Simple Estimation of Transition Losses in Bends of Wide Optical Waveguides by a Ray Tracing Method

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***Abstract*—Numerical simulation methods based on modal theory are not suitable for wide waveguides where the number of guided modes increases greatly. A simple ray tracing method for treating this situations is proposed, and its results are validated with experimental measurements of fabricated waveguides. The important agreement between theory and experiments makes this method an easy way to design bent waveguides with transitions between sections with different curvature.**

***Index Terms*—Integrated optics, simulation, waveguide bends, waveguide transitions.**

I. Introduction

THE PRESENCE of curves in a waveguide implies an unavoidable increase of attenuation losses, both in the curve itself (radiation losses) and in the transition between waveguides of different curvatures (transition losses) [1], [2].

Our research group has wide experience in the fabrication of antiresonant reflecting optical waveguides (ARROW) [3], which have been the basis of the design of an optochemical sensor of higher sensitivity than conventional ones [4]. As it is based on the absorbance of a sensing membrane, it uses total guided power and does not require the waveguides to be single mode. The next step in this development is a new configuration for the sensor to make it more suitable for real field conditions, and this new configuration demands the introduction of bent waveguides (see Fig. 1). Therefore, it has been necessary to study our waveguides to find the optimal bending parameters, in order to meet the dimensional characteristics required without this involving excessive attenuation.

The tolerance requirements for this design implied the use of multimode 50-μm optical fiber in diameter and, in order to minimize coupling losses, the introduction of waveguides of similar width, which are expected to show high transition losses if they have bends. Moreover, when the size of waveguides (and, as a consequence, the number of modes) increases, classical numerical methods fail to make accurate estimations or are excessively time consuming. As an example, a waveguide like that in Fig. 2, with a rib width of 50 μm, supports above 80 guided modes, a number which would require very large computational power. Consequently, a simple method to predict this kind of losses for these waveguides is an interesting investigation goal in this field.

Manuscript received August 8, 2003; revised November 18, 2003.

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Digital Object Identifier 10.1109/LPT.2004.823712

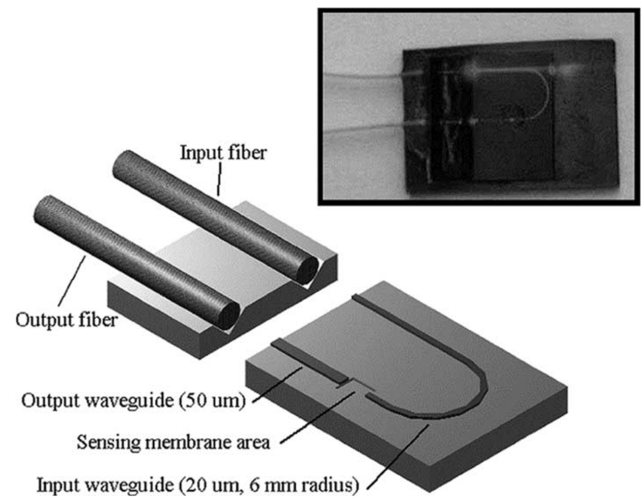

Fig. 1. Optochemical sensor employing bent ARROW waveguides (light outflow in the input waveguide of the photography is not due to the transition between curvatures but to the fact that light is injected using a multimode waveguide to increase packaging tolerances).

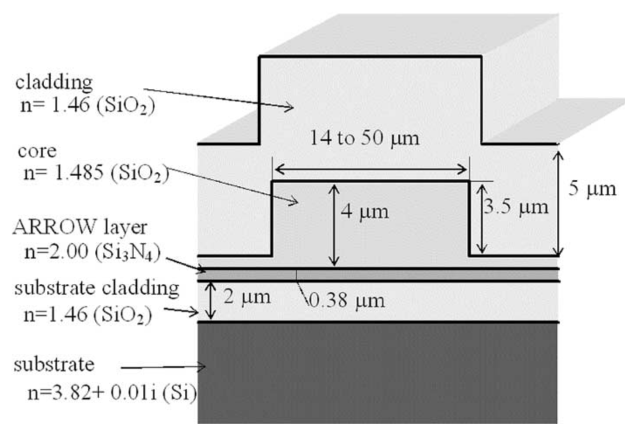

Fig. 2. Structure of the ARROW waveguides fabricated.

