

Controlling polarization of vertical-cavity surface-emitting lasers using amorphous silicon subwavelength transmission gratings

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Control of the polarization of vertical-cavity surface-emitting lasers (VCSELs) using a 240-nm-thick amorphous silicon subwavelength transmission grating (SWTG) is demonstrated. The grating, which has a strong polarization dependent reflectance and transmittance, was placed in front of the output window of a VCSEL. It was found that the SWTG can fix the VCSEL's polarization in the direction perpendicular to the grating fingers, switch polarization directions, enhance the polarization ratio from 20:1 to over 200:1, and decrease the threshold current. Integration of these gratings into the VCSEL structure is discussed. © 1996 American Institute of Physics. [S0003-6951(96)03927-7]

Vertical-cavity surface-emitting lasers (VCSELs) have become a focus of research over the past several years due to their promising application in areas such as optical communications, optical interconnections, optical neural networks, and optical signal processing. VCSEL characteristics, such as low threshold current and single mode operation, as well as their ability to be fabricated in high-density arrays, make them an ideal device for use in integrated optoelectronic circuits. In applications where polarization sensitive components are widely used, such as magneto-optic recording and coherent detection systems, the ability to effectively control the polarization of the VCSELs is a necessity.

The output light of VCSELs can exist in two linearly polarized orthogonal modes. These modes are along the $\langle 011 \rangle$ and $\langle 0\bar{1}\bar{1} \rangle$ crystal direction, denoted as P_{\parallel} and P_{\perp} , respectively.¹ Under normal operation, one of the modes will dominate over the other, with a typical polarization ratio of 20:1. Depending on the injection current, switching between the two modes can sometimes occur. In an isotropic cavity, the dominant mode is random and cannot be controlled. Efforts have been made to control the polarization by such methods as anisotropic transverse cavity geometries,^{2,3} induced active layer stress from an elliptical window,⁴ asymmetrically designed active layers,⁵ and metal gratings on the bottom reflector of the VCSEL.⁶ However, these methods all involve a direct alteration of the laser cavity, making it difficult to obtain uniformity and simplicity in processing. It is more desirable to obtain polarization control without significantly changing the cavity structure. In this letter, we demonstrate a method of controlling polarization proposed previously.⁷ This method uses optical feedback from an ultrathin dielectric subwavelength transmission grating placed in front of the VCSEL output window. In doing so, we have achieved polarization mode locking, mode switching, and mode enhancement.

The principle of controlling a VCSEL's polarization is based on the observation that subwavelength amorphous silicon transmission gratings (SWTGs) have a polarization dependent reflectivity.⁷ When a SWTG is put in the output window of a VCSEL, one mode is reflected back into the laser cavity more favorably than the other mode, forcing the

lasing polarization to be locked in the favored reflected mode. Therefore, a SWTG can either enhance the polarization or switch the polarization. In polarization enhancement, the SWTG is arranged to make the output light of the dominant mode be more favorably reflected back into the cavity, causing it to become stronger and the weaker mode to become significantly reduced. In polarization switching, the SWTG is arranged to make the output light of the weak mode be more favorably reflected back, causing it to switch over to the dominant mode.

The SWTGs consist of a thin amorphous Si grating with nanoscale finger widths and spacing on a fused silica substrate. Gratings with a thickness of 240 nm, periods ranging from 50 to 900 nm, and an area of $20 \mu\text{m} \times 20 \mu\text{m}$ were patterned using electron-beam nanolithography. Details of the fabrication have been published elsewhere.⁷ The transmittance and reflectance of the TE mode (polarization parallel to grating fingers) and TM mode (polarization perpendicular to grating fingers) of the SWTGs were measured using a VCSEL, a linear polarizer, and a photodetector. The VCSEL used was purchased commercially and has a 20- μm -diam circular cavity with an output wavelength of 850 nm. Under normal operating conditions the VCSEL has a single transverse and longitudinal mode.⁸ Figure 1 shows the measured and theoretical TE and TM mode reflectance of the SWTGs for different grating periods. The theoretical data was obtained using a rigorous modal expansion simulation. The absorption of the gratings is negligible, since the sum of the measured reflectivity and transmittivity is close to unity (except for periods larger than 600 nm, which will be discussed later). The negligible absorption is due to the large effective band gap of the amorphous Si and the small thickness. For periods smaller than 400 nm and larger than 600 nm, the experimental data deviates from the theoretical simulation. The discrepancy may be due to the fact that the simulation assumes the gratings to have a square shape, while the actual grating shape for these small periods is a sine wave.⁹ For periods larger than 600 nm, diffraction effects from the gratings become significant and cause losses in the total transmitted and reflected light, leading to a difference in the experimental data and simulation. As can be seen from Fig.

