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Supercontinuum generation in square photonic crystal fiber with nearly zero ultra-flattened chromatic dispersion and fabrication tolerance analysis

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ABSTRACT

This paper presents a simple index-guiding square photonic crystal fiber (SPCF) where the core is surrounded by air holes with two different diameters. The proposed design is simulated through an efficient full-vector modal solver based on the finite difference method with anisotropic perfectly matched layers absorbing boundary condition. The nearly zero ultra-flattened dispersion SPCF with low confinement loss, small effective area as well as broadband supercontinuum (SC) spectra is targeted. Numerical results show that the designed SPCF has been achieved at a nearly zero ultra-flattened dispersion of 0 ± 0.25 ps/(nm·km) in a wavelength range of 1.38 μm to 1.89 μm (510 nm band) which covers E, S, C, L and U communication bands, a low confinement loss of less than 10^{-7} dB/m in a wavelength range of 1.3 μm to 2.0 μm and a wide SC spectrum (FWHM = 450 nm) by using picosecond pulses at a center wavelength of 1.55 μm. We then analyze the sensitivity of chromatic dispersion to small variations from the optimum value of specific structural parameters. The proposed index-guiding SPCF can be applicable in supercontinuum generation (SCG) covering such diverse fields as spectroscopy applications and telecommunication dense wavelength division multiplexing (DWDM) sources.

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1. Introduction

The excellent propagation properties of photonic crystal fibers (PCFs) [1–3] have been widely recognized by researchers. One of the appealing properties of PCFs is the dispersion properties over the conventional optical fibers. The artificially-periodic cladding consists of micrometer-sized air holes which allow the flexible tailoring of the dispersion curves. The task of controlling chromatic dispersion is an important setback of designing practical optical communication systems [4], dispersion controllers [5], and nonlinear systems [6]. Index-guiding PCFs with multiple air holes periodically arranged around the solid core, possess numerous unusual properties, such as wide single-mode wavelength range [7] and great controllability in chromatic dispersion [8], and effective core area [9,10]. Due to these unusual properties, PCFs are expected to comprehend various kinds of functional devices. PCFs are attractive for the study of nonlinear effects, as they can be designed to have very small effective areas, increasing the nonlinear effects and generate broad supercontinuum (SC) spectra.

However, there exists a trade off in the PCFs' design, that is by using conventional PCFs (air holes with the same diameter), it is difficult to control dispersion and low confinement loss in a wide wavelength range. In PCFs, since there is a finite number of air holes in the cladding, the guided mode is intrinsically leaky, so confinement losses exist even if other losses such as Rayleigh scattering and imperfection are negligible. In index-guiding PCFs, since the periodicity in the cladding region is not essential to confine the guiding light into the core region, it is possible to target for dispersion and confinement loss in a wide wavelength range by varying the air hole diameters of each air hole ring as well as other parameters.

Several designs for the PCFs have been proposed to achieve the nearly zero ultra-flattened chromatic dispersion and supercontinuum generation (SCG) properties. Conventional PCF designs are those that have air holes with the same diameter [11–14], others include structures with two-defective air hole rings [15], nonlinear PCFs with several kinds of air hole diameters [16–18], modified hexagonal PCFs [19], square PCFs [20] and polarization maintaining highly nonlinear PCF [21]. The PCFs' structure in ref. [5] significantly reduces the ring number of the air holes, but the design procedure becomes complicated because four or five rings of different air hole diameters for each ring and one pitch are needed to achieve nearly zero ultra-flattened dispersion. Since in conventional PCFs [11–14], the ratio of air hole diameter to air hole pitch is small in order to realize nearly zero ultra-flattened dispersion, many air hole rings are required in the cladding region to significantly reduce the confinement loss. The SCG has not performed in highly nonlinear PCFs [17,18]. The PCF structure proposed in ref. [19] inserted an extra air hole between two consecutive air holes which imposes fabrication challenges. In our other previous work [20], the proposed SPCF demonstrated flattened

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dispersion and low confinement losses but fabrication precision requirement and SCG have not been considered. However, it has been demonstrated both experimentally [13] and theoretically [22] that small parameter deviations from the target design, due to fabrication inaccuracies can lead to a significant deviation from the anticipated dispersion properties. Understanding the sensitivity of the dispersion properties to fabrication errors for different structural designs is thus an important issue. Considering this, in this work dispersion sensitivity is verified by changing different parameters.

In this paper, we propose and numerically investigate simple index-guiding SPCF. In the analysis, a full-vector modal solver based on the finite difference method (FDM) [23,24] is utilized. Anisotropic perfectly matched layers (PMLs) absorbing boundary are positioned outside the outermost ring of holes in order to reduce the simulation window and to evaluate the confinement loss of the SPCF with a finite number of rings of holes. It is possible to design an SPCF with a nearly zero ultra-flattened chromatic dispersion over a wide wavelength range by optimizing only three geometrical parameters. Numerical results show that the proposed SPCF has a nearly zero ultra-flattened chromatic dispersion of 0 ± 0.25 ps/(nm·km) in a wavelength range of 1.38 μm to 1.89 μm (510 nm band) covering E, S, C, L and U communication bands (1.38 to 1.675 μm) and low confinement loss of less than 10^{-7} dB/m in a wavelength range of 1.3 μm to 2.0 μm, which are found to be a more near-zero value and a wider band width than those of reported triangular and square PCFs [5,11–21]. Moreover, the proposed SPCF can generate 450 nm bandwidth broad SC spectra in full width at half maxima (FWHM) which are novel properties in an ultra-flattened dispersion design. We then analyze the sensitivity of the proposed SPCF dispersion property to fabrication errors which allows us to deduce some geometrical guidelines for obtaining the desired dispersion characteristics. It is also exhibiting reasonable fabrication tolerance to parameter variations. The proposed SPCFs may be suitable for applications such as chromatic dispersion controller, dispersion compensator, dense wavelength division multiplexing (DWDM) transmission systems, and as a candidate for nonlinear optical applications, such as wide band supercontinuum generation, soliton pulse transmission, and so on because of its small effective area. In DWDM communication systems, it is essential to maintain a uniform response in the different wavelength channels, which requires that the transmission line approach ultra-flattened dispersion and moreover, with moderately low dispersion to minimize four-wave mixing nonlinearities [25]. In all these cases, the efficiency of the system very much depends on the degree of dispersion flatness and the proposed SPCF exhibit such appealing achromatic behavior.

