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Theoretical Design of Single-Layer Antireflection Coatings on Laser Facets

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Single-layer antireflection coating films are used to transform semiconductor injection lasers into different kinds of active devices such as superluminescent diodes or optical amplifiers. In this paper, optimum film parameters (thickness h and index of refraction n) are established for a wide range of InGaAsP lasers emitting at 1.3 μm. Optimum film parameters are different for the TE and TM polarizations. The minimum theoretical power reflectivity is higher for the TM polarization than the minumum reflectivity for the TE polarization by a factor of about three. Both are very low, on the order of 10^{-6}. Tolerances in film parameters for a power reflectivity $R \leqslant 10^{-3}$ (which is acceptable for most practical applications) are calculated for a typical laser having a spot size $a = 0.5$ μm. The tolerances are $\Delta h \cong \pm 50$Å and $\Delta n/n \cong \pm 3$ percent for the TE polarization and $\Delta h \cong \pm 43$Å and $\Delta n/n \cong \pm 2.4$ percent for the TM polarization. Processing of high-quality antireflection coating films on InGaAsP devices is possible according to these tolerances by using sputtered Si_3N_4, which allows a very slow deposition rate (on the order of 75Å/min) and the tailoring of the film index by adjusting the nitrogen pressure in the plasma.

I. INTRODUCTION

Single-layer antireflection (AR) coating films can be very useful in transforming semiconductor injection lasers into different kinds of active devices. For example, a laser whose emitting facet reflectivities (one or both) are reduced to zero is transformed into a superlumines-

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cent diode[1] or an amplifier-modulator,[2] respectively. Such matching layers are analyzed in this paper. The purpose of the analysis is to

1. Establish the optimum parameters (thickness and index of refraction) of a matching layer for a given laser
2. Estimate the minimum theoretical reflection from a matching layer
3. Calculate the allowed tolerances of the film parameters for an acceptable reflectivity
4. Compare the reflectivities of TE and TM polarized light for possible explanation of the observed preferential polarization in practical devices.[1]

II. THEORY

The device shown in Fig. 1 is assumed to have the properties described in the following paragraphs.

The laser diode's index of refraction is $n_1 = 3.52$, which is that of the InGaAsP active region in which the field is largely confined. We ignore the step in the index due to the cladding material to simplify the calculations. Kaplan and Deimel have shown that in most cases this simplification has a very small effect on the resulting reflectivity.[3] In some cases, however, this index step cannot be ignored and one should use a weighted average of the indices or resort to the rigorous calculation presented in Ref. 3.

The emitted beam is assumed to be Gaussian in both transverse directions. A Gaussian functional form is a good approximation to the emitted beam of practical devices[1] and enables us to characterize the laser in terms of a measurable parameter, the spot size. The spot size measured is that of the emitted beam and is slightly different from the spot size of the field inside the device. This is because of the

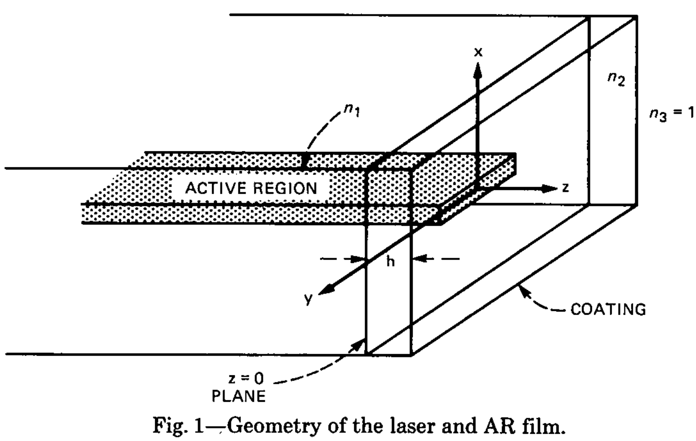


Fig. 1—Geometry of the laser and AR film.

angular-dependent reflection coefficient of the AR film. The difference between the two is negligible however.

The spot size in the direction perpendicular to the junction (X direction) is assumed to be much smaller than the corresponding spot size in the Y direction. Therefore, it is reasonable to analyze a two-dimensional model in the XZ plane (see Fig. 2). This model is valid for most lasers with the possible exception of buried structure lasers, which emit a nearly circular beam. The electric field is assumed to be linearly polarized along the Y, or along the X directions (TE or TM polarization, respectively.) The problem at hand is approached in a manner similar to the problem of calculating the modal reflectivity of a laser.[4,5] There, a narrow guided beam is impinged on a semiconductor-air interface, while here, the same guided beam impinges on an AR matching layer.

