Influence of Package Structure on the Performance of the Single Emitter Diode Laser

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***Abstract*— The package structure critically influences the major characteristics of semiconductor lasers, such as thermal behavior, output power, wavelength, and far-field distribution. In this paper, a new single emitter package structure called F-mount is designed and compared with the conventional package structure C-mount. The influence of package structure on their performances is characterized and analyzed. The thermal resistances of lasers with different package structures are calculated through simulation, and are contrasted with experimental results. Some devices are also tested for the maximum output power level. Under the continuous wave (CW) condition, the maximum power of F-mount reaches 12.6 W at 808 nm while the output power only reaches 10.9 W for C-mount. Under the condition of 0.5% duty cycle (100 μs, 50 Hz), the catastrophic optical mirror damage level reaches 58.7 W at 74 A for F-mount, and 54.8 W at 57 A for C-mount are reported for the first time. It is experimentally found that there is an obvious wavelength difference between the two type structure lasers: about 1.37 nm in CW mode and 2.89 nm in quasi CW mode. Theoretical analysis shows that red-shift and blue-shift is a result of external strain in the package process of F-mount and C-mount, respectively. It is also found that the package structure has an effect on the divergence angle of slow axis far fields, but little impact on that of fast axis far fields. The analysis shows that package structure has a strong influence on the performance of the laser; therefore, the package should be optimized to achieve better performance for some special applications.**

***Index Terms*— Component architectures, semiconductor device packaging.**

I. Introduction

HIGH power semiconductor lasers have been widely used for solid-state laser pumping, and as direct high power light sources for industrial, research, and medical applications [1]–[5]. With the increasing applications, there is a continuous demand for high conversion efficiency, high output power, and high reliability, which are critically influenced by the package structure. As the performance from package improves, more and more direct semiconductor laser applications become feasible for medical treatment and material processes. Therefore, the effects of package structure on the performance of lasers, such as maximum output power, thermal resistance, and so on [6]–[10], are hot topics of study in the field of high-power semiconductor lasers. However, there are few papers researching the influence of package structure on the natural wavelength and far-field properties. In this paper, packaging structure's impact on the wavelength and far field is proposed and studied in detail. The analysis shows that package structure has strong influence on the performance of the laser; therefore, the package should be optimized to achieve a better performance for some special applications.

Commercially, there are numerous types of packaged 808-nm single emitter semiconductor lasers, such as C-mount and CT-mount. In this paper, a new package structure called F-mount is designed and compared with the typical package structure C-mount. They have different thermal management strategies, soldering procedures, and heat sink architectures. Through comparative analyses, the performances, including thermal behavior, output power, wavelength, and far fields influenced by different package structures are studied.

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II. Package Structure Design

A. Package Structure Design

In order to achieve high power, high efficiency, and long lifetime, the operation temperature of the laser diode should be kept as low as possible. Therefore, the cooling capabilities of the package are of especially great importance, resulting in the fact that the package structure design is dominated by the cooling aspect.

C-mount package is one of the typical single emitter laser packages available commercially. It always has two types: 1) using copper submount and Indium solder and 2) using copper-tungsten (CuW) submount and golden-tin (AuSn) solder. Currently, high reliability and long lifetime has become the trend of diode laser [11], [12]. Therefore, CuW submount and AuSn solder structure with high reliability has been developed in this paper. The laser chip is epi-down mounted onto a CuW substrate, which is the p-side connection, as shown in Fig. 1(a). A flylead is attached to the substrate as the

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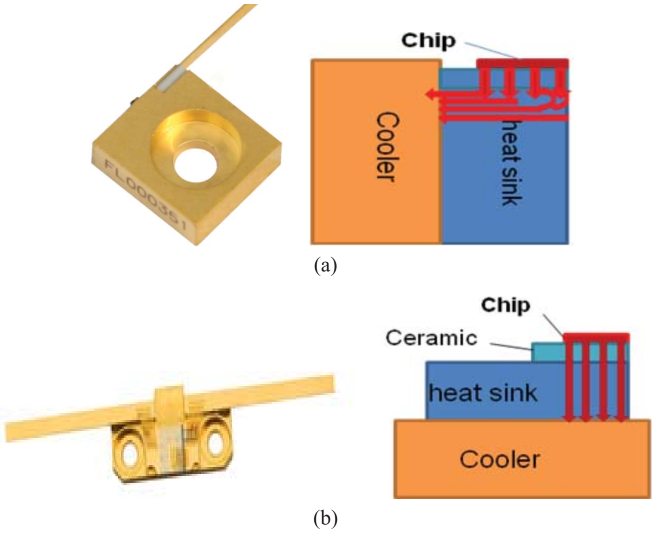


