Few-cycle Pulse Generation Using Solid-core Photonic Quasi-crystal Fiber

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Abstract— In recent years, the generation of few cycle pulses has been of great scientific and technological interest. In this line, the microstructured optical fibers have been playing a vital role since the desired optical properties can easily be engineered by adjusting the geometrical parameters. The recent results reveal that the quasicrystals exhibit several interesting photonic properties over periodic crystals. A solid core photonic quasi-crystal fiber (SC-PQF) is a novel microstructured fiber with quasi periodicity in structure and has a long range order with aperiodic arrangement in its cladding region. The structure of the cladding region consists of air holes of diameter d and pitch, Λ, with five rings of air holes. In the central region, the air hole is removed and the resulting solid silica core acts as a defect and gives rise to the propagation of guided modes. The photonic quasi-crystal fiber provides very large nonlinearity and sufficiently low dispersion that could be exploited for generating single cycle pulses. We look for the hitherto mentioned optical properties in the proposed SC-PQF by carefully optimizing the geometrical parameters namely, core diameter and the pitch. Eventually, with the proposed fiber, we study both dispersion and nonlinearity for a range of wavelengths from 0.6 to 1.1 μm and demonstrate sufficiently low dispersion ($-1.9478\,\mathrm{ps}^2/\mathrm{m}$) with zero confinement loss and enhanced nonlinearity ($\gamma = 578\,\mathrm{W}^{-1}\mathrm{m}^{-1}$) for a wavelength of 0.85 μm. The soliton effect compression of the femtosecond pulses in the proposed SC-PQF at 0.85 μm wavelength is numerically studied. A 15 fs pulse compressed down to 4 fs results in nearly 1.4 cycles of pulse generation.

1. INTRODUCTION

The search for the attosecond laser pulses is at the lead of the research in the laser physics. Pulses in the attosecond range may give rise to the development of attoelectronics, making it possible to study the dynamics and to control electronic processes in biology, chemistry, and solid-state physics, in the same way femtosecond laser technology led to femtochemistry [1–3]. Soliton effect pulse compression and propagation has been experimentally studied in the temporal domain in fibers [4], fiber Bragg gratings [5], photonic nanowires [6] and photonic crystal fibers [7–10]. In recent years, the generation of few and single cycle pulses in highly nonlinear photonic crystal fibers (PCFs) has been numerically studied [11, 12]. These few cycle pulses are generated by the mode-locked lasers and fiber-based pulse compression techniques. This fiber-based pulse compression technique is smartly used with the play of the dispersion and nonlinearity. In the fiber based lasers, mainly, there are two important pulse compression processes, namely, adiabatic pulse compression and soliton effect pulse compression. In the adiabatic pulse compression, the compressed pulses suffer from pedestals that arise because of the energy distribution in the wings of the intense output pulse [13]. More recently, the study of the higher order soliton effect pulse compression in a waveguide has been carried out [14].

In this work, we design a SC-PQF that exhibits very less confinement loss for a wide range of wavelengths. Besides, we also compute the enhanced optical properties, namely, low group velocity dispersion and high nonlinearity. These optical properties may be exploited for generating few-cycle pulses as well as supercontinuum [15–20].

2. GEOMETRIC DESIGN OF SC-PQF

Figure 1 shows the geometric structure of the proposed SC-PQF using finite element method with nine rings of air holes in its cladding region. The perfectly matched layer is designed for calculating the confinement loss of the proposed SC-PQF. This SC-PQF design has the basis of Stampli quasicrystal structure [21, 22]. This type of quasicrystal structure has the repetition of the

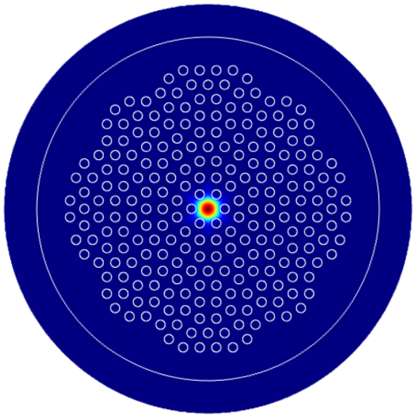

Figure 1: Fundamental mode of the proposed SC-PQF for 0.85 µm.

