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Strong power transfer between photonic bandgaps of hybrid photonic crystal fibers

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ABSTRACT

This work reports the strong nonlinear power transfer between two adjacent photonic bandgaps of hybrid photonic crystal fibers. The nonlinear phenomenon originates from the generation of a resonant radiation in a particular bandgap, which is ensured by launching a femtosecond pulse near the zero-dispersion wavelength of a lower-order adjacent bandgap, where its correspondent soliton is formed. A theoretical description based on fiber dispersion properties and phase-matching conditions is presented to contribute to the interpretation and understanding of the highly efficient energy transference. Furthermore, various experimental results are reported, including the resonant radiation that peaks at 8.5 dB above that of the initial pulse, which represents a significant enhancement in the nonlinear efficiency compared to previous published works in the literature.

1. Introduction

Photonic crystal fibers (PCFs) have been intensively used in the last two decades because of their remarkable and unique optical properties [1]. Contrary to the early days of optical fibers, PCF technology provides new degrees of freedom in terms of light guidance, fabrication techniques and fiber materials and structures. These remarkable advances allow them to yield several interesting and technologically enabling properties, which are superior to the traditional optical fibers in numerous aspects and diverse applications.

For the first time, hybrid PCFs enables light propagation in an optical fiber via two propagation mechanisms simultaneously [2]: total internal reflection and antiresonant effect. These fibers are typically based on an undoped silica core surrounded by a wavelength-scale two-dimensional photonic crystal, which is formed using air holes arranged in a hexagonal pattern and a line of high-index inclusions. The high-index inclusions are composed of germanium rods, which form antiresonance regions and photonic bandgaps. Thus, light at wavelengths that satisfy this condition is guided in the pure silica core.

After its invention in 2006, hybrid PCFs based on different geometries have been proposed and analyzed. For example, L. Xiao et al presented some numerical results of a hybrid PCF with a hexagonal array of high-index rods and a line of air holes [3]. Ould-Agha et al. recently proposed a new structure of one ring of six high-index rods to extend the transmission band by at least 200% [4]. Moreover, hybrid PCFs have been investigated for linear and nonlinear applications such as broadband polarizers [5] optical amplifiers [6] optical sensors [7] soliton generation [8,9] and supercontinuum generation [10,11]. This work presents an analytical description and experimental results on highly efficient power transfer between the second and third photonic bandgaps (PBGs) of different hybrid PCFs.

2. Hybrid photonic crystal fibers

Light guidance in conventional optical fibers is based on two concentric regions with different doping levels: the core and cladding regions, whereas in PCFs, it is based on subtle variations in the refractive index by corralling light in a microscopic and periodic array of air holes. This property makes the cladding index strongly wavelength-dependent, which enables new degrees of freedom in terms of light propagation. Considering the propagation mechanism of light guidance in PCFs, there are basically four types of

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PCFs: index-guiding PCF based on the modified total internal reflection (TIR); hollow-core PCF, which enables light propagation in air using the PBG effect; all-solid PBGF based on the antiresonant effect, which is central to the PBG effect in these fibers; hybrid PCF, which provides light guidance using both propagation mechanisms simultaneously; Kagomé PCF, which guides light via inhibited coupling between the core and cladding modes.

Particularly, hybrid PCFs are composed of air holes and germanium-doped silica rods, which are disposed around an undoped silica core, as shown in Fig. 1a. The air holes are arranged in a hexagonal pattern as in the index-guiding PCFs, whereas the high-index rods replace a single row of air holes along one of the PCF axes and form a one-dimensional PBG in this direction. Compared with the traditional PCFs, one more design parameter must be included: the rod diameter D. Light guidance in hybrid PCFs occurs only in restricted bands of wavelength, which coincide with the photonic bandgaps because both propagation mechanisms are responsible for light confinement in the hybrid PCF core [2]. The possibility of exploiting the TIR and photonic bandgap effect in a unique fiber enables nonlinear fiber-optic experiments in new dispersion regimes.

The relevant properties of hybrid PCFs, such as dispersion and nonlinearity, are closely related to their modal intensity patterns [1,2]. The pattern of the hybrid-PCF modes are believed to arise when the more dispersive modes of the high-index rods intersect with the mode of a standard index-guiding PCF, which causes anti-crossings. The hybrid modes are linear combinations of the core mode with the corresponding high-index rod mode, which is the closest one to be resonant.

The hybrid PCF design has been realized using the PCFDT (Photonic Crystal Fiber Design Tool) [12], which is our numerical tool based on the Finite Element Method (FEM). The main goal was to obtain hybrid PCFs with a zero dispersion wavelength (λ_0) near 805 nm, which is the central wavelength of our femtosecond system. The selected design parameters of the three hybrid PCFs for the nonlinear experiments are summarized in Table 1. The Ge rods present a gradual refractive index and maximum step Δn = 2.03%. All fibers were fabricated at the University of Bath in the UK.

