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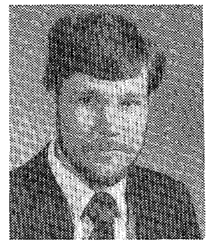

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Transmission Characteristics of Dielectric-Coated Metallic Waveguide for Infrared Transmission: Slab Waveguide Model

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Abstract—**A metallic hollow waveguide with inner dielectric multilayers is proposed for the transmission of infrared light and its basic transmission characteristics are fully analyzed by using a two-dimensional slab waveguide model. The power loss in the waveguide is shown to be extremely reduced by coating dielectric layers properly. Simple loss formulas are also presented which consider absorptions of dielectric materials, and minimum possible losses are theoretically estimated. Finally, relations to bending losses in the waveguide are discussed.**

I. Introduction

DEVELOPMENT of low-loss flexible waveguides is of great concern for high-powered CO_2 lasers in various applications such as welding, cutting, heat-treating, and laser surgery [1]. There are two types of waveguides which have been proposed or fabricated so far to transmit infrared light. One is a solid-core waveguide, i.e., so-called fiber. Since the first paper appeared which shows that polycrystalline KRS-5 fibers can be fabricated by the extrusion technique with transmission losses of around 0.5 dB/m at 10.6 μm [2], there has been increasing interest in infrared transmissive fibers [3]-[13]. Another is a hollow-core waveguide such as leaky waveguides [14], [15] or metallic (or lossy dielectric) hollow waveguides [16]-[26] whose basic properties were analyzed by Marcatili and Schmeltzer [27]. From the viewpoint of the transmission of a high-powered CO_2 laser, metallic or lossy dielectric waveguides seem to be the most likely candidates among waveguides thus far proposed.

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In this paper, we propose a metallic hollow waveguide with inner dielectric multilayers to obtain sufficiently low transmission losses. As far as a metallic waveguide with a single inner dielectric layer is concerned, transmission characteristics have been analyzed for the millimeter or submillimeter wavelengths in the late 1950's and more recently [28]-[32] for the transmission of TE_{0m} modes. Basic analyses must be done for the infrared because metals are properly characterized by a complex refractive index in the infrared rather than by a large conductivity. Furthermore, we are interested in the transmission of HE_{1m} modes not TE_{0m} modes in a circular waveguide and their basic transmission properties are able to be understood by analyzing those of modes in two-dimensional slab waveguides. On the other hand, Yeh *et al.* [33], [34] have done extensive analyses on a hollow-core waveguide with periodic dielectric layers which is called Bragg fiber. However, to realize low-loss waveguides with a finite number of dielectric layers, metallic waveguides seem to be preferable because large reflection is expected at the surface of a metal.

In Section II, we present a general theory for attenuation constants of the TE and TM modes in a two-dimensional slab waveguide by use of the idea of a surface impedance or admittance.

In Section III, transmission losses in a waveguide with a single inner dielectric layer are discussed for various kinds of metals. It is shown that the attenuation constant of the TM mode can be reduced significantly for suitable choice of the width of the dielectric layer. In order to reduce the attenuation constant of the TE or TM mode drastically, we propose a waveguide with inner dielectric multilayers in Section IV.

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The effect of the absorption losses of dielectric materials are fully discussed and simple loss formulas are also presented.

II. General Expression for Attenuation Constant in 2-D Hollow Waveguide

Consider a two-dimensional symmetric slab waveguide uniform along the y and z axes with a hollow-core width $2T$. The electric field E_y of the TE_p mode propagating along the z axis is expressed by

$$E_y = \cos\left(\frac{u}{T}x - \frac{p\pi}{2}\right)e^{-j\beta z} \tag{1}$$

in $|x| < T$. β and u/T are the axial and transverse phase constants related via

$$\beta^2 + \left(\frac{u}{T}\right)^2 = (n_0 k_0)^2 \tag{2}$$

where n_0 ($\simeq 1$) is a refractive index in $|x| < T$.

Introducing the normalized surface impedance z_{TE} defined by

$$\left.\frac{E_y}{H_z}\right)_{x=T} = \frac{\omega\mu_0}{n_0 k_0} z_{\mathrm{TE}} \tag{3}$$

one obtains the characteristic equation to determine u as

$$u \tan\left(u - \frac{p\pi}{2}\right) = j\,\frac{n_0 k_0 T}{z_{\mathrm{TE}}}. \tag{4}$$

By dividing u into real and imaginary parts as

$$u = u_0 + ju_i \tag{5}$$

and assuming that u_i is much smaller than u_0, one obtains from (4)

$$u_0 \tan\left(u_0 - \frac{p\pi}{2}\right) = -\mathrm{Im}\left(\frac{n_0 k_0 T}{z_{\mathrm{TE}}}\right) + \mathrm{Re}\left(\frac{n_0 k_0 T}{z_{\mathrm{TE}}}\right) \cdot u_i \tan\left(u_0 - \frac{p\pi}{2}\right), \tag{6}$$

$$u_i\left[u_0 + \tan\left(u_0 - \frac{p\pi}{2}\right)\right] = \mathrm{Re}\left(\frac{n_0 k_0 T}{z_{\mathrm{TE}}}\right) + \mathrm{Im}\left(\frac{n_0 k_0 T}{z_{\mathrm{TE}}}\right) \cdot u_i \tan\left(u_0 - \frac{p\pi}{2}\right) \tag{7}$$

where higher order terms than u_i^2 are neglected.

By eliminating $\tan(u_0 - p\pi/2)$ in (6) and (7) and neglecting small terms of u_i^2, one obtains

$$u_i = \frac{z_0 \,\mathrm{Re}\,(z_{\mathrm{TE}})}{|z_{\mathrm{TE}}|^2 + [1 + \mathrm{Im}\,(z_{\mathrm{TE}})/n_0 k_0 T]\, z_0^2} \tag{8}$$

where

$$z_0 = \frac{n_0 k_0 T}{u_0} \tag{9}$$

and the unknown quantity u_0 is determined by the following transcendental equation:

$$\left[\left|\frac{z_{\mathrm{TE}}}{n_0 k_0 T}\right|^2 + \mathrm{Im}\left(\frac{z_{\mathrm{TE}}}{n_0 k_0 T}\right)\right]\tan^2\left(u_0 - \frac{p\pi}{2}\right) + u_0\left[\left|\frac{z_{\mathrm{TE}}}{n_0 k_0 T}\right|^2 - \frac{1}{u_0^2}\mathrm{Im}\left(\frac{z_{\mathrm{TE}}}{n_0 k_0 T}\right) - \frac{1}{u_0^2}\right] \cdot \tan\left(u_0 - \frac{p\pi}{2}\right) - \mathrm{Im}\left(\frac{z_{\mathrm{TE}}}{n_0 k_0 T}\right) = 0 \tag{10}$$

which is obtained from (6) and (7) by elimination of u_i.