Fig. 1. Physical structure of the single emitter laser. (a) C-mount laser. (b) F-mount laser.

n-side connection. The n-side of the chip is wire-bonded to the flylead. When the laser works, the heat primarily spreads to the heat sink vertically, and then horizontally spreads to the cooler by heat sink. Therefore, there is a thermal path overlapping that of heat conducts along the chip cavity. This overlapped path leads to the rise of junction temperature of the device, and further influences the device performance. Fig. 1(b) shows the F-mount structure we designed. The flip-chip is mounted onto ceramic submount (AlN), which can effectively relieve the mismatch of coefficient of thermal expansion (CTE). The n-side metal is wire-bonded to the substrate placed on top of the cooler. When the laser works, the heat generated from chip can be easily dissipated downward to the cooler through the heat sink. The parallel thermal path of the laser can greatly improve the thermal dissipation efficiency.

The thermal behavior is studied using finite element analysis (FEA), and the condition of 5-W output power and 50% conversion efficiency at 25 °C is assumed. According to the thermal analysis, the distribution of temperature field is obtained, as shown in Fig. 2. It is found that the maximum temperature of F-mount structure is 36.2 °C, while the C-mount structure is 40.1 °C. Simulation results show that the thermal resistances of F-mount and C-mount lasers are 2.24 K/W and 3.02 K/W, respectively. It indicates that F-mount has better thermal management than that of C-mount.

III. Performance Characterization

Whether used as pump resource or directly applied, output power, wavelength, and divergence angle are the most important parameters for semiconductor laser. In order to study the influence of package structure on performance of the laser, some F-mount and C-mount structure lasers are fabricated using the neighboring chips (200-μm stripe width with 2-mm cavity length) obtained from the same wafer. The performances of two type structure lasers are characterized, by contrast, from output power, thermal behavior, wavelength, and far fields.

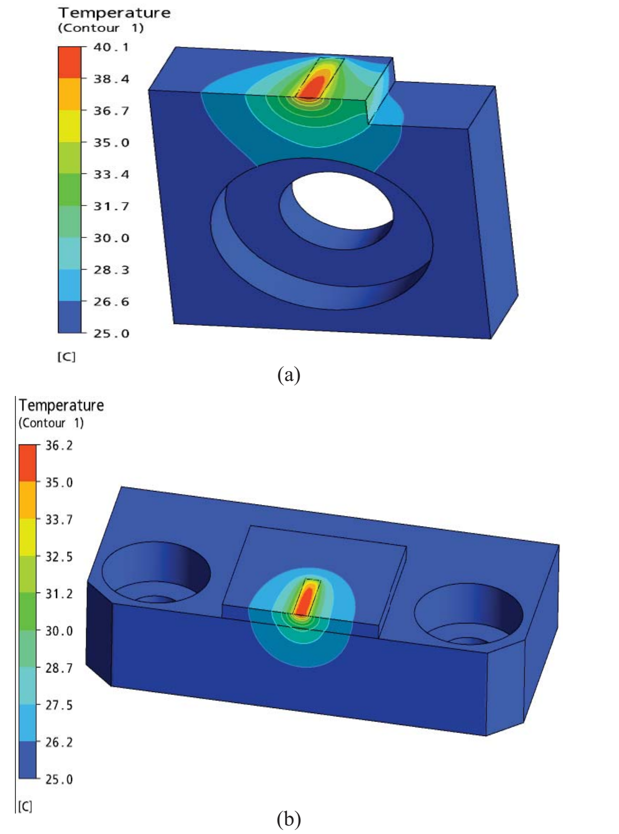


Fig. 2. Simulation of C-mount and F-mount lasers thermal distribution of working performance. (a) C-mount laser. (b) F-mount laser.

