The dashed lines extending beyond I_{max} indicate the damped relaxation frequencies.

If the SA layer is far from the active region the range of self-pulsations is limited due to weak coupling with the active region. However, as the SA layer is moved closer to the active region it will become more susceptible to permanent saturation, and damped oscillations will ensue. It is apparent from Fig. 2 that there is an optimum position for the SA layer within the rear multilayer stack to achieve the maximum range of pulsation frequencies.

This work neglects nonlinear gain and the linewidth enhancement factor, both of which will affect the pulse shape and the range of pulsation frequencies. These and other complexities will be the subject of future publications. Small signal analysis has also been applied to the rate equations to predict the regions of self-pulsations, and these results are included in Fig. 2.

Conclusions: The generation of self-sustained pulsations from surface emitting lasers with a layer of saturable absorption has been simulated using a set of coupled rate equations. Self-pulsating behaviour is affected by the strength of interaction between the gain region and the absorbing layer, and it can be shown that there is an optimum position of the absorber layer within the multilayer reflector stack to produce the widest range of pulsation frequencies.

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Vertical-cavity surface-emitting lasers with integrated refractive microlenses

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Indexing terms: Vertical cavity surface emitting lasers, Optical polymers, Lenses

The fabrication and performance of a vertical cavity surface emitting laser array integrated with microlenses are reported. The lasers emit at 967nm through the substrate with integral polyimide microlenses. This design reduces beam divergence and provides an integrated device that emits a nearly collimated beam for applications such as optical interconnects.

As increasingly larger numbers of input/output (I/O) channels are required for interconnect applications such as three-dimensionally stacked multichip modules (MCMs) and computer backplanes, massively parallel solutions incorporating photonic devices become increasingly attractive. In particular the inherent parallelism associated with arrays of vertical-cavity surface-emitting lasers (VCSELs) makes them ideal for optical interconnect technology. Despite a much smaller divergence angle than edge emitting devices, spreading of the beam perpendicular to the surface of the VCSEL causes difficulties in alignment in a MCM package and limits the transmitter distance, as well as decreasing tolerances in packaging.

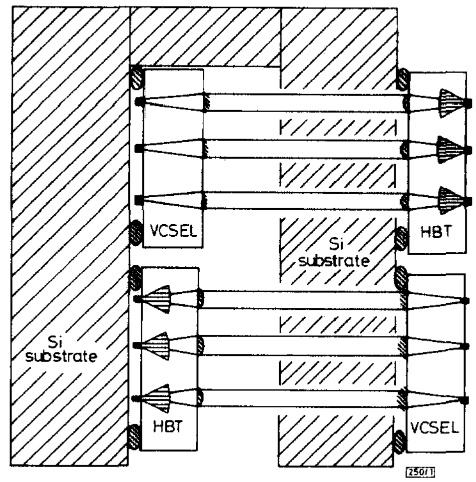

Fig. 1 *Cross-section of two layer demonstration stack using silicon MSM substrates, VSCELs on GaAs substrates and HBT photoreceivers on InP substrates with integrated microlenses*

In our application [1], VCSELs are to transmit information optically to heterojunction bipolar transistor (HBT) detectors located 850μm away, through a 100μm diameter via hole drilled in the Si carrier, as shown in Fig. 1. By integrating a bottom emitting VCSEL array with a polyimide microlens array, we demonstrate a decreased divergence of the beam, which results in a significantly larger fraction of the power transmitted through a 100μm pinhole 850μm away from the substrate.

The VCSELs operate in the 960–970nm region emitting through the transparent GaAs substrate. The growth and fabrication processes of similar devices are described elsewhere [2] except that mirrors are modified appropriately to obtain emission through the substrate. The device aperture, defined by a proton implant, is 15μm. The GaAs substrate is lapped down to a thickness of 325μm, polished, and the polyimide microlenses are then fabricated on the thinned substrate in alignment with the VCSELs. The fabrication process for our microlenses is exceedingly simple. A thick layer of polyimide is spun on and baked, followed by a layer of photoresist. We use an infra-red aligner to position the microlenses relative to the VCSELs. The photoresist is exposed (at ~400nm) to define circles of the desired lens diameter, which in our case is 50μm. On its development, the polyimide is exposed using deep UV (at ~250nm) and developed away forming a cylinder of polyimide and photoresist. Next, a small amount of the underlying GaAs substrate is removed by reactive ion etching (RIE) to form an abrupt, 0.2–0.3μm tall pedestal under the polyimide and photoresist. Finally the photoresist is removed and the lens is formed by reflowing the polyimide at 290°C for 5 min on a hot plate. Constrained by the sharp edge of the GaAs pedestal, the polyimide cannot flow freely, thus forming a spherical surface with a diameter defined by the dimension of the etched pedestal. We measured the light-current (L-I) characteristics of VCSELs before and after this process to ensure that the performance of the VCSELs is not degraded by the microlens process. We are confident that this is the case, because the threshold currents and maximum powers of the lasers do not change. Similar lenses fabricated in photoresist, rather than polyimide, have been demonstrated by others [3], but not integrated with VCSELs. The polyimide has the advantage over photoresist in that it is more transparent in the near infra-red wavelength range and has a higher glass transition temperature T_g, thus ensuring greater thermal stability.

