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Philippe Brechignac, Yeung Lak Lee, Huynh Thanh Dat
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INVESTIGATION OF OPTICAL PROPERTIES OF CIRCULAR LATTICE PHOTONIC CRYSTAL FIBERS BASED ON GEO$_2$-SIO$_2$ GLASSES

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Abstract. In this paper, we design SiO_2-based photonic crystal fibers with cores replaced by 85%SiO_2-15%GeO_2 glasses to improve dispersion and nonlinear properties of the fibers. Effective refractive index and dispersion were analyzed in detail to propose two optimal structures suitable for supercontinuum generation application. Based on numerical simulation results, two optimal fibers are proposed with flat all-normal and anomalous dispersion. The dispersion value as small as 0.298 ps/nm.km and −0.311 ps/nm.km at the pump wavelength and small effective refractive index of 1.375 and 1.386 are important conditions that make these two fibers able to be supercontinuum sources with broad spectra, replacing glass core fibers.

Keywords: *Photonic crystal fibers, SiO_2-GeO_2 glasses, flat dispersion, small effective refractive index.*

I. INTRODUCTION

Silica (SiO_2)-based solid-core photonic crystal fibers (PCFs) have demonstrated their important role in generating high-intensity and broad supercontinuum (SC) spectra. Unfortunately, the spectral width does not exceed the 2.5 µm wavelength because the phonon energy of silica is relatively high, about 1100 cm^{-1} [1]. There has been interested in developing broadband sources in various optical media to avoid this silica limitation. Some publications show that liquid-infiltrated hollow-core PCFs with high nonlinearity can extend the spectrum up to 3.0 µm [2–4]. Soft glass solid-core fibers, such as fluoride [5, 6] or chalcogenide [7, 8], can be used to generate SC in the mid-infrared region (MIR) but these fibers are often expensive, fragile, and quite difficult to handle. Germania (GeO_2) has similar physical properties to silica but it has a lower phonon energy of about 820 cm^{-1} [1], which gives the GeO_2-doped SiO_2 fibers a longer transmission window towards the MIR [9]. Besides, their fabrication based on drawing methods for silica fibers has been demonstrated in practice [10]. Recently, several publications have shown SC spectrum expansion in the MIR region using germanium-doped core silica fibers [9, 10–13]. Some silica fibers with a GeO_2 doped core with concentrations ranging from 51 mol% to 97 mol% [14, 15] and loss below 120 dB/km at 1.9–2 µm have been experimentally fabricated.

In this work, we investigated the dispersion and effective refractive index of silica fibers doped GeO_2 with a concentration of 15% mol. The variation of the effective refractive index strongly depended on the change in the lattice parameters. The difference in the diameters of the air holes in the cladding layers also contributed to improve dispersion properties of the fiber. We obtained both all-normal and anomalous dispersion, flat and small dispersion curves at 1.55 µm, which are suitable for SC generation.

II. NUMERICAL MODELLING OF PCFs

We simulated the structures and optical properties of PCFs with SiO_2 substrates using Lumerical Mode Solution (LMS) software. The method of the full-vector finite-difference eigenmode was used to solve the Maxwell wave equation with the boundary condition that the perfectly matched layers of rectangles help absorb incoming waves from the computed region without any reflections. The circular lattice was selected in the fiber geometry data in the LMS system.

The structure of the PCFs consisted of six evenly spaced layers of air holes with spacing Λ (Fig 1a), the diameter of the first air hole was varied with the filling factor $d_1/\Lambda = 0.3–0.65$ while the diameter of the air hole from the second layer onwards was kept fixed with $d_2/\Lambda = 0.95$. The SiO_2 substrate and the doping GeO_2 were declared through the coefficients of the Sellmeier equation (1–3) [16, 17]. The core had a diameter that was determined through the formula $D_c = 2\Lambda - d_1$ and was doped 15% mol GeO_2. The wavelength range investigated is 0.5–2.0 µm which was compatible with existing LMS data. By skillfully tuning the lattice structure parameters, the PCFs confined the light well in the core (Fig 1b).