The results presented in this letter show that an approach based on ray theory [5], as it is used in multimode fibers [6], can be useful for achieving an accurate estimation of transition losses.

II. Design Method

The main objective of this work is to find an easy and fast method to estimate the transition losses of wide waveguides, and so the extreme simplicity of the theoretical model employed. Nevertheless, the results obtained must be compared to experimental measurements in order to assure the adequacy of our assumptions.

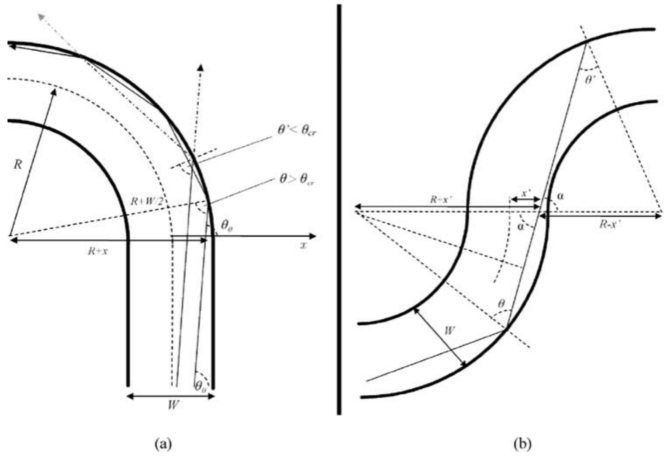

Fig. 3. (a) Ray tracing in the transition between a straight and a curved waveguide and (b) in the transition between two waveguides of opposite curvatures.

The rib ARROW structure under study, designed to be used with working wavelengths around 650 nm, is shown in Fig. 2. The relative dimensions of the core width and height, together with the fact that this kind of waveguide allows only one guided mode transversal to the antiresonant layers, give us the basis to reduce the ray tracing to the plane containing the curvature, ignoring rays which follow skew trajectories. In fact, the rib waveguide can be transformed into its equivalent planar waveguide, using a simple effective index method [7].

Now we assume that transition losses in a change of curvature are originated by the rays guided in the first section of the waveguide which do not remain guided after the transition. In order to evaluate these losses, it is necessary to calculate the incidence angle of rays after the change of curvature (θ) related to their angle θ_0 and position x before that change.

Fig. 3(a) shows the transition between a straight waveguide and another of constant radius R. Rays in dotted lines are those which fail to complete Snell's law total reflection condition

$$\theta(\theta_0, x) \geq \theta_{\rm cr}, \qquad \sin\theta_{\rm cr} = \frac{n_{\rm clad}}{n_{\rm core}} \tag{1}$$

where $n_{\rm clad}$ and $n_{\rm core}$ are the waveguide cladding and core effective refraction indexes obtained using the effective index method. This condition, through some geometrical calculations, implies the following restriction for rays to be totally reflected:

$$\begin{aligned}(\sin.\text{theorem})\frac{R+x}{\sin\theta(\theta_0,x)} &= \frac{R+\frac{W}{2}}{\sin(\pi-\theta_0)} = \frac{R+\frac{W}{2}}{\sin\theta_0}\\ \Rightarrow \sin\theta(\theta_0,x) > \sin\theta_{\rm cr} &\Leftrightarrow \sin\theta_0\frac{R+x}{R+\frac{W}{2}} > \frac{n_{\rm clad}}{n_{\rm core}}. \end{aligned} \tag{2}$$

Assuming that refracted rays—those which do not fulfill (2)—are entirely lost after a short length, transition losses due to this change of curvature can, thus, be evaluated as the ratio in decibels between guided power after (P_t) and before (P_0) the transition

$$a_{\rm tsc} = -10\log\frac{P_t}{P_0} = -10\log\frac{\int_{-\theta_{\rm cr}}^{\theta_{\rm cr}} d\theta_0 \int_{R-W/2}^{R+W/2} f(\theta_0,x)dx}{\int_{-\theta_{\rm cr}}^{\theta_{\rm cr}} d\theta_0 \int_{R-W/2}^{R+W/2} dx} \tag{3}$$

where

$$f(\theta_0,x) = \begin{cases} 1, & \text{if } \theta_0, x \text{ meet (2)} \\ 0, & \text{in any other case.} \end{cases}$$

In order to make this expression simpler, a uniform power distribution over θ_0 and x at the transition is assumed, as light has previously propagated through a straight and wide waveguide section.