The technique used is that of the angular plane wave spectrum representation.[6] The calculation is an extension of two previous papers by R. H. Clarke,[7,8] and details are given in the appendix.

III. RESULTS

The power reflectivity R of an optimum AR layer was calculated for a wide range of laser spot sizes. Detailed results for a 0.5-μm spot size, typical of practical devices, are shown in Figs. 3, 4, and 5. (The spot size is defined as the electric field radius at its 1/e point.)

The reflected power in the case of TE polarization is shown either in Fig. 3a as a function of film thickness assuming optimum film index $n_2 = 1.8346$, or in Fig. 3b as a function of film index assuming optimum normalized thickness $hn_2/\lambda = 0.2606$. Similar results are shown in Figs. 4a and b for the TM polarization. The optimum index and thickness are $n_2 = 1.9361$ and $hn_2/\lambda = 0.2511$, respectively. In these expressions λ is the free-space wavelength = 1.3 μm.

The minimum reflectivity under the theoretically optimum conditions is very low ($R < 10^{-6}$). This extremely low reflectivity is of little importance, however, since achieving it in practice would require tolerances too stringent for the film parameters. Assuming, for ex-

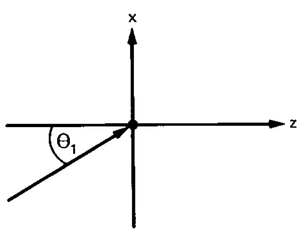
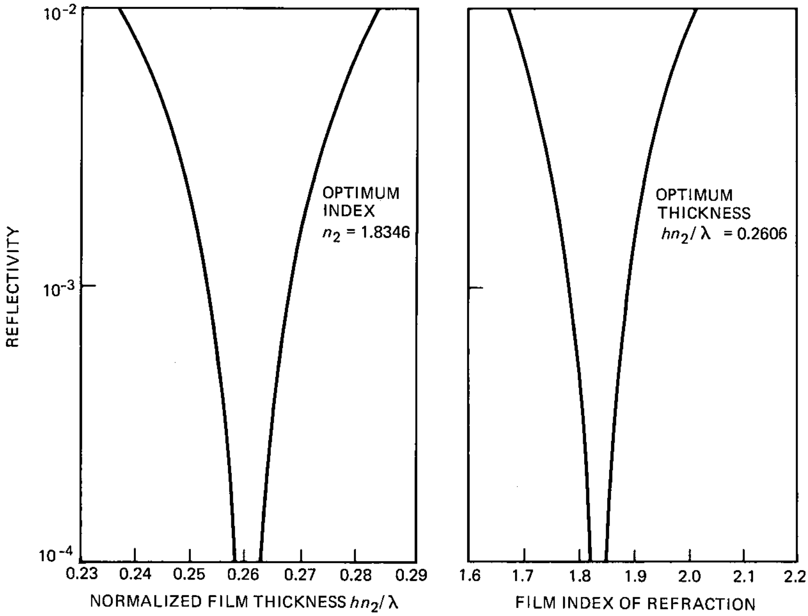
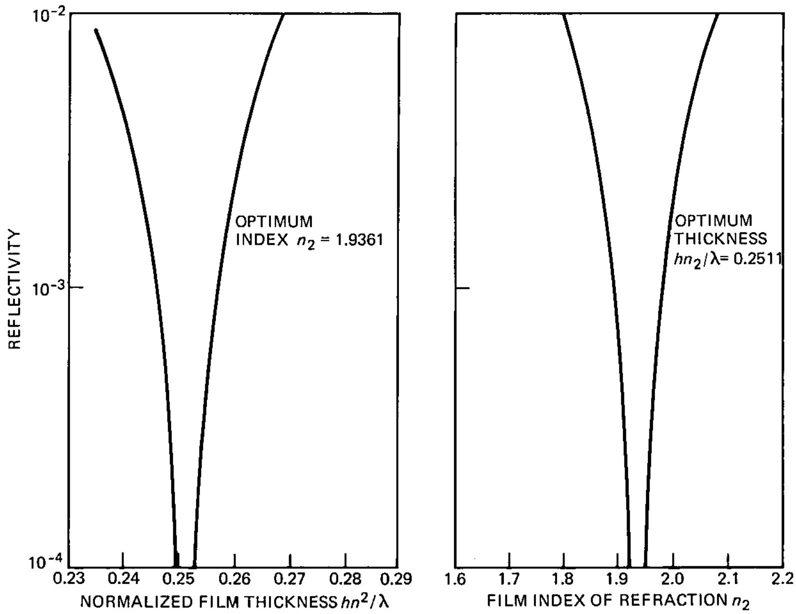


Fig. 2—Definition of the coordinate system and the angle of incidence.