Therefore, the attenuation constant α^{TE} of the mode, which is obtained from (2) as

$$\alpha^{\mathrm{TE}} = \frac{u_0 u_i}{n_0 k_0 T^2} \tag{11}$$

is expressed by

$$\alpha^{\mathrm{TE}} = \frac{1}{T}\,\frac{\mathrm{Re}\,(z_{\mathrm{TE}})}{|z_{\mathrm{TE}}|^2 + [1 + \mathrm{Im}\,(z_{\mathrm{TE}})/n_0 k_0 T]\, z_0^2} \tag{12}$$

where it is assumed that $n_0 k_0 T \gg 1$ and, therefore, $\mathrm{Re}\,(\beta) \simeq n_0 k_0$ in (11).

For the TM modes, introducing the normalized surface admittance y_{TM} defined by

$$\left.\frac{H_y}{E_z}\right)_{x=T} = -\frac{n_0 k_0}{\omega\mu_0} y_{\mathrm{TM}} \tag{13}$$

one can similarly express the attenuation constant α^{TM} as follows:

$$\alpha^{\mathrm{TM}} = \frac{1}{T}\,\frac{\mathrm{Re}\,(y_{\mathrm{TM}})}{|y_{\mathrm{TM}}|^2 + [1 + \mathrm{Im}\,(y_{\mathrm{TM}})/n_0 k_0 T]\, y_0^2} \tag{14}$$

$$y_0 = \frac{n_0 k_0 T}{u_0} \tag{15}$$

where u_0 is determined by (10) where z_{TE} is replaced by y_{TM}. One should note that (12) and (14) take an alternative form for low-loss waveguides of

$$\left.\begin{matrix}\alpha^{\mathrm{TE}}\\ \alpha^{\mathrm{TM}}\end{matrix}\right\} = \frac{u_0}{4 n_0 k_0 T^2}\,\frac{1 - R}{1 + \sin(2u_0 - p\pi)/2u_0} \tag{16}$$

where R is defined by

$$R = \begin{cases} \left|\dfrac{z_{\mathrm{TE}} - z_0}{z_{\mathrm{TE}} + z_0}\right|^2; & \text{TE modes} \\[2ex] \left|\dfrac{y_{\mathrm{TM}} - y_0}{y_{\mathrm{TM}} + y_0}\right|^2; & \text{TM modes.} \end{cases} \tag{17}$$

Equation (16) is able to be directly deduced from (4) for TE modes and from the corresponding equation for TM modes; details will be mentioned elsewhere [35]. It is seen that low-loss waveguides can be realized either when $|z_{\mathrm{TE}}|/z_0$ ($|y_{\mathrm{TM}}|/y_0$) is much larger or smaller than unity.

When $|z_{\mathrm{TE}}|/z_0$ or $|y_{\mathrm{TM}}|/y_0$ is sufficiently small, one easily obtains

$$u_0 \simeq \frac{p+1}{2}\pi \qquad (p = 0, 1, 2, \cdots) \tag{18}$$

and then

$$\left.\begin{matrix}\alpha^{\mathrm{TE}} \\ \alpha^{\mathrm{TM}}\end{matrix}\right\} = n_0 k_0 \frac{u_0^2}{(n_0 k_0 T)^3} \operatorname{Re}\left\{\begin{matrix} z_{\mathrm{TE}} \\ y_{\mathrm{TM}} \end{matrix}\right\}. \tag{19}$$

The attenuation constant of the TE_p or TM_p mode is proportional to $(p+1)^2$ if no media exist in $|x| > T$ with the refractive index n_0.

On the other hand, when $|z_{\mathrm{TE}}|/z_0$ or $|y_{\mathrm{TM}}|/y_0$ is sufficiently large, one has

$$u_0 \simeq \frac{p\pi}{2} \qquad (p = 0, 1, 2, \cdots) \tag{20}$$

and then

$$\left.\begin{matrix}\alpha^{\mathrm{TE}} \\ \alpha^{\mathrm{TM}}\end{matrix}\right\} = \left(1 - \frac{1}{2}\delta_{po}\right) \frac{1}{T} \operatorname{Re}\left\{\begin{matrix} z_{\mathrm{TE}}^{-1} \\ y_{\mathrm{TM}}^{-1} \end{matrix}\right\} \tag{21}$$

which shows that the attenuation constants of all modes do not depend on the mode number p except for that of the TE_0 or TM_0 mode.

III. Attenuation Constant in 2-D Metallic Hollow Waveguide with Single Inner Dielectric Layer

In order to understand basic properties of a metallic hollow waveguide with inner dielectric multilayers, we first consider a metallic waveguide with a single dielectric layer whose refractive index profile $n(x)$ is expressed by

$$n(x) = \begin{cases} n_0; & |x| < T \\ a_1 n_0; & T < |x| < (1+\delta)T \\ n_l n_0 = (n - j\kappa) n_0; & |x| > (1+\delta)T. \end{cases} \tag{22}$$

For the determination of z_{TE} or y_{TM}, one can use the transverse transmission line model [14], [36] schematically shown in Fig. 1 corresponding to the refractive index profile $n(x)$, where the transverse phase constant u_1/T in $T < |x| < (1+\delta)T$ is approximated by use of the assumption $n_0 k_0 T \gg u_0$ as

$$\frac{u_1}{T} \simeq (a_1^2 - 1)^{1/2} n_0 k_0 \tag{23}$$

and normalized impedance z_1, z_l and admittance y_1, y_l are given by

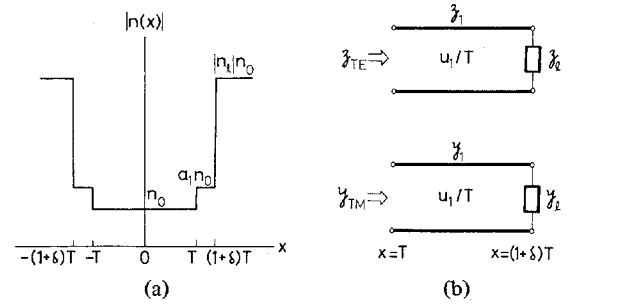

Fig. 1 (a) Refractive index profile of a metallic hollow waveguide with a single dielectric layer in the two-dimensional slab waveguide. (b) Transverse transmission line model corresponding to the waveguide where u_1/T and $z_1(y_1)$ are transverse phase constant and normalized impedance (admittance) in $T < X < (1+\delta)\ T$, respectively, and z_l (y_l) is the normalized impedance (admittance) of the metal.

