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# Highly Nonlinear and Near-zero Ultra-Flattened Dispersion Dodecagonal Photonic Crystal Fibers

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**Abstract**—This paper presents a novel and robust design for a new kind of photonic crystal fiber with dodecagonal and circular array of air holes, aiming at a highly nonlinear coefficient, ultra-flattened dispersion and ultra-low confinement loss. In this structure, circular lattices are added in two inner layers to obtain both ultra-low dispersion and ultra-flattened dispersion in a wide wavelength range. The proposed structure has a modest number of design parameters for easier fabrication. The finite difference method with perfectly matched boundary layer is used to analyze guiding properties. Analysis results prove that the proposed highly nonlinear dodecagonal photonic crystal fiber obtains a nonlinear coefficient greater than 43 $(\mathrm{W \cdot Km})^{-1}$ and low dispersion slope 0.003 ps/(km · nm) at 1.55 μm wavelength. Ultra-flattened dispersion of 0.8 ps/(km · nm) is also obtained ranging from wavelength 1.3 μm to 1.7 μm with confinement loss lower than $0.5 \times 10^{-6}$ dB/m in the same wavelength range.

## 1. INTRODUCTION

Photonic crystal fibers (PCFs) have claddings that contain a central defect region surrounded by multiple air holes running along the fiber length. They have been one of the most interesting developments in recent fiber optics. The dispersion, confinement loss, and nonlinearity can be easily controlled by varying the structural parameters of the PCF such as the size of the air holes and their number and position [1–4]. Controlling dispersion and achieving high nonlinearity along with low confinement loss is very crucial in PCFs. Highly nonlinear PCFs (HN-PCF) are suitable for a variety of novel applications including wavelength conversion [5], optical parametric amplification and supercontinum generation [6–8]. Also, they are attractive candidates for application in future high capacity, in all optical networks.

In order to reduce the physical length and required operating powers, and to maximize the operating bandwidth of many such devices, it is generally desirable to use fibers with the highest nonlinearity, lowest confinement loss and flattened group velocity dispersion. HN-PCFs with identical air holes have been reported [8-10], which have small nonlinear coefficient of 19 $(\mathrm{W \cdot Km})^{-1}$ or relatively large dispersion slope; however, these small core PCFs with large-sized air holes tend to shift zero-dispersion wavelengths toward shorter wavelengths. Therefore, PCFs with identical air holes are not suitable to design HN-PCFs for a telecommunication window. Typically, the air holes are arranged on the vertex of an equilateral triangle with six air holes in the first ring surrounding the core, and this type is called the hexagonal PCF or conventional PCF.

It is worth to mention that controlling dispersion and dispersion slope along with high nonlinearity at a broadband telecommunication band is difficult when conventional PCFs with all same air holes diameter in the cladding region are used. Consequently, the deformation based on hexagonal arrangement of cladding air holes is used [11–13]. Among the studies of HNL-PCF to achieve better properties than conventional silica-based fibers, a HNL-PCF with a nonlinear coefficient of 36.5 $(\mathrm{W \cdot Km})^{-1}$ and confinement loss of approximately $10^{-2}$ dB/Km at 1.55 μm has been proposed [14].

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In other works, an eight ring PCF has been reported with nonlinear coefficient larger than $33\,(\mathrm{W}\cdot\mathrm{Km})^{-1}$ and an ultra-flat dispersion with a value $0.98\,\mathrm{ps}/(\mathrm{Km}\cdot\mathrm{nm})$ [15]. Besides hexagonal PCF, other design structures such as square-lattice [16], octagonal-lattice [4], decagonal PCF [17, 18] and other novel structures [19, 20] have been proposed as PCF designs. So far, octagonal PCFs have been reported having significant single mode wavelength range, more circular field distribution, high inherent non-linearity and low confinement losses.

Up till now, nonlinear flattened dispersion dodecagonal photonic crystal fiber has not been reported. In this paper, a new kind of PCF with dodecagonal structure is proposed to fulfill the requirement of high nonlinearity and both ultra-low dispersion and ultra-flattened dispersion beside ultra-low confinement loss in a wide wavelength range in designing of PCF. The calculated results show novelty of the proposed dodecagonal PCF with such properties as high nonlinearity, wide band ultra-flattened chromatic dispersion, and low confinement loss may pave the way for applications in optical parametric amplification, wavelength conversion, and all optical signal processing. The robustness of our design is also taken into consideration.

This paper is organized as follows. The proposed dodecagon PCF has been described in Section 2, and the methods of calculating the properties of PCF have been reviewed in Section 3. In Section 4, the simulation results has been demonstrated, and the impact of the structural parameters on the properties of proposed dodecagonal PCF has been investigated in Section 5. Finally, the paper is closed by a short conclusion.