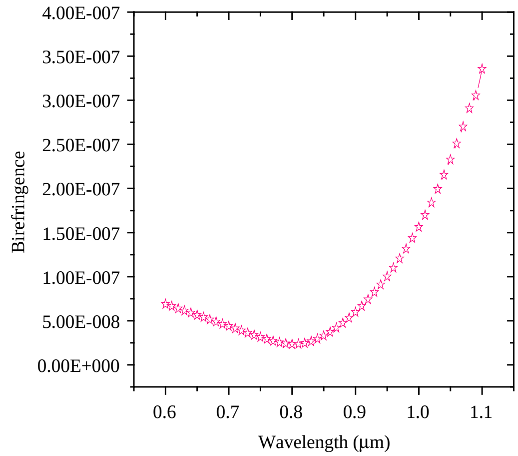

Figure 2: Birefringence of the proposed SC-PQF for 0.6 to 1.1 µm.

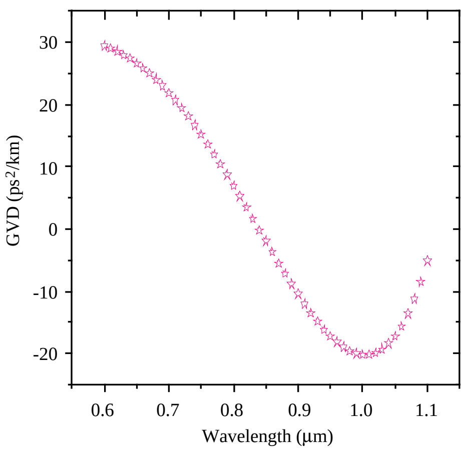

Figure 3: Group velocity dispersion as a function of wavelength.

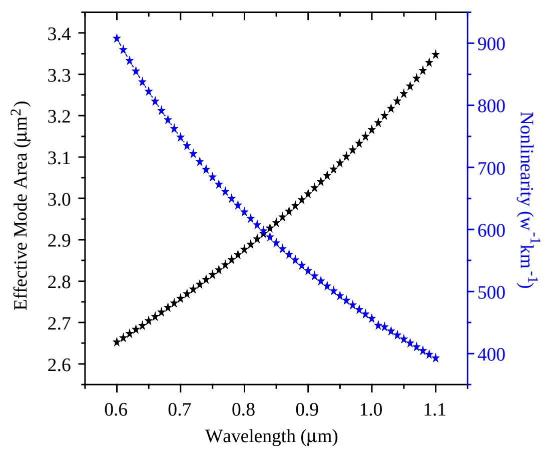

Figure 4: Effective mode area and nonlinearity as a function of wavelength.

square and the triangle arrangement of air holes in its cladding region. We calculate the effective refractive index (n_{eff}) of the fundamental mode for the proposed design and the same, is used to compute the dispersion from 0.6 to 1.1 µm wavelength.

3. OPTICAL PROPERTIES OF SC-PQF

In this section, we explore the various waveguiding properties of the proposed SC-PQF such as birefringence, group velocity dispersion, confinement loss, effective mode field area and nonlinearity.

Figure 2 describes the birefringence, B, of the proposed fiber and the same is determined by the difference between the effective indices of two orthogonal polarization modes. Initially the birefringence decreases from 0.6 µm to till 0.8 µm and above 0.8 µm wavelength, the birefringence gradually increases upto 1.1 µm. This is due to a relatively large effective refractive index difference between x and y polarization components for higher wavelengths. The birefringence observed for 0.85 µm wavelength is 3.27882×10^{-8}.

Figure 3 explains second order dispersion for a range of wavelengths from 0.6 to 1.1 µm. We have been able to achieve a low GVD ($-1.9478\,\mathrm{ps}^2/\mathrm{km}$) at 0.85 µm wavelength. These properties are crucial for the requirements of the few-cycle pulse generation. For the proposed SC-PQF, we calculate the confinement loss using the imaginary part of the effective refractive index of the fundamental mode with the perfectly matched layer.

Next, we compute the effective mode field area and nonlinearity by calculating the fundamental mode field area as shown in the Figure 4. We obtain a nonlinearity of $578\,\mathrm{W}^{-1}\mathrm{km}^{-1}$ at 850 nm wavelength. Here, the nonlinearity decreases as the wavelength increases. This is due to the fact that the mode confinement is tight at lower wavelengths and it becomes less as the wavelength increases.