A. Output Power

The point of vertical intersection (PVI) curves of five F-mount and five C-mount structure lasers are measured under the output power 6 W [continuous wave (CW) mode] at room temperature, as shown in Fig. 3(a) and (b). By calculation, the average operating current of F-mount is about 5.81 A, compared to 6.03 A of C-mount. The average slope efficiency of F-mount is about 1.22 W/A, compared to 1.19 W/A of C-mount. The average conversion efficiency of F-mount is 53.8%, while the C-mount is 52.1%. Fig. 3 shows two typical PVI curves of C-mount and F-mount.

Generally, the reliable output power $P_{\text{rel}} = (0.3\text{-}0.5)\ P_{\max}$, which shows that the maximum output power ($P_{\max}$) can be of guidance for diode laser designs. The output power of a single emitter laser is limited either by thermal rollover or by catastrophic optical mirror damage (COMD). Thermal rollover happens when more heat is generated than dissipated in the device or there is carrier leakage at high current and high temperature [13]. The COMD is mainly caused by optical absorption and nonradiative recombination at the front facet, which lead to localized overheating [14]. Fig. 4 shows the thermal rollover and COMD level of the F-mount and C-mount lasers with 200-μm stripe width and 2-mm cavity length as a faction of CW/quasi CW (QCW) current. It is found that under the CW condition, the maximum power of F-mount reaches 12.6 W at 808 nm, where the output power only reaches 10.9 W for C-mount. On the other hand, the COMD

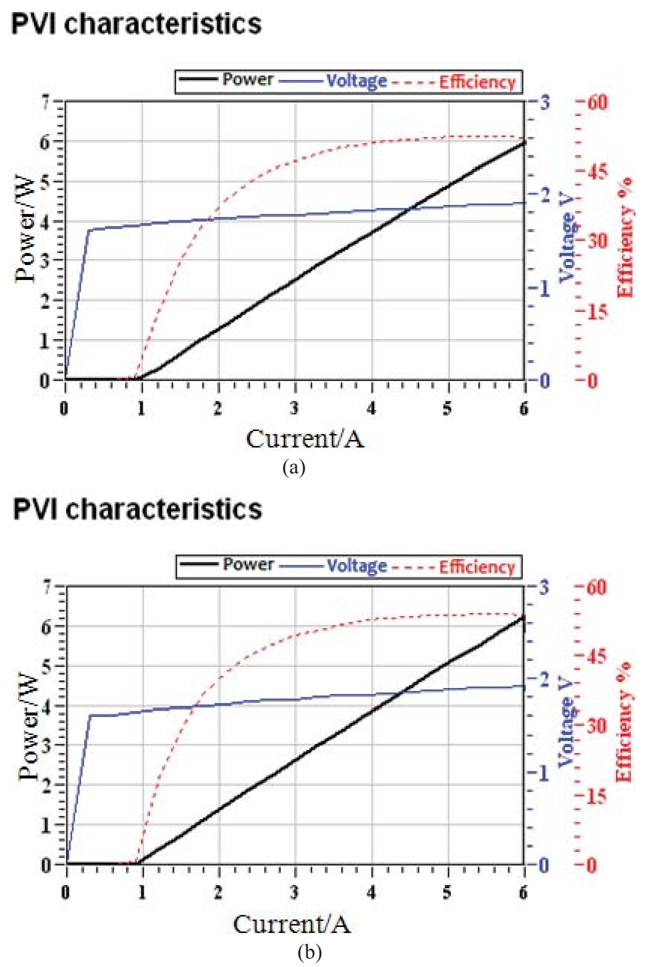


Fig. 3. PVI curve of C-mount and F-mount. (a) C-mount laser. (b) F-mount laser.

