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Stable Polarization Control of 980 nm High-power Vertical-cavity Surface-emitting Lasers Using Sub-wavelength Rectangular-metal-gratings

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Abstract: The polarization control of vertical-cavity surface-emitting lasers with high power emission is demonstrated by using metal-grating to import non-isotropic gain. The grating with a period of 186 nm and a duty ratio of 0.5 was fabricated on the GaAs-cap layer to provide additional reflectance for TE polarization. The pairs of p-DBRs were reduced and the GaAs-cap between grating stripes was etched to force the current to be injected linearly along grating stripes to realize the maximum non-isotropic gain. A polarization ratio of 4.8, an output power of 780 mW and high temperature performance were demonstrated for a 550 μm aperture device.

Key words: vertical-cavity surface-emitting laser; metal-grating; polarization controlling

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利用亚波长矩形金属光栅稳定 980 nm 高功率垂直腔面发射激光器偏振

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摘要：利用亚波长矩形金属光栅的偏振特性，在垂直腔面发射激光器的有源区引入各向异性增益从而达到控制其偏振的目的。光栅参数设计基于均匀介质理论和抗反射理论，光栅设计周期为 186 nm，占空比为 0.5，并且光栅制作于 GaAs 盖层来对 TE 偏振光提供额外的反射率。经过设计分析对 p-DBRs 的对数进行了缩减，并且将光栅条之间的盖层区域刻蚀掉，刻蚀深度为 1 μm 左右。盖层刻蚀的结果使电流注入的方向严格沿着光栅条线性注入的有源区，从而增加了非均匀增益并提高了偏振比。通过多物理场有限元分析软件对器件进行了模拟分析，结果基本上符合设计要求。通过优化工艺步骤，最终得到了 550 μm 孔径器件的输出功率为 780 mW，并且偏振比达到 4.8 的结果。

关　键　词：垂直腔面发射激光器；金属光栅；偏振控制

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1 Introduction

Due to the attractive features of the vertical emitting geometry, vertical-cavity surface-emitting lasers (VCSELs) have shown many advantages over conventional edge-emitting lasers, such as a circular light-output mode, a high packing density for two-dimensional arrays and single longitudinal mode emission due to the inherent short cavity length[1-3]. Historically, VCSELs have been mostly confined to low-power applications (a few mW at most), such as high-speed data transmission[4-5], but high-power VCSELs are more widely used for industrial and defense application in resent studies. The characteristics of high-power VCSELs such as threshold current, wall-plug efficiency, beam quality and output power have been improved considerably[6-8]. High-power VCSELs with stable single polarization are particularly attractive for applications including laser display[9], communication[10] and sensing[11]. Strong polarization selectivity is especially required for intra-cavity frequency doubling to achieve high efficiency and high power operation. Cylindrically symmetrical VCSELs are inclined to polarization instabilities due to the symmetrical current distribution across the active region and furthermore the symmetrical gain distribution. Several approaches have been presented to improve the polarization properties of VCSELs. These approaches can be divided into three categories: external cavity optical feedback[12], externally applied stress[13], and non-isotropic gain[14]. However, the approaches above are all applied to small aperture device due to its simple mode characteristics. Apparently the output power is limited due to the small aperture of VCSEL. Few investigations have been reported on the polarization control of large aperture VCSELs due to complex high order transverse mode characteristics, which is resulted from large aperture and non-uniform current distribution across the active region of VCSELs. Rectangular aperture of non-isotropic gain was used by our group to increase the polarization selectivity of large aperture VCSELs. An output power up to 660 mW was realized at a current of 5 A and the highest polarization ratio can be up to 2[15]. On the other hand, rectangular aperture of VCSELs has an obvious drawback of noncircular output beam, which might limit their application where high power density or high fiber coupling efficiency was required.

