Polarization control and mode optimization of 850 nm multi-mode VCSELs using surface grating

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Abstract

To control the polarization of 850 nm multi-mode oxide-confined vertical-cavity surface-emitting lasers (VCSELs), monolithically integrated surface gratings are investigated. VCSELs with different grating parameters are simulated by the rigorous coupled-wave analysis (RCWA) method. Optical field intensity of two polarization orientations with different grating periods and duty cycles is obtained. The mode characteristics of VCSELs with different grating parameters are achieved by FDTD method. 850 nm surface grating VCSELs are fabricated and characterized, a maximum orthogonal polarization suppression ratio (OPSR) of 20.7 dB is observed. Meanwhile, VCSEL's output mode characteristics are improved by integrating the surface grating. Application of integrated surface grating technique to achieve dynamically polarization-stable multi-mode VCSELs which enable polarization division multiplexed data transmission, the data throughput over a given link can be doubled.

1 Introduction

Vertical-cavity surface-emitting lasers (VCSELs) have gained a large market share in the last few decades. They have low cost, low threshold current, high-speed modulation, easy fabrication in two-dimensional arrays and circular symmetric output beam [1]. Due to the symmetry of a VCSEL device which has no well-defined and stable polarization [2–7], emission occurs along the [011] or [0–11] crystal axis. As a result, the polarization can spontaneously switch between these two directions during operation of the VCSELs, which cannot be tolerated in many important

applications. We can mention, for instance, atomic clocks [8] as well as other atomic sensors like magnetometers, gyroscope [9] and optical mouse [10]. These sensing schemes usually require VCSELs with a well-defined and stable polarization. Furthermore, in single-mode VCSELs, current modulation in a region of unstable polarization greatly strengthens the laser noise and can thoroughly deteriorate the data transmission behavior [11–13].

To stabilize the polarization of VCSELs, one has to introduce a polarization-selective mechanism which is always stronger than all the other influences on the polarization. These methods can roughly classify into four groups: polarization-dependent gain [14], asymmetric resonators [15], external optical feedback [16] and polarization-dependent mirror [17].

Among all ideas for polarization control, monolithically integrated shallow surface gratings have turned out to be the most promising method. The method is to apply semiconductor grating to one of the Bragg mirrors of the VCSEL laser cavity [18]. In order to improve VCSEL's polarization performance, researchers have studied the influence of surface grating on polarization performance of VCSELs. In 2005, Ostermann et al. [19] utilized surface grating shallow etching technology, the output wavelength of the device was 763 nm, the single-mode output power was greater than 2.5 mW and the polarization suppression ratio reached 26 dB. In 2011, Samaneh et al. [20] used surface grating method to

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produce the device with an output wavelength of 894.6 nm and a maximum polarization suppression ratio as high as 21 dB. Liu et al. [21] utilized surface-etched grating to control polarization of VCSELs in 2019, the output wavelength of the device was 890 nm and a stable orthogonal polarization suppression ratio reached about 20 dB.

In this paper, the polarization control characteristics of the 850 nm VCSELs with a surface grating are presented. First, the rigorous coupled-wave analysis method is used to calculate the relationship between the relative optical intensity difference of TM polarization and TE polarization with the grating period and duty cycle. At the same time, the FDTD method is used to obtain the mode characteristics of VCSELs with grating period from 600 to 1200 nm. Then, 850 nm surface grating VCSELs are fabricated. The stable polarization output is achieved, and the maximum OPSR reaches 20.7 dB for the surface grating VCSEL with the period of 600 nm. The maximum output power reaches 1.1 mW at 7 mA, and the SMSRs is greater than 20 dB.

2 Surface grating theory and simulation

According to the electric field component of the incident light, the light whose electric field direction is parallel to the grating direction is referred to as TE light, and the light with electric field direction is perpendicular to the grating direction is referred to as TM light. The grating is etched on the surface of the VCSEL, and by adjusting the grating parameters, the modulation of the reflectivity of the TE and TM light incident on the grating surface can be achieved. According to the laser threshold formula

$$R_1 R_2 e^{2L(G-a)} = 1, \quad (1)$$

where the parameters R_1 and R_2 are the reflectance of the front and rear cavity surfaces, respectively; L is cavity length; G is threshold gain; a is optical loss. The polarization mode with the higher reflectivity has higher cavity quality factor and lower threshold pump current for gain. As a result, the polarization with the higher reflectivity will become the dominant lasing mode. Owing to the shallow semiconductor ridges, diffraction and absorption losses can be kept acceptable. So that the polarization control of the VCSEL can be realized by surface grating.

