Electro-optic birefringence induced polarization anisotropy in vertical-cavity semiconductor optical amplifiers (VCSOAs)

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Abstract: The polarization anisotropy including polarization dependent gain (PDG) and frequency splitting in VCSOAs are measured. Measurements of the output polarization state show that the cause of this polarization anisotropy in VCSOAs is electro-optic birefringence.

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OCIS codes: (260.1440) Birefringence; (230.5440) Polarization-sensitive devices; (160.2100) Electro-optical materials; (190.2640) Frequency shifting; (190.1450) Bistability;

1. Introduction
In the past few years, Vertical-Cavity Semiconductor Optical Amplifiers (VCSOAs) have drawn increasing research attention [1,2]. As compared to in-plane SOAs, they exhibit several advantages including higher coupling efficiency to optical fibers and lower noise figure due to their circular geometry and small dimensions, respectively. Previously, we have reported the first observation of optical bistability in a VCSOA operated in reflection mode (input signal enters and exists from the same side of the device) and demonstrated the first vertical-cavity optical AND gate based on this nonlinearity [3,4]. However, the polarization dependent characteristics of VCSOAs have not been investigated and reported in the literature.

There are many potential contributions to polarization anisotropy in VCSELs and VCSOAs. One mechanism is geometric imperfections, either deliberate or unintentional, which break the circular symmetry [5-7]. Structural modifications also contribute to anisotropy in gain between polarization states (dichroism). Another cause is birefringence due to residual stress or strain, which modifies the index of refraction via the elasto-optic effect [8, 9]. The electro-optic effect in VCSELs and VCSOAs can also cause birefringence. These effects and their relative strengths have been studied in detail for VCSELs [10-12]. The conclusion of those analyses is that linear birefringence (electro and elasto-optic) is the dominant factor causing the separation of polarization modes and selection of linear polarization in electrically pumped VCSELs. Furthermore, the electro-optic effect appears to be the most influential contribution to this birefringence in actual devices [10]. Most of the contribution is from the built-in field and charge discontinuities between layers in the DBR mirrors [10, 13]. Dichroism is manifested primarily in a difference in the linewidth of orthogonal modes.

In this paper, the polarization dependent gain (PDG) characteristics of a VCSOA are measured, and the cause of the PDG determined. It is often assumed that the polarization states of a VCSOA are degenerated, because of the circular geometry of the device. Experiments show that this assumption is not true in practice, and it is found that VCSOAs possess a dominant linear polarization state and a small difference in frequency between polarization states. The difference in resonant frequency causes the PDG of the VCSOA. Measurements of polarization states show that the cause of the splitting is electro-optic birefringence.

2. Polarization anisotropy in VCSOAs
Studies of polarization anisotropy in VCSELs suggest several consequences for VCSOAs. First, electro-optic and elasto-optic birefringence will give rise to two orthogonally polarized modes, with some frequency difference between them. These resonant modes will likely be linearly polarized, or nearly so. Additionally, dichroism in the VCSOA will manifest itself as a difference in amplitude and width of the gain windows for the polarization modes.

The VCSOAs used are electrically pumped, circularly symmetric, proton-implanted devices manufactured by Emcore. The lasing wavelength is about 850nm. The gain was measured vs. input power for orthogonal directions of linearly polarized input light, using the experimental setup described in an earlier publication [14]. The polarization directions are chosen by observing the dominant polarization state just above threshold, and using that orientation as the reference for two orthogonal directions. The gain at low input power (0.5 µW) was recorded to construct a graph of the gain window. The results for the two polarizations are plotted in Figure 1. Additionally, the
gain windows were measured at several bias currents, and the results from two bias points are shown. The dashed lines correspond to the direction of the dominant state just above threshold, which is 6.25 mA.

Figure 1: Polarization resolved VCSOA gain vs. wavelength for 6.1, 6.4 mA bias. Dashed and solid lines depict orthogonal polarizations.

The first thing to notice in Figure 1 is the displacement of the peaks. The separation is about 0.02 nm, or 8 GHz. The peaks are clearly separated, and similar in magnitude and width, though generally not exactly equal. The observed splitting compares well with the separation documented in VCSELs [10]. Dichroism is also evident in Figure 1. The two polarizations show unequal gain at a bias of 6.1 mA, and the weaker gain window is also slightly wider. As the bias is increased, the gain curves become approximately equal in amplitude and width. This may be due to gain-clamping as the bias is raised above the lasing threshold.

Figure 2: Azimuth and shape of polarization state vs. device #, with three aperture sizes. Squares = 8 µm, circle = 15 µm, triangle = 20 µm. Solid circles = shape. Dotted line shows the average, and the gray bands show the range of values.

The emission from 10 VCSOAs was characterized both above and below threshold, in order to determine if the VCSOA favors a particular type of polarization. The measured orientation and Stokes vector shape parameter ($|S|$) for these devices is plotted in Figure 2. An $|S|$ value of 0.0 corresponds to linear polarization and 1.0 corresponds to circular polarization. The $|S|$ parameter for all but one of the devices was less than 0.2, indicating the devices favor linear polarization. The devices sampled came from 4 different dies and were fabricated with three different apertures. The consistent preference for a linear polarization state is evidence of some systematic effect, which is independent of random fabrication errors. Further evidence of a systematic contribution to symmetry breaking is obtained by examining the orientation of the polarization state. In Figure 2, the polarization azimuth of
the VCSOA emission is plotted relative to the bottom edge of the device die. In all cases, the azimuth is within 20° of the edges of the chip.

3. Conclusions
From these measurements, it is clear the VCSOAs exhibit a dominant linear polarization state, with a preferred orientation, which is parallel to the chip edges. Since the vast majority of GaAs wafers are grown in the [100] direction, and the natural cleavage planes in GaAs are the [110], and [11T0] planes [15], it is a safe assumption to equate the die edges with these crystal directions. This assumption has been confirmed by fracturing a VCSOA die and examining the fragments to identify the cleavage planes. These findings are consistent with previous measurements and analysis for GaAs VCSELs [10,13], and are evidence that the electro-optic effect is the dominant mechanism, which breaks the circular symmetry in these devices.

These findings have several implications for system applications of VCSOAs. If mode splitting exists and can be resolved, the gain of a VCSOA will vary according to the polarization state of the input signal. Furthermore, one expects the polarization state of the signal to be altered by the amplifier as well, since the gain experienced by the two polarizations is not necessarily equal. Even in polarization independent systems such as fiber-optic data transmission, the gain variation with polarization needs to be considered. In polarization dependent systems, the asymmetry might be applied to use the VCSOA as a polarization state converter or rectifier, among other applications. Additionally, if the polarization modes of the VCSOA are not degenerate, they can be used to control and probe states for nonlinear applications. Using orthogonal polarization states, it may be possible to perform four-wave mixing, cross-gain or phase modulation, or gain clamped operation.

In summary, the gain of VCSOAs is found to be anisotropic, depending on the polarization of the input signal. The anisotropy can be explained by frequency splitting due to electro-optic induced birefringence in the amplifier material. Such frequency splitting is observed in the gain windows of the VCSOA, with a separation of 8-10 GHz. Furthermore, electro-optic birefringence should result in a preference for emission in a linear polarization state, oriented along specific crystal axes. The polarization state of emission for several VCSOAs of various sizes is shown to exhibit such a preference, even below the lasing threshold. The direction of vibration for the devices tested is within 20° of the expected axes, and the emission is linearly polarized, with an |S| value less than 0.2. These results show that the polarization anisotropy in electrically pumped VCSOAs can be attributed mainly to the electro-optic effect, as in VCSELs.

Reference: