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Coupling coefficient of two-core microstructured optical fiber

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Abstract

In this paper, coupled-mode theory is applied to a two-core microstructured optical fiber for the first time to calculate the coupling coefficients for different fiber structures by employing a simple effective index model approach. The dependence of the mode coupling properties upon the geometrical parameters of the two-core structures (air-hole arrangement, hole size, and pitch size) and wavelength are evaluated systematically. The effective index coupled-mode theory is compared with the finite-element method based super-mode theory in details and the results show good agreement. The coupling characteristics are proven to be insensitive to the longitudinal strain by considering the photoelastic effects.

Keywords: Microstructured optical fiber; Effective index method; Coupled-mode theory; Coupling coefficient; Strain; Photoelastic effect

1. Introduction

Microstructured optical fiber (MOF) is a new class of optical fiber that has emerged in recent years [1]. It is formed by an array of air holes running along the fiber length and guides light by total internal reflection between the solid core and the holey cladding region. This new type of fiber is fascinating because of its various novel properties, including endlessly single-mode operation [2], scalable dispersion and nonlinearity, and the surprising phenomenon of a short wavelength bend loss edge [3], etc. These novel transmission characteristics make such fiber ideal candidate for wide range of applications in optical communication systems. In particular, by considering the MOF's unusual cladding structure, researchers have fabricated many novel devices based on mode coupling effects, such as long period gratings (LPG) [4], fiber Bragg gratings (FBG) [5], fused couplers [6], multi-core fibers [7], etc. Among these devices, multiple-core MOFs can be easily obtained by simply using multiple solid rods as defects in the stack and drawing fabrication process. Many useful devices based on a symmetric two-core fiber can be realized, such as directional couplers, wavelength division multiplexers, and polarization beam splitters. In conventional fibers, coupled-mode theory has been systematically analyzed and mode coupling in conventional two-core structures has been studied in details [8]. For two-core MOF, many works have been done on the numerical calculation of coupling lengths [12,13]. However, these numerical methods are very computationally inefficient and so far the coupled-mode theory in two-core MOFs has not been investigated. Hence, in this paper we build up the coupled-mode theory for MOFs based on an effective index model. The dependence of coupling coefficient on the microstructure of the cross-section, such as the air-hole arrangement, hole-to-hole distance and air-hole size will be analyzed in detail. The wavelength dependence of the coupling properties is also investigated. The environment, such as temperature, stress, compression and strain, can change the microstructure. Due to the photoelastic effects, mechanical strain in the longitudinal direction will not only

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reduce the scale of the fiber cross-section, but also cause the stress re-distribution inside the fiber material. For this reason, we characterize, for the first time to our knowledge, the variation of the coupling properties in this novel two-core structure under different strain conditions.

2. Effective index coupled-mode theory

In a standard optical fiber, light launched into the core at angles greater than the critical angle can propagate for long distances in the high refractive index interior with little loss in intensity by means of total internal reflection. As is well known, there is an exponentially attenuated component of the internally reflected wave in the transverse direction that extends into the low-index region. If another high refractive index region is placed near enough, the attenuated wave can couple into this region and propagate within it. Thus, energy transfer can occur between the two waveguides. In conventional two-core fiber, energy transfer occurs in a spatially periodic fashion between the two cores, and this phenomenon can be modeled accurately with the coupled-mode theory to study devices based on evanescent-field coupling.

In case of the two-core MOF structure as shown in Fig. 1(a), where Λ is the hole-to-hole lattice distance, d is the air-hole diameter, S is the separation between the centers of two cores and the refractive index of background material (fused silica) is taken to be 1.45. Since the coupled-mode theory in a conventional two-core fiber has been systematically investigated, we use the effective index method to get the equivalent step index profile of the two-core MOF. The fundamental space-filling mode [9] in the infinite periodic cladding is calculated firstly and the whole periodic space is divided into hexagonal unit cells. The equivalent structure is obtained as shown in Fig. 1(b), where the effective index of the cladding acts as refractive index of the homogenous cladding material and pure silica acts as core. R is the equivalent core radius and strongly depends on the microstructure. We calculated the fundamental mode of two-core MOF and the equivalent two-core fiber, and the same effective mode index for both structures is achieved by tuning the equivalent core radius R between $\sqrt{3}\Lambda/2$ and Λ. An analytical expression of the effective core radius has been shown recently [10]

