Measurement of the Modal Reflectivity of an Antireflection Coating on a Superluminescent Diode

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***Abstract*—A method for measuring the modal reflectivity of the antireflection coating applied to a laser diode is described and demonstrated. It is based on measurements of the Fabry–Perot modulation depth of the resulting superluminescent diode (SLD) output spectrum at the threshold current of the original laser. A modal reflectivity of less than 2×10^{-4} has been obtained.**

Introduction

A SUPERLUMINESCENT diode (SLD) may be fabricated by applying an antireflection (AR) coating to the output facet of any semiconductor laser for the purpose of eliminating or suitably reducing the optical feedback [1]. The effective output efficiency may be improved substantially by introducing a high reflector at the back facet [2]. As an estimate, the product of the power reflectivities R_1 and R_2 for the output and back facets, respectively, must be less than 10^{-2} to realize significant superluminescent gain without laser oscillation.

It is our purpose here to describe and demonstrate a simple method for measuring R_1, which is the fractional power reflected back into the waveguide mode of the active layer by the AR coated facet. Note that because of the limited numerical aperture of the guide and the fact that the width of the wave function is comparable to an optical wavelength, the modal reflectivity for a given AR coating differs significantly from the plane-wave reflectivity of the same coating [3]. Similarly, the modal reflectivity of a cleaved laser facet differs from the Fresnel reflectivity of a corresponding planar interface [4]. The measurement method is demonstrated for a nominal quarter-wave AR coating on a 1.3 μm wavelength InGaAsP SLD fabricated from a ridge-waveguide laser [1].

Analysis

A conventional analysis of steady-state amplification begins as follows [5]. Consider a semiconductor laser with a planar active layer of length L bounded by mirrors of modal power reflectivities R_1 and R_2, as depicted in Fig. 1. A spontaneously generated optical field $E(0)$ at $z = 0$ traveling to the left experiences logarithmic power gain G_- in the transit to the mirror at $z = -L$ and, similarly, G_+ is the gain on traveling between mirrors in the opposite direction. For $R_1 = R_2 = R_l$, symmetry gives

$$G_+ = G_- = G_l. \quad (1)$$

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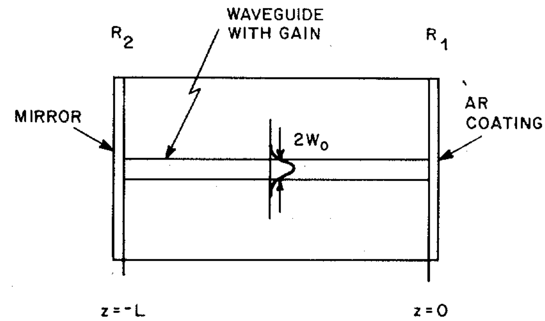

Fig. 1. Laser diode with back mirror R_2 and AR coating R_1 added to form an SLD. The waveguide mode in the planar active layer has a spot size w_0.

After N complete roundtrips, the field has the value

$$E'(0) = E(0) \sum_0^N a^n = E(0)(1 - a)^{-1} \quad (2)$$

where $N \to \infty$ and the roundtrip amplification factor is

$$a = R_l e^{2j\beta L} e^{G_l} \quad (3)$$

with $2\beta L$ the roundtrip phase shift. In order to conserve energy, $|a| \leqslant 1$, and at laser threshold $a \approx 1$.

Now consider a nonideal superluminescent diode fabricated by coating the laser facets so that the mirrors at $z = 0$ and $-L$ have modal reflectivities R_1 and R_2, respectively, which may differ from R_l. Then, in a practical SLD.

$$a = \sqrt{R_1 R_2}\, e^{2j\beta L}\, e^{1/2(G_+ + G_+)} \quad (4)$$

and $a \ll 1$. In the ideal SLD, $R_1 R_2 = 0$.

The power transmitted through the mirror at $z = 0$ due to the initial spontaneous emission at $z = 0$ is $(1 - R_1)|E(0)|^2 |1 - a|^{-2}$ and, integrating the initial incoherent spontaneous emission over the length of the SLD, the total output power spectrum is

$$P(\lambda) = P_z (1 - R_1) |1 - a|^{-2} \quad (5)$$

where P_z is the integrated initial spontaneous emission power. The SLD spectrum consists of the emission spectrum of the gain medium modulated by Fabry–Perot fringes, as illustrated in Fig. 2 for a ridge waveguide SLD. The maxima and minima occur when the roundtrip phase shift in (4) is an integer multiple of 2π and π, respectively.

