Novel design of highly nonlinear photonic crystal fibers with flattened dispersion*

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Novel highly nonlinear photonic crystal fibers (HN-PCFs) with flattened dispersion are proposed by omitting 19 air holes as the fiber core. The simulation results show that the high nonlinearity and the flattened dispersion can be achieved simultaneously by employing only two types of air holes in the cladding. To reduce the confinement loss, the modified designs are presented. The confinement loss is below 0.1 dB/km at 1.55 μm, when seven layers of air-hole rings are introduced to the cladding. After modifying, the dispersion can change from -0.5 ps/(nm • km) to +0.5 ps/(nm • km) in the range from 1.35 μm to 2.06 μm, and the effective mode area is as low as 2.27 μm^2 at 1.55 μm.

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Photonic crystal fiber (PCF)[1,2] as a new kind of optical fiber has lots of intriguing properties which are hardly achievable in conventional fiber. Highly nonlinear dispersion-flattened PCFs are suitable for such applications as wavelength conversion[3], supercontinuum generation[4,5], and so on. However, the tradeoff between high nonlinearity and flattened dispersion requires that the flexibility of fiber design has to be enhanced. By employing different types of air holes, HN-PCFs with flattened dispersion have been achieved[6-8]. However, it is a difficult task to design HN-PCFs and prepare fiber performs with so many structural parameters. By adding a small air hole in the core, high nonlinearity and flattened dispersion can be achieved when using only two types of air holes[9]. However, the mode profile is not Gaussian type any longer. Besides pure silica and hexagonal arrangement of air holes, HN-PCFs with flattened dispersion can also be achieved by doping the core[10], adding extra air holes in hexagonal cladding lattice[11] or employing octagonal structures[12,13]. In those studies, either the merit of single material is lost or the preparation of fiber perform is very difficult.

In this paper, novel HN-PCFs with flattened dispersion are proposed by omitting 19 air holes as the fiber core. By employing only two types of air holes in the cladding, flattened dispersion in telecommunication window and the effective mode area $A_{\rm eff}$ of less than 3 μm^2 at 1.55 μm can be achieved simultaneously. To further reduce the confinement loss, modified designs are also presented. Confinement loss of below 0.1 dB/km at 1.55 μm can be achieved with seven layers of air-hole rings, while effective nonlinearity is nearly unchanged. To the best of my knowledge, the dispersion-flattened HN-PCFs which omit multiple air holes as the core are novel and have not previously been explored.

Fig.1 shows the cross sections of the proposed HN-PCFs with ten layers of hexagonal arranged air holes. Different from traditional HN-PCFs, the core of our design is formed by omitting 19 air holes instead of one. The hole to hole pitch is labeled as Λ, and the air-hole diameters of the inner and outer layers are labeled as d_1 and d_2, respectively. For three designs of PCF1, 2 and 3, the numbers of inner air-hole layers $N_{\rm in}$ are 2, 3 and 4, respectively.

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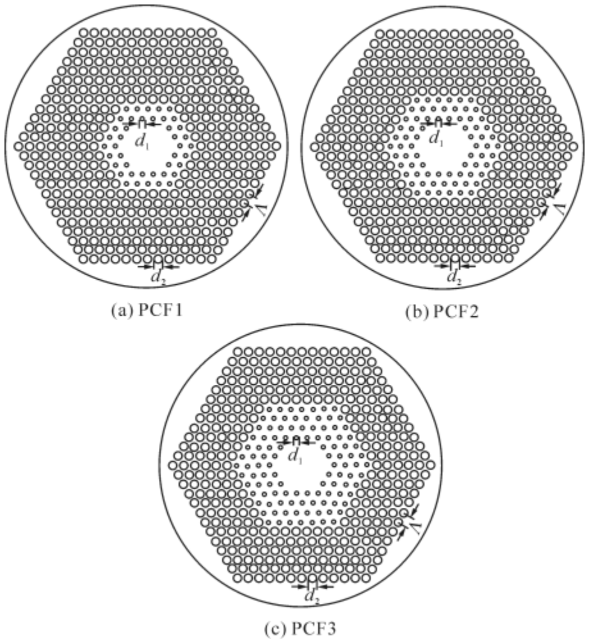


Fig.1 Cross sections of the proposed HN-PCFs with two types of air holes and ten layers of air-hole rings

As mentioned above, the three models are different from each other only because of the number of inner and outer air-hole layers. If d_1 equals d_2, those models can not be distinguished. Thus, we start our analysis with a specific model with $d_1/\Lambda=d_2/\Lambda=0.5$. The impacts of air-hole pitch on the dispersion of PCF1, 2 and 3 are investigated in Fig.2. Seen from Fig.2, the slopes of the dispersion curves are negative at most of the concerned wavelength range. With the increase of Λ, dispersion curves rise as a whole while the slopes in the linear region are almost the same. Therefore, Λ is mainly for tailoring the magnitude rather than changing the slope of the dispersion curve.

