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High power external-cavity surface-emitting laser with front and end pump*

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High power optically pumped vertical-external-cavity surface-emitting lasers with front and end pump are reported. The gain chip consists of 15 repeats of $In_{0.26}GaAs/GaAsP_{0.02}$ multiple quantum wells and 30 pairs of $Al_{0.2}GaAs/Al_{0.98}GaAs$ distributed Bragg reflectors. The maximum output power of 3 W, optical-to-optical conversion efficiency of 22.4%, and slope efficiency of 29.8% are obtained with 5-°C heatsink temperature under the front pump, while the maximum output power of 1.1 W, optical-to-optical conversion efficiency of 23.2%, and slope efficiency of 30.8% are reached with 5-°C heatsink temperature under the end pump. Influences of thermal effects on the output power of the laser with front and end pump are discussed.

Keywords: surface-emitting laser, external-cavity, high power, pump geometry

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1. Introduction

A new type of semiconductor lasers, optically pumped vertical-external-cavity surface- emitting lasers (OP-VECSELs), also known as semiconductor disk lasers (SDLs), have the unique feature of the combination of excellent beam quality, output power scalability, and emitting wavelength adjustability.[1,2] These features make VECSELs have a very wide range of applications in scientific research, biomedicine, industrial production, and military fields. At present, the emission wavelengths of VECSELs are mainly between 800 nm and 1200 nm, and the involved technologies are relatively mature.[3–6]

VECSELs can be pumped with front or end geometry according to the different demands of the laser. Generally, a VECSEL with a front pump is proper for high-power continuous-wave running, stable mode-locked working and second harmonic generation, while a VECSEL with an end pump is more suitable for a compact and miniature device in some special utility.[7–10]

By the use of a front pump, Leinonen *et al.* reported a VECSEL with the maximum output power of 33 W and emitting wavelength at 1275 nm under a heat-sink temperature of −5 °C.[11] The laser cavity was composed of a highly reflective mirror (i.e., the distributed Bragg reflector in the gain chip) and an output coupler with 2.5% transmittance. With similar laser cavity and pumping geometry, Heinen *et al.* presented a continuous-wave output power of 106 W at a heatsink temperature of 3 °C in 2012. The laser operated in transversal multimode, and the emitting wavelength was 1028 nm.[5] Kantola *et al.* used a V-shaped cavity and a nonlinear LBO crystal for second harmonic generation and got a 588-nm yellow VECSEL with 20-W output power in 2014. The maximum conversion efficiency from absorbed pump power to yellow output power was 28%, which is the highest output power in the visible waveband.[12] A front pump mode-locked VECSEL with 400-fs pulse width and 4.35-kW peak power were reported by Keith *et al.* in 2013, the average output power was 3.3 W and the repetition rate was 1.67 GHz at the center wavelength of 1013 nm, which is the highest peak power of mode locking VECSELs.[13]

Compared to a front pump, VECSELs with an end pump have better mode matching and are easier to arrange in the cavity structure for laser miniaturization, which is of high demand in various applications that require a compact module. In 2006, Lee *et al.* demonstrated an end pumped VECSEL with more than 9.1-W continuous-wave output power at a wavelength of 1079 nm.[10] Then, by combination of the end pump geometry and the efficient intra-cavity frequency doubling, Lee *et al.* reported a highly efficient continuous wave green light at 535 nm, where the laser output power of more than 7 W was obtained when the pump power was 26 W,

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and the optical-to-optical conversion efficiency of 27% was achieved.[14] In the same year, Kim *et al.* demonstrated a high power end pumped VECSEL emitting at 532 nm and 460 nm. 2.7-W green and 1.4-W blue output powers with good beam quality were achieved by intra-cavity frequency doubling.[15] In 2007, Cho *et al.* proposed a novel lens-less optical end pump scheme and compact green VECSEL. A maximum output power of 1.1 W and an optical-to-optical conversion efficiency of 15.7% were achieved. The end pump was performed by placing a single laser diode directly behind the gain chip, and the pump geometry were without any optical elements for beam focusing and shaping.[16]

