

Design of Low-Dispersion Fractal Photonic Crystal Fiber

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ABSTRACT— In this paper, a fractal photonic crystal fiber (F-PCF) based on the 1st iteration of Koch fractal configuration for optical communication systems is presented. Complex structure of fractal shape is build up through replication of a base shape. Nowadays, fractal shapes are widely used in antenna topics and its usage in PCF is investigated in this paper. The purpose of this research is to compare normal photonic crystal fibers (N-PCFs) with F-PCFs through the simulation and optimization procedure based on the finite element method (FEM). The effective mode index of the fundamental mode is found for different PCF structures. In addition, dispersion properties of F-PCF are numerically calculated and compared by N-PCF.

KEYWORDS: Fractal PCF, photonic crystal fiber, optical communications, dispersion.

I. INTRODUCTION

Nowadays, optical communication systems have very important role in transferring data. Particularly, with multichannel systems such as wavelength division multiplexing (WDM) and optical time division multiplexing (OTDM), it is possible to send more than one hundred channels simultaneously on same optical fiber in high bit rates. But the dispersion and dispersion slope of fibers restrict the performance of modern optical systems. The dispersion is a phenomenon that causes to broaden optical pulses, when they propagate in the optical fibers. So when a broaden pulse arrive to receiver, it is not

possible to distinguish whether it was 1 or 0. In WDM communication systems, it is essential to maintain a uniform response in the different wavelength channels, which requires that the transmission line approach the ideal state of ultra-flattened dispersion and near zero dispersion [1].

Meanwhile, the technology of manufacturing photonic crystals has led to a new generation of optical fibers, namely “Photonic Crystal Fibers”. Showing interesting and unique characteristics, photonic crystal fibers promise a brilliant future for the telecommunications. One of such useful advantages of data transmission through these fibers is the possibility of keeping them as single-mode for a wide range of wavelengths. Using the most available bandwidth, such an advantage increases the capacity of network, especially in wavelength division multiplexing systems and networks. Another important advantage of photonic crystal fibers is controlling the dispersion and dispersion slope properties through the PCF structural parameters set. The photonic crystal fibers offer greatly enhanced design freedom compared to standard optical fibers. The photonic crystal fiber is formed from a strand of silica glass with an array of microscopic air channels running along its length [2]. A defect in the center of this array is deliberately created to form the core of the fiber.

In this paper, a solid core or index guiding F-PCF is introduced. In index guiding F-PCF, the refractive index of the core is higher than that of the core's surrounding area; hence the transmission in this type of PCFs is mainly due to the total internal reflection (TIR).

Reducing dispersion and dispersion slope in broad range of wavelengths are of the main concerns in designing PCFs. In conventional PCFs with uniform holes with equal diameters, proper control of dispersion and particularly its slope in a broad range of wavelengths is difficult to maintain. Today, on the other hand, exploiting multiple design parameters such as diameter and shape of the holes, the number of air hole rings and the spacing between these holes facilitates development of PCFs with improved properties.

Already, many reports have been published about PCFs with nearly zero dispersion and ultra-flattened chromatic dispersion properties. The dispersion slope of standard nonlinear step-index fibers is on the order of 2×10^{-2} ps/(km-nm²). Reduction of the slope can be obtained by introducing a depressed cladding region around the core and fibers with a slope as low as 1.3×10^{-2} ps/(km-nm²) have been demonstrated [3]. The limitation in this method of slope reduction is the index contrast between the core and the depressed cladding set by the obtainable doping levels.

Hansen offered a hybrid-core photonic crystal fiber with three-fold symmetry that the lowest slope was obtained 1×10^{-3} ps/(km-nm²) which is one order of magnitude lower than conventional slope reduced nonlinear fibers [4]. In recent years, better results have been observed [5-21] as a result of different approaches adopted, e.g. modifying the form of the hole into elliptical [5, 6], gradually increasing the diameter of the hole from inner ring to the outer [7], selectively filling the PCF with liquids [10], application of double cladding [12, 15], etc.

In this paper, In order to minimize the dispersion and dispersion slope of the index guiding photonic crystal fibers, we present a

new controlling technique of chromatic dispersion in PCF. Moreover, our technique is applied to design PCF with both zero-dispersion and ultra-flattened dispersion in wide wavelength range.

