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Calculating transfer and loss coefficients in bent slab single mode micro-waveguides and micro-rings considering bending and coupling losses

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ABSTRACT

In this work, using boundary element numerical method, monochromatic wave propagation equation was solved in a bent micro-waveguide coupled with two direct waveguides. In the previous works, bent micro-waveguides have been generally considered by themselves without comparison with any direct waveguides; however, in this study, the bent waveguide was assumed to be connected to two direct waveguides at both ends. Transfer matrix was proposed in a multi-mode bent waveguide. Using the components of this matrix, loss coefficients were calculated. Results of modeling for the single-mode waveguide were compared with those from FDM method, which showed that the proposed method had higher accuracy and needed less time for calculation. Finally, by eliminating the effects of coupling, a model was presented for calculating loss coefficient in micro-rings and the behavior of loss coefficient was investigated in terms of radius and wavelength.

1. Introduction

Considering the growing expansion in the application of optical waveguides in various fields, it is important to investigate all aspects of these waveguides. In an ideal waveguide, waveguide modes propagate without any loss; but, in reality, no completely ideal waveguide exists. Various factors attenuate characteristic modes in optical waveguides. Losses caused by diffraction or propagation are among the ones generated due to the microscopic structure. Another attenuation type is absorption loss caused by molecular structure and the impurities existing in waveguides. Bending losses are also divided into two micro and macro types. Micro-bending losses are caused by the variation of core diameter and fine bending during construction, pressure, and tension. Macro-bending losses occur when the curvature of optical waveguides exceeds a certain limit. When an optical waveguide is bent, the propagated light may disappear because of losses [1]. Furthermore, light might move from one mode to another conducted mode, a phenomena known as mode coupling [2]. Considering the increasing application of optical fibers and cables in various fields, it is necessary to investigate environmental effects and mechanical forces applied to fibers and cables. Thus, it is essential to present a complete model for macro losses in the design of the fibers made for optical communications [3,4] or optical instruments with bent fibers in their structures such as micro-rings [5], amplifiers in which optical fibers are in a torus shape [6], fiber laser when fibers are in a torus shape [7], and some other forms of optical sensors used for measuring voltage, pressure, tension, and temperature [3,8,9].

Studies on the effect of bending in optical fibers are highly important because of its destructive effect on transmitted power [10] and also its unavoidable nature in different construction and application steps, which results in the application of mechanical forces to fibers. In addition, optical fibers are sometimes used at high powers including transferring laser light when laser is needed to be located further and its light is to be used [11]. In these cases, losses not only can have destructive effects such as temperature damage to fibers or cables, but may also be hazardous in safety terms.

Since bending loss increases with decreasing radius and increasing wavelength [1], most recent standards have defined a maximum wavelength for the fiber [12]. Effect of temperature on bending loss in multi-mode fibers is caused by the dependence of refractive index on temperature, which is negligible [10]; however, experiments have shown that, in single-mode fibers, temperature [13] and presence of coating layer [14] affect rate of bending loss.

Bent dielectric waveguides play an important role in photonics, some of which were mentioned above; hence, bending loss of optical fibers has been studied using different methods. Primary models

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of bent waveguides have been introduced by Marcatili [15] in 1969 and Marcuse [16] in 1971. By calculating electric and magnetic fields for bent waveguides and finding Poynting vector, Marcuse proposed a general method for the calculation of bending loss [17]. In 1986, Harris investigated bending loss in a bent single-mode waveguide by considering the coupling between propagation field and reflected field from the coating [18].

Boechat et al. [2] examined the bending losses in two fibers of silicon with plastic coating and completely silicon; after comparing the results with the experimental ones, they proposed a model through which bending loss could be predicted as a function of fiber (core diameter and numerical aperture) and bending (radius and bending length) properties. They concluded that irregular optical coupling along the fiber could cause irregular power distribution among the conducting modes [2]. Marcuse calculated bending loss in slab and cylindrical waveguides using Fraunhofer diffraction theory and verified the obtained relations by comparing them with the experimental ones [19].

So far, several methods have been employed to calculate bending loss, which include beam propagation methods [20–22], linear methods [23], finite difference method [24], finite element method [25], and conformal mapping method [26,27].

Faustini and Martini [28] investigated bending loss at the wavelengths of 800–1600 nm and bend radii of 13.5–27.5 mm for two different types of fibers. They considered that the bent fiber's leaking modes were resulted from a weak perturbation within the distribution of a conducted field in direct fibers as well as weak modes reflected from the fiber coating that were assumed to be direct. Then, they compared the obtained results with the equations proposed by Renner [14] for bending loss in bent waveguides with step-wise refractive index [28].