## 2. THE PROPOSED DODECAGONAL PCF

As mentioned before, it is difficult to design HNL-PCF along with flattened dispersion for the telecommunication window band based on uniform cladding structures. By increasing the periodicity of the cladding, different components of frequency of the pulse which propagates in the core region experience same condition of propagation by modifying the structural parameters. Therefore, it is expected that the dispersion becomes flattened and can be managed easily. Consequently, Dodecagonal PCF exhibits flattened dispersion in comparison with decagonal, octagonal and hexagonal PCF. Additionally, one of the techniques for managing dispersion coefficients is the deforming of the two first rings of the proposed fiber. To have confinement loss considered, dodecagonal PCF has more air holes than decagonal or octagonal PCF, which leads to low confinement loss as a result of lower refractive index around core and better confinement of light in the core region [8, 12].

A dodecagonal structure in which circular lattices are added in the two inner layers has been proposed to obtain high nonlinearity beside both ultra-flat dispersion and near zero dispersion. The proposed five-ring Highly Nonlinear Dodecagonal PCF (HN-DoDecPCF) is shown in Figure 1. It is made of pure silica with a germanium (Ge)-doped silica core in the center [8]. The first ring has a

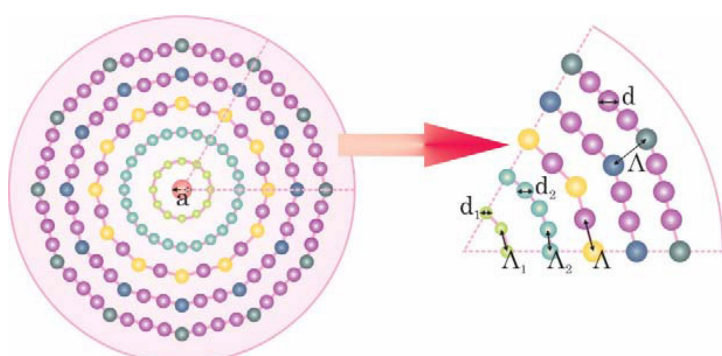



**Figure 1.** Cross section of proposed HN-dodecagonal PCF with 5 ring of air holes. $\mathbf{d}_1 = 0.355\,\mu\mathrm{m}$ (the diameter of the first ring), $\mathbf{d}_2 = 0.5304\,\mu\mathrm{m}$ (the diameter of the second ring air holes), $\mathbf{d} = 0.74\,\mu\mathrm{m}$ (the diameter of the third to fifth ring air holes). $\mathbf{\Lambda}_1 = 1.72\,\mu\mathrm{m}$ (the pitch of the first ring ), $\mathbf{\Lambda}_2 = 0.762\,\mu\mathrm{m}$ (the Pitch of the second ring ), $\mathbf{\Lambda} = 1.6\,\mu\mathrm{m}$ (the Pitch of the third ring to fifth ring).

significant influence on the nonlinearity and chromatic dispersion [21], thus the dimensions of the first and second rings are lowered to control the nonlinearity and chromatic dispersion. In this proposed design, the slope of dispersion is controlled by the second ring. The air-hole diameters of the third to fifth rings are larger than other rings, which causes a decrease in the confinement loss.

The air-hole diameters of the first and second rings are called $\mathbf{d}_1$ and $\mathbf{d}_{2,}$, respectively, and the air hole diameters of the third to fifth rings are named $\mathbf{d}$. The distance between the centers of neighboring air holes (the air hole pitch) for the first and second rings and the remaining rings have been labeled as $\boldsymbol{\Lambda}_1$, $\boldsymbol{\Lambda}_2$ and $\boldsymbol{\Lambda}$, respectively. The normalized refractive index difference ($\triangle n$) of Ge doped core is 3.0%, and the core diameter called $\mathbf{a}$ is 0.96 µm. The proposed HNL-DoDecPCF has three types of diameters. The first ring diameter is $\mathbf{d}_1 = 0.355$ µm, the second ring diameter $\mathbf{d}_2 = 0.5304$ µm and the other rings diameter $\mathbf{d} = 0.74$ µm. The Pitch $\Lambda_1$ is related to $\Lambda$ by the relation $\Lambda_1 = 2.1\Lambda$ and $\Lambda_2$ related to $\Lambda$ by the relation $\Lambda_2 = 2.2\Lambda$. Air hole pitch $\Lambda = 1.6$ µm. These parameters are listed in Table 1.

**Table 1.** The parameters of proposed dodecagonal PCF.

| **Parameters** | **Diameters of air Holes (µm)** | | | **Air hole Pitches (µm)** | | | **Diameter of core (µm)** |
|---|---|---|---|---|---|---|---|
| **values** | $\mathbf{d}_1$ | $\mathbf{d}_2$ | $\mathbf{d}$ | $\Lambda_1$ | $\Lambda_2$ | $\Lambda$ | |
| | 0.355 | 0.5304 | 0.74 | 0.72 | 0.762 | 1.6 | 0.96 |