(a) (b)

Fig. 3—Reflectivity: (a) as a function of film thickness (with optimum index), and (b) as a function of index (with optimum thickness) in the TE case for spot size $a = 0.5$ μm and $\lambda = 1.3$ μm.



(a) (b)

Fig. 4—Reflectivity as a function of: (a) thickness (with optimum index), and (b) as a function of index (with optimum thickness) in the TM case for spot size $a = 0.5$ μm and $\lambda = 1.3$ μm.

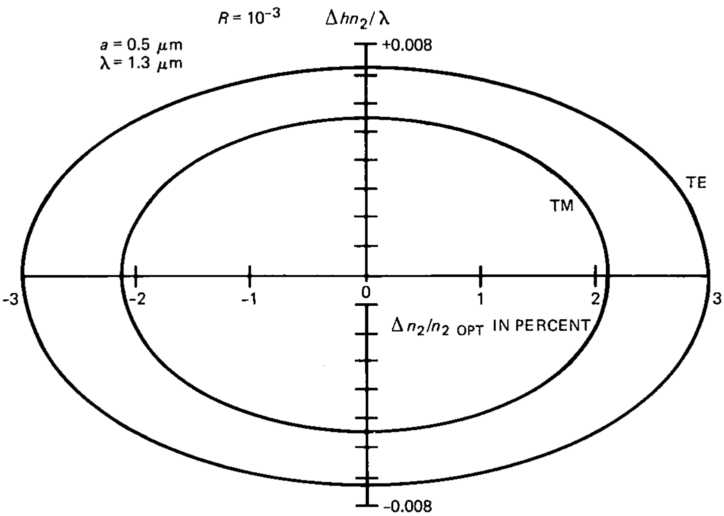


Fig. 5—Tolerances in thickness and index of refraction for $R = 10^{-3}$ for TE and TM polarizations.

ample, that a reflectivity $R \leqslant 10^{-3}$ is acceptable, we deduce from Fig. 5 the tolerances in the film parameters to achieve this reflectivity. They are assuming $n_2 = 1.8346$ and $hn_2/\lambda = 0.2606$, $\Delta hn_2/\lambda \cong \pm 0.00744$ ($\Delta h \cong \pm 50\text{Å}$) *and* $\Delta n_2/n_2 \cong \pm 3$ percent for the TE polarization, and assuming $n_2 = 1.9361$ and $hn_2/\lambda = 0.2511$, $\Delta hn_2/\lambda = 0.2511$, $\Delta hn_2/\lambda \cong \pm 0.0064$ ($\Delta h \cong \pm 43\text{Å}$) and $\Delta n_2/n_2 \cong \pm 2.4$ percent for the TM polarization. The tolerances in film thickness and index can be traded for each other according to the contours described in Fig. 5.

Similar calculations were performed for a wide range of laser spot sizes. Optimum film parameters as a function of laser spot size are shown in Figs. 6a and b for the TE and TM polarizations, respectively. In both cases spot sizes $a > 3.5$ μm (*for* $\lambda = 1.3$ μm) approach the condition of a plane wave, i.e., $hn_2/\lambda = 0.25$ and $n_2 = \sqrt{n_1}$. Small spot sizes, however, deviate significantly from these asymptotic conditions. Figure 6 should be used as a design curve for optimum AR films for a given laser.

IV. DISCUSSION

The reflectivity of AR matching layers on the emitting facet of an injection laser was calculated for a wide range of laser spot sizes. The calculation assumes that the optical field is Gaussian and that the spot size in the direction perpendicular to the junction is much smaller than the corresponding spot size in the direction parallel to the junction. This allows for a two-dimensional model that is valid for

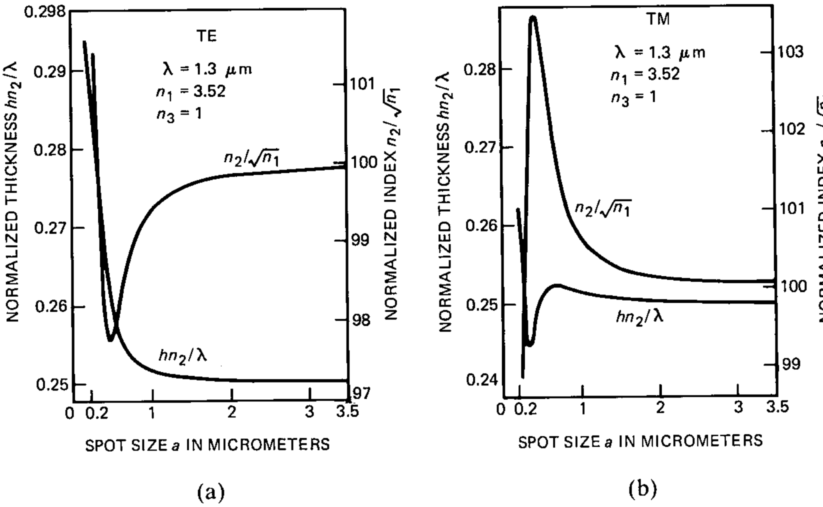


Fig. 6—Optimum film parameters as a function of spot size for: (a) TE polarization and (b) TM polarization.

most lasers. For lasers with an essentially circular spot the results presented here can be used only qualitatively.