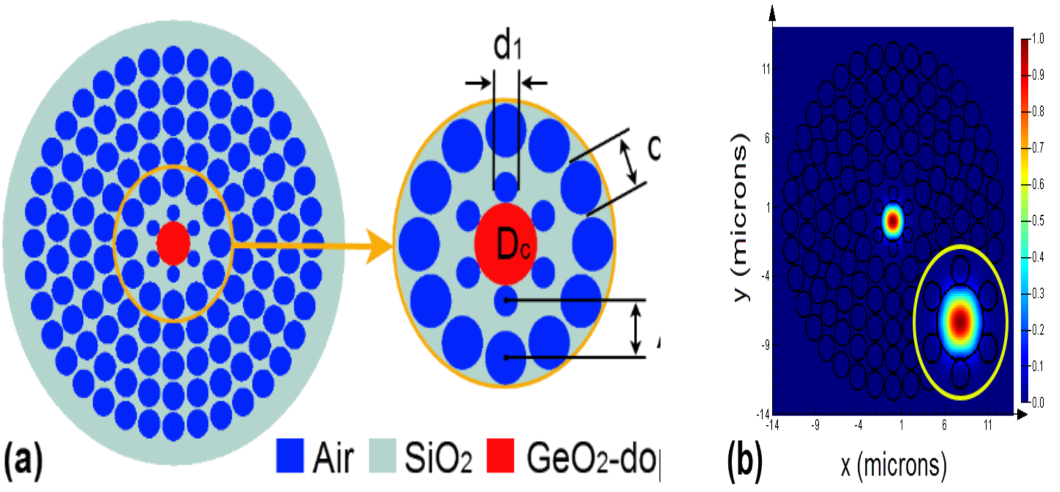

Fig 1. *Cross-section view of the circular SiO_2-GeO_2 PCF (a), and the light confinement in the core of PCF with $\Lambda = 2.0$ µm; $d_1/\Lambda = 0.55$ (b)*

$$n_{SiO_2}(\lambda)=\sqrt{1+\frac{0.6961663\lambda^2}{\lambda^2-4.679148\times10^{-3}}+\frac{0.4079426\lambda^2}{\lambda^2-1.3512063\times10^{-2}}+\frac{0.8974794\lambda^2}{\lambda^2-97.93400254}} \quad (1)$$

$$n_{GeO_2}(\lambda)=\sqrt{1+\frac{0.80686642\lambda^2}{\lambda^2-4.75722\times10^{-3}}+\frac{0.71815848\lambda^2}{\lambda^2-2.3705545\times10^{-2}}+\frac{0.85416831\lambda^2}{\lambda^2-140.2313298}} \quad (2)$$

$$n_{(GeO_2\text{-}SiO_2)}(\lambda)=\sqrt{1+\sum_{i=1}^{3}\frac{[SB_i+X(GB_i-SB_i)]\lambda^2}{\lambda^2-[SC_i+X(GC_i-SC_i)]^2}} \quad (3)$$

where *SB*, *SC*, *GB*, *GC* were the Sellmeier confficients for the SiO_2 and GeO_2 glasses, respectively, and *X* is the mole fraction of GeO_2 ($X = 0.15$).

Fig 2 depicted the dependence of the refractive index of pure SiO_2, pure GeO_2 and a composite of 85% SiO_2 - 15% GeO_2 on wavelength. Although the refractive index of pure GeO_2 was the largest in the whole investigated wavelength range, PCFs based on it exhibited a significant loss [13]. Therefore, the PCF core doped with GeO_2 is a new structure to improve optical properties, reduce loss, and enhance SC generation efficiency. However, the GeO_2 doped molar concentration should also be taken into account because the loss will increase as the GeO_2 molar concentration increases.

