<td>1.0</td>
<td>-4 to -7</td>
</tr>
<tr>
<td>Goelden, <em>et al.</em></td>
<td>20</td>
<td>10</td>
<td>-9</td>
</tr>
<tr>
<td>Lovejoy</td>
<td>80 and &gt;110</td>
<td>12</td>
<td>-7</td>
</tr>
<tr>
<td>Economou, <em>et al.</em></td>
<td>30, 50, and 85</td>
<td>10</td>
<td>-4.9, -3.8, -7.6, resp.</td>
</tr>
</tbody>
</table>

**Bandstop Filters**

Electrically tunable, double-spurline microstrip filters were also built and tested. The spurlines were a quarter-wavelength long and had notch frequencies at 50 and 85
GHz. The notch frequencies were tunable by 3% when an electric field of 0.19 V/μm was applied across the LC layer. The minimum stopband transmission parameter, $S_{21}$, reached lower than -50 dB for both filters, while the stopband return loss parameters varied from -3.3 to -15.2 dB. The LC 1917 layer, which was 38 μm thick, contributed less than -1 dB/cm insertion loss up to 110 GHz. The -3 dB passband widths were 12.2 and 28.3 GHz for the 50 and 85 GHz filters, respectively, resulting in a Q-factor of 3-4. Furthermore, S-parameter simulations performed on filter models were in agreement with experiment.

**Significance**

The presented results of the proof-of-concept devices clearly indicate that the LC based microwave and millimeter wave filters can operate over a wide range of frequencies due to the fact that there is little dispersion in the studied LC materials (constant group delay). It is the lack of resonances in the GHz frequencies that makes it possible to employ the same physical principles and technology to design and build filters operating at 30 as well as 90 GHz. Actually, we expect that devices in sub-THz frequencies can be realized. This opens, in our view, new opportunities to create tunable devices operating in frequencies up to hundreds of GHz.

Finally, the developed filter structures open a new opportunity for studies of the fundamental properties of LC materials, far beyond their scope in the RF and microwave signal processing applications. Since the primary resonance of the filters is dependent on the relative permittivity of the used LC, these devices offer a new method for effectively determining the dielectric permittivity. In fact, multiple passband resonances, which are
a normal feature of open-stub and spurline filters, allow one to determine the dispersion relation of LC materials over a wide range of frequencies. Moreover, only a small quantity of LC material is needed when compared with other methods mentioned previously. This new metrology for determination of dielectric properties is not just limited to LCs, but fluids or solid in general at sub-THz frequencies.

Suggestions for Improving Future LC-based Filters

The 50 GHz open stub filter presented in Chapter III, to the best of the author’s knowledge, has a higher passband transmission than other LC-based filters presented in the literature. This value can be further improved for the existing filters if excess CPW and microstrip at the input and output of the filters are removed (e.g. if the device is further miniaturized). However, the LC cells must also be sealed with glue, which currently takes up about 1 mm of space along the CPW and up to 1 mm of space as it seeps into the LC/microstrip region. Glues with higher viscosity and/or printed mechanically (instead of by hand) could free up space, allowing the designer to reduce the excess microstrip.

Improvement can also be made towards aligning the top and bottom substrates, since the filters assembled in this study were done by hand. Better alignment of the two substrates, and therefore the CPW-microstrip transition region, could substantially improve the impedance match of the filter device. Another possibility for improving the passband transmission is to increase the width of the trace and microstrip to reduce eddy current losses that take place in the metallization. In order to maintain 50 Ω characteristic impedance, however, the thickness of the LC would have to increase. If the LC becomes
too thick, LC molecules near the center of the cell will begin to lose alignment as fluidic, thermodynamic, and hydrodynamic forces take over. Prior research indicates that the LC maintains its alignment even when 100 µm thick. Therefore, one could at least double the thickness of the current LC cells but would have to redesign the trace and microstrip dimensions.

Greater effort can also be placed in characterizing the relative permittivity of the substrate (Borofloat 33) in GHz frequencies. As explained previously, one can design an open stub filter with longer stubs intended for an empty (air-filled) cell. Measured resonances of the air-filled cells can then be compared with simulations to extract the relative permittivity of the glass in GHz frequencies. Also, since there is a degree of uncertainty in the relative permittivity values of all materials used, it is recommended that stub filters with slightly different stub lengths be developed to see if one produces a better impedance match than the other.

