Observation of confined propagation in Bragg waveguides

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(Received 10 January 1977; accepted for publication 25 February 1977)

A new type of waveguiding in a slab dielectric bounded on one side by air and on the other by a periodic layered medium (grown by molecular beam epitaxy) has been demonstrated.

PACS numbers: 42.80.Lt, 68.55.+b, 84.40.Ed

Periodic layered media present high reflectivity to incident monochromatic radiation which satisfies the Bragg condition. Fox[1] has suggested that such reflection can be used in a new type of a dielectric waveguide in which the conventionally used substrate is replaced by a layered medium. Yariv and Yeh[2] used a Bloch wave formulation of propagation in layered media to obtain the dispersion relation of Bragg waveguides and showed that, unlike ordinary dielectric waveguides, confined guiding with arbitrarily low loss is possible even when the guiding layer possesses an index of refraction which is lower than that of the periodic layers.

In the following we report the first experimental observation of Bragg waveguiding.

The index-of-refraction profile of the waveguide is shown in Fig. 1. The propagation may be considered formally as that of a plane wave zigzagging inside the guiding (n_g) layer and undergoing total internal reflection at the interface ($x=-t$) with the low-index medium (n_a) and Bragg reflection at the interface ($x=0$) with the layered medium. For high Bragg reflectivity it is necessary that the incidence angle satisfy the Bragg condition or more exactly that the propagation conditions inside the layered medium fall within one of the "forbidden" gaps.

The exact dispersion relation for a Bragg waveguide with a semi-infinite layered medium on one side is[2]

$$k_g\left(\frac{q_a\cos k_g t - k_g\sin k_g t}{q_a\sin k_g t + k_g\cos k_g t}\right) = -ik_{1x}\frac{\exp(-iK\Lambda)-A-B}{\exp(-iK\Lambda)-A+B} \quad (1)$$

where a propagation factor $\exp(i\beta z)$ is assumed.

$$k_g = \{[(\omega/c)n_g]^2 - \beta^2\}^{1/2},$$

$$q_a = \{\beta^2 - [(\omega/c)n_a]^2\}^{1/2},$$

$$A = \exp(-ik_{1x}a)\left[\cos k_{2x}b - \frac{i}{2}\left(\frac{k_{2x}}{k_{1x}} - \frac{k_{1x}}{k_{2x}}\right)\sin k_{2x}b\right], \quad (2)$$

$$B = \exp(ik_{1x}a)\left[-\frac{i}{2}\left(\frac{k_{2x}}{k_{1x}} - \frac{k_{1x}}{k_{2x}}\right)\sin k_{2x}b\right],$$

$$C = B^*, \quad D = A^*,$$

$$k_{1x} = \{[(\omega/c)n_i]^2 - \beta^2\}, \quad i=1,2$$

and

$$\exp(-iK\Lambda) = \tfrac{1}{2}(A+D) \pm \{[\tfrac{1}{2}(A+D)]^2 - 1\}^{1/2}. \quad (3)$$

The Bloch wave in the n_1 layers of the periodic medium is in the form

$$E_n(x) = E_K(x)\exp(iKx)$$
$$= (\{a_0\exp[ik_{1x}(x-n\Lambda)] + b_0\exp[-ik_{1x}(x-n\Lambda)]\}$$
$$\times \exp[-iK(x-n\Lambda)])\exp(iKx),$$

