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Strip-Loaded Film Waveguide

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Low-loss strip-loaded guides, consisting of 7059 glass film on fused quartz substrate with sputtered SiO_2 as the loading strip, have been investigated. The number of modes supported by the strip-loaded structures were determined experimentally and compared with the values predicted by the application of an equivalent index analysis. Agreement between theory and experiment is good in the case of the smaller number of modes which result from small loading, with the 7059 film thickness far away from cutoff.

Current interest in optical fibers and thin film devices for use in optical communication systems has prompted the development of several new guided wave structures. One of these is a single material (SM) fiber[1] representing an unclad fiber with a structural support. Basically, this is a planar slab waveguide structure with an increase in slab thickness in the central region where the guided light is concentrated. The region with the increased thickness can be considered a strip which loads a planar slab waveguide.[2]

Another type of a strip-loaded structure is shown in Fig. 1(a) where the planar waveguide has the higher index material and a strip of slightly lower index material acts as the loading. Since, within the region of the strip, most of the energy is confined in the *film*, requirements on the edge roughness of the strip are no longer as severe as in rectangular film waveguides[3] and therefore strip-loaded structures seem easier to fabricate.

Recently, Noda et al.[4] have demonstrated guiding in curved strip-loaded guides using a glass film waveguide with photoresist strip loading. They also analyzed the modal distribution of the structure by using a variational technique which, however, requires extensive computer calculations.

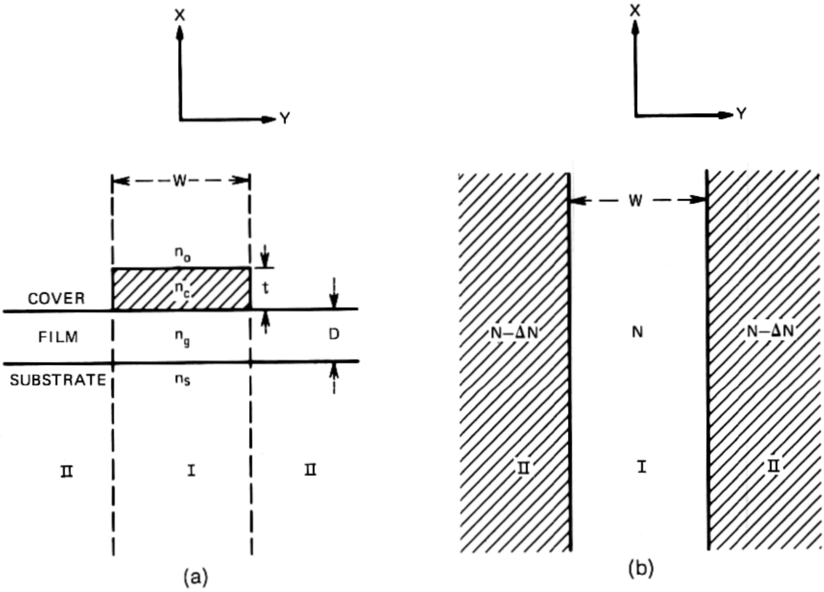

Fig. 1—Geometry of (a) strip-loaded film waveguide and (b) equivalent symmetrical waveguide.

In this paper we report studies on a strip-loaded guide consisting of 7059 glass film on quartz substrate with SiO_2 as the loading strip. We use this structure to explore the characteristics of strip-loaded guides in greater detail. We confirm the observations of Noda et al. on the guiding properties of strip-loaded structures. In addition, we use our low-loss structures to determine the number of modes supported by the strip-loaded guides and compare these results with the values predicted by the application of an equivalent index approach. This equivalent index concept is helpful in understanding the guiding characteristics of the relatively complex structure in a simple manner.

Figure 1(a) shows the geometry of a strip-loaded film waveguide. Wave propagation effects can be studied conveniently by dividing the structure into two regions. Region II represents an asymmetrical planar waveguide with n_o, n_g, and n_s as the refractive indices of the cover, film, and substrate, respectively. D is the thickness of the guiding film. Region I, on the other hand, includes a strip of superstrate of width W, thickness t, and index n_c.

The energy is confined in the x direction because of the high index film. When viewed from above, we see that the structure is symmetrical about the x-axis and can be considered an equivalent symmetrical guide [Figure 1(b)] with the loaded section having a higher index, thereby providing the confinement of energy in the y direction. We assume, however, that this equivalent symmetrical guide is unbounded in the x direction. Each mode in regions I and II can be characterized by its own phase velocity and the corresponding effective refractive index,[5] $N_{\mathrm{I}} = \beta_{\mathrm{I}}/k$ and $N_{\mathrm{II}} = \beta_{\mathrm{II}}/k$. The difference in effective index between the two regions is responsible for the confinement of the energy within the loaded section in the plane of the film and is given by