Finally, the idea of aligning the LC molecules by rubbing the copper microstrip mechanically should be revisited. A prior study demonstrated that it was possible to set the nematic director for a LC material by rubbing the copper mechanically (in the same way that the polyimide in this study is rubbed). This would completely eliminate the extra step of applying a polyimide layer and baking the cells under vacuum, thereby saving time and reducing the chance of oxidizing the copper. However, the copper must be deposited in an ideal vacuum environment (at least ~10^{-7} Torr) and the appropriate pressure for rubbing the copper must be determined.
Other Directions

Filters Based on Dual Frequency Liquid Crystals

In addition to building LC based filters that operate at higher frequencies (>100 GHz), as explained previously, other directions can also be pursued. For example, other types of LCs could be used. A filter device integrated with a dual frequency liquid crystal (DFLC) would be tunable by varying both the amplitude and frequency of an AC bias signal. Frequency tuning of the central passband frequency of a 30 GHz, three stub filter has already been demonstrated using the 1909c DFLC from MUT. Figure 4.1 shows the transmission, $S_{21}$, versus frequency of the filter at various frequencies of the AC bias signal. The bias signal is fixed at 36 V$_{pp}$, while its frequency is swept from 1 to 20 kHz. As can be seen, a bias signal with frequency of 12 kHz is all that is needed to fully tune the passband of the filter structure. Unfortunately, a filter device that utilized abrupt CPW-microstrip transitions was used to test this LC, resulting in poor impedance match. Nevertheless, the location of the resonances allowed us to determine the minimum and maximum LC relative permittivity values at 30 GHz to be 2.83 and 3.34, respectively. Tuning between
these values could be achieved either by maintaining a steady voltage of 36 V\textsubscript{pp} while sweeping the frequency of the driving signal (as seen in Figure 4.1), or by increasing the voltage of a 1 kHz driving signal from 0 to 36 V\textsubscript{pp} (see Figure 4.2). In Figure 4.2, this is demonstrated; the transmission, S\textsubscript{21}, versus frequency is measured in the same filter structure, but at various voltages. The same amount of tuning occurs, and happens primarily between 0 and 15 V\textsubscript{pp}.

As a final word, other DFLCs located at UCCS may be of interest for developing bias frequency controlled microwave devices. These include the proprietary MLC2048\textsuperscript{149,150,151,152} from EMD Chemicals Inc., as well as the 1910c from MUT (not published). Another benefit to using these DFLCs, is that the switching time is shorter than an ordinary nematic LC by at least a factor of 10. The reason for this is that the LC molecules are reoriented with an electric field back to the planar alignment, rather than letting them relax to this orientation by simply turning off the voltage. Using a DFLC, one could build bias frequency controlled filter structures that can be tuned in only a few milliseconds.

![Figure 4.2. Filter with DFLC, 1909c: S\textsubscript{21} versus frequency at various AC bias voltages (1 kHz).](image-url)
Liquid Crystal Ferroelectric Colloids in Microwave Devices

Another direction one could take is to integrate LC colloids in microwave devices. LC colloids are LCs doped with an ultrafine concentration of ferroelectric or ferrimagnetic nanoparticles, typically with an average diameter on the order of 10 nm. Briefly, ferroelectric nanoparticles such as Barium Titanate are useful for improving the switching time of LCs, as well as for reducing the Freedericksz transition voltage of the LC. The ferroelectric nanoparticles have an electric coupling with the LC molecules, and essentially guide the reorientation of LC molecules when an electric field is applied across the LC. Although LC colloids have been around for a few decades, no LC colloids have yet been used in combination with planar microwave transmission structures (to the author’s knowledge). However, a nanoparticle-doped nematic LC has been developed and studied at 30 GHz by O. H. Karabey. In this study, different LC colloids consisting of BaTiO₃ nanospheres, gold nanorods, and silver nanospheres were studied at 30 GHz using a cavity perturbation method.