$$z_1 = \frac{n_0 k_0 T}{u_1} \simeq (a_1^2 - 1)^{-1/2}, \tag{24}$$

$$z_l \simeq (n_l^2 - 1)^{-1/2}, \tag{25}$$

$$y_1 = a_1^2 \frac{n_0 k_0 T}{u_1} \simeq a_1^2 (a_1^2 - 1)^{-1/2}, \tag{26}$$

$$y_l \simeq n_l^2 (n_l^2 - 1)^{-1/2}. \tag{27}$$

Therefore, one can express z_{TE} and y_{TM} as follows:

$$\begin{aligned} z_{\mathrm{TE}} &= z_1 \frac{z_l + j z_1 \tan(\delta u_1)}{z_1 + j z_l \tan(\delta u_1)} \\ &= (a_1^2 - 1)^{-1/2} \frac{(n_l^2 - 1)^{-1/2} + j(a_1^2 - 1)^{-1/2} \tan[\delta(a_1^2 - 1)^{1/2} n_0 k_0 T]}{(a_1^2 - 1)^{-1/2} + j(n_l^2 - 1)^{-1/2} \tan[\delta(a_1^2 - 1)^{1/2} n_0 k_0 T]}, \end{aligned} \tag{28}$$

$$\begin{aligned} y_{\mathrm{TM}} &= y_1 \frac{y_l + j y_1 \tan(\delta u_1)}{y_1 + j y_l \tan(\delta u_1)} \\ &= a_1^2 (a_1^2 - 1)^{-1/2} \frac{n_l^2 (n_l^2 - 1)^{-1/2} + j a_1^2 (a_1^2 - 1)^{-1/2} \tan[\delta(a_1^2 - 1)^{1/2} n_0 k_0 T]}{a_1^2 (a_1^2 - 1)^{-1/2} + j n_l^2 (n_l^2 - 1)^{-1/2} \tan[\delta(a_1^2 - 1)^{1/2} n_0 k_0 T]}. \end{aligned} \tag{29}$$

Values of the normalized impedance or admittance are listed in Tables I and II for various metals and transparent dielectrics at 10.6 μm. Generally speaking, the normalized impedance of most metals is very small, whereas the normalized admittance is large in magnitude. For infrared waveguides, we have always $n_0 k_0 T \gg 1$ and, therefore, $|z_l| \ll n_0 k_0 T$. However, $|y_l|$ is not far from $n_0 k_0 T$ in magnitude although it is less than $n_0 k_0 T$. One should notice that in microwave regions $|y_l| \gg n_0 k_0 T$ is satisfied because κ is extremely large.

In order to realize low-loss infrared waveguides with a single dielectric layer, we have to design the waveguide such that

$$|z_{\mathrm{TE}}| \ll z_0 \tag{30}$$

or

$$|y_{\mathrm{TM}}| \ll y_0 \tag{31}$$

by suitable choice of a width of the dielectric layer. In these cases, by substituting (28) and (29) into (19) and making some

TABLE I
COMPLEX REFRACTIVE INDEXES OF VARIOUS MATERIALS AT $\lambda = 10.6\ \mu$m DEDUCED FROM THE DATA [37] BY INTERPOLATION. NORMALIZED IMPEDANCE AND ADMITTANCE ARE ALSO SUMMARIZED

Material	$n = n - j\kappa$		Normalized impedance	Normalized admittance
	n	κ	$\frac{1}{(n_t^2-1)^{1/2}}$	$\frac{n_t^2}{(n_t^2-1)^{1/2}}$
Al	20.5	58.6	$5.32\times10^{-3}+j1.52\times10^{-2}$	20.5-j58.6
Ag	13.4	75.2	$2.30\times10^{-3}+j1.29\times10^{-2}$	13.4-j75.2
Au	17.1	56.0	$4.99\times10^{-3}+j1.63\times10^{-2}$	17.1-j56.0
Cu	14.1	64.5	$3.23\times10^{-3}+j1.48\times10^{-2}$	14.1-j64.5
Sn	17.4	43.5	$7.92\times10^{-3}+j1.98\times10^{-2}$	17.4-j43.5
Zn	15.6	48.5	$6.01\times10^{-3}+j1.87\times10^{-2}$	15.6-j48.5

TABLE II
FIGURES OF MERIT FOR VARIOUS DIELECTRIC-COATED METALLIC WAVEGUIDES AT $\lambda = 10.6\ \mu$m. THE PARAMETER A IS ALSO SHOWN FOR METALS DESCRIBING THE WAVELENGTH DEPENDENCE OF THE FIGURE OF MERIT F

Dielectrics	Mode	Normalized impedance or admittance	Metal			
			Al	Ag	Au	Cu
Ge (a_1=4.0)	TE	.258	3.89×10^{-3}	2.57×10^{-3}	4.38×10^{-3}	3.44×10^{-3}
	TM	4.131	2.26×10^{2}	3.42×10^{2}	2.01×10^{2}	2.55×10^{2}
ZnSe (a_1=2.4)	TE	.458	1.24×10^{-3}	8.16×10^{-4}	1.39×10^{-3}	1.09×10^{-3}
	TM	2.640	5.53×10^{2}	8.37×10^{2}	4.92×10^{2}	6.25×10^{2}
KCl (a_1=1.47)	TE	.928	3.01×10^{-4}	1.99×10^{-4}	3.39×10^{-4}	2.66×10^{-4}
	TM	2.006	9.58×10^{2}	1.45×10^{3}	8.52×10^{2}	1.08×10^{3}
KRS-5 (a_1=2.37)	TE	.465	1.20×10^{-3}	7.91×10^{-4}	1.35×10^{-3}	1.06×10^{-3}
	TM	2.614	5.64×10^{2}	8.54×10^{2}	5.02×10^{2}	6.38×10^{2}
Parameter A of Eq. (41)			0.09	0.12	0.17	0.16