$$\Delta N = \Delta\beta/k = N_{\mathrm{I}} - N_{\mathrm{II}}. \tag{1}$$

In order to determine the effective index N_{I} in Figure 1(b), we assume $W \gg t$ so that region I can be considered a planar 4-layered structure. We assume that $n_g > n_s, n_c > n_o$. Using Maxwell's equations and matching the tangential field components at the interfaces, we can obtain the transcendental equation describing the propagation characteristics of the TE modes

$$\kappa D = \phi_{co} + \phi_s + m\pi \qquad m = 0, 1, 2, 3 \cdots, \tag{2}$$

where ϕ_s and ϕ_{co} are the phase changes on total internal reflection at the film boundaries given by

$$\phi_s = \tan^{-1}\frac{\gamma_s}{\kappa}, \tag{3}$$

$$\phi_{co} = \tan^{-1}\frac{\gamma_c}{\kappa}\,\frac{1 - \eta e^{-2\gamma_c t}}{1 + \eta e^{-2\gamma_c t}}, \tag{4}$$

and the parameter

$$\eta = \frac{\gamma_c - \gamma_o}{\gamma_c + \gamma_o}. \tag{5}$$

The transverse propagation constant in each layer is given by

$$\gamma_o^2 = \beta^2 - (kn_o)^2, \tag{6}$$

$$\gamma_c^2 = \beta^2 - (kn_c)^2, \tag{7}$$

$$\kappa^2 = (kn_g)^2 - \beta^2, \tag{8}$$

$$\gamma_s^2 = \beta^2 - (kn_s)^2, \tag{9}$$

where $k = \omega/c = 2\pi/\lambda$ is the free-space propagation constant and β is the propagation constant in the planar structure of region I.

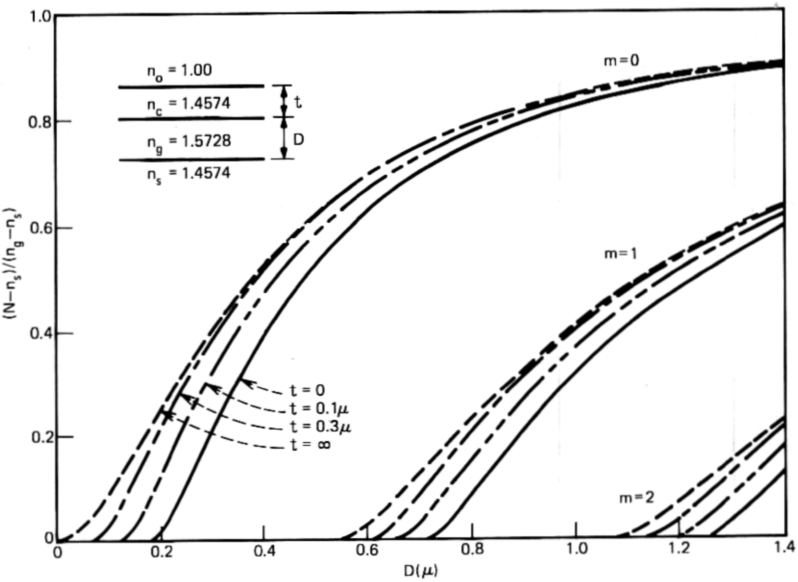

Fig. 2—Dependence of effective refractive index N on film thickness D and loading height t.

The effective index N can be obtained by solving eq. (2) by means of a computer. As an illustration, Fig. 2 shows the behavior of the effective index N as a function of film thickness D with the loading height t as the parameter for a specific set of values of the layer indices. By letting $t = 0$ in (4), we can obtain the propagation constant β of the planar guide in region II. We note the effective index $N(t)$ for a finite t is always larger than the case when $t = 0$. Therefore, the loaded region of the equivalent symmetrical guide [Fig. 1(b)] has an index N which is higher than that of the unloaded region by an amount ΔN. Figure 3 shows the plot of ΔN for the same parameters of the waveguide structure illustrated in Fig. 2. It is clear from Fig. 3 that, while ΔN increases with the height t of the loading, it does not have to be very large to achieve a reasonable value (of the order of 10^{-2}) of ΔN. In fact, the difference in ΔN between the cases $t = 0.3\ \mu$ and $t = \infty$ is indeed very small.

The total number of modes p in the equivalent symmetrical guide is obtained from the cutoff condition[6] as

$$p = 1 + \frac{2W}{\lambda}\{N^2(t) - N^2(0)\}^{\frac{1}{2}} \approx 1 + \frac{2W}{\lambda}(2N\Delta N)^{\frac{1}{2}}, \quad \Delta N \ll 1. \qquad (10)$$

By using the computed values for $N(t)$ and $N(0)$ in (10), the number of modes in the strip-loaded structure can be determined.

We made several strip-loaded guides using RF-sputtered 7059 film waveguides on glass on fused quartz substrates. The film thickness was above cutoff, allowing at least one propagating mode in the film without the loading. To avoid using photoresist in the sputtering system, a thin layer of SiO_2 was sputtered on the 7059 film first and then, using photolithographic techniques, the SiO_2 film was etched everywhere except over a strip region using buffered HF as the etchant. Etching was carried out in small steps to control the depth carefully. The loading strip width W was varied from 5 to 12.5 μ. The height of the loading strip was 0.1 to 0.4 μ, and the values for the thickness of the film were chosen to be between 0.2 to 0.5 μ.

