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# Supercontinuum generation for optical coherence tomography using magnesium fluoride photonic crystal fiber

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ABSTRACT

Supercontinuum (SC) in visible and near-infrared regions is used as a source for optical coherence tomography (OCT) method to measure vascular oxygen saturation in retinal and choroidal circulations. To generate SC in these regions, we first study magnesium fluoride ($MgF_2$) solid core photonic crystal fibers (PCFs) with submicron air-holes. Then by varying the air-holes diameter we engineer the dispersion and nonlinear parameters as desired. We demonstrate by launching input pulses with center wavelengths of 532 and 640 nm into an engineered PCF, supercontinua as wide as 530 and 580 nm can be obtained that cover the entire visible range and a part of near infrared region making it a suitable source for both white-light and OCT applications.



## 1. Introduction

Photonic crystal fiber (PCF) is a suitable medium for the appearance of nonlinear phenomena [1,2]. In this kind of fiber, cladding consists of several air holes but both core and cladding regions are made of the same material. Therefore the effective refractive index of cladding is less than that of the core and the light propagation mechanism inside the PCF is governed by the total internal reflection (TIR) [3]. One of the main reasons of using solid core PCF over a conventional step index fiber is its capability of being engineered for a desired dispersion [4]. Nonetheless, possibility of modifying the cladding air-hole periodicity and dimensions offers additional degrees of freedom in engineering guiding properties and dispersion profile of a PCF, in a way that is not possible for a conventional optical fiber [5].

The PCFs due to their relatively small core diameters can propagate single optical modes over a wide wavelength range. Therefore by passing a very short (femtosecond) and coherent optical pulse with high peak power through PCF supercontinuum (SC) spectrum in different regions such as visible, near-infrared, and mid-infrared can be obtained [6]. Supercontinuum generation (SCG) has attracted much attention due to its variety of applications in different fields such as optical communication based on dense wavelength division multiplexing [7,8], fluorescence microscopy for the Effect of treatment by electrostatic field [9], designing tunable ultrafast nanosecond and femtosecond laser sources [10,11], precise measurement of optical frequencies [12], mid-infrared SCG for spectroscopy [13–15], and non-invasive imaging of sensitive surfaces based on optical coherence tomography (OCT) [16–19]. Using the OCT imaging technique, we can observe, each of the retina's

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layers distinctively [20]. These images help ophthalmologist map and measure the thickness of each layer and finally provide treatment guidance for retinal and glaucoma diseases [21]. Leon-Sava, et al. achieved the planned spectral broadening for OCT by decreasing the effective area of conventional fiber via tapering technique [22]. It is a suitable method for those applications need cm lengths. However, for other applications that are needed more length of tapering, this technique is not an accurate approach [23]. Champert et al. demonstrated the simultaneous excitation of PCF in its normal and anomalous dispersion regimes using the fundamental and second harmonic signals of a laser that leads to a homogeneous SC in the visible and near-infrared range for OCT [24]. It needs to couple two signals simultaneously into a PCF which is relatively a complicated task. Another research group presented a cobweb PCF with zero dispersion wavelength (ZDW) centered about 540 nm to generate SC in visible region [25]. It can be used as a nonlinear medium for visible SCG but the fabrication process is too complicated. Kudlinski, et al. experimentally have demonstrated a SCG for OCT with a spectrum covering the region from 470 nm to more than 1750 nm by using a 300-m-long GeO2-doped-core PCF with decreasing ZDW along its length. However, the presence of GeO2 in silica enhances the Kerr and Raman responses of the material which is important for SCG, but the fabrication of this fiber is challenging for PCF manufacturers [26]. One of the key parameters for SCG is having a low dispersion value close to central wavelength of the input optical pulse. This criterion results in single-mode phase-matching of the nonlinear phenomena that broaden the output spectrum. Optimizing dispersion relaxes the need for high intensity, allowing SCG for larger cores or longer pulses [27].

