Large Negative Dispersion in Photonic Crystal Fiber by Applying Gold Nanoparticles in Square Cladding

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Abstract

In this paper, a new structure of photonic crystal fibers (PCFs) with large negative dispersion is presented in order to compensate the positive dispersion at a wavelength of 1.55 μm. The proposed PCF has square lattice structure. In the basic structure of the cladding, it consists of four square rings, so that each ring has a number of circular holes. In the final proposed structure, the two inner rings of the cladding are reshaped relative to the two outer rings. The first inner ring near the core has stellar shaped holes with gold nanoparticles in its center, and the second inner ring has circular holes with a smaller diameter than the two outer rings. The base material of this fiber is silica. The use of stellar shaped holes with gold nanoparticles cores causes a large amount of negative dispersion, which compensates the positive dispersion. Simulation results show that the minimum dispersion is -4593 ps/(nm.km) at a wavelength of 1.55 μm which bring a significant improvement compared to other similar references.

1. Introduction

Photonic crystal fibers (PCFs) are one of the favorable issues which have attracted great deal of attention in optical communication applications. A PCF is a two-dimensional photonic crystal, containing a central defect region surrounded by multiple air holes. Many optical devices can be made using photonic crystals, such as optical switches [1][2], filters [3][4], and optical fibers [5].

PCFs have different types of geometric structures such as square or hexagonal lattices [6][7]. PCF has unique features such as endlessly single mode propagation, highly configurable dispersion, high birefringence, optical components, wavelength division multiplier and also material processing compared to conventional optical fiber .Photonic crystal fibers have the ability to modulate dispersion, which is very important in the design of dispersion fibers. In fact, if a fiber has a negative dispersion in a wavelength range; it can compensate positive dispersion in this wavelength range. To minimize losses and reduce costs, the dispersion of fiber should be as small as possible [8].

Dispersion in a fiber occurs when an optical pulse moves through an optical fiber and its power changes over time, resulting in the pulse propagating over a wider period of time. Chromatic dispersion is one of the properties of optical fiber that causes different wavelengths of light to propagate at different speeds and move along the optical fiber [8]. In [9] and [10], PCF structures with low losses and dispersion have been proposed.

Long-distance transmission causes the pulse to become too wide and information to be lost. It is necessary to use dispersion compensation fiber in the transmission path. A dispersion fiber with a negative dispersion value re-compresses the flattened pulse. The idea of using PCF to compensate for dispersion is proposed in [11].

Many structures have been proposed for dispersion compensation in photonic crystal fibers. In [12], highly negative dispersion PCF with the central index dip in the low germanium doped core is presented.

In [13], a modified hexagonal circular photonic crystal fiber with large negative dispersion is presented. Large negative dispersion of − 1044 ps/(nm.km) at the wavelength of 1.55 μm for the optimum geometrical parameters was reported. In [14], a PCF having a hybrid lattice structure with low values for the dispersion and confinement loss has been presented. Circular PCF with dispersion of 103.50 ps/(nm.km) and confinement loss of 5.97×10^{-6} dB/m was created by considering its first ring with octagonal hole lattice with eight holes.

A simple circle-based star shape PCF is presented in [15]. Geometrical structure is very suitable for acquiring ultra low effective material loss and very large effective area. Higher core power fraction, single mode operation over the whole investigating range, negligible scattering loss of 1.235e-15 dB/cm has been calculated at f = 1.0 THz.

Ref. [16] presents a PCF filled with carbon-disulfide-filled photonic crystal fibers (CS2-PCFs) with ultra-high nonlinearity and tunable nearly-zero flattened dispersion. The nonlinear coefficient is 7940 W-1km-1, total loss lower than 0.3 dB/m, the dispersion is 0.00007 ps/(nm.km) and a dispersion slope of 0.0000018 near 1550 nm wavelength.

In [17], three zero scatter wavelengths (ZDW) is presented. This structure show a very influential spectral density compared to that of single or double ZDW PCFs. The chromatic dispersion is obtained − 220.39 ps/(nm.km), at the wavelength range of 1.53–1.8 μm. These characteristics can be used for applications such as supercontinuum generation, soliton pulse transmission, and detecting or sensing and optical communication systems.

In [18], a 1×4 photonic crystal fiber power splitter (PCFPS) which have very low dispersion and very low loss is proposed. An optofluidic material was added in some of inner holes in addition changing their diameters to obtain an optimal case of dispersion and loss in PCF. The lowest dispersion below 2.5 ps/(nm.km) and loss below 0.025dB/cm was reported in the paper.

