Femtosecond Pulse Propagation in Gas-filled Hollow-Core Photonic Crystal Fibers

Sílvia Rodrigues[1], Margarida Facão[2], Sofia Latas[3] and Mário Ferreira[4]
I3N-Institute of Nanostructures, Nanomodelling and Nanofabrication, Department of Physics, University of Aveiro, 3810-193 Aveiro, Portugal

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Abstract: We investigate the ultrafast dynamics of femtosecond pulse propagation in a gas-filled kagome hollow-core photonic crystal fiber (HC-PCF). We show that, by varying the gas pressure, the zero dispersion wavelength of such fiber can be tuned across the ultraviolet (UV), visible and near-infrared spectral regions. The soliton effect compression, deep-UV light and supercontinumm generation are investigated using a generalized nonlinear Schrödinger equation.

1 INTRODUCTION

Hollow–core photonic crystal fibers (HC-PCF) (Russel, 2003; Russel, 2006) with a hexagonal arrangement of holes in the cladding guide light by the photonic bandgap mechanism which offer low-loss transmission. These fibers offer an effective environment for nonlinear optics in gases, providing long interaction lengths while avoiding beam diffraction (Russel, 2006). The main drawback of these fibers is their intrinsically narrow transmission bandwidth determined by the bandgaps, which excludes its implementation in a large number of applications in ultrafast nonlinear optics requiring broadband guidance or guidance in the visible and UV.

An alternative HC-PCF design replaces the hexagonal lattice cladding with a kagome lattice (Couny et al., 2006; Pearce et al., 2007). In kagome-type HC-PCFs the field overlap with the surrounding silica structure is particularly low (Couny et al. 2007). In contrast to the photonic bandgap-type fibers, the guiding mechanism is based on the inhibited coupling between the core and cladding modes (Couny et al., 2007) and not the bandgap-effect.

Kagome HC-PCF offers in addition broadband transmission and weak anomalous dispersion from the UV to the near-IR. These properties not only help support ultrafast soliton dynamics, but also allow the guidance of any UV light that is subsequently generated at a relatively low loss of ~3 dB/m (Joly et al., 2011). The possibility of adjusting the gas species and gas pressure inside the fiber core also offers a new degree of freedom over conventional fibers, providing a perfect environment for demonstrating many different nonlinear effects (Mak et al., 2013).

In this paper we investigate the ultrafast dynamics of femtosecond pulse propagation in a gas-filled kagome HC-PCF. In Section 2 we show that by varying the gas pressure, the normal group-velocity dispersion (GVD) of the filling gas can be balanced against the anomalous GVD of the kagome PCF allowing the zero dispersion wavelength (ZDW) to be tuned across the ultraviolet (UV), visible and near-infrared spectral regions. A generalized nonlinear Schrödinger equation (GNLSE) is used in Section 3 to describe ultrashort pulse propagation in a gas-filled kagome PCF. The soliton self-compression effect and the generation of dispersive wave radiation in the UV region are described.

2 DISPERSION PROPERTIES

In kagome-type HC-PCFs the field overlap with the surrounding silica structure is particularly low (Couny et al., 2007), since a good confinement of

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the optical field in the core can be generally achieved. Fig. 1 shows the mode field profile of a kagome HC-PCF with a core diameter of 40 μm filled with 10 bar of Xe.

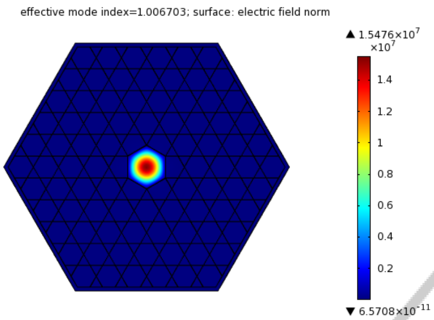


Figure 1: Mode field profile of a kagome PCF with a core diameter of 40 μm filled with 10 bar of Xe.

