High-Power Vertical-Cavity Surface-Emitting Laser With an Extra Au Layer

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***Abstract*—We report the performance of a high-power vertical-cavity surface-emitting laser (VCSEL) with an extra Au layer. By using the extra Au layer, the far-field divergence angle from a 600-μm diameter VCSEL device is suppressed from 30° to 15°, and no strong sidelobe is observed in far-field pattern. There is a slight drop in optical output power due to the introduction of the extra Au layer. By improving the device packaging method, the VCSEL device produces the maximum continuous-wave optical output power of 1.95 W with lasing wavelength of 981.5 nm. The aging test is carried out under constant current mode at 60 °C, and the preliminary result shows that the total degradation of output power is less than 10% after 800 h.**

***Index Terms*—Aging test, far-field pattern, vertical-cavity surface-emitting lasers (VCSELs).**

I. Introduction

VERTICAL-CAVITY surface-emitting lasers (VCSELs) have become the most promising semiconductor laser source due to their most remarkable features such as circular output beam, monolithic two-dimensional array processing, on-wafer testing, or single longitudinal mode, etc. [1], [2]. VCSELs with high output power and good beam quality have much more potential for application in nonlinear optics, laser pumping, laser printing, and data storage [3]–[5]. Especially, high-power laser devices with a good quality laser beam and narrow spectral width in the 940–980 nm wavelength range are desired for the pumping of Er- or Yr-doped fiber amplifiers or fiber lasers [6], [7]. A continuous-wave (CW) optical power of 0.89 W at room temperature was reported for a single VCSEL with large aperture (320-μm diameter) in 0.9–1.1 μm wavelength [8]. More than 1 W of CW optical output power at room temperature for a VCSEL array consisting of 19 elements was also realized [9]. Commercial VCSELs with large aperture have reached room temperature CW optical output power 0.1 W [10]. For higher output power, a single VCSEL device with larger aperture or VCSEL array with larger size should be employed. At the same time, a novel vertical external cavity surface-emitting laser (VECSEL) was also reported in more than 1 W by using extra cavity mirror structure [11]. Since the approach of the arraying of elements or VECSELs is more complicated than a monolithic VCSEL diode structure in the device fabrication and application, we put our efforts on the fabrication of a single VCSEL with large aperture, which combine high optical output power at CW operation condition and good beam quality. However, strong sidelobes appear in the far-field pattern from VCSEL with large aperture. In order to obtain high power with good beam quality from VCSELs with large aperture, we employed a new VCSEL device structure with an extra Au layer in this letter. By using this kind of device structure, the far-field divergence angle from a 600-μm diameter VCSEL is suppressed from 30° to 15°, and the maximum CW optical output power of 1.95 W with lasing wavelength of 981.5 nm is obtained. Besides sufficient output power, the reliability of the device is also investigated.

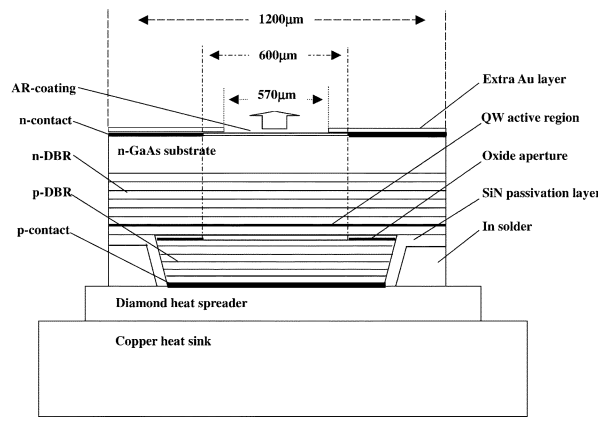

Fig. 1. Schematic diagram of the device structure.

II. Device Structure and Processing

The device structure consists of a multiple quantum-well active region sandwiched between n- and p-type distributed Bragg reflector (DBR) mirrors (see Fig. 1). The active region contains three $In_{0.16}Ga_{0.84}As$ quantum wells embedded in $GaAs_{0.92}P_{0.08}$ barriers for lasing 980-nm wavelength. Two AlGaAs claddings are used to build the one wavelength thick cavity. The p-type DBR consists of 35.5 pairs of $Al_{0.9}Ga_{0.1}As$–$Al_{0.12}Ga_{0.88}As$. A 30-nm-thick $Al_{0.98}Ga_{0.02}As$ layer located between the active region and the p-type mirror,

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and the layer is oxidized and converted to Al_xO_y in the fabrication process for current confinement. The n-type DBR has only 25.5 pairs of $Al_{0.9}Ga_{0.1}As$–$Al_{0.12}Ga_{0.88}As$ for bottom emitting through the GaAs substrate. The VCSEL epitaxial wafers in this work were all prepared by metal–organic vapor phase epitaxy grown on n^+-GaAs (100) substrates.

