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A new low-dispersion and large-effective-area PCF based on a fractal design

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ABSTRACT

In this paper we propose new structures of fractal photonic crystal fiber (F-PCF) based on modifications of second and third order Sierpinski fractal. These structures allow to confine the field in the center of the fiber without the need for a differentiated core. This property could be applied to obtain an increase of the effective area values and thereby reducing the nonlinear parameter. The values of the dispersion parameter for this structures are also analyzed.

1. Introduction

Photonic crystal fibers (PCFs) have attracted much interest in the last years due to their applications in nonlinear optics, supercontinuum generation, soliton propagation and photonic signal processing [1–6]. In the field of telecommunications the fiber's nonlinearities play a crucial role, the transmission of data through the fiber in multichannel systems can be negatively influenced by these nonlinear effects.

The large effective area fibers (LEAFs) have been studied in different fields of research for use in many applications such as fiber lasers, attenuation of nonlinear effects and high-power delivery systems [7]. The structural characteristics of the PCFs can be used for this purposes, allowing to decrease the values of the fiber's nonlinear parameters.

The relationship between the effective area and the nonlinear parameter is expressed by [8,9]

$$\gamma(\lambda) = \frac{2\pi}{\lambda}\frac{n_2}{A_{\text{eff}}(\lambda)} \tag{1}$$

where

$$A_{\text{eff}}(\lambda) = \frac{\left(\int\int I(r)\text{dxdy}\right)^2}{\int\int I^2(r)\text{dxdy}} \tag{2}$$

n_2 is the nonlinear-index coefficient and $I(r)$ is the intensity of the near-field of the propagating mode at radius r from the axis of the fiber. So it would be desirable to work with the larger possible values of effective area to diminish the effect of the nonlinearity.

On the other hand, the nonlinear effects are often employed to compensate the dispersion of the pulses. If we work with low nonlinear parameter values, the dispersion parameter must be also small to avoid the distortion of the propagating pulse. The dispersion parameter is given by [10]

$$D(\lambda) = \frac{-\lambda}{c}\frac{d^2 n_{\text{eff}}(\lambda)}{d\lambda^2} \tag{3}$$

where n_{eff} is the effective index of the propagating mode.

In order to obtain the effective index and the field distribution for a determined wavelength, the modal equations of the studied fiber must be solved as an eigenvalue problem.

$$(\nabla_t^2 + k_0^2\varepsilon_r)E_t + \nabla_t(\varepsilon_r^{-1}\nabla_t\varepsilon_r E_t) = \theta^2 E_t \tag{4}$$

where the subscript t refers to the transverse component of the electric field, ε_r is a function of the relative dielectric constant of the PCF geometry and θ represents the propagation constant. The real part of the calculated eigenvalue is related to the modal effective index by $n_{\text{eff}} = \theta/k_0$, and the associated eigenvector gives us the field distribution for this propagation mode [11]. Several methods have been developed in order to solve this problem, a higher order finite differences scheme has been employed in this paper.

Generally the air holes structure of a PCF can influence decisively on the prior parameters. Propagation characteristics of the

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photonic crystal fibers with square-lattice structures have been recently studied and reported [12,13]. We can even get a better setting for the propagation if we combine the advantages of PCFs with a fractal design [14]. In this paper we propose a F-PCF designed from the modified fractal Sierpinski Carpet.

PCF's are typically manufactured using a technique for stacking silica capillary tubes equal size in a hexagonal lattice pattern [15], but fibers with different geometries and size holes arrangement have been described and manufactured from preforms of different types [16]. In our case, the proposed fiber designing can be easily manufactured from solid and hollow preform of different diameter appropriately stacked.

The structure of the paper is as follows. In the second section it is explained the design and characteristics of the modified Sierpinski fractal PCF (SF-PCF). Then, in the third section, are showed the results of the simulations and, finally, in the last section we conclude the advantages of the SF-PCFs over others normal PCFs (N-PCF).