simplification by use of the condition $n^2 + \kappa^2 \gg a_1^2$ and $\kappa \gg n$, we finally express α^{TE} and α^{TM} as follows:

$$\alpha^{\mathrm{TE}} = \frac{2}{1 + \dfrac{a_1^2 - 1}{n^2 + \kappa^2}} \cdot \frac{\alpha_{\mathrm{metal}}^{\mathrm{TE}}}{1 - \left[1 - \dfrac{4(a_1^2 - 1)\, n^2}{(n^2 + \kappa^2)^2}\right]^{1/2} \sin\left[2\delta(a_1^2 - 1)^{1/2}\, n_0 k_0 T - \psi_{\mathrm{TE}}\right]} \tag{32}$$

$$\alpha^{\mathrm{TM}} = \frac{2}{1 + \dfrac{a_1^2 - 1}{a_1^4}(n^2 + \kappa^2)} \cdot \frac{\alpha_{\mathrm{metal}}^{\mathrm{TM}}}{1 + \left[1 - \dfrac{4a_1^4}{a_1^2 - 1}\, \dfrac{n^2}{(n^2 + \kappa^2)^2}\right]^{1/2} \sin\left[2\delta(a_1^2 - 1)^{1/2}\, n_0 k_0 T - \psi_{\mathrm{TM}}\right]} \tag{33}$$

where ψ_{TE} and ψ_{TM} are defined by

$$\psi_{\mathrm{TE}} = \tan^{-1}\left[\frac{n^2 + \kappa^2}{2(a_1^2 - 1)^{1/2}\kappa}\right] \simeq \frac{\pi}{2} \tag{34}$$

$$\psi_{\mathrm{TM}} = \tan^{-1}\left[\frac{(a_1^2 - 1)^{1/2}}{2a_1^2}\, \frac{n^2 + \kappa^2}{\kappa}\right] \simeq \frac{\pi}{2} \tag{35}$$

and $\alpha_{\mathrm{metal}}^{\mathrm{TE}}$ and $\alpha_{\mathrm{metal}}^{\mathrm{TM}}$ are attenuation constants of the TE and TM modes in the metallic waveguides without a dielectric layer expressed by

$$\left.\begin{array}{l}\alpha_{\mathrm{metal}}^{\mathrm{TE}} \\ \alpha_{\mathrm{metal}}^{\mathrm{TM}}\end{array}\right\} = n_0 k_0 \frac{u_0^2}{(n_0 k_0 T)^3} \times \left\{\begin{array}{l}\dfrac{n}{n^2 + \kappa^2} \\ n\end{array}\right. . \tag{36}$$

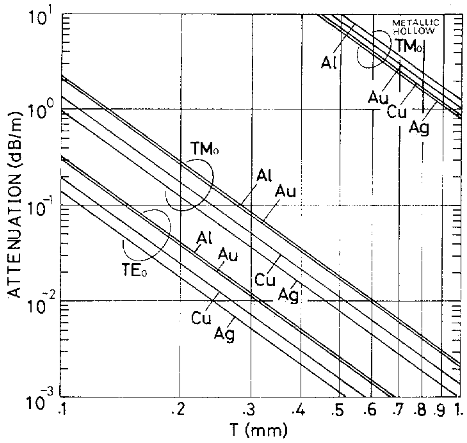

Fig. 2. Minimum power losses of the TE_0 and TM_0 modes in various waveguides with an inner zinc selenide ($a_1 = 2.4$) layer at $\lambda = 10.6$ μm. Power losses of the TE_0 and TM_0 modes in the waveguides without a dielectric layer are also shown, where power losses of the TE_0 mode cannot be distinguished from those in the dielectric-coated metallic waveguides in the figure.

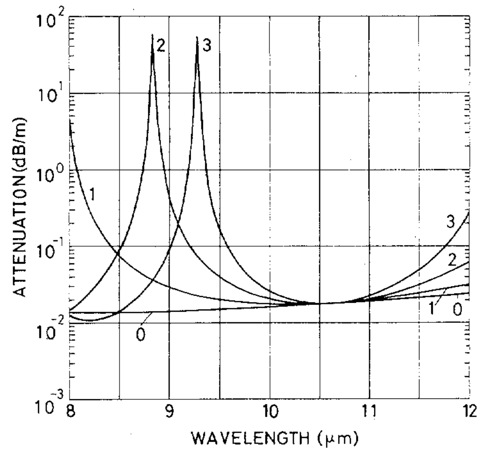

Fig. 3. Wavelength dependence of the power loss of the TM_0 mode in the aluminum waveguide with an inner zinc selenide layer, where T = 500 μm and it is assumed that $n_l = 20.5 - j58.6$ and $a_1 = 2.4$ are constant over the wavelengths. The number on each curve represents q in (37).

In the derivation of (32)-(36), we have assumed $n^2 + \kappa^2 \gg a_1^2$, which is almost satisfied for most of the metals and transparent dielectrics around 10.6 μm.

As seen from (32) and (33), the attenuation constants of the modes have minimum when

$$\delta(a_1^2 - 1)^{1/2} n_0 k_0 T = \begin{cases} q\pi, & q = 0, 1, 2, \cdots; \quad \text{TE modes} \\ (q + \frac{1}{2})\pi, & q = 0, 1, 2, \cdots; \quad \text{TM modes} \end{cases} \tag{37}$$

and their minimum values $\alpha_{\min}$ are approximated by

$$\alpha_{\min} = n_0 k_0 \frac{u_0^2}{(n_0 k_0 T)^3} \frac{n}{n^2 + \kappa^2} \times \begin{cases} \dfrac{1}{1 + \dfrac{a_1^2 - 1}{n^2 + \kappa^2}}; & \text{TE modes} \\ \dfrac{a_1^4}{a_1^2 - 1} \dfrac{1}{1 + \dfrac{a_1^4}{a_1^2 - 1} \dfrac{1}{n^2 + \kappa^2}}; & \text{TM modes.} \end{cases} \tag{38}$$

Fig. 2 shows minimum power losses of the TE_0 and TM_0 modes in various metal waveguides with a single dielectric (ZnSe) layer. The power losses in the waveguides without a dielectric layer are also shown. One can see that the power losses in the waveguides are reduced by two or three orders of magnitude for TM modes, whereas appreciable loss reduction cannot be expected for the TE mode by coating a single dielectric layer. This does not depend on the width of the dielectric layer as far as (37) is satisfied. However, the wavelength dependence of the power losses varies with the width and relatively thinner dielectric layer, i.e., smaller q in (37) is preferable to have broad wavelength dependence of the power losses as shown in Fig. 3.

