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Waveguiding properties of a silicon nanowire embedded photonic crystal fiber

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ABSTRACT

We design a photonic silicon nanowire embedded microstructured optical fiber which is a special class of waveguide whose core diameter is of subwavelength or nanometer size with the air holes in the cladding. We study the optical waveguiding properties, namely, waveguide dispersions, fractional power and effective nonlinearity by varying the core diameter. The results reveal that the air-clad silicon subwavelength nanowire exhibits several interesting properties such as tight-confinement, a large normal dispersion (82,385 ps^2/km) for 300 nm core diameter and a large anomalous dispersion (−6817.3 ps^2/km) for 500 nm core diameter at 1.95 μm wavelength. The structure offers two zero dispersions, one at 1.26 μm wavelength for a core diameter of 300 nm and another at 1.83 μm wavelength for 400 nm core diameter. Besides, it provides a large nonlinearity (5672.7 W^{-1} m^{-1}) at 0.450 μm wavelength for 300 nm core diameter. These enhanced optical properties might be suitable for various nonlinear applications.

1. Introduction

Over the past few decades, dielectric optical waveguides with diameters ranging from micrometers to sub-micrometers have found promising applications in various fields such as optical communication, optical sensing, and optical power delivery systems [1]. It is known that minimizing the width of the waveguides ultimately could result in widening the scope of the photonic device based applications. However fabricating such low-loss optical waveguides with subwavelength diameters remains challenging because of high precision requirement [2]. Recently, several types of dielectric submicrometer and nanometer diameter wires of optical qualities have been fabricated [3] and also demonstrated for guiding light within the visible and near infrared spectral ranges [1,4–6].

Thanks to the advancement in nanotechnology, the realization of nanowire in fiber optics called photonic nanowire (PN) has become a reality [2]. PN with core diameter less than 1 μm, which is lesser than the optical wavelength, has attracted a significant attention owing to the myriad of interesting optical properties such as tight mode optical confinement, large waveguide dispersion, and high effective nonlinearity [7]. In addition, the dispersion due to this waveguide can be changed by varying the core diameter, ultimately, facilitating positive, negative and zero dispersion operations [8]. This waveguide with tailored dispersion finds applications in soliton-self compression [9], dispersion compensation, supercontinuum generation [4,6,10] and biosensing [11] due to its smaller core diameter.

In recent times, PNs have been fabricated from a variety of high-low index glasses such as silica glass [6,12], chalcogenide glass [13] and silicon [14,15]. However, of these materials, silicon is highly preferred to the rest for the reasons mentioned in what follows. First, silicon exhibits excellent transmission properties in the near infra-red wavelength range and, in particular, in the communication window. When compared to silica, silicon possesses a large nonlinearity by four order [16]. Recently, single mode operation, group velocity and waveguide dispersion have been studied experimentally using silicon nanowires [1]. Analysis of modal ellipticity and modal hybridness in a silicon nanowire has been presented [17]. Silicon waveguides find many applications in Raman lasers [18], supercontinuum generation [19,20], all-optical regeneration [20] and pulse compression [9].

It is observed that the PN provides enhanced optical properties when embedded with a photonic crystal fiber (PCF) and the resulting waveguide is known as nanowire embedded PCF or PCF-photonic nanowire (PCF-NW) [21]. In this work, we design a silicon nanowire embedded PCF (SN-PCF) and analyze the various enhanced optical properties.

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The paper is laid out as follows. In Section 2, we discuss the design of a SN-PCF using fully-vectorial finite element method. Upon reducing the core diameter from 1000 to 300 nm, in Section 3, we explore the various optical properties including group velocity dispersion (GVD), higher order dispersions, fractional power within the core, effective mode area and effective nonlinearity. Finally, we summarize the findings in Section 4.

2. Proposed structure

Fig. 1 shows the geometrical cross-section of the proposed air-hole SN-PCF. The salient feature of this proposed structure is that the center of the core is smaller than that of the conventional PCF. In this structure, the cladding of the PCF consists of five rings of air holes distributed in a triangular pattern around the core region. In general, the number of air hole rings in the cladding decides the confinement loss and in this work, we optimize the number of rings to five for ensuring better light confinement. In this design, as the core diameter (d_c) is less than 1 μm, the pitch (Λ) is kept at 1.4 μm and air hole diameter at 1.12 μm. At this juncture, it would be fitting to present the possible fabrication procedures for the various nanowire embedded fibers. The hybrid waveguides have been fabricated by means of the pressure-cell filling technique, splice-filling technique and direct fiber drawing technique [22]. The following elements, namely, Au, Ag, Ga and Ge [23] and chalcogenide glasses [24] have been embedded by splice-filling technique. Further, pressure-cell technique helps embed Tellurite glass in the silica PCF [21]. As the melting temperature of silicon and silica is nearly the same, the filling of silicon into the holes of photonic crystal fiber (PCFs) becomes challenging, although feasible [22]. Thus, we are of the opinion that the direct fiber drawing technique might turn out to be a viable means of realizing the proposed SN-PCF.

