Influence of Optical Field Design on Catastrophic Optical Damage in Laser Chips

Hui-wu Xu 1,2,3, Xian-jie Li1, Li-hua Yan2,3,*, Jiang-li Niu2,3, Ji-feng Ning1, Hai-tao Peng1, Yan Zhang1

1School of Beijing University of Posts and Telecommunications, Beijing, China
2The 13th Research Institute of China Electronics Technology Group Corporation, Shijiazhuang, China
3Shijiazhuang METDA Electronic Technology Corporation, Shijiazhuang, China

*Corresponding author e-mail: Yanlihua_cetc@163.com

Abstract. As high-power semiconductor lasers are applied more and more widely, the catastrophic optical damage (COD) is getting larger and larger. In this paper, the influence of COD is demonstrated in detail through in-depth analysis on the phenomenon and formation mechanism of high-power semiconductor laser chip COD, and finally, the optical field distribution in the chip is optimized through experiment. As the result, the conventional Gauss field distribution is optimized to the flat-toped beam distribution; both the peak power density of the cavity surface and the non-radiation level of the cavity surface are reduced; and the COD value of laser chip is improved by 15%–20%. The results proves the correctness of the theoretical analysis, and provides a technical reference for improving the overall parameters of high-power semiconductor.

1. Introduction

With the increasing maturity of high-power semiconductor laser chip technology, it is applied more and more widely, and has gradually covered all fields of optoelectronics, with the trend of becoming the core technology of Optoelectronics practical devices. The research progress of high-power semiconductor lasers is very rapid in foreign countries. As reported in the literature, the maximum efficiencies is up to 73%[1-3], and the single array 40-150 W has been commercialized. By contrast, the application of high power semiconductor lasers in China started later. Although a great progress has been made, the cavity surface COD phenomenon is still the main factor restricting the further improvement of the output power of semiconductor lasers. In the paper, on the basis of domestic 100W single-chip, the micro-channel cooling technology is adopted to test and analyze the relationship between the generation of cavity surface optical damage (COD) and the influence of the optical field parameters in the laser chip.

Figure 1. Structure of 100W single bar chip

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In order to improve the reliability, the non-injecting chip structure of the cavity surface current is designed to reduce the non-radiation recombination probability of the cavity carrier, reduce the heat production of the cavity surface and improve the anti-burning characteristic of the cavity surface. By improving the lateral optical field distribution of the chip, and optimizing the depth of the waveguide corrosion, the abnormal enhancement of the optical field on the edge of the light emitting region is reduced and the uniformity of the distribution of the optical field is improved, which avoids the local burning of the edge of the light emitting region. The optimization design of chip layout aims at modeling the uniformity of current injection of single light emitting unit, homogenizing the transverse distribution of injection current, improving the uniformity of light power of each light emitting unit, and increasing the long-term reliability of the device.

2. Analysis of COD phenomena and influencing factors

2.1 COD phenomenon
As generally considered, catastrophic optical damage is caused by local melting and high density defects due to rapid temperature rise near the cavity surface. In the process of laser operation, the COD phenomenon is a typical failure mode. Two typical COD feature pictures are listed below.

![Figure 2. Burning on the front facet and burning point in the cavity](image)

2.2 Influence factors of COD
COD production mechanism: Upon the occurrence of optical absorption, the electron-hole and the non-radiation compound are produced, which causes the temperature to increase, and the temperature rise will lead to the contraction of the material band gap at the end face, making the light absorption further increases and the temperature further rises. When the output power of the semiconductor laser is small, the temperature difference between the end face and the light emitting region is maintained, and a certain thermal equilibrium state is achieved. When the output power increases to a certain extent, the cavity surface defects increase and the equilibrium state is broken, resulting in a vicious cycle. When the temperature rises above the melting point of the material, the front will suddenly fail, that is, the COD phenomenon.

3. Distribution of optical field inside the chip

3.1 The relationship between the optical field and COD in the chip
For high power semiconductor lasers, the semiconductor materials on the cavity surface are prone to damage at high power density. Therefore, we need an optimized design of the optical field structure. In this paper, we also call it the design of flat top optical field. Therefore, destroying the reflection or transmission of the cavity surface, can result in damage to the laser device. This is the phenomenon of optical catastrophic damage (COD) on the cavity surface. The COD phenomenon is the main factor limiting the further improvement of output power of semiconductor lasers. According to the formula below:

\[
P_{\text{COD}} \propto W_{OUT} \times \frac{d}{\Gamma}
\]  
(1)
In Formula (1), $W_{OUT}$ is strip-width and $d/\Gamma$ is near field spot size, where $D$ is the width of quantum well and $\Gamma$ is the limiting factor. Increasing the near-field spot size can reduce the optical power density on front facet, increase the COD threshold of the cavity surface, and improve the operation current and life of the laser. Reducing the chip voltage can reduce the generation of waste heat. However, increasing the near-field spot size and reducing the voltage is the basic direction to improve the working characteristics of high power lasers [7-9].

First of all, in order to improve the reliability, it is one of the trends in the field of LD design and application. The material with large optical cavity is the material with large cavity surface near spot size. For the same output power, the density of the material with large optical cavity is relatively lower, the heat absorption will lead to the slow degradation rate of the surface material, thus improving the surface burning characteristic and improving the high power reliability. On the other hand, for the same work output power, the output power density on the surface of the material with large optical cavity is lower, the heat absorption will lead to the slow degradation rate of the surface and cavity in the material, thus improving the burning of the laser cavity surface and the reliability of the laser. The traditional large power laser adopts a large optical cavity structure, only the epitaxial structure is designed to increase the thickness of the waveguide. The size of the light spot in the direction of the epitaxial layer is increased, the light power density is reduced, and the high optical damage threshold of the cavity surface is obtained. However, the fast axis optical field is concentrated in the active region, and the optical power density in the active region is still high, so there is no essential change in the reliability of the laser. There are still defects such as high working voltage and low efficiency of electro-optical conversion.