## 3. THE CALCULATION EQUATIONS

The FDM method with anisotropic perfectly matched layers (PMLs) is used to analyze the nonlinearity, chromatic dispersion and confinement loss of the proposed HN-DoDecPCF. Once the effective refractive index $n_{eff}$ is obtained by solving an eigenvalue problem drawn from the Maxwell's equations using the FDM, the parameter chromatic dispersion $D(\lambda)$, confinement loss $L_c$ and effective area $A_{eff}$ can be obtained. The chromatic dispersion $D$ in [ps/(km · nm)], of PCFs is easily calculated from the plot of $n_{eff}$ values versus the wavelength using the following equation [8]:

$$D(\lambda) = -\frac{\lambda}{c}\frac{d^2\mathrm{Re}[n_{eff}]}{d\lambda^2} \tag{1}$$

where $\mathrm{Re}(n_{eff})$ is the real part of the refractive index, $\lambda$ the operating wavelength, and $c$ the velocity of light in a vacuum. The material dispersion can be obtained directly from the three-term Sellmeier formula. Subsequently, the confinement loss $L_c$, with unit of dB/m, is obtained from the imaginary part of $n_{eff}$ as follows [8]

$$L_c = 8.686 k_0 \mathrm{Im}\left[n_{eff}\right] \tag{2}$$

where $\mathrm{Im}[n_{eff}]$ the imaginary is part of the refractive index, and $k_0 = 2\pi/\lambda$ is the wave number in free space. The complex index of the fundamental modes can be solved from Maxwell's equations as an eigenvalue problem with the FDM effective measure of the area over which the fundamental mode is confined during its propagation can be calculated from effective area. The effective area equation is given as

$$A_{eff} = \frac{\left(\iint \left|E\left(x,y\right)\right|^2 dxdy\right)^2}{\iint \left|E\left(x,y\right)\right|^4 dxdy} \tag{3}$$

where, $E(x, y)$ is the electric field in the medium obtained by solving an eigen value problem from Maxwell equations. A low effective area provides a high density of power needed for nonlinear effects to be significant. The nonlinearity is typically only observed at very high light intensities. PCFs can confine high-intensity light; therefore, PCFs are expected to possess high nonlinearity. The nonlinear coefficient in $(\mathrm{W \cdot km})^{-1}$ is calculated by the following equation

$$\gamma = \frac{2\pi}{\lambda}\left(\frac{n_2}{A_{eff}}\right) \tag{4}$$

where $n_2$ is the nonlinear refractive index.

## 4. THE SIMULATION RESULTS

Figure 2 represents the wavelength dependence properties of chromatic dispersion and nonlinear coefficient of the proposed HN-DoDecPCF in the wavelength range of 1.25 µm to 1.75 µm. As shown in Figure 2, the flattened dispersion of less than $-1$ ps/(km · nm) is obtained in wavelength range of 400 nm (1400 nm to 1800 nm), and it is obvious that it covers communication bandwidth. Besides, the nonlinear coefficient is obtained as 63.48 $(\mathrm{W \cdot km})^{-1}$ at 1.31 µm and 43.7 $(\mathrm{W \cdot km})^{-1}$ at 1.55 µm. It is clear that the nonlinear coefficient becomes smaller by increasing the wavelength, as a result of high refractive index difference between the core and cladding areas, so the light can be confined in the core region, while the light diffuses to the cladding region as the wavelength increases. Therefore, the effective area becomes larger, and the nonlinear coefficients gets smaller. The properties at 1.31 µm and 1.55 µm have been included in Table 2.

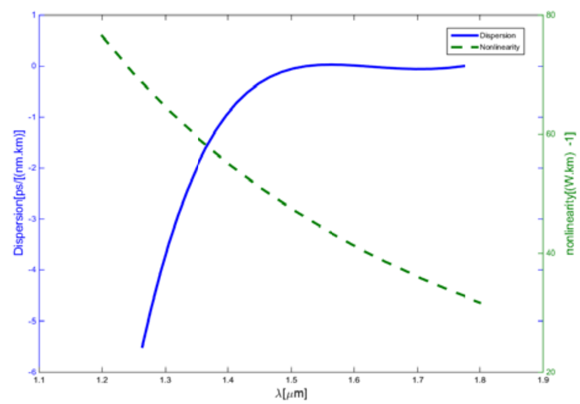



**Figure 2.** The chromatic dispersion and nonlinear coefficient of the proposed HN-DoDecPCF in the wavelength of 1.25 µm to 1.75 µm. The structural parameters are included in Table 1.

**Table 2.** The properties of proposed HN-DoDecPCF at 1.31 µm and 1.55 µm.

| | $D$ ps/(km · nm) | $\gamma$ $(\mathrm{W \cdot km})^{-1}$ | Loss (dB/m) |
|---|---|---|---|
| **at 1.31 µm** | $-3.65$ | 63.48 | $2.02 \times 10^{-7}$ |
| **at 1.55 µm** | 0.003 | 43.67 | $0.55 \times 10^{-4}$ |

## 5. DISCUSSION

This section intends to highlight the importance of diameter ($d_1$) and hole-to-hole spacing ($\Lambda_1$) of the first ring air holes on the characteristics of introduced fiber. Subsequently, there is a comprehensive comparison between the main properties of dodecagonal, decagonal and octagonal PCFs with the same parameters, to point out the superiority of proposed dodecagonal PCF over others, and in the end this paper inclines to compare the feature of an optimum octagonal fiber with that of a dodecagonal fiber to indicate the dominant priority of dodecagonal fiber over octagonal one in terms of efficiency.

