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Effective Area Control by Varying the Air Core Size of Cylindrical Photonic Crystal Waveguides

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Abstract

Air-core photonic crystal waveguides with cylindrically periodic index variations are first proposed, thereby making low-index cores. The proposed waveguide can provide numerous novel properties including large or small effective areas. Based on two computational analyses of the finite-difference time-domain and finite difference method for accurate and cross-verified results, sizing the core hole provides a decent way to control the effective area. Also, it is noticed that the effective areas at the longer wavelength generally result in larger values for each different hole radius.

Keywords: *Effective area, Cylindrical photonic crystal waveguides, Optical components.*

1. Introduction

Optical waveguides work as one of the most crucial parts for data transmission medium and [2]light-signal processing component in lightwave communication systems. Photonic crystal waveguides from very new advanced technology have attracted considerable attention in research communities during recent decades for the purpose of enhancing the performance of existing optical communications [1] [2] [3] [4] [5] [6] [7]. Basically, the photonic crystal waveguides (PCWs) can be made of a single material, in contrast to all other types of conventional optical fibers, which are normally manufactured with two or more materials. Only by properly designing the geometrical structures of the photonic crystal waveguides, numerous novel properties, such as single mode operation over the entire wavelength range of interest, zero or anomalous group-velocity dispersion, and large or small effective areas, can be obtained. Moreover, adding an air hole in the central core region, for air-core cylindrical photonic crystal waveguides (APCWs) in this research, may offer more opportunities for new and reliable fiber-optic devices.

Since a great deal of interest has been focused on optical system elements with wider bandwidths and better performances, photonic crystal microstructures may have provided important solutions. Especially, enlargement of effective mode area can provide advantages of reduced nonlinear effects combined with a high beam quality and so better job in coupling light from large focal spot device [8] [9]. Only delicately designing the optical microstructures enables special ways to create new advanced optical applications.

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In this paper, APCWs as distinctive variants of the PCW are first proposed, and design parameters are explained in order to investigate influences of air-core size and cladding periodicity conditions. For exact computational analyses, finite-difference time-domain (FDTD) technique is briefly described considering employment during initial investigation and then the rigorous full-vector finite difference method (FDM) is extensively utilized for the accurate calculation of light-field characteristics. Remarkable design of the APCW with enormously large effective area as well as fairly reasonable guidance properties for device applications is addressed in consecutive order. This new type of computational design approach can be reasonably expected to be useful in manufacturing processes and for fabrications of variety optical waveguide components.

2. FDTD and FDM algorithms for the APCW analyses

Optical light is electromagnetic wave in nature, and thus its propagation properties are governed by the laws of electrodynamics which are collectively known as Maxwell's equations. It is known that guiding of light signals in the PCW with photonic bandgap structures relies on constructive interference effect due to the periodic arrangement of identical air holes, and the lightwave interaction between the core and cladding provides light confinement and hence guidance of light along the waveguide. Although the propagation characteristics of complicated structures like arbitrary APCWs cannot be calculated easily using analytical methods, there are ways to solve electromagnetic problems numerically.

Figure 1(a) shows a proposed APCW with cylindrically periodic index variations. Here, it is noticed that a central air hole is located at the core region, making low-index core with a variable radius of r1, surrounded by a clad region composed of alternating-index and equal-thickness rings. As shown in Figure. 1(a), da and dg in the refractive index profile for the proposed geometry denote thicknesses of air and pure-silica glass layers, respectively. The 3-dimensional view of a general PCW is also illustrated in Figure. 1(b).

In this research, two numerical techniques of FDTD and FDM are addressed considering extension to the analysis of holey optical fibers with arbitrary air-hole distributions. Each of these techniques has certain advantages. Using the FDTD method, the continuous electromagnetic field in a finite volume of space is sampled at distinct points in a space lattice and at equally spaced sampling points in time. The sampled data at the points are used for numerical calculations of allowed modes, without generating spurious mode solutions, in a given waveguide.

Despite being an effective technique for calculation of propagation constants of guided modes, the FDTD method is not well suited for the evaluation of individual mode field distributions. This is because the source is an impulse function in the time domain covering an infinite spectrum, thus field-distribution solutions are superposition of all possible modes. To alleviate this problem with propagation constants available from FDTD, individual mode field distributions are obtained using the FDM, which can quickly and conveniently provide individual mode field solutions.

