Polarization Switching in Vertical-Cavity Surface-Emitting Lasers With Anisotropic Cavity Geometry and Injection

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***Abstract*— Vertical-cavity surface-emitting lasers with anisotropic cavity geometry and current injection capable of bias-dependent polarization switching are demonstrated. A cruciform-shaped photonic crystal defect and ion-implanted aperture defines the transverse cavity which is combined with perpendicularly positioned metal contacts for orthogonal electron injection paths. The dominant polarization is determined by the direction of current injection rather than the crystallographic axes as found in isotropic cavities. In addition to polarization control and switching, this type of laser has potential for a novel digital modulation scheme with low-operating-power and high-extinction ratio. The authors achieve 9-dB switching contrast with ≤200-mV switching amplitude, with the modulation speed thermally limited.**

***Index Terms*— Laser modulation, photonic crystal, polarization control, polarization switching, vertical-cavity surface-emitting lasers (VCSELs).**

I. Introduction

VERTICAL-CAVITY surface-emitting lasers (VCSELs) with quantum-well active region typically lack polarization selection mechanisms [1] due to their cylindrical geometry and isotropic gain [1], [2]. Nevertheless, polarization control is crucial in applications such as optical spectroscopy and optical communications, as well as in systems utilizing polarization-sensitive optical components. Various monolithic polarization control schemes for VCSELs have been demonstrated, which include anisotropic stress [3], anisotropic quantum well gain from non-[100] substrates [4], polarization-selective mirrors [5], [6], differential reflection from surface [7] or buried [8] grating, and anisotropic cavity geometry [9], [10]. In addition, anisotropic current injection [11] or a combination of both anisotropic cavity and injection [12] has been shown to enable polarization switching.

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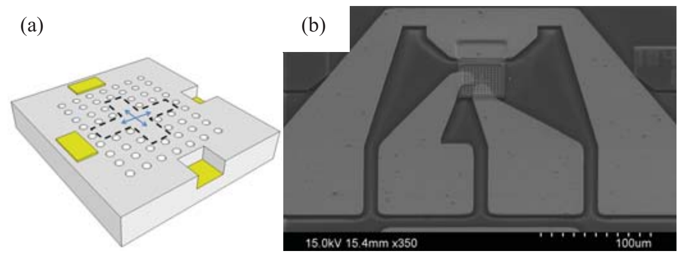
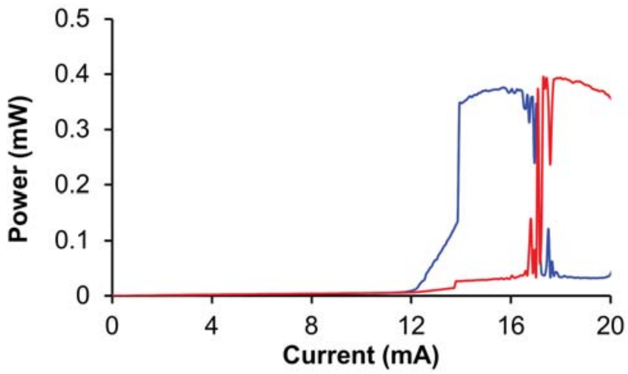


Fig. 1. (a) Device sketch with the black dashed line outlining the optical cavity and the blue arrows indicating the supported orthogonal polarizations. (b) SEM image of a completed laser.

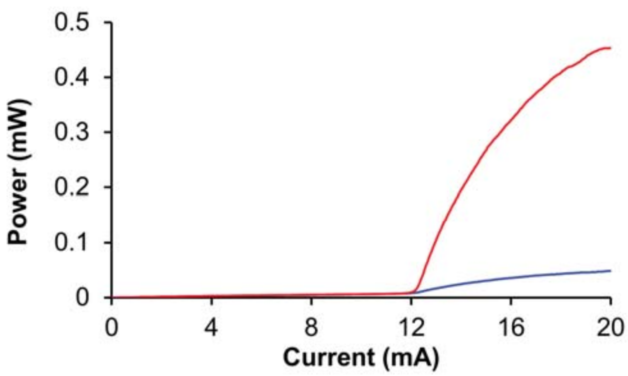
In this letter, anisotropic optical cavity and current injection in a VCSEL is achieved using a cross-shaped optical aperture defined by photonic crystal structure combined with metal contacts orthogonally positioned on the arms of a cruciform current aperture defined by proton implantation. A photonic crystal defect cavity has previously been shown to enable polarization control in VCSELs with an isotropic cavity [13]. We demonstrate that the dominant polarization of VCSEL emission in our devices with anisotropic cavity and injection current will follow the direction of current injection rather than the crystallographic axes, which is found for isotropic laser cavities [2]. Experimental results of bias-dependent polarization selectivity are also shown for a novel scheme of low power and high extinction ratio digital laser modulation.

