Novel Vertical-Cavity Surface-Emitting Lasers with Integrated Optical Beam Router for Massively Parallel Free-Space Interconnection

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Abstract

We report a novel vertical-cavity surface-emitting lasers (VCSEL) with monolithically integrated phase-shifters. Optical beams emitting at angles of 0° to 9.6° from the surface-normal direction have been achieved. Dynamic switching of the radiation angle has also been successfully demonstrated by turning on/off the phase-shifted region of the VCSEL. This novel device can reduce the complexity and size of switching nodes, and increase reliability of the interconnect system. The high-density integration and wafer scale fabrication capability make them particularly attractive for massively parallel free-space optical interconnection.

Introduction

Spatial-variant optical beam router is very attractive for free-space optical interconnection. It has the advantages of high spatial bandwidth, high data transmission rate, and could overcome the transmission bottle-neck and crosstalk effects in the large-scale digital system. Among free-space interconnection, fixed tilting angles created by computer-generated holograms (CGHs) [1], prisms[2], or gratings[3] have been investigated. Edge-coupled beam steering devices have been realized by differentially pumped twin-strip lasers [4,5]. The far-field pattern could be scanned in phase-locked laser diodes arrays with multiple contacts[6], or in lasers with spatial phase controller [7]. However, these devices need external optical components or cleaved facets and are not suitable for wafer-scale fabrication.

Vertical-cavity surface-emitting lasers offers several advantages over conventional edge-emitting laser diodes, especially in communications and integrated optics. The symmetric far field patterns and narrow beam divergence permit high couple efficiency into single mode optical fibers. Recent progress in epitaxial growth and fabrication techniques has led to substantial improvement in the performance of VCSEL's. Two dimensional arrays with high integration densities ($>10^6/\mathrm{cm}^2$) [8] are also attractive for dense optical interconnect applications. Combining VCSELs with optical beam routing capabilities will greatly enhance its functionality for optical interconnect. Unlike edge-coupled devices, the facets of VCSEL's are located on the surface of the substrate. This allows the output facet reflectivities and phase shifts to be engineered in two dimensions using wafer scale processing. In-phase far-field pattern of two dimensional VCSEL array has been reported [9]. However, the optical beam routing and steering capability of VCSEL has not been explored.

In this paper, we report a novel VCSEL with integrated beam router. The far field pattern emitting at an angle as large as 9.6° away from the surface-normal direction has been achieved with device of 4 μm × 8 μm mesa size. The beam router is fabricated without altering the VCSEL design nor reflectivity. The dimensions of the beam-routing VCSEL's are comparable to those of the standard VCSEL's. Therefore, low threshold current, low power consumption and single transverse mode properties are maintained. It can be used as fixed optical beam router in optical interconnections for spatially coded data and configuration of short distance parallel bus interconnection [10]. We also demonstrate the dynamic switching ability of the beam-routing VCSEL by turning on/off the phase-shifting region of the VCSEL. This novel device can be used to implement the functions of spatial switching, reconfigurable routing, and optical logic operator. It also reduces the complexity and size of switching nodes and is particularly attractive for massively parallel optical interconnect applications.

Fabrication

The schematic cross-sectional diagram of the VCSEL with spatial-variant phase shifter is shown in Fig. 1(a). The epitaxial layers are grown by metalorganic chemical vapor deposition (MOCVD) on an n^+ GaAs substrate. Lateral device formation employs wet chemical etching with nonselective H_2SO_4:H_2O_2:H_2O etching solution. The same photoresist pattern was used as the mask for subsequent ion implantation which was used for device isolation and lateral current confinement. The VCSEL consists a 35-pair n-doped quarter-wave GaAs/AlGaAs distributed Bragg reflector (DBR) stack, a one-wavelength long active region with three InGaAs/GaAs strained quantum well active layers, a 25-pair p-doped GaAs/AlGaAs top DBR mirror, and a $3\lambda/4$ p^+ GaAs cap layer. After mesa etching and ion implantation, a 2000-Å thick spin on glass (SOG) was applied and cured at 380 °C. Top contact windows are opened by reactive ion etching (RIE). The phase shifter is created by removing part of the