In order to see the effect of coating in more detail, we introduce a figure of merit defined by

$$\alpha_{\min} = \frac{\alpha_{\text{metal}}}{1 + F} \tag{39}$$

which leads to

$$F = \begin{cases} \dfrac{a_1^2 - 1}{n^2 + \kappa^2}; & \text{TE modes} \\ \dfrac{a_1^2 - 1}{a_1^4}(n^2 + \kappa^2); & \text{TM modes.} \end{cases} \tag{40}$$

One should note that the figure of merit does not depend on the core width, thickness of the dielectric layer, and the mode number p. Typical examples of the figures of merit at 10.6 μm are summarized in Table II for various waveguides. One can see that large figures of merit are obtained for the TM modes. Especially, the optimum value of the refractive index a_1 is $2^{1/2}$ for the TM modes.

As the refractive indexes of most transparent dielectrics do not depend much on the wavelength, wavelength dependence of the figure of merit is mainly determined by $n^2 + \kappa^2$ of metals. By using data deduced from [37], one can reasonably approximate F as

$$F/F_{10.6} = \begin{cases} [1 + A(\lambda - 10.6)]^{-1}; & \text{TE modes} \\ [1 + A(\lambda - 10.6)]; & \text{TM modes} \end{cases} \tag{41}$$

where $F_{10.6}$ is the figure of merit at $\lambda = 10.6$ μm and A is around 0.1-0.2, as summarized in Table II, which shows that F is relatively insensitive to the wavelength.

We finally mention a metal as a waveguide constituent. Power losses of the TE or TM modes are approximately determined by only one parameter $n/(n^2+\kappa^2)$ for metals as seen in (38). Although this parameter depends on a particular metal, the loss reduction rate of the TM modes is very large and it is not essential to select the metal as the waveguide constituent from the viewpoint of transmission characteristics.

IV. Attenuation Constant in 2-D Hollow Waveguide with Multiple Inner Dielectric Layers

In the analyses in Section III, we found that the transmission losses of the TE modes in the metallic hollow waveguide cannot be reduced significantly by coating a single inner dielectric layer. In this section, we shall consider a waveguide which reduces the attenuation constant of the TE or TM mode drastically. A basic idea to have low-loss waveguide is to reduce or increase $|z_{\mathrm{TE}}|/z_0$ or $|y_{\mathrm{TM}}|/y_0$ compared with unity as seen in (16) and (17). We propose a metallic hollow waveguide coated by two kinds of dielectrics as shown in Fig. 4, where the thickness of dielectric layers $\delta_i T (i=1,2)$ and that of dielectric layer δT adjacent to the metal are chosen such that

$$\delta_i T = \frac{\pi}{2}\,\frac{1}{(a_i^2-1)^{1/2}\,n_0 k_0} \qquad (i=1,2) \tag{42}$$

$$\delta T = \frac{\pi}{2}\,\frac{1}{(a_1^2-1)^{1/2}\,n_0 k_0} \times \begin{cases} 2; & \text{TE modes} \\ 1; & \text{TM modes.} \end{cases} \tag{43}$$

The corresponding transverse transmission line model is shown in Fig. 5, where

$$u_i/T = (a_i^2-1)^{1/2}\,n_0 k_0 \qquad (i=1,2) \tag{44}$$

$$z_i = (a_i^2-1)^{-1/2} \qquad (i=1,2) \tag{45}$$

$$y_i = a_i^2 (a_i^2-1)^{-1/2} \qquad (i=1,2). \tag{46}$$

We first assume that dielectric materials are free from absorptions, i.e., $a_i (i=1,2)$ are real quantities. It is easily found that

$$z_{\mathrm{TE}} = (n_l^2-1)^{-1/2}\,C^m \simeq \frac{n+j\kappa}{n^2+\kappa^2}\,C^m \tag{47}$$

$$y_{\mathrm{TM}} = \frac{a_1^4}{a_1^2-1}\,\frac{(n_l^2-1)^{1/2}}{n_l^2}\,D^m \simeq \frac{a_1^4}{a_1^2-1}\,\frac{n+j\kappa}{n^2+\kappa^2}\,D^m \tag{48}$$

where C and D are defined by

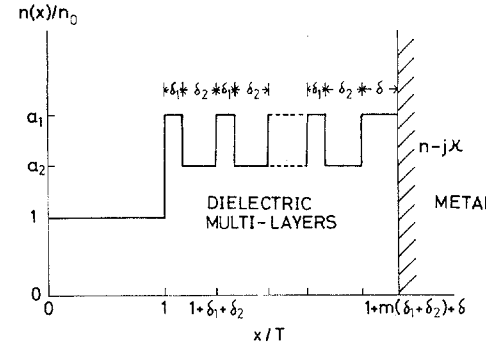

Fig. 4. Refractive index profile of a symmetric 2-D hollow waveguide with multiple inner dielectric layers. The thickness of the material with a refractive index of $a_1 n_0$ or $a_2 n_0$ is $\delta_1 T$ or $\delta_2 T$ defined by (42) except for the nearest layer to the metal with $a_1 n_0$ of δT defined by (43).

