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Increased Catastrophic-Optical-Damage Output Power for High-Power Semiconductor Lasers Coated with High-Refractive-Index Films

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Mirror facet coating with a high-refractive-index film such as TiO_2 and Ta_2O_5 is proposed to obtain high-power short-wavelength semiconductor lasers. A drastic increase in the output power attainable before catastrophic optical damage occurs is theoretically predicted for such a laser without the need to decrease facet reflectivity. This increase is shown to originate from destructive interference of laser light fields in the vicinity of the coated mirror facet when the film's refractive index is larger than the square root (≈1.8–1.9) of the laser's effective refractive index.

KEYWORDS: catastrophic optical damage, high-power, semiconductor laser, TiO_2, Ta_2O_5, facet coating, destructive interference, refractive index, facet reflectivity

1. Introduction

Catastrophic optical damage (COD) at laser mirror facets has been an issue for high-power operation of short-wavelength semiconductor lasers, such as 0.6-μm AlGaInP lasers, 0.8-μm AlGaAs lasers, and 0.98-μm InGaAs/AlGaAs lasers. It is well known that the COD occurs due to optical-absorption-induced thermal runaway at the laser mirror facet,[1] when the optical density inside the semiconductor in the vicinity of the mirror facet reaches a threshold level (henceforth, the COD density) of 2–3 MW/cm^2 for AlGaInP lasers[2] or 6–9 MW/cm^2 for AlGaAs lasers.[3] One conventional method to achieve large output power from those lasers while keeping the optical density below the COD density has been to decrease the mirror-facet reflectivity by coating the facet with a thin film.[4] This was done because the output power density with respect to the power density inside the semiconductor has been believed to increase as the facet reflectivity decreases. The drawback of this method is that a decrease in the facet reflectivity increases the mirror loss and hence deteriorates laser performance, such as the threshold current and characteristic temperature. Thus, there has been a trade-off between the COD output power and other laser characteristics. In the above-mentioned conventional high-power-laser design, the COD output power has been believed to be determined by the facet reflectivity no matter what film is used for the facet coating since a formulae for COD output power was determined by Hakki and Nash in 1974.[3,5] Recently, the present author found that this is not necessarily the case. According to a new formulae in this work, the COD output power depends not only on the reflectivity but also on the coating-film refractive index. Based on this formulae, drastically higher COD output power is predicted for lasers coated with high-refractive-index films (such as TiO_2 and Ta_2O_5) than those with conventional low-refractive-index films (such as Al_2O_3[6] and SiO_2), without the need to decrease the reflectivity.

2. Theory and Results

The prediction in this work is based on the well-known Maxwell equations. What differs from the approach of Hakki and Nash was that the boundary conditions were taken into account more carefully, as shown below.

Figure 1 shows a schematic view of a semiconductor laser whose front mirror facet is coated with a thin film. The boundary conditions for the optical fields are expressed as a system of two linear equations in a matrix form,

$$\begin{pmatrix} E_3^R \\ E_3^L \end{pmatrix} = \tilde{n}_3^{-1}\tilde{n}_2\tilde{D}_2\tilde{n}_2^{-1}\tilde{n}_1 \begin{pmatrix} E_1^R \\ 0 \end{pmatrix} \equiv \begin{pmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{pmatrix} \begin{pmatrix} E_1^R \\ 0 \end{pmatrix}, \tag{1}$$

where,

$$\tilde{n}_i \equiv \begin{pmatrix} 1 & 1 \\ n_i & -n_i \end{pmatrix}, \quad i = 1, 2, 3, \tag{2}$$

and

$$\tilde{D}_2 \equiv \begin{pmatrix} \exp(2\pi i \cdot n_2 d_2/\lambda) & 0 \\ 0 & \exp(-2\pi i \cdot n_2 d_2/\lambda) \end{pmatrix}. \tag{3}$$

