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Light propagation in gas-filled kagomé hollow core photonic crystal fibres

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ABSTRACT

We study the propagation of light in kagomé hollow core photonic crystal fibres (HC-PCFs) filled with three different noble gases, namely, helium, xenon and argon. Various properties, including the guided modes, the group-velocity dispersion, and the nonlinear parameter were determined. The zero dispersion wavelength and the nonlinear parameter vary with the gas pressure which may be used to tune the generation of new frequencies using the same pump laser and the same fibre. In the case of the kagomé HC-PCF filled with xenon, the zero dispersion wavelength shifts from 693 to 1973 nm when the pressure is increased from 1 to 150bar, while the effective Kerr nonlinearity becomes comparable to that of silica. We have simulated the propagation of femtosecond pulses launched at 790 nm in order to study the generation of supercontinuum and UV light in kagomé HC-PCFs filled with the noble gases.

1. Introduction

Light guidance through dielectrics in specific trajectories has been possible since the discovery of the total internal reflection effect in the 19th century [1]. However, this mechanism of guidance imposes certain limitations on the dielectric structures configuration, , namely, the core materials should have higher refractive index than the surrounding materials.

Using photonic crystals [2–4], light can be guided in any material that we want provided that the surrounding structure has a particular periodicity that leads to full 2D photonic band gap, low density of states (DOS) or low coupling between core and cladding modes. The hollow core photonic crystal fibres (HC-PCF) are one example of these waveguides whose guiding relies on this new kind of mechanisms [5].

HC-PCFs may be filled with gases or liquids. In fact, these fibres offer an effective environment for the observation of various nonlinear optical phenomena in those media [6], providing long interaction lengths, as well as avoiding beam diffraction. In particular, kagomé HC-PCFs [7] also offer broad band transmission and small dispersion. Their properties allow the occurrence of ultrafast nonlinear dynamics and generation of new frequencies in ranges that are dictated by the dispersion characteristics of the filling fluid. Tunable UV light and supercontinuum generation can be achieved using this type of fibres [8].

Supercontinuum generation is the process that occurs when light of narrow spectrum evolves into light of a very broad spectrum. It results generally from the synergy between several fundamental nonlinear processes, such that self-phase modulation, cross-phase modulation, stimulated Raman scattering, and four-wave mixing [9]. The spectral locations and powers of the pumps, as well as the nonlinear and dispersive characteristics of the fibre determine the relative importance and the interaction between these nonlinear processes. A supercontinuum light source can find applications in several areas, such as: optical communications [10], spectroscopy, pulse compression, the design of tunable ultrafast femtosecond laser sources [11], optical coherence tomography [12,13], optical frequency metrology [11,14], fluorescence lifetime imaging [15], gas sensing [16,17], food quality control [18], and early cancer diagnostics [19].

Besides the hollow-core PCF considered in this work, supercontinuum generation has been observed also in solid-core PCFs with distinct geometries, such an equiangular spiral PCF [20], a layered spiral PCF [21,22], a composite PCF [23], or a graded-index PCF [24,25].

In this paper, we will study the ultrashort pulse propagation and the subsequent generation of UV light and supercontinuum in gas-filled kagomé HC-PCFs. In Section 2 we will provide the basic theory concerning pulse propagation in these fibres, while in Section 3 we will present our numerical results. Section 4 summarizes the main findings achieved in this work.

2. Theoretical background

In order to find the modes of the light that propagates in fibres studied in this work, we have solved the following master equation [3]:

$$\nabla \times \left(\frac{1}{n^2(\lambda, r)} \nabla \times \mathbf{H}(\lambda, r) \right) = \frac{4\pi^2}{\lambda} \mathbf{H}(\lambda, r); \quad (1a)$$

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Table 1
Kerr coefficients for various noble gases at pressure $p = 1$ atm (after Ref. [31])