So far, there has been no reported VECSEL with front and end pumps simultaneously, and the performances of VECSELs with different pumping have not yet been compared. We present high power VECSELs with front and end pump here. Furthermore, a stability of the VECSEL has been presented and the wavelength can be tuned from 1096 nm to 1106 nm. In the semiconductor gain wafer, $In_{0.26}GaAs/GaAsP_{0.02}$ multiple quantum wells (MQWs) are grown to obtain an emission wavelength of 1096 nm, and $Al_{0.2}GaAs$ /$Al_{0.98}GaAs$ distributed Bragg reflector (DBR) is grown to produce high reflectivity centering at 1096 nm with about 100-nm bandwidth. Under front pumping, a maximum output power of 3 W is achieved when the pump power reaches 12.8 W, the optical-to-optical conversion efficiency and the slope efficiency are 22.4% and 29.8%, respectively. For end pumping, the maximum output power is up to 1.1 W when the pump power is 5.5 W, the optical-to-optical conversion efficiency and the slope efficiency are 23.2% and 30.8%, respectively. Performances of VECSELs with different pumps are compared, and influences of the thermal effects on the output power of lasers with front and end pumps are discussed.

2. Experimental setup

VECSELs with front and end pumps are illustrated in Fig. 1. A 3 mm×3 mm gain chip is directly bonded to a silicon carbide heatsink using the capillary action of water, and then the GaAs substrate is removed by the use of wet chemical etching.[17] An 808-nm semiconductor laser (the maximum output power in continuous-wave is 31.5 W and the laser linewidth is 2 nm) is delivered via a multi-mode fiber and focus on the gain chip at an incident angle of approximately 30°, and the pump spot is about 200-μm diameter at the gain chip. The output coupler (OC) is a spherical mirror with radius of curvature of 100 mm, the resonant cavity is formed by the DBR at the bottom of the gain chip and OC, and the length of the total cavity is about 96 mm.

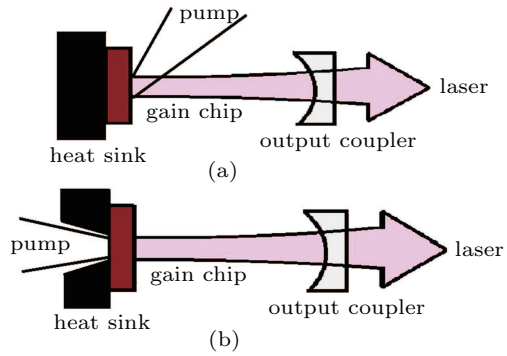


Fig. 1. (color online) Schematics of VECSELs with front (a) and end (b) pumps.

3. Results and discussions

Figure 2 shows the photoluminescence and laser spectrum (the resolution of the spectrometer is 0.035 nm) of the VECSEL when the incident pump power is 12.8 W. The photoluminescence spectrum has two peak wavelengths of 1050 nm and 1093 nm, respectively. The central wavelength of the laser is 1096 nm and the full width at half maximum (FWHM) is about 3 nm, which is a little bit smaller than 1093 nm. This may be caused firstly by the reflectance of DBR in 1093 nm (nearly100%) being higher than that in 1050 nm, therefore, the mode gain of the laser at 1093 nm is higher than that at 1050 nm, and the 1093 nm mode is easier to oscillate than the 1050-nm mode. Secondly, the thermal effects of quantum wells in the active region make the output laser wavelength redshift from 1093 nm to a longer wavelength, 1096 nm. The laser oscillates at 1096 nm instead of the peak wavelength of 1050 nm of photoluminescence, and this may decrease the quantum efficiency of the laser partly and limit the maximum output power of the laser.

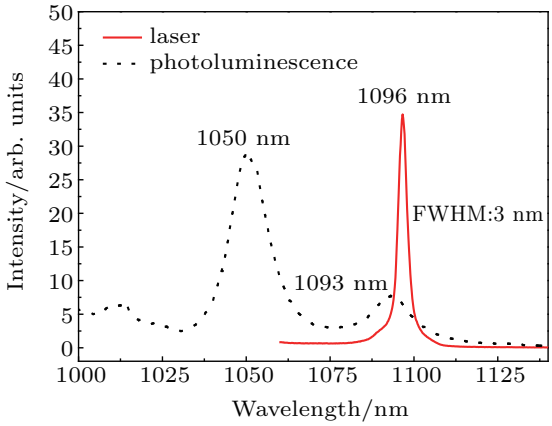


Fig. 2. (color online) Photoluminescence and laser spectrum of the VECSEL.

