# Supercontinuum Generation in Elliptical Silicon Nanowire Embedded Spiral Photonic Crystal Fiber

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**Abstract**— In this paper, we design an elliptical core silicon nanowire embedded spiral photonic crystal fiber (SN-SPCF) using fully vectorial finite element method. Further, we analyze the various optical properties, namely, waveguide dispersion, birefringence and effective nonlinearity by varying the ellipticity for a wide range of wavelengths from 0.450 μm to 2.050 μm. The proposed structure exhibits a high birefringence of 0.74143 for a small ellipticity of 0.3 at a longer wavelength of 2.05 μm. Besides, we investigate the evolution of supercontinuum generation both in spectral and temporal domains as a function of ellipticity at 1.550 μm wavelength for an input pulse of width 100 fs and peak power of 50 W in a fiber of 2 mm length. The numerical results corroborate that the proposed SN-SPCF provides a wider bandwidth of supercontinuum (600 to 2600 nm) and the findings of this work may be useful in ultrahigh-resolution optical coherence tomography.

## 1. INTRODUCTION

In recent times, supercontinuum (SC) generation in photonic crystal fibers (PCF) has attracted considerable attention because of its wide applications in the fields of the optical communications, optical coherence tomography (OCT), optical metrology, time resolved absorption and spectroscopy [1–3]. Photonic crystal fibers are ideal media for SC as the desired dispersion can be achieved to help generate supercontinuum for a specific wavelength. By this way, it is possible to convert a light of fixed wavelength into both longer and shorter wavelengths around the operating wavelength. The basic requirements for the generation of broadband continuum are anomalous group velocity dispersion (GVD) with a small third order dispersion (TOD) and a high nonlinearity at the operating wavelength [4].

Recently, the generation of SC in photonic nanowires (PhNs) has received significant interest because of their unique properties and wide range of applications [5]. The dielectric waveguides with a nanocore diameter exhibit a remarkably strong field confinement, enhanced light-matter interactions and strong control over linear and nonlinear optical properties. When a nanowire made of silicon is embedded into a photonic crystal fiber, the resulting structure is referred to as a silicon nanowire embedded photonic crystal fiber (SN-PCF) wherein the core diameter is lesser than the operating wavelength [6, 7]. This SN-PCF provides the enhanced linear and nonlinear optical properties and hence, it has attracted considerable interest in the recent past. Thus, with this special nanowire, it is possible to generate supercontinuum within a short length of fiber with less input power.

The motivation for choosing a novel biomimetic spiral structure PCF stems from a myriad of possible applications in nonlinear optics, especially, in SCG and pulse compression with the properties of high nonlinearity assisted by tunable dispersion [8]. The main advantages of the spiral PCF are the improved field confinement and the less air filling fraction in comparison to conventional PCF. Here, we report the supercontinuum of bandwidth wider than 1500 nm with less input peak power (50 W) using a short piece (2 mm) of SN-PCF.

In this work, we design a silicon nanowire embedded spiral photonic crystal fiber (SN-SPCF) with elliptical nanocore for generating supercontinuum with the requirements mentioned above. The paper is laid out as follows. In Section 2, we present the design analysis of the proposed structure. In Section 3, we study the optical properties of the fundamental mode, namely, the group velocity dispersion (GVD), third order dispersion (TOD), birefringence and effective nonlinearity by varying the ellipticity of SN-SPCF. Further, we investigate the evolution of SC in both spectral and temporal domains at 1.550 μm wavelength in Section 4. Finally, we summarize the findings in Section 5.

## 2. DESIGN OF THE PROPOSED SN-SPCF

The schematic cross section of the proposed SN-SPCF is as shown in Fig. 1(a). It is composed of circular air holes in the cladding arranged in a spiral array and an elliptical defected core, with **a** and **b** being the major and the minor axes diameters, respectively. Generally hybrid waveguides have been fabricated by means of the pressure-cell filling technique, splice-filling technique and direct fiber drawing technique [9]. In the proposed structure, the outer cladding air hole distribution is composed of 9 spiral arms each containing 5 air holes. In each spiral arm, the first air hole is at a distance of $r_0 = 1.2\,\mu\text{m}$ from the center and each successive air holes are placed at an angular displacement of $\theta$. The distance of the $n$th air hole of that spiral arm is $r_n = r_{n-1} + (0.8 \times d_h)$ with an angular displacement of $\theta_n = 360°/(n \times N)$ from the previous hole of the spiral arm. Here, $N$ is the total number of spiral arms and $d_h$ ($= 600\,\text{nm}$) is the diameter of the air hole in each arm.

