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.

Keywords Fiber optic · PCF · Negative dispersion · Gold nanoparticle · Square lattice

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 (Takiguchi Apr. 2020; Rao et al. 2020), filters (Zare and Gharaati 2020; Mirjalili et al. 2020), and optical fibers (An, et al. 2021).
PCFs have different types of geometric structures such as square or hexagonal lattices (Lee et al. 2018; Faisal et al. 2018). 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 (Monfared and Mojtahedinia 2014).

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 (Monfared and Mojtahedinia 2014). In (Khoobjou et al. 2021) and (Khoobjou et al. Nov. 2020), 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 Kumar et al. (2016).

Many structures have been proposed for dispersion compensation in photonic crystal fibers. In (H. lei Li, S. qin Lou, T. ying Guo, W. guo Chen, L. Wang, and S. sheng Jian 2009), highly negative dispersion PCF with the central index dip in the low germanium doped core is presented.

In (Biswas 2019), a modified hexagonal circular photonic crystal fiber with large negative dispersion is presented. Large negative dispersion of $-1044 \text{ ps/(nm.km)}$ at the wavelength of $1.55 \mu\text{m}$ for the optimum geometrical parameters was reported. In (Dhanu Krishna et al. 2018), a PCF having a hybrid lattice structure with low values for the dispersion and confinement loss has been presented. Circular PCF with dispersion of $103.50 \text{ ps/(nm.km)}$ and confinement loss of $5.97e-6 \text{ dB/m}$ was created by considering its first ring with octagonal hole lattice with eight holes.

A simple circle-based star shape PCF is presented in Ahmed et al. (2019). 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 $1.235e-15 \text{ dB/cm}$ has been calculated at $f = 1.0 \text{ THz}$.

Ref. (Monfared and Ponomarenko 2018) 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 $7940 \text{ W}^{-1} \text{ km}^{-1}$, total loss lower than $0.3 \text{ dB/m}$, the dispersion is $0.00007 \text{ ps/(nm.km)}$ and a dispersion slope of $0.0000018$ near $1550 \text{ nm}$ wavelength.

In (Kwasi Amoah et al. 2019), 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 $-220.39 \text{ ps/(nm.km)}$, at the wavelength range of $1.53–1.8 \mu\text{m}$. These characteristics can be used for applications such as supercontinuum generation, soliton pulse transmission, and detecting or sensing and optical communication systems.

In (Naghizade and Mohammadi 2019), a $1 \times 4$ 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 0.025 dB/cm was reported in the paper.

In (Fiaboe et al. 2019), 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 Mohammadzadehasl and Noori (2018) 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 Eq. 1 (Saitoh and Koshiba 2003; Begum et al. 2007).

\[
D_C = \frac{1}{L} \frac{\Delta t_C}{\Delta \lambda} = -\frac{\lambda}{C} \frac{d^2 \text{Re}(n_{\text{eff}})}{d \lambda}
\]

where \(D_C\) is the chromatic dispersion coefficient, \(\Delta t_C\) is time spreading, \(L\) is the fiber length, \(\Delta \lambda\) is the spectrum width, \(\lambda\) is the wavelength, \(C\) is the light speed in vacuum and \(\text{Re}(n_{\text{eff}})\) is the real part of refractive index.

The basic proposed structure of the PCF is shown in Fig. 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, \(d_1\) is the diameter of the small circular holes, \(d_2\) is the diameter of the big circular holes, and \(\Lambda\) 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 Fig. 2. As shown in Fig. 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 Fig. 2, \(d_1\) is the diameter of the small circular holes, \(d_2\) is the diameter of the big circular holes, \(\Lambda\) is the distance between the centers of the two circular holes, \(d_5\) is the diameter of the stellar shaped circular holes, and \(\Lambda_s\) 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. By increasing or decreasing the
Fig. 1 The basic structure of square lattice PCF

Table 1 The parameters of the basic structure fiber

| Parameter                                                | Symbol | Value (μm) |
|----------------------------------------------------------|--------|------------|
| The diameter of the air holes of the second ring         | \( d_1 \) | 0.40       |
| The diameter of the air holes of the other rings (except the second ring) | \( d_2 \) | 0.80       |
| The distance between holes in the square lattice structure | \( \Lambda \) | 1.00       |

Fig. 2 The final proposed fiber structure with a stellar-shaped inner ring and gold nanoparticles
values of $d_1$, $d_2$, $\Lambda$, $d_s$, and $\Lambda_s$, the absolute value of the negative dispersion decreases and becomes out of the optimal state. The value of these parameters is optimized using the PSO algorithm in Lumerical software. Actually, in optimization configuration section of the software, the PSO algorithm is selected as the optimization solver. In fact, in this paper, the minimum dispersion value is obtained for the values parameters mentioned in Table 2. The minimum dispersion value at 1.55 μm is $-4593$ ps/(nm.km).