Figure 3 presents the beam quality M^2 factor of the VECSEL. As can be seen from Fig. 3, the M^2 factors of the laser beam in x and y directions are about 1.12 and 1.10, respectively. The spot sizes ω of laser beam at different distances z are measured using a CCD, and then the experimental curve

is fitted by the hyperbolic method, and the beam quality M^2 factor is calculated by $M^2 = (\pi/\lambda)\omega_0\theta$.

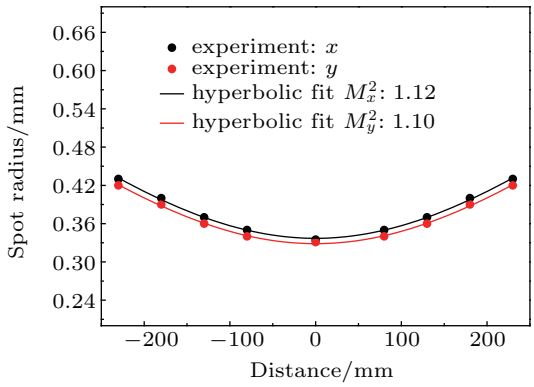


Fig. 3. (color online) Beam quality M^2 factors of the VECSEL.

Output powers of the front pumped VECSEL with different OC transmittance are plotted in Fig. 4. The temperature of the heatsink is 10 °C, and the radius of curvature of the OC is 100 mm. It can be seen from Fig. 4 that the differences of output powers under different OC transmittances are not clear when the incident pump power is below 3.8 W. However, when the incident pump power is higher than 3.8 W, differences of output powers under different OC transmittances obviously become more and more. A maximum output power of 2.6 W and a slope efficiency (SE) of 28.6% are obtained from the VECSEL with OC transmittance of 3%, and the output powers of the laser increase almost linearly with increased pump powers until the incident pump power is up to 12.2 W.

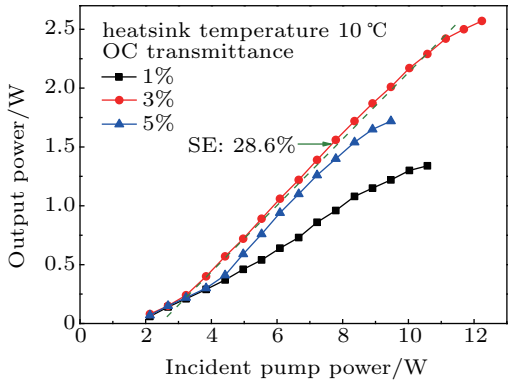


Fig. 4. (color online) Output powers of the front pumped VECSEL with different OC transmittances.

Output powers of the front pumped VECSEL under different heatsink temperatures are depicted in Fig. 5. The transmittance of the OC is 3%, and the radius of curvature of the OC is 100 mm. As can be seen from Fig. 5, the maximum output power of the laser is 2.3 W under conditions of 15-°C heatsink temperature and 11.7-W incident pump power. When the heatsink temperature drops to 10 °C, the maximum output power rises to 2.6 W. A maximum output power of 3 W and slope efficiency of 29.8% are reached when the heatsink temperature is 5 °C. Influence of heatsink temperature on the output power of the laser is obvious: a lower heatsink temperature means a lower temperature of QWs in the active region, therefore higher material gain of QWs and higher mode gain of the laser, meanwhile higher output power of the laser.

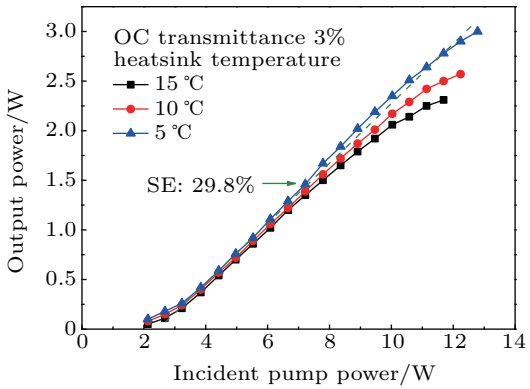


Fig. 5. (color online) Output powers of the front pumped VECSEL under different heatsink temperatures.