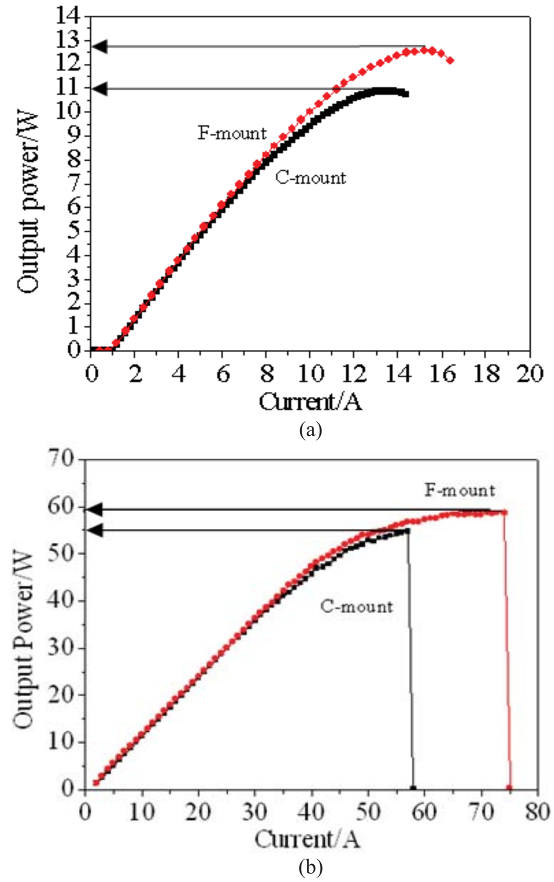


Fig. 4. Output power of 808-nm semiconductor lasers versus the operational current. (a) CW mode. (b) QCW mode.

power level is also tested in QCW mode, as shown in Fig. 4(b). Under the condition of 0.5% duty cycle (100 μs, 50 Hz), the output power reaches 58.7 W at 74 A for F-mount. There is also COMD when the output power reaches 54.8 W at 57 A for C-mount. The experimental results demonstrate that the maximum output power level is significantly affected by the package structure. The maximum output power can be shifted to a higher level with a better thermal design.

B. Thermal Resistance

The performance of the semiconductor laser is greatly dependent on junction temperature. The high device junction temperature will result in high threshold current, decreased conversion efficiency, and output power reduction. The junction temperature of the device can be calculated by

$$T = T_h + R_{\text{th}}(IV - P) \tag{1}$$

where T_h is the heat sink temperature, R_{th} is the device thermal resistance, I, V, and P are driving current, voltage, and output power, respectively. The formula (1) shows that the laser's junction temperature is mainly determined by the heat sink temperature and the thermal resistance. The heat sink temperature is dependent on the using conditions; therefore, the thermal resistance is the primary limitation of junction temperature. The thermal resistance can be calculated by

$$R_{\text{th}} = \frac{\Delta T}{\Delta Q} = \left(\frac{\Delta\lambda}{\Delta T}\right)^{-1}\left(\frac{\Delta\lambda}{\Delta Q}\right) \tag{2}$$

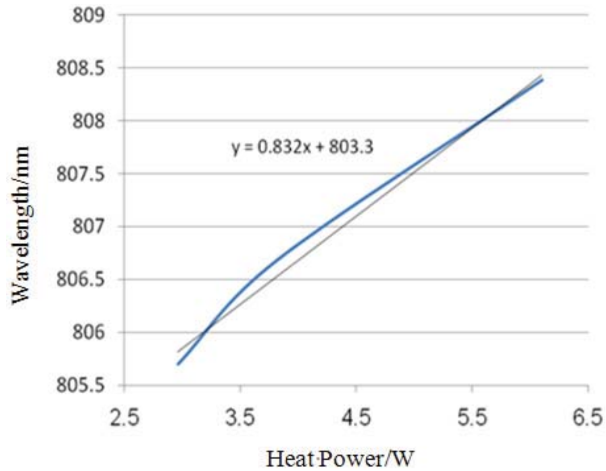
where Q is generated heat, $\Delta\lambda/\Delta T$ is the wavelength temperature coefficient, and $\Delta\lambda/\Delta Q$ is the wavelength heat coefficient. Typically, for GaAs-based 808-nm laser devices, the wavelength shifts with 0.28 nm/K toward longer wavelengths. The heat generation of a laser package can be calculated by