Melloni et al. assumed bending as a perturbation in a waveguide and used the relations for direct waveguide fields to represent modes of bent waveguides [29].

Bienstman et al. [30] proposed a model for the shape transformation of a bent waveguide. In their study, it was found out that, due to the lack of adjustment between bent and direct waveguides, propagation occurred when light was propagated between bent and direct waveguides [30].

In order to study bending loss in a slab dielectric waveguide, Hiremath et al. [31] assumed the electric field as an exponential function and propagation constant of bent modes, due to radial loss, as a complex number. Then, considering Maxwell's equations, they obtained the field inside the waveguide as the linear combination of the first and second kind Bessel functions. The field outside the waveguide was also found as Hankel functions. They concluded that, for a bending with large radii, bending modes could be almost quasi-symmetrical to the modes of direct waveguide. By decreasing the bend radius, vertical shearing modes became more and more bending and subsequently losses increased; also, when the losses increased, maximum value of the field moved toward the outermost boundary of the bending [31].

In order to present a model for bending loss in single-mode fibers with multiple coating layers, Wang et al. [32] divided the total bending loss into two components: one caused by the loss in the bent part and another due to the inequality of propagation modes in the bent and direct parts of the waveguide; the displacement of propagation modes caused losses. This model showed that the inner coating layers had a more effect on bending loss. Finally, they concluded that, in addition to the above-mentioned points, a coupling occurred between primary propagation field and radial field reflected from the coating layer. Results of their study showed the existence of some maximal points in the diagram of drop in terms of bend radius. They obtained a relation between power drop and bend radius in a single-mode fiber as the first kind Bessel function [32].

Matthijsse and Griffioen [1] concluded that, in general, bending loss was sharply increased by decreasing bend radius or increasing wavelength. After measuring several fibers, they found that, depending on the bend radius, bending loss was sometimes linearly related to bend radius and, in some other cases, a logarithmic relation was established. Bending loss can be calculated either directly or indirectly according to the lifetime of light in fiber; this article showed the consistency between these two methods [1].

Schermer and Cole [33] studied simulation results for a bent fiber using BPM and modified the equations previously proven by Marcuse which have been used for single- and multi-mode fibers. This simulation showed that high-order modes had higher loss. This property can be used for eliminating high-order modes and thus, by managing a large area of the mode, single-mode conditions can be achieved [33].

Today, there are different numerical and analytical methods for analyzing light propagation in waveguides and calculating losses caused by bending. When using analytical methods, some approximations are used for problem solving which may excessively reduce accuracy. Analytical methods cannot be used for solving some problems. With the progress of computer sciences, there has been increased growth in the use of numerical methods for problem solving. Boundary element method is one of the appropriate numerical methods for solving differential equations and problems related to electromagnetics, which has higher accuracy and speed than other methods. This method has been used in solving thermal problems in solid state lasers [34–37] and analysis of photonic crystals [38,39] and has been compared with other methods as well.

In this work, to simulate monochromatic wave propagation in bent slab waveguides with a radius of a few microns, Helmholtz equation was solved using numerical boundary element method. First, this equation was transformed into boundary integral equations using second form of Green's theorem; then, it was solved using conventional boundary element methods. In most of the reported studies, coupling effect of direct waveguide to bent waveguide has not been considered and the bent part has been separately analyzed. However, in the proposed model, bending loss and the loss caused by coupling of the bent to direct waveguides were taken into account. Finally, a method was presented for eliminating the coupling effect of direct waveguides and bending losses were calculated for different angles. Then, by extrapolating the obtained data, the amount of loss for a bend with the angle of 2π, equal to a micro-ring, was calculated. Loss variations in terms of wavelength and micro-ring radius were examined to propose a relation for calculating loss in the micro-rings made of glass.

2. Theoretical model

Assume that a bent waveguide with opening, mean radius, bend angle, and length of a, $\bar{\rho}$, θ_B and $L_B = \bar{\rho}\theta_B$, respectively, is connected to two direct waveguides at both ends (Fig. 1). Electromagnetic wave, either in a transverse electric (TE) or a transverse magnetic (TM) mode, enters the bent waveguide from the side of direct waveguide (I), then enters the direct waveguide (O), after passing through the bent one. While passing through the bent part and entering the direct waveguide, the wave is attenuated for two reasons; the first cause of loss is the bent path of wave which is called bending loss. The second cause of loss is the passing wave through the bent path is transformed, at the end of the path, the characteristic mode of the direct waveguide is no longer. Consequently, a part is lost after entering the direct waveguide and another part is propagated in it as the characteristic mode of the direct waveguide. In this article, this loss was called coupling loss. This phenomenon also occurs when the wave enters the bend from the direct waveguide. In the proposed model, these effects were included. Additionally,