Figure 6 shows output powers of the end pumped VECSEL with different OC transmittances, the radius of curvature of the OC is 100 mm and the temperature of heatsink is 10 °C. The maximum output powers of the VECSEL are 0.9 W and 0.8 W when the transmittances of OC are 3% and 1%, respectively. Similar to Fig. 4, output powers of the laser with 3% OC transmittance are always bigger than that of the laser with 1% OC transmittance. We do not know if the 3% transmittance of OC is the optimum transmittance of the laser since there are no sufficient mirrors with different transmittance for this experiment.

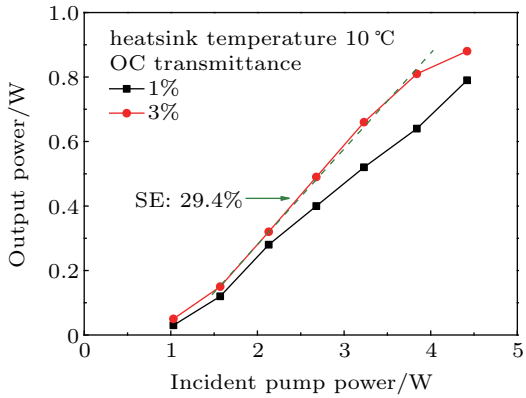


Fig. 6. (color online) Output powers of the end pumped VECSEL with different OC transmittances.

Output powers of the end pumped VECSEL with the different heatsink temperature are plotted in Fig. 7, the radius of curvature of the OC is 100 mm, and the transmittance of the OC is 3%. As can be seen from Fig. 7, in the case of 10-°C heatsink temperature, output powers of the laser begin to decrease when the incident pump power exceeds 4.4 W, while the output powers keep rising until the incident pump power is more than 5.5 W under condition of 5-°C heatsink temperature. The maximum output power of 1.1 W and slope effi-

ciency of 30.8% are yielded when the heatsink temperature is 5 °C.

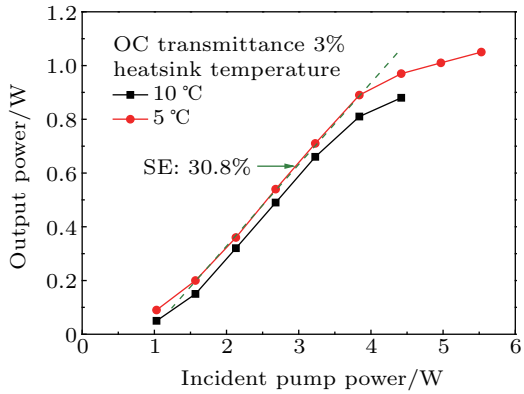


Fig. 7. (color online) Output powers of the end pumped VECSEL under different heatsink temperatures.

Comparison of the output powers of VECSELs with front and end pumps is shown in Fig. 8, the heatsink temperature is 5 °C and the transmittance of the OC is 3%. The inset is the schematics of mode match under different pump geometries. It can be seen from Fig. 8 that the laser thresholds of front and end pumped VECSELs are 2.1 W and 1.0 W, respectively. The threshold of front pumped VECSEL is higher, and the output power is smaller than that of end pumped VECSEL when the incident pump power is less than 5.5 W. When the incident pump power exceeds 5.5 W, the end pumped VECSEL suffers thermal rollover, however, output powers of front pumped VECSEL increase linearly until the incident pump power is beyond 12.8 W. The maximum output power of the front pumped VECSEL is over 3 W, and the optical-to-optical conversion efficiency and the SE are 22.4% and 29.8%, while the maximum output power of the end pumped VECSEL is 1.1 W, and the optical-to-optical conversion efficiency and the SE are 23.2% and 30.8%, respectively.

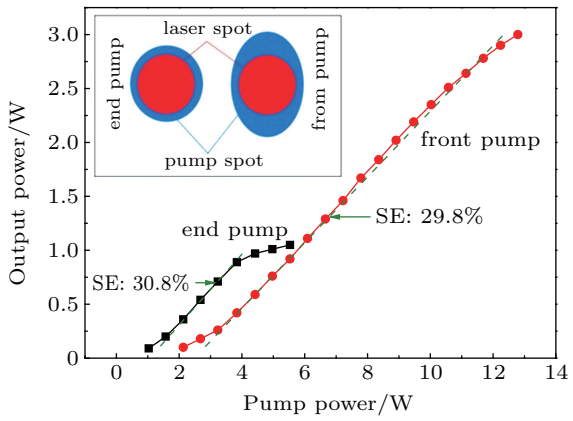


Fig. 8. (color online) Comparison of the output powers of VECSELs with front and end pumps.