Sub-wavelength metal-grating microstructure is an appropriate candidate to introduce non-isotropic gain. When the period of the grating is much smaller than the incident wavelength, the light polarizing perpendicular to the stripes is transmitted through the grating and only the light polarizing along the stripes is reflected back to establish the laser oscillation[16]. The first attempt of introducing sub-wavelength metal grating in VCSELs was reported by Iga's group in 1995[17]. In his work briefringent metal/dielectric or metal/semiconductor polarizers were used, this polarization control structure provided an extremely large reflectivity difference of about 10% between the two polarizations, and the maximum output power was 0.3 mW. Ze'ev Bomzon theoretically presented an approach to design and analyze space-variant polarization elements using sub-wavelength metal stripe gratings[18]. In his work the elements were formed on GaAs as well as ZnSe substrates and designed for laser radiation at 10.6 μm. High-quality space-variant polarized beams with a polarization purity of over 99% was realized in his work. Dielectric grating is more widely used in the recent studies due to their low overall losses and the polarization ratio can reach more than 24 dB, but only for those whose lasing modes are not too much complicated[19]. As we know, there are no other reports except our work on the polarization control of high power VSCEL up to now[20].

In this letter, we presented a novel approach to achieve higher non-isotropic gain and further highly selective polarization of large aperture high-power VCSELs. Here the polarizations vibrating along and orthogonal to 〈110〉 were designated TE and TM respectively. The pairs of p-side DBRs were reduced to decrease the reflectance of two orthogonal polarizations and accordingly the threshold current of both orthogonal polarizations was increased. By coupling the additional reflectance which was provided by sub-wavelength metal-grating, the threshold gain of TE was decreased remarkably compared with TM. In addition, in order to inject the current non-uniformly and furthermore to enhance non-isotropic gain, the GaAs-cap between the metal gratings was etched to force the current to be injected linearly along stripes of grating. As a result more carriers would be injected for TE oscillation.

2 Device Fabrication

Fig. 1(a) shows a cross-section of the Grating-VCSEL structure in which the GaAs-cap between the stripes of the gratings was etched. The VCSEL was grown by metal-organic chemical vapor deposition (MOCVD) on n-doped 〈100〉-oriented GaAs substrates. The active region contained three compressively strained $In_{0.2}Ga_{0.8}As/GaAs$ quantum wells. To realize high power operation of bottom-emitting VCSELs, the reflectance of n-DBRs needs to maintain as low as possible. Traditionally in our design of high power VCSELs, the n-DBRs of 20 pairs of $GaAs/Al_{0.9}Ga_{0.1}As$ with the reflectance of 99.3% and the p-DBRs of 30 pairs of $GaAs/Al_{0.9}Ga_{0.1}As$ with the reflectance of 99.97% were used to realize high output power of 1.95 W. In this letter, in order to achieve high polarization selectivity of high power VCSELs, the pairs of p-DBRs were reduced to 17 pairs with the reflectance of 98.6%. By coupling the additional reflectance which was provided by sub-wavelength metal-grating, the reflectance of the p-side for TE was increased to 99.96% compared with the reflectance 98.6% of TM. As a result the threshold gain of TE was decreased remarkably in comparison with TM.

For metallic-grating, a thin layer of Ti with a thickness of 5 nm and a thick layer of Au with a thickness of 122 nm were grown on the surface of the top DBRs by electron beam evaporation. Then the metal gratings were etched with a period of 186 nm and a duty ratio of 0.5. Gratings were aligned to 〈110〉 crystal orientations and provided 95% reflectance for TE. On the one hand, in order to maximize the gain difference of the two orthogonal polarizations, the GaAs-cap between the grating stripes was etched, thus the current was injected along metal gratings and allow more carriers to be injected into the active region for TE oscillation. And on the other hand, in order to realize maximum reflectivity difference between two orthogonal polarizations, HfO_2 as anti-reflective film was coated between the stripes of the gratings. The structures whose GaAs-cap between the grating stripes was etched (structure A) and the structure whose GaAs-cap wasn't etched (structure B) were fabricated on the same wafer adjacent to each other, and the apertures of two structures were 550 μm.