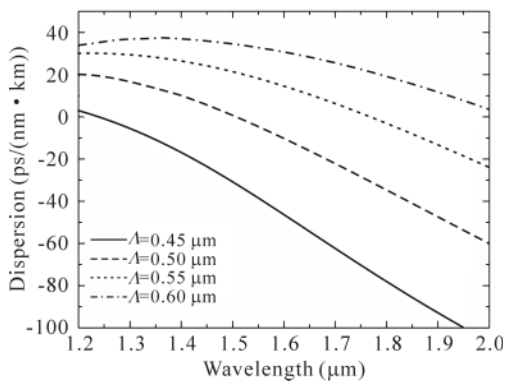


Fig. 2 Dispersion of PCFs with $d_1/\Lambda= d_2/\Lambda$=0.5 and different Λ values

Next, we set Λ=0.5 μm and d_2/Λ=0.5, and d_1/Λ varies from 0.3 to 0.6 at a step of 0.1. The effects of inner air holes on dispersions of PCF1, 2 and 3 are all depicted in Fig.3 for comparison. In Fig.3, we can see that the change of d_1/Λ has similar impact on PCF1, 2 and 3. With the increase of d_1/Λ, the dispersion increases at shorter wavelength while decreases at longer wavelength. Because the air holes investigated here are in the inner cladding, their influence on dispersion is strong. However, from Fig.3, we can not state that the influence of inner air holes on the dispersion of PCF3 is stronger than that on PCF1 and 2, though PCF3 contains more layers of inner rings.

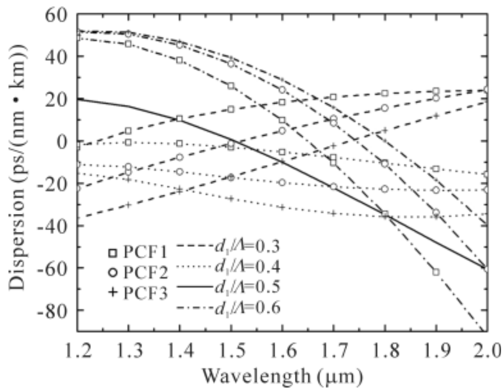


Fig.3 Dispersion of PCFs with Λ=0.5 μm, d_2/Λ=0.5 and different d_1/Λ of 0.3, 0.4, 0.5 and 0.6

Then, d_2/Λ is changed from 0.4 to 0.7 at a step of 0.1while keeping Λ=0.5 μm and d_1/Λ=0.5. From Fig.4, we can see that for all three models, the dispersion slopes get larger negative values when the outer air holes are smaller. With the increase of d_2/Λ, the dispersion curves become flatter. Also, the change of d_2/Λ imposes stronger impacts on the dispersion of PCF1 than on that of PCF2 and 3 due to there are more outer air-hole layers in PCF1. Larger air holes in cladding are in favor of loss reduction, and flattened dispersion and low loss can be achieved simultaneously.

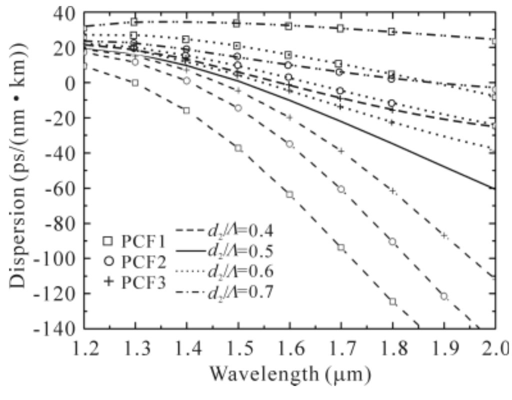


Fig.4 Dispersion of PCFs with Λ=0.5 μm, d_1/Λ=0.5 and different d_2/Λ of 0.4, 0.5, 0.6 and 0.7

