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THE THEORY FOR THE DIELECTRIC SLAB WAVEGUIDE WITH COMPLEX REFRACTIVE INDEX APPLIED TO GaAs LASERS

Jens Buus^{*}

ABSTRACT

In this paper we investigate the homogeneous dielectric slab waveguide in the case of complex dielectric constants. A method for calculating the field distribution in a dielectric waveguide with an arbitrary symmetrical variation in the refractive index is developed, and some of the results are presented. The results are applied to the GaAs laser. It is found that the guiding mechanism is a combination of gain guiding and index antiguiding.

Based on the calculations an explanation of the kinks on the light current characteristics is suggested.

INTRODUCTION

The theory of the homogeneous dielectric slab waveguide in the case of pure real dielectric constants is well-known. This theory is extended to complex dielectric constants. Although the abrupt change in ϵ is a crude approximation to the transverse structure of the active layer in GaAs lasers the theory gives qualitative information about the guiding mechanism and the mode structure.

The transverse field variation can be found explicitly in the case of parabolic variation in ϵ , but ϵ is parabolic in a narrow region only, and the results are of limited validity. Since the transverse intensity variation is fundamental when coupling to optical fibers it is important to obtain a better description.

THEORY FOR THE HOMOGENEOUS SLAB

The geometry considered is shown in fig. 1. The field, E , is given by $\cos(u \frac{x}{t})$ or $\sin(u \frac{x}{t})$ (even or odd modes) for $|x| \leq t$ and $\exp(-w \frac{|x|-t}{t})$ for $|x| > t$. Only TE modes are considered. The normalized frequency, v , and normalized propagation constant, b , are given by

$$v^2 = u^2 + w^2 = (\epsilon_1 - \epsilon_2) k^2 t^2 \quad \text{and} \quad (1)$$

$$b = \frac{(\frac{\beta^2}{k^2}) - \epsilon_2}{\epsilon_1 - \epsilon_2} \quad (2)$$

k and β are the propagation constants

Fig. 1. Geometry of the slab waveguide.

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in free space and the slab, respectively. The values of u and w are found from the characteristic equation obtained from the condition that $\frac{dE}{dx}$ should be continuous at $x = \pm t$. b , v , u and w are related by $u = v\sqrt{1-b}$ and $w = v\sqrt{b}$.

In order to get physically acceptable solutions we must require $\text{Im}\{\epsilon_1 - \epsilon_2\} > 0$, and if furthermore $\text{Re}\{\epsilon_1 - \epsilon_2\} > 0$, the lowest order (0'th) mode always exists [1]. If, however, $\text{Re}\{\epsilon_1 - \epsilon_2\} < 0$, a cutoff frequency for the lowest mode exists. The guiding mechanism depends on the v -value as shown schematically in fig. 2. The cutoff condition is $\text{Re}\{w\} = \text{Re}\{v\sqrt{b}\} = 0$, where b is found from the characteristic equation. Fig. 3 shows the cutoff values of v for the 5 lowest modes.

Fig. 2. Guiding mechanisms for complex v -values.

Fig. 3. Cutoff conditions for the lowest modes.

The filling factor Γ is defined as the fraction of the intensity propagating in the region $|x| \leq t$

$$\Gamma = \frac{\int_{-t}^t |E|^2 dx}{\int_{-\infty}^{\infty} |E|^2 dx} \quad (3)$$

For a pure real guide ($\kappa_1 = \kappa_2 = 0$) we have

$$\Gamma_{\text{even}} = \pm b + \frac{(1+b) v\sqrt{b}}{1 + v\sqrt{b}} \quad (4)$$

For the complex guide we have derived the general expression

$$\Gamma_{\text{even}} = \frac{\text{Re}\{w\}\text{Im}\{w\}}{\text{Re}\{w\}\text{Im}\{w\} + \text{Re}\{u\}\text{Im}\{u\}} = \text{Re}\{b\} + \frac{\text{Re}\{v^2\}}{\text{Im}\{v^2\}} \text{Im}\{b\} \quad (5)$$

As an example Γ is calculated for the 2nd mode (fig. 4). It is found, that Γ decreases with increasing mode number, hence the effective gain

$$g_{\text{eff}} = \frac{4\pi}{\lambda} (\kappa_2 + (\kappa_1 - \kappa_2)\Gamma) \quad (6)$$

will be highest for the lowest modes. For high values of $|v|$, however, Γ is close to 1 for several modes.