$$R = c_1\Lambda \Big/ \left\{ 1 + \exp\left[\left(\frac{d}{\Lambda} - c_3 \right) \Big/ c_2 \right] \right\}, \tag{1}$$

where c_1, c_2 and c_3 are 0.686064, 0.265366, and 1.291080, respectively. This effective index method is used here to build up a simple and straightforward coupled-mode theory, and we call it effective index coupled-mode theory. For this paper, we used a very simple structure to demonstrate the coupled-mode theory in a microstructure: the two separate cores are identical, lossless and monomode. The generalized analysis for non-identical, multi-mode cores will be similar to conventional structures with homogeneous cladding. The detailed analysis has been presented in [8].

The coupling coefficient C^{js}_{pq} is a quality factor of the overlap of the pth mode in core $j(e^{(j)}_p)$ and the qth mode in core $s(e^{(s)}_q)$. Its general form is

$$C^{js}_{pq} = \frac{\omega}{2} \int_{A^{(s)}} (\varepsilon^{(s)} - \varepsilon) e^{(j)}_p \cdot e^{(s)}_q \, \mathrm{d}A, \tag{2}$$

where both fields are at frequency ω, $(\varepsilon^{(s)} - \varepsilon)$ is the difference between the dielectric constants of the core s and its cladding, and $e^{(j)}_p(x,y)$ is the transverse electric field profile of mode p in core j in the absence of core s. $e^{(s)}_q(x,y)$ is the transverse electric field profile of mode q in core s in the absence of core j. For single-mode two-core fibers in which the two cores are identical, the coupling coefficients between the two cores are equal, i.e., $C_{12} = C_{21}$. Then Eq. (2) can be simplified as [11]

$$C_{12} = C_{21} = C = \sqrt{2\Delta} \frac{u^2}{RV^3} \frac{K_0(wS/R)}{K_1^2(w)}, \tag{3}$$

where S is the separation between the two cores, R is the radius of the cores, V is the normalized frequency which is given by: $V = k_0 R n_{\mathrm{co}} \sqrt{2\Delta}$, where $\Delta = (n^2_{\mathrm{co}} - n^2_{\mathrm{cl}})/2n^2_{\mathrm{co}}$ is the refractive index difference between core and cladding with n_{co} and n_{cl} being the refractive index of the core and the cladding. The modal parameter u is a solution of the characteristic equation

$$uJ_1(u)/J_0(u) = wK_1(w)/K_0(w), \tag{4}$$

where $w = \sqrt{(k_0R)^2(n^2_{\mathrm{co}} - n^2_{\mathrm{cl}}) - u^2}$, $k = 2\pi/\lambda$, J_0 and J_1 are the zeroth and first order Bessel functions of the first kind, and K_0 and K_1 are the zeroth and first order modified Bessel functions of the second kind, respectively.

Eqs. (3) and (4) cannot be solved analytically, so we need to use numerical methods to calculate the coupling coefficient. For the equivalent two-core structure of MOF, core-to-core distance S, effective core radius R and effective cladding index n_{cl} are the three principle parameters to control the coupling coefficient. For MOFs, decreasing the air-hole size while keeping the pitch size (Λ) constant is equivalent to decreasing core cladding index contrast since cladding air-filling fraction is smaller. This increases the coupling coefficient significantly as shown in

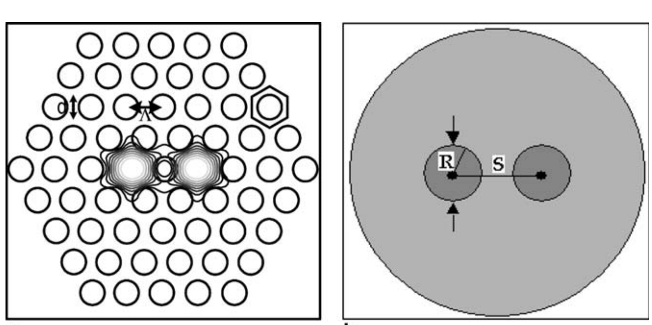

Fig. 1. (a) Cross-section of a two-core MOF formed with hexagonal unit cells, the transverse mode profile shown with the contour map; (b) cross-section of the equivalent two-core fiber.