### 5.1. Investigating of the Impact of Two Major Parameter on the Properties of proposed Dodecagonal PCF

The properties of the designed dodecagonal PCF is strongly dependent on the diameter ($\mathbf{d}_1$) and hole-to-hole spacing ($\mathbf{\Lambda}_1$) of the first ring air holes. In addition, the designed fiber properties will be altered with the variation of these two parameters ($\mathbf{d}_1$, $\mathbf{\Lambda}_1$). It is certain that all applied parameters generally

**Table 3.** The properties values based on variation of the first ring air holes diameter ($\mathbf{d}_1$).

| $\mathbf{d}_1$ µm | $\mathbf{A}_{eff}$ µm$^2$ | | $\gamma$ $(\mathbf{W}\cdot\mathbf{km})^{-1}$ | | $D$ ps/(km·nm) | | Loss dB/m | |
|---|---|---|---|---|---|---|---|---|
| | at 1.55 µm | at 1.31 µm | at 1.55 µm | at 1.31 µm | at 1.55 µm | at 1.31 µm | at 1.55 µm | at 1.31 µm |
| **0.295** | 4.423 | 3.599 | 39.485 | 57.409 | 2.324 | −15.316 | $0.490\times10^{-4}$ | $2.107\times10^{-7}$ |
| **0.315** | 4.254 | 3.475 | 41.049 | 59.463 | 1.414 | −12.188 | $0.518\times10^{-4}$ | $2.105\times10^{-7}$ |
| **0.335** | 4.096 | 3.359 | 42.634 | 61.509 | −0.280 | −8.1207 | $0.541\times10^{-4}$ | $2.051\times10^{-7}$ |
| **0.355** | 3.950 | 3.255 | 44.209 | 63.482 | 0.003 | −3.296 | $0.573\times10^{-4}$ | $2.018\times10^{-7}$ |
| **0.375** | 3.814 | 3.158 | 45.790 | 65.418 | 1.827 | 2.725 | $0.596\times10^{-4}$ | $1.962\times10^{-7}$ |
| **0.395** | 3.688 | 3.071 | 47.353 | 67.290 | 4.707 | 9.204 | $0.617\times10^{-4}$ | $1.882\times10^{-7}$ |
| **0.415** | 3.568 | 2.987 | 48.939 | 69.163 | 8.617 | 16.239 | $0.638\times10^{-4}$ | $1.797\times10^{-7}$ |

**Table 4.** The properties values based on variation of the first ring pitch ($\mathbf{\Lambda}_1$).

| $\mathbf{\Lambda}_1$ µm | $\mathbf{A}_{eff}$ µm$^2$ | | $\gamma$ $(\mathbf{W}\cdot\mathbf{km})^{-1}$ | | $D$ ps/(km·nm) | | Loss dB/m | |
|---|---|---|---|---|---|---|---|---|
| | at 1.55 µm | at 1.31 µm | at 1.55 µm | at 1.31 µm | at 1.55 µm | at 1.31 µm | at 1.55 µm | at 1.31 µm |
| 0.62 | 3.46 | 2.6838 | 50.45 | 76.9866 | −89 | −60.992 | $3.3\times10^{-4}$ | $1.0387\times10^{-7}$ |
| 0.67 | 3.67 | 2.9533 | 47.58 | 69.9625 | −35 | −23.907 | $1.19\times10^{-4}$ | $3.9757\times10^{-7}$ |
| 0.72 | 3.95 | 3.2547 | 44.208 | 63.4826 | 0.003 | 3.2955 | $0.55\times10^{-4}$ | $2.0266\times10^{-7}$ |
| 0.77 | 4.28 | 3.5769 | 40.8 | 57.7636 | 23 | 9.3144 | $0.33\times10^{-4}$ | $1.2576\times10^{-7}$ |
| 0.82 | 4.62 | 3.9036 | 37.8 | 52.9298 | 36 | 17.655 | $1.81\times10^{-4}$ | $0.9115\times10^{-7}$ |