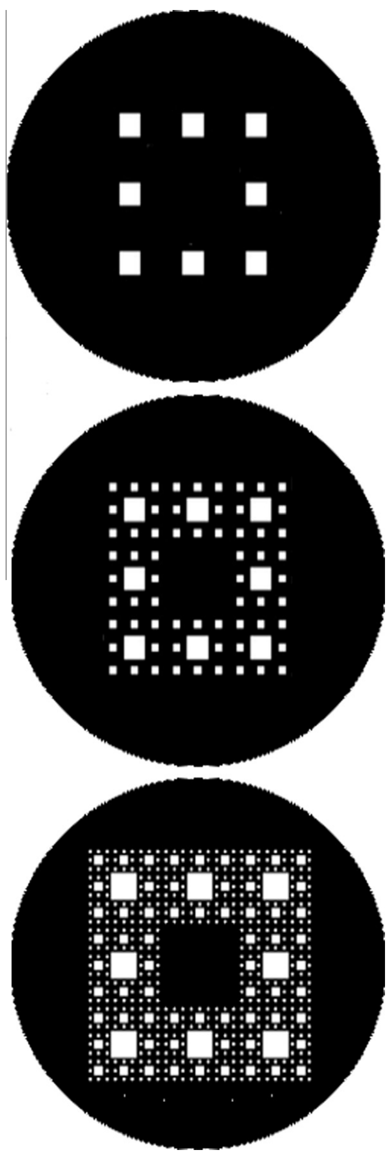

Fig. 1. Schematic structures of the proposed second and third order SF-PCFs respectively. The big squares length in all SF-PCFs is 1/9 of the simulation window, middle squares in the third and fourth order SF-PCFs are 1/27 of the simulation window, and small squares in the fourth order SF-PCF are 1/81 of the simulation window. The cladding index in all three fibers is n_{clad} = 1,42.

2. Design of the SF-PCFs

The Sierpinski Carpet is a generalization of the Cantor set to two dimensions [17–19]. The carpet is a fractal object that can be constructed by iteration. The construction of our modified carpet begins with a square, which is cut into 9 congruent subsquares in a 3×3 grid, and the central subsquare is removed. The same procedure is then applied recursively. The Sierpinski Carpet is the limit after an infinitum number of steps.

The 3D generalization of the carpet is the Menger sponge. This object has been studied in its application in the field of photonic

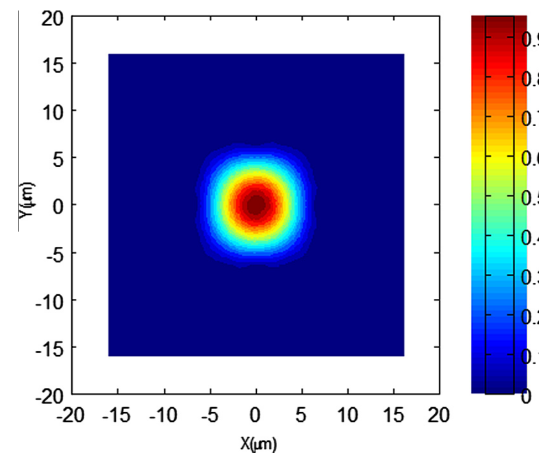

Fig. 2. Electric field's total intensity distribution in the second order SF-PCF. The field is confined in the nucleus of the fiber without the need of a differentiated core.

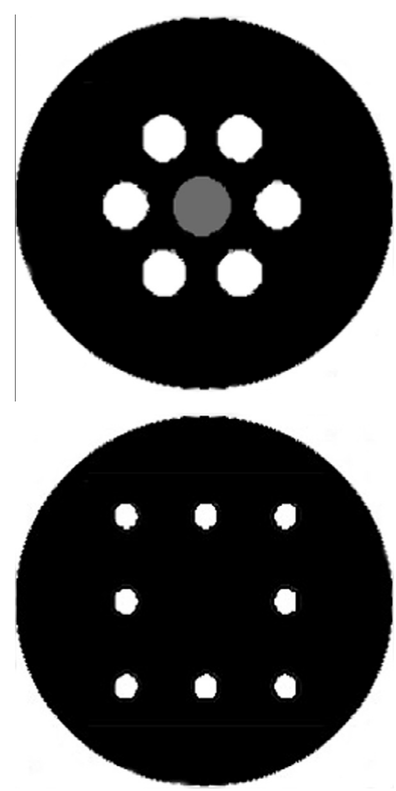

Fig. 3. Schematic structures of the hexagonal NF-PCF and SF-PCF of second order with circular air holes. The distance between the air holes in the NF-PCF is Λ = 5 μm and their radius R_{air} = 2 μm, the nucleus radius is $R_{nucleus}$ = 2 μm and its index n_{air} = 1,45. In the SF-PCF the radius of the air holes is R_{air} = 1,78 μm. In both fiber the cladding index is n_{clad} = 1,42.