A finite element method (FEM) with the perfectly matched layers (PML) boundary conditions is used to analyze the dispersion properties. The numerical results show it is possible to design a F-PCF with dispersion fluctuates between 1.1×10^{-10} ps/(km-nm) and 1.64×10^{-10} ps/(km-nm) in 0.9 μ m to 1.8 μ m wavelength range which is suitable for optical communication systems. In future work, we plan to minimize the dispersion, dispersion slope, and confinement loss, and to obtain large effective mode area.

II. DESIGN OF F-PCF

Investigation on the performance of various structures of PCFs (different shape of air holes like circular, oval, and so on) and different lattices structure like hexagonal and octagonal have been reported well so far. Although, the structure of air holes are mainly designed as circular or elliptical, but some other structures are also designed and investigated [22-25]. Figure 1 shows the cross section of the proposed F-PCF. There are some methods to design and fabricate the PCFs including various hole shapes, although the fractal holes can be created more difficult with respect to the circular or elliptical holes [7, 19, 22, 26-30].

As shown in Fig. 1, the electric field distribution is well concentrated in the center of the fiber like normal structure of PCF. The 1st iteration of the Koch shape is used in the structure of the PCF for its air holes. The structure of holes in more detail is illustrated in Fig. 2. As shown, two circles are considered in the Koch fractal shape with d_1 and d_2 as their radius ($d_1=2r_1$ and $d_2=2r_2$). The distance between the centers of every two adjacent air holes is L .

III. SIMULATION RESULTS

In order to design a F-PCF with the minimum dispersion near to zero in the wide range, four parameters of d_1 , d_2 , L , and N_r (the number of air holes) are varied in a proper range to investigate their effects on the performance of the F-PCF. It is intended to find the optimum values for each of the design parameters finally.

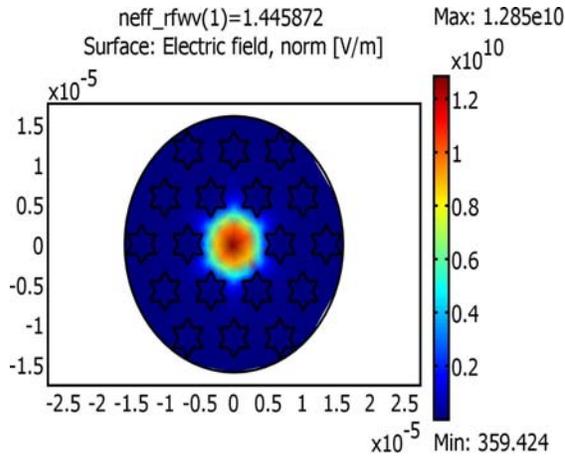


Fig. 1. The cross section of the proposed F-PCF with electric field distribution.

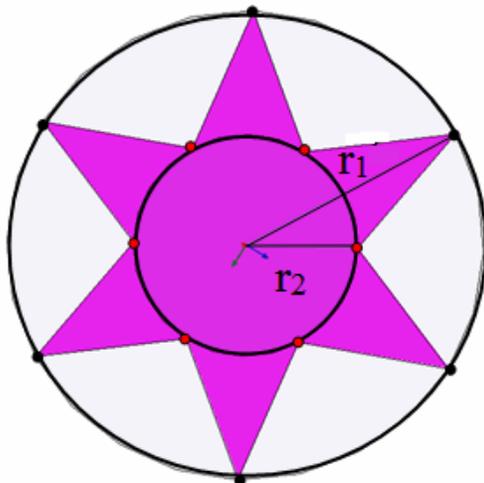


Fig. 2. The structure of air holes in more detail, $d_1=2r_1$ and $d_2=2r_2$.

At the first stage, it is intended to investigate the performance of a normal PCF with the circular air holes and the fractal PCF. It is necessary to mention that the radius of the circular air hole is chosen the same as d_1 in F-PCF. Various simulations have been carried out with different design parameters. Table 1

describes three different structures of the F-PCF and normal PCF [31] which all have been simulated.