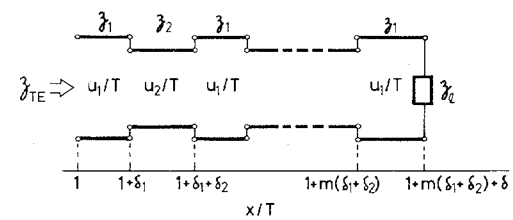

Fig. 5. Transverse transmission line model for the TE modes corresponding to the waveguide whose refractive index profile is shown in Fig. 4. For the TM modes, one simply replaces z by y.

$$C = \frac{a_2^2-1}{a_1^2-1} \tag{49}$$

$$D = \frac{a_1^4}{a_2^4}\,\frac{a_2^2-1}{a_1^2-1}. \tag{50}$$

By substituting (47) and (48) into (12) and (14), one can express the attenuation constants of the TE and TM modes, designated by α_0^{TE} and α_0^{TM}, as follows:

$$\alpha_0^{\mathrm{TE}} = \frac{n_0 k_0 u_0^2}{(n_0 k_0 T)^3}\,\frac{n}{n^2+\kappa^2}\;\frac{C^m}{1+\dfrac{\kappa}{(n^2+\kappa^2)\,n_0 k_0 T}\,C^m+\dfrac{u_0^2}{(n^2+\kappa^2)(n_0 k_0 T)^2}\,C^{2m}} \tag{51}$$

$$\alpha_0^{\mathrm{TM}} = \frac{a_1^4}{a_1^2-1}\,\frac{n_0 k_0 u_0^2}{(n_0 k_0 T)^3}\,\frac{n}{n^2+\kappa^2}\;\frac{D^m}{1+\dfrac{a_1^4}{a_1^2-1}\,\dfrac{\kappa}{(n^2+\kappa^2)\,n_0 k_0 T}\,D^m+\dfrac{a_1^8}{(a_1^2-1)^2}\,\dfrac{u_0^2}{(n^2+\kappa^2)(n_0 k_0 T)^2}\,D^{2m}}. \tag{52}$$

It is clear that low-loss waveguides can be obtained either when $C<1$ $(D<1)$ or $C>1$ $(D>1)$. However, it is preferable to choose $C<1$ for TE modes and $D<1$ for TM modes. For, as $n_0 k_0 T$ is large, considerable layers are required for the third terms in the denominators of (51) and (52) to predominate. Therefore, we hereafter consider the waveguides with $C<1$ for TE modes and $D<1$ for TM modes. In these cases, (51) and (52) are simplified as

$$\left.\begin{matrix}\alpha_0^{\mathrm{TE}}\\ \alpha_0^{\mathrm{TM}}\end{matrix}\right\} = \frac{n_0 k_0 u_0^2}{(n_0 k_0 T)^3}\,\frac{n}{n^2+\kappa^2} \times \begin{cases} C^m \\ \dfrac{a_1^4}{a_1^2-1}\,D^m \end{cases} \tag{53}$$

for any m, where u_0 is defined by (18). One should notice that a considerable amount of the loss reduction is expected by large number m. However, at the same time for larger m, one has to take absorptions of the dielectric materials into account.

Let the complex refractive indexes of dielectric materials be $(a_i - ja_i')\ n_0$ $(i = 1, 2)$. The corresponding transverse transmission line is simply obtained by replacing u_i/T, z_i, and y_i by

$$\frac{u_i}{T} \rightarrow \frac{u_i}{T}\left(1 - j\frac{a_i a_i'}{a_i^2 - 1}\right) \tag{54}$$

$$z_i \rightarrow z_i\left(1 + j\frac{a_i a_i'}{a_i^2 - 1}\right) \tag{55}$$

$$y_i \rightarrow y_i\left(1 - j\frac{a_i^2 - 2}{a_i^2 - 1}\frac{a_i'}{a_i}\right) \tag{56}$$

in (44)-(46).

By using the conditions of (42) and (43) and neglecting higher order terms of $a_i'^2$ $(i = 1, 2)$ and $(n^2 + \kappa^2)^{-2}$, one can express z_{TE} and y_{TM} after rather complicated calculations as

$$z_{\mathrm{TE}} = \frac{n + j\kappa}{n^2 + \kappa^2} C^m\,(1 + \epsilon_{\mathrm{TE}}) \tag{57}$$

$$y_{\mathrm{TM}} = \frac{a_1^4}{a_1^2 - 1}\frac{n + j\kappa}{n^2 + \kappa^2} D^m\,(1 + \epsilon_{\mathrm{TM}}) \tag{58}$$

where ϵ_{TE} and ϵ_{TM} are defined by

$$\epsilon_{\mathrm{TE}} = \frac{\pi}{2}(n - j\kappa)\left\{\left[\frac{a_1 a_1'}{(a_1^2 - 1)^{1/2}} + \frac{a_2 a_2'}{(a_2^2 - 1)^{1/2}}\right] \cdot \frac{1}{a_2^2 - 1}\frac{C^{-m} - 1}{C^{-1} - 1} + \frac{2a_1 a_1'}{(a_1^2 - 1)^{3/2}}\right\} \tag{59}$$

$$\epsilon_{\mathrm{TM}} = \frac{\pi}{2}(n - j\kappa)\left\{\left[\frac{a_1'}{a_1(a_1^2 - 1)^{1/2}} + \frac{a_2'}{a_2(a_2^2 - 1)^{1/2}}\right] \cdot D^{-1}\frac{D^{-m} - 1}{D^{-1} - 1} + \frac{a_1'}{a_1(a_1^2 - 1)^{1/2}}\right\}. \tag{60}$$

Therefore, the attenuation constants α^{TE} and α^{TM} of the TE and TM modes are expressed by

$$\alpha^{\mathrm{TE}}/\alpha_0^{\mathrm{TE}} = 1 + \frac{n^2 + \kappa^2}{n}\frac{\pi}{2}\left\{\left[\frac{a_1 a_1'}{(a_1^2 - 1)^{1/2}} + \frac{a_2 a_2'}{(a_2^2 - 1)^{1/2}}\right] \cdot \frac{1}{a_2^2 - 1}\frac{C^{-m} - 1}{C^{-1} - 1} + \frac{2a_1 a_1'}{(a_1^2 - 1)^{3/2}}\right\} \tag{61}$$

$$\alpha^{\mathrm{TM}}/\alpha_0^{\mathrm{TM}} = 1 + \frac{n^2 + \kappa^2}{n}\frac{\pi}{2}\left\{\left[\frac{a_1'}{a_1(a_1^2 - 1)^{1/2}} + \frac{a_2'}{a_2(a_2^2 - 1)^{1/2}}\right] \cdot D^{-1}\frac{D^{-m} - 1}{D^{-1} - 1} + \frac{a_1'}{a_1(a_1^2 - 1)^{1/2}}\right\}. \tag{62}$$

Fig. 6 shows power losses in the hollow aluminum waveguide with multiple dielectric layers consisting of zinc selenide and germanium as a function of numbers of layer pairs. One can see that absorption-limited power losses of the waveguide are extremely small and possible numbers of layer pairs are $m \simeq 10$ in this particular case. In the figures results predicted by the following very simple loss formulas, which are obtained by linear approximations of exact ones, are also shown in dashed lines as