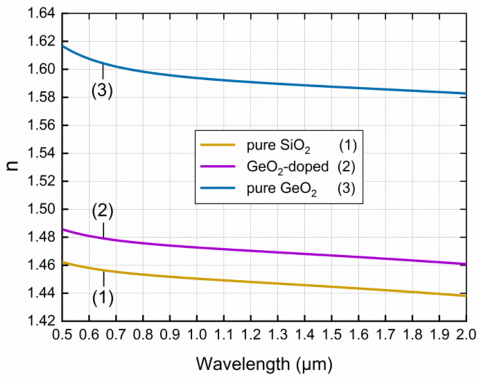

Fig 2. *The real parts of the refractive index of pure SiO_2, pure GeO_2, and composite SiO_2-GeO_2*

III. SIMULATION RESULTS AND ANALYSIS

The large refractive index difference between the core and the cladding will limit the leakage of modes from the core to the cladding and between layers of the cladding. The effective refractive index was wavelength dependent, which was dominated by the lattice structure parameters (Fig 3).

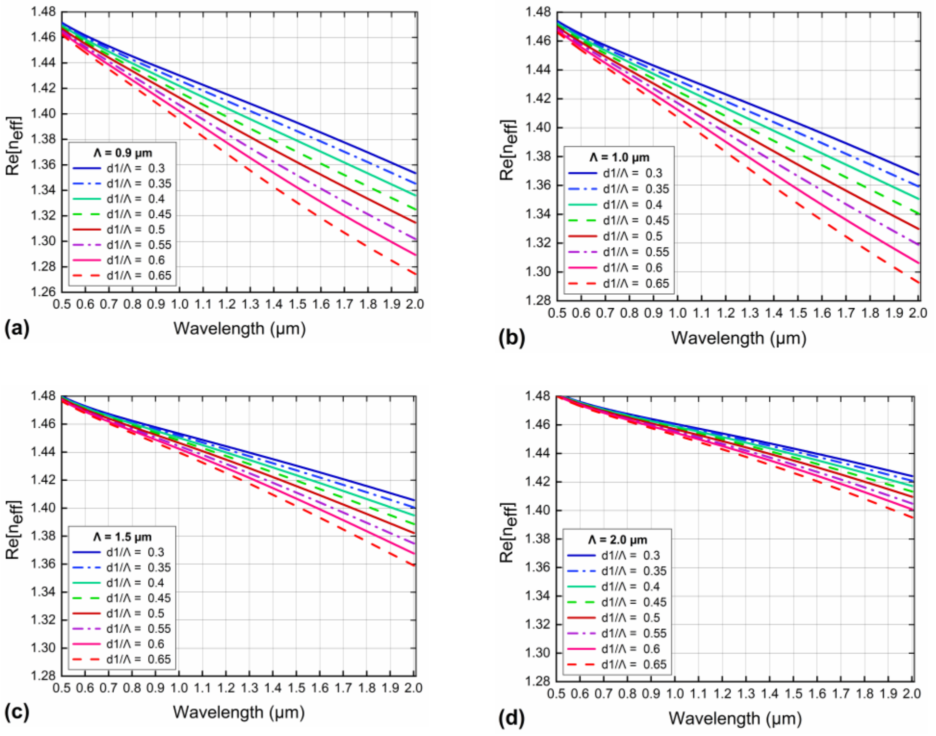

Fig 3. *The real part of effective refractive index of SiO_2-GeO_2 PCFs with various values of d_1/Λ and Λ = 0.9 μm (a), 1.0 μm (b), 1.5 μm (c), and 2.0 μm (d)*

In all cases, increasing wavelength reduced the real part of the effective refractive index because long wavelengths had difficulty penetrating the core region of PCFs. When

Λ was fixed, the effective refractive index decreased with the increase of the filling factor d_1/Λ.