The effective modal refractive index of the HE_{11} mode in a kagome HC-PCF is accurately approximated by that of a glass capillary and is given by

$$n_{eff}(\lambda, p, T) = 1 + \delta(\lambda)\frac{p}{2p_0}\frac{T_0}{T} - \frac{\lambda^2 u_{01}^2}{8\pi^2 a^2} \tag{1}$$

where λ is the vacuum wavelength, $\delta(\lambda)$ the Sellmeier expansion for the dielectric susceptibility of the filling gas, p the gas pressure, p_0 the atmospheric pressure, T the temperature, T_0 = 273.15 K, a the core radius and u_{01} is the first zero of the Bessel function J_0. Finite element simulations and numerous experiments have confirmed the reliability of this expression (Nold et al., 2010; Chang et al., 2011).

The propagation constant $\beta(\omega)$ is given by

$$\beta(\omega) = \frac{\omega n_{eff}}{c} \tag{2}$$

Mathematically, the effects of fiber dispersion are accounted for by expanding $\beta(\omega)$ in a Taylor series about the carrier frequency ω_0 at which the pulse spectrum is centred:

$$\beta(\omega) = \beta_0 + \beta_1(\omega - \omega_0) + \frac{1}{2}\beta_2(\omega - \omega_0)^2 + ... \tag{3}$$

where

$$\beta_k = \left(\frac{d^k\beta}{d\omega^k}\right)_{\omega=\omega_0} \quad (k = 0, 1, 2, \ldots) \tag{4}$$

For pulse propagation purposes, one are specially interested on the group velocity dispersion (GVD) that is characterized by the parameter β_2.

The kagome HC-PCF provides ultrabroadband guidance at low loss levels and it presents, when evacuated, weak anomalous GVD over the entire transmission window. However, when filled with a noble gas, the normal GVD of the gas can be balanced against the anomalous GVD of the fiber, allowing the ZDW to be tuned across the ultraviolet (UV), visible and near-infrared spectral regions. This can be observed in Fig. 2, which shows the group velocity dispersion of a kagome HC-PCF with a 30 μm core diameter, filled with 0 to 20 bar Ar.

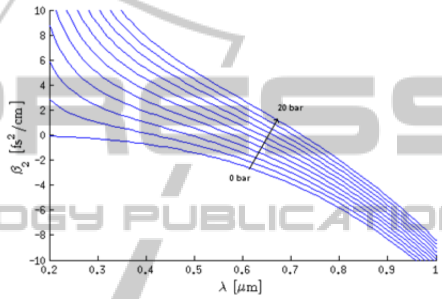


Figure 2: Dispersion curves of a kagome PCF with a 30 μm core diameter, filled with 0 to 20 bar Ar (2 bar steps).

We can compare the above results with those of a solid core PCF, where the shortest ZDW that can be achieved is about 500 nm. Moreover, the dispersion magnitude is significantly smaller in a kagome PCF, which means that ultrafast pulses broaden much less quickly in this case.

3 ULTRAFAST NONLINEAR DYNAMICS

The propagation of ultrashort pulses in gas-filled PCF can be described by the following generalized nonlinear Schrödinger equation (GNLSE):

$$\frac{\partial U(z,t)}{\partial z} - i\sum_{k\geq 2}\frac{1}{k!}\beta_k i^k \frac{\partial^k}{\partial \tau^k}U(z,t) = i\gamma U(z,t)|U(z,t)|^2 \tag{5}$$

where, U is the normalized amplitude of the optical field, β_k are the coefficients given by Eq. (4) , and γ is the fiber nonlinear parameter, defined as (Ferreira, 2011):

$$\gamma = \frac{\omega_0}{c}\frac{n_2(\omega_0)}{A_{eff}} \tag{6}$$

where n_2 the Kerr parameter of the gas and

$$A_{eff} = \frac{\left(\iint |F(x,y,\omega_o)|^2 \, dxdy\right)^2}{\iint |F(x,y,\omega_0)|^4 \, dxdy} \qquad (7)$$

is the effective mode area, $F(x,y,\omega_0)$ representing the spatial distribution of the transverse electric field mode in the fiber's cross section.