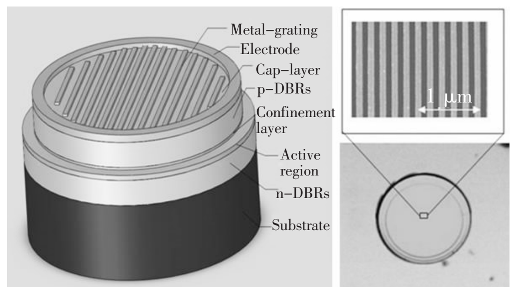

Fig. 1 (a) Schematic cross-section of metal-grating VCSEL. (b) SEM images of metal-grating VCSEL.

3 Simulation

The current density distributions of both the structure A and the structure B were simulated by Comsol Multiphysics software. The two structures were simplified to several layers, in which the electrical conductivity of the p-DBR are non-isotropic (2 761, 2 761, 445.4) $(\Omega \cdot m)^{-1}$. As a result, Fig. 2(a) and Fig. 2(b) are the potential distribution of the two structures, the white lines are isopotential lines. Obviously the potential distributions of structure A appear non-isotropic, while those of structure B appear uniform. And the current density of the region below the grating stripes is higher than the region between grating stripes. As a conclusion the carriers of structure A were forced to be injected along 〈110〉 to enhance non-isotropic gain by etching GaAs-cap between the grating stripes. The threshold current densities of two orthogonal polarizations of the two structures were calculated and shown in Fig. 2(c). The threshold currents are 180 A/cm^2 and 240 A/cm^2 of TE and TM of structure A respectively when the reflectance of p-DBRs is 98.6%, and the threshold current of TE and TM of structure B is 185 and 233 A/cm^2, respectively. The threshold current difference of two orthogonal polarizations of structure A is 60 A/cm^2 higher than that of structure B, which means the non-isotropic gain of structure A is stronger than that of structure B and the sub-wavelength grating microstructures which GaAs-cap was etched introduce more non-isotropic gain than single sub-wavelength metal gratings.

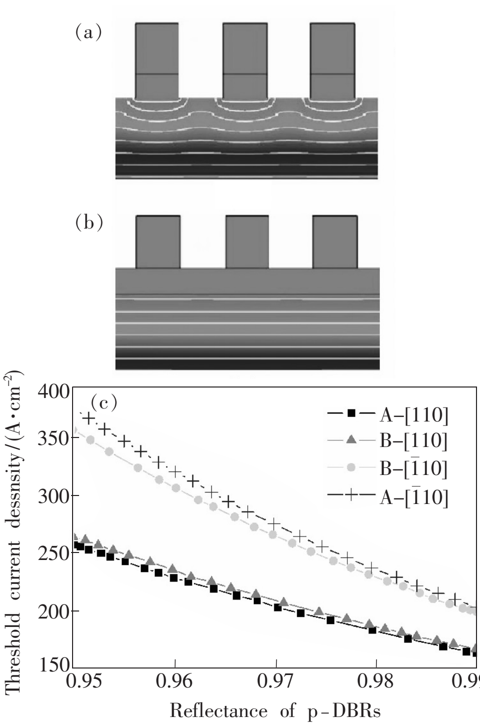

Fig. 2　(a) Electrical potential distributions of structure A. (b) Electrical potential distributions of structure B. (c) Dependences of the threshold current density of the two structure on the reflectivity of p-DBR.

4　Results and Discussion

The typical light output power-current characteristics of structure A is demonstrated in Fig. 3(a). The black squares represent the total power. The short dotted line and white squares represent the current dependences of TE and TM polarization output power, respectively. The threshold current of TE and TM are 0.6 A and 2 A respectively, which is in accordance with the simulated result in Fig. 2(b). The output power of TE and TM are 625 mW and 130 mW at the current of 5 A, and the polarization ratio of 4.8 is achieved. Strong polarization stabilization over the entire range of operating current is observed. The polarization characteristics of structure B are shown in Fig. 3(b) as a comparison. The threshold current of TE is 0.8 A, which is higher than that of structure A. And the threshold current of TM is 1.5 A. These results indicate that the threshold current difference between TE and TM of structure A is effectively increased by etching the GaAs-cap between grating stripes. The output power of TE and TM of structure B is 590 mW and 196 mW respectively at the current of 5 A, and the polarization ratio is only 3, which is lower than that of structure A. This provides strong evidence that the non-isotropic gain created by metal grating is further enhanced by etching the GaAs-cap between grating stripes.