According to Table 1, simulation for different number of air holes ($N_r=2, 3$, and 4) has been done and the results are shown in Fig. 3. Simulation for $N_r=2$ shows more satisfactory results in F-PCF than N-PCF. As it can be seen, the slope of effective mode index in the F-PCF is smaller than N-PCF which has direct effect on dispersion value and it will be proved in further simulation. Simulation for $N_r=4$ does not show that much different in two cases of F-PCF and N-PCF.

According to Table 1, configuration 1 has been simulated for $N_r=1,3,4$. Figure 4 shows the results. As it can be seen changing the number of air holes from 3 to 4 does not change the dispersion value that much and they are coincident well. In the range of wavelength from $0.9\mu\text{m}$ to $1.7\mu\text{m}$ the value of dispersion can be supposed to be linear with fluctuation around $5.7 - 7.15\text{ps}/\text{nm}\cdot\text{km}$.

Intersection of the curves at $1.33\mu\text{m}$ and $1.55\mu\text{m}$ in Fig. 4 is noticeable. These two wavelengths are applicable in communication system and for ease of manufacturing a PCF with $N_r=1$ is preferred. The results show two advantages of F-PCF in comparison with N-PCF. According to the result of [31] wider wavelength range and smaller value of dispersion have been achieved with F-PCF structure.

Table 1 The design parameters for three different structures.

No.	Fractal PCF			Normal PCF	
	$d_1(\mu\text{m})$	$d_2(\mu\text{m})$	$L(\mu\text{m})$	$d(\mu\text{m})$	$L(\mu\text{m})$
1	5	1.45	6.75	5	6.75
2	6	1.75	6.75	6	6.75
3	5	1.45	8.75	5	8.75

Configuration 1 shows its priority with 2 and 5 air hole rings. Figure 5 shows its outstanding result of simulation. The dispersion curve in a wide range of wavelength from $0.8\mu\text{m}$ to $1.8\mu\text{m}$ is fluctuated between $1.1 \times 10^{-10}\text{ps}/(\text{km}\cdot\text{nm})$ and $1.64 \times 10^{-10}\text{ps}/(\text{km}\cdot\text{nm})$. It can be deduced that the value of dispersion is so near to zero. This result was

predictable according to the previously achieved value of n_{eff} in Fig. 3.

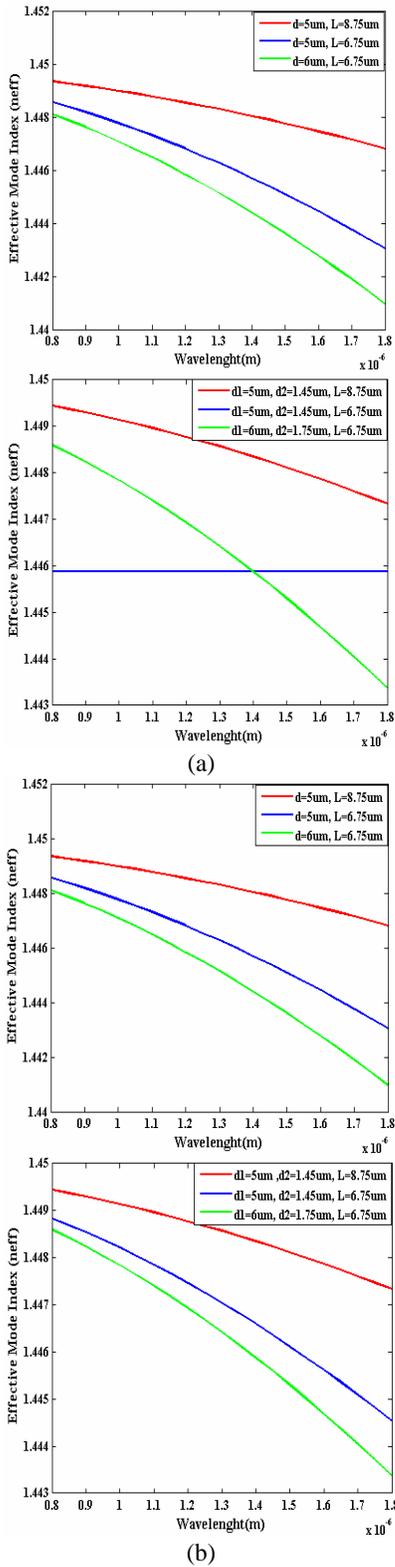


Fig. 3. Effective mode index for different structures and number of air holes for (a) N-PCF with $N_r=2$ and (b) F-PCF with $N_r=4$.