In principle, one could develop a LC colloid and integrate it into a filter structure in attempt to improve the power consumption of the device, reduce the switching time, and reduce the Freedericksz transition voltage at microwave frequencies. The VNA probe station at UCCS would be ideal for this experiment, since an AC bias configuration was developed to work with the VNA. If a DC bias is used instead, drifting of the nanoparticles can occur; this can be prevented using an AC bias field.
Magnetically Tunable Microwave Filter Devices

In principle one could build a LC based microwave filter device whose passband frequency can be tuned by applying a static magnetic field across the LC cell gap. However, magnetic field-induced reorientation of LC molecules is not commonly utilized due to the low sensitivity of LCs to magnetic fields. Magnetic fields up to 10 kOe are generally needed to see a complete magneto-optical (MO) response in a typical LC. As a result, there has been an interest in developing colloids which aim to improve magnetic field sensitivity compared with their pure LC counterparts. Past studies have had success in using ferromagnetic nanoparticles as the dispersed phase of these colloids.\textsuperscript{157,158} Such colloids exhibit enhanced sensitivity to magnetic fields due to the coupling that occurs between the magnetic moments of the nanoparticles and the LC mesogens. This results in a collective magnetic behavior of the colloid that depends on the concentration and size of the nanoparticles. Ferromagnetic nanostructures have been effectively used in both lyotropic and thermotropic LCs.

One example of a ferronematic colloid is the LC 13739 doped with magnetic nanorods of Fe$_3$O$_4$.\textsuperscript{159,160} The colloid with a 1\% weight by weight (w/w) dispersion of 40 nm x ~200 nm nanorods was shown to be the best for reducing the magnetic Freedericksz transition of the LC. Furthermore, the nanorods reduced the time “off” of the LC (the time for the LC molecules to relax from the homeotropic to planar alignment) by a factor of 9 when the LC was controlled under a crossed electric/magnetic field set-up (see Figure 4.3).

A microwave filter integrated with a LC doped with magnetic nanorods may be worth investigating. One could disperse Fe$_3$O$_4$ nanorods, with concentration and size as
reported above, into the nematic LC1917 or 2020. A filter device that is filled with this LC colloid could have a reduced magnetic Freedericksz transition and reduced time “off” if controlled under a crossed electric/magnetic field configuration. Location of the filter passband would be controllable with both electric and magnetic fields. Even more exciting, is the fact that the permeability could be determined from the measured resonances of the filter as a magnetic field is applied. Also, the magnetic loss tangent of the LC as a function of frequency could be determined from the reflection and transmission parameters measured. This is analogous to the techniques used to characterize the dielectric properties of LCs in the microwave frequency range, as described in this dissertation. This would open the door to studying the magnetic properties of LCs or other materials in the 1 to 1000 GHz range.

Figure 4.3. MOKE system at UCCS.
APPENDIX A – PUBLICATIONS ASSOCIATED WITH THIS DISSERTATION

E. C. Economou, J. L. Lovejoy, I. Harward, J. E. Nobles, P. Kula, J. Herman, A. Glushchenko, and Z. Celinski, Liquid crystal based tunable spurline microstrip filters with notch frequencies at 50 and 85 GHz, to be published in Microwave and Optical Technology Letters (2017).


APPENDIX B – A BRIEF HISTORY OF LIQUID CRYSTALS

The first discovery of LCs and the liquid crystalline phase is largely attributed to Friedrich Richard Reinitzer (b. 25 February 1857 in Prague – d. 16 February 1927 in Graz), an Austrian botanist and chemist. While studying the properties of cholesteryl acetate and cholesteryl benzoate at the German University of Prague, he observed changes in color as he melted the two chemicals. Furthermore, he noticed a “double melting” behavior in cholesteryl benzoate. Raising the temperature to 145.5º C would change it from the solid crystalline phase into a cloudy fluid. Upon raising the temperature to 178.5º C, the cloudiness would disappear and a clear fluid was observed. Reinitzer published these results on May 3, 1888. He mentioned in his paper that other scientists including Planar, Raymann, and Lobisch observed similar color phenomena in other chemicals. However, Reinitzer was the first to observe the “double-melting” behavior and recognized the importance of the cloudy phase seen in cholesteryl benzoate. Consequently, Reinitzer decided to contact Otto Lehmann, a German physicist with a specialty in polarization microscopy. In their collaboration, they both agreed that a certain class of materials could take on a phase that was liquid while simultaneously showing crystalline properties. Lehmann subsequently ushered the term “liquid crystal” and wrote his 1889 paper on the subject while he was at the University of Karlsruhe.