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top cap layer. Different thickness will correspond to different phase shift, however, it will also affect the reflectivity of the top DBR mirror at the same time. Uniform reflectivity is desired for fundamental mode operation inside the cavity. The same high reflectivity of top DBR mirror can be maintained if the etch depth is an integral multiple of $\lambda/2$. A phase shifter of $\lambda/2$ thickness introduced an optical path difference of 120° for transmitted light. It is noted that the phase shift for the light reflected back into the cavity is 0°, such that this phase shifter does not perturb the fundamental mode operation of the VCSEL. Figure 1(b) shows the photograph of the VCSEL with integrated phase shifters that are precisely defined to be one half of the mesa size. The interference between the phase-shifting and non-phase-shifting beams tilts the emitting angle away from surface-normal direction. The beam angle can be precisely controlled by the separation between them. It can also be fine controlled by the phase shifter thickness and the lasing wavelength [11] (thermal tuning).

Experimental Results

Quantitative measurements of the far field distribution were obtained by projecting the laser wavefront on a charged coupled device (CCD) board camera and displaying the trace on a oscilloscope. The lasers were pumped under CW condition. It was mounted on a copper heat sink and operated at 15 °C. We used a standard VCSEL to calibrate the axis (0°) of the far-field angle. Figure 2 shows the comparison between the experimental beam profile and the theoretical far field pattern. Excellent agreement of the steering angle and beam profile were observed. Figure 3(a) shows the beam profile versus mesa size. Figure 3(b) shows the scan angle versus mesa size. Smaller mesa size corresponds to larger off-axis angle. By using different mesa size, the beam-routing VCSEL can communicate with different spatial channel. This device combines the functions of position switching and routing into a single compact component.

By individually pumping the phase-shifted region and the non-phase-shifted region, dynamic switching of the emitted beam angle is achieved, as shown in Fig. 4. The top metal contact for this beam-switchable VCSEL is separated for the phase-shifted region and non-phase-shifted region. When only one of the region is pumped, the device becomes similar to standard VCSEL's and surface-normal emission (0°) is obtained. This is illustrated in Fig. 4 (a). The pumped region could be either phase-shifted or non-phase-shifted regions. When both regions are turned on simultaneously, the optical beam will deviate from the surface-normal direction as described earlier. This is illustrated in Fig. 4 (b). The switching speed is only limited by the relaxation oscillation frequency of the VCSEL, which is faster than other mechanisms such as steering the beam by tuning wavelength [12] or by changing refractive index through free-carrier injection [5].

In summary, a vertical cavity surface-emitting laser (VCSEL) with integrated spatial-variant optical beam router is demonstrated for the first time. Optical beams emitting at angles of 0° to 9.6° away from surface-normal direction has been achieved. Dynamic switching of the far-field angles is also successfully demonstrated. This device maintains all the advantages of VCSEL's: it has low threshold current, low power consumption, and fundamental spatial mode operation. Dense two-dimensional arrays of these beam-switching VCSELs can also be formed. This novel device is very useful for applications in ultra-dense free-space optical interconnect.

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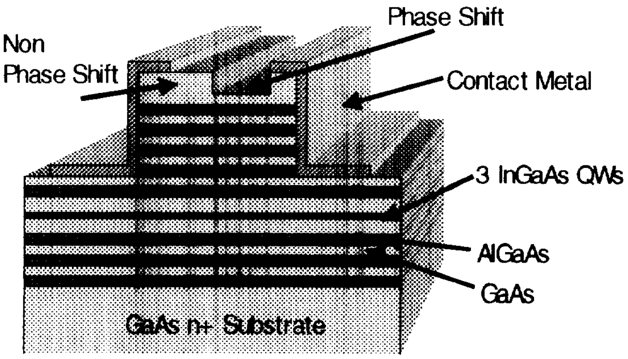

Figure 1(a). Schematic structure of the VCSEL with monolithic integrated phase shifter