II. Device Design and Fabrication

The generic VCSEL epitaxial material contain 21 p-type top distributed Bragg reflector (DBR) periods, 37 n-type bottom DBR periods, surrounding an active region with strained quantum-wells having a nominal lasing wavelength of 940 nm, which tend to favor certain polarization. A sketch of our device is shown in Fig. 1(a) with the black dashed line outlining the optical cavity and the blue arrows indicating the supported orthogonal eigen polarizations. The square-lattice photonic crystal with air holes has a cross-shaped defect to define the transverse optical cavity. Multiple device designs were studied where the photonic crystal parameters subject to variation are hole pitch a and hole diameter b. The two orthogonal eigen polarizations are allowed due to index-guiding and loss effects. The current aperture is also lithographically defined in a cruciform shape, and injection anisotropy is achieved by



(a)



(b)

Fig. 2. Polarization resolved light output of cruciform VCSEL ($a = 3.0\ \mu$m, $b/a = 0.7$) when (a) horizontal or (b) vertical arm is forward biased. The blue and red curves are for the polarizer oriented in the horizontal and vertical direction, respectively.

the bias applied to the two orthogonally positioned pairs of metal contacts. The cathode contact is positioned in the lower n-type DBR.

Laser fabrication starts with photolithographic patterning of the photonic crystal within a mesa, followed by inductively-coupled reactive ion etching (ICP-RIE). The steps that follow are deposition of lower n- and upper p-metal contacts, proton implantation of cruciform current apertures, planarization using HD-4000 polyimide, and deposition of ground-signal-signal-ground (GSSG) coplanar interconnect metal contacts. Fig. 1(b) shows the scanning electron microscope (SEM) image of a completed device. The lower contacts are obstructed by the polyimide planarization layer, hence are not visible in the SEM image. The implant depth is not optimized for 940-nm VCSELs; hence the VCSEL threshold current and power could still be improved.

III. Experimental Results

VCSELs with photonic crystal hole pitch of 3 μm, b/a ratio of 0.7, and 5 air holes removed in each of the horizontal (H) and vertical (V) directions perform the best in terms of polarization selectivity and representative results are presented in Fig. 2. Current injection in one arm creates one dominant laser polarization in the direction of the current injection, as indicated in Fig. 2. This figure shows the polarization-resolved continuous wave (cw) laser output (blue and red curves are for

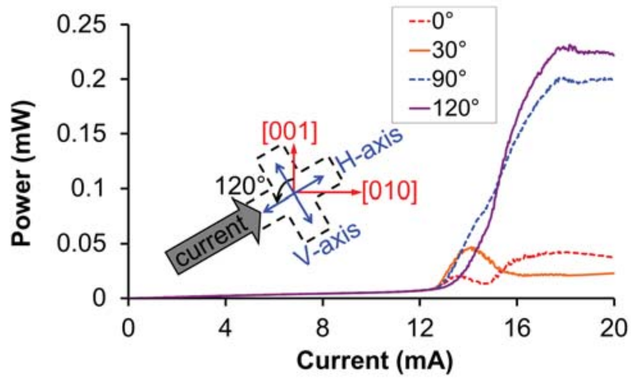


Fig. 3. Polarization-resolved output of rotated cruciform VCSEL when the horizontal arm is electrically pumped. The inset defines the crystallographic and cavity axes as well as the curve-labeling angles. 0° and 90° correspond to crystallographic axes [001] and [010], while 30° and 120° are rotated V- and H-cavity axes.

the polarizer oriented in the H and V direction, respectively) when the H (Fig. 2(a)) or V (Fig. 2(b)) arm is forward-biased. Note that higher order modes appear with increased bias current, and polarization selection becomes less effective as evident in Fig. 2(a). The appearance of higher order modes and the polarization discontinuity in Fig. 2(a) indicate the dominance of the thermal lens over the photonic crystal index guiding.