After the initial work performed by Reinitzer and Lehmann, LC science slowly grew throughout the early 1900’s. More LCs were discovered, and many materials were shown to have multiple LC phases between the solid and liquid phase. Lehman also described the alignment of LCs with surfaces, which would later become important for the development of LCDs later in the century. Optical effects as well as a kinetic theory of LCs were also described in this time period. The biggest contribution of LC science in the early 1900’s, however, was from Georges Friedel. His article in 1922 helped solidify the scientific community’s acceptance of LCs and summarized the progress of LC research. It provided information not only on the many techniques and LCs developed by the community, but also classified different LC phases. It distinguished the nematic, smectic, and chiral nematic phases from one another.

The next biggest historical landmark was through the Faraday Society in London at the 1933 symposium, “Liquid Crystals and Anisotropic Fluids – A General Discussion.” It was the first symposium on LCs and grouped together the most important experts in the field. Five of the 24 papers presented at this gathering were from Daniel Vorländer. Vorlander’s research led to an understanding of LCs in terms of their molecular structure. In particular, that many LCs have rod-shaped molecules. Also relevant at the symposium, and in continuing research until the late 1950’s, were studies on 1) the influence of electric and magnetic fields on LCs, 2) thermotropic and lyotropic LCs, 3) the alignment of LCs with surfaces, 4) the continuum theory of LCs and theory of curvature elasticity, 5) anisotropic physical properties of LCs, 6) the relationship between LC properties and molecular structure, and 7) the utility of polarization microscopy. These developments helped create the foundation for modern LC science and in bringing LCs to the market.

The modern era of LCs is hallmarked by the advent of LCDs, which were first introduced at the International Liquid Crystal Conference in the 1960’s. These conferences were organized in 1965 by Glenn Brown at Kent State University in Ohio.
1968, a group of researchers from the Radio Corporation of America (Heilmeier, Castellano, Goldmacher, and Williams) introduced the concept of LC based display devices through these conferences. Afterwards, the 1970’s saw an explosion in LCD technology. Many display types were developed including dynamic scattering, Freedericksz, twisted nematic, cholesteric memory, and cholesteric-nematic phase change displays. Most notable was the emergence of the twisted nematic LC electro-optic display mode, patented by Schadt, Helfrich, and Fergason. This display mode, in combination with the cyanobiphenyl LCs and the cyclohexane and pyrimidine analogs, initiated the electro-optical display industry in the 1970’s.

The late 1900’s also saw further development in the types of LC phases, such as the smectic and blue phases which are useful in applications demanding fast switching time. New switching techniques, lyotropic LCs (relevant to the oil, food, and detergent industries), LC polymers, polymer dispersed LCs, surface stabilized ferroelectric LC devices, and metallomesogens are also notable developments in the 1900’s. The field of LCs is so diverse that the reader is best referred to Demus. Today’s LC research shows us that applications are no longer limited to optical displays. Instead, we are seeing a merging of various scientific fields. LCs are finding utility in medicine, biology, nanotechnology, material science, and communication. These fields are growing very rapidly in today’s society and LCs are increasingly finding new applications.
APPENDIX C – COMPLETE TUNABLE FILTER FABRICATION PROCESS

The following list outlines the complete UCCS manufacturing process for the LC based microwave filters. The AZ nLOF 2035 photolithography process for the filters was developed in coordination with the UCCS LC/Microwave group. Crucial changes were also made to existing sputtering and lift-off procedures in order to improve surface adhesion of the microstrip structures to the glass. Some steps in the LC cell assembly process (specific to the tunable microwave devices) were developed, since standard procedures were not adequate.

The work flow begins with preparation of the filters using photolithographic and thin film deposition processes. After the filters are prepared, LC cell assembly is performed to obtain the final product. The entire manufacturing process typically takes four to five days to complete.

The materials used in the photolithography and sputtering process include 1.1 mm thick Borofloat 33 borosilicate glass (B33) from SCHOTT, AZ nLOF 2035 negative photoresist, AZ 300 MIF developer, AZ 400T resist stripper, acetone, isopropyl alcohol (IPA), de-ionized water (DIW), and copper and stainless steel targets.

The materials used in the assembly process involve a 1:4 solution of RN1744 polymer:#21 solvent, solid glass microspacers (Cospheric), solder, 25.4 µm thick conducting tape, NOA68T photopolymer (Norland Products, Inc.), nematic LC2020 and LC1917 (MUT, Warsaw, Poland).