The n_1 and n_2 are the refractive indices of the air ($n_1 \approx 1$) and the coating film of thickness d_2, respectively. The n_3 is the effective refractive index (n_{eff}) of the semiconductor laser waveguide. By solving eq. (1), both the output-field amplitude E_1^R and the reflected-field amplitude E_3^L are determined as responses to the incident-field amplitude E_3^R. The output power density and the density inside the laser cavity are expressed as,

$$P_{\mathrm{out}}^{\mathrm{coated}} = |E_1^R|^2, \tag{4}$$

and

$$P_{\mathrm{in}} = n_{\mathrm{eff}} \times |\, E_3^R + E_3^L|^2, \tag{5}$$

respectively. Because COD is believed to occur when P_{in} reaches the COD density P_{COD}, the COD output power of this coated laser is defined as,

$$P_{\mathrm{COD}}^{\mathrm{coated}} = \frac{P_{\mathrm{out}}^{\mathrm{coated}}}{P_{\mathrm{in}}} \times P_{\mathrm{COD}} \times S = \frac{1}{n_{\mathrm{eff}}} \times \frac{1}{|s_{11}+s_{21}|^2} \times P_{\mathrm{COD}} \times S \tag{6}$$

where S is the near-field cross-section. On the other hand, the COD output power of an uncoated laser is expressed as,

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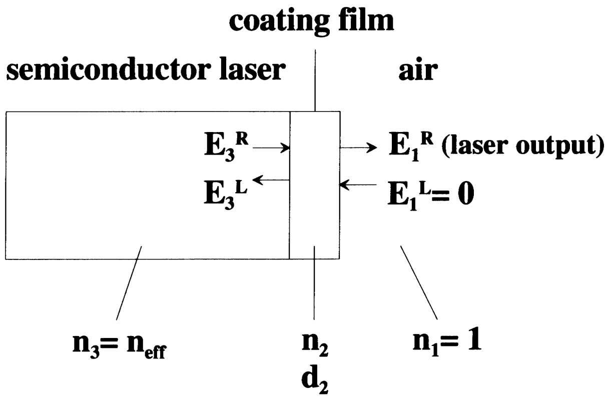

Fig. 1. Schematic view of a coated laser. A front mirror facet of a laser is coated with a one-layer thin film of thickness d_2 and whose refractive index is n_2. As a boundary condition, E_1^L must be zero.

$$P_{\rm COD}^{\rm uncoated} = \frac{1}{n_{\rm eff}} \times P_{\rm COD} \times S. \tag{7}$$

Consequently, the COD power for a coated laser is larger than that for an uncoated laser by a factor (henceforce, the COD power ratio, $P_{\rm c}$) of,

$$P_{\rm c} \equiv \frac{P_{\rm COD}^{\rm coated}}{P_{\rm COD}^{\rm uncoated}} = \frac{1}{|s_{11} + s_{21}|^2}, \tag{8}$$

while the facet reflectivity is determined as,

$$R \equiv \left|\frac{E_3^L}{E_3^R}\right|^2 = \left|\frac{s_{21}}{s_{11}}\right|^2. \tag{9}$$

Figure 2 shows sample results indicating the correlation between the COD power ratio $P_{\rm c}$ and the facet reflectivity R. These results were calculated from eqs. (8) and (9) after numerically solving eq. (1). The coating-film refractive index n_2 was assumed to be various values including values close to those of high-refractive-index films such as TiO_2 (n_2=2.2–2.5)[7] and Ta_2O_5 (2.2–2.6),[7] as well as those of conventional films such as Al_2O_3 (1.68) and SiO_2 (1.46). The $n_{\rm eff}$ was assumed to be 3.30 for a typical AlGaInP laser. When d_2 was increased from 0 to $\lambda/4n_2$ for each n_2 in Fig. 2, the relation $(R, P_{\rm c})$ moved from $(0.3, 1)$ along each solid curve and reached the upper boundary shown by the dashed curve. When d_2 was further increased from $\lambda/4n_2$ to $\lambda/2n_2$, the relation $(R, P_{\rm c})$ moved back to the original point $(0.3, 1)$ along the same solid curve.

Figure 2 clearly shows that it is possible to increase the COD output power without decreasing the facet reflectivity. One can increase it by using a film that has a higher refractive index, while tuning the film thickness to keep the reflectivity unchanged. For example, the COD output power increases by a factor of 3 when a 10%-reflectivity Al_2O_3 coating film is replaced with a 10%-reflectivity TiO_2 film.