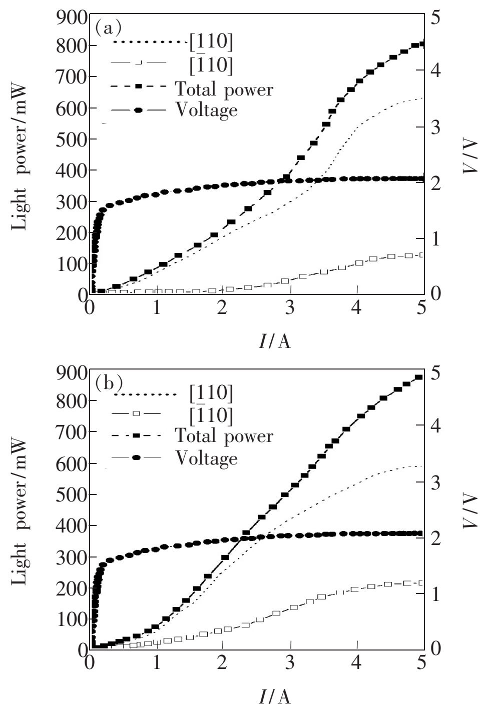

Fig. 3　Polarization-resolved *L-I-V* characteristics of metal-grating VCSEL. (a) structure A. (b) structure B.

Many applications require that the lasers can adapt to high temperature environment. In order to examine high temperature performance of our VCSELs, the polarization ratios were measured at different temperatures from 298 to 353 K at the current of 5 A, as shown in Fig. 4. The polarization ratio decreases from 4.8 to 3.4, as the device temperature increases from 298 to 353 K, the decrease of the polarization ratio becomes smoother when the temperature is higher than 343 K. Even at 353 K, the polarization ratio of structure A is still much higher than that of structure B at room temperature.

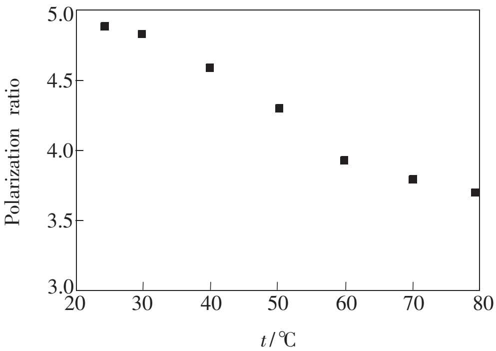

Fig. 4 Temperature dependence of the polarization ratio of structure A at a current of 5 A

As we know, structure A shows high power and high polarization stability in the high temperature environment.

5 Conclusion

A perspective of this work is to fabricate metal-grating on p-DBRs of the VCSEL to control its polarization. In our work, the integration of metal grating and the etching of the GaAs-cap between the stripes of grating successfully increased the TE polarization and suppressed the TM polarization. The maximum output power of 780 mW and the polarization ratio of 4.8 were firstly demonstrated for a large aperture VCSEL. This design also exhibits its high polarization stabilization even at high temperature.

References:

[1] Kosaka H. Smart integration and packaging of 2D VCSEL's of high speed parallel links[J]. *IEEE Select. Topics Quant. Elect.*, 1999, 5(2):184-192.

[2] Huffaker D L, Deppe D G, Kumar K, *et al.* Native-oxide defined ring contact for low threshold vertical-cavity lasers [J]. *Appl. Phys. Lett.*, 1994, 65(1):97-99.