The manufacturing process is performed in the following manner:

1. Photolithography
   a. Preparation
      i. Transfer some AZ nLOF 2035 photoresist from the fridge in the Liquid Crystal Chemistry Lab to a separate container and allow it to warm up to room temperature. Do this in the clean room environment where the resist will be shielded from UV coming from the overhead lights.
      ii. Warm the hot plate to a steady 110 °C.
      iii. Clean all tools, containers, and surfaces where photolithography will be performed.
      iv. Prepare a large dish with the developer and a separate container for rinsing. Have dispensing bottles with acetone, IPA, and DIW readily available.
   b. Prepare two 3.25”x3.25” pieces of B33 glass using the manual glass-scribing machine or the precision-cutter in the Liquid Crystal Chemistry Labs. The excess overhang on the glass is needed to prevent edge-effects from disrupting the photoresist spin-coating. It is also necessary to provide room for gripping the substrate edges without damaging the resist coating in the design area.
   c. Substrate Cleaning
      i. Rinse the glass with acetone, IPA, and DIW (in this exact order).
      ii. Blow dry with N₂ (Open the valve on the N₂ tank in the storage closet before going in to the cleanroom).
iii. Bake the glass at 110 °C to remove residual solvents. Let the substrate cool to room temperature afterwards.

d. Photoresist Application
   i. Set glass on the spin-coater substrate holder and cover the majority of the glass with photoresist.
   ii. Spin-coat the resist at 2700 RPM for 36 seconds with 500 RPM/s ramp. This spin-coating time assumes that the spin-coater starts timing as soon as the substrate begins to spin.

e. Pre-bake
   i. Bake the substrate at 110 °C for 60 seconds.
   ii. Immediately cool to room temperature on a clean, metallic or heat-sink surface.

f. Exposure
   i. Set the substrate on the MJB4 Mask Aligner (SUSS MicroTec) substrate holder. MJB4 operation quick-start procedures may be referenced in the manual to the mask aligner or via the website, www.suss.com/en.
   ii. Open the main valve to the nitrogen tank (designated for the mask aligner) and turn on the vacuum pump to the mask aligner if they aren’t already. Turn on the mask aligner and allow the lamp to warm up.
   iii. Place the photomask on the mask holder and insert the holder into the mask aligner.
   iv. Set the recipe to Align + Expose mode with eight seconds of UV exposure.
   v. Bring the substrate up to the photomask and align its corners with the cross hairs on the photomask, using the microscope. The filter designs should be aligned with the edge of the glass.
   vi. Close the contact lever and expose the substrate to UV for eight seconds.

g. Post-bake: Bake sample at 110 °C for 60 seconds. Then immediately cool to room temperature on a clean, metallic surface.

h. Develop the sample in 300 MIF for 57 seconds, and then immediately rinse with DIW. Be careful not to get IPA on the photoresist. Blow dry gently with N₂.

i. Repeat Steps (c) – (h) for the bottom substrate with filter structures.

j. Check the quality of the samples under a microscope before sputtering. The filter structures are locations where the photoresist is stripped away (so that only the glass is visible). There should be a sharp contrast between the photoresist and the glass. Immediately cover the substrates to prevent dust contamination, and shut down all equipment and close the nitrogen tanks.

2. Thin Film Deposition and Lift-off
   a. Both the top substrate (ground plane) and bottom substrate (filters) need to be sputtered separately using the magnetron sputtering system. Place one of the substrates on the chimney in the main chamber and allow the system to pump-down over night. The chamber pressure should be lower than 0.5 µTorr in order to obtain high quality thin-film surface adhesion.
   b. Sputter 6-7 nm of stainless steel for the adhesion layer.
   c. Sputter 2.25 µm of copper in 10 minute intervals, with 10 minute breaks.
d. Remove sample from system and measure the conductivity using the conductivity measurement system provided in the Microwave Lab.

e. Place sample in 400T stripper over night or early morning at 80 - 100 °C with gentle stirring (3-4x on cleanroom hotplate). Lift-off may take anywhere from 4-12 hours depending on the stripper temperature and other factors.

f. Periodically coax the residual photoresist and copper from the sample with a gentle pipetting action.

g. Retrieve the sample from the lift-off bath and rinse with acetone and IPA. A plastic foam swab may be used to remove residual copper from the structures. Check the structures under a microscope.