Diffractive optics have also been used to collimate the output of VCSEL arrays [4, 5]. The performance of the refractive microlenses described here is comparable to the best diffractive element performance, yet it can be achieved using a considerably simpler process than the multiple lithography and dry etching steps required for diffractive optics fabrication.

Fig. 2 *Scanning electron micrograph (SEM) of 50μm polyimide microlens*

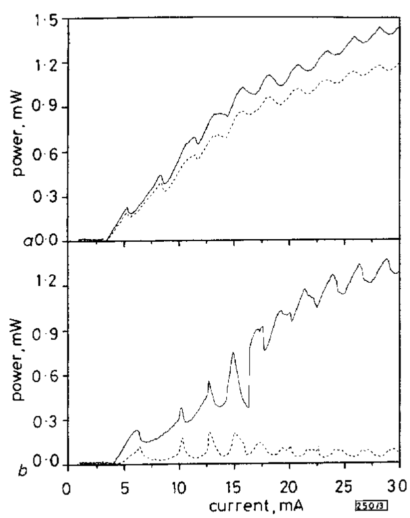

Fig. 3 *Power-current (L-I) characteristic of the VSCEL with and without an integrated microlens on the substrate measured through the 100μm* pinhole 850μm away from the substrate and measured without the pinhole, letting the beam spread freely
a With a microlens
b Without a microlens
——— without pinhole
– – – – with pinhole

A scanning electron micrograph (SEM) of a polyimide microlens is shown in Fig. 2. The exceptional smoothness of the polyimide surface assures good optical quality of the VCSEL beam. The focal length of the microlenses was measured to be near 100μm, which we calculated to be the optimum for transmission through a 350μm thick substrate, in order to obtain a quasicollimated beam at a distance of 850μm. To measure the fraction of the VCSEL power that will couple through the 100μm via in the Si substrate in our system, we measured the L-I characteristics of the two adjacent VCSELs through a 100μm pinhole located 850μm away. A control VCSEL without a microlens was fabricated adjacent to a VCSEL integrated with a microlens. The results of this measurement are illustrated in Fig. 3*a* and *b* for the laser with and without the microlens, respectively. Clearly, the device with a microlens performs significantly better with more than 80% of the available power coupling through the pinhole. In contrast, when the microlens is omitted, only 8% of the incident power is detected on the other side of the pinhole. This surprisingly low fraction is largely a result of the VCSEL lasing in higher order modes, which have more power in the off axis regions. By comparing the size of the beam at several distances we calculated the divergence angle and found that an integrated microlens decreases it from 5° half angle to 1° half angle. The ripple in the L-I characteristic is caused by the Fabry-Perot fringes due to the polished substrate. These could be easily eliminated by depositing a layer of index matching material such as SiO_xN_{1-x} between the lens and the substrate. Optical feedback into the VCSELs due to microlenses is currently being investigated, although preliminary results indicate that it is negligible.

We are also working on transferring the polyimide lenses into the GaAs substrate using dry etching techniques. The etch rate of GaAs can be greater than that of polyimide allowing for higher lens curvatures, which coupled with a larger refractive index of GaAs results in a faster lens. On the other hand, the all polyimide microlenses can be fabricated on any substrate using the same process, which can be advantageous for InP based detectors and GaAs based sources as required in our system, as well as a variety of other materials such as GaN, Si and sapphire.

In conclusion, we have demonstrated the integration of a VCSEL array with a refractive microlens array. Substantial improvement in performance is observed with the microlenses, leading to relaxed tolerances in alignment of the sources to the detectors or fibres.

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