3.2 Flat top optical field design

In the study, the flat top optical field structure was used to achieve uniform distribution of the top of the fast axis field and reduce the optical power density of the active region. The near-field spot size is increased, the optical power density of the cavity surface is reduced, and the burnout resistance of the cavity surface is improved.

First of all, in order to improve the reliability and working life, the use of the material with large optical cavity is one of the trends of semiconductor laser design and application. For the same output power, the cavity surface power density of the large cavity material is lower, the degradation rate of the cavity surface material will be slow, which can improve the laser cavity surface burning and the reliability of the laser power. The traditional high-power laser adopts the structure with large optical cavity. The design of the epitaxial structure, which increases the thickness of the waveguide, increases the size of the optical spot in the direction of the epitaxial layer, reduces the light power density, and obtains the high optical damage threshold of the cavity surface. However, the fast axis optical field is concentrated in the active region, and the optical power density in the active region is still very high, so there is no essential change in the reliability of the laser.

| Name                               | Component      | Thickness | Doping concentration |
|------------------------------------|----------------|-----------|----------------------|
| Electrode contact layer            | GaAs           | 0.15μm    | 1E20 /cm²            |
| Upper limit layer                  | Al0.5GaAs      | 1μm       | 1E18 /cm²            |
| Upper light field interaction layer| Al0.5GaAs      | 0.2μm     | 1E18 /cm²            |
| Upper waveguide layer              | Al0.3GaAs      | 0.5μm     | 5E17 /cm²            |
| Quantum well layer                 | InAlGaAs       | 6nm       | -                    |
| Lower waveguide layer              | Al0.3GaAs      | 0.5μm     | 1E17 /cm²            |
| Lower light field action layer     | Al0.5GaAs      | 0.2μm     | 1E18 /cm²            |
| Lower limit layer                  | Al0.5GaAs      | 1μm       | 1E18/cm²             |
| Buffer layer                       | GaAs           | 0.5μm     | 1E18/cm²             |
| Substrate                          | GaAs N⁺        | -         | -                    |
Table 2 Design of 808nm conventional optical field structure

| Name                        | Component       | Thickness | Doping concentration |
|-----------------------------|-----------------|-----------|----------------------|
| Electrode contact layer     | GaAs            | 0.15μm    | 1E20/cm²             |
| Upper limit layer           | Al0.5GaAs       | 1μm       | 1E18/cm²             |
| Upper light field interaction layer | Al0.3GaAs | 0.5μm    | 5E17/cm²             |
| Quantum well layer          | InAlGaAs        | 6nm       | -                    |
| Below waveguide layer       | Al0.5GaAs       | 0.5μm     | 1E17/cm²             |
| Lower limit layer           | Al0.5GaAs       | 1μm       | 1E18/cm²             |
| Buffer layer                | GaAs            | 0.5μm     | 1E18/cm²             |
| Substrate                   | GaAs N⁺         | -         | -                    |

In this study, the flat top optical field structure with LOC structure is used to achieve uniform distribution on the top of the fast axis field and reduce the optical power density in the active region. The data about the specific structure is given in Tables 1 and 2. The near-field spot size is increased, so that the optical power is no longer concentrated on a certain point or line, which reduces the optical power density of the cavity surface and enhances the burn resistance of the cavity surface. The flat top optical field structure is used to achieve uniform distribution on the top of the fast axis field and reduce the optical power density in the active region. The near-field spot size is increased, the output power density of the cavity surface is reduced, and the catastrophic optical damage threshold of the cavity surface is increased.

Figure 3. Comparison of conventional optical field (left) and flat top optical field (right)

From Fig.3, we can see that the normal field structure has a near-field spot size of 0.6um, and the optical field is of Gauss distribution. The structure of the material in the flat top optical field increases the near-field spot size to 1.3um, and the top of the optical field is distributed evenly, which improves the reliability of the laser.

Figure 4. Far field spot before and after the optimization of the structure
3.3 COD test results

With the flat top optical field and large optical cavity chip design structure, the chip COD is obviously improved, which can be controlled over 13.8W, greater than 138mW/μm. Based on above technology, the chip pulse with a luminous aperture of 100 μm is tested for 14A, and the power is greater than 14W. After the design of the optical field, the COD value of the chip is incrementally increased to 20%, increasing to 16.6A. There is no burning out on the cavity surface, and the power density of the cavity surface is more than 170mW/μm\(^1\).
In this way, the material design ensures the reliability while the electro-optical conversion efficiency is taken into account to meet product requirements.

4. Conclusion

This paper analyzes the phenomenon and formation mechanism of high-power semiconductor laser chip COD, and demonstrates the influence of optical field distribution design on COD in detail. Finally, through experiment, the optical field distribution in the chip is optimized, and the COD parameters of the chip are improved. The far field spot before and after the optimization of the structure is obviously improved, and COD is increased by about 15~20%, which provides the reference direction for the reliability improvement of the high-power laser chip. At the same time, the flat top optical field structure will increase the near-field spot size and lead to the increase of threshold current and opening voltage.

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