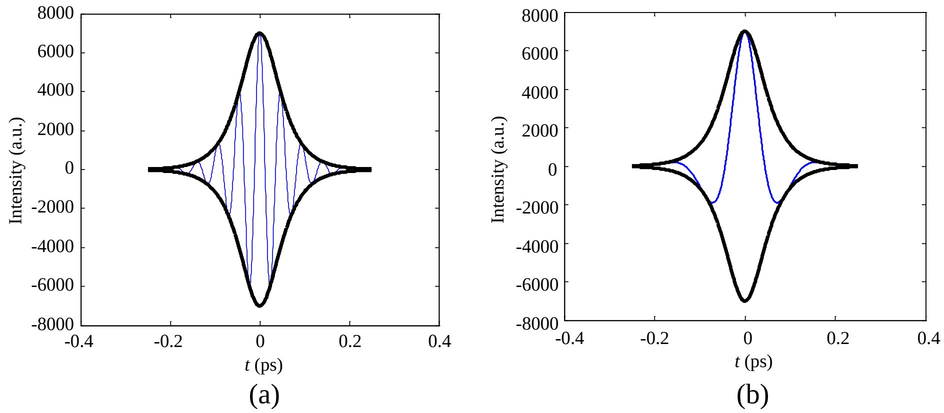

Figure 5: (a) & (b) Represent the input pulses and output pulses with number of oscillations for the proposed SC-PQF at 0.85 μm.

4. PULSE COMPRESSION USING SC-PQF

In this work, we present a higher-order pulse compression with high nonlinear effects in the proposed SC-PQF. The evolution of the pulses inside the proposed SC-PQF is governed by the higher-order nonlinear Schrodinger equation (HNLSE) which includes the effects of anomalous GVD, self-phase modulation, self-steeping and stimulated Raman scattering. We adopt the usual split-step Fourier method to solve the HNLSE numerically. The generalized form of the HNLSE for the propagation of femtosecond pulses in an optical fiber is written in the form [23],

$$\frac{\partial A}{\partial z}+\frac{i\beta_2}{2}\frac{\partial^2 A}{\partial T^2}-\frac{i\beta_3}{6}\frac{\partial^3 A}{\partial T^3}=i\gamma\left[|A|^2 A+\frac{i}{\omega_0}\frac{\partial}{\partial T}\left(\left|A^2\right| A\right)-T_R A\frac{\partial |A|^2}{\partial T}\right],$$

where A is the field envelope, T is the physical time in the retarded frame, z is the physical distance, β_2 is the second-order dispersion, β_3 is the third-order dispersion, γ is the nonlinear coefficient and T_R is the response time of the Raman effect. We consider the propagation of Nth order soliton whose envelope field is chirp-free hyperbolic secant pulse given as,

$$A(o,T)=\sqrt{P_0}\sec h\left(\frac{T}{T_0}\right),$$

where P_0 is the peak power and T_0 is the input soliton duration. A chirp-free hyperbolic secant pulse $A(o,T)$ is launched into the fiber with $\beta_2=-1.9478\,\mathrm{ps}^2/\mathrm{km}$, $\gamma=578\,\mathrm{W}^{-1}\mathrm{km}^{-1}$, $T_R=3\,\mathrm{fs}$. The full width at half maximum (FWHM) of the initial pulse is 15 fs. Here the pulse compression is achieved by choosing the fiber length suitably so that the initial pulse undergoes the required temporal narrowing. In the present work, as is evident from the Figure 7, we demonstrate a compression of an input pulse of width 15 fs to less than 4 fs which consists of 1.4 cycles, using a SC-PQF of core diameter at an operating wavelength of 0.85 μm.

Figure 5(a) explains the number of oscillations of the input pulses. We take input pulse width of 15 fs with 5.34 cycles. Figure 5(b) represents the output pulse which consists of 1.4 cycles with less than 4 fs for the proposed SC-PQF at 0.85 μm.

5. CONCLUSION

The waveguiding properties of a SC-PQF with a solid-core have been investigated. It has been found that the proposed SC-PQF exhibits the desired optical properties over a wide range of wavelengths from 0.6 to 1.1 μm.

Further, we have been able to achieve sufficiently low dispersion ($\beta_2=-1.9478\,\mathrm{ps}^2/\mathrm{m}$) with zero confinement loss and enhanced nonlinearity ($\gamma=578\,\mathrm{W}^{-1}\mathrm{m}^{-1}$) for a wavelength of 0.85 μm. The soliton effect compression of the femtosecond pulses in the proposed SC-PQF at 0.85 μm wavelength has also been numerically studied. The crux of the work lies in a 15 fs pulse having been compressed to 4 fs encompassing 1.4 cycles of pulse generation. We are of the opinion that the proposed structure would turn out to be an appropriate candidate for the supercontinuum generation.

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