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A single mode hybrid cladding circular photonic crystal fiber dispersion compensation and sensing applications ☆

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Abstract

In this paper, we propose a highly birefringent and highly nonlinear polarization maintaining single mode hybrid cladding circular photonic crystal fiber (HyC-CPCF). The proposed structure is extremely attractive for compensation of chromatic dispersion of standard single mode fiber (SMF) over 1360 to 1640 nm wavelength band. Guiding properties are investigated using finite element method (FEM) with perfectly matched layer boundary condition. Simulation results confirm the possibility of large negative dispersion coefficient and relative dispersion slope of −650 ps/(nm km) and 0.0036 nm^{-1}, respectively, at 1550 nm wavelength and effective dispersion coefficient of about ±0.5 ps/(nm km) from 1360 to 1640 nm wavelength. The proposed fiber also demonstrates a high birefringence of order 2.1×10^{-2} at 1550 nm wavelength that allows the fiber to maintain a single polarization. In addition, effective *V* parameter ensures the single mode operation of the designed fiber over the entire band of interest. To realize the practical feasibility, the sensitivity of the fiber dispersion properties to a ±2% of structural parameter variation around the optimum value is evaluated and reported. Moreover, effective dispersion and nonlinear coefficient are also presented and discussed. The proposed fiber can be a promising candidate in high speed transmission system for broadband dispersion compensation, sensing and nonlinear applications as well.

Keywords: Chromatic dispersion; Dispersion compensating fiber; Nonlinearity; Birefringence; Photonic crystal fiber

1. Introduction

Photonic crystal fibers (PCFs) have become one of the most interesting platforms for the design of electromagnetic structures over the past few years. In recent times, PCFs have been extensively studied due to their novel optical properties essentially required in many areas of optical systems which are unachievable in conventional single mode fibers (SMFs) [1]. PCFs have a microscopic array of air channel running down their length that makes a low index cladding around the undoped silica core [2]. PCFs provide a variable index contrast between core and cladding with more degrees of design freedom effectively used for tailoring various guiding properties such as chromatic dispersion, birefringence, nonlinearity, and effective area [3–5]. In optical communication system, pulse broadening due to dispersion is the key issue that reduces transmission data rates and overall bandwidth of the system. Recently,

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dense wavelength division multiplexing (DWDM) technique is gaining attention for their capability of handling high bit rate data transmission even higher than 40 Gbps. However, the transmission impairment produced by dispersion in SMFs is also severe that lowers the possibility of such high bit rate data transmission [6]. As a potential solution, dispersion compensation is extremely necessary in long haul optical transmission systems [7]. One of the most convenient ways for the realization of dispersion compensation over a long distance is to use dispersion compensating fibers (DCFs). It is to be mentioned here that a standard single mode optical fiber has positive dispersion of ~10 to 20 ps/(nm km). For effective compensation of such positive dispersion with minimum length and then cost, the DCF should have large negative dispersion [8–10]. In addition, this negative dispersion should span over a wide spectrum for dispersion compensation in DWDM systems where simultaneous compensation of dispersion and dispersion slope are required for all frequencies [11]. High negative dispersion over wide band is difficult to achieve with conventional DCFs [12]. Moreover, they have some limitations related to their structure as well.

To date, different PCFs structures have been designed and reported for dispersion compensation applications by many research groups. Birks et al. [3] first proposed the idea of using PCFs for dispersion compensation application, however, effective area of the design is relatively small that would result a large coupling loss with SMFs. A similar approach is used by Shen et al. [10], whereby, the designed PCF is optimized for broadband dispersion compensation with a negative dispersion coefficient of approximately −475 ps/(nm km). A dual core PCF is proposed in Ref. [13] for dispersion compensation which achieves a large dispersion peak of about −59,000 ps/(nm km). The major pitfalls of this design are very low compensation bandwidth and more fabrication difficulties due to doping. On the other hand, the birefringence of those designs was not significantly high enough for their suitability in sensing applications.

Recently, several attempts have been made by other research groups with the aim of simultaneously achieving high negative dispersion with maximizing the compensation bandwidth and high birefringence required for various novel applications including sensing, fiber laser with single polarization output and gyroscopes. For example, Habib et al. [14] proposed a dispersion compensating PCF based on spiral structure which successfully achieves negative dispersion coefficient of −327 ps/(nm km) with a birefringence of about 1.79×10^{-2} which are not considerably high at 1550 nm wavelength. The shortcoming of this design is fabrication complexity which limits the practical realization of such spiral PCF [1,6]. Square lattice PCF is proposed in Ref. [15] that shows negative dispersion of −204.4 ps/(nm km) requiring relatively longer fiber for compensation. Octagonal PCF is proposed in Ref. [16] that provides a negative dispersion of −588 ps/(nm km), birefringence of 1.88×10^{-2} and nonlinearity of 31.85 $W^{-1}\,km^{-1}$ at 1550 nm wavelength, however, the bandwidth covered for dispersion compensation was only S to L communication bands. The fiber nonlinearity is essential for telecommunication and supercontinuum generation applications [17]. PCF based nonlinear threshold device is proposed in Ref. [18] for optical code division multiple access application that has a nonlinear coefficient of 31 $W^{-1}\,km^{-1}$. However, no advanced research direction is provided about how to explore the possibility of single mode operation in their proposed designs.

In this work, we propose a HyC-CPCF that ensures the broadband dispersion compensation capability with high birefringence and high nonlinearity. According to simulation, it is seen that the designed HyC-CPCF operates as a single mode fiber over E + S + C + L bands and provides a high negative dispersion of −650 ps/(nm km) with RDS of 0.0036 nm^{-1} at 1550 nm wavelength. The proposed design also exhibits simultaneously high birefringence of 2.1×10^{-2} and high nonlinear coefficient of 45.5 $W^{-1}\,km^{-1}$ at the 1550 nm wavelength. In addition to this, the designed fiber has an effective dispersion range of ±0.5 ps/(nm km) over E + S + C + L wavelength band. The main advantages of the proposed structure include the design simplicity, high negative dispersion with high birefringence and high nonlinearity. It is highly expected that HyC-CPCF would be useful in high speed DWDM optical transmission systems for effective dispersion compensation, nonlinear optics and sensing applications.

2. Design approach of the proposed PCF

Fig. 1 depicts the transverse cross section of the proposed HyC-CPCF that has five air-hole rings. The cladding is formed in combination with the circular and elliptical air holes. The symmetry of the core is intentionally broken by removing two circular air-holes while replacing those with elliptical air-holes. The main purpose to design the fiber with introducing defects into the core is increasing the fiber asymmetry about the core region. The fiber asymmetry does play an important role in tuning the birefringence of the fiber and this degree of asymmetry in core region is managed to realize high birefringence. However, some extra elliptical air-holes