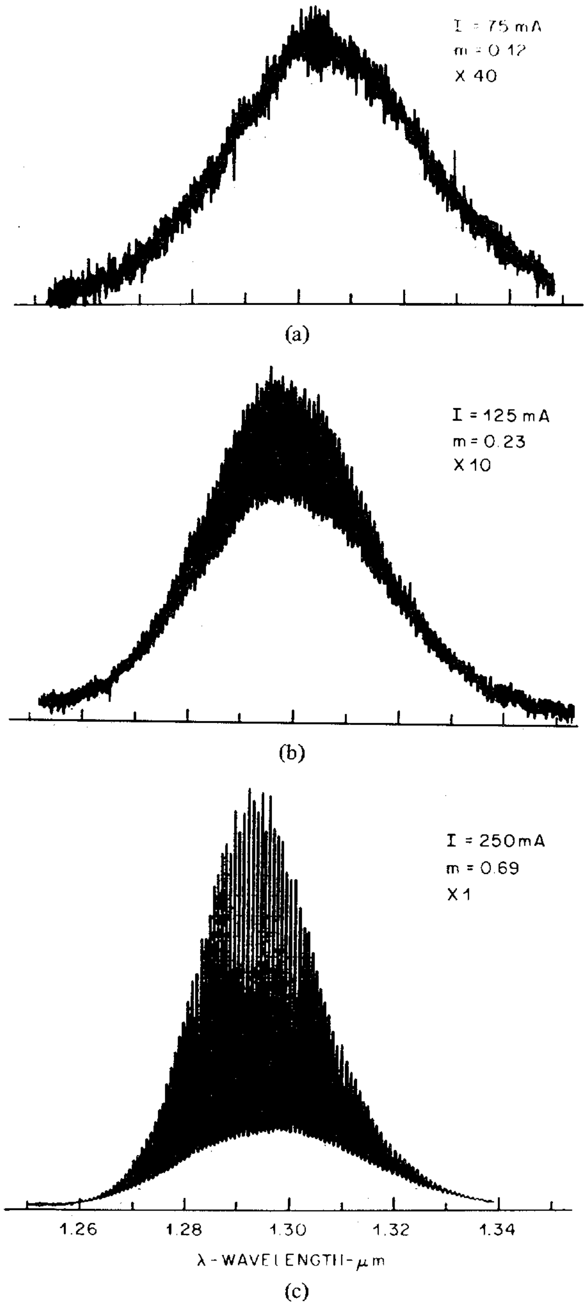

Fig. 2. Output spectra of SLD at 20°C at (a) $I = 75$ mA, $m = 0.12$, magnification $\times 40$, (b) $I = 125$ mA, $m = 0.23$, $\times 10$, (c) $I = 250$ mA, $m = 0.69$, $\times 1$. For the original laser, $I_t = 120$ mA.

If we define a modulation index

$$m = \frac{P_{\max} - P_{\min}}{P_{\max} + P_{\min}} \tag{6}$$

where $P_{\max}$ and $P_{\min}$ are taken at the peak of the SLD spectrum, then, with (5),

$$m = \frac{2|a|}{1 + |a|^2}. \tag{7}$$

For an ideal laser, $m = 1$ and for an ideal SLD, $m = 0$.

Suppose that I_t is the threshold current for the original laser and that gain saturation at $I \approx I_t$ is negligible for both the laser and SLD so that for the SLD at I_t,

$$G_+ = G_- = G_l. \tag{8}$$

Then, assuming $a = 1$ for the original laser, (3), (4), (7), and (8) yield

$$R_1 R_2 = (|a| R_l)^2 \tag{9}$$

where $|a|$ is obtained from (7) for the SLD at drive current $I = I_t$. Thus, we can estimate the reflectivity R_1 of the output mirror of an SLD from (7) and (9) by measuring m at $I = I_t$ in two special cases: (a) when $R_2 \approx 1$ and (b) when $R_2 = R_1$. Since $R_l \approx 0.3$ for an InGaAsP laser and $R_1 < 10^{-2}$ for a practical SLD, m will be less than 0.6 for case (a) and less than 0.07 for case (b). Because of the difficulty in measuring small m in the presence of noise, (a) is preferable when R_1 is small.