where the unit-cell width is Λ and the integer n is the

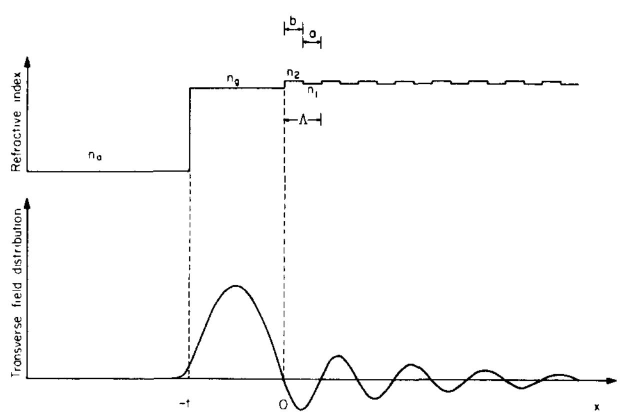

FIG. 1. The refractive-index profile of a Bragg waveguide (upper) and its calculated transverse field distribution (lower). The indices of refraction are $n_a=1$ (air), $n_g=3.24$ ($Al_{0.38}Ga_{0.62}As$), $n_2=3.43$ (GaAs), and $n_1=3.35$ ($Al_{0.20}Ga_{0.80}As$) at a wavelength $\lambda=1.15$ μm.

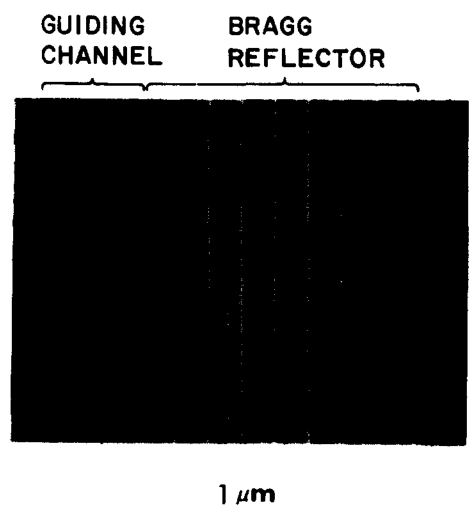

FIG. 2. A scanning electron micrograph of a cleaved section of a Bragg waveguide composed of alternating layers of GaAs and $Al_{0.20}Ga_{0.80}As$.

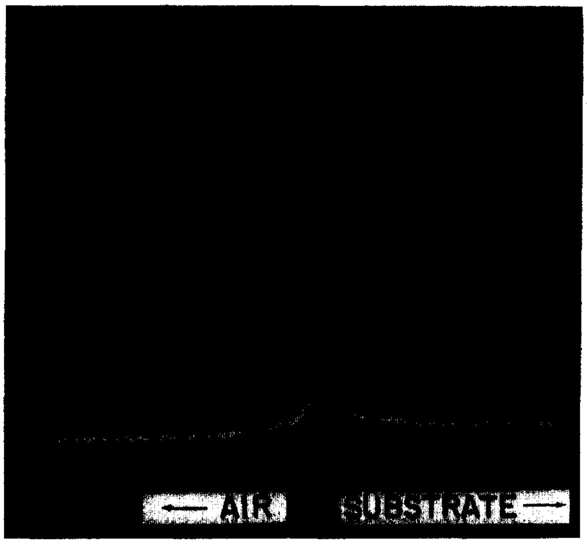

FIG. 3. Measured transverse intensity distribution of a confined mode in a Bragg waveguide 2 mm long. The horizontal scale is about 10 μm per (big) division.

cell index and a_0 and b_0 are the components of the eigenvector

$$\begin{pmatrix} a_0 \\ b_0 \end{pmatrix} = \begin{pmatrix} B \\ \exp(-iK\Lambda) - A \end{pmatrix}. \tag{4}$$

Confined lossless modes result when β, q_a, and k_g are all real. This, according to Eqs. (1) and (3) can only happen when the Bragg condition

$$[\tfrac{1}{2}(D+A)]^2 > 1 \tag{5}$$

is satisfied. This causes the Bloch wave number K to be complex

$$K = m\pi/\Lambda + iK_i \tag{6}$$

resulting in an evanescent oscillatory decay in the x direction as shown in Fig. 1.