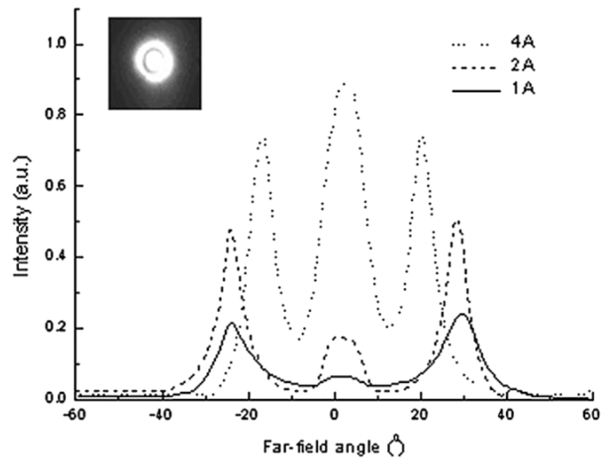
Wet chemical etching is used to define circular mesas. The exposed $Al_{0.98}Ga_{0.02}As$ layer is oxidized in a water vapor atmosphere using nitrogen as the carrier gas at 420 °C to form a 600-μm diameter current aperture. After oxidation, the surface is passivated with Si_3N_4 passivation layer, and the p-type Ti–Pt–Au contact on the top of the mesa is evaporated and serves as a metal pad for soldering. The GaAs substrate is thinned and polished down to about 120 μm to minimize its contribution to the series resistance, and an antireflection coating is deposited with 600-μm diameter. Self-aligned lithography is used to define the n-type Au–Ge–Ni electrical contact surrounding the emission windows. An extra Au layer is introduced into the device structure, as shown in Fig. 1. The Au layer is deposited on the top of the n-type electrical contact as the modal filter, and the whole light output aperture diameter is reduced from 600 to 570 μm. The extra Au layer makes an ohmic contact with the substrate, and it helps to derive good ohmic contact. A single device is separated by the dicing technology. The device is simply bonded on a copper heat sink with In solder, and the junction down bonding method is used due to its efficient heat diffusion.

III. Device Performances

The device operates at room temperature under CW condition for the test of the performance characteristics. The aging test is carried out under constant current mode.

The comparison of far-field patterns between devices with and without an extra Au layer is carried out in the experiment. From the device without an extra Au layer, strong sidelobes appear in the far-field patterns under all injection current ($I = 1, 2$, and 4 A), as shown in Fig. 2(a), and the far-field divergence as the half-angle at half-maximum intensity is about 30°. The near-field pattern at 4 A is shown in the inset of Fig. 2(a). The device operates at high-order transverse modes. This kind of optical energy distribution pattern is a disadvantage for optical coupling output application. Fig. 2(b) shows the far-field patterns of the device with an extra Au layer, and the beam divergence angle is suppressed down to about 15°. There is no obvious strong sidelobe energy distribution observed, and the maximum intensity is approximately on the symmetry axis. The near-filed pattern at 4 A is shown in the inset of Fig. 2(b); the laser operates in lower order transverse modes for the modal filtering effect of the gold layer. Due to the circularly symmetric patterns with low beam divergence angle, the beam of the device can be easily focused or collimated into a fiber in a simple butt-coupling arrangement for broad applications.

Fig. 3 shows the experimental output power characteristics from the same devices with and without an extra Au layer. The maximum CW optical output power at room temperature is 0.91 W in the device without extra Au layer (solid line), and the optical CW output power is 0.90 W in the device with an extra Au layer (dash line). There is a slight drop in optical output power in the device with an extra Au layer, and the drop in output power can be attributed to the scattering loss in edge of the extra layer and the absorption in the Au layer. The whole light output aperture diameter is further reduced to 550 μm



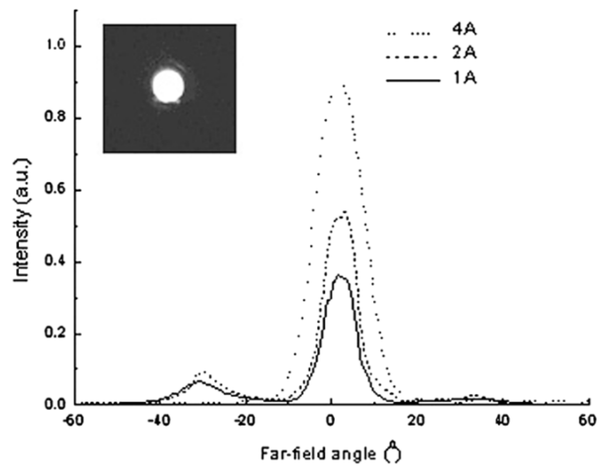


Fig. 2. Comparison of measured far-field pattern at different injection current ($I = 1, 2$, and 4 A) between devices with and without an extra Au layer. (a) Without an extra Au layer. Inset: Near-field pattern at $I = 4$ A. (b) With an extra Au layer. Inset: Near-field pattern at $I = 4$ A. Dotted line: 4 A. Dashed line: 2 A. Solid line: 1 A.