## 3 Simulation and results

The basic proposed structure and the final proposed structure were simulated by Lumerical software. To simulate fiber optics, we first defined the structure, dimensions and materials in the proposed fiber optic in Lumerical software. Lumerical software applies the numerical solution methods (such as the finite element method) to solve the equations governing on the fiber optic (such as Snell’s law and Maxwell’s equations, etc.) and calculates and draws different curves such as dispersion curve.

The mode field distribution and the refractive index of the basic square fiber are shown in Figs. 3, 4, respectively.

| Parameter                                      | Symbol | Value (μm) |
|------------------------------------------------|--------|------------|
| The diameter of the air holes of the second ring | $d_1$  | 0.4        |
| The diameter of the air holes of the other rings (except the second ring) | $d_2$  | 0.8        |
| The distance between holes in the square lattice structure | $\Lambda$ | 1          |
| The diameter of air and gold holes in the stellar structure | $d_s$  | 0.18       |
| The distance between holes in the stellar structure | $\Lambda_s$ | 0.2       |

![Fig. 3](image-url)
The dispersion diagram of the basic proposed structure is shown in Fig. 5. The dispersion versus wavelength is illustrated from 1.4 to 1.68 μm. According to the dispersion characteristic of the basic fiber in Fig. 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
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The mode field distribution and the refractive index of the final proposed PCF are shown in Figs. 6, 7, respectively.

Refractive index is the ratio of the speed of light in the vacuum to the speed of light in the environment. The complex reflective index is defined in lossy environments. The imaginary part of the refractive index shows its value in the lossy media. The lower the imaginary part of the reflective index makes the lower the dispersion.

Complex index of refraction $n_{\text{eff}}$ is defined as

$$n_{\text{eff}} = n + ik$$

(2)

where $n$ is the real part of refractive index and $k$ is the imaginary part of refractive index.

The relationship between $k$ and wavelength is:
where $\lambda$ is the wavelength, $\omega$ is angular frequency and $C$ is the speed of light in the vacuum.

Lumerical software calculates and plots curve of $k$ in terms of wavelength using the above equations (Figs. 4 and 7).

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

According to Fig. 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

![Fig. 8 Dispersion coefficient diagram in the final proposed fiber](image)

$$k = \frac{2\pi}{\lambda} = \frac{\omega n_{eff}}{C}$$  \hspace{1cm} (3)

| PCF structure          | Wavelength band (μm) | Negative dispersion (ps/(nm.km)) | Negative dispersion (ps/(nm.km)) at $\lambda = 1.55$ μm |
|------------------------|----------------------|----------------------------------|-----------------------------------------------|
| Begum (2009)           | 1.46–1.625           | −190 to −405                     | −                                             |
| Kaijage May (2009)     | 1.53–1.625           | −226 to −290                     | −239.5                                        |
| Ehteshami and Sathi (2012) | 1.35–1.65       | −                                 | −204.4                                        |
| Selim Habib et al. (2013) | 1.40–1.60       | −130 to −360                     | −                                             |
| Haque et al. (2013)    | 1.34–1.64            | −248.65 to −1069                 | −790.12                                        |
| This work              | 1.53–1.64            | −50 to −4593                     | −4593                                         |
the other structures. As a result, this proposed structure can be used to compensate for the positive dispersion.

As shown in Table 3, the negative dispersion value of the proposed structure has a significant reduction in the wavelength of 1.55 μm compared to the other studies. In (Adams and Henning 1990), it has been shown that the amount of losses in this wavelength is minimal and for this reason this wavelength is mostly used in fiber optic communications. The main purpose of our proposed structure is to have a large negative dispersion at a wavelength of 1.55 μm in order to compensate for the positive dispersion. The use of gold nanoparticles in the fiber cladding structure has caused this large amount of negative dispersion.

In (Bulbul et al. Nov. 2020), a rectangle-based, porous-core photonic crystal fiber has been presented. The rectangular air holes are used in fiber core and cladding. Also, a novel PCF-based sensor has been presented in Al-Mamun Bulbul et al. (2021) to sense different chemicals and bio components. The use of metal nanoparticles (like our proposed structure) in the fiber cladding structure in these two references can help reduce the 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.

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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.

Declarations

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

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