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A novel and accurate method for analysis of single-mode dispersion-shifted and dispersion-flattened fiber directional coupler

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ABSTRACT

Employing the simple series expression for fundamental mode based on Chebyshev technique, we present a simple but accurate analysis of coupling characteristics of identical single-mode dispersion-shifted trapezoidal and dispersion-flattened graded W and step W fibers directional couplers. Analytical expressions of the relevant parameters are formulated and the concerned calculations require simple and little computations. We show that our formulations on coupling characteristics of such type of fibers directional couplers provide excellent results.

1. Introduction

Directional coupler formed by single-mode optical fibers using evanescent field coupling between two adjacent parallel single-mode fibers have come out as the most prospective device in optical-fiber sensor [1–4], nonlinear optics [5], wavelength filter [6] etc. In order to design this type of coupling appropriately in various field of use, one should have proper knowledge on all types of coupling parameters. The directional coupling characteristics of step-index fiber have been accurately explained over the practical range of parameters [7] using coupled-mode theory [8,9]. Based on Chebyshev formalism, the characteristics of graded-core fiber directional couplers [10] have also been estimated accurately. However, to the best of our knowledge, there is no such analysis available on the characteristics of the directional couplers formed by a pair of dispersion-shifted trapezoidal fiber [11] or dispersion-flattened graded W fiber [12] or dispersion-flattened step W fiber [13,14] till date. We know that, single-mode optical fiber emerges as the most effective medium in long-haul optical communication system. The operating wavelength in this context ranges from 1.3 to 1.6 μm such silica has minimum attenuation loss to the extent of 0.2 dB/km at the wavelength 1.55 μm while material dispersion vanishes at the wavelength 1.3 μm.

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Thus, if zero dispersion wavelength is shifted to 1.55 μm, one can obtain minimum attenuation loss and zero dispersion simultaneously. Fibers belonging this category are called dispersion shifted fibers and importance of those have been well realised in view of the fact that Erbium-doped fiber amplifier operates at wavelength 1.55 μm [15,16]. In case of dispersion-flattened fibers, the material dispersion almost nullifies waveguide dispersion over a range of wavelengths. Accordingly such kind of fiber is best suited to enhance the information carrying capacity by means of wavelength division multiplexing [17]. Hence, they have a great importance in modern-day optical communication system. Therefore, it is very relevant to make a significant study on such type of fiber directional couplers. Moreover, investigations of different kinds of directional coupler are of tremendous importance in the field of optical technology. Accordingly, investigations performed in different laboratories have been constantly enriching the literature. In this respect, it is relevant to mention some research work as follows. The measurement of field bandwidth achievable with directional couplers using two dissimilar optical fibers is available in literature [18]. Side by side, directional couplers with Kerr nonlinearity is also a potential problem in current scenario [19]. Several strategies for fabrication of porous sub wavelength fibers together with measurement of transmission losses in terahertz using a novel non-destructive directional coupler method, have been reported [20]. Study of mismatched directional couplers has been added to literature [21]. Taking into consideration that nonlinearity causes periodic mismatch between axially uniform twin cores, such study is also important in the context of nonlinear coupling [21]. Thermo-optic modulation has been also employed for measurement of beat length in the directional coupler [22]. Further, photonic directional coupler has been designed as phase selector [23]. Fabrication and measurement of a compact 3 dB hybrid plasmonic directional coupler for silicon photonics integrated circuits have been successfully implemented [24]. The investigations on substrate integrated wave guide based directional coupler for 3 dimensional integrated circuits have been reported [25].

To use the coupled-mode theory, one should have clear idea about the modal field distributions of two single-mode fibers when they are non-interacting. The fundamental modal field for a single-mode dispersion-shifted and dispersion-flattened fiber can be calculated by applying numerical techniques or approximate methods. However, the simplest method under this circumstance is Gaussian approximation method [26] but it does not predict the modal field distribution in the cladding region accurately. Again, the characteristic of single-mode parabolic core fiber directional coupler predicted by the Gaussian-exponential-Hankel function employing variation technique [27,9] has also been prescribed with very high degree of accuracy. But this technique involves enormous computation. A very simple but accurate power series expression [28] by using Chebyshev technique has been reported for the fundamental mode of such dispersion-managed fibers [29]. In this communication, we report analysis about the fundamental mode of directional coupler formed by either two identical single-mode dispersion-shifted trapezoidal or dispersion-flattened graded W fibers or dispersion-flattened step W fibers by above mentioned method in a very simple and accurate manner.

2. Theory

We consider directional coupler made between a pair of identical single-mode fibers having refractive index profile as expressed below,

$$\begin{aligned} n_s^2(R) &= n_1^2\left[1-\delta f(R)\right], \quad 0<R\le 1 \\ &= n_2^2, \qquad\qquad\qquad R>1 \end{aligned} \tag{1}$$

where $\delta = \left(n_1^2 - n_2^2\right)/n_1^2$ is the grading parameter with n_1 and n_2 being the axial core and cladding refractive indices, with R being equal to r/a (a = core radius). Here, $f(R)$ defines the shape of the refractive index profile.

The profile function $f(R)$ for relating to some, dispersion-managed fibers is given below,

(I) Trapezoidal fiber [11]

$$\begin{aligned} f(R) &= 0, \qquad 0<R\le S \\ f(R) &= \frac{R-S}{1-S}, \quad S<R\le 1 \end{aligned} \tag{2}$$

(II) Graded W fiber [12]

$$\begin{aligned} f(R) &= \rho R^q, \quad R\le \frac{1}{C} \\ f(R) &= \rho, \qquad \frac{1}{C}<R\le 1 \end{aligned} \tag{3}$$

(III) Step W fiber [13]

$$\begin{aligned} f(R) &= 0, \quad R\le \frac{1}{C} \\ f(R) &= \rho, \quad \frac{1}{C}<R\le 1 \end{aligned} \tag{4}$$