We study the optical properties of the fundamental mode by increasing the ellipticity (**b**/**a**) value by keeping **a** constant and by varying **b** as a function of the wavelength from $0.450\,\mu\text{m}$ to $2.050\,\mu\text{m}$. We fix the major core diameter as $\mathbf{a} = 550\,\text{nm}$ and slightly increase the ellipticity (**b**/**a**) from 0.3 to 0.7 in steps of 0.1. At this juncture, we point out that this range of ellipticity (**b**/**a**) results in a dimension comparable to that of the diameter of the nanowire, i.e., less than $1\,\mu\text{m}$ [10]. In the simulation, we fix the diameter of the air-holes in the cladding to be higher than the major core diameter **a** to meet with the requirements of SC generation. The electric field distribution of the $x$-polarized fundamental mode for SN-SPCF with the parameter of **b**/**a** being 0.5 at $1.55\,\mu\text{m}$ wavelength is as shown in Fig. 1(b).

## 3. LINEAR PROPERTIES

In this section, we delineate the important linear effects, namely, second and third order dispersions and birefringence. It is known that the dispersion does depend on both operating wavelength and the nanocore diameter. The core diameter dependent GVD and TOD of the $x$-polarized mode have

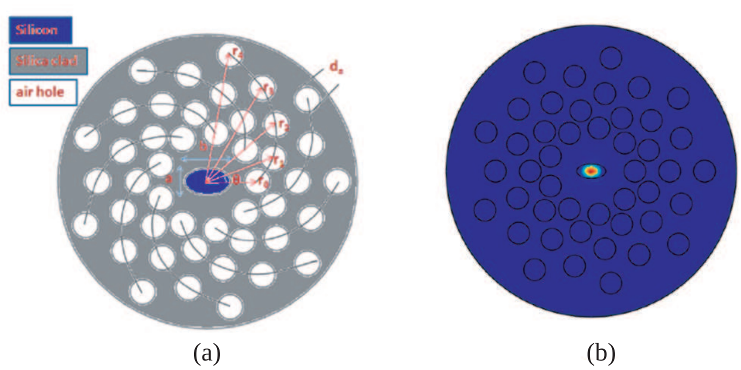


Figure 1: (a) Geometrical structure and (b) mode field distribution of the proposed SN-SPCF with an ellipticity of 0.7.

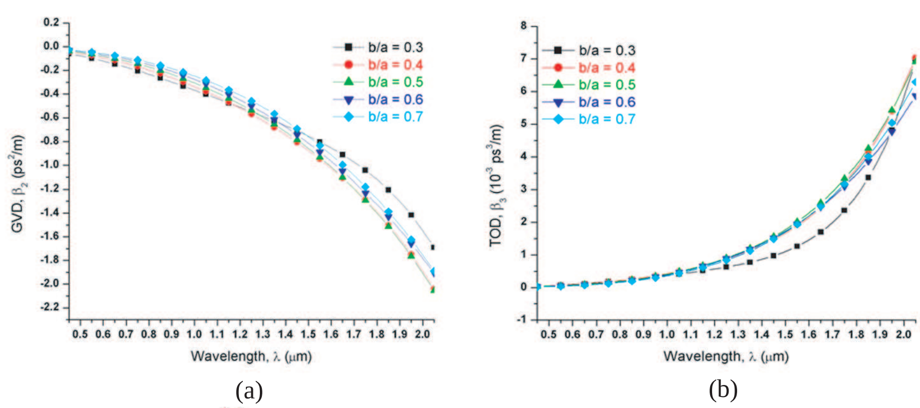


Figure 2: (a) Group velocity dispersion and (b) third order dispersion of the proposed SN-SPCF for various ellipticity.

been determined from the second and third derivatives of the computed $n_{eff}$. The variations of GVD and TOD of the $x$-polarized mode over the entire wavelength for various ellipticity are as shown in Figs. 2(a) and (b).