The structural parameters of the three HN-PCFs with flattened dispersion are given in Tab.1. We can see that the air-hole pitch of PCF1 is the smallest of the three, and its A_{eff}=2.27 μm^2 at 1.55 μm is also the lowest. However, its confinement loss of 0.82 dB/m at 1.55 μm is much higher than that of the other two designs. In most fiber-based nonlinear applications, only tens of centimeters of fiber length is sufficient if the fiber possesses such a high nonlinearity. This level of confinement loss is low enough for most of nonlinear applications. For PCF2 and 3, the confinement losses are much lower, while their effective mode areas also increase. PCF3 has the lowest confinement loss of 0.4 dB/km and the largest A_{eff}= 3.63 μm^2 at 1.55 μm. The bandwidth of flattened dispersion for PCF1 is much narrower compared with that of PCF2 and 3. It is more obviously observed in Fig.5 that for PCF2 and 3, the dispersion curves are shaped like letter "N", while the dispersion curve of PCF1 has the shape of a quadratic curve.

Tab.1 Structural parameters and optical properties of the designed HN-PCFs

	Λ(μm)	d_1/Ë	d_2/Ë	Dispersion (ps/(nm•km))	Wavelength range (μm)	A_{eff} (μm^2) at 1550 nm	Confinement loss (dB/km) at 1550 nm
PCF1	0.42	0.41	0.60	-0.7−0.6	1.32−1.66	2.27	8.2 × 10^2
PCF2	0.52	0.41	0.61	-0.1−0.75	1.21−1.74	2.98	11
PCF3	0.58	0.38	0.68	-0.8−0.67	1.2−1.78	3.63	0.4

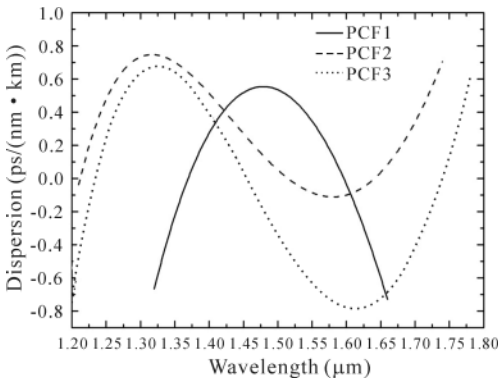


Fig.5 Dispersions of the designed PCFs with the parameters in Tab.1

Due to the small air-hole pitch, more than ten layers of air-hole rings are needed to make sure the confinement loss less than 0.1 dB/km at 1.55 μm for the HN-PCFs designed above. To enhance the confinement ability, modified designs are proposed. First, keep all the structural parameters of the original model while reducing the number of air-hole layers. To achieve this goal, five layers of air holes are reserved. Then, a cladding with two layers of large air holes is added outside the five-ring cladding. The cross sections of modified HN-PCFs are shown in Fig.6. The air-hole pitch and diameter of the extra cladding are labeled as Λ_{ext} and d_{ext} , respectively.

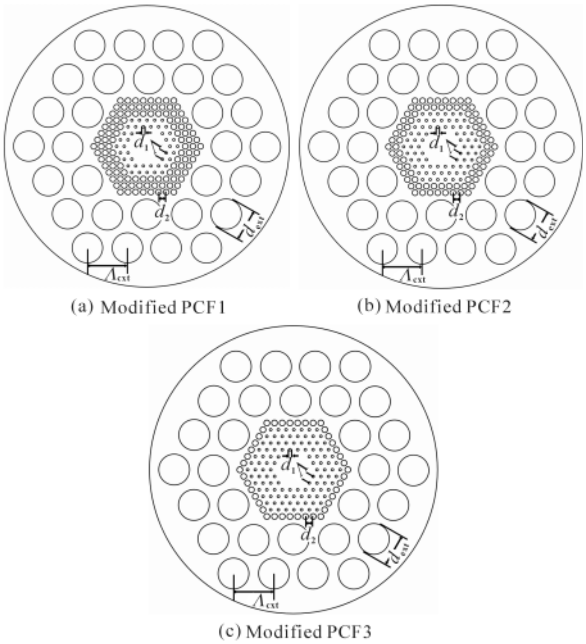


Fig.6 Cross sections of the modified design of HN-PCFs with two layers of large air holes added outside the original design model with five layers of air-hole rings

