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LETTER

Effects of Trench Location on the Attenuation Constant in Bent Step-Index Optical Waveguides

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SUMMARY Pure bend loss of a fiber with a trench section is calculated by the alternating-direction implicit finite-difference method. The dependence of the loss on the trench location is evaluated. The mechanism of the oscillatory behavior of the loss is discussed in terms of a modal approach in a dielectric slab waveguide.

key words: *bent optical waveguides, pure bend loss, finite-difference method*

1. Introduction

Waveguide bends with small radii are indispensable for increasing the packaging density of integrated optical circuits [1], [2]. The introduction of a trench section at the outer side of the bend is an effective means to reduce bend loss. Although some theoretical papers concerning the effects of the trench on the bend loss have been published [3]-[7], the effects of the trench location on the attenuation constant (pure bend loss) have not been fully studied.

The purpose of this letter is to report on the attenuation constant of a bent step-index fiber with a trench. In the analysis, we use the alternating-direction implicit finite-difference method (ADIM) [8], [9] with a transparent boundary condition [10], since it is an efficient means of analyzing the propagating beam in three-dimensional optical waveguides, as compared with the conventional FFT-beam-propagation method. The mechanism of the oscillatory behavior of the attenuation constant is discussed in terms of a modal approach in a dielectric slab waveguide [11].

2. Bent Fiber with Trench Section

A single-mode fiber with a core radius of $a=5\ \mu$m is considered. A stepped approximation is used for the circular core [7]. The refractive indices of the core and cladding are $N_{CO}=1.503$ and $N_{CL}=1.5$, respectively. A wavelength of $\lambda=1.55\ \mu$m is used in this analysis.

To apply the ADIM to the analysis of the bent fiber, we employ a technique in which the index profile is transformed to that of an equivalent straight fiber [1]. A trench section is placed in the cladding at the outer side of the bend, as shown in Fig. 1. The refractive index N_{TR} of the trench is taken to be smaller than N_{CL}, i.e., $N_{TR}=1.497$ in this analysis. Due to the symmetry of the configuration with respect to the y axis, the region is subdivided into 128 horizontal and 64 vertical zones. The spacings $\Delta(=\Delta x=\Delta y)$ and Δz are chosen to be $a/6\cong 0.833\ \mu$m and 2 μm, respectively [9].

Figure 2 shows the attenuation constant α (pure bend loss) as a function of the spacing between the core and the trench. Bending radius R is taken to be 1.75 cm. The attenuation constant is evaluated from the steady-state differential-power-loss level [1], when the fiber is excited with the fundamental mode LP_{01} of the straight fiber. It is found that α is small when the trench is made near the core. The appropriate location of the trench is close to the so-called radiation point

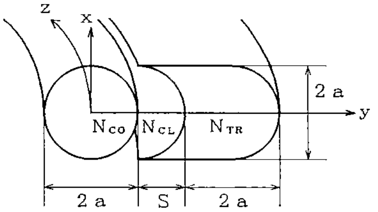

Fig. 1 Configuration of bent fiber with trench.

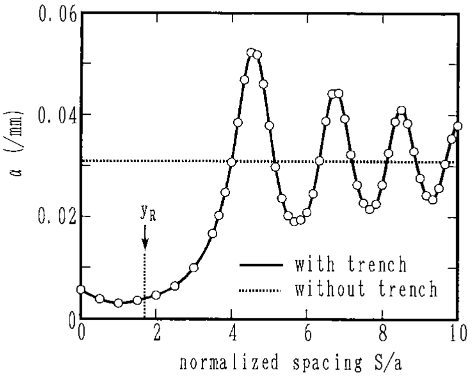

Fig. 2 Attenuation constant vs. spacing between core and trench.

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y_R. The radiation point is the point in the cladding where the propagation constant satisfies $\beta = k_0 N_E(y)$, in which $k_0 = 2\pi/\lambda$ and N_E is the index profile of the equivalent straight fiber. The radiation point on the y axis corresponds to a normalized spacing of $S/a = 1.7$ for a bending radius of $R = 1.75$ cm.

