Beam Steering Modulation with Phased Vertical Cavity Laser Arrays

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Electronically steerable laser sources have applications in areas such as optical display, free space communications, and illumination. Among the multiple figures of merit for beam steering, speed is still a limiting factor for many applications including laser radar [1]. While mechanical methods clearly have inertial limitations, even the fastest available liquid crystal optical phased array techniques are limited to speeds under 10 kHz [2, 3]. We show that electronic beam steering using phased vertical cavity surface emitting laser (VCSEL) arrays [4-6] can be steered as fast as 100 MHz while possessing the inherent advantages of system robustness, radiation hardness, and energy efficiency.

The phased VCSEL arrays operate nominally at 850 nm and are arranged in a 2x1 configuration utilizing a photonic crystal and ion implantation pattern to achieve optical and carrier confinement, respectively. The arrays are designed to reliably operate out-of-phase or in-phase [4], where a variable phase change between elements can be controlled with current injection to achieve steering [5]. Images of the phased VCSEL array are shown in Figure 1. The missing photonic crystal holes create the array elements and have aligned implant apertures the same size as the defect, as shown by the cross-sectional diagram in Figure 1c. Also shown by this diagram is the preferential current injection into either aperture, which is enabled by ion implantation and a focused ion beam etch into the top metal contact.

To measure the speed of beam steering, the current to the left array element is held constant while the current to the right element is modulated with a square wave. A photodetector with an angular width of 1.6° is placed above the array, and the optical signal is obtained at incremental locations along the direction of beam steering (perpendicular to the direction of propagation). The received signal amplitudes corresponding to the times of low and high current injection are then obtained and mapped to their corresponding angular locations. In this manner we recreate the far field profiles at the times of low and high modulation. This is shown in Figure 2 for an array operating between in-phase and out-of-phase ($\Phi_{\text{right}} = 0.7\pi$) at the relatively slow modulation rate of 100 Hz. The beam is steered to the right as the current injection into the right element is increased, a phenomena consistent with DC measurements. The phase lag increase in the right aperture between the low and high signals, $\Delta \Phi_{\text{right}}$, is determined as approximately $0.3\pi$ [6], requiring a current difference, $\Delta I_{\text{right}}$, of less than 100 $\mu$A.

When the same array is modulated at a faster rate of 100 kHz, the beam continues to steer to the right with increased current to the right element, but with a significant delay, as shown in Figure 3. This steering is also caused by a relative phase lag in the array element under increased current injection. Both the delay and the apparent increase in the optical path length through the semiconductor with increased current are common to all arrays characterized in the sub-MHz regime, given sufficient current confinement. Both phenomena indicate that the thermo-optic effect [7] is the dominant phase shifting mechanism in these phased VCSEL arrays from DC to sub-MHz operation.

Varying steering effects are observed when arrays are modulated at a faster rate of 100 MHz: some arrays show little to no steering to the right from low to high current injection into the right element. An entirely different phase shifting mechanism is evident in two arrays, where the beam is found to steer to the left from low to high current injection, as shown in Figure 4 for an array operating out-of-phase. This translates to a relative phase lead in the array element with increased current, where $\Delta \Phi_{\text{right}} = -0.2\pi$ for $\Delta I_{\text{right}} = 240$ $\mu$A. This is consistent with the carrier-induced index change, where the refractive index decreases with increasing current [8]. Note from Figures 2 and 4 that an overall increase in intensity is evident in the far field profiles associated with the higher current levels at various modulation rates. This could be circumvented with push-pull modulation [9].

In conclusion, we have demonstrated phased VCSEL array beam steering at an equipment-limited modulation speed of up to 100 MHz. We conclude that the thermally induced index change is the dominant phase-shifting mechanism for modulation speeds in the sub-MHz regime. At sufficiently high modulation rates the thermal dynamics are effectively neutralized while the carrier-induced index change eventually dominates the phase-shifting mechanism, steering the beam in the opposite direction with increased current. While these arrays are applicable to standard applications in beam steering, they also hold potential promise for optical interconnect systems, as they are not dynamically limited by the cavity carrier and photon densities in the same way as directly modulated VCSELs. This work was partially supported by the Navy SBIR N11A-024-0476.
REFERENCES


Figure 1. Phased VCSEL array image shown with (a) scanning electron microscope and (b) operating in-phase, as noted by the small central lobe. The cross-sectional view (c) illustrates the alignment of the photonic crystal and ion implantation, as well as the preferred current path for injection into the left contact.

Figure 2. 100 Hz modulation: (a) far field profiles showing steering to the right with increased current injection into the right element and (b) time domain signals for current to the right aperture and the photocurrent at the angular locations of 3.5 and 0.5°. The high and low far field profiles were obtained by scanning the detector and extracting the detected intensity values at the corresponding times of high and low current injection. Also shown (a) is the angular detector width.

Figure 3. Delayed modulation response at 100 kHz detected at angular locations of 0 and 3°.

Figure 4. 100 MHz modulation: (a) far field profiles showing steering to the left with increased current injection into the right element and (b) time domain signals for current to the right aperture and the photocurrent at the angular locations of 1.5 and -0.5°.