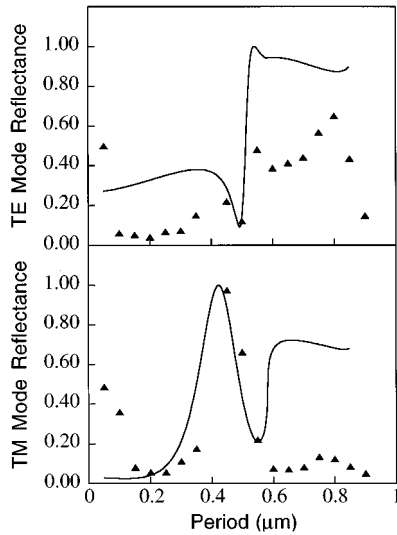


FIG. 1. Reflectance of the SWTGs vs grating period for the TE and TM polarization modes. The lines represent the stimulated reflectance and the markers represent the measured reflectance.

1, the SWTGs can have low reflectance for one mode and high reflectance for the other, depending on the period. This allows the SWTGs to behave as partially polarizing reflectors, necessary for controlling a VCSEL's polarization. The SWTG with a grating period of 100 nm is found to have the best characteristics for polarization locking. Namely, it has a very low TE mode reflectance (5%) but a decent TM mode reflectance (35%).

To produce optical feedback for polarization locking, the output light from the VCSEL is collimated into a parallel beam using an objective lens. Because of the small grating area, another objective lens is used to focus the beam onto the SWTG to a spot having a diameter of 10 μm . The laser spot and SWTG are monitored by an optical microscope and camera through a beam splitter. However, during measurements the beam splitter was removed to reduce birefringence. The light transmitted through the SWTG is again collimated and analyzed using a linear polarizer with an extinction ratio of 1000:1 and a photodetector.

Figure 2(a) shows the output light power of the VCSEL versus injection current for the P_{\parallel} and P_{\perp} modes without a SWTG. The VCSEL has a threshold current of 9 mA, and P_{\parallel} is the dominant mode. Figure 2(b) shows the output power for the P_{\parallel} and P_{\perp} modes with a 100 nm period SWTG placed in front of the VCSEL's output window and the grating fingers parallel to the P_{\parallel} direction. As pointed out before, in this orientation light from the P_{\perp} mode is more favorably reflected back to the cavity, therefore the P_{\perp} mode is switched from the weak mode to the dominant mode, and the P_{\parallel} mode becomes nearly zero. Figure 2(c) shows the output power when the SWTG is rotated 90° so that the grating fingers are parallel to the P_{\perp} direction. The P_{\parallel} mode is now more favorably reflected back to the cavity. This causes the P_{\parallel} mode to remain dominant, but the P_{\perp} mode is substantially suppressed, and therefore the polarization ratio is greatly enhanced. The polarization locking is better illustrated in Fig. 3, which shows the polarization ratio of the dominant to the weak mode versus the injection current with