3. Discussion

The physical mechanism of this newly discovered dependence of COD output power on the film refractive index in Fig. 2 was studied analytically as follows. Although it was impossible to algebraically solve eq. (1) for an arbitary film thickness d_2, it was solved for the special case where d_2 equals a quarter wavelength in each film ($\lambda/4n_2$) as,

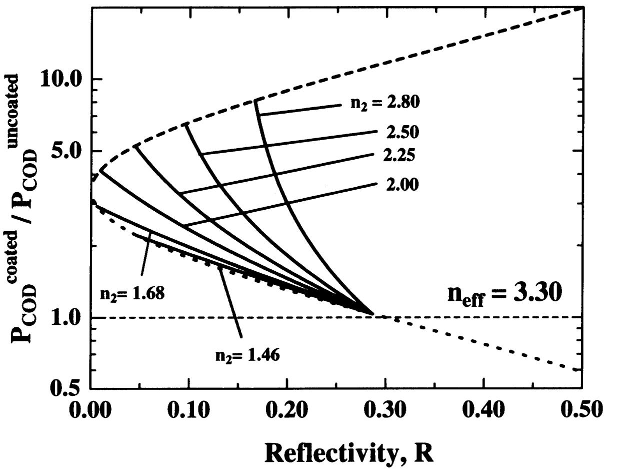

Fig. 2. Calculated COD power ratio. These results predict a significantly higher COD output power for a laser coated with a high-refractive-index film such as TiO_2 (n_2=2.2–2.5) and Ta_2O_5 (2.2–2.6), as compared with conventional high-power lasers coated with Al_2O_3 (1.68) and SiO_2 (1.46). The effective refractive index ($n_{\rm eff}$) of the laser waveguide was assumed to be 3.3 ($\sqrt{n_{\rm eff}}$=1.82).

$$E_3^L = -\frac{n_2^2 - n_{\rm eff}}{n_2^2 + n_{\rm eff}} E_3^R, \tag{10}$$

and

$$E_1^R = -2i \frac{n_2 \cdot n_{\rm eff}}{n_2^2 + n_{\rm eff}} E_3^R, \tag{11}$$

by using the symbolic mathematics language Maple V (Waterloo Maple, Inc.). Equations (10) and (11) lead to,

$$E_3^R + E_3^L = \frac{i}{n_2} E_1^R, \tag{12}$$

$$P_{\rm c} \equiv \frac{P_{\rm COD}^{\rm coated}}{P_{\rm COD}^{\rm uncoated}} = n_2^2, \tag{13}$$

and

$$R \equiv \left|\frac{E_3^L}{E_3^R}\right|^2 = \left|\frac{n_2^2 - n_{\rm eff}}{n_2^2 + n_{\rm eff}}\right|^2. \tag{14}$$

As a consequence, the COD output power ratio $P_{\rm c}$ in eq. (8) is connected to the reflectivity R in eq. (9) as,

$$P_{\rm c} \equiv \frac{P_{\rm COD}^{\rm coated}}{P_{\rm COD}^{\rm uncoated}} \begin{cases} = n_{\rm eff} \times \dfrac{1-R}{(1-\sqrt{R})^2} & (n_2 \geq \sqrt{n_{\rm eff}}) \\ = n_{\rm eff} \times \dfrac{1-R}{(1+\sqrt{R})^2} & (n_2 < \sqrt{n_{\rm eff}}). \end{cases} \tag{15}$$

When n_2 is larger than $\sqrt{n_{\rm eff}}$ (≈1.82), the sign of the denominator in eq. (15) is negative. It turned out that eq. (15) with a negative sign corresponds to the upper boundary (dashed curve) in Fig. 2. On the other hand, eq. (10) shows that E_3^R and E_3^L interfere destructively under this condition. Thus, we can conclude that the increase in the COD output power for a laser coated with a high-refractive-index film originates from the destructive interference between E_3^R and E_3^L.

As clearly seen in Fig. 2, there exists an optimum refractive index $n_2^{\rm opt}$ which gives a maximum COD output power for