On comparison, the end pumped VECSEL has a smaller laser threshold, higher optical-to-optical conversion efficiency, bigger SE, but significantly small maximum output power. This can be explained by the different way of mode-matching of the laser. In the end pumped VECSEL, the pump spot is an ideal circular light spot, just as the laser spot at the gain chip, so both of them can be matched very well, as can be seen from the inset in Fig. 8. As for the front pumped VECSEL, the pump spot is an elliptical light spot and the laser spot is circular, and this would result in the decrease of the overlapped area of the pump and laser spot, which means a weaker mode matching of the laser. On the other hand, it should be noticed that the heatsink is hollowed out in the end pumped VECSEL, which means poorer heat removal, causing serious thermal effects. When the pump power is relatively small, the advantage of mode matching is sufficient to counteract the disadvantages of thermal effects, so the performance of the end pumped VECSEL is superior to the front pumped VECSEL, i.e., smaller laser threshold, higher optical-to-optical conversion efficiency, and bigger SE. When the pumping becomes more intense, thermal effects become dominated, and the advantage of mode matching is suppressed. In this case, the end pumped VECSEL suffers a fatal thermal rollover, while the output power of the front pumped VECSEL keeps increasing and climbs to a higher maximum power.

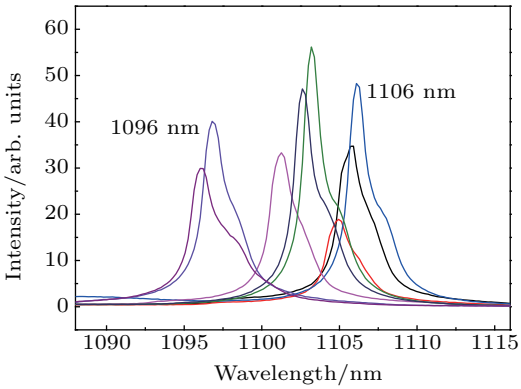


Fig. 9. (color online) The wavelength tuning range of the VECSEL.

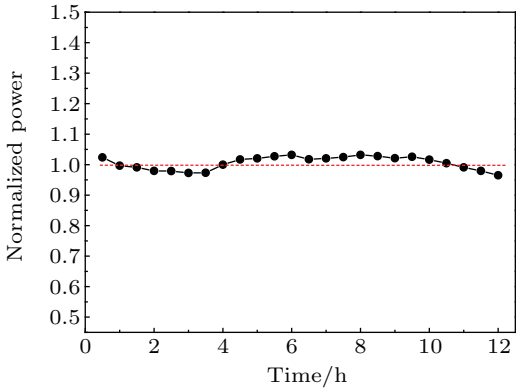


Fig. 10. (color online) The fluctuation of output power versus observing time.

Figure 9 shows the wavelength tuning range of the VECSEL by the use of a 0.15-nm thickness Quartz Fabry Perot etalon.[18,19] As can be seen from Fig. 9, the laser wavelength can be tuned from 1096 nm to 1106 nm when the incident pump power is 2.7 W and the heatsink temperature is

15 °C. Compared with ceramic lasers,[20–22] VECSELs may have wider wavelength tuning range (it can be further extended by changing the design of MQWs), more adjustable emitting wavelength (based on the well-known band engineering), and higher output power with good beam quality.

The stability of the VECSEL is plotted in Fig. 10, the horizontal axis is observing time and the longitudinal axis is normalized output power. It can be seen from Fig. 10 that the output power fluctuates in the range of about 4%, which indicates acceptable power stability.

4. Conclusion

In conclusion, we have demonstrated a high power VECSEL with front and end pump. The maximum output power of 3 W, optical-to-optical conversion efficiency of 22.4%, and slope efficiency of 29.8% are obtained with a 5-°C heatsink temperature for the front pumped VECSEL, while the maximum output power of 1.1 W, optical-to-optical conversion efficiency of 23.2%, and slope efficiency of 30.8% are reached with a 5-°C heatsink temperature for the end pumped VECSEL. Different performances of VECSELs with different pump geometry are determined by their way of mode matching and their ability of heat removal. Our experiments show that a front pumped VECSEL is suitable for high output power while an end pumped VECSEL is more appropriate for miniature laser application.

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