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Design of all normal dispersion highly nonlinear photonic crystal fibers for supercontinuum light sources: Applications to optical coherence tomography systems

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In this paper, we investigate the generation of supercontinuum (SC) light source based on a highly nonlinear Germanium (Ge) doped photonic crystal fiber (HNL-GePCF) with all normal group velocity dispersion (GVD). By doping 3% higher refractive index Ge inside silica, nonlinear coefficient γ is increased as large as 110.6 $W^{-1}\,km^{-1}$ at 1.31 μm. Using finite element method (FEM) with a circular perfectly matched boundary layer (PML), it is shown through simulations that the proposed HNL-GePCF offers an efficient SC generation for dental optical coherence tomography (OCT) applications at 1.31 μm. By propagating $sech^2$ picosecond optical pulses having 2.5 ps and 1.0 ps pulsewidth at a full width at half maximum (FWHM) through the proposed HNL-GePCF, output optical pulses are analyzed by the split-step Fourier method to obtain the spectral contents. Simulation results show that 105 m of the proposed HNL-GePCF can produce 100 nm spectrum (10 dB bandwidth) at 1.31 μm for 2.5 ps input optical pulse and 110 m of such HNL-GePCF can produce 140 nm *spectrum* (10 dB bandwidth) for 1.0 ps input optical pulse. Therefore, the highest longitudinal resolutions in the depth direction for dental OCT are found about 3.28 μm for enamel and 3.51 μm for dentin.

1. Introduction

Broadband light sources are needed for the low coherence based imaging techniques such as OCT systems [1]. Typical sources for OCT are superluminescent diodes (SLDs) and sources based on amplified spontaneous emission (ASE) from doped fibers or semiconductors. All of these sources are limited spectral bandwidth and restricted to wavelength range. Due to insufficient longitudinal resolution for identifying individual cell or assessing sub cellular structures such as nuclei, SLDs having 10−15 μm longitudinal resolution [2] that are used for most of the standard OCT applications are being replaced by PCF based SC [3–10] light sources.

PCFs with all normal GVD for pulse preserving SC generation are demonstrated in Refs. [11–15] as the generated SC spectrum in all normal GVD are suitable for time resolved applications due to suppression of soliton dynamics [11]. Mainly, the SC generation in all normal GVD is due to self-phase modulation [12] and optical wave breaking [13]. The key benefit of SC generation in normal dispersion region is the conservation of a single ultrashort pulse in the time domain with smooth and recompressible phase distribution [14]. Therefore, it becomes a way to avoid spectral fluctuations [15] by allowing the pump pulses to work in the normal dispersion region. In Refs. [16,17], PCFs have been designed in all normal dispersion region for medical applications. The first one is optimized at 1.06 μm for biomedical OCT applications and the second one is optimized at 1.31 μm for dental OCT applications. Although very good performance is shown in the respective domains, authors have not considered the fourth order dispersion parameter which has a profound effect on spectral broadening. In Ref. [18], authors demonstrated the applications of SC spectrum generated from air–silica microstructured fiber for ultra-high resolution OCT imaging and claimed that a highest free-space longitudinal resolutions of 2.5 μm at 1.3 μm center wavelength is achieved. However, that study was done based on femtosecond pulse generated by a commercial Kerr-lens mode-locked Ti:Sapphire laser which is very expensive. High cost of this type of femto-order pulse width laser source limits the widespread use in OCT systems. Research is ongoing to produce

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ultra-high resolution OCT systems using less expensive picosecond pulse laser sources by replacing femtosecond pulse lasers.

In this paper, we design a HNL-GePCF with all normal GVD for dental OCT applications at 1.31 μm center wavelength since the penetration depths in the biological tissues are very high in the wavelength range from 1.3 to 1.5 μm [19,20]. In this demonstration, we use a picosecond optical pulse which can be easily produced by picosecond laser, distributed feedback laser diode [21]. By propagating a sech^2 input optical pulses having 2.5 ps and 1.0 ps pulse width at a full width at half maximum (FWHM) through the proposed HLN-GePCF, output optical pulse is analyzed by the split-step Fourier method to obtain the spectral contents and coherent lengths of generated SC light sources are found 7.57 μm and 5.41 μm respectively. Therefore, the highest longitudinal resolutions in the depth direction for dental OCT are found about 3.28 μm for enamel and 3.51 μm for dentin assuming a typical value of refractive index 1.65 for enamel and 1.54 for dentin [22].

2. Design procedures of HNL-GePCF

Fig. 1 shows the geometry of the proposed HNL-GePCF with the optimized air-hole diameters d_1, d_2, d_3, d_4, d_5, 3% higher refractive index Ge-doped core diameter d_{ge} and pitch Λ. Hexagonal structure with five rings is selected as it is the best arrangement to shape the dispersion curves [23]. We scale down significantly the diameters of the 1st ring to shape the desired curve and the 2nd, 3rd, 4th and 5th ring are used to change little bit to adjust the desired curve at near-zero value. By keeping air-filling fractions d/Λ at bigger values, we concentrate to reduce confinement loss as much as possible and to confine the field better within small core since HNL-PCFs (small core PCFs) are very much leaky [24] due to small distance between the core and the solid region beyond the cladding for small pitch values. By following a simple design procedures described in Refs. [24,25], we successfully design this HNL-GePCF with all normal GVD. To optimize the design parameters, a simple technique described in Ref. [25] is applied. First, a relatively higher d/Λ of all air-hole dimension is chosen in the range from 0.5 to 0.95. Particularly, we have set it by observing the better field confinement to select initial guess refractive index value which is very important parameter for further processing. Then, value of d_1/Λ is examined