In [19], ultra low confinement loss PCF with flattened dispersion is presented that applied hexagonal PCF structure with six rings of holes. There are three inner rings of elliptical holes arranged in a rhombic shape in its structure. The authors report very low dispersion (less than 10 ps/(nm.km)) at higher communication wavelength. Meanwhile, zero dispersion has been obtained at smaller optical wavelengths and the confinement loss is ultra low.

A dual concentric cladding PCF was presented in [20] that it has low-loss and near-zero ultra flattened dispersion. Ultra flattened dispersion of 1.69 ± 0.08 ps/(nm.km) was achieved in the wavelength range from 1 to 2 μm. The PCF has a loss below $10e^{-14}$ dB/km. This design presents low dispersion with the lowest confinement loss and the largest effective area.

In this paper, a novel photonic crystal fiber with a large negative dispersion coefficient is presented. Gold nanoparticles are used in the center of the proposed stellar structure in the inner ring of the fiber. As a result, the dispersion coefficient of the final proposed structure is a large negative value and this can compensate a larger positive dispersion value.

The rest of this paper is organized as follows: In Sect. 2, the proposed PCF structure is presented. Simulation results and discussion are presented in Sect. 3. Finally, conclusions are presented in Sect. 4.

2. The Proposed Structure

One type of fiber dispersion is chromatic dispersion, which occurs because different components of the wavelength of a light pulse move at different speeds within the fiber. Chromatic dispersion is the most important dispersion factor in single-mode fibers and is calculated by Equation 1 [21], [22].

$$D_C = \frac{1}{L}\frac{\Delta t_C}{\Delta\lambda} = -\frac{\lambda}{C}\frac{d^2 \mathrm{Re}(n_{eff})}{d\lambda^2} \qquad (1)$$

where D_c is the chromatic dispersion coefficient, Δtc is time spreading, L is the fiber length, Δλ is the spectrum width, λ is the wavelength, C is the light speed in vacuum and $\mathrm{Re}(n_{eff})$ is the real part of refractive index.

The basic proposed structure of the PCF is shown in Figure 1. Cladding has a square geometric shape. There are four square rings with circular holes in this structure. The diameter of the holes in the second ring (from the core side) is half the diameter of the other holes in the cladding. In this figure, d1 is the diameter of the small circular holes, d2 is the diameter of the big circular holes, and Λ is the distance between the centers of the two circular holes. The parameters of the basic proposed fiber are shown in Table 1.

In the next step to develop the design, the final PCF is proposed in Figure 2. As shown in Figure 2, the first ring (from the core side) has changed than the basic design. This inner ring consists of five small circular holes which we called the stellar structure. Its central circle hole is filled with gold nanoparticles. In Figure 2, d1 is the diameter of the small circular holes, d2 is the diameter of the big circular holes, Λ is the distance between the centers of the two circular holes, ds is the diameter of the stellar shaped circular holes, and Λs is the distance between the centers of the two circular holes in the stellar structure. The parameters of the final proposed structure are given in Table 2.

3. Simulation And Results

The basic proposed structure and the final proposed structure were simulated by Lumercial software. The mode field distribution and the refractive index of the basic square fiber are shown in Figure 3 and Figure 4, respectively.

The dispersion diagram of the basic proposed structure is shown in Figure 5. The dispersion versus wavelength is illustrated from 1.4 to 1.68 μm. According to the dispersion characteristic of the basic fiber in Figure 5, the minimum dispersion equal to -847 ps/(nm.km) at a wavelength of 1.57 μm.

In the final proposed fiber structure, the inner ring has stellar-shaped holes with gold nanoparticles in their centers. The use of this structure causes a large negative value of dispersion. The mode field distribution and the refractive index of the final proposed PCF are shown in Figure 6 and Figure 7, respectively.

The dispersion diagram of the final proposed PCF is shown in Figure 8. The dispersion versus wavelength is illustrated from 1.5 to 1.68 μm.

According to Figure 8, in this structure, the minimum dispersion is more negative compared to the basic structure. The minimum dispersion has been transferred from -847 ps/(nm.km) at a wavelength of 1.57 μm in the basic structure to -4593 ps/(nm.km) at a wavelength of 1.55 μm.