Table 1. *The real part of the effective refractive index of SiO₂-GeO₂ PCFs at 1.55 µm*

d_1/Λ	Λ = 0.9 µm	Λ = 1.0 µm	Λ = 1.5 µm	Λ = 2.0 µm
0.3	1.389	1.4	1.433	1.446
0.35	1.382	1.393	1.43	1.444
0.4	1.375	1.386	1.427	1.442
0.45	1.366	1.378	1.423	1.44
0.5	1.357	1.37	1.42	1.438
0.55	1.346	1.361	1.416	1.435
0.6	1.337	1.352	1.411	1.433
0.65	1.324	1.341	1.407	1.43

Conversely, when d_1/Λ was constant, the effective refractive index increased as Λ increases. The values of the real part of the calculated effective refractive index at 1.55 µm showed in Table 1. The maximum and minimum values of effective refractive index were 1.446 and 1.324 respectively, for fibers with Λ = 2.0; d_1/Λ = 0.3, and Λ = 0.9; d_1/Λ = 0.65.

The dispersion properties of the PCFs govern the appearance of nonlinear effects and influence the spectral width in SC generation. Chromatic dispersion includes material dispersion and waveguide dispersion.The relationship between dispersion (D) and the derivative of the effective refractive index for wavelength was described in equation (4) [18].

$$D = -\frac{\lambda}{c}\frac{\partial^2 \mathrm{Re}[n_{\mathrm{eff}}]}{\partial\lambda^2} \tag{4}$$

where λ and c were the wavelength and the speed of light in a vacuum, respectively, and $\mathrm{Re}[n_{\mathrm{eff}}]$ was the real part of the effective index of the guided mode.

The dispersion curves versus wavelength of the SiO₂-GeO₂ PCFs were presented in Fig 4. The dispersion properties were relatively diverse, including all-normal and anomalous dispersion with one or two zero dispersion wavelengths (ZDWs). For PCFs with small Λ (Λ = 0.9 µm and 1.0 µm), we obtained both all-normal and anomalous dispersions.

When Λ was larger (Λ = 1.5 µm; 2.0 µm) only anomalous dispersion was found. The flattest anomalous dispersion curve were obtained with the structure Λ = 0.9 µm, d_1/Λ = 0.4. With all-normal dispersion, the Λ = 1.0 µm, d_1/Λ = 0.45 structure had the flattest dispersion curve and was the closest to zero.