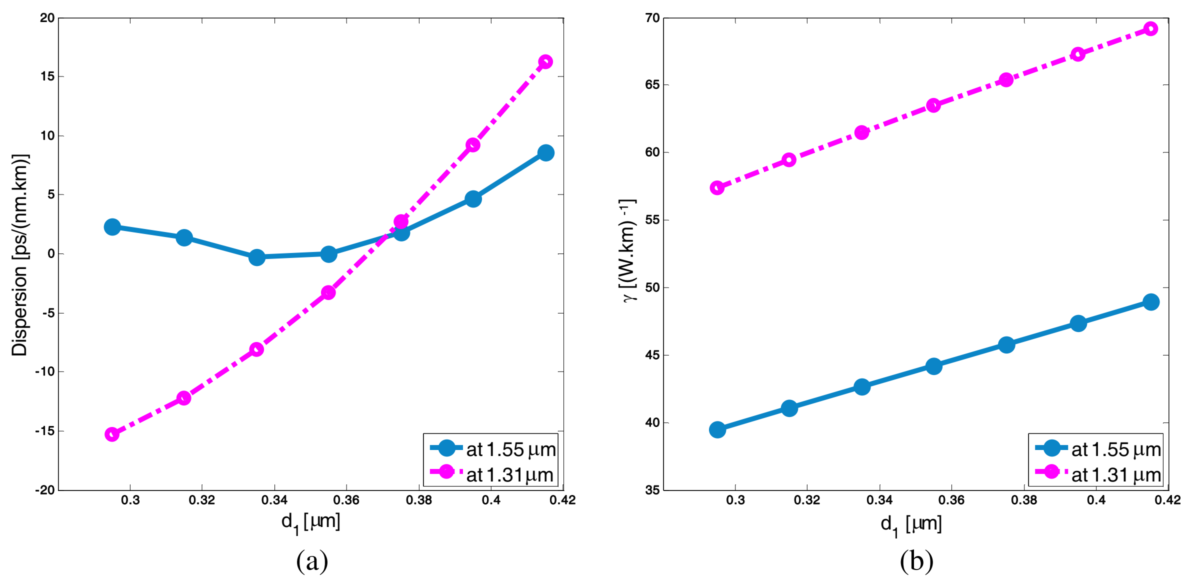



**Figure 3.** (a) The chromatic dispersion and (b) the nonlinear coefficient versus varying the first ring air holes diameter ($\mathbf{d}_1$) at 1.31 µm and 1.55 µm. The other parameters are based on Table 1.

have impact on its properties; however, these two parameters ($\mathbf{d}_1$, $\mathbf{\Lambda}_1$) are more influential. The impact of diameter of the first ring air holes ($\mathbf{d}_1$) and hole-to-hole spacing of the first ring air holes ($\mathbf{\Lambda}_1$) on fiber characteristics over 1.55 µm and 1.31 µm have been indicated in Table 3 and Table 4, respectively.

The chromatic dispersion and nonlinear coefficient have been calculated by increasing the first ring air-holes diameter $\mathbf{d}_1$ at 1.55 µm and 1.31 µm. The results have been illustrated in Figure 3. The changes

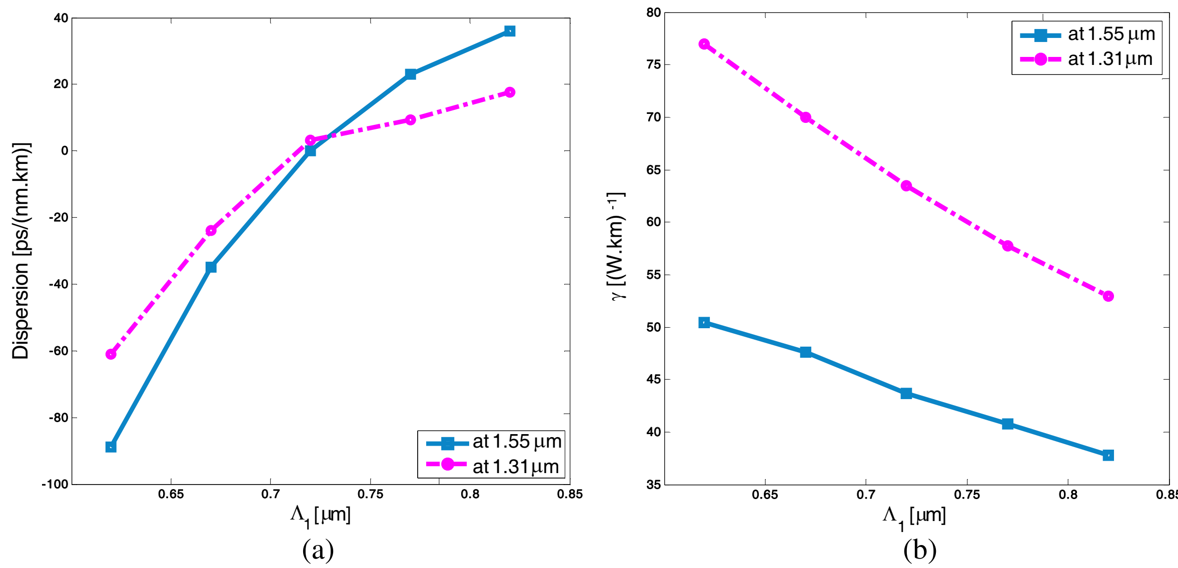



**Figure 4.** (a) The chromatic dispersion and (b) the nonlinear coefficient versus varying the first ring pitch ($\mathbf{\Lambda}_1$) at 1.31 μm and 1.55 μm. The other parameters are based on Table 1.