Table 3 shows the results of the final proposed structure with other similar researches. The dispersion value of our proposed structure has a large negative value compared to the other structures. As a result, this proposed structure can be used to compensate for the positive dispersion.

4. Conclusion

In this paper, a new PCF structure with a large negative dispersion value is presented. The geometric shape of the cladding is square. In the original design, four rings of circular holes are used so that the circle diameter of the second ring (from the core side) is half the diameter of the other circular holes. This structure was simulated using Lumerical software. The simulation results show a minimum dispersion value of -847 at the wavelength of 1.57 μm. The original design was completed by replacing the inner ring with five smaller star-shaped circles. In this proposed structure, gold nanoparticles are used in the center of the stellar structure. The simulation result shows a minimum dispersion value of -4593 at the wavelength of 1.55 μm, which shows a significant decrease compared to the basic structure. The use the stellar structure in the inner ring, as well as the use of gold nanoparticles in its center, creates a large negative dispersion in the PCF characteristic. As a result, we can use this proposed structure to compensate the positive dispersion.

Declarations

Funding: For this study, no funding was received.

Conflict of Interest: The authors declare that they have no conflict of interest.

Availability of data and material: All data (used in this study) are available inside the paper.

Code availability: The proposed structure was simulated using Lumerical software.

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Tables

Table 1. The parameters of the basic structure fiber

Value (μm)	Symbol	Parameter
0.40	d1	The diameter of the air holes of the second ring
0.80	d2	The diameter of the air holes of the other rings (except the second ring)
1.00	[illegible]	The distance between holes in the square lattice structure

Table 2. The parameters of final proposed structure

Value (μm)	Symbol	Parameter
0.4	d1	The diameter of the air holes of the second ring
0.8	d2	The diameter of the air holes of the other rings (except the second ring)
1	□	The distance between holes in the square lattice structure
0.18	ds	The diameter of air and gold holes in the stellar structure
0.2	□s	The distance between holes in the stellar structure

Table 3. Comparison between properties of the proposed PCF and other previous PCFs

PCF structure	Wavelength band (μm)	Negative Dispersion (ps/(nm.km))	Negative Dispersion (ps/(nm.km)) at λ=1.55 μm
[23]	1.46-1.625	-190 to -405	-
[24]	1.53-1.625	-226 to -290	-239.5
[25]	1.35-1.65	-	-204.4
[26]	1.40-1.60	-130 to -360	-
[27]	1.34-1.64	-248.65 to -1069	-790.12
This work	1.53-1.64	-50 to -4593	-4593