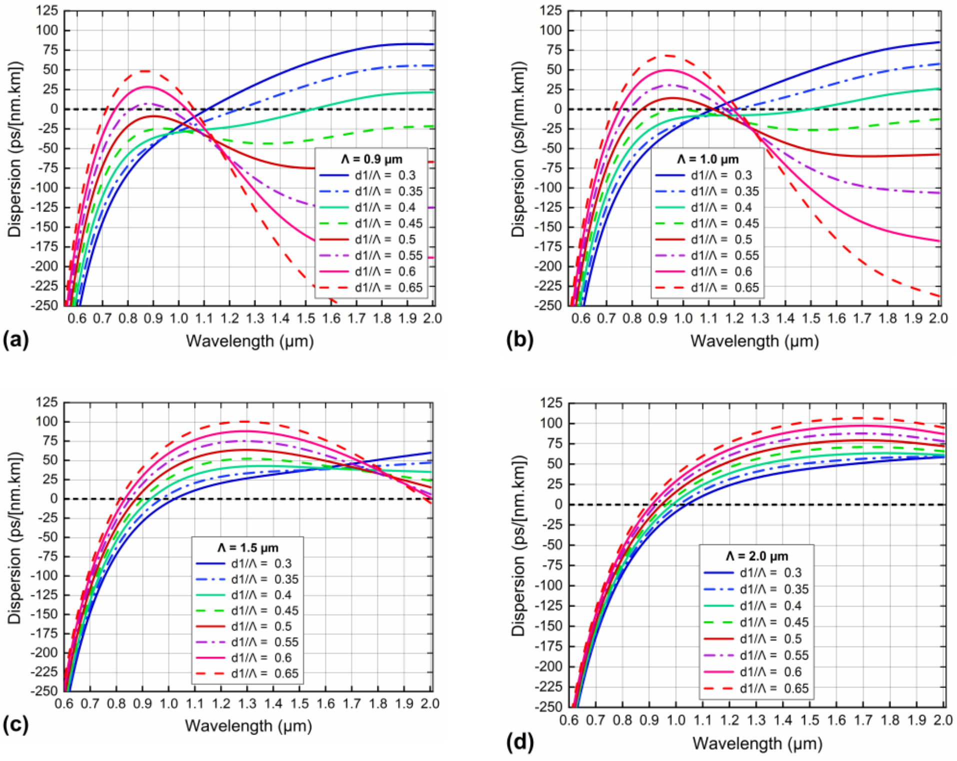

Fig 4. *The chromatic dispersion characteristics of SiO_2-GeO_2 PCFs with various values of d_1/Λ and Λ = 0.9 µm (a), 1.0 µm (b), 1.5 µm (c), and 2.0 µm (d)*

We proposed these two structures as #F_1, #F_2 for SC generation application, where #F_1 fiber was expected to generate a broad spectrum with the domination of soliton dynamics. The #F_2 fiber with all-normal dispersion will give a wide, smooth, and highly coherent SC spectrum due to the self-phase modulation effect. The very small dispersion values of 0.298 ps/nm.km at a pump wavelength of 1.526 µm (#F_1 fiber) and −0.311 ps/nm.km at a pump wavelength of 0.985 µm (#F_2 fiber) are also important factors to improve the efficiency of SC generation (Fig 5). Compared with previous publications [13, 14] on PCF based on SiO_2-GeO_2 composite, the obtained dispersion values are much smaller.

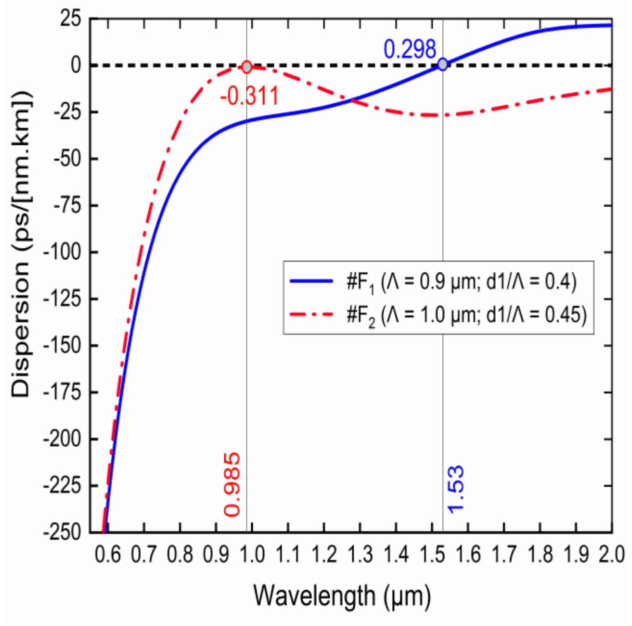

Fig 5. *The optimal dispersion structures*

Skillfully modifying the structural parameters and choosing a reasonable GeO_2 doping concentration, we obtained a flatter dispersion and the dispersion value at the pump wavelength was smaller than that of the works [13, 14].

IV. CONCLUSIONS

We designed new PCF structures with the solid core replaced by SiO_2-GeO_2 composite (15% mol concentration of GeO_2) to improve the nonlinearity of the fibers. The effective refractive index and dispersion were numerically simulated and analyzed in detail. Flat, low-value all-normal and anomalous dispersion at pump wavelengths are suggested for SC application. Our proposed fibers can be new sources of SC generation replacing glass core fiber sources.

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