Novel vertical-cavity surface-emitting lasers with integrated optical beam router

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Indexing terms: Vertical cavity surface emitting lasers, Integrated optics, Phase shifters

A novel vertical-cavity surface-emitting laser (VCSEL) with integrated optical beam router is reported. The output beam of the VCSEL has been steered by as much as 9.6° away from the surface-normal direction. Integration of the beam routers with VCSELs significantly reduces the complexity and size of the switching nodes. This device is useful for ultra-dense optical interconnects in massively parallel computers.

Optical interconnects have received a great deal of interest recently because they can be used to reduce the communication bottlenecks in massively parallel multiprocessors. There are two basic elements in optical interconnection networks: optical sources that convert signals into photons and optical beam routers that redirect the optical beams. Vertical-cavity surface-emitting lasers (VCSELs) have established themselves as the preferred optical sources for free-space optical interconnects because of their low threshold currents, small beam divergence angles, and their ability to form two-dimensional arrays [1]. Optical beam routers have been realised by various refractive and diffractive optical elements such as prisms, gratings [2], and computer-generated holograms [3]. It is desirable to integrate the beam routers with the optical sources because this increases the functionality of the switching nodes and, therefore, permits denser optical interconnections. Attempts have been made to integrate optical beam routers with edge-emitting lasers [4]. However, such a structure is limited to one-dimensional scanning. Two-dimensional steering of optical beams is desirable for sophisticated optical interconnection networks. This can be achieved by integrating optical beam routers with VCSELs. There are several advantages to integrating optical beam routers with VCSELs. Since the output mirrors are on the surface of the wafer, precise optical phase shifters can be fabricated monolithically by photolithography and microfabrication. Phase shifters with 180° phase shift have been used to achieve in-phase far-field patterns in phase-locked two-dimensional VCSEL arrays [5]. However, optical beam routers have not been realised. In this Letter, we report the first demonstration of a novel VCSEL with integrated optical beam router. Optical beams emitting at an angle as large as 9.6° away from the surface-normal direction have been realised without increasing the threshold currents of the VCSEL (4.2mA for 4 × 8μm² devices). This device can be used as a basic building block for interconnection networks such as Banyan networks.

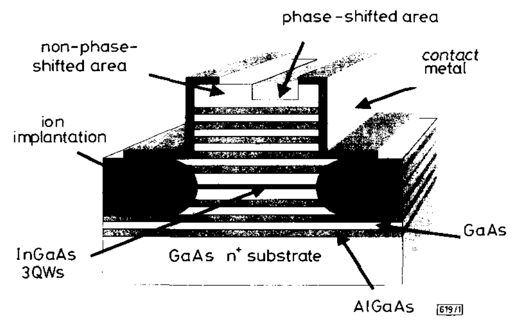

Fig. 1 *Schematic diagram of VCSEL with integrated optical beam router*

The schematic structure of the VCSEL with integrated beam router is shown in Fig. 1. A phase shifter is incorporated on half of the VCSEL surface. The fabrication processes are described in the following. The VCSEL consists of a 35 pair *n*-doped quarter-wave GaAs/AlGaAs DBR bottom mirror, a λ-cavity with three InGaAs/GaAs strained quantum well active region, and a 25.5 pair *p*-doped top DBR mirror with a 3/4λ-thick *p*+ GaAs cap layer. The VCSELs are grown by the metal organic chemical vapour deposition (MOCVD) technique. The phase shift is realised by etching the top DBR mirror. It is important that the phase shifter does not perturb the reflectivity of the DBR mirror so that the fundamental transverse mode operation and low threshold current are maintained. If the etching depth is equal to an integral number of half-wavelengths, uniformly high reflectivity across the active mesa is achieved. The top electrodes which simultaneously pump the phase-shifted and non-phase-shifted region are then deposited by evaporation and lift-off processes. Fig. 2 shows the scanning electron micrograph (SEM) of the finished device with a mesa size of 8 × 8μm².