It is interesting to note that α shows oscillatory behavior as the spacing is further increased. Since this behavior is very similar to that observed in two-dimensional waveguides [6], we next interpret this phenomenon using a modal approach in a dielectric slab waveguide.

3. Mechanism of Oscillatory Behavior of Attenuation Constant

Consider the bent slab waveguide with a trench which has the same width as the core, shown in Fig. 3(a). The refractive indices are taken to be $N_{CO} = 1.002$, $N_{CL} = 1.000$ and $N_{TR} = 0.9994$, respectively. The core width of $2D$ is 7.546 μm and a wavelength is $\lambda = 1$ μm, leading to a normalized frequency of $V = 1.5$. The bending radius is $R = 1.26$ cm. Numerical parameters for the analysis are the same as those in Ref. [6]. The waveguide is excited with the fundamental mode TE_0 of the straight waveguide.

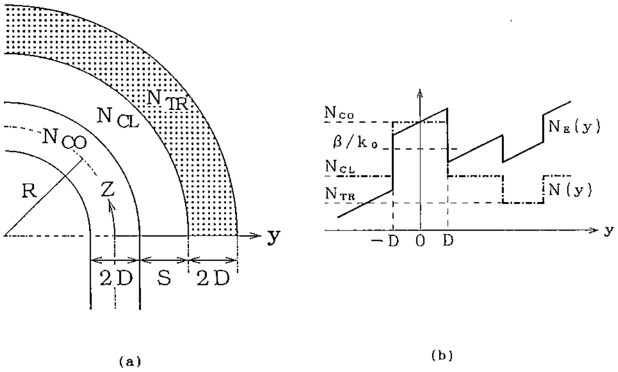
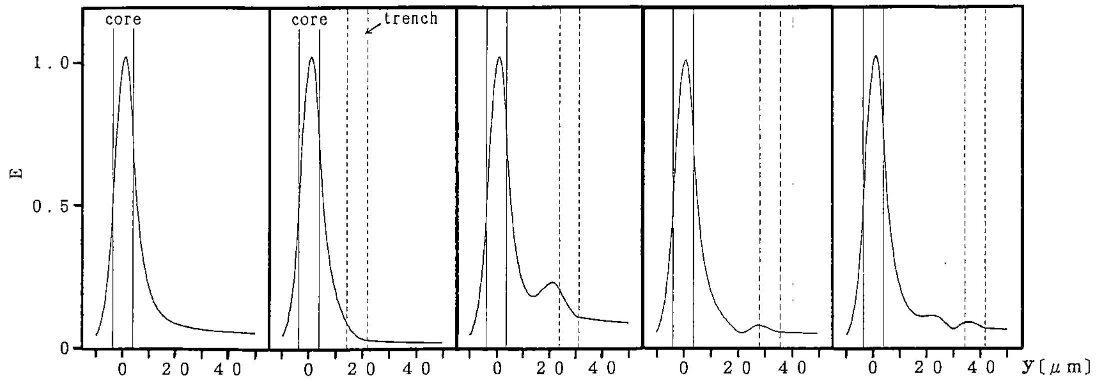


Fig. 3 (a) Configuration of bent slab waveguide with trench and (b) index profile.