The FDTD technique has gained considerable popularity in recent years, because this method provides robust solutions, based on Maxwell's equations [10], and can readily accommodate complex-valued material properties. An arbitrary material object can be approximated by building up unit cells for which field component positions are disposed with the desired values of permittivity and permeability. Once the geometry of the object is specified in the numerical simulation region, source condition is modelled somewhere in the region.

Initially, it is assumed that all fields within the calculation domain are identically zero. Then, an incident wave is enforced to enter the numerical calculation region.

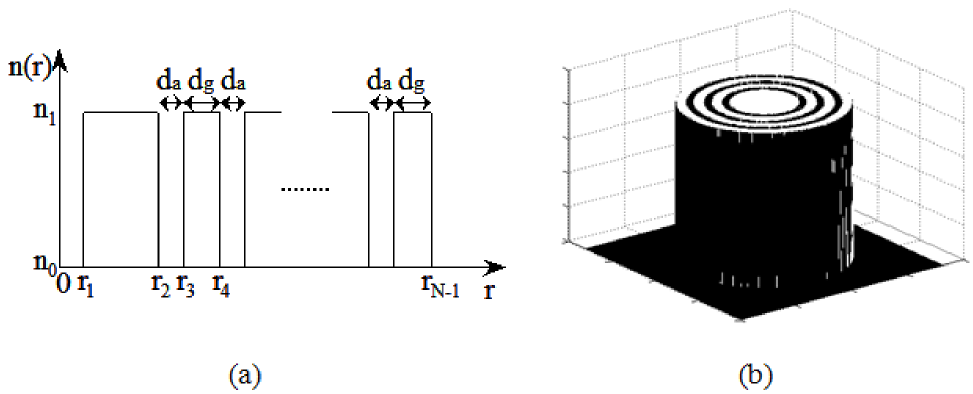

Figure 1. Schematics of (a) the refractive index profile of an APCW with an air core, and (b) by the 3-dimensional view of a general PCW

Expanding the curl expressions and equating the like components, the system of six coupled partial differential equations are formed for the FDTD analysis of electromagnetic wave interactions with general three-dimensional objects. It should be noted that the electric and magnetic field components (Ex, Ey, Ez, Hx, Hy, and Hz) are interrelated. That is, Maxwell's equations do not directly yield electric and magnetic field values, but rather relate the rate of change between electric and magnetic field values.

Since cylindrically-varying PCWs have periodic index variations in the radial direction only, a high-index core PCW as in Figure. 1(b) with r1 = 10 μm, da = 0.2 μm, dg = 0.3 μm, and six layers is considered for initial design. When assuming the glass portion of the designed waveguide has a refractive index of 1.45 with no material dispersion and operating the high-index core PCW at wavelength of 1.3 μm, the FDTD analysis produces the normalized propagation constant of 1.44923. Meanwhile, the FDM technique yields the effective refractive index of 1.44917 about the same operation wavelength. Only negligible difference of 6×10^{-5} can be noticed. For the other low-index core APCW design with parameters of r1 = 0.3 μm, r2 = 10 μm, da = 0.2 μm, dg = 0.3 μm, and seven layers, the effective index results from the FDTD and FDM techniques are 1.44465 and 1.44885, respectively, showing reasonable agreement as well.

3. Results and discussion

For the purpose of comparison of effective mode area variations in APCWs by tailoring the central core hole, another optimistic APCW is also designed with parameters of r1 = 2 μm, r2 = 10 μm, da = 0.2 μm, dg = 0.3 μm, and seven layers. Figure 2 illustrates the normalized propagation constant versus the operation wavelength (λ) for the fundamental mode, obtained by FDM approach taking into account the material dispersion effect.