Tab.2 shows the structural parameters of the modified HN-PCFs, and the dispersions as a function of wavelength are shown in Fig.7. Compared with the HN-PCFs in Tab.1, the confinement losses of the modified designs have been reduced tremendously. The confinement loss of modified PCF1 is reduced to 7.7×10^{-2} dB/km at 1.55 μm. The effective mode areas, which are mainly related to core diameter and inner air-hole rings, are still the same. From Fig.7, we can see that compared with Fig.6, the dispersion of modified PCF1 varies from -0.5 ps/(nm•km) to + 0.5 ps/(nm•km) in the range from 1.35 μm to 2.06 μm, and its shape changes from a quadratic curve to letter "N". For modified PCF3, the dispersion has little change in the wavelength band.

The effects of d_{ext} and Λ_{ext} on the dispersions are investigated in Figs.8 and 9. For modified PCF3, d_{ext} increased or Λ_{ext} reduced by 5% would result in the intersection of air

Tab.2 Structural parameters and optical properties of the modified HN-PCFs

	$Ë_{ext}$ (im)	d_{ext} /$Ë_{ext}$	Dispersion (ps/(nm•km))	Wavelength range (im)	A_{eff} (im^2) at 1550 nm	Confinement loss (dB/km) at 1550 nm
Modified PCF1	1.35	0.95	-0.5−0.5	1.35−2.06	2.27	7.7×10^{-2}
Modified PCF2	1.60	0.8	-0.15−0.75	1.21−1.74	2.98	4.8×10^{-2}
Modified PCF3	1.70	0.8	-0.8−0.67	1.2−1.78	3.63	1.5×10^{-2}

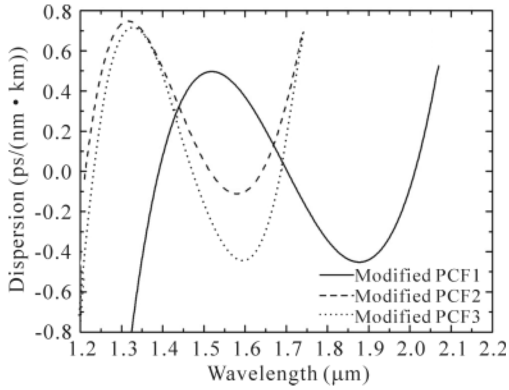
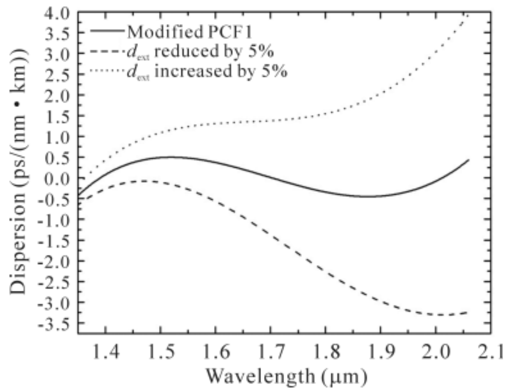


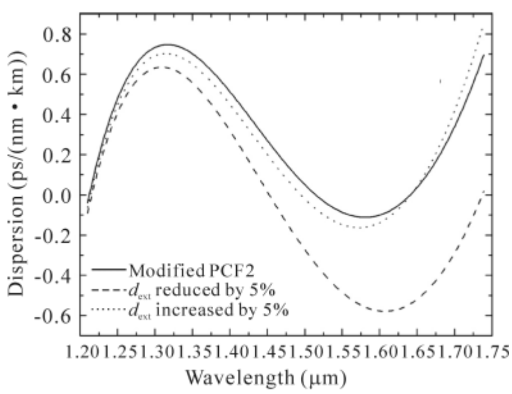
Fig.7 Dispersions of modified PCFs with the parameters in Tab.2

holes, so only the condition with d_{ext} reduced and Λ_{ext} increased by 5% is investigated in Fig.8(c) and Fig.9(c), respectively. From Figs.8 and 9, we can conclude that the dispersion is more sensitive to the change of Λ_{ext} than the change of d_{ext}. For modified PCF1, the flatness of dispersion is more susceptible to the structural deformation. A small deformation in extra cladding can deteriorate the flatness of the dispersion greatly as shown in Fig.8(a) and Fig.9(a). Though its nonlinearity is the highest and the bandwidth of flattened dispersion is the widest of the three, more effort is needed to realize it.