A Gaussian He–Ne laser beam was apertured and used to excite the strip-loaded guide by means of a prism coupler placed directly on the strip (Fig. 4). Coupling to the strip-loaded guide was easier when the height t was small. In addition to the use of a rotating table in the

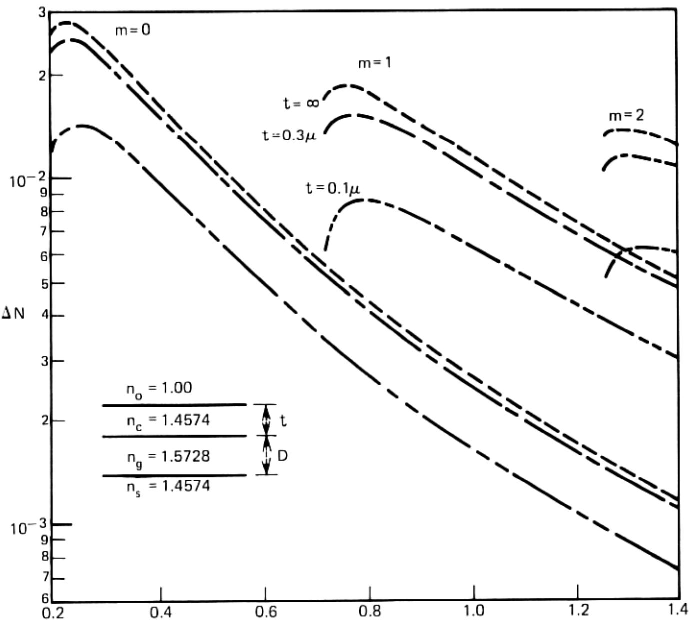

Fig. 3—Difference in effective refractive index between regions I and II vs film thickness D.

Fig. 4—Propagation of light beam guided in a strip-loaded guide. At the point where the strip is scratched, the light is radiated.

prism coupler arrangement, provision was made to tilt the entire assembly in the plane perpendicular to the plane of the table. Each mode was excited by varying the position of the beam as well as by changing the angle of excitation. Where there are only few modes and very little mode conversion, the modes can be identified by viewing the far field pattern, and the number of modes can be counted by varying the exciting conditions.

In order to compare the measured number of modes with the predictions of eq. (10), we determine N and ΔN from Figs. 2 and 3. For this purpose, the refractive index n_g and thickness D of the 7059 film was obtained by measuring the synchronous angles using a prism coupler.[7] The thickness t was measured using a Tally-Surf thickness measuring machine and the width W by viewing the structure in a microscope. The index of SiO_2 film was assumed to be the same as that of the quartz disc used in sputtering. By computing $N(t)$ and $N(0)$, the number of modes p was calculated and is shown in Fig. 5.

Each measured point (▲) in Fig. 5 represents one guide structure. We find the agreement between theory and experiment is good in the case of smaller number of modes which result from small loading with the film thickness D far away from cutoff. Since it was rather difficult to excite the structure with a large strip thickness using the present techniques, investigation of structures with large strip thickness was not possible. Moreover, as the number of modes increased, the higher-order modes could not be resolved because of mode conversions resulting from imperfections. In the case of higher-order modes, the measured

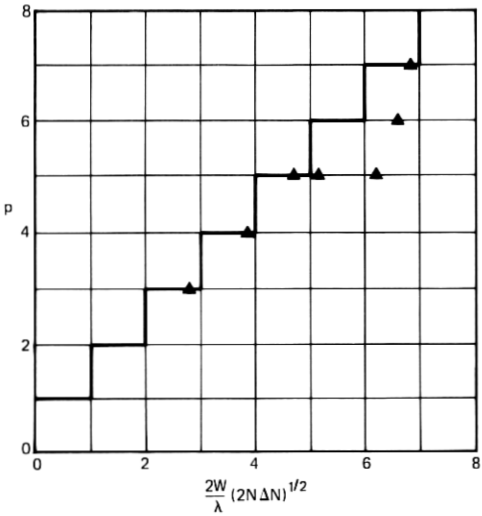

Fig. 5—Number of modes in the strip-loaded guide. The ▲ points represent the experimental results. Note that N and ΔN are functions of λ to be determined from Figs. 2 and 3.

losses in the structure were as high as 1.5 to 2 dB/cm when the strip edge roughness was $\approx$ 6000 Å and the lowest measured loss was 0.5 dB/cm for the fundamental mode. It is also interesting to note that the edge roughness problem once again becomes important with the increased loading resulting from the increase in the energy content in the strip.

A more generalized approach to these new guided wave structures has been developed by Marcatili[8] and our results are in agreement with his analysis.

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