Figures

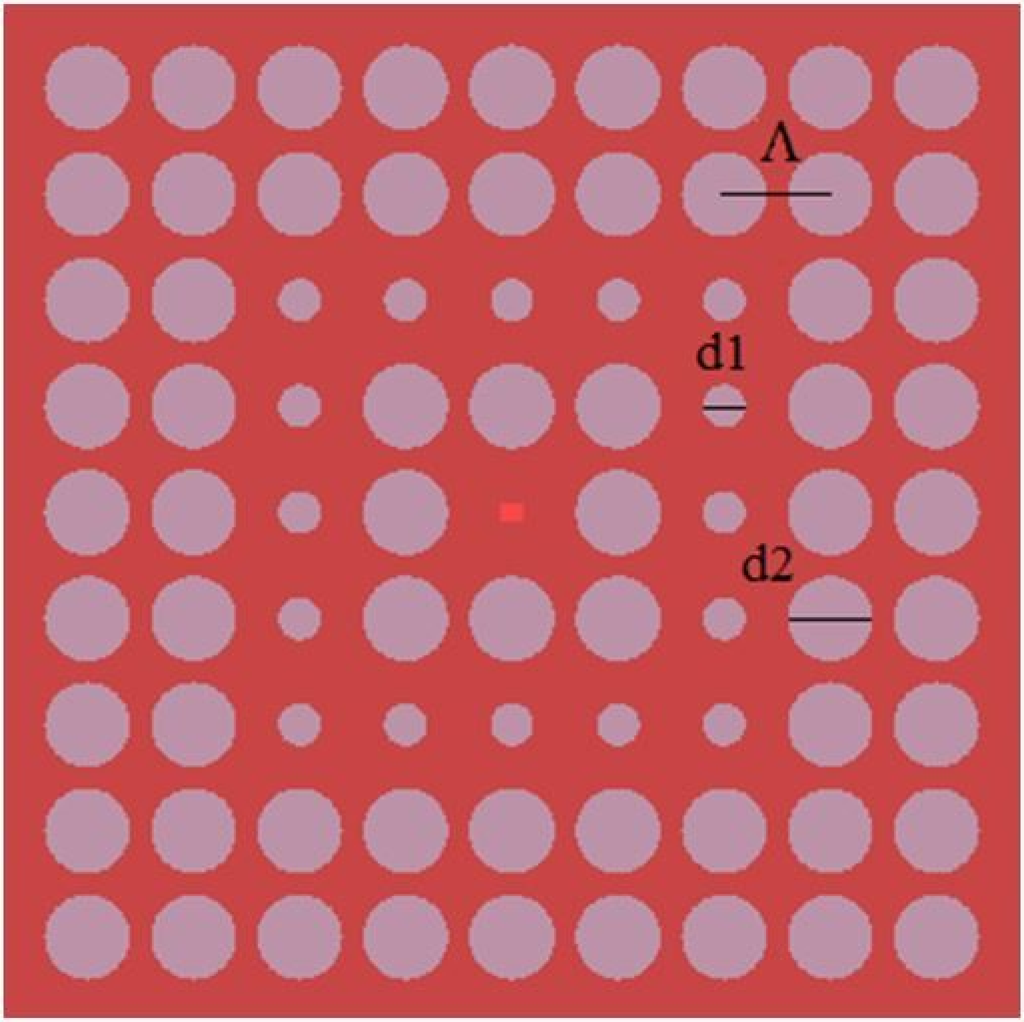

Figure 1

The basic structure of square lattice PCF

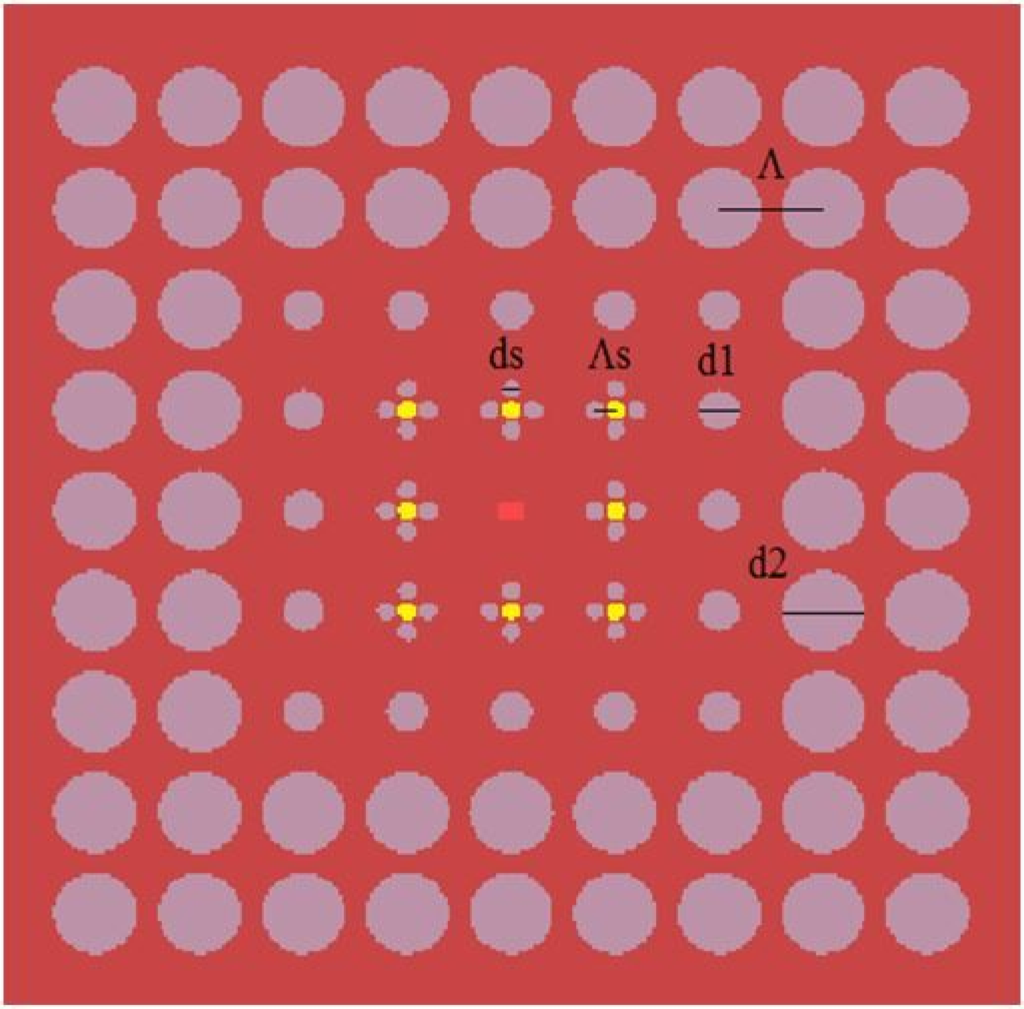