From Fig. 2(a), it is clear that the SN-SPCF exhibits anomalous GVD for all ellipticity at a chosen wavelength as the field distribution inside the elliptical nanocore increases gradually towards the cladding region. Upon increasing the wavelength, the GVD value increases on the negative side as a result of less confinement within the core and the same trend is observed for all ellipticity values. We achieve a less anomalous GVD of $-0.0265\,\mathrm{ps^2/m}$ for an ellipticity of 0.7 at $0.450\,\mu\mathrm{m}$ wavelength. We find almost a flattened TOD up to $1.050\,\mu\mathrm{m}$ wavelength for all ellipticity values. It is noticed that for further increase in wavelength, the TOD increases slowly. We report a less value of TOD as $0.018 \times 10^{-3}\,\mathrm{ps^3/m}$ at $0.450\,\mu\mathrm{m}$ wavelength for 0.7 ellipticity. Next, we turn to compute the birefringence for the proposed fiber. The SN-SPCF exhibits a high birefringence of 0.4017 for 0.3 ellipticity at $1.55\,\mu\mathrm{m}$ wavelength, which is two to three orders of magnitude higher than that of the elliptical PCF ($1.94 \times 10^{-2}$) and conventional elliptical-hole PCF ($4.91 \times 10^{-3}$) at $1.55\,\mu\mathrm{m}$ [11, 12].

## 4. NONLINEAR PROPERTY

Due to the small core diameter and high nonlinear index coefficient of silicon ($4 \times 10^{-18}\,\mathrm{m^2/W}$), the SN-SPCF exhibits tight light confinement compared to that of the conventional PCF. The variations of the effective nonlinearity ($\gamma^V$) against wavelength of the fundamental mode for various ellipticity values are depicted in Fig. 3. The small core ellipticity exhibits tight mode confinement and very high nonlinearity ($1908\,\mathrm{W^{-1}m^{-1}}$) at $0.450\,\mu\mathrm{m}$ wavelength compared to other ellipticity fibers.

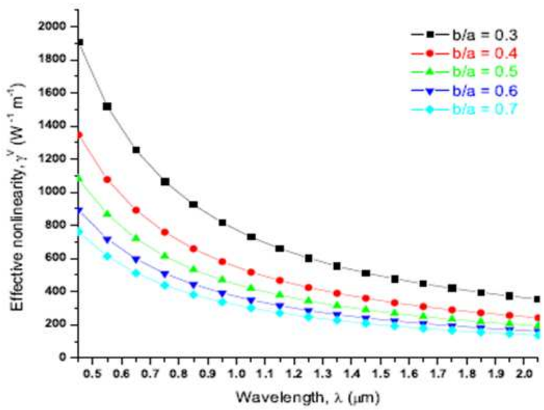


Figure 3: Variation of effective nonlinearity of the SN-SPCF for different ellipticity.

## 5. SIMULATION OF SUPERCONTINUUM GENERATION

To investigate the generation of SC in SN-SPCF, we employ the modified nonlinear Schrödinger equation in which the loss ($\alpha \approx 0$ and $\alpha^f \approx 0$), higher order dispersion ($\beta_2$ and $\beta_3$), nonlinear response function ($R(T-\tau)$) and $\gamma^V$ can be expressed in time domain as follows [13],

$$\frac{\partial A}{\partial z} = -\frac{1}{2}\left(\alpha + \alpha^f\right)A - \frac{i}{2}\beta_2\frac{\partial^2 A}{\partial T^2} + \frac{\beta_3}{6}\frac{\partial^3 A}{\partial T^3} + i\gamma^V\left[1 + \frac{\omega}{\omega_0}\right]A\int_{-\infty}^{\infty}\left[R(T-\tau)|A|^2\right]d\tau \qquad (1)$$

where, $A(z,T)$ is the field envelope. $R(t)$ is defined by [13], $R(t) = (1 - f_R)\delta(t) + f_R h_R(t)$, with fractional Raman contribution $f_R = 0.043$. The delayed Raman response $h_R(t)$ of silicon is expressed as: $h_R(t) = \Omega_R^2 \tau_1 \exp(\frac{-T}{\tau_2})\sin(\frac{T}{\tau_1})$, where $\tau_1 = 10\,\mathrm{fs}$ and $\tau_2 = 3\,\mathrm{ps}$ correspond to the Raman shift and Raman gain spectrum, respectively. The pulse propagation in SN-SPCF is solved by symmetrized split-step Fourier method [14].

We consider the input soliton order, $N$, having an envelope field expression given by [15]: $A(0,t) = N\sqrt{P_0}\mathrm{sech}[\frac{t}{T_0}]$, where $P_0$ is the peak power and $T_0$ is the input soliton duration defined as $T_{\mathrm{FWHM}}/1.763$. The soliton order of the input pulse $N$ $[= \sqrt{\frac{T_0^2 P_0 \gamma}{\beta_2}}]$ is determined by both pulse and fiber parameters.