in dispersion based on the diameter of the first ring air holes at 1.31 μm and 1.55 μm wavelengths have been demonstrated in Figure 3(a). As shown in Figure 3(a), at 1.55 μm the dispersion coefficient is increased slightly by increasing the diameter of first ring. As obvious in Figure 3(a), the difference of these curves underlines significant characteristics between two wavelengths which point out the fact that the lower wavelength is more intensive to modifying the structural parameters. In fact, the structural parameters have been optimized for 1.55 μm. Therefore, the dispersion curve shows more stability than 1.31 μm. Figure 3(b) shows the change of nonlinearity as a function of diameter of the first ring air holes at 1.31 μm and 1.55 μm. It is clear in Figure 3(b) that the nonlinearity at 1.31 μm wavelength has higher value than 1.55 μm wavelength; nonetheless, the dispersion rises steadily. As depicted in Figure 3(b), the nonlinear coefficients of both wavelengths are increased by enlarging the first ring air-holes diameter. As a matter of fact, at a specific wavelength, the effective area decreases with increasing $\mathbf{d}_1$. So, the nonlinear coefficient increases. In other words, the light can be confined in a small area because of high refractive index, as a result of enlarging $\mathbf{d}_1$. Therefore, a smaller effective area and larger nonlinear coefficient can be achieved by enlarging the diameter of first ring air holes.

The variations of dispersion based on the alteration of the hole-to-hole spacing of the first ring air holes ($\Lambda_1$) at 1.31 μm and 1.55 μm have been illustrated in Figure 4(a). As the proportion of the hole-to-hole spacing of the first ring ($\Lambda_1$) increases, the dispersion is increased. By increasing hole-to-hole pitches of the first ring, the nonlinear coefficient is decreased, as illustrated in Figure 4(b). This is because of enlarging the effective area of confined mode into the core region, which is described before.

### 5.2. Comparison of DoDec-PCF and Octagonal and Decagonal Using Same Parameters

The proposed HN-DoDecPCF is compared with octagonal and decagonal PCFs using the same parameters. By comparing the properties of these three proposed fibers shown in Figure 5, it can be concluded that the dispersion slope of the proposed HN-DoDecPCF is flattened compared with octagonal and decagonal PCF, and its bandwidth is wider. Also, HN-DoDecPCF has lower confinement loss than the proposed octagonal and decagonal PCFs. As listed in Table 5, the effective mode area and nonlinearity have the same values for three PCFs. As mentioned before, it is expected that the dispersion slope becomes flattened by increasing the periodicity of the cladding arrangement. This is because of providing the same condition of propagation for different components of frequency of the pulse propagated in the core. Additionally, low confinement loss has been accomplished by increasing the periodicity of the cladding air holes, as a result of increasing air holes around the core and lowering refractive index around the core, so better confining of light in the core region.

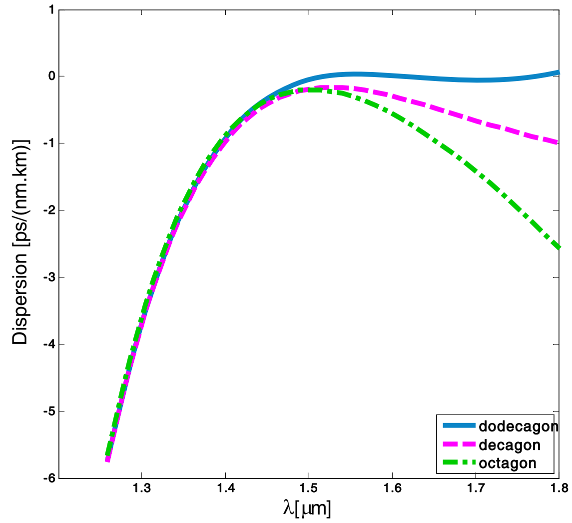



**Figure 5.** The comparison between dispersion of three PCFs.

**Table 5.** The properties of three proposed HN-PCFs at 1.55 m.

| | $\mathbf{A}_{eff}$ **(μm)$^2$** | $\gamma$ **(w · km)$^{-1}$** | $D$ **ps/(km · nm)** | **Loss dB/m** |
|---|---|---|---|---|
| Dodecagonal PCF | 3.89 | 43.66 | 0.003 | $0.55 \times 10^{-4}$ |
| Decagonal PCF | 3.93 | 44.43 | −0.2 | $2.41 \times 10^{-4}$ |
| Octagonal PCF | 3.95 | 44.21 | −0.3 | $4.5 \times 10^{-3}$ |