3.1 Soliton-effect Compression

The If the input pulse propagates in the anomalous-GVD regime of the fiber, it becomes compressed through an interplay between SPM and GVD. This compression mechanism is related to a fundamental property of the higher-order solitons., which follow a periodic evolution pattern such that they go through an initial narrowing phase at the beginning of each period. If the fiber length is suitably chosen, the input pulses can be compressed by a factor that depends on the soliton order, *N*, given by

$$N^2 = \frac{\gamma P_0 t_0^2}{|\beta_2|} \qquad (8)$$

where P_0 and t_0 are the soliton peak power and width, respectively.
The optimum pulse compression factor, F_{opt}, of a soliton-effect compressor can be estimated from the following empirical relations (Ferreira, 2011):

$$F_{opt} \approx 4.1N \qquad (9)$$

In practice, extreme pulse compression is limited by higher order effects, namely by higher order dispersion. However, this limitation becomes less significant in the case of a kagome PCF, since it presents a relatively smaller dispersion slope. Compressed pulses with a duration of some few fs can be achieved. This is illustrated in Fig. 3, which shows the spectral and temporal evolution of a 30 fs pulse through a kagome PCF with a 30 µm diameter core filled with Ar, presenting a ZDW at 500 nm. The pumping is realized at 800nm, situated in the anomalous dispersion region, and the corresponding soliton order is N = 3.5. As a consequence of the soliton self-compression effect, the pulse temporal profile is dramatically sharpen, producing a ~2 fs pulse. For higher values of N the self-compressed pulses can achieve subcycle durations, but the corresponding quality factor is reduced.

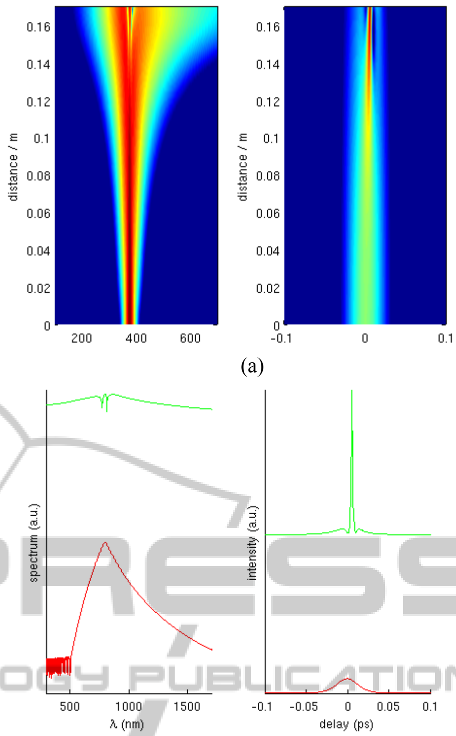


Figure 3: (a) Spectral and temporal evolution of self-compression of a 30 fs input pulse at 800 nm through a kagome PCF with a 30 µm diameter core filled with Ar (ZDW at 500 nm). (b) Initial (red) and final (green) pulse profiles in spectral and time domains.

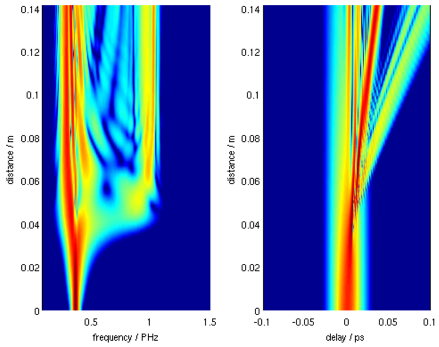
2.1 Dispersive-wave Generation

Extreme soliton-effect pulse compression of the input pulse results in a spectral expansion that overlaps with resonant dispersive-wave frequencies, which are consequently excited in the UV region. Fig. 4 shows this effect in the case of kagome PCF with a 30µm diameter core filled with 9.8 bar Ar, presenting a ZDW at 600 nm, pumped at 800 nm with pulses of duration τ_{FWHM} =15 and 60 fs. The same normalized soliton order $S = N / \tau_{FWHM} = 0.26$ is assumed in both cases.