Optimum film index and thickness were calculated, as well as the allowed tolerances, to ensure a reflectivity $R = 10^{-3}$, which is an acceptable reflectivity for most practical applications. Optimum film parameters for TE and TM polarizations were found to differ slightly. The minimum reflectivity for TM polarization is slightly higher than for TE polarization. Moreover, the tolerances for the TE case are higher. Therefore, we can assume that in practical devices, the reflectivity for the TM component of the optical field is higher than for the TE component. However, a practical superluminescent diode has most of its power polarized TE (more than 75 percent).[1] We have to conclude, therefore, that this observed preferential polarization is not due to the reflectivity but rather due to differences in internal gain and losses.

The reflectivity of practical AR films on superluminescent diodes was found to be on the order of 10^{-4} to 10^{-3} (see Refs. 9 and 10). This reflectivity is quite realistic according to the tolerances calculated.

Finally, the tolerances calculated tell us that the use of sputtered Si_3N_4 on InGaAsP devices can result in high-quality AR coatings. Indeed, the slow deposition rate (on the order of 75Å/min) and the possibility of tailoring the film index by adjusting the nitrogen pressure in the plasma allow the processing of films with the required tolerances.

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APPENDIX

Calculation of Modal Reflectivity

We assume a Gaussian beam (with spot size a) to the left of the laser facet ($Z = 0$)

$$E(X, 0) = \exp(-X^2/a^2). \tag{1}$$

A time-variation $\exp(i\omega t)$ is assumed throughout. This field can be represented as an angular spectrum of plane waves incident at different angles Θ (see Fig. 2):

$$F_i(s) = \frac{n_2}{\lambda} \int_{-\infty}^{\infty} E(x, 0) \exp\left(i \frac{2\pi n_1}{\lambda} sx\right) dx, \tag{2}$$

where $s = \sin\Theta$ and λ = free space wavelength = 1.3 μm. Equation 2 becomes

$$F_i(s) = \frac{\sqrt{\pi} a n_1}{\lambda} \exp\left(-\frac{s^2}{\left(\frac{\lambda}{\pi a n_1}\right)^2}\right). \tag{3}$$

The amplitude reflection coefficient $r(s)$ for each plane wave incident on the AR film (thickness h, index of refraction n_2), followed by a semi-infinite region ($n_3 = 1$) is[11]

$$r(s) = \frac{r_{12} + r_{23}\exp(-2i\beta)}{1 + r_{12}r_{23}\exp(-2i\beta)}, \tag{4}$$

where

$$\beta = \frac{2\pi h n_2}{\lambda} \sqrt{1 - \left(\frac{n_1 s}{n_2}\right)^2} \tag{5}$$

and $r_{12}(s)$, $r_{23}(s)$ are the well-known Fresnel reflection coefficients at the first and second boundaries, respectively. (Note that the Fresnel coefficients for the TE or TM polarizations are different from one another.)

The reflected wave $F_r(s)$ is easily found to be

$$F_r(s) = r(s)F_i(s). \tag{6}$$

The power reflection coefficient of the film R is found by calculating the portion of the reflected wave that is coupled back into the laser mode and the proper normalization, i.e.,

$$R = \frac{\left| \int_{-\infty}^{\infty} r(s)Q(s) \exp\left(-\frac{2s^2}{\left(\frac{\lambda}{n_1 \pi a}\right)^2}\right) ds \right|^2}{\left| \int_{-\infty}^{\infty} \exp\left(-\frac{2s^2}{\left(\frac{\lambda}{n_1 \pi a}\right)^2}\right) ds \right|^2}, \tag{7}$$

where $Q = \cos\Theta$ in the TE case and $Q = (\cos\Theta - \sin^2\Theta)/\cos\Theta$ in the TM case.[8] The integration range is from $s = -\infty$ to $s = \infty$. The corresponding angle is real for $|s| < 1$ and becomes complex for $|s| > 1$; its value is $\Theta = \pm\pi/2 \pm i\psi$. ψ varies from 0 to ∞ as $|s|$ varies from 1 to ∞. The integrals in eq. (7) are solved numerically and the results are plotted in Figs. 3, 4, 5, and 6.

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