A PCF-based supercontinuum source, which extends from 450 to 1700 nm, was launched at the hybrid PCFs' input to measure their photonic. Fig. 1b shows the transmission spectrum of fiber B, which was obtained with a one-meter-long sample. It shows three bandgaps and low-attenuation windows in the silica transparency wavelength range: the 1st PBG is from 1060 to 1350 nm; the 2nd PBG is centered at approximately 750 nm; the 3rd PBG is at approximately 530 nm. The positions of the 2nd and 3rd PBGs are favorable to optimize their power transfer. Fibers A and C have notably similar transmission properties with fiber B; they also provide three PBGs in the silica transparency window. However, the PBGs are translated to shorter and longer wavelength ranges because as soon as the high-index diameter is increased, the PBG edges are shifted to longer wavelengths. Consequently, an opposite effect occurs when the rod diameter is decreased, i.e., the PBG edges are moved to shorter wavelengths.

The numerical simulations of the chromatic dispersion in the second PBG for the three hybrid PCFs are presented in Fig. 2. As

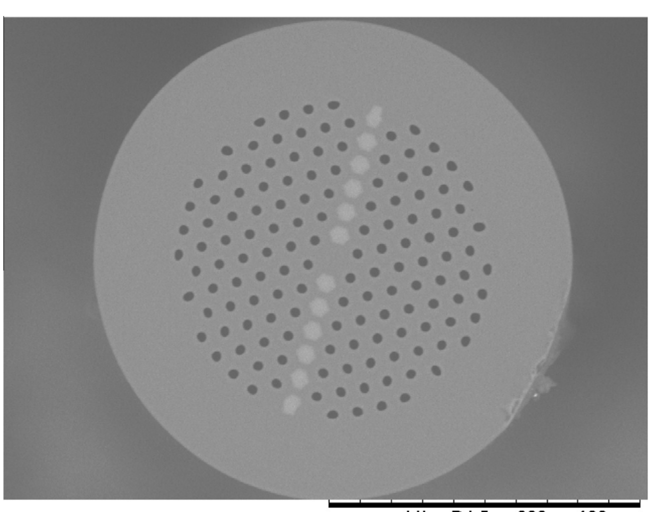

Fig. 1a. Hybrid photonic crystal fiber: the air holes are arranged in a hexagonal pattern as in the index-guiding PCFs, whereas the high-index rods replace a single row of air holes along one of the PCF axes. SEM image.

Table 1
Design parameters of the hybrid PCFs in micrometers (μm).

Fiber name/ parameter	Air hole diameter	Inter-hole spacing	Rod diameter
Fiber A	1.61	3.75	2.70
Fiber B	1.76	4.04	2.81
Fiber C	1.85	4.31	2.96

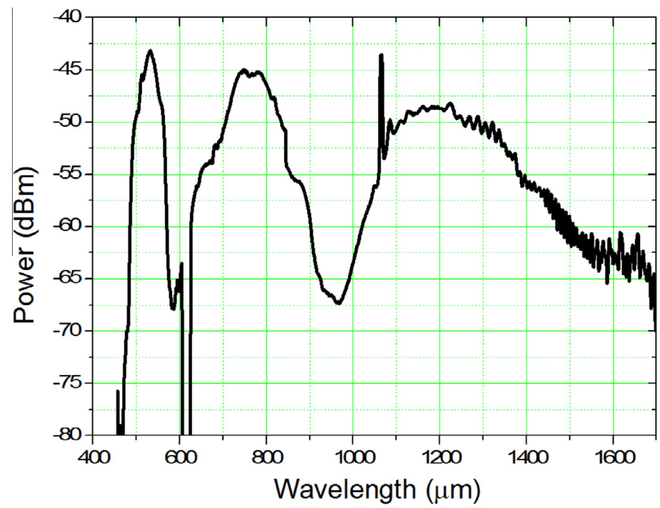

Fig. 1b. Measured transmission spectrum of Fiber B. The bandgaps are the three low-attenuations windows: the 1st PBG is from 1060 to 1350 nm; the 2nd PBG is centered at approximately 750 nm; the 3rd PBG is at approximately 530 nm.

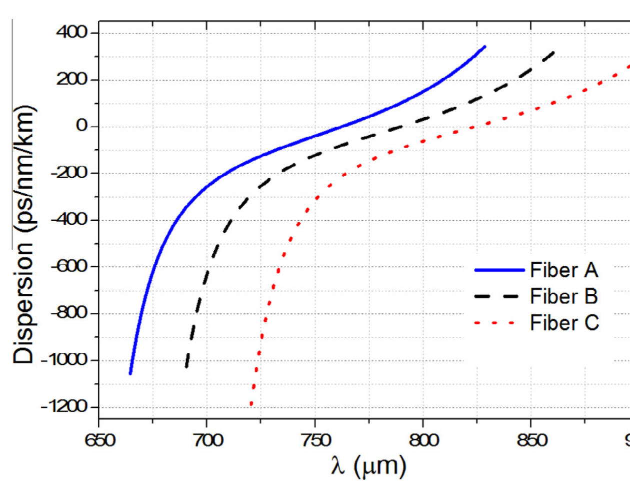

Fig. 2. Numerical simulations of the chromatic dispersion of the three hybrid PCFs in the nonlinear experiments.