To optimize the polarization control properties of the 850 nm surface grating VCSELs, optical field intensity and diffraction loss of two polarization orientations with different grating periods and duty cycles are simulated by the rigorous coupled-wave analysis method. This method converts the Maxwell's equations of the grating region into the solution of the characteristic function, the electromagnetic field expression formed by the coupling of the characteristic

function is obtained. Then, the boundary conditions of the interface between the other regions and the grating are solved. Finally, optical field distribution of the grating is achieved. In the simulated structure, the upper and lower DBR pairs are 20 pairs and 35 pairs, respectively, and the incident light source wavelength is 850 nm. Figure 1a shows that when the duty cycle of the grating is 0.5 and the etching depth is 60 nm, the optical intensity in the two polarization directions changes with the grating periods. It can be seen that the intensity of TE polarized light is much smaller than the TM polarized light. This is because the reflectivity of the surface grating to incident TE polarized light is less than that of TM polarized light and diffraction loss of the TE polarized light being much greater than TM polarized light. The relative light intensity difference of the two polarization modes is defined as ΔI

$$\Delta I = (I_{\text{TM}} - I_{\text{TE}})/(I_{\text{TM}} + I_{\text{TE}}), \quad (2)$$

I_{TM} and I_{TE} represent the optical intensity of TM and TE modes, respectively. Figure 1c shows the relative optical intensity difference of surface grating VCSELs varies with grating period, and the etching depth is 60 nm. For surface gratings with the same duty cycle, when the period increases from 600 to 1200 nm, the ΔI of the two polarization modes basically decreases gradually. When the grating period is 600 nm and the duty cycle is 0.5, the relative optical intensity difference between TM polarized light and TE polarized light is the largest, so the strongest polarization suppression effect can be achieved.

At the same time, the mode characteristics of VCSELs with different grating parameters have been simulated by FDTD method. When the duty ratio is 0.5 and the etching depth is 60 nm, the evolution of the near-field mode by changing the grating period is shown in Fig. 2. It can be seen that the electric field amplitudes of the grating groove and the grating ridge at the grating-air interface are different, because the grating ridge and the grating groove have different effective reflectance. When the grating is combined with the Bragg mirror, the reflectance at the groove of the grating is small and the loss is large. The field intensity is concentrated in the center and the side lobes are well suppressed when the grating period is 800 nm. The coupling between the periodic grating and the cavity is different, which affects the near-field distribution.

As shown in Fig. 3, the divergence angle in the far-field orthogonal to the grating grooves direction with the grating period increases from 600 to 1200 nm. The active diameter of the simulated VCSELs is 6 μm and these VCSELs have a full-width at half maximum (FWHM) divergence of 7.5°. For grating periods of 600 nm, 700 nm and 800 nm, no side-lobes can be seen, since for grating periods less than the emission wavelength, the part of the

Fig. 1 **a** Optical field calculation of VCSELs with different grating periods; **b** refractive index distribution of VCSEL structure; **c** relative optical intensity difference of surface grating VCSELs varies with grating period

Fig. 2 Calculated near-field amplitudes of the fundamental mode of surface grating VCSELs with different periods and a standard VCSEL

Fig. 3 Simulated divergence angle of the far-field intensity distribution orthogonal to the grating grooves for different grating periods, inset: the enlarged view of side lobes

electromagnetic emission responsible for the side lobes in the far-field experiences a total internal reflection at the semiconductor–air interface. The angles under which the maximum of the side lobes is observed in the far-field are 60, 56, 55 and 40 degrees for grating periods of 900 nm, 1000 nm, 1100 nm and 1200 nm, respectively. When the grating period is 1100 nm, double side lobes appear, and the total intensity is greater than the side lobe intensity at 1000 nm. It indicated that the intensity of the side lobes increases with increasing grating period. Therefore, the larger the grating period is, the greater the diffraction loss of the VCSEL will be.

3 Device structure and fabrication

Schematic of a single 850 nm VCSEL structure is shown in Fig. 4a. The epitaxial wafer used in this study is grown on the *n*-type GaAs substrate by metal–organic chemical vapor deposition. N-DBR consists of 35 pairs of $\text{Al}_{0.12}\text{Ga}_{0.88}\text{As}/\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$, and P-DBR consists of 23 pairs of $\text{Al}_{0.12}\text{Ga}_{0.88}\text{As}/\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$. N-DBR and P-DBR are *n*-type doping and *p*-type doping, respectively. The active region with three GaAs quantum wells is separated by the undoped $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ separate confinement heterostructure layer, which is sandwiched between N-DBR and P-DBR. A high-aluminum content layer is placed near the first pair of the P-DBR to later form the oxide aperture. The topmost

Fig. 4 **a** Schematic of 850 nm surface grating VCSEL device; **b** magnified image of a device with integrated surface grating

DBR layer is a 50 nm-thick highly $p+$ -doped GaAs layer, which is on the top of the p -type DBR as a low contact resistance layer. Optical micrograph of a fully processed VCSEL with surface grating is shown in Fig. 4b.

As the first step of fabrication, the surface grating is realized using electron-beam lithography and dry etching, as shown in Fig. 5. The manufactured surface gratings with periods from 600 to 1200 nm have a duty cycle of 70% and an etch depth of 60 nm. Then, the mesa structure is formed, which isolates various VCSEL devices and exposes the high-aluminum content layer for oxidation. The technique includes the deposition of the SiO_2 layer by the process of plasma-enhanced chemical vapor deposition. Such a dielectric layer is then patterned by using standard optical lithography and wet chemical etching. This patterned dielectric is served as the mask for the mesas which are etched by inductively couple plasma. The high-aluminum content layer is then selectively oxidized by wet oxidation to form the aperture. After that, an electrode ring contact pattern is formed by secondary photolithography and a light aperture pattern is produced by the third lithography. In order to form a p -type ohmic contact, Ti-Pt-Au layers are evaporated and then lifted off. On the back side, the substrate is thinned to less than 150 μm thick, followed by Au-Ge-Ni evaporation to form n -type electrode.