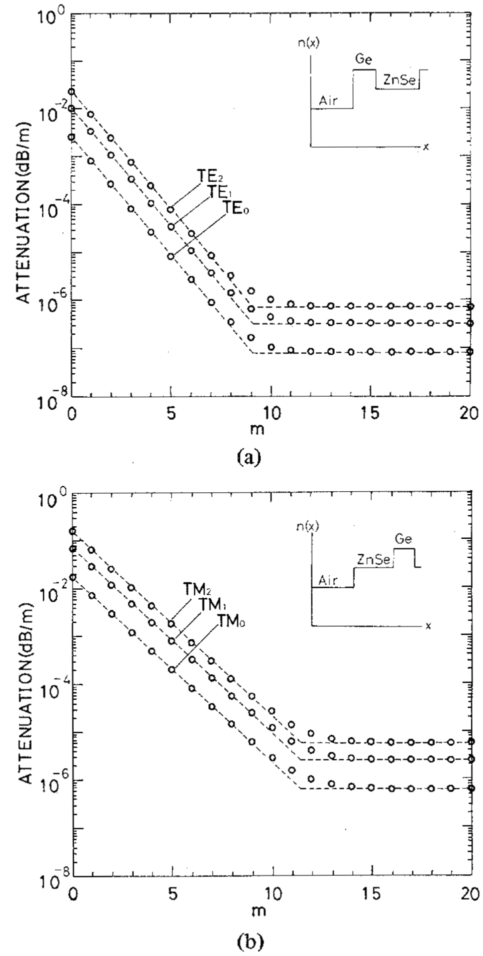

Fig. 6. Power losses of several (a) TE modes and (b) TM modes in the aluminum hollow waveguide with multiple inner dielectric layers composing of the zinc selenide whose complex refractive index is 2.4-j3.36 $\times$ 10^{-8} and the germanium of 4.0-$j10^{-6}$ as a function of m at λ = 10.6 μm and T = 500 μm. The nearest layer to the metal or hollow core is the germanium for TE modes and the zinc selenide for TM modes, respectively, as shown in insets. Dashed lines represent power losses predicted by (63) and (64).

$$\alpha^{\mathrm{TE}} = \begin{cases} \dfrac{n_0 k_0 u_0^2}{(n_0 k_0 T)^3}\dfrac{n}{n^2 + \kappa^2} C^m; & m < m_s \\ \dfrac{n_0 k_0 u_0^2}{(n_0 k_0 T)^3}\dfrac{\pi}{2(a_1^2 - a_2^2)}\left[\dfrac{a_1 a_1'}{(a_1^2 - 1)^{1/2}} + \dfrac{a_2 a_2'}{(a_2^2 - 1)^{1/2}}\right]; & m > m_s \end{cases} \tag{63}$$

$$\alpha^{\mathrm{TM}} = \begin{cases} \dfrac{n_0 k_0 u_0^2}{(n_0 k_0 T)^3}\dfrac{n}{n^2 + \kappa^2}\dfrac{a_1^4}{a_1^2 - 1} D^m; & m < m_s \\ \dfrac{n_0 k_0 u_0^2}{(n_0 k_0 T)^3}\dfrac{\pi}{2}\dfrac{a_1^4}{a_1^2 - 1}(1 - D)^{-1}\left[\dfrac{a_1'}{a_1(a_1^2 - 1)^{1/2}} + \dfrac{a_2'}{a_2(a_2^2 - 1)^{1/2}}\right]; & m > m_s. \end{cases} \tag{64}$$

m_s represents the maximum number of efficient layer pairs for the power loss reduction over which no reduction is possible and it is defined by

$$m_s = \begin{cases} \log\left\{\dfrac{n^2+\kappa^2}{n}\dfrac{\pi}{2(a_1^2-a_2^2)}\left[\dfrac{a_1 a_1'}{(a_1^2-1)^{1/2}}+\dfrac{a_2 a_2'}{(a_2^2-1)^{1/2}}\right]\right\}\Big/\log C; \\ \qquad \text{TE modes} \\ \log\left\{\dfrac{n^2+\kappa^2}{n}\dfrac{\pi}{2}(1-D)^{-1}\left[\dfrac{a_1'}{a_1(a_1^2-1)^{1/2}}+\dfrac{a_2'}{a_2(a_2^2-1)^{1/2}}\right]\right\}\Big/\log D; \\ \qquad \text{TM modes.} \end{cases} \tag{65}$$

One should note that minimum attainable losses depend on mode number (or u_0), core width, wavelength, and properties of dielectric materials and do not depend on the properties of metals used. This is because electromagnetic fields decay sufficiently at the metal surface. On the other hand, the maximum number of efficient pair layers m_s depends on $(n^2+\kappa^2)/n$ of metals. The larger $(n^2+\kappa^2)/n$ is, the smaller m_s becomes. In examples shown in Fig. 6, we have used the least absorptions for the zinc selenide and the gemanium so far reported [38]. Actually, the minimum attainable losses are limited by the absorptions losses of the germanium. In order to see the effect of absorptions of dielectric materials in more detail, we consider the possible minimum losses and efficient number of layer pairs based on (63)-(65) by assuming $a_1' = a_2'$ for simplicity.

Fig. 7 shows the minimum power losses and maximum number m_s of the efficient pair layers for various combinations of transparant dielectric materials at 10.6 μm as a function of $a_1'(=a_2')$. It is shown that waveguides with small power losses can be expected even for materials with high absorptions such as $a_1' = a_2' = 10^{-4}$ in the two-dimensional slab waveguide.

In closing this section, we consider the bending loss in the dielectric-coated metallic waveguide. A previous analysis [39] shows that the attenuation constant α in uniformly bent hollow slab waveguides characterized by small $|z_{\text{TE}}|/z_0$ or $|y_{\text{TM}}|/y_0$ is generally expressed by

$$\alpha/\alpha_\infty = \begin{cases} 1-\dfrac{2}{3}\left(1-\dfrac{15}{4u_0^2}\right)\left(\dfrac{n_0 k_0 T}{u_0}\right)^4\left(\dfrac{T}{R}\right)^2; \\ \qquad \text{large bending radius} \\ \left(\dfrac{n_0 k_0 T}{u_0}\right)^2 \dfrac{T}{R}; \qquad \text{small bending radius} \end{cases} \tag{66}$$

where α_∞ is the attenuation constant in straight waveguides, R is the bending radius, and u_0 is defined by (18) for TE_p or TM_p modes. Equation (66) clearly shows that the waveguide with small α_∞ such as the dielectric coated metallic waveguide has a small bending loss or it is bent with a small bending radius as well.