### 5.3. Comparison between an Optimum Octagonal and Proposed Dodecagonal PCFs

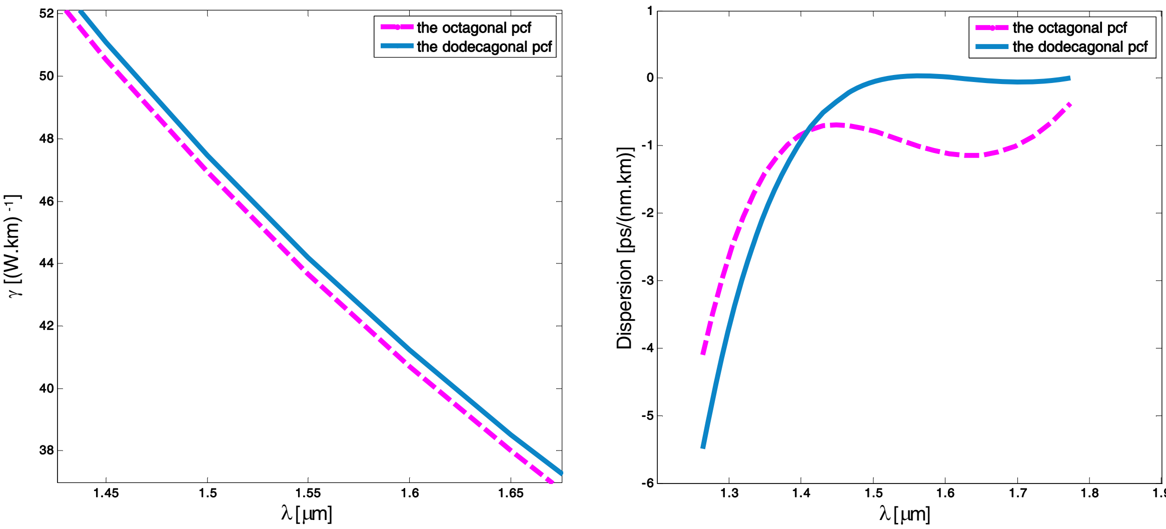
In this section, the properties of optimum octagonal fiber and dodecagonal fiber have been fully compared to indicate the superiority of the dodecagonal in terms of its nonlinearity and dispersion. Parameters of this octagonal fiber are described in Table 6, and its properties such as effective mode area ($A_{eff}$), nonlinearity, dispersion ($D$), and loss are listed in Table 7. As illustrated in Figure 6(a), not only is the difference of the nonlinearity in dodecagonal fiber a bit higher than octagonal fiber, but also is dispersion flat and ultimately zero in communication band width. Figure 6(b) shows that although the dispersion of octagonal fiber is flat and almost zero, dodecagonal fiber's dispersion is clearly superior in this term that in a vast band width it is utterly close to zero.

**Table 6.** The parameters of octagonal PCF.

| **Parameters** | **Diameters of air Holes (μm)** | | **Air hole Pitches (μm)** | | **Diameter of core (μm)** |
|---|---|---|---|---|---|
| **values** | $\mathbf{d}_1$ | **d** | $\mathbf{\Lambda}_1$ | $\mathbf{\Lambda}$ | |
| | 0.386 | 0.9 | 0.745 | 1.4 | 0.5 |

**Table 7.** The properties values based on variation of the first ring pitch ($\mathbf{\Lambda}_1$).

| **Structure** | $\mathbf{A}_{eff}$ **μm$^2$** | | $\gamma$ **(W · km)$^{-1}$** | | $D$ **ps/(km · nm)** | | **Loss dB/m** | |
|---|---|---|---|---|---|---|---|---|
| | **at 1.55 μm** | **at 1.31 μm** | **at 1.55 μm** | **at 1.31 μm** | **at 1.55 μm** | **at 1.31 μm** | **at 1.55 μm** | **at 1.31 μm** |
| **Octagonal PCF** | 3.98 | 3.28 | 43.88 | 65.87 | −0.96 | −2.3 | $14 \times 10^{-3}$ | $7\times10^{-6}$ |
| **Dodecagonal PCF** | 3.89 | 3 25472 | 43.67 | 63.48 | 0.003 | −3.65 | $0.55 \times 10^{-4}$ | $2.02 \times 10^{-7}$ |




(a) (b)

**Figure 6.** The comparison between (a) the nonlinearity and (b) the dispersion of the proposed dodecagonal PCF and the optimum octagonal PCF.

## 6. CONCLUSION

In this paper, a PCF with exclusively unique structure has been introduced, and neither its structure, which is dodecagon, nor its properties such as high nonlinearity and near-zero flattened dispersion have been worked on or considered before. This paper introduces the most important parameters in terms of its structure which has been attended to be minimized, therefor helps its easy fabrication. Furthermore, this dodecagonal fiber has high nonlinearity and near-zero flattened dispersion, which are desirable and have been described. Both of these characters intensely depend on the radius of the first ring air holes and the hole-to-hole spacing of the first ring air holes discussed in detailed. In addition, there has been a rigorous comparison among octagonal, decagonal and dodecagonal PCFs with the same parameters in which the superiority of the dodecagonal fiber has been shown. In the end, the properties of an optimum octagonal and the proposed dodecagonal PCFs were comparatively described, and this comparison includes nonlinearity and dispersion. It has been elaborately indicated that nonetheless there is this merit in dodecagonal HN-PCF that its dispersion is by far more desirable than octagonal HN-PCF which underlines its practicality.

