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Highly nonlinear photonic crystal fiber with ultrahigh birefringence using a nano-scale slot core

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A new type of highly nonlinear birefringent photonic crystal fiber (HNL_PCF) with nano-scale slot core is proposed and numerically simulated. Benefit from the slot effect induced sub-wavelength mode confinement, ultrahigh nonlinear coefficient up to $3.5739 \times 10^4\ W^{-1}\ km^{-1}$ can be achieved for the quasi-TM mode at the wavelength of 1.55 μm. Additionally, the modal birefringence can go up to 0.5015 due to the asymmetry of the fiber structure. Leveraging the extraordinary features, the proposed HNL-PCF offers large potential in miniature fiber devices for all-optical signal processing.

1. Introduction

In the past decade, photonic crystal fibers (PCFs) have been extensively studied due to their extensive applications in optical fiber communication, fiber lasers, nonlinear devices, high-power transmission, optical fiber sensors, and other areas. Normally, PCFs can be classified into two main categories according to their light-guiding mechanism: index-guiding PCFs and photonic bandgap PCFs [1,2]. Similar to conventional optical fibers, PCFs belonging to the first category are guiding light in a solid core according to the principle of modified total internal reflection which is caused by the positive refractive index difference between the core region and the photonic crystal cladding, where the air-hole presence leads to a lower average refractive index. On the contrary, when the PCF core region has a lower refractive index than the surrounding photonic crystal cladding, light is guided by the photonic bandgap effect. In this condition, light is confined to the low index core region since the photonic bandgap effect makes propagation in the cladding region impossible. This guiding mechanism cannot be achieved in conventional optical fibers and it opens a whole new set of interesting possibilities.

Compared to conventional fibers, PCFs have a variety of unique properties, such as high nonlinear coefficient [3,4], novel chromatic dispersion [5,6], endlessly single-mode operation [7], large mode area [8], high birefringence [9,10], low confinement loss [11], and so on. Among these features of PCFs, nonlinearity is one of the most interesting characteristics. Large nonlinear coefficient in PCFs can be realized by using a small core and a large air holes cladding. Nowadays, highly nonlinear PCFs are interesting candidates for many practical applications including supercontinuum generation, all optical wavelength conversion and optical parametric amplification [12,13]. However, for such PCFs, controllability of chromatic dispersion is crucial for optical communication as it limits the information carrying capacity of the optical fiber. In order to mitigate dispersion effect, dispersion-shifted fibers and zero-dispersion single-mode fibers are designed at the wavelength of 1.55 μm. Furthermore, birefringence is another important factor in many practical applications for all- optical signal processing since many nonlinear effects in optical fiber are polarization-sensitive. Hence, to design a highly nonlinear birefringent PCF with zero dispersion at 1.55 μm is a continual challenge.

Our recent investigations show that ultrahigh nonlinearity, ultraflattened dispersion and ultrahigh birefringence can be obtained by using a slot spiral fiber design [14,15]. Nevertheless, these ultrahigh nonlinear slot spiral PCFs are made of silicon, and it is well known that it is difficult to achieving ultrahigh nonlinearity of the order of $10^3\ W^{-1}\ km^{-1}$ and ultrahigh birefringence of the order of 10^{-1} in conventional silica PCFs. In this letter, in order to overcome the above limitation, we employ the index-guiding square-lattice silica PCF structure with a traditional

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circular-airhole cladding, as well as a nano-scale slot core to obtain ultrahigh nonlinearity and ultrahigh birefringence. The optical properties of the fundamental mode of the fiber structures with different fiber parameters within the wavelength range from 1.4 μm to 1.7 μm are numerically investigated. One interesting finding from our simulation is that the nonlinear coefficient of the fundamental quasi-TM mode can be up to $3.5739 \times 10^4\ W^{-1}\ km^{-1}$ at the wavelength of 1.55 μm while the modal birefringence is as high as 0.5015 at the same wavelength. Furthermore, we also show that zero dispersion value of the fundamental quasi-TM mode at 1.55 μm can be achieved simply by modifying the air hole size.

2. Geometric structure

The cross section of the proposed HNL-PCF used in our simulation is illustrated in Fig. 1. The cladding of the proposed PCF consists of a square lattice of circular air holes with a diameter d and a pitch Λ in fused silica. In contrast to the traditional PCF structure, there are two high index rectangular silicon strips in the fiber core region of our design, which form a nano-scale slot. These two silicon strips are considered as identical. The width of the silicon strips or the slot is w, the height of each silicon strip is h_p and the height of the slot is h_s.

3. Results and discussions

3.1. Modal properties of quasi-TM mode

In order to calculate the field distribution and its modal effective indices, we use a full-vector finite element method to solve Maxwell equations on the fiber structure and output the complex eigenvalues, as well as the modes profiles. In particular, with the PML boundary conditions, the modal effective index (n_{eff}) can be obtained, and then, the chromatic dispersion $D(\lambda)$, effective mode areas A_{eff} and nonlinear coefficient γ can be calculated [16]. The material dispersions of Si and SiO_2 can be obtained from the Sellmeier equation [15].