3. Pre-Assembly preparation of top and bottom substrates

a. Use the precision glass-cutting machine (Model M0025 from Villa Precision, Inc.) to separate the ground planes from each other. The high-precision cutting is necessary for producing smooth, non-jagged cuts alongside the edge of the ground plane CPW-microstrip transition. The cuts should be made as close as possible to the transition region without peeling the copper away from the glass.

i. Turn on all precision-cutter equipment (two power strips, a switch on the main panel, and a power switch on the panel behind the cameras) and clean the platform with a brush.

ii. On the main panel of the precision cutter, make sure “AirVAC” and “Interlock Override” are switched on. Turn the two knobs if necessary to adjust the scribe pressure to 40 psi. Set the scribe head to “Normal” and “Single Step.”

iii. Select the 0E1 Program at the top of the saved programs list and select “Edit” on the monitor.

iv. The program is set to bring the scribe near the center of the cutting platform at coordinates (7.0375, 5.995) where small substrates can be placed over one of the suction holes. A single cut is performed with designated penetration depth of 0.02 (for Borofloat 33 glass), 40 psi scribe pressure, and desired length. The next page of the program can be modified to produce subsequent cuts if necessary. Hit “Escape” on the keyboard to back out of the Edit program and select “Scribe” on the monitor.

v. Place a 3”x3” square-shaped scrap of glass over the center suction hole and a piece of square-shaped scrap glass on each side. Tape the glass on both sides to the platform to secure the center glass in place. The purpose of have glass on each side is to allow the scribe to smoothly transition to the sample and also to secure the sample. Using Single-Step Mode, have the scribe perform a single cut across the glass by pressing “Scribe.” Press “Reset” immediately to bring the scribe back to its original position.

vi. If necessary, the red “Stop” button on the right of the main panel can be used to stop the scribe in case of emergency or if equipment is malfunctioning. To return back to work, lift the “Stop” button up and press “Reset.”
vii. Use the cameras to view the scribe that was made on the center glass. There is a “Light Source” knob on the left side of the platform to control the lighting. You can view through both cameras in split-screen mode using the toggle switches on the panel behind the cameras. Set the cameras over the far ends of the cut and align the fiducials with the cut. Lock the cameras into place so that they can’t move.

viii. Replace the scrap glass with the top substrate (ground plane) you want to cut and secure it with glass on both sides. Align the ground plane edge with the camera fiducials and perform the cut. Check the substrate under a microscope to make that the copper hasn’t been lifted by the scribe.

ix. Cut the remaining ground planes and then shut down all equipment.

b. Cut the bottom substrate to separate the “cells” with the filters.

c. Pair up the bottom substrates with their corresponding top substrates and put the pairs in separate containers.

d. Apply the low-adhesive, blue tape (provided in the Liquid Crystal Chemistry lab) to regions of the top/bottom substrates where electrical contact will be made. This will prevent polymer from covering these areas when spin-coating is performed.

   i. Apply the blue tape to the two edges of the ground planes with the CPW-microstrip transition regions. The tape should not extend beyond the ends of the alignment markers surrounding the transition regions.

   ii. Completely cover the CPW pads on the bottom substrate with the blue tape. The tape should not cover any part of the filters.

4. **Liquid Crystal Cell Assembly**

   a. **Polyimide Application**

   i. Shake the polymer in solvent for two minutes (with the mechanical vile shaker provided in the Liquid Crystal Chemistry Lab), and then use a syringe with a filter to dispense the polymer over the entire substrate surface in the spin-coating machine.

   ii. Spin-coat the polymer onto both top/bottom substrates at 2000 RPM for 30 seconds.

   iii. Remove the blue tape carefully, so as not to peel off the copper film.

   iv. Bake the substrates at 80 °C until the solvent evaporates from the surface. Remove from hot plate immediately and cool to room temperature.

   v. Bake the substrates at 100 °C under vacuum for 75 minutes to cure the polyimide. This low-temperature, vacuum environment is necessary to mitigate chemical interaction between the copper and the polymer/solvent, as well as prevent the copper from oxidizing.

   vi. Cool substrates to room temperature and cover to prevent dust contamination.

   b. **Mechanical rubbing of polyimide**

   i. Use a glass scribe to mark the direction of rubbing on the back of each substrate. The rubbing direction on the bottom substrate should be antiparallel with the rubbing direction on the top substrate.