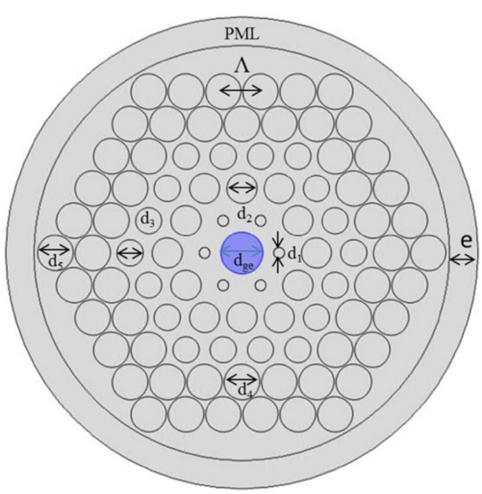

Fig. 1. The proposed HLN-GePCF with circular PML. The diameter of air-holes of the 1st ring, 2nd, 3rd, 4th and 5th ring are $d_1 = 0.29\Lambda$, $d_2 = 0.78\Lambda$, $d_3 = 0.83\Lambda$, $d_4 = d_5 = 0.95\Lambda$ respectively where pitch $\Lambda = 0.73$ μm and the 3% higher refractive index Ge-doped core diameter is $d_{ge} = 1.12\Lambda$.

by investigating the dispersion curve from several iterations. As there is most significant role of first ring d_1/Λ on dispersion curve variation, second ring d_2/Λ, and third ring d_3/Λ are also varied for fine tuning the dispersion curve at desired location.

3. Simulation results and discussions

Simulation is conducted using FEM to simulate the properties of the proposed HNL-GePCF. To damp backscattering at the boundaries of the simulation area, a circular PML is imposed inside the simulation domain since PML is the most efficient absorption boundary conditions [26] and circular design of PML is defined to improve calculations modes propagation in optical fibers [27]. The proposed HNL-GePCF is designed within circular computational window having 10 μm diameter. Triangular lattice of air holes are placed within a circular area with 4.2 μm radius and rest of 0.8 μm is provided for the thickness of a uniform circular PML. Once the electric field $E(x,y)$ and the modal effective index n_{eff} are obtained by the FEM, effective area A_{eff}, the chromatic dispersion parameter $D(\lambda)$, confinement loss L_c and GVD β_2 can be obtained by the following equations [28,35]:

$$A_{eff} = \frac{\left(\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} |E(x,y)|^2\, dx\, dy\right)^2}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} |E(x,y)|^4\, dx\, dy} \tag{1}$$

$$D(\lambda) = -\frac{\lambda}{c}\frac{d^2 Re[n_{eff}]}{d\lambda^2} \tag{2}$$

$$L_c = 8.686 k_0 Im[n_{eff}] \tag{3}$$

$$\beta_2 = \frac{\lambda^2}{2\pi c} D(\lambda) \tag{4}$$

where $Re[n_{eff}]$ is the real part of n_{eff}, $Im[n_{eff}]$ is the imaginary part of n_{eff}, λ is the wavelength, and c is the velocity of light in vacuum. As the holey cladding in PCF makes the large difference of refractive index between the silica core and cladding, light concentrates more into a very small area of the core, resulting in enhanced effective nonlinearity. A small effective area provides the high optical power density necessary for nonlinear effects to be significant, and the nonlinear coefficient γ is calculated by using the following equation [29]:

$$\gamma = \left(\frac{2\pi}{\lambda}\right)\left(\frac{n_2}{A_{eff}}\right) \tag{5}$$

Here, n_2 is the nonlinear refractive index and n_2/A_{eff} is a nonlinear constant. Since the n_2 of pure silica core is 2.1×10^{-20} m^2/W [30–32] and nonlinear coefficient γ of pure silica core is of the order of 1 W^{-1} km^{-1} [24], our proposed HNL-GePCF with all normal GVD is designed by reducing the pitch diameter significantly and composing 3% higher refractive index Ge-doped core ($n_{ge} = 1.4935$) inside the silica material ($n_{silica} = 1.45$) to enhance nonlinear refractive index and thereby nonlinear coefficient. This nonlinear refractive index n_2 of 3% higher refractive index core inside silica material is calculated by the following expression [33]:

$$n_2 = (0.505 \times \Delta_{eff} + 2.507) \times 10^{-20} \tag{6}$$

where Δ_{eff} is the effective refractive index difference (%).

Fig. 2 shows flattened dispersion, GVD and dispersion slope of the proposed PCF for optimized parameters $d_1 = 0.29\Lambda$, $d_2 = 0.78\Lambda$, $d_3 = 0.83\Lambda$, $d_4 = d_5 = 0.95\Lambda$ where pitch $\Lambda = 0.73$ μm and the 3% higher refractive index Ge-doped core diameter $d_{ge} = 1.12\Lambda$. Parabolic curve having near-zero dispersion, very small GVD and dispersion slope are observed at 1.31 μm. For optimized parameters, dispersion, GVD, and dispersion slope are −0.44 ps/(nm.km),