4 Experimental results and discussions

VCSELs with different grating periods were fabricated. Figure 6 shows the polarization-unresolved light-current (L-I) characteristics of a standard device and the

integrated grating devices with periods from 600 to 1200 nm. The oxide apertures are both 7 μm . As can be noticed that the output power and slope efficiency of surface grating VCSELs decrease compare with no grating VCSELs. The reason is that the surface grating induces a large diffraction loss, and the larger the grating period, the greater the diffraction loss of the device will be. Therefore, the output power decreases with the increment of surface grating period. Figure 7 illustrates the comparison of the output spectrum of a surface grating VCSEL and a standard VCSEL with the same oxidation aperture. It can be seen from the figure that the VCSEL's output spectrum from multi-mode to few-mode and its output mode characteristics are improved by integrating the surface grating. Figure 8 shows the polarization-unresolved spectrogram of the 6 μm aperture VCSEL with 600 nm and 800 nm grating period. As can be seen, the side mode suppression ratios (SMSRs) of VCSELs are greater than 20 dB for grating period of 600 nm. The SMSRs of the device with a grating period of 800 nm in the linear operating region are about 30 dB, which is consistent with the simulation results.

To illustrate the polarization control with surface grating, the polarization-resolved L-I characteristics and OPSR values of the VCSEL with and without surface gratings are manufactured and characterized. The output powers of two polarization directions are measured by rotating the polarizer's transmission direction orthogonal and parallel to the surface grating lines. For the entire current operating range of VCSEL, the polarization is along the $[0-11]$ crystal axis, which is orthogonal to the grating grooves. The OPSR is defined as

Fig. 5 SEM images of surface grating with periods from 600 to 1200 nm

Fig. 6 Polarization-unresolved L–I curve of 7 μm aperture devices with different grating periods

Fig. 7 Spectral comparison of a standard VCSEL (left) and a surface grating VCSEL, the grating period is 900 nm (right)

$$\text{OPSR} = 10 \log \left(\frac{P_{[0-11]}}{P_{[011]}} \right), \quad (3)$$

and is shown in Fig. 9. For a standard VCSEL without any extra surface structure, the OPSR decreases sharply and the value is very low. For the grating period of 600 nm, the stable polarization output characteristics are achieved and the OPSR reaches 20.7 dB at an output power of 1.1 mW. The polarization orientation is along the $[0-11]$ crystal axis up to the thermal rollover. Furthermore, a standard VCSEL and surface grating VCSELs with grating period of 600 nm, 700 nm, 800 nm and 900 nm are measured, the OPSRs value of these devices are shown in Fig. 9. As can be seen that the OPSRs are greater than 15 dB when the grating period is

600 nm and 900 nm, and the OPSRs are greater than 10 dB when the grating period is 700 nm and 800 nm. Compared with the standard VCSEL structure, the stable polarization output characteristic of VCSELs can be obtained by integrating surface grating (Fig. 10).

5 Conclusion

To conclude, we theoretically demonstrate optical field intensity of two polarization orientations of surface grating VCSELs. We find that the intensity of TE polarized light is much smaller than the TM polarized light for all grating periods. The relative optical intensity difference

Fig. 8 Polarization-unresolved spectrogram of the 6 μm aperture VCSEL with 600 nm (left) and 800 nm grating period (right)

Fig. 9 Polarization-resolved L–I characteristics and OPSR values of a standard VCSEL (left) and a grating VCSEL with an oxide aperture diameter of 7 μm , the grating period is 600 nm (right)

of the two polarization modes basically decreases gradually when the period increases from 600 to 1200 nm. When the grating period is 600 nm and the duty cycle is 0.5, the relative optical intensity difference of TM and TE modes is the largest, so the strongest polarization suppression effect can be achieved. At the same time, the mode characteristics of VCSELs with grating period from 600 to 1200 nm are achieved by FDTD method. The simulation results show that when the grating period is greater than the incident wavelength, the intensity of the side lobes in the far-field increases with the increment of grating period. When the grating period is 800 nm, the intensity of the light field is concentrated in the center and the side lobe is suppressed.

L–I characteristics, spectra and OPSRs value of devices with different grating periods are measured. The output power of surface grating VCSELs decreases with the increment of grating period. In addition, the VCSEL's output spectrum from multi-mode to few-mode by integrating the surface grating and the SMSRs of the device with a grating period of 800 nm in the linear operating region is about 30 dB. The stable polarization output characteristics are achieved and the maximum OPSR reaches 20.7 dB for the surface grating VCSEL with the period of 600 nm. For the next step to improve the OPSR, the grating parameters such as duty cycle and etch depth need to be further optimized.

Fig. 10 OPSR values of a standard VCSEL and surface grating VCSELs with the grating period from 600 to 900 nm

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