Fig. 2(a) shows the intensity distribution of the fundamental mode at the wavelength of 1.55 μm with fiber parameters, $\Lambda = 500$ nm, $d = 0.8\Lambda$, $w = 360$ nm, $h_p = 140$ nm and $h_s = 30$ nm. It is apparent that the fundamental quasi-TM mode is well confined in the slot region, which means that a very small effective mode area can be obtained in the proposed PCF. The confinement factor and effective mode area of the fundamental quasi-TM mode as function of wavelength are shown in Fig. 2(b). The confinement factor Γcan be defined as: $\Gamma = \int\int |E|^2 dxdy / \int\int_\infty |E|^2 dxdy$ [17]. From this figure, one can learn that the confinement factor decreases with the wavelength increment. Such as the confinement factor decreases from 0.396 to 0.316 when the wavelength increases from 1.4 μm to 1.55 μm. Furthermore, one can also observe that the effective mode area increases with the wavelength increasing. Luckily, the effective mode areas are all smaller than $0.16\ \mu m^2$ in the wavelength range from 1.4 to 1.7 μm. Combining with nonlinearity coefficient formulation $\Gamma = (2\pi/\lambda) \cdot (\overline{n_2}/A_{eff})$ [18], we can learn that ultrahigh nonlinear can be achieved in our proposed PCF since the effective mode area is really small.

3.2. Influence of the fiber parameters on nonlinearity and chromatic dispersion of quasi-TM mode

Fig. 3 shows the influence of the slot width and the slot height on the nonlinearity of fundamental quasi-TM mode for our proposed PCF in the wavelength range from 1.4 to 1.7 μm (other fiber parameters remain unchanged). According to the Fig. 3(a), one can observe that all the three nonlinear coefficient curves increase significantly with the wavelength decreasing. The reason is that the effective area decreases as the wavelength decreases. Another interesting discovery is that the nonlinear values become larger over the whole wavelength span when the slot width increases from 300 nm to 350 nm. However, if the width increases from 350 nm to 400 nm, the influence on nonlinearity becomes smaller. For example, the nonlinear coefficient at 1.55 μm can increase from 2.6106×1.0^4 to $3.1932 \times 1.0^4\ W^{-1}\ km^{-1}$ when the slot width increases from 300 to 350 nm. But if the slot width increases from 350 to 400 μm, the variation of the nonlinearity is only $3.8071 \times 1.0^3\ W^{-1}\ km^{-1}$. As shown in Fig. 3(b), the nonlinear coefficient increases in the wavelength range from 1.4 to 1.7 μm when the slot height decreases, and the influence of the slot height on the nonlinearity decreases with the wavelength increasing.

The influence of the silicon strip height and the air-hole size on the nonlinearity is also investigated, which is illustrated in Fig. 4(a) and (b), respectively. Fig. 4(a) illustrates the nonlinear coefficient of the fundamental quasi-TM mode as a function of the silicon strip height with fixed $\Lambda = 500$ nm, $d = 0.8\Lambda$, $w = 360$ nm, and $h_s = 30$ nm. It is clear that the nonlinear coefficient increases when h_p is enlarged because expanding h_p further improves the light confinement ability of the proposed PCF, and then decreases the effective mode area. For example, if the fiber parameter h_p is adjusted from 135 nm to 145 nm, the nonlinear coefficient at 1.55 μm increases from $2.6901 \times 10^4\ W^{-1}\ km^{-1}$ to $3.9158 \times 10^4\ W^{-1}\ km^{-1}$. Fig. 4(b) shows the nonlinear coefficient of the fundamental quasi-TM mode with fixed $\Lambda = 500$ nm, $w = 360$ nm, $h_p = 140$ nm, $h_s = 35$ nm, and verified d. The nonlinear coefficient increases over the whole

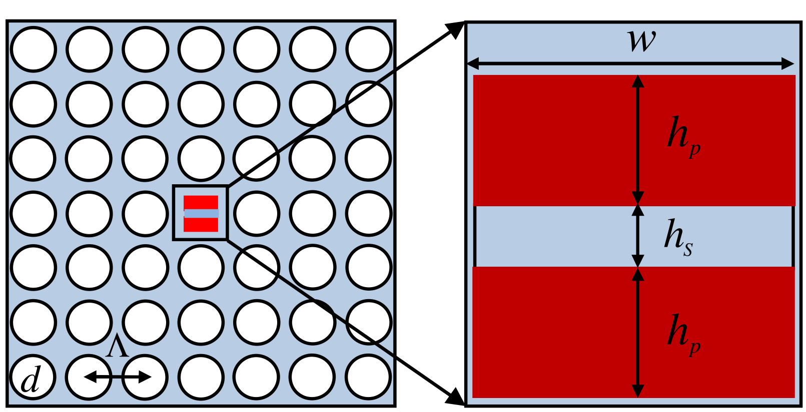

Fig. 1. Cross-sectional view of the proposed HNL-PCF.