The analysis can be carried a bit further by taking the net gain to be a linear function of current and length [6].

$$\frac{G_+ + G_-}{2} = \left(\gamma \frac{I}{I_t} - \alpha\right) L \tag{10}$$

where γ is the power gain coefficient at $I = I_t$ and α the power loss coefficient. For the laser at threshold, $G_l = (\gamma - \alpha)L$. Then, with (3), (4), and (10), we have for the SLD,

$$\ln |a| = (\gamma L) \frac{I}{I_t} - \left(\gamma L - \ln \frac{\sqrt{R_1 R_2}}{R_l}\right). \tag{11}$$

Thus, when I_t and R_l are known for the original laser, the slope of $\ln a$ versus I/I_t gives the gain coefficient γ and, with (3), the loss coefficients α; and the intercept at $I/I_t = 0$ gives $R_1 R_2$. The function in (11) is expected to be linear only for low I/I_t; at higher currents, the gain tends to saturate so that γ decreases as the stimulated emission increases and the device approaches oscillation. Laser oscillation corresponds to $\ln a \approx 0$. Hakki and Paoli [6] have used measurements of the Fabry–Perot modulation depth of the output spectrum of a GaAs laser below threshold to determine the variation of net gain with λ. They clearly observe gain saturation at $I \approx I_t$.

Experiment

An SLD was fabricated [1] from a 15 μm wide, 250 μm long ridge waveguide laser having a threshold $I_t = 120$ mA at 20°C. A gold mirror was evaporated over a thin Si_3N_4 layer on the back facet to produce $R_2 > 0.9$ [7]. A Si_3N_4 layer having $n \approx 1.85$ at 1.3 μm and a thickness of about $\lambda/4n$ was sputtered on the output facet to produce R_1. The interference color was orange-red. The sputtering target was pressed Si_3N_4 and the discharge was in an Ar/N_2 atmosphere. The effective waveguide index is somewhat less than 3.52, the index of the InGaAsP active layer, so that n^2 closely approximates the guide index as required for a quarter-wave AR coating.

The dominant output polarization (~75 percent) of the SLD was TE. The CW SLD output spectrum at 20°C and $I \approx I_t$ is shown in Fig. 2(b). A polarizer was used to select the TE output. The estimated modulation depth at $I = I_t$ is $m = 0.22$ ($|a| = 0.11$) and, with Fresnel reflectivities $R_l = 0.31$ and

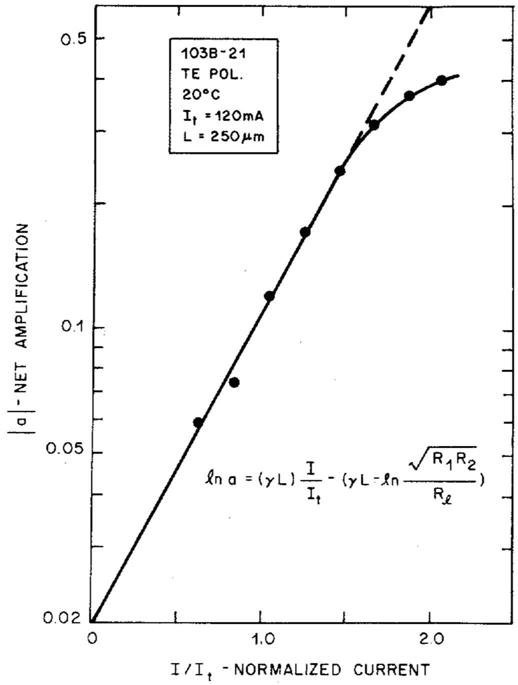

Fig. 3. Roundtrip amplification $|a|$ versus I/I_t for $T = 20°C$. R_2 is a high reflector.

$R_2 \approx 1$, (9) gives a reflectivity $R_1 \approx R_1 R_2 = 1.2 \times 10^{-3}$. According to theory [4], the modal reflectivity of a cleaved facet for a waveguide TE mode may be as high as $R_l = 0.4$. Then we calculate $R_1 \approx R_1 R_2 = 1.9 \times 10^{-3}$.