$$Q = IV - P. \tag{3}$$

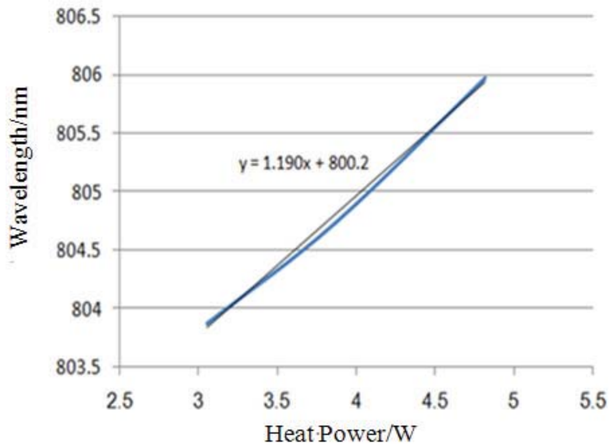
It can be concluded that the wavelength heat coefficient of F-mount is 0.832 nm/W, while that of C-mount laser is 1.19 nm/W, as shown in Fig. 5. From (2) and (3), we can calculate that the thermal resistance of F-mount laser is only 2.97 K/W, but that of the C-mount is 4.25 K/W. The results confirm that F-mount has better thermal management than C-mount. It is also found that the experimental results of thermal resistance are larger than that of the simulation results. This is mainly because the simulation is conducted in perfect solder layer. In practice, there are always some solder voids.

C. Wavelength

In order to compare the influence of the different package structures on the wavelength of the laser, we have tested the



(a)



(b)

Fig. 5. Wavelength varies with the heat power. (a) F-mount. (b) C-mount.

spectral performance of five F-mount and five C-mount lasers, using the neighboring chips from the same wafer under the same conditions, as shown in Fig. 6.

There is an obvious wavelength difference, about 1.37 nm, between the two different package structures under CW mode, and the measurement is also performed under pulsed operation (100 μs at 50 Hz) to avoid temperature effect. It is found that the mean-wavelength difference is 2.89 nm, as shown in Fig. 6. Therefore, the wavelength of C-mount is shorter than that of F-mount in both the CW and QCW modes. It is well known that the wavelength depends directly on the bandgap of the laser's active region, which is influenced by temperature and thermal stress (due to the CTE mismatch between the laser chip and bonding carrier). When operated in QCW mode there is hardly any heat generated, so the wavelength difference is mainly caused by the stress. When operated in CW mode there is a great deal of heat generated; both types of lasers will be red-shifted due to the thermal effect. In consideration of lower heat dissipation efficiency of C-mount than that of F-mount, there is more red-shift in C-mount. Therefore, the wavelength difference decreases in CW mode.

In order to study the wavelength varying under external stress from different package structures, a simplified mode

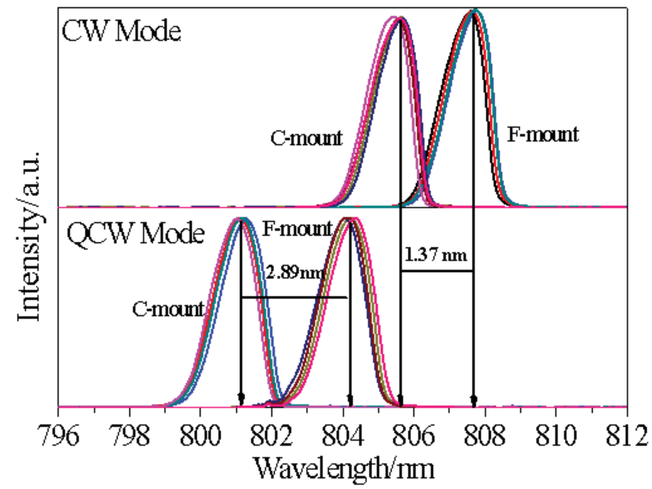


Fig. 6. Wavelength difference between F-mount and C-mount in CW and QCW modes.