Figure 6 depicts the simulation result of configuration 2. The L parameter is constant for both configurations of 1 and 2 but the size of air holes is smaller in the first configuration. Coarsely, it can be deduced that configuration 2 shows better performance in some ranges of wavelength in comparison with configuration 1 for $N_r=1, 3$, and 4. But obviously, it shows worse performance for $N_r=2$ and 5 of configuration 1.

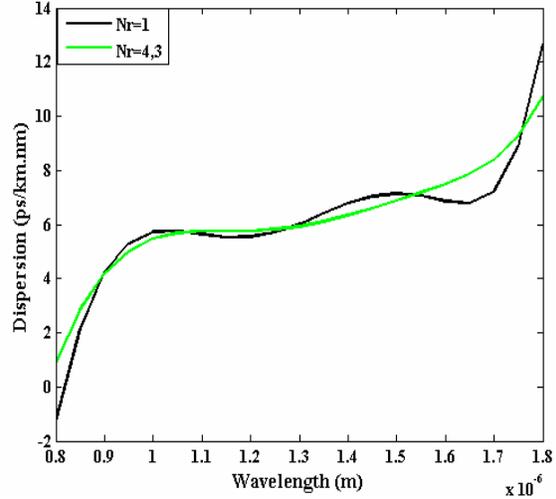


Fig. 4. Dispersion curves of F-PCF as a function of wavelength for different number of air hole rings ($N_r=1, 3$, and 4) for configuration 1 ($d_1=5 \mu\text{m}$, $d_2=1.45 \mu\text{m}$, and $L=6.75 \mu\text{m}$).

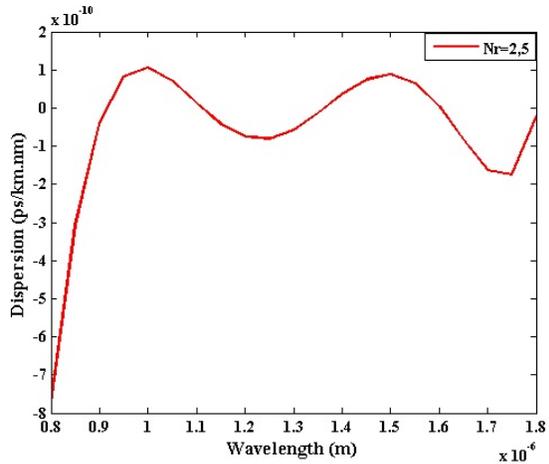


Fig. 5. Dispersion curves of F-PCF as a function of wavelength for different number of air hole rings ($N_r=2$ and 5) for configuration 1 ($d_1=5 \mu\text{m}$, $d_2=1.45 \mu\text{m}$, and $L=6.75 \mu\text{m}$).

It is acceptable that increasing the ratio of d/L increases the value of dispersion too. Our

simulation for F-PCF with $N_r=1, 3,$ and 4 are in agreement with this rule but for $N_r=2$ and 5 the F-PCF structure shows exactly the reverse rule. It can be concluded that no general rule can predict the relation of d/L and dispersion value in F-PCF structures.

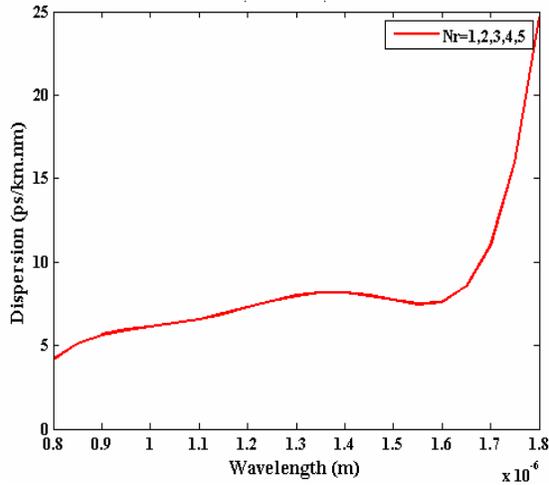


Fig. 6. Dispersion curves of F-PCF as a function of wavelength for different number of air hole rings ($N_r=1, 2, 3, 4,$ and 5) for configuration 2 ($d_1=6 \mu\text{m}, d_2=1.75 \mu\text{m},$ and $L=6.75 \mu\text{m}$).