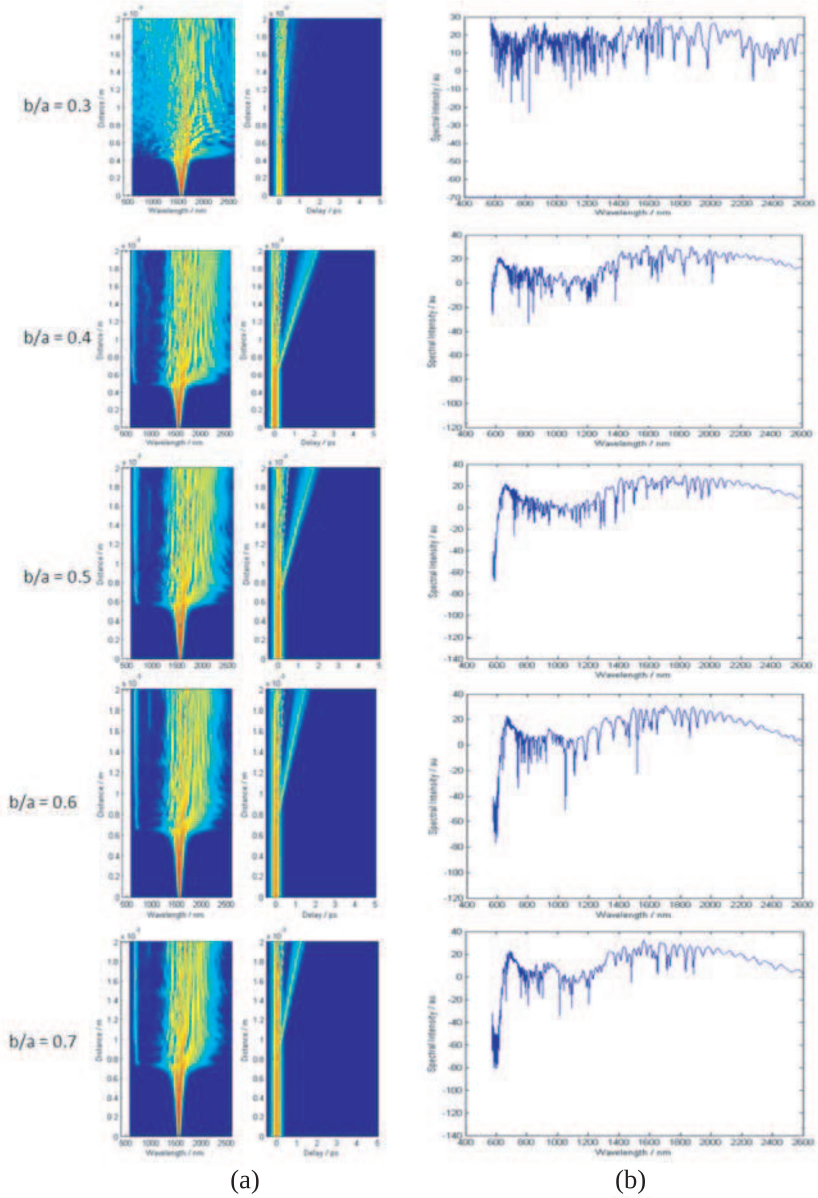


Figure 4: (a) Spectral, temporal evolution and (b) spectral intensity of supercontinuum pulse for 50 W power of different ellipticity at 1.550 μm wavelength.

We consider the propagation of a hyperbolic secant pulse of width 100 fs with a peak power of 50 W in a short piece of fiber (2 mm). Figs. 4(a) and (b) represent the evolution of the waveforms and their spectral components at 1.550 μm wavelength. As can be seen in Fig. 4, a relatively wider SC spectrum (600 to 2600 nm) is observed due to the combined action of self-phase modulation, Raman effect and soliton fission.

## 6. CONCLUSION

In this paper, we have proposed an elliptical silicon nanowire embedded spiral photonic crystal fiber and studied the optical properties using a fully-vectorial finite element method. We have numerically investigated the supercontinuum generation using a short piece (2 mm) of SN-SPCF at an operating wavelength of 1.55 μm with a less input power of 50 W for the input pulse of 100 fs. Further, we have been able to achieve a wider bandwidth of 2000 nm. We are of the opinion that the proposed SN-SPCF would turn out to be a right candidate for the precise measurement of optical frequencies, high resolution noninvasive medical imaging (optical coherence tomography), atomic spectroscopy and telecommunication wavelength division multiplexing.

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