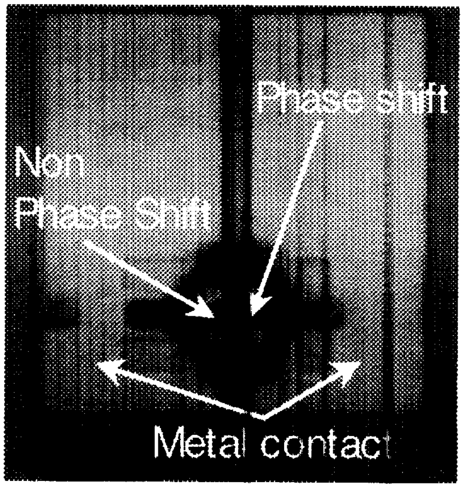

Figure 1(b). Photograph of the novel VCSEL with integrated beam router

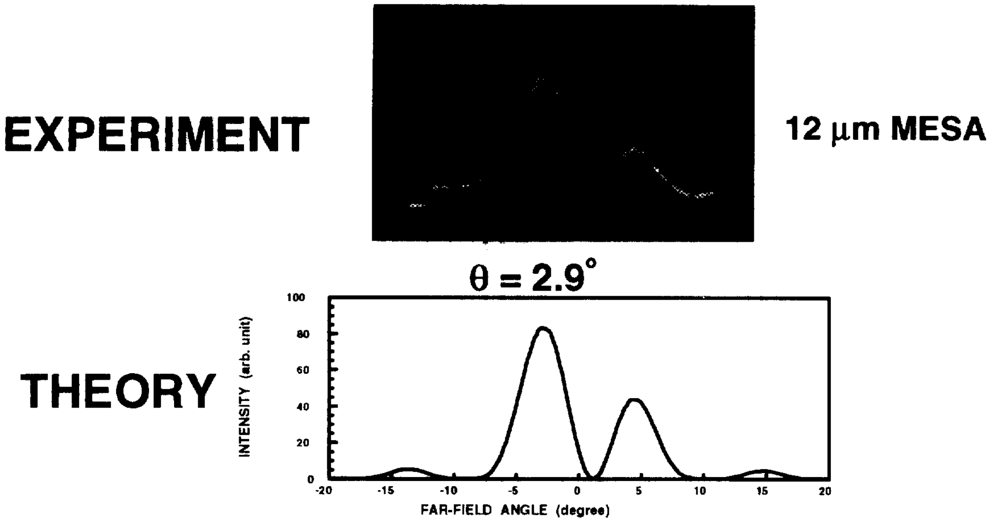

Figure 2. Comparison between the experimental beam profile and the theoretical far field pattern.

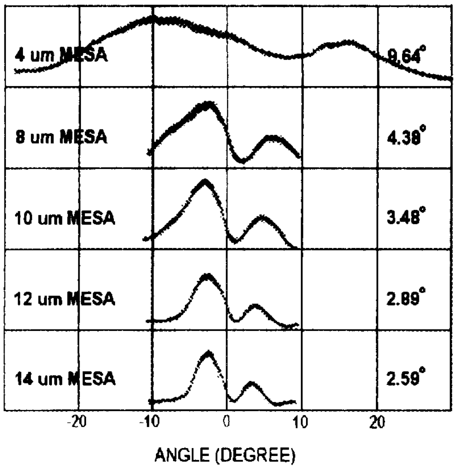

Figure 3(a). Beam profile versus mesa size

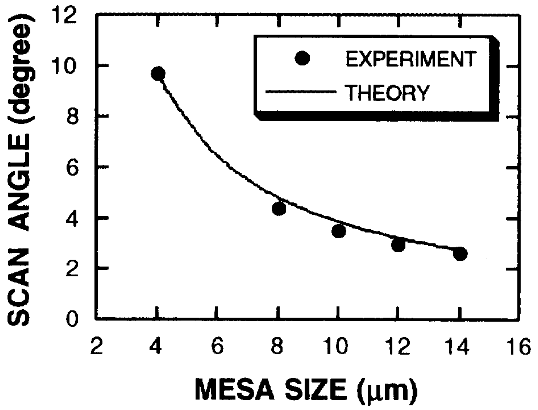

Figure 3(b). Beam scan angle versus mesa size

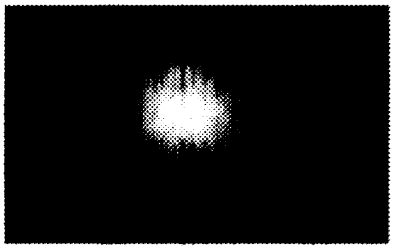

Figure 4(a). Far field patten maintains surface-normal emission, when only one region is pumped

Figure 4(b). When both phase-shifted and non phase-shifted regions are turned on simultaneously , the beam deviates from the surface-normal direction