APPLICATION TO GaAs LASERS

The theory can be applied to GaAs lasers of the oxide insulated or proton-bombarded types. The active layer is modelled by a slab structure where the electron density in the central region is high due to the pump current; in the outer regions the electron density (from carrier diffusion) is low.

From a calculation of the gain [2] and use of the Kramers-Kronig relations

[3] we have $\Delta n = n(N - N_c) - n(N=0) \approx -0.01$ where N_c is the critical electron density. This order of magnitude is confirmed by experiment [4]; the measured value is $\Delta n \approx -0.007$. From the gain values in [5] we deduce $\kappa_1 \approx 3 \cdot 10^{-4}$, $\kappa_2 \approx 11 \cdot 10^{-4}$; this gives for $\lambda = 8800 \text{ \AA}$ and $n(N=0) = 3.6$: $|v| \approx 8.0 \frac{t}{5\mu\text{m}}$ and $\arg(v) = 1.47$.

The effective gain for $t = 5\mu\text{m}$ for the 3 lowest modes is 3209 m^{-1} , 758 m^{-1} and -3502 m^{-1} , for $t = 10\mu\text{m}$: 4168 m^{-1} , 3820 m^{-1} and 3247 m^{-1} . This shows that the effective gains are approaching each other for wide stripes. If the end loss is lower for high order modes, the laser can shift to higher modes.

GENERAL MODEL

When a laser is operating at a high intensity level spatial holeburning in the electron density profile is likely to occur [6]. This will change the complex index profile, and the homogeneous slab model will be inadequate. In order to solve the field equation the variation in ϵ is expanded in orthogonal functions and Galerkin's method is used.

EFFECT OF HOLEBURNING

In order to investigate the effect of holeburning we have used an electron density profile given by

$$N(x) = \left\{ \left(1.1 - \frac{x}{3} \right) \cos\left(\frac{\pi}{3} \frac{x}{t}\right) - x \cos\left(\pi \frac{x}{t}\right) \right\} N_0, \quad |x| \leq \frac{3}{2} t, \quad t = 5\mu\text{m} \quad (7)$$

The dielectric constant was assumed to be

Fig. 4. Filling factor for the 2nd mode.

$$\varepsilon(x) - \varepsilon(\infty) = (3,6 + A \cdot N(x) + j \cdot B \cdot N(x))^2 - (3,6 - j \cdot 0,0011)^2 \quad (8)$$

with $N_0 = 1.7 \cdot 10^{24} \text{ m}^{-3}$, $A = -5 \cdot 10^{-27} \text{ m}^3$ and $B = 9 \cdot 10^{-28} \text{ m}^3$. We define the modegain G by

$$G = \frac{4\pi}{\lambda} \int_{-\infty}^{\infty} \kappa(x) |E(x)|^2 dx / \int_{-\infty}^{\infty} |E(x)|^2 dx \quad (9)$$

G is shown in fig. 5 for the various modes. If a laser is operating in the 0'th transversal mode and the intensity is increased we can expect holeburning to occur (corresponding to higher χ). This will produce a local increase in the real part of the refractive index, hence the mode will be self-focused. Further increase of the intensity will give a deeper hole and a better confinement, but on the other hand the mode-gain will be reduced, and another mode begins to dominate. The shift from one mode to another will produce a re-distribution of the electrons, and we suggest, that this gives rise to a kink. In order to get a better understanding of this mechanism, however, it is necessary to couple the field equation to an equation for the electron density profile.

CONCLUSION

The guiding mechanism and mode structure for GaAs lasers were discussed by applying models for dielectric waveguides. An explanation of the kinks on the light-current characteristic was suggested, and supported by numerical calculations.

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Fig. 5. Mode gain as a function of χ .

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