(some factors have been neglected) is established as follows:

$$\varepsilon = \varepsilon_{\text{ip}} + \varepsilon_{\text{out}}. \tag{4}$$

The major contributors of strain ε are internal strain ε_{in} and external strain ε_{out}. ε_{in} is induced by lattice-mismatch of chip. ε_{out} is caused by the CTE mismatch between the chip and substrate. Since using the adjacent chips obtained from the same wafer, we can assume that ε_{in} can be negligible. Under external stress, the shift of the bands can be calculated by [15]

$$\Delta E_g = -2a\frac{C_{11} - C_{12}}{C_{11}}\varepsilon_{\text{out}} \tag{5}$$

where a is the deformation index, C_{11} and C_{12} are elastic stiffness constants. For GaAs chip, a is -8.68 ev, C_{11} is 11.88, C_{12} is 5.38. So (5) can be simplified as

$$\Delta E_g = 1.11 \times 10^5 \varepsilon_{\text{out}}. \tag{6}$$

In this paper, σ describes the stress in the region of the joint between two isotropic materials and ε_{out} is directly proportional to σ, i.e., $\sigma \propto C \cdot \varepsilon$, where C is referred to as Young's modulus, so $\Delta E_g \propto \sigma$. The external stress σ can be calculated by (7), as a function of their thermal expansivity and temperature

$$\sigma = \frac{E_1 E_2}{E_1 + E_2}(\alpha_1 - \alpha_2)(T_f - T_s) \tag{7}$$

where E_i is elasticity modulus of materials, α_i is CTE, T_f, and T_s are the solder solidification temperature and ambient temperature, respectively. The submount materials of F-mount laser and C-mount laser are AlN and CuW, respectively. The CTE of AlN, CuW, and GaAs are 4.5 ppm/K, 7 ppm/K, and 6.5 ppm/K [16], respectively, and the elasticity modulus of ceramic, CuW, and GaAs are 3.08×10^5 MPa, 3.72×10^5 MPa, and 0.85×10^5 MPa, respectively, from which we can calculate that F-mount is about -25.8 MPa, which is negative, and C-mount is about 19.6 MPa. Therefore, the thermal stress of F-mount is tensile stress, which decreases the bandgap and leads to red-shift of the device; the substrate of C-mount hastened the chip shrunk from the role of compressive stress,

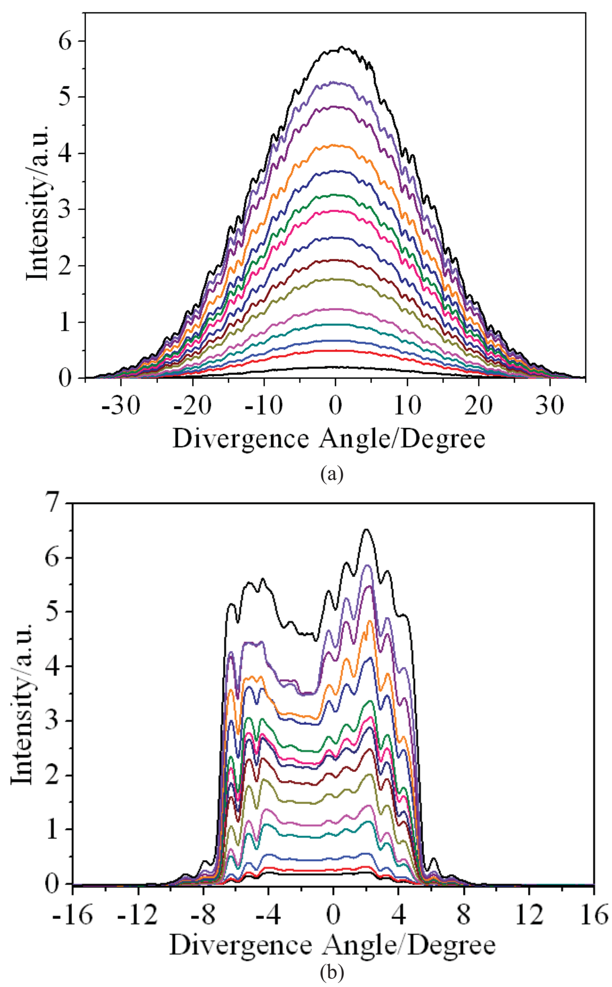


Fig. 7. Far-field patterns of C-mount laser package measured under CW condition with increasing current 1–8 A from bottom to top. (a) Fast axis far-field patterns. (b) Slow axis far-field patterns.

