The dashed lines extending beyond $J_m$ 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 multi-plexer 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 multi-plexer reflector stack to produce the widest range of pulsation frequencies.

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References


Vertical-cavity surface-emitting lasers with integrated microcavities


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

The fabrication and performance of a vertical cavity surface emitting laser array integrated with microcavities are reported. The lasers emit at 987 nm through the substrate with integral polyimide microcavities. 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.

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

The VCSELs operate in the 960-970 nm 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 15 μm. The GaAs substrate is lapped down to a thickness of 325 μm, polished, and the polyimide microcavities are then fabricated on the thinned substrate in alignment with the VCSELs. The fabrication process for our microcavities 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 microcavities relative to the VCSELs. The photoresist is exposed (at ~400 nm) to define circles of the desired lens diameter, which in our case is 50 μm. On its development, the polyimide is exposed using deep UV (~250 nm) 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, 0.2-0.3 μm tall pedestal under the polyimide and photoresist. Finally the photoresist is removed and the lens is formed by refluxing 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 microcavities 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

![Cross-section of two layer demonstration stack using silicon MSM substrates, VCSELS on GaAs substrates and HBT photoreceivers on InP substrates with integrated microcavities.](image-url)
others [3], but not integrated with VCSELs. The polyimide has the advantage over photore sist 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 micro lenses described here is comparable to the best diffractive element performances; 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 micro lens.](image)

![Fig. 3 Power-current (I-I) characteristic of the VCSEL with and without an integrated micro lens on the substrate measured through the 100μm pinhole 850μm away from the substrate and measured without the pinhole, letting the beam spread freely.](image)

A scanning electron micrograph (SEM) of a polyimide micro lens 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 micro lenses was measured to be near 100μm, which we calculated to be the optimum for transmission through a 500μm thick substrate, in order to obtain a quasicoherent 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 I-I characteristics of the two adjacent VCSELs through a 100μm pinhole located 850μm away. A control VCSEL without a micro lens was fabricated adjacent to a VCSEL integrated with a micro lens. The results of this measurement are illustrated in Fig. 3a and b for the laser with and without the micro lens, respectively. Clearly, the device with micro lens performs significantly better with more than 80% of the available power coupling through the pinhole. In contrast, when the micro lens 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 micro lens decreases it from 5° half angle to 1° half angle. The ripple in the I-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$_2$, between the lens and the substrate. Optical feedback into the VCSELs due to micro lenses 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 micro lenses 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 micro lenses array. Substantial improvement in performance is observed with the micro lenses, leading to relaxed tolerances in alignment of the sources to the detectors or fibres.

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