Using the equivalent straight waveguide, the index profile is changed, as shown in Fig. 3(b). It is seen that if the trench is made in the vicinity of the radiation point, the cladding index close to the core is suppressed to a value of less than the effective index β/k_0 of the bent waveguide. This leads to the evanescence of the cladding field, as will be seen in Fig. 4 (b), with a subsequent small attenuation constant. It should be noted that, as the spacing S between the core and the trench is increased, the sandwiched region between the core and the trench turns to a quasi-waveguiding region. Consequently, we can assume the effective index in the sandwiched region. This means that a first-mode-like field must propagate in the sandwiched region, particularly when the effective index in the sandwiched region is close to the effective index β/k_0 of the bent waveguide [11]. Since the index at the outer side of the trench is large, the field must be a leaky wave, leading to a large attenuation constant. As the spacing S is further increased, the effective index in the sandwiched region becomes again close to β/k_0; therefore, a second-mode-like field must propagate in the sandwiched region, leading to a large attenuation constant. When the trench is located midway between the points where the attenuation constant shows the first and second maxima, the difference between the effective index of the sandwiched region and β/k_0 of the bent waveguide is large. Therefore, the evanescence of the field is somewhat enhanced due to the depressed index of the trench, as will be seen from Fig. 4(d), leading to a relatively small attenuation constant.

Figure 4 shows the steady-state field observed at large propagation distances in the bent slab waveguide. Each field is normalized to unity at the center of the core. It is found that the evanescence of the cladding field is enhanced when the trench is properly placed. (See Fig. 4(b).) In contrast, in Fig. 4(c), the field



(a)without trench (b)α:first minimum (c)α:first maximum (d)α:second minimum (e)α:second maximum

Fig. 4 Steady-state field in bent slab waveguide with trench.

propagates with a local maximum in the sandwiched region, which suggests first-mode-like behavior. In Fig. 4(e), we can find two local maxima in the propagating field of the sandwiched region, which suggests second-mode-like behavior.

It can be said that the method of placing a trench section is an effective means for reducing the pure bend loss, provided the trench is located between the core and the radiation point of the waveguide.

4. Conclusions

We have analyzed a bent step-index fiber with a trench section using the alternating-direction implicit finite-difference method. The dependence of the attenuation constant on the trench location is studied in a three-dimensional waveguide and the mechanism of its oscillatory behavior is discussed in terms of a modal approach in a two-dimensional waveguide.

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References

[1] Saijonmma, J. and Yevick, D., "Beam-propagation analysis of loss in bent optical waveguides and fibers," *J. Opt. Soc. Am.*, vol. 73, no. 12, pp. 1785–1791, 1983.

[2] Baets, R. and Lagasse, P. E., "Loss calculation and design of arbitrarily curved integrated-optic waveguides," *J. Opt. Soc. Am.*, vol. 73, no. 2, pp. 177-182, 1983.

[3] Kawakami, S., *Optical waveguides*, Chap. 7, Asakura Shoten, 1980.

[4] Neumann, E. G., "Low loss dielectric optical waveguide bends," *Fiber and Integrated Optics*, vol. 4, no. 2, pp. 203-211, 1982.

[5] Marcuse, D., "Influence of curvature on the losses of doubly clad fibers," *Appl. Opt.*, vol. 21, no. 23, pp. 4208-4213, 1982.

[6] Yamauchi, J., Ikegaya, M. and Nakano, H., "Bend loss of step-index slab waveguides with a trench section," *Microwave and Optical Tech. Lett.*, vol. 5, no. 6, pp. 251-254, 1992.

[7] Yamauchi, J., Ikegaya, M. and Nakano, H., "Analysis of bent step-index optical fibres by the beam propagation method," *IEE Proc.* Part J, vol. 139, no. 3, pp. 201-207, 1992.

[8] Press, W. H., Flannery, B. P., Teukolsky, S. A. and Vetterling, W. T., *Numerical recipes: the art of scientific computing*, pp. 644–645, Cambridge Univ. Press, New York, 1986.

[9] Yamauchi, J., Ando, T. and Nakano, H., "Beam-propagation analysis of optical fibres by alternating direction implicit method," *Electron. Lett.*, vol. 27, no. 18, pp. 1663-1665, 1991.

[10] Hadley, G. R., "Transparent boundary condition for beam propagation," *Opt. Lett.*, vol. 16, no. 9, pp. 624-626, 1991.

[11] Kawakami, S., Private communications, 1991.