The waveguide structure (see Fig. 2) consists of a guiding layer of $t = 1.37$ μm thick $Al_{0.38}Ga_{0.62}As$ and eight pairs of alternating layers of $a = 0.26$ μm thick GaAs and $b = 0.26$ μm thick $Al_{0.2}Ga_{0.8}As$ on a GaAs substrate. The layer thicknesses were chosen so that only one mode can exist at the excitation wavelength of 1.15 μm and so that the propagation conditions correspond to the center of the first optical forbidden gap. The waveguide was grown by conventional molecular beam epitaxy (MBE) techniques on a GaAs substrate.[3] Layers were grown at a substrate temperature of 580–600 °C at a rate of 1 μm/h. Ion beam etching was employed subsequent to the growth in order to obtain different thicknesses of the guiding layer.

The intensity distribution of the guided mode was obtained by focusing the output of a 1.15-μm He-Ne on the cleaved edge of the sample and by scanning the magnified (×43) image of the output edge[4,5] past a narrow slit and detector combination. The resulting intensity distribution for a Bragg waveguide 2 mm long is shown in Fig. 3. The oscillatory behavior in the layered medium, which has a period of ~0.52 μm, could not be resolved with the f1 optics of our imaging system which has a resolution of ~1 μm at the wavelength used. Despite the resolution limit, we have demonstrated guiding in the Bragg waveguide and the experimental results are consistent with the calculated values.

Because the Bragg reflector has a finite number of periods, the reflection coefficient at the interface between the guiding channel and the Bragg reflector is somewhat less than unity (i.e., the waveguide is slightly "leaky"). The calculated attenuation coefficient of the Bragg waveguide due to the resulting losses into the substrate, but neglecting the loss due to the bulk absorption,[6] is $\alpha = 14.97$ and 0.355 cm^{-1} for 8 and 16 periods, respectively. The attenuation coefficient decreases rapidly as the number of periods in the Bragg reflector increases. A rough experimental determination of the mode loss based on comparing the outputs of a number of Bragg waveguides of varying lengths under similar input conditions yielded $\alpha = 25 \pm 5$ cm^{-1}. This eliminates the possibility that the observed mode is that of a leaky waveguide, since the latter will, using the parameters of our waveguide, possess a loss constant $\alpha = 7.5 \times 10^3$ cm^{-1}.

The demonstration of Bragg waveguiding described above suggests a number of possibilities: The need to satisfy simultaneously the transverse resonance condition[7] in the guiding layer (i.e., a transverse round-trip phase delay equal to an integer times 2π) and the Bragg condition in the periodic medium makes it possible to design Bragg waveguides with transverse dimensions large compared to wavelength which can support only one transverse mode. Conventional dielectric waveguides with similar dimensions and index discontinuities would support several transverse modes.

Symmetric Bragg waveguides (i.e., guides with periodic layers on both sides) could be used for guiding in the medium to long x-ray region of the spectrum. Such guiding should possess high wavelength selectivity. The novel Bragg waveguide discussed in this paper is a selective transmission waveguide (bandpass filter), while a conventional periodic grating[8] is a selective reflector; these two different optical functions are therefore complementary to each other.

*Work done at California Institute of Technology was supported by the Office of Naval Research and by the National Science Foundation Optical Communication Program.
[1]A.J. Fox, Proc. IEEE 62, 644 (1974).
[2]P. Yeh and A. Yariv, Opt. Commun. 19, 427 (1976).
[3]A.Y. Cho and J.R. Arthur, *Progress in Solid State Chemistry* (Pergamon, New York, 1975), Vol. 10, pp. 157–191.
[4]W.L. Bond, B.G. Cohen, R.C.C. Leite, and A. Yariv, Appl. Phys. Lett. 2, 57 (1963).
[5]E. Garmire, H. Stoll, A. Yariv, and R.G. Hunsperger, Appl. Phys. Lett. 21, 87 (1972).
[6]J.L. Merz and A.Y. Cho, Appl. Phys. Lett. 28, 456 (1976).
[7]P.K. Tien, Appl. Opt. 10, 2395 (1971).
[8]D.C. Flanders, H. Kogelnik, R.V. Schmidt, and C.V. Shank, Appl. Phys. Lett. 24, 194 (1974).