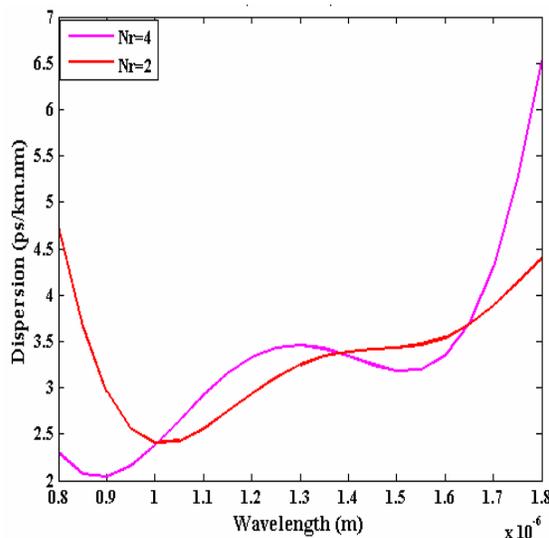


Fig. 7. Dispersion curves of F-PCF as a function of wavelength for different number of air hole rings ($N_r=2$ and 4) for configuration 3 ($d_1=5 \mu\text{m}, d_2=1.45 \mu\text{m},$ and $L=8.75 \mu\text{m}$).

Investigating the effect of L value on the performance of F-PCF structure, configuration 3 is considered in comparison with

configuration 1. Figure 7 shows the result of simulation configuration 3 with $N_r=2$ and 4 . Considering Fig. 4, configuration 3 has better value of dispersion in comparison with configuration 1 but for $N_r=2$, the 1st configuration still shows its great advantage.

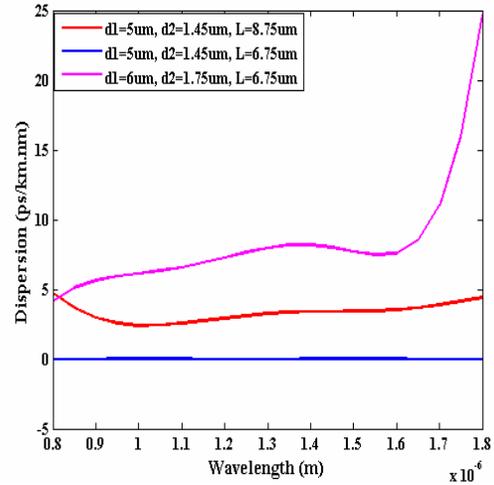


Fig. 8. Dispersion curves of F-PCF as a function of wavelength for $N_r=5$ in different configurations.

From all simulated results configuration 1 with $N_r=2$ and 5 shows the best performance due to the least value of dispersion. It is well approved that increasing the number of air hole rings concentrate the light more in center of PCF, so $N_r=5$ is noticed more in Fig. 7.

In Fig. 8 the most outstanding performance of F-PCF structure is compared again to emphasize on the best configuration. As it can be seen configuration 1 shows considerably the least value of dispersion among other configurations in wide range of wavelength which is also better than normal structure of PCF.

IV. CONCLUSION

The usage of fractal shape (1st iteration of Koch shape) in the structure of PCF for the air hole shape has been introduced and its performance has been investigated by several simulations. F-PCF structure showed better performance than normally PCF in some cases. Four design parameters of PCF structure were considered and the effect of their changes on the whole performance of F-PCF has been shown. Finally an optimum configuration of F-

PCF has been proposed which has the least value of dispersion over the wide range of wavelength. The numerical results have shown the designed F-PCF has the dispersion fluctuates between 1.1×10^{-10} ps/(km·nm) and 1.64×10^{-10} ps/(km·nm) in 0.9 μ m to 1.8 μ m wavelength range which was suitable for optical communication systems. In future work, we plan to investigate and to optimize the physical parameters of the proposed F-PCF considering confinement loss, dispersion, dispersion slope, and effective mode area.

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