$n_{kerr} \times 10^{16}$ [m^2/W]				
helium	*neon*	*argon*	*krypton*	*xenon*
5.21×10^{-9}	1.31×10^{-8}	1.27×10^{-7}	3.07×10^{-7}	9.16×10^{-7}

$$\mathbf{E}(\lambda, r) = \frac{i}{\omega \epsilon_0 n^2(\lambda, r)} \nabla \times \mathbf{H}(\lambda, r); \tag{1b}$$

where $n(\lambda, r)$ is the refractive index in each point of the fibre cross section, λ is the wavelength of the light and ω its frequency, $\mathbf{H}$ is the magnetic field and $\mathbf{E}$ is the electric field. Eq. (1a) can be solved on two different domains: (i) considering the whole cross section of the PCF, or (ii) only on a cell of its cladding and applying periodic boundary conditions. With these two approaches we obtain different, but consistent, information about the fibres: with the former method we obtain the propagation modes in the core, and optical properties such as dispersion and the nonlinear parameter; with the latter method we obtain the properties of the cladding structure such as the bandgap regions.

The effective refractive index, $n_{eff}(\lambda)$, can be numerically computed by the first method mentioned above, i.e., solving Eq. (1a) with $n(\lambda, \mathbf{r}) = n_{gas}$ at the hollow parts and $n(\lambda, \mathbf{r}) = n_{silica}$ at the solid parts (n_{silica} was calculated following Ref. [26]). Alternatively, in the case of kagomé HC-PCFs, $n_{eff}(\lambda)$ can be theoretically approximated by that of a glass capillary, which is given by [27]:

$$n_{eff} = n_{gas} - \frac{1}{2}\left(\frac{u_{01}\lambda}{\pi d_f}\right)^2, \tag{2}$$

where d_f is the core-diameter and u_{01} is the first zero of the J_0 Bessel function and n_{gas} is the refractive index of the core-filling gas, which is given by [28]:

$$n_{gas} = \sqrt{1 + \frac{p}{p_0} \cdot \frac{T_0}{T} \cdot \left[\frac{b_1 \lambda^2}{\lambda^2 - c_1} + \frac{b_2 \lambda^2}{\lambda^2 - c_2}\right]_{p_0, T_0}} \tag{3}$$

whose coefficients b_i and c_i were taken from Ref. [28], p is the pressure of the fibre core, $p_0 = 1$ bar, T_0 is the standard room temperature and T is the temperature of the fibre core.

In order to simulate the propagation of a pulse through the fibre we have solved a generalized nonlinear Schrödinger equation (GNLSE), which can be expressed, in the time domain, as [9,29]:

$$\frac{\partial u(z,t)}{\partial z} - i \sum_{k>1} \frac{1}{k!} i^k \beta_k \frac{\partial^k}{\partial \tau^k} u(z,t) = i\gamma \left(1 + i\tau_{shock} \frac{\partial}{\partial \tau}\right) u(z,t) |u(z,t)|^2, \tag{4}$$

where u is the normalized amplitude of the optical field, z is the distance along the fibre, $\tau_{shock} = 1/\omega$ is a timescale associated with effects such as the self-steepening and/or the optical shock formation, and the terms $\beta_k = \left.\frac{d^k\beta}{d\omega^k}\right|_{\omega=\omega_0}$ represent the effects of the dispersion. In particular the parameter β_2 represents the group velocity dispersion of the fibre. γ is the fibre's nonlinear parameter defined as:

$$\gamma = \frac{2\pi n_{kerr}}{\lambda A_{eff}}, \tag{5}$$

where n_{kerr} is the Kerr nonlinear coefficient and A_{eff} is the effective mode area. The Kerr coefficient increases linearly with the gas pressure, namely, $n_{kerr}(p) = p n^0_{kerr}$ [30], where p is pressure and n^0_{kerr} is the value of this coefficient at 1 atm. Table 1 shows n_{kerr} at 1 atm for different noble gases.

Alternatively, we can express Eq. (3) in the frequency domain:

$$\frac{\partial \tilde{u}(z,\omega)}{\partial z} - i\left[\beta - \beta_0 - \beta_1 . (\omega - \omega_0)\right] \tilde{u}(z,\omega) = i\gamma \left(1 + \frac{\Delta\omega}{\omega_0}\right) F\left\{u(z,t)\left(u(z,t)\right)^2\right\}, \tag{6}$$

where $\tilde{u}$ is the Fourier transform of u, and F represents the Fourier transform. Eq. (6) is theoretically identical to Eq. (4) for infinite number of β_k terms. However, solving Eq. (6) is more accurate than solving Eq. (4) for finite number of β_k terms.