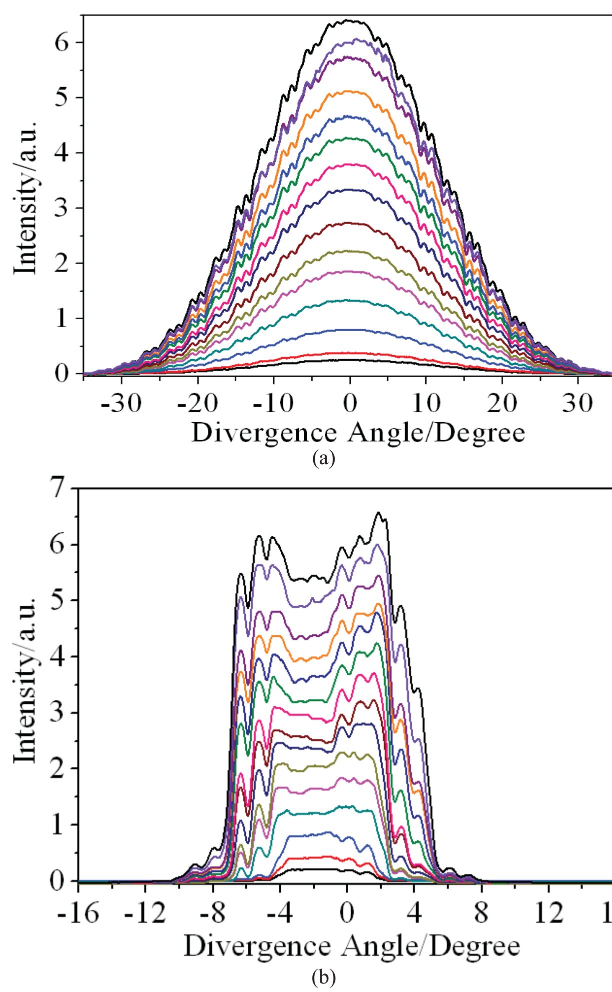


Fig. 8. Typical far-field patterns of F-mount laser package measured under CW condition with increasing current 1–8 A from bottom to top. (a) Fast axis far-field patterns. (b) Slow axis far-field patterns.

resulting in blue-shift of the device. It is confirmed that the package structure has impact on the wavelength.

D. Far-Fields Properties

The beam quality of single emitter lasers is of great importance for efficient coupling. The far-field patterns of the C-mount and F-mount structure lasers have been investigated both under CW and QCW (100 μs, 300 Hz) conditions with increasing current 1–8 A every 0.5 A, as shown in Figs. 7 and 8.

From Figs. 7(a) and 8(a), we can see that the fast axis far-field patterns are pretty good, and the full width of half maximum (FWHM) divergence angle of the far field can be calculated from Gaussian fitting of the far-field patterns. Figs. 7(b) and 8(b) show that the slow axis far-field patterns are multimode and are not Gaussian shape. We also test the far-field properties under QCW condition, which shows a smoother curve but the nearly same results.

Fig. 9 summarizes the FWHM divergence angle of the far field as a function of driving current of different package configurations. It is found that the fast-axis divergence angle is nearly constant over the operation current range. The fast-axis divergence angle is very close for both CW and QCW operation, and is little affected by the different package structures. In contrast, the slow-axis divergence angle is significantly affected by the driving current and package structure. For both the packages, the slow-axis divergence increases rapidly initially with increasing current (below 1.5 A), however, the divergence difference is small. After 1.5 A, the divergence increase rate slows down and the influence of package structure on the performance appears. There is a different increment between the lasers with different packaging when the current increases. It is also found that the divergence difference between the CW and QCW mode significantly increases for all assembly configurations.

The FWHM divergence angle can be approximately expressed by [17]

$$\theta(\text{rad}) \approx 4 \times \left(n_2^2 - n_1^2\right) \times \frac{d}{\lambda_0} \tag{8}$$

where θ(rad) is FWHM divergence angle, n_1 and n_2 are the refractive indexes of the waveguides, which are influenced by temperature, d is the depth of the active region, λ_0 is the wavelength of the laser. The refractive indexes can be