Here, we study all the optical properties for the various core diameters ranging from 1000 to 300 nm. The justification for this range of study is due to the fact that the confinement becomes challenging below 300 nm and the proposed structure behaves like a conventional PCF above 1000 nm. In simulation, the refractive indices of the silicon and silica have been considered to be 3.5 and 1.45, respectively [1]. Fig. 2 illustrates the mode field distribution at 1.55 μm wavelength when the core diameter is 500 nm. In order to determine the dispersion of SN-PCF, it is necessary to compute the effective refractive index of the fundamental mode HE_{11} and the same is done by finite element method. In Fig. 3, we plot the effective index as a function of wavelength for various core diameters. The effective index is calculated for a range of

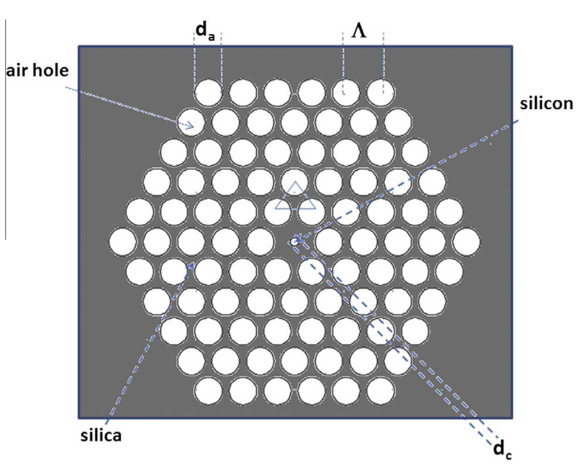

Fig. 1. Geometrical structure of the SN-PCF of 500 nm core diameter.

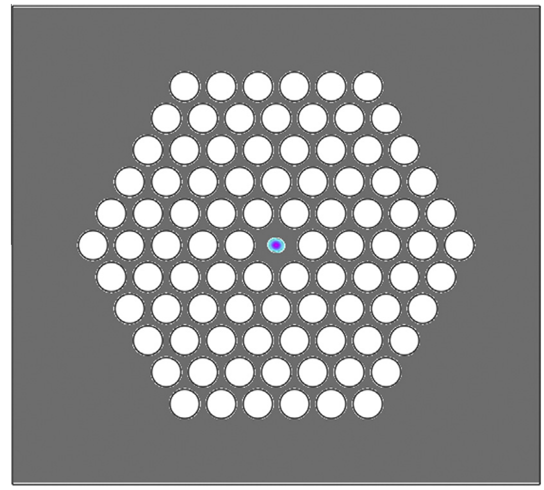

Fig. 2. Mode field distribution at 1.55 μm wavelength for 500 nm core diameter.

wavelengths from 0.450 to 1.95 μm. As is seen in Fig. 3, as the wavelength increases, the effective index of the fundamental mode decreases upon decreasing the core diameter. It may be noted here that, while for lower wavelength range, light is tightly confined within the core, for longer wavelength range, the light is getting leaked as evanescent field. However, as the wavelength is increased further, the modal field spreads considerably into the cladding. So, the effective index tends to reduce at a faster rate with the increase in wavelength.

3. Waveguiding properties

In this section, we explore the various linear and nonlinear properties. In Section 3.1, we study the impact on various dispersions extending up to fifth order for different core diameters. Next, we analyze the fractional power inside the core in Section 3.2. Finally, in Section 3.3, we compute the nonlinearity by calculating the effective mode area.

3.1. Linear properties: Waveguide dispersion

It is established that the dispersion due to nanowires depends both on the operating wavelength and the core diameter [1]. The core diameter dependent group velocity dispersion (GVD) facilitates shifting of the zero dispersion point in photonic nanowires. Controlling light propagation by tailoring the waveguide dispersion is widely practised, particularly in ultrafast nonlinear processes, dispersion and chirp compensation, and short pulse fiber lasers and amplifiers. The group velocity dispersion, (β_2), is determined from the second derivative of the effective mode index as a function of the wavelength. We use the following equations for determining the GVD and third order dispersion (TOD).

$$\beta_2 = \frac{d}{d\omega}\left[\frac{dk}{d\omega}\right] = \frac{\lambda^3}{2\pi c^2}\frac{d^2 n_{eff}}{d\lambda^2} \tag{1}$$

and

$$\beta_3 = \frac{d}{d\omega}\left[\frac{d^2 k}{d\omega^2}\right] \tag{2}$$

where k is the wavenumber, ω is the angular frequency and c is the velocity of light in vacuum. In this work, we have ignored the effect of material dispersion on account of the fact that its magnitude is very much lesser than that due to waveguide dispersion. In Fig. 4, we plot the GVD as a function of wavelength for different core