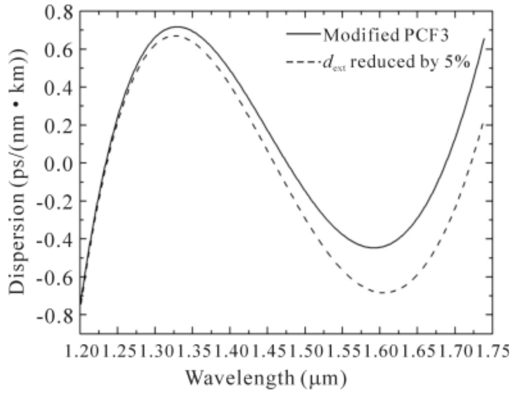
In summary, three HN-PCFs with flattened dispersion



(a) Modified PCF1 with different d_{ext} values

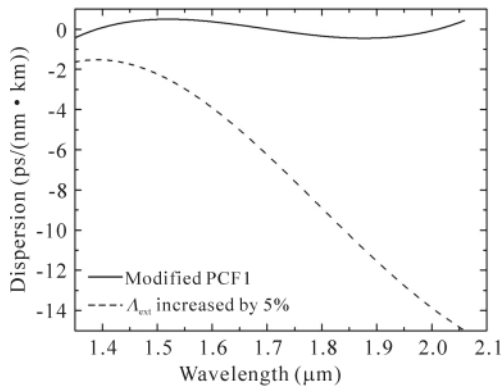


(b) Modified PCF2 with different d_{ext} values

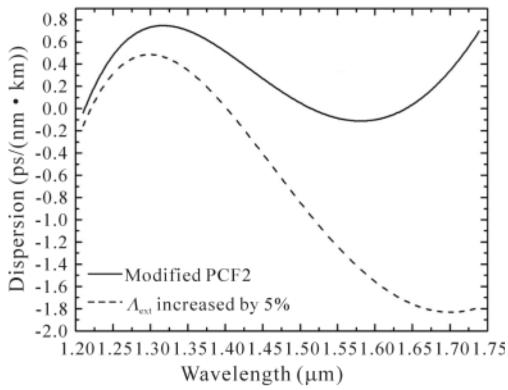


(c) Modified PCF3 with different d_{ext} values

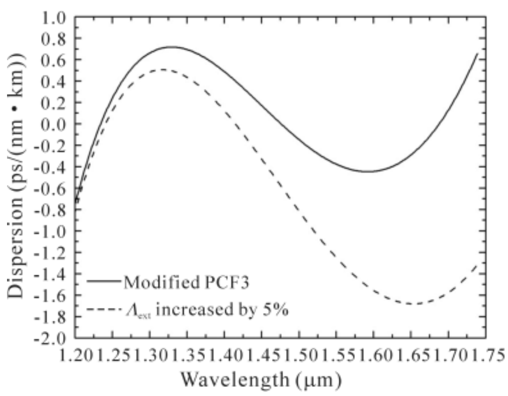
Fig.8 Dispersions of modified PCFs with different d_{ext} values



(a) Modified PCF1 with different Λ_{ext} values



(b) Modified PCF2 with different Λ_{ext} values



(c) Modified PCF3 with different Λ_{ext} values

Fig.9 Dispersions of modified PCFs with different Λ_{ext} values

have been designed by omitting 19 air holes as the core and employing only two types of air holes in the cladding. For PCF2, the dispersion fluctuates from -0.1 ps/(nm•km) to +0.75 ps/(nm•km) in the range from 1.21 μm to 1.74 μm, and its A_{eff} is as low as 2.98 μm^2 at 1.55 μm. To further reduce the confinement loss, modified designs are also investigated. The confinement loss can be reduced to below 0.1 dB/km at 1.55 μm with seven layers of air-hole rings, while the effective mode areas still get the same value. For modified PCF1, the dispersion changes from -0.5 ps/(nm•km) to +0.5 ps/(nm•km) in the range from 1.35 μm to 2.06 μm, and A_{eff} is as low as 2.27 μm^2 at 1.55 μm. To the best of my knowledge, the design of dispersion-flattened HN-PCFs by omitting multiple air holes as the core has not previously been explored. These novel PCFs with high nonlinearity, nearly zero and flattened dispersion are suitable for such applications as optical parametric amplification, wavelength conversion, ultra-short soliton pulse transmission and supercontinuum generation.

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