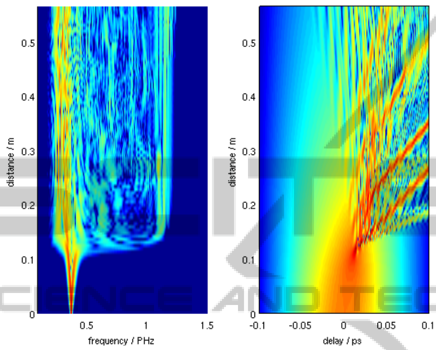
The temporal evolution in Fig. 4 shows clearly the soliton fission phenomenon, which occurs approximately at a characteristic length

$$L_{fiss} = \frac{L_D}{N} \qquad (10)$$

where $L_D = t_0^2 / |\beta_2|$ is the dispersion length. We observe also from the spectral evolution in Fig. 4 that the UV band is generated approximately at the soliton fission length. The quality of the UV



(a)



(b)

Figure 4: Spectral and temporal evolution of 15 fs (a) and 60 fs (b) input pulses at 800 nm through a kagome PCF with a 30µm diameter core filled with 9.8 bar Ar, (ZDW at 600 nm).

emission can be evaluated by the ratio between the spectral power within the FWHM of the strongest UV peak and the total spectral power in the UV region. Fig. 4 shows that such quality is relatively high for the 15 fs pulse, but it degrades significantly at 60 fs. Such degradation is due to the reduced quality factor of the pulse self-compression for high values of *N*.

The above results suggest that an ultrafast and coherent UV light source could be constructed using a kagome HC-PCF, that is tunable by varying the gas pressure or the pulse characteristics. Such tunable UV source could find numerous potential applications in spectroscopy and metrology or even in the seeding of a free-electron laser.

When the soliton order *N* assumes sufficiently high values, the UV band develops a considerably fine structure and evidence of modulation instability (MI) can be observed. This is illustrated in Fig. 5, which shows the spectral and temporal evolution of a 600 fs pulse with an energy of 10 µJ (N ~245) at 800 nm in a kagome PCF with a 30µm diameter core filled with 25 bar Ar (ZDW at 750 nm). Quantum noise has been included in the simulation. The fission of the input pulse into a large number of ultrashort solitons, that subsequently undergo multiple collisions, can be clearly observed in the temporal domain. In the spectral domain, this produces a smooth and flat supercontinuun extending from 0.2 to 0.8 PHz.

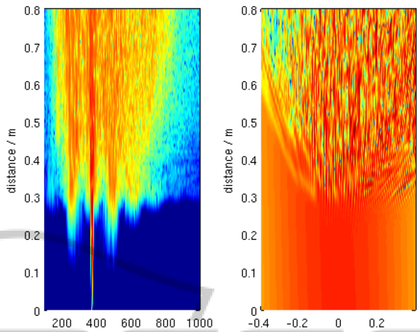


Figure 5: Spectral and temporal evolution of a 600 fs pulse with an energy of 10 µJ (N ~245) at 800 nm in a kagome PCF with a 30µm diameter core filled with 25 bar Ar (ZDW at 750 nm).

4 CONCLUSIONS

In this paper we investigated the ultrafast dynamics of femtosecond pulse propagation in a gas-filled kagome HC-PCF. We have shown that by varying the gas pressure, the normal group-velocity dispersion (GVD) of the filling gas can be balanced against the anomalous GVD of the kagomé PCF allowing the zero dispersion wavelength to be tuned across the ultraviolet (UV), visible and near-infrared spectral regions. A generalized Schrödinger equation has been used to describe ultrashort pulse propagation in a gas-filled kagome PCF. The soliton self-compression effect has been observed, providing pulses with some few fs. We demonstrated that such extreme self-compression can lead to a highly efficient deep-UV dispersive wave generation. Input pulse durations shorter than ~60fs are necessary for obtaining high-quality UV spectra.

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