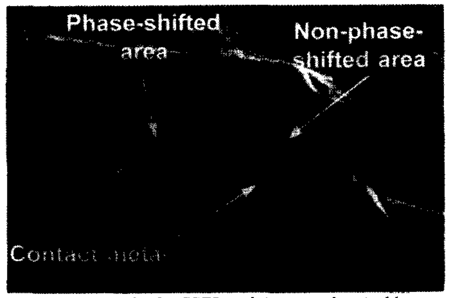

Fig. 2 *SEM photograph of VCSEL with integrated optical beam router*

The phase-shifted area is etched by a thickness of λ/2 to create a 129° phase shift

The beam steering characteristics were confirmed experimentally. Fig. 3 shows the experimentally measured and theoretically simulated far-field patterns of a 12 × 8μm² VCSEL with integrated beam router. The resulting phase shift is equal to $\phi = 2\pi/\lambda(n-1)\cdot\lambda/2n = \pi\cdot(1-1/n) = 129°$, where λ is the wavelength in free-space and *n* is the refractive index of the phase shifter. The steering angle of the optical beam is equal to $\theta = \sin^{-1}(\lambda/2\pi d\cdot\phi) = 2.9°$ in this configuration (*d* is the centre-to-centre spacing between the phase-shifted and non-phase-shifted regions). Both the steering angle and the beam profile agree very well with theory.

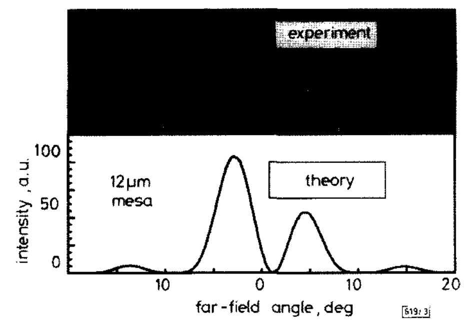

Fig. 3 *Experimental and theoretical far-field patterns of 12 × 8μm² VCSEL with integrated beam router*

As shown in the above analysis, it is possible to design VCSELs with different beam steering angles by changing: the centre-to-centre spacing, the refractive index of the phase shifter, or the thickness of the phase shifter (an integral number of half-wavelengths). The first design can readily be incorporated by microfabrication without additional complexity. Fig. 4 shows the measured and calculated beam steering angle against the centre-to-centre spacing, *d*. The centre-to-centre spacing here is equal to half of the active mesa size. Again, very good agreement between experiment and theory is observed. A beam steering angle as large as 9.6° is obtained from the VCSEL with active mesa size of 4 × 8μm². The threshold current remains as low as for a standard VCSEL (4.2mA). It is possible to form two-dimensional arrays with two-dimensional steering capability, a property very useful for implementing three-dimensional free-space optical interconnect architectures. It is also possible to extend the static steering of optical beams described in this Letter to dynamic switching. Dynamic switching can be realised by, for example, individually modulating the phase-shifted (or non-phase-shifted) part of the VCSEL. This is currently under investigation and will be reported separately.

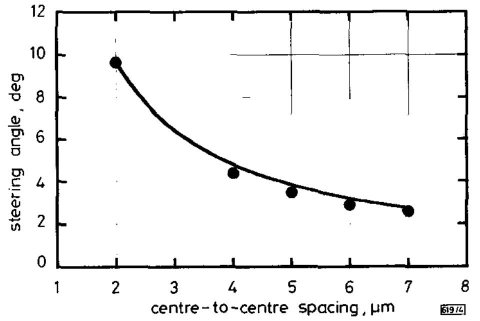

Fig. 4 *Measured and calculated beam steering angles against centre-to-centre spacing between phase-shifted and non-phase-shifted area*

● experiment
——— theory

In conclusion, a novel vertical cavity surface-emitting laser (VCSEL) with integrated optical beam router has been experimentally demonstrated for the first time. An optical beam routing angle as large as 9.6° has been achieved with 4 × 8µm² beam-steering VCSELs. This approach maintains the advantages of standard VCSELs (low threshold currents and low beam divergence angles) while adding the new ability to steer the output optical beams. This new device is very useful for free-space optical interconnects for massively parallel computers.