In circular cavities, the eigen polarizations tend to align with the crystallographic axes [2] due to elasto-optic [14] or electro-optic effect [15] effects. To confirm that the direction of the eigen polarizations follow that of the cavity and injection current in our anisotropic devices, we also investigate lasers which have their cruciform cavity rotated relative to the substrate. Fig. 3 shows the cw polarization-resolved output of a rotated laser when the horizontal arm is electrically pumped, each curve corresponds to the angle between the polarizer and the [001] crystallographic axis (see inset of Fig. 3). The device clearly lases with a polarization in the direction of the rotated H-axis. Under pulsed operation the polarization control is much less effective, which is consistent with a thermal lens induced by the injection current in selecting the polarization.

Polarization modulation can be enabled by controlling polarization switching with varying bias current in both cruciform arms. In Fig. 4 we show the polarization contrast for varying injection currents (in mA) into each arm of the device in Fig. 1 and 2. Over a range of injection currents roughly greater than 10 mA in either arm, the dominant polarization is usually in the direction of greater current injection. Exceptions to this behavior (e.g. lower left hand corner of Fig. 4) are related to higher order modes and intrinsic polarization [10]. To perform polarization modulation, we can DC-bias both arms to a quiescence point (for example 10 mA in Fig. 4) and increase the current in one arm while reducing the current in the other to maintain roughly the same total output power, yet create two orthogonal logic levels with either H or V-polarization state dominant. A polarized photodetector oriented in H or V direction will detect a digitally varying output with potentially high extinction ratio due to orthoganality of the eigen polarizations.

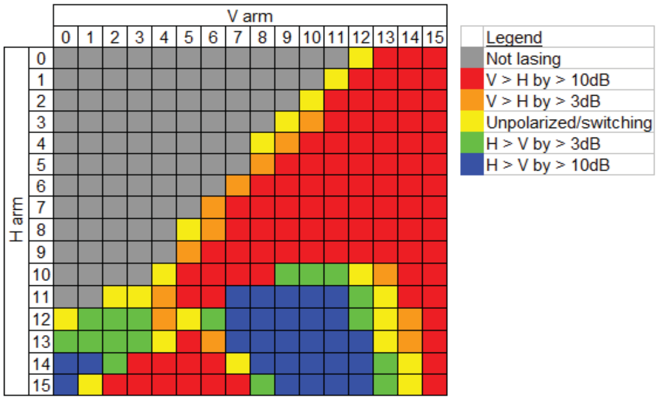


Fig. 4. Matrix of polarization contrast when the two arms are maintained at different current. The numbers are bias current in mA.

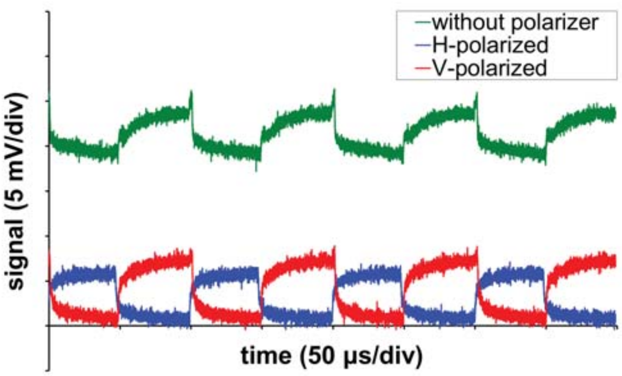


Fig. 5. Unpolarized and polarization-resolved detector output from cruciform VCSEL with 10-mA bias in each arm and polarization modulated as described in text. The polarized outputs are 180° out-of-phase.

Note that the modulation rate is in principle not related to relaxation oscillation, thus such modulation scheme might enable low-power laser modulation.

In preliminary switching measurements depicted in Fig. 5, we have acheived polarization modulation using only $\leq$ 200 mV modulation amplitude at 10 kHz. The unpolarized detected output has a high and approximately continuous wave signal level, but with some variation due to unequal power from each arm with equal current. The polarized detector signals have an off state at nearly no light and are 180° out-of-phase with 9 dB switching contrast; the on state is lower than the unpolarized level due to polarizer loss. The required 200 mV switching amplitude is an upper bound, limited by the experimental equipment. The polarization modulation speed is limited to $\leq$ 50 kHz, presumably by thermal lensing from the current injection [16] which presently dominates the anisotropic cavity confinement.

IV. Conclusion

Controlled polarization switching of VCSEL emission is demonstrated using a cruciform cavity and anisotropic current injection. The current injection direction selects and controls the dominant polarization direction, but arises from the resultant thermal lensing. Increasing the refractive index contrast from the photonic crystal should overcome this thermal effect as well as decrease the threshold current due to stronger index guiding, enabling greater switching rates of a potentially low power digital modulation approach.

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