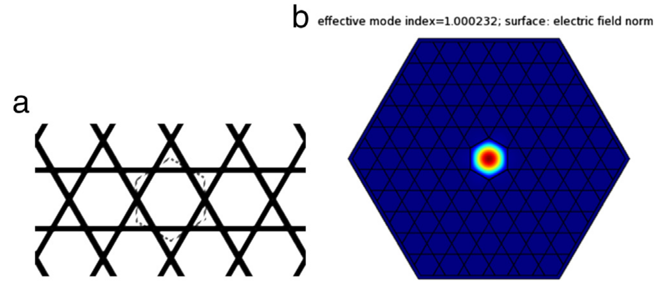

Fig. 1. (a) The unit cell of the cladding of a kagomé HC-PCF; (b) the fundamental propagation mode of a kagomé HC-PCF filled with helium: core diameter $d_{core} = 40.0$ μm, thickness of the glass strands $t = 0.1$ μm, and gas pressure $p = 10.0$ bar, @λ=790 nm.

In order to study the coherence between the different light pulses propagating in a kagomé HC-PCF, we consider the following expression [32]:

$$g^{(1)}(\lambda, z) = \left| \frac{\left\langle E_a^*(\lambda, z) E_b(\lambda, z)\right\rangle}{\sqrt{\left\langle |E_a(\lambda, z)|^2\right\rangle \left\langle |E_b(\lambda, z)|^2\right\rangle}} \right|, \tag{7}$$

where E_a and E_b denote two outputs resulting from two independently generated inputs with random noise, and the angle brackets denote an average calculation on a set of pairs. The random noise of each pulse was added using the same approach as in Ref. [8].

3. Numerical results

In this work we have considered a kagomé HC-PCF with a core diameter of 40.0 μm, and thickness of the glass strands of 0.1 μm. Using the MIT photonic bands software [33] applied to the unit cell of the fibre cladding (see Fig. 1(a)), we have found that the guidance in this kagomé HC-PCF is due to low density of states (DOS) in the fibre's cladding since the cladding structure has no full bandgap, but the DOS is close to zero. Using COMSOL Multiphysics [34], we have solved the master equation for the full draw of the fibre's cross section, including the hollow core, and we have found the propagation modes and their characteristics. In Fig. 1(b) we show the fundamental mode of a helium-filled kagomé fibre, for a pressure of 10 bar and a pumping wavelength of 790 nm.

The experimental setup typically used in the gas-filling process of kagomé HC-MOFs consists of two gas cells, one at each fibre end. These cells are both equipped with a high-quality window for launching and extracting light. Using this setup, the fibre is first evacuated, purged several times and then filled with the gas to the desired pressure [6]. Gas filling times are typically less than 1 min [35].

Fig. 2 Illustrates the variation of group velocity dispersion,β_2, in (a) with pressure for a helium filled kagomé HC-PCF and in (b) for different filling gases at 10 bar. At pumping wavelengths lower than the zero dispersion wavelength (λ_{ZD}) the dispersion regime of these fibres is normal, whereas at pumping wavelengths higher than λ_{ZD} the dispersion regime is anomalous (Fig. 2(a)). From Fig. 2(b) we see that the group velocity dispersion curves are different for different gases; in particular, they are different in the region of the pumping wavelength (790 nm) that will be considered below. Therefore, we can change the dispersion profile and the position of the fibre's λ_{ZD}, by changing the pressure (Fig. 2(a)), or by changing the filling gas (Fig. 2(b)).

Fig. 3 shows the dependence of λ_{ZD} with pressure for various gases. In the case of helium, and for pressures up to 150 bar, we always have anomalous dispersion at $\lambda_{pump} = 790$ nm; however, for the other gases the anomalous regime at 790 nm only happens for smaller pressures.