Output spectra were measured at various currents as indicated in Fig. 2 in order to obtain m and a as functions of I/I_t. The ln $|a|$ versus I/I_t curve is shown in Fig. 3. The curve is linear for $I/I_t \lesssim 1.5$, substantiating the approximation in (8) of unsaturated gain for $I \lesssim I_t$. From the slope we calculate $\gamma = 68$ cm^{-1} and $\alpha = 21$ cm^{-1} and from the intercept $R_1 \approx R_1 R_2 = 1.1 \times 10^{-3}$, when we take $R_l = 0.31$. If we take $R_l = 0.4$, then we calculate $\gamma = 68$ cm^{-1}, $\alpha = 31$ cm^{-1} and $R_1 \approx R_1 R_2 = 1.9 \times 10^{-3}$.

Discussion

It can be seen from Fig. 3 that the condition for laser oscillation $a \approx 1$ would be satisfied at $I/I_t = 2.2$ for the case of unsaturated linear gain. However, gain saturation due to superluminescence assures that the SLD will not oscillate even for $I/I_t \gg 2$ when the back mirror and AR coating give $R_1 R_2 < 2 \times 10^{-3}$. Recently, we made an SLD with an Au mirror and Ar coating that gave $R_1 R_2 < 2 \times 10^{-4}$ ($m = 0.04$). This device should operate without oscillation at still larger values of I/I_t and for lower temperatures. Further oscillation suppression, at the expense of output coupling efficiency, can be realized by AR coating both facets.

The reflectivity R from a planar film of thickness τ and index n between an input medium of index n_1 and an output medium of index n_2 is given in standard texts [8]. Near the condition for an ideal planar quarter-wave AR coating, i.e.,

$$n^2 = n_1 n_2 (1 + \nu), \qquad |\nu| \ll 1 \tag{12}$$

$$k\tau \cos\theta = \frac{\pi}{2}(1 + \mu), \qquad |\mu| \ll 1 \tag{13}$$

where $k = 2\pi n/\lambda$ and θ is the angle between the normal to the interface and the propagation direction in the film, R reduces to

$$R \approx \nu^2 + \frac{n_1 - n_2}{n_1 n_2}\left(\frac{\pi\mu}{4}\right)^2 \tag{14}$$

in the lowest order in μ and ν. This expression is probably a reasonable approximation to the modal reflectivity for an AR coating on a waveguide for R sufficiently far removed from the AR minimum, e.g., $R > 10^{-4}$. More rigorous calculations [3] for the waveguide case indicate that R has a nonzero minimum due to the spread of angles of the plane waves that represent the waveguide mode. The minimum occurs for $\mu \neq 0$, $\nu \neq 0$.

For $\mu = 0$ and $R_1 = 1 \times 10^{-3}$, (14) gives $\nu = 0.03$. With $n_1 = 3.52$, $n_2 = 1$, and $\sqrt{n_1 n_2} = 1.87$, an error of 0.06 in n could account for $R_1 = 1 \times 10^{-3}$. For $\nu = 0$, $R_1 = 1 \times 10^{-3}$ corresponds to $\mu = 0.05$. At normal incidence ($\theta = 0$) and $\lambda/4n = 1740$ Å, an error in τ of 83 Å could account for R_1. Further, if $\tau = \lambda/4n$ but we allow a range of angles $\Delta\theta$ to represent a waveguide mode with spot size $w_0 = \lambda/\pi n(\Delta\theta) \approx 0.5$ µm, then we obtain a range of μ, $\Delta\mu = 0.02$, and an estimated minimum $R \approx 2 \times 10^{-4}$. For smaller spot sizes, the minimum R is correspondingly larger.

Conclusion

Clearly, considerable control of thickness and index are required to obtain AR coatings with $R \approx 10^{-3}$ or less. The refractive index of stoichiometric Si_3N_4, $n = 1.85$, turns out to be a suitable match for 1.3 µm InGaAsP. Sputtering from a Si_3N_4 target in an Ar/N_2 atmosphere provides a sufficiently low deposition rate (~80 µm/min) to permit the needed thickness control, and also allows for some adjustment of stoichiometry and refractive index by varying the N_2 pressure. Our latest results give an AR coating with $R_1 = 2 \times 10^{-4}$.

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