Figure 2

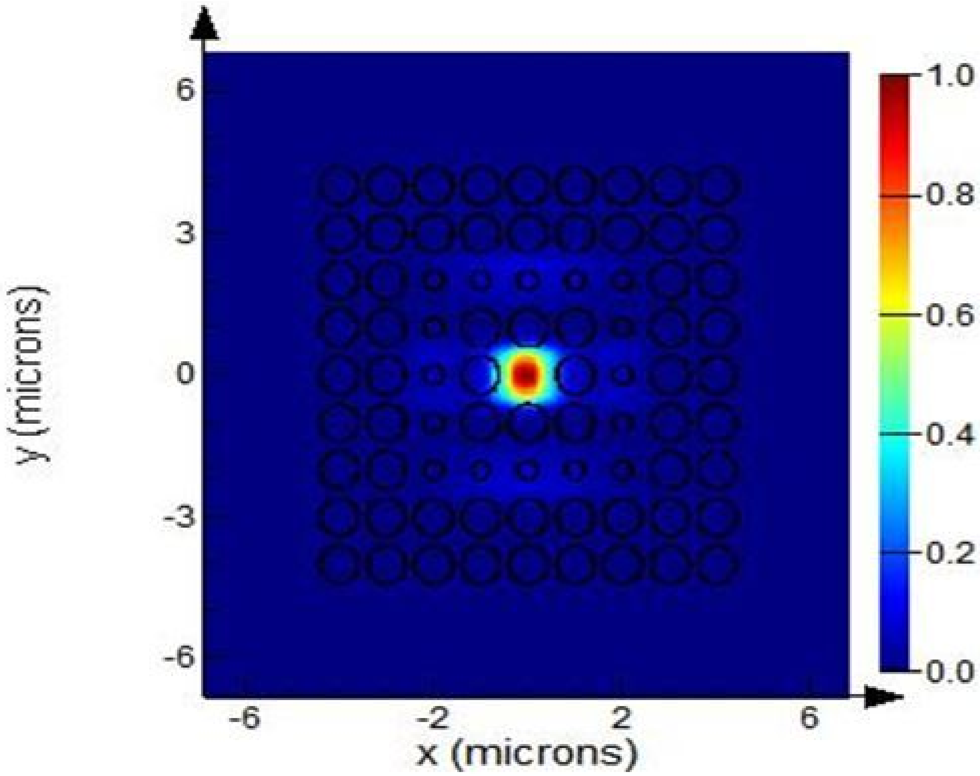

Figure 3

The mode field distribution of the basic square lattice fiber at the wavelength of 1.55 μm