There are many efforts to engineer dispersion as desired. In some of them, researches by varying dimensions such as air-hole diameter, pitch size and the number of the air-hole rings tried to achieve flat dispersion in wide wavelength range [28]. In [5] we presented linear and nonlinear properties of PCF in terms of wavelength to investigate the effects of changing the fiber dimensions on the dispersion profile and its nonlinear parameter that is the basis of this paper. We propose an engineered magnesium fluoride ($MgF_2$) solid core submicron photonic crystal fiber as a nonlinear medium for SCG in visible and near infrared regions for OCT application.

We engineer and optimize both dispersion and nonlinear parameters by varying the diameter of air holes and pitch size to obtain the ZDW of 525 nm. In this paper, we consider the generalized nonlinear Schrödinger equation (GNLSE) for pulse propagation modelling inside the PCF. This equation doesn't have any analytical solution and is solved by a numerical method called symmetrized split step Fourier method (S-SSFM). The numerical results obtained by this model has already been shown to resemble very much the experimental results [6]. Our simulation results demonstrate that by launching an optical pulse with 50 fs width, 5 kW peak power and center wavelength of 532 nm in anomalous dispersion regime into a 100-mm long PCF, a SC as wide as 830 nm is obtained at the end of the fiber. This spectrum covers the entire visible range and a part of infrared region that is a suitable source for both white light and optical coherence tomography applications. There are two techniques for PCF fabrication known as 'stack-and-draw' [29,30] and 'casting' [31]. Magnesium fluoride is an inorganic white compound with a formula $MgF_2$. It is transparent over a wide wavelength range [32], with commercial uses in optical devices. Prisms and lenses, made of this material can be used over the entire range of wavelengths from 0.120 μm (vacuum ultraviolet) to 8.0 μm (infrared) [32]. Its refractive index of 1.37 is suitable for anti-reflective coatings. It is used as background material of PCF presented in this paper.

The rest of this paper is organized as follows. In Section 2, profiles for wavelength dependence of the linear and nonlinear parameters for different air holes diameters of the PCF under study are plotted and an appropriate one is chosen. In Section 3, using numerical values for the linear and nonlinear parameters of our desired PCF, GNLSE is rewritten and numerically solved, employing the S-SSFM across the fiber. Also, the spectral distributions of the PCF outputs verses the center wavelengths of the input optical pulses for different peak powers are illustrated and compared. In Section 4, we present an OCT setup based on the proposed PCF. Finally, the paper is closed by conclusion in Section 5.

## 2. Fiber structures and parameters

### 2.1. Structures

We have designed a PCF with solid core, including a five-ring triangular lattice with submicron diameter air-holes in a $MgF_2$ background. The cross sectional view of the proposed PCF is plotted in Fig. 1(a). The PCF pitch size and length are taken to be $\Lambda = 700$ nm and $L = 100$-mm, respectively. In our calculations, we investigate four PCFs with air-holes diameters of $d = 400$, 480, 520, and 560 nm. Choosing five air-hole rings, is large enough to make, hence the change in the PCF's dispersion is negligible when an extra ring on the outer side of the cladding is added [4]. Also, 2D schematic view of the fundamental mode distribution in cross sectional view for central wavelength of 532 nm is demonstrated in Fig. 1(b) that is achieved by the numerical calculations by the Eigen-mode analysis.

### 2.2. Linear parameters

It is easier to apply a closed-form equation of the refractive index of $MgF_2$ instead of using a table presenting its real refractive index versus wavelength. This is generally done by approximating the evolution of $n(\lambda)$ with the Sellmeier equation [33]

$$n(\lambda) = \left\{ 1 + 0.413\,\lambda^2 \left(\lambda^2 - 0.0013\right)^{-1} + 0.505\lambda^2 \left(\lambda^2 - 0.0081\right)^{-1} + 2.49\,\lambda^2 \left(\lambda^2 - 565\right)^{-1} \right\}^{0.5} \tag{1}$$