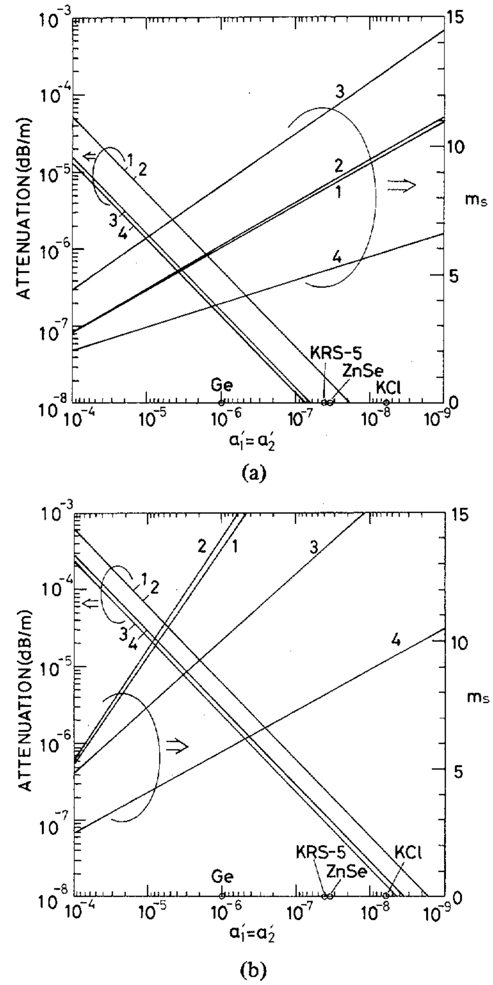

Fig. 7. Minimum power losses and maximum efficient numbers m_s of pair layers for (a) the TE_0 mode and (b) the TM_0 mode as a function of $a_1'(=a_2')$ in the aluminum waveguide with $T = 500$ μm coated by various combinations of dielectric materials, where 1) ZnSe-KCl, 2) KRS-5-KCl, 3) Ge-ZnSe, 4) Ge-KCl. The smallest absorption coefficients (a_i') of actual materials so far reported [38] are also shown by small circles.

V. Conclusion

A metallic hollow waveguide with inner dielectric multilayers is proposed for the transmission of infrared light and its basic transmission characteristics are fully analyzed by using a two-dimensional slab waveguide model. Waveguides with small power losses can be expected by coating even dielectric materials with relatively high absorptions in a straight waveguide structure. The waveguide is also shown to have a small bending loss.

A general theory for evaluating power losses in a circular waveguide structure will be reported in a subsequent paper and an optimum design theory of the dielectric-coated metallic waveguide will be discussed.

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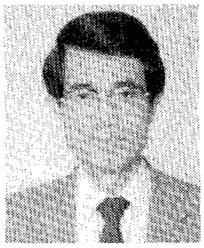

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Q-Switched Semiconductor Diode Lasers

DEAN Z. TSANG, MEMBER, IEEE, AND JAMES N. WALPOLE

(Invited Paper)

Abstract—**Diode lasers with an intracavity electroabsorption modulator have been operated with full on/off modulation at rates of 3 GHz. In addition, modulation of the lasers has been shown up to a detector-limited frequency of 6 GHz. A new model of these devices, which includes amplified spontaneous emission and high gain is developed in this paper. A quasi-static gain approximation is introduced and the dynamics of the electron and photon population are modeled by three coupled nonlinear difference equations which can be numerically solved with very little computation time. The model predicts the possibility of a new mode of *Q*-switched operation with the capacity for repetition rates of tens of gigahertz and binary pulse position modulation at rates of the order of 10 Gbits/s.**

I. Introduction

Q-SWITCHED semiconductor diode lasers are of interest for applications in optical fiber communication systems or generally as a source of optical pulses when high peak power and large depth of modulation are required at high repetition rates. An actively *Q*-switched laser in which the intracavity loss can be electrically driven is desirable for these applications. In this paper we first briefly review previous work and then present theoretical and experimental results for a diode laser actively *Q*-switched by an intracavity p-n junction electroabsorption modulator [1]–[3]. The model is then applied to study digital modulation at rates of the order of 10 Gbits/s.

Q-switching lasers by rapidly switching the intracavity optical loss is a technique for producing optical pulses with high peak power [4] and high repetition rates [5], [6]. In early studies with diode lasers, large optical pulses were seen at the end of the diode excitation pulse. This phenomenon, seen primarily in single heterostructure lasers, was called "*Q*-switching," but was not associated with variations of the optical loss [7]. Variations in the optical loss can be produced through passive means in which the loss is not directly modulated or active means in which the loss is directly modulated. Passive *Q*-switching due to saturable absorption has been observed in diode lasers with two nonuniformly pumped gain sections [8], [9]. Actively *Q*-switched lasers can be directly modulated, an advantage for many applications. The first proposals for actively *Q*-switched diode lasers included the use of electrooptically switched [10] and acoustooptically switched [11] distributed feedback gratings as a means of varying mirror reflectivities. The first actively *Q*-switched laser operation has been previously reported by the authors and co-workers [1]–[3] using diode lasers with an intracavity electroabsorption modulator at rates up to 2.5 GHz. Short pulses have also been produced at lower repetition rates in a diode laser with a dye-laser-pumped passive section in a combination of active *Q*-switching and active gain switching [12]. Electrical variation of the optical coupling to an adjacent guide [13] or the optical confinement [14] are two other recently proposed schemes to *Q*-switch diode lasers. In this paper we report full on/off modulation at 3 GHz as well as modulation of the lasers up to a detector-limited frequency of 6 GHz.

Previous theoretical treatments of actively *Q*-switched diode lasers have been modifications of the conventional rate equations in which the gain and loss are evenly distributed over the cavity [10], [11]. In order to include the effects of high gain and amplified spontaneous emission (ASE), a new treatment based on a rate equation approximation has been developed [3], [15] and will be described in detail in this paper for a laser with separate gain and loss sections.

This new treatment constitutes a major part of this paper. We show that a quasi-static gain approximation can be made which significantly reduces the amount of numerical compu-

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