Similar though more complicated calculations must be performed for the curve-to-curve transition shown in Fig. 3(b). The condition for rays to be totally reflected in the second curved section can be obtained as

$$\begin{aligned}(\sin.\text{theorem})\frac{R+\frac{W}{2}}{\sin\alpha} = \frac{R+x'}{\sin\theta}&;\frac{R+\frac{W}{2}}{\sin\alpha} = \frac{R-x'}{\sin\theta'}\\ \Rightarrow \sin\theta' > \sin\theta_{\rm cr} &\Leftrightarrow \frac{R-x'}{R+x'}\sin\theta > \frac{n_{\rm clad}}{n_{\rm core}} \end{aligned} \tag{4}$$

and the initial distribution of rays over θ and x' should now be obtained from the previous analysis of the straight to curve transition. As expected, the fraction of rays which remain guided after this transition is much lower than in the former situation.

Finally, the analysis of the curve-to-straight transition provides an unexpected conclusion: In our approximation, there are no transition losses, as every guided ray in the curve fulfills the total reflection condition in the subsequent straight section. Of course, this curve-to-straight transition will actually have losses, due to modal shape mismatch aspects which are not taken into account in our model. Our point is that this kind of loss can be neglected when treating with a large number of modes. This asymmetrical behavior is in contradiction with classical modal studies of bendings, which predict exactly the same transition losses for a straight-to-curve transition than for the curve-to-straight case [8], as attenuation is directly related to the factor $(R_1^{-1} - {R_2}^{-1})^2$ (in a Gaussian profile approximation), with R_1 and R_2 as the radii of the two sections which form the transition. This last point reinforces our statement that modal methods can hardly be applied to wide transitions and the convenience of introducing an alternative treatment for them.

III. Results

The method described in the previous section has been applied to ARROW waveguides as those in Fig. 2, with rib widths ranging from 14 to 50 μm and curvature radii from 1 to 6 mm. In order to compare our predictions with experimental results, the corresponding waveguides have been fabricated in two different configurations (see Fig. 4): "C" waveguides, which present no transitions, and "S" waveguides, with one of each type of transition mentioned before (straight-to-curve, curve-to-curve, and curve-to-straight). Total excess losses for these waveguides have been measured by end-fire coupling, and then, subtracting to the attenuation of an "S" waveguide the attenuation of its matching "C" and the corresponding straight sections (about 0.3 dB/cm, calibrated previously), transition losses are directly obtained. Our study has indicated that, in the range of waveguide widths (tens of micrometers) and radii (millimeters) investigated, transition losses are usually the main source of attenuation due to

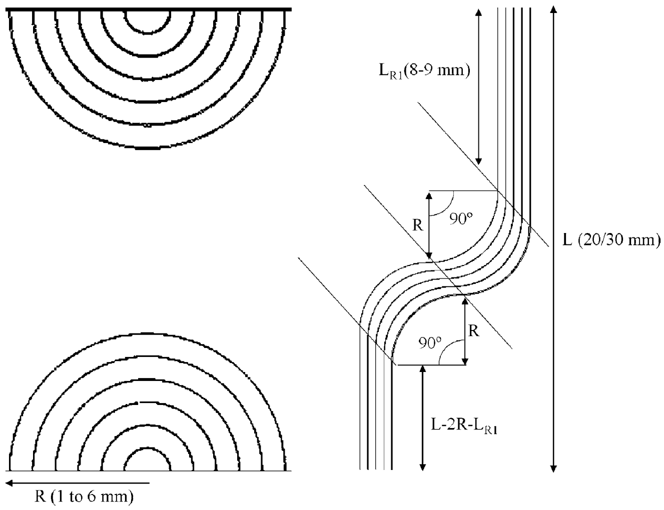

Fig. 4. Details from the masks employed in the fabrication of "C" and "S" waveguides. Total length of "S" chips is 20 mm for radii ranging from 1 to 3 mm, and 30 mm for larger radii.