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Passive alignment of a tapered laser with more than 50% coupling efficiency

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Indexing terms: Semiconductor junction lasers, Optical couplers, Optical fibres

Coupling efficiencies of > 50% have been obtained by passively aligning precision-cleaved large-spot-sized lasers to singlemode fibre on a silicon micromachined substrate. This is the highest known coupling figure reported for passive alignment.

Introduction: The packaging of semiconductor laser chips has always presented a range of technical problems due to the submicrometre tolerances required to obtain optimum coupling of the small laser spot size to the larger spot size of a singlemode fibre. Lasers have been reported [1] that can ease these tolerances by matching the laser spot size to that of cleaved fibre. This is achieved by tapering the active layer to adiabatically expand the laser mode size. Work has also been reported on the use of silicon waferboards and flip-chip packaging to obtain coupling efficiencies of ~7% to cleaved fibre [2]. However, for such a technology to be viable much higher coupling efficiencies are required. In this Letter we report on the combination of a precision-cleaved large-spot laser and a silicon micromachined optical bench to achieve high coupling efficiencies by purely passive alignment. This combination of technologies will offer a viable route to obtaining the very low-cost packaged devices required for fibre to the home.

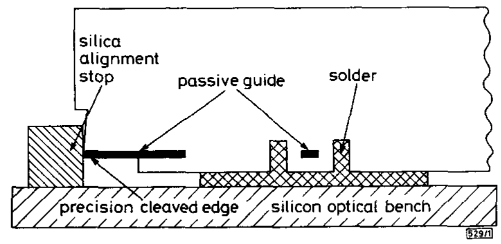

Fig. 1 *Schematic diagram of precision-cleaved laser on optical bench showing oxide alignment stop and scribe lane*

Laser design and fabrication: The device was a 1.55µm Fabry-Perot laser with an 8 well compressively strained active layer, the planar design having been reported previously [1] (see Fig. 1). The first stage of photolithography was used to define both the passive guide of the large-spot-size device [3] and to form channels at the edges of the device to define the scribe lanes. This allows the edges of the scribe lanes to be defined with an accuracy of ~±0.2µm, determined by the undercut of etchants used at later stages, relevant to the passive guide. The fabrication process is then virtually identical to that of the recently reported large-spot-size device [3], until the final stages of processing when the buried scribe channels are exposed and the scribe lanes etched using 4:1 H_3PO_4:HCl. This forms a U-shaped channel ~20µm deep and 5µm wide, the top corners of which are defined by the 1.1µm quaternary of the passive guide. The fabricated devices were cut into devices 1.1mm long by 300µm wide (defined by the scribe lanes). The length of the device comprised 340µm of untapered active region, a 460µm tapered region and 300µm passive region. Optimised coupling measurements of the devices on conventional headers yielded coupling efficiencies of up to 62% to cleaved-ended singlemode fibre.

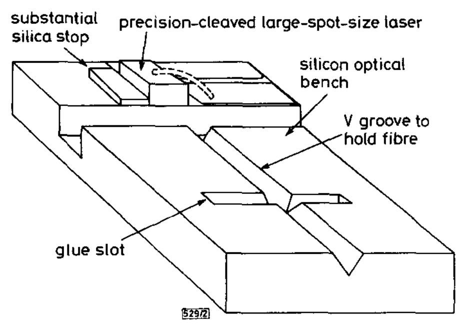

Fig. 2 *Schematic diagram of silicon optical bench*

Silicon optical bench: Silicon micromachining techniques were used to fabricate the optical bench on which the optical components were passively aligned. The main features of the silicon optical bench are V-grooves for fibre attachment and silica stops against which the cleaved edges of the laser chips can be aligned (Fig. 2). The 15µm high silica stops were deposited by plasma-enhanced chemical vapour deposition and etched by a combination of reactive ion etching and wet chemical etching. Bondpads were formed