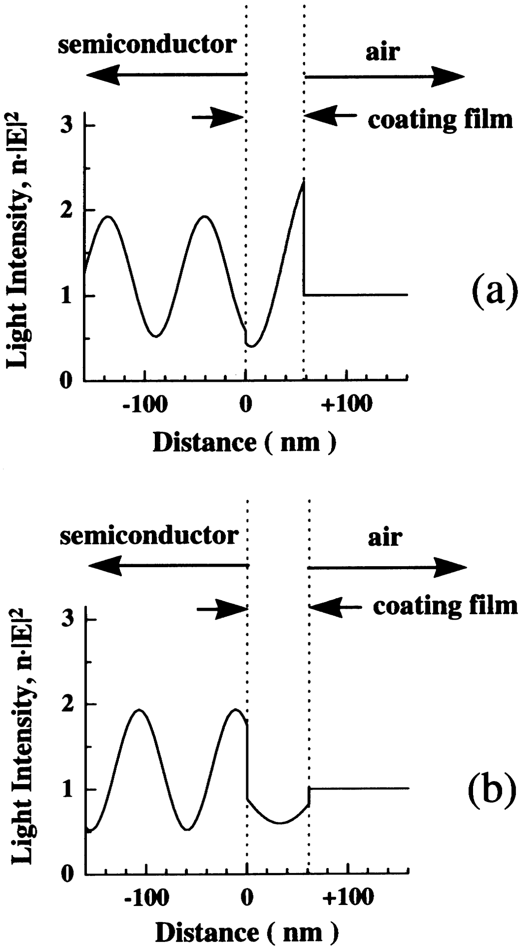

Fig. 3. Laser-light-intensity distribution. (a) n_2=2.50, d_2=0.227×λ/n_2, R=0.10, P_c=5.64. (b) n_2=1.68, d_2=0.163×λ/n_2, R=0.10, P_c=1.90.

each reflectivity R. The n_2^{opt} is obtained by solving eq. (14) [or more easily by combining eqs. (13) and (15)] as,

$$n_2^{\mathrm{opt}} = \sqrt{n_{\mathrm{eff}} \times \frac{1-R}{(1-\sqrt{R})^2}}. \qquad (16)$$

The value of n_2^{opt} is 2.52 when R is 0.1 and n_{eff} is 3.30, for example.

In contrast, the sign of the denominator in eq. (15) is positive when n_2 is smaller than $\sqrt{n_{\mathrm{eff}}}$. Under this condition, E_3^R and E_3^L interfere constructively as seen from eq. (10). Equation (15) with a positive sign exactly matches the conventional COD output power formulae proposed by Hakki-Nash.[3] In Fig. 2, this formulae corresponds to the lower boundary (dotted curve).

Hakki and Nash have shown[3] that their formulae reproduced the measured values of COD output power in the work of Ettenberg *et al.*,[4] which appears to conflict with the calculations reported here. From our perspective, however, the descripancy between Hakki-Nash's prediction [using eq. (15) with a plus sign in the denominator] and that of the present work [using eq. (15) with a minus sign] was too small to be detected in their work. Ettenberg *et al.* used silicon-oxide (SiO) films for the facet coating, whose refractive index was reported to be 1.9.[4] The effective refractive index n_{eff} was 3.59, according to Hakki and Nash.[3] The film refractive index (n_2) was, therefore, close to $\sqrt{n_{\mathrm{eff}}}$ (=1.89). In such a case, the descripancy between Hakki-Nash's prediction and that of the present work is small, as already shown in Fig. 2.

The condition $n_2 = \sqrt{n_{\mathrm{eff}}}$ is a critical one lying between the two above-mentioned alternative inequality conditions. This condition has already been well recognized as a requirement for an anti-reflection coating. In Fig. 2 this critical condition lies at ($R = 0, P_c = 3.30$), where the upper boundary (dashed curve) coincides the lower boundary (dotted curve).

In Fig. 3, the laser-light-intensity distribution in a laser coated with a high-refractive-index film (n_2=2.50, as of TiO_2 for example) was compared with that with a conventional film (n_2=1.68, as of Al_2O_3). The laser intensity is normalized by the laser-output intensity. The coating-film thickness d_2 for each sample was determined to obtain a reflectivity R of 0.10. The laser wavelength λ was assumed to be 633 nm. Figure 3 shows that destructive interference occurs at the high-index-coated semiconductor facet (a) as mentioned above, while constructive interference occurs in a conventional laser (b). The COD power ratio for the high-index-coated laser was 3.0 times larger than that for the low-index-coated laser, as shown already in Fig. 2 for R=0.10. Figure 3(a) also indicates that the first constructive interference inside the high-index-coated laser occurs at a depth of approximately $\lambda/4n_{\mathrm{eff}}$ (=48 nm) from the facet. This depth could be important for further study.

4. Conclusions

The use of high-refractive-index films was proposed to obtain high-power semiconductor lasers. A 3.0 times larger COD output power was predicted for a 10%-TiO_2-coated laser (n_2≈2.5) for example, as compared with that for a conventional 10%-Al_2O_3-coated laser (n_2=1.68). The increase in the COD output power was shown to originate from destructive interference between optical fields in the vicinity of the laser mirror facet.

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