   ii. Set the height of the substrate platform on the rubbing machine to 2.3 (by turning the knobs on both sides of the platform). Turn on the rubbing
c. Conducting tape application
   i. Blow-dry the substrates with N₂.
   ii. Cut a small piece of the conducting tape (~5 mm long) and place in between the CPW-microstrip transitions on the top substrates (indicated by the alignment slits). Some ground planes may require two conducting tape strips between the transitions. The conducting tape strip should not extend beyond the length of the slit. Compress the tape tightly against the copper to establish good electrical contact. Wrap the tape around the edge of the glass to secure it.
   iii. Apply the conducting tape between the transitions on every top substrate.

d. Microspacer Application and Assembly
   i. Blow-dry the bottom substrate with N₂ and place it on the chuck in the spin-coating machine.
   ii. Disperse the microspacers in a vile of IPA and use an aggressive pipetting action to distribute the spacers.
   iii. Use a pipette to transfer the spacers suspended in IPA to the substrate. Cover the majority of the substrate. Spin-coat at 1400 RPM for 20 seconds. The spin-coating speed may be varied slightly to optimize the distribution of spacers on the substrate (the distribution should be as homogeneous as possible).
   iv. Set the bottom substrate (with microspacers) on a clean, flat surface. Blow-dry the top substrate with N₂ and immediately place it on top of the bottom substrate (such that the two substrates are in anti-parallel alignment).
   v. Compress the two substrates together across the whole cell—especially along the edges where excess, protruding glass may disrupt the cell thickness. Apply a binding clip to one side of the cell.
   vi. Under the microscope, align the two substrates so that the solid, square alignment markers are within the open square markers. Also look at the CPW-microstrip transition to make sure the top transition region is aligned with the bottom transition region. Be aware of parallax effects while looking through the microscope during this step.
   vii. Carefully apply NOA68T photopolymer to the cell without disrupting the substrate alignment, and expose the cell to UV (60-100%) for 1 minute. Apply glue in other areas of the cell for further stability. A good cell typically has a circular interference pattern (a few rainbow lines) in the center of the cell. However, it may be difficult to see this over the copper surface.
5. **Liquid Crystal Insertion**
a. Place the LC cell in the vacuum chamber provided in the Liquid Crystal Chemistry Lab. Make sure the cell is right-side up so that LC may be inserted.
b. Secure a capillary tube on an alligator clip attached to the end of the right arm. At the end of the left arm, secure an open vile containing the LC material.
c. Bring the system to vacuum level, using the capillary tube on the right arm to insert the LC into the cell.
d. Bring the system back to room pressure and remove the cell.
e. Clean residual LC and spacers from the CPW region of the cell.

6. **Final Steps**
a. Solder the individual conducting tape strips to the ground CPW pads of the cell. Make sure that the solder does not short the trace/ground of the CPW. However, the solder should be as close as possible to the transition region for proper grounding.
b. Seal the cell completely with glue (no photopolymer). Do not expose the LC cell to UV at this point, since the LC 1917 and 2020 are sensitive to the UV.
REFERENCES


22 Z. Zhang, J. Liu, H. Ding, Z. Feng, and Y. Nie, Microwave Bandpass Filters Tuned by the Magnetization of Ferrite Substrates, IEEE Magnetics Letters, 16712614 (2016), pp. 1-4. DOI: 10.1109/LMAG.2016.2623717.


89 S. Onstott, AutoCAD 2017 and AutoCAD LT 2017 Essentials (John Wiley and Sons, Inc., Indianapolis, IN, USA, 2016).


91 M. Golio and J. Golio, RF and Microwave Circuits, Measurements, and Modeling, 2 ed. (Taylor and Francis Group, Boca Raton, FL, USA, 2008).


On-Wafer Vector Network Analyzer Calibration and Measurements: Application Note, Cascade Microtech, Inc., USA, 2017


141 X. Li, Z. Shao, Z. He, and M. Shen, A miniaturized electrically tunable dual-mode bandpass filter based on liquid crystal technology for microwave applications, Microwave and Optical Technology Letters 58, 7 (2016), pp. 1686-89. DOI: 10.1002/mop.29892.


P. Yeh and C. Gu, Optics of Liquid Crystal Displays (John Wiley and Sons, Inc., NJ, USA, 2010), 2 ed.


N. Podoliak, O. Buchnev, D. V. Bavykin, A. N. Kulak, M. Kaczmarek, and T. J. Sluckin, Magnetite nanorod thermotropic liquid crystal colloids: Synthesis, optics and


161 F. Reinitzer, Contributions to the knowledge of cholesterol, Liquid Crystals 5, 1 (1989), pp. 7-18. DOI: 10.1080/02678298908026349.