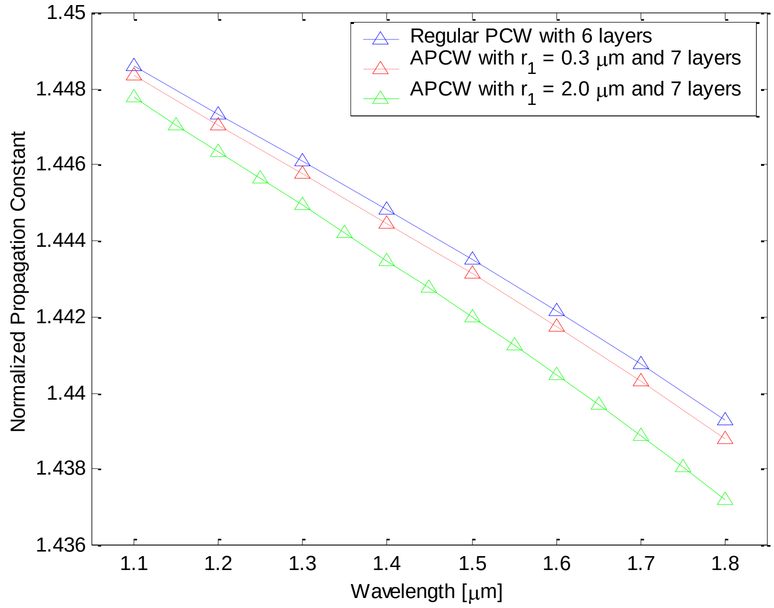

Figure 2. Variations of the normalized propagation constant versus the operation wavelength

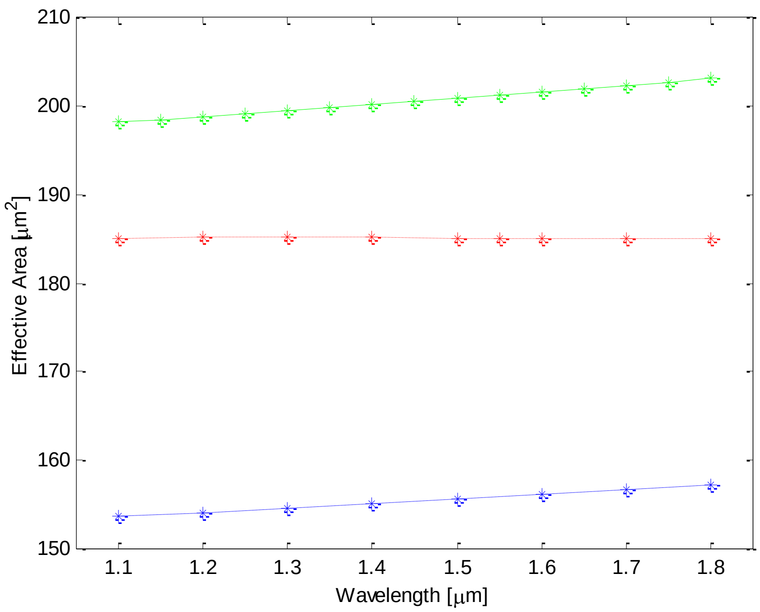

Figure 3. Variations of the effective mode area versus the operation wavelength

In Figure. 2, it is noticed that three representative designs with and without the central air hole for the aim of best effective area result provide fairly reasonable propagation characteristics, because low-index air holes at the cores in the two APCW cases make the effective index lowered in comparison with the 6-layer regular PCW. Here, effective index results for the APCWs with r1 = 2.0 μm and r1 = 0.3 μm, and the 6-layer PCW are depicted by the green solid, red dotted, and blue dashed curves with the triangle symbol, respectively.

The effective area for the fundamental mode is also evaluated by using the field distribution results and plotted in Figure. 3. It is noted that the effective core area tends to increase with the size of the central air hole at both the operation wavelengths. The reason is that with bigger core hole the electromagnetic fields spread further into the cladding region. Thus sizing the core hole provides a decent way to control the effective area. Also, notice that the effective areas at the longer wavelength generally result in larger values for each different hole radius.

4. Conclusion

Based on two computational analyses of the FDTD and FDM for accurate and cross-verified results, it is noticed that when the operating wavelength is shorter, electromagnetic fields are more confined to the core region and only the core region has a major impact on the optical guidance properties. Conversely, when the operating wavelength is longer, fields spread more to the cladding region and the index profile of the cladding region has more influence on these. Even thought the proposed APCWs have complicated geometries, which require a full vectorial approach instead of a scalar-wave approximation and make the electromagnetic analysis difficult, the results in this investigation can be utilized as a general guide. And depending on the desired applications, the APCWs with different design parameters are expected to be useful for novel developments related to lightwave communications.

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