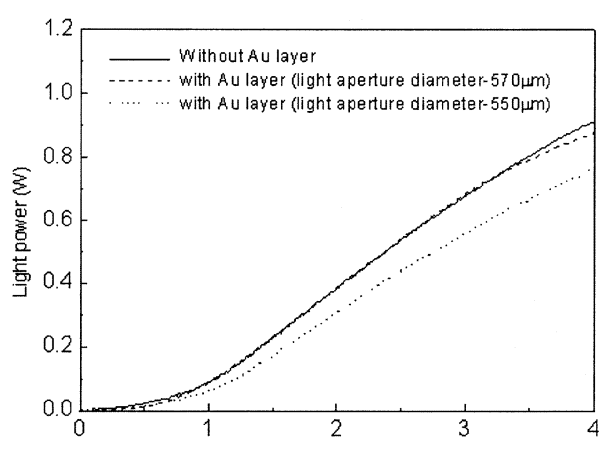


Fig. 3. Comparison of optical output power characteristics between devices with and without an extra Au layer. Solid line: Without an extra Au layer. Dashed line: With an extra Au layer (light aperture diameter: 570 μm). Dotted line: With an extra Au layer (light aperture diameter: 550 μm).

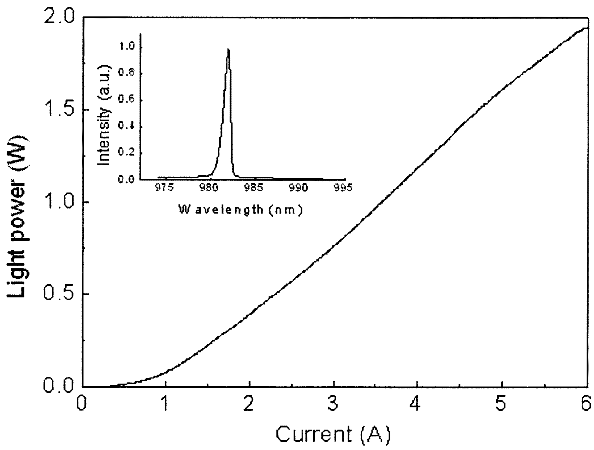


Fig. 4. Optical output power characteristics of the device. Inset: Measured lasing wavelength at injection current of 6 A.

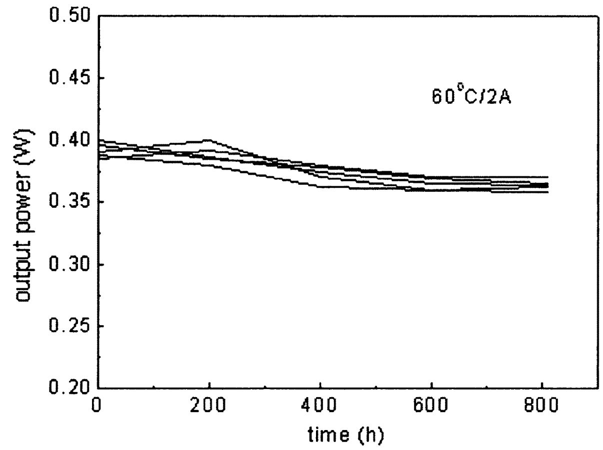


Fig. 5. Aging test of VCSEL devices (60 °C/2 A).

with the extra Au layer, and the obvious drop in optical output power is observed, as shown in Fig. 3 (dotted line). The far-field pattern is measured, and the far-field divergence angle is less than 10°. The good beam quality comes with a price, and the maximum output power decreases down to 0.77 W.

For improving the device packaging method, the device with an extra Au layer (light aperture diameter 570 μm) is soldered junction down on a metallized diamond heat spreader with In solder; then the whole chip is attached onto a copper heat sink with the same solder for mechanically stability, good thermal, and electrical conductivity. The device operates under CW condition at room temperature, and the light output power versus injection current is shown in Fig. 4. The maximum optical CW output power is up to 1.95 W at 6 A, which is the limit of the current source used in our experiment. The light power increases with injection currents between 1.5 and 6 A, with the maximum slope efficiency coefficient of 0.37 W/A. The threshold current is about 1.1 A, corresponding of the threshold current density of 500 A/cm^2.

The lasing wavelength at injection current of 6.0 A is shown in the inset of Fig. 4, and the lasing peak wavelength is 981.5 nm, with full-width at half-maximum 0.9 nm.

Besides sufficient output power and good beam quality, the proof of the reliability is also essential for applications. Therefore, several tens of randomly picked devices are chosen for aging test. The aging test is carried out under constant current mode at high temperature condition. During the aging test, the devices are driven by a constant current of 2 A ($I \approx 2I_{\rm th}$), and the optical output power is about 0.39 W at the test beginning. The temperature is controlled at 60 °C. Fig. 5 shows the output power during the aging test. The total degradation of output power is less than 10% after 800-h burn-in test, and there is no sudden failure. The aging test is still ongoing.

IV. Conclusion

We have presented a high-power VCSEL with an extra Au layer. By using the extra Au layer, the far-field divergence angle is suppressed from 30° to 15°, and there is a slight drop in optical output power due to the introduction of the extra Au layer. By improving the device packaging method, the device produces the maximum CW optical output power of 1.95 W with lasing wavelength of 981.5 nm. The aging test is carried out under constant current mode, and the initial reliability test at 60 °C shows that the total degradation of output power is less than 10% after 800 h.

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