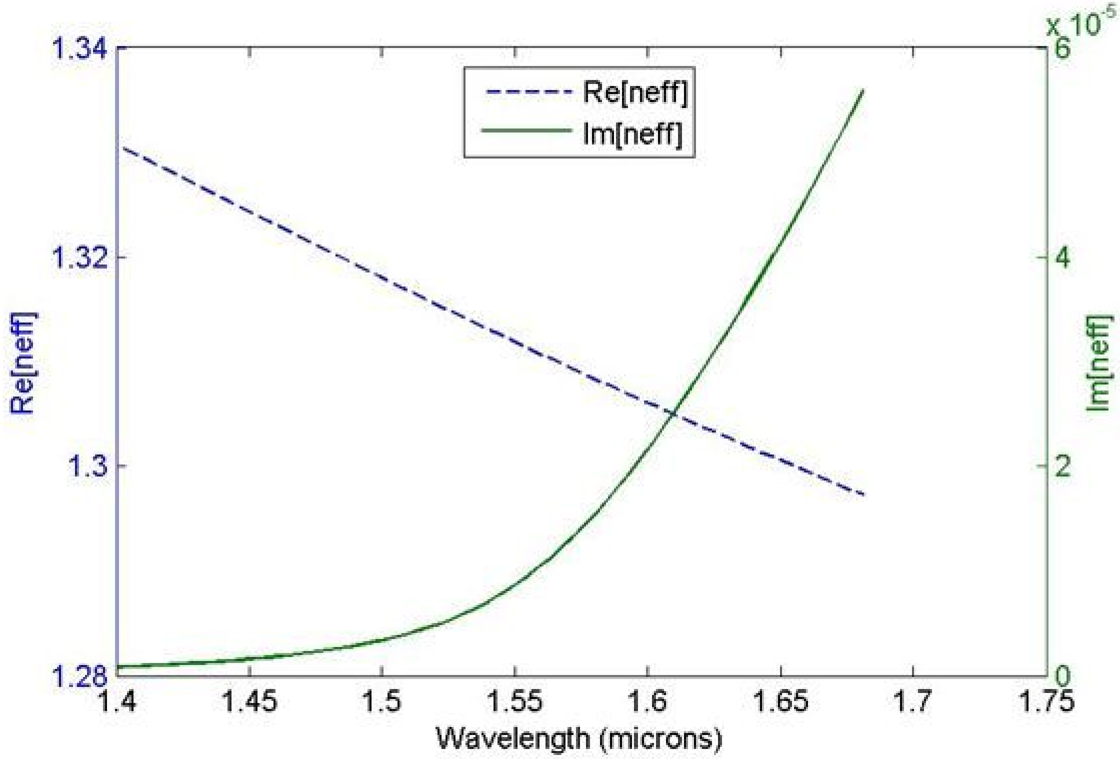

Figure 4

Refractive index of the basic square lattice fiber

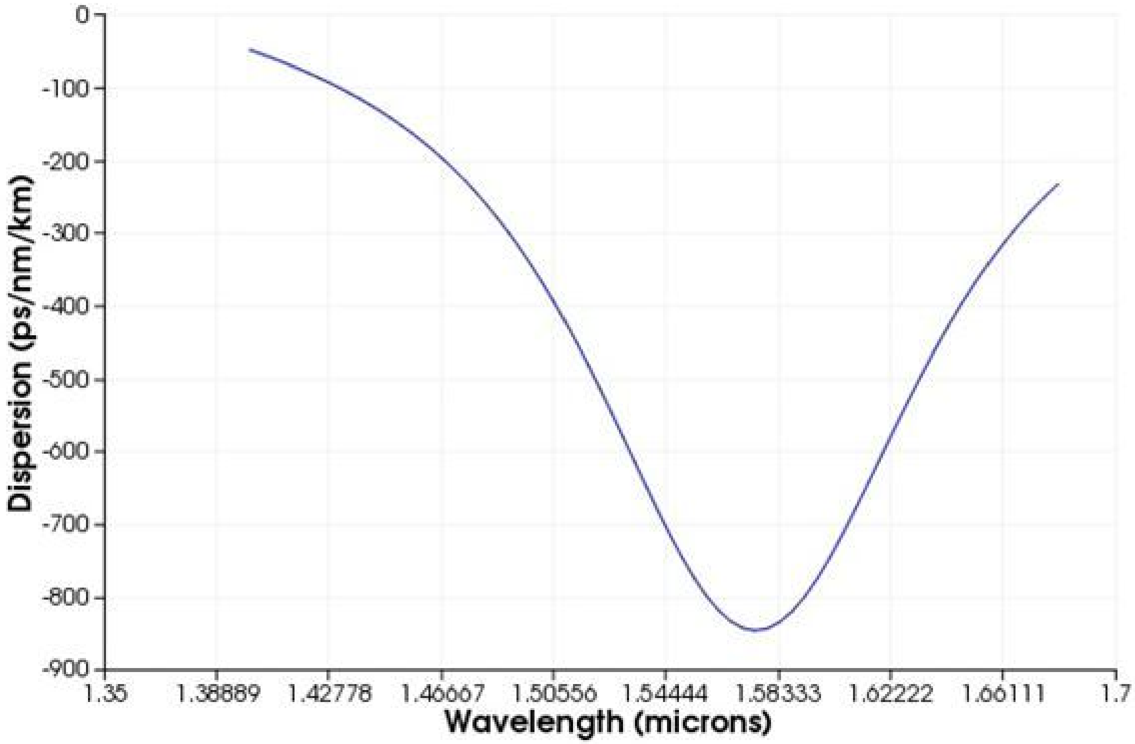

Figure 5

Fiber dispersion coefficient diagram