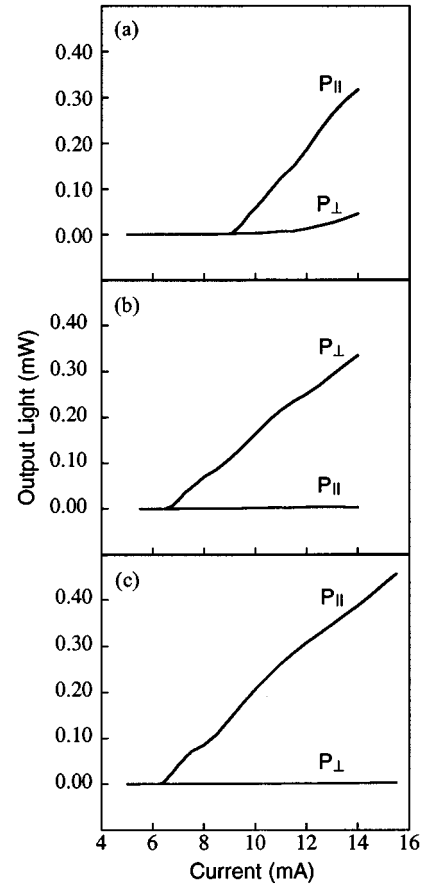


FIG. 2. Lightout put vs injection current (a) without feedback, (b) with SWTG grating fingers parallel to P_{\parallel} and feedback in P_{\perp} direction, (c) with SWTG grating fingers perpendicular to P_{\parallel} and feedback in P_{\parallel} direction. Grating period is 100 nm.

the 100 nm period SWTG. When there is no feedback, the polarization ratio of the output light has a maximum value of 20:1. However, with the SWTG in place, this ratio is greater than 100:1 for both mode switching and mode enhancement over most of the range of injection current. The maximum polarization ratio is about 200:1, and is observed for mode enhancement. For injection currents well above threshold, it is believed that higher-order transverse modes begin to emerge, reducing the polarization ratio of the output light. Furthermore, because the SWTG increases the effective reflectivity of the output window, it lowers the threshold cur-

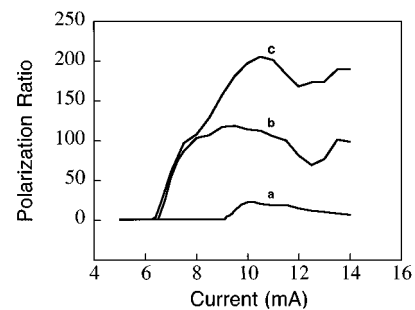


FIG. 3. Polarization ratio vs injection current (a) without feedback, (b) with SWTG fingers parallel to P_{\parallel} and feedback in P_{\perp} direction, (c) with SWTG grating fingers perpendicular to P_{\parallel} and feedback in P_{\parallel} direction. Grating period is 100 nm.

rent in both mode switching and mode enhancement.

Polarization mode switching and enhancement are also observed for grating periods ranging from 150 to 400 nm, although the effects of mode locking and switching are poor, due to comparable reflectances for the TE and TM modes. For the 450 nm period SWTG, the intra-cavity polarization ratio is observed to be greater than 300:1, which is caused by the near total reflectance of the TM mode at the SWTG. However, this high reflectance also prevents the enhanced light from passing through the SWTG, leading to a low extra-cavity power output for that mode. For periods greater than 500 nm, diffraction effects start to become significant, reducing the coherency and polarization ratio of the light transmitted through the SWTG.

The SWTGs hold great promise for use in integrated optoelectronic devices. The SWTG has a very small thickness of 240 nm, about 1/3 the wavelength. It can easily be integrated onto the VCSEL, and would allow the polarization of neighboring VCSELs in an array to be individually controlled. Furthermore, the SWTG could replace the distributed Bragg reflector (DBR) stack as the top reflector in the VCSEL cavity.

In summary, we have demonstrated a method of controlling VCSEL's polarization using optical feedback from an ultrathin amorphous Si subwavelength transmission grating. This method allows not only enhancement of the preexisting polarization mode, but also the ability to switch between modes. The polarization of the output light is of very good quality, having a ratio of over 100:1 throughout the operation range. Because of the small thickness of the gratings, it is possible to integrate them directly onto the VCSEL structure for complete polarization control.

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