2. Proposed SPCFs schematic diagram

Fig. 1(a) shows the schematic cross-section of the conventional SPCF with five rings, which is composed of circular air holes in the cladding arranged in a square array, where Λ is the center-to-center spacing between the air holes, d is the air hole diameter, d/Λ is the normalized diameters of the air holes in the cladding, and $2a = 2\Lambda - d$ is the core length. The background material is silica. The structure of the proposed index-guiding SPCF design is shown in Fig. 1(b), which is reshaped from SPCF shown in Fig. 1 (a). In this design, there are three degrees of freedom, first ring diameter d_1, outer four rings diameter d, and air hole pitch Λ. In conventional PCFs (air holes with the same diameter in the cladding region), it is difficult to control dispersion and low confinement loss in a wide wavelength range. This is permitted for index-guiding PCFs as periodicity is not essential to guide light in the core region based on the total internal reflection (TIR) mechanism. We break the uniformity of the cladding region by scaling down the air hole diameter of the first ring and increasing the air hole diameter of the rest of the rings. The dispersion characteristics are effectively affected by the air hole sizes of the inner rings.

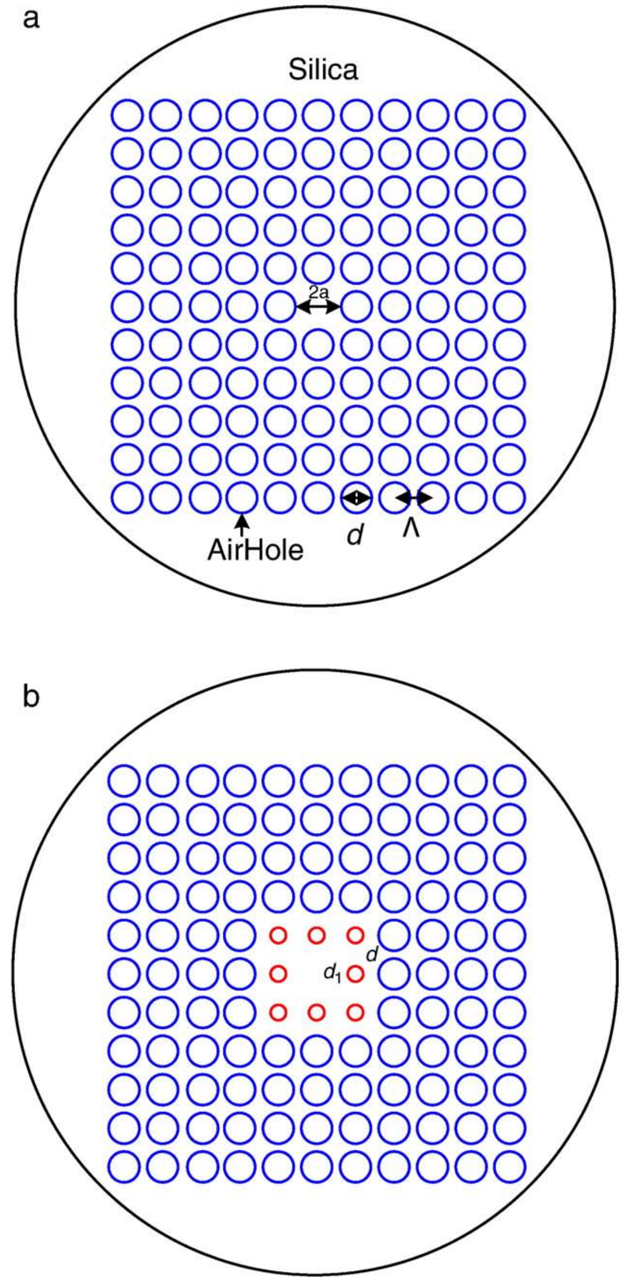

Fig. 1. (a) Schematic cross-section of the conventional SPCF with five air hole rings and the geometrical parameters of the air hole diameter d, pitch Λ, and the core length $2a = 2\Lambda - d$. (b) Proposed index-guiding SPCF with five rings of air holes. Smaller air hole diameter d_1 is for the inner rings and larger diameter d for the outer four rings.

Therefore, after careful selection of the first ring air hole diameter, it is possible to achieve the desired dispersion properties. For the outer four rings the air hole is kept large enough to decrease the confinement loss and keep below the Rayleigh scattering level.

3. Calculation equations of chromatic dispersion, confinement loss, and effective area

In order to calculate the wavelength dependence of the refractive index with the high accuracy required for calculating different properties of PCFs, we employ a full-vector mode solver based on the FDM [23,24]. Anisotropic PMLs absorbing boundary are positioned outside the outermost ring of holes in order to reduce the simulation window and to evaluate the confinement loss of the proposed fiber

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