[3] Seurin J F, Ghosh C L, Khalfin V, *et al.* High-power high-efficiency 2D VCSEL arrays [J]. *SPIE*, 2008, 6908:690808-1-14.

[4] Geels R S, Corzine S W, Coldren L A. InGaAs vertical cavity surface emitting lasers [J]. *IEEE J. Quantum Elect.*, 1991, 27(6):1359-1367.

[5] Iga K, Ishikawa S, Ohkouchi S, *et al.* Room temperature plused oscillation of GaAlAs/GaAs surface emitting injection laser [J]. *Appl. Phys. Lett.*, 1984, 45(4):348-350.

[6] Tell B, Lee Y H, Brown-Goebeler K F, *et al.* High-power cw vertical-cavity top surface-emitting GaAs quantum well lasers [J]. *Appl. Phys. Lett.*, 1990, 57(18):1855-1857.

[7] Zhang X, Ning Y Q, Zeng Y G, *et al.* Optimization of element structure in 980 nm high-power vertical-cavity surface-emitting laser array [J]. *Opt. Precision Eng.* (光学 精密工程), 2011, 19(9):2014-2022 (in Chinese).

[8] Wang Z F, Ning Y Q, Zhang Y, *et al.* High power and good beam quality of two-dimensional VCSEL array with integrated GaAs microlens array [J]. *Opt. Exp.*, 2010, 18(23):23900-1-6.

[9] Chong C H, Sarma J. Lasing mode selection in vertical cavity surface emitting laser diodes [J]. *IEEE Photon. Technol. Lett.*, 1993, 5(7):761-763.

[10] Bond A E, Dapkus P D, O'Brien J D. Aperture dependent loss analysis in vertical-cavity surface-emitting lasers [J]. *IEEE Photon. Technol. Lett.*, 1999, 11(4):397-399.

[11] Grabherr M, King R, Jäger R, *et al.* Volume production of polarization controlled single-mode VCSELs [J]. *SPIE*, 2008, 6908(1):690803-1-8.

[12] Schnabel B, Kley E B, Frank W. Efficient coupling into polymer waveguides by gratings [J]. *Appl. Opt.*, 1997, 36(36):9383-9390.

[13] Kou J L, Chen Y, Xu F, *et al.* Miniaturized broadband highly birefringent device with stereo rod-microfiber-air structure [J]. *Opt. Exp.*, 2012, 20(27):28431-28436.

[14] Takahashi Y, Neogi A, Kawaguchi H. Polarization dependent nonlinear gain in semiconductor lasers [J]. *IEEE J. Quant. Elect.*, 1998, 34(9):1660-1672.

[15] Wang W, Ning Y Q, Tian Z H, *et al.* Coherent polarization stabilization in large-aperture rectangular post bottom-emitting vertical-cavity surface-emitting lasers [J]. *Opt. Commun.*, 2011, 284(5):1335-1338.

[16] Jiao D, Jin J M. Three-dimensional orthogonal vector basis functionsf or time-domain finite element solution of vector wave equations [J]. *IEEE Trans. Anten. Prop.*, 2003, 51(1):59-66.

[17] Wulf K T, Zamora M, Kanwar R, K. *et al.* Processing of photonic crystals in InP membranes by focused ion beam milling and plasma etching [J]. *Microelectron. Eng.*, 2013, 102(1):25-28.

[18] Bomzon Z, Kleiner V, Hasman E. Spatial fourier-transform polarimetry using space-variant subwavelength metal-stripe polarizers [J]. *Opt. Commun.*, 2001, 26(21):1711-1713.

[19] Wilkinson C I, Woodhead J, Frost J E F, *et al.* Electrical polarization control of vertical-cavity surface-emitting lasers using polarized feedback and a liquid crystal [J]. *IEEE Photon. Technol. Lett.*, 1999, 11(2):155-157.

[20] Sun Y F, Ning Y Q, Li T, *et al.* Large aperture VCSELs with a continuous-wave output power of 1.95 W [J]. *J. Lumin.*, 2007, 122-123:886-888.

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