of the basic square lattice fiber

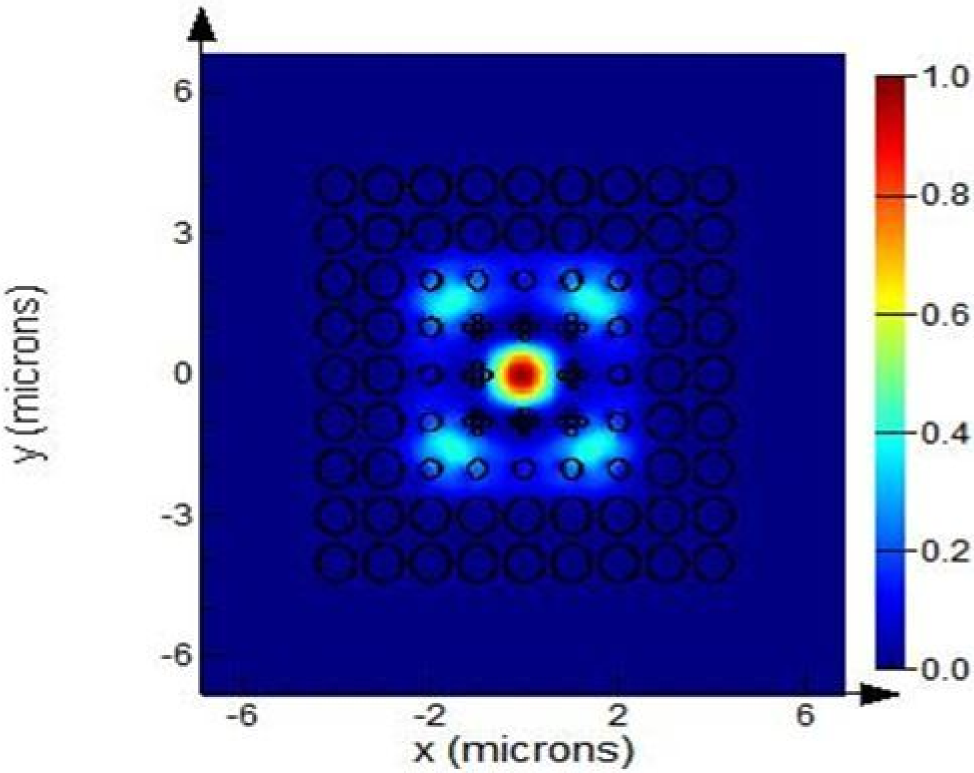

Figure 6

The mode field distribution of the final proposed fiber (with stellar shapes) at a wavelength of 1.55 µm