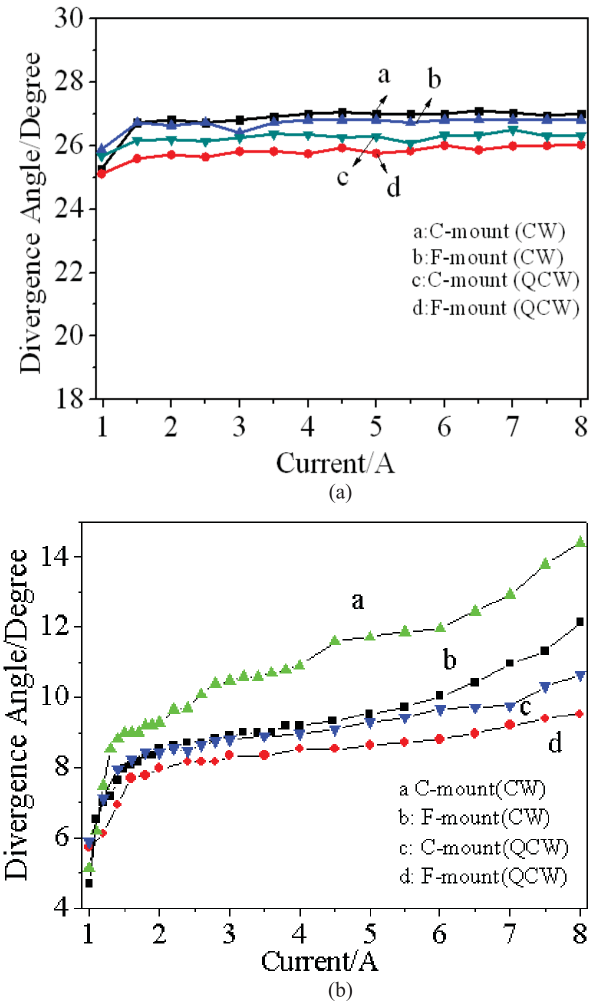


Fig. 9. Comparison of the fast-axis and slow-axis FWHM divergence angle as a function of driving current of different package configurations. (a) Fast-axis divergence angle. (b) Slow-axis divergence angle.

described by

$$n_1 = n_{10} + \Delta n_1$$

and

$$n_2 = n_{20} + \Delta n_2.$$

n_{10} and n_{20} are initial values of the refractive indexes, which are determined by design of laser chip. Δn_1 and Δn_2 are the parameters that vary with the temperature. Therefore, the factors that influence FWHM divergence angle can be simplified to

$$\theta(\text{rad}) \propto (\Delta n_2 - \Delta n_1). \quad (9)$$

Because Δn_1 and Δn_2 vary with the temperature, θ(rad) is influenced by the temperature difference between the waveguide layers of the active region. In the fast-axis direction, the value of d is only several micrometers and the temperature difference is very small. Therefore, the temperature variation has hardly any effect on the fast-axis divergence angle. But in the slow-axis direction, the d is more than one hundred micrometers, the temperature effect is obvious. Moreover, since the C-mount has worse thermal management, the increase rate of the temperature gradient is faster than that of F-mount when the current increased. Therefore, the divergence difference between C-mount and F-mount become larger. In QCW mode, there still exists thermal accumulation and the slow-axis divergence angle becomes obviously larger when the thermal accumulation reaches a certain level both in C-mount and F-mount structure lasers. Clearly the increase rate of C-mount is significantly faster than that of F-mount.

The results indicate that the package structure exerts a significant influence on the slow-axis divergence angle, and better thermal management results in better far-field performance. Therefore, it is important to reduce the thermal resistance in order to control the slow-axis divergence.

IV. Conclusion

In summary, we have investigated the effects of package structure on the performance of the single emitter laser. Through FEA, we know that the thermal resistances of F-mount and C-mount lasers are 2.24 K/W and 3.02 K/W, respectively. It is also found that package structure has appreciable influence on the bandgap. Blue-shift or red-shift will happen in the package process. In QCW mode with the current of 5 A, the wavelength of F-mount laser is 2.89 nm longer than that of C-mount laser; however, the wavelength difference becomes 1.37 nm under CW mode due to thermal effect. The far field test results indicated that the package structure exerts a significant influence on the slow-axis divergence angle, and the better the thermal management, the better the far-field performance. The simulated and experimental results demonstrated that F-mount devices have smaller thermal resistance and divergence angle, higher power, and higher efficiency at room temperature, all because F-mount has better package structure. Consequently, according to the performance influence by the package structure, the structure can be optimized to achieve a better performance for some special applications.

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