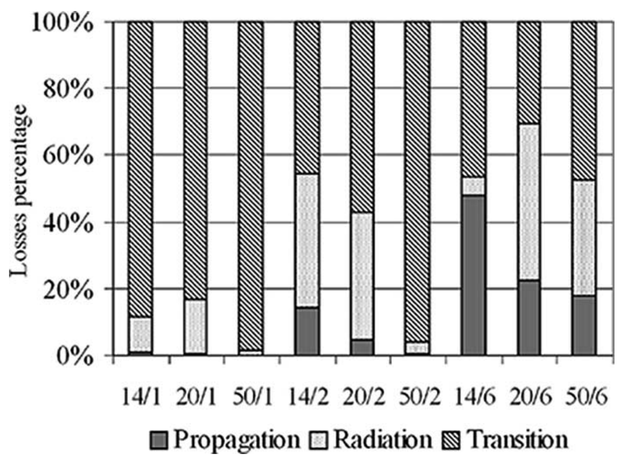

Fig. 5. Distribution of losses in the curved rib ARROW waveguides fabricated among the possible attenuation causes. W/R indicates a waveguide of rib width W and radius R.

curvature (see Fig. 5). This reinforces the utility of our estimation method.

Fig. 6 shows predicted and measured total transition losses for different "S" waveguides. A 50-μm-width 1-mm-radius waveguides produce complete attenuation of the guided light according to our model. This in fact is in agreement with experimental data, since the measured attenuation of these waveguides is under the dynamic range of our system (65 dB). Therefore, this point is not represented in the graph, although it contributes to theory–experiment matching.

The rest of the graph data sustains the validity of our estimation method. It allows the prediction of the magnitude of transition losses for a given waveguide within the tolerance given by the packaging processes, which are usually one of the main sources of attenuation. Experimental measurements are slightly above the calculated values, probably due to modal matching losses in the transitions, which are not taken into account. In

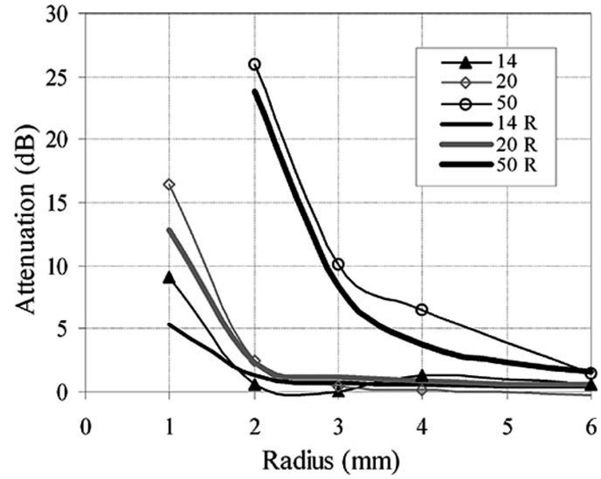

Fig. 6. Predicted (labeled with "R") and measured total transition losses for different "S" waveguides at $\lambda = 678$ nm.

fact, results are worse for the 14-μm-wide waveguides with smaller radii, where modal effects in transitions begin to be significant. For rib widths under this, our method would only provide a rough estimation of transition losses, useful for a first design approach.

IV. Conclusion

A simple but powerful method for the study of transition losses in wide optical waveguides has been developed. Its performance has been validated by comparing the results obtained with this method to experimental measurements of fabricated rib ARROW waveguides with various rib widths and curvature radii. The agreement between theory and experiment confirms this method as suitable for a fast and easy estimation of total losses of a waveguide prior to its fabrication.

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