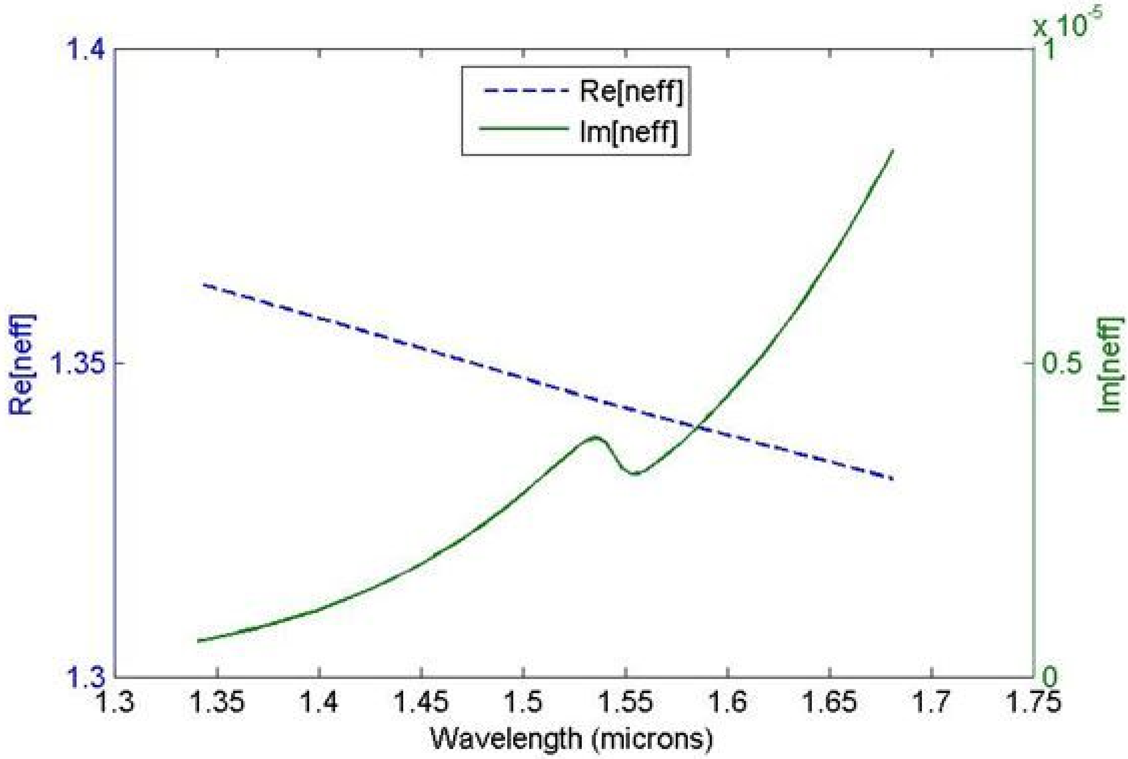

Figure 7

Refractive index of the final proposed fiber

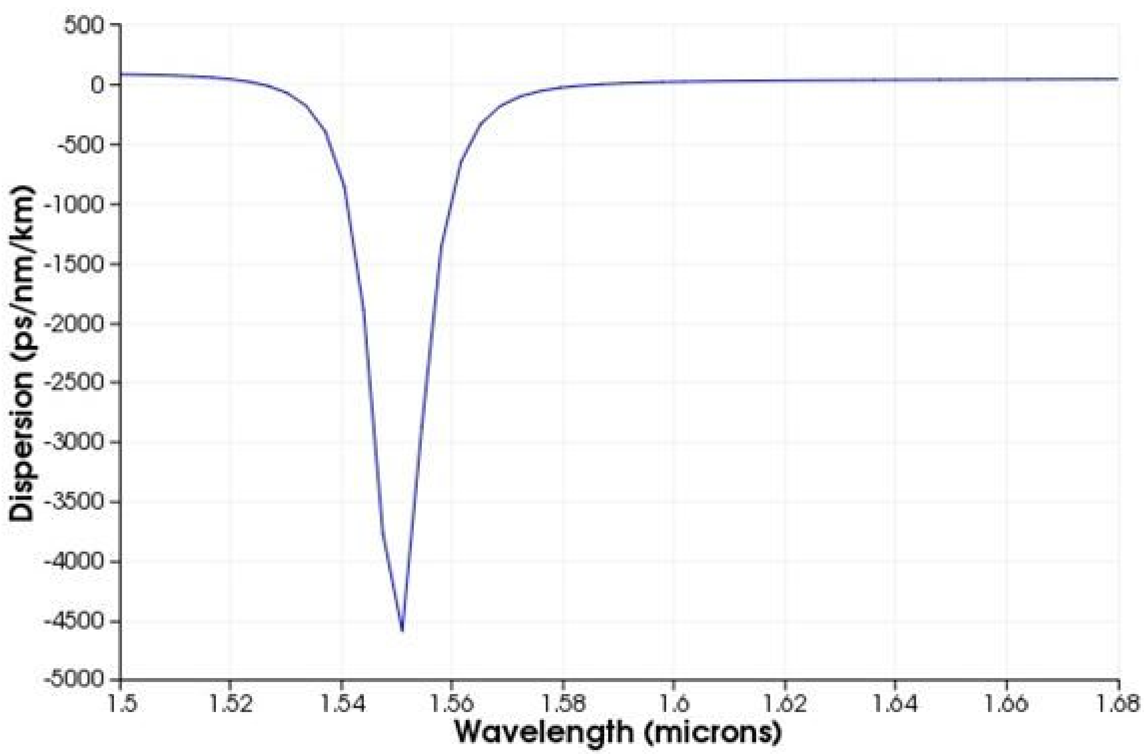

Figure 8

Dispersion coefficient diagram in the final proposed fiber