## REFERENCES


1. Li, X., Z. Xu, W. Ling, and P. Liu, "Design of highly nonlinear photonic crystal fibers with flattened chromatic dispersion," *Appl. Opt.*, Vol. 53, 6682–6687, 2014.
2. Liao, J., J. Sun, Y. Qin, and M. Du, "Ultra-flattened chromatic dispersion and highly nonlinear photonic crystal fibers with ultralow confinement loss employing hybrid cladding," *Optical Fiber Technology*, Vol. 19, No. 5, 468–475, October 2013.
3. Su, W., S. Lou, H. Zou, and B. Han, "A highly nonlinear photonic quasi-crystal fiber with low confinement loss and flattened dispersion," *Optical Fiber Technology*, Vol. 20, No. 5, 473–477, October 2014.
4. Abdur Razzak, S. M. and Y. Namihira, "Proposal for highly nonlinear dispersion-flattened octagonal photonic crystal fibers," *IEEE Photonics Technology Letters*, Vol. 20, No. 4, February 15, 2008.
5. Zhang, A. and M. S. Demokan, "Broadband wavelength converter based on four-wave mixing in a highly nonlinear photonic crystal fiber," *Optics Letter*, Vol. 30, 2375–2377, 2005.

6. Nair, A. A., S. K. Sudheer, and M. Jayaraju, "Design and simulation of octagonal photonic crystal fiber for supercontinum generation," *Advanced in Optical Science and Engineering*, Chapter 25, Springer, India, 2015.
7. Yamamoto, T., H. Kubota, S. Kawanishi, M. Tanaka, and S. Yamaguchi, "Supercontinuum generation at 1:55 μm in a dispersion-flattened polarization maintaining photonic crystalfiber," *Opt. Express*, Vol. 11, 1537–1540, 2003.
8. Namihira, Y., J. Liu, T. Koga, F. Begum, Md. A. Hossein, N. Zou, S. F. Kaijage, Y. Hirako, H. Higa, and Md. A. Islam, "Design of highly nonlinear octagonal photonic crystal fiber with near-zero flattened dispersion at 1.31_m waveband," *Optical Rev.*, Vol. 18, No. 6, 436–440, 2011.
9. Finazzi, V., T. M. Monro, and D. J. Richardson, "Small-core holey fibers: Nonlinearity and confinement loss trade-offs," *J. Opt. Soc. Am. B*, Vol. 20, 1427–1436, 2003.
10. Bjarklev, A., J. Broeng, and A. S. Bjarklev, *Photonic Crystal Fiber*, Kluwer Academic Publisher, Boston, 2003.
11. Xu, H., J. Wu, K. Xu, Y. Dai, and J. Lin, "Highly nonlinear all-solid photonic crystal fibers with low dispersion slope," *Appl. Opt.*, Vol. 50, 5798–5802, 2011.
12. Olyaee, S. and F. Taghipour, "Ultra-flattened dispersion hexagonal photonic crystal fibre with low confinement loss and large effective area," *IET Optoelectron.*, Vol. 6, 82–87, 2012.
13. Zhang, Y. N., L. Y. Ren, Y. K. Gong, X. H. Li, L. R. Wang, and C. D. Sun, "Design and optimization of highly nonlinear low dispersion crystal fiber with high birefringence for four-wave mixing," *Appl. Opt.*, Vol. 49, 3208–3214, 2010.
14. Abdur Razzak, S. M., M. A. Goffar Khan, Y. Namihira, and M. Y. Hussain, "Optimum design of a dispersion managed photonic crystal fiber for nonlinear optics applications in telecom systems," *Proceedings of the Fifth International Conference on Electrical and Computer Engineering (ICECE)*, 570–573, 2008.
15. Saitoh, K., N. J. Florous, and M. Koshiba, "Ultra-flattened chromatic dispersion controllability using a defected-core photonic crystal fiber with low confinement losses," *Opt. Express*, Vol. 13, 8365–8371, 2005.
16. Tan, X., Y. Geng, Z. Tian, P. Wang, and J. Yao, "Study of ultraflattened dispersion square-lattice photonic crystal fiber with low confinement loss," *Optoelectron. Lett.*, Vol. 5, 124–127, 2009.
17. Abdur Razzak, S. M., Md. A. Goffar Khan, F. begum, and S. Kaijage, "Guiding properties of a decagonal photonic crystal fiber," *Journal of Microwaves and Optoelectronics*, Vol. 6, No. 1, 2007.
18. Abdur Razzak, S. M., F. Begum, S. Kaijage, and N. Zou, "Design of a decagonal photonic crystal fiber for ultra-flattened chromatic dispersion," *IEICE Trans. Electron.*, Vol. E90-C, No. 11, 2007.
19. Li, D.-M., G.-Y. Zhou, C.-M. Xia, C. Wang, and J.-H. Yuan, "Design on a highly birefringent and nonlinear photonic crystal fiber in the C waveband," *Chin. Phys. B*, Vol. 23, 044209, 2014.
20. Kim, J., "Design of nonlinear photonic crystal fibers with a double-cladded coaxial core for zero chromatic dispersion," *Appl. Opt.*, Vol. 51, 6896–6900, 2012.
21. Poletti, F., V. Finazzi, T. M. Monro, N. G. R. Broderick, V. Tse, and D. J. Richardson, "Inverse design and fabrication tolerances of ultra-flattened dispersion holey fibers," *Optics Express*, Vol. 13, No. 10, 3728, 2005.