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Influence of interstitial air holes in index-guiding photonic crystal fibers on their basic properties

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ABSTRACT The modal properties of index-guiding photonic crystal fibers (IGPCFs) with and without interstitial air holes (IAHs) are numerically investigated by the multipole method. It is shown that the IAHs can favorably decrease the confinement loss and the effective mode area of IGPCFs, and simultaneously increase the nonlinear coefficient in the IGPCFs. In addition, at the same air hole diameter d and pitch Λ, IGPCFs with IAHs can shift the position of the zero-dispersion wavelengths to the shorter wavelengths and make the group-velocity dispersion more flattened in the region of anomalous dispersion. By comparing the optical properties of the PCFs in the presence/absence of IAHs and at the same air-filling fractions, it is shown that the change in the optical properties induced by the presence of IAHs is different from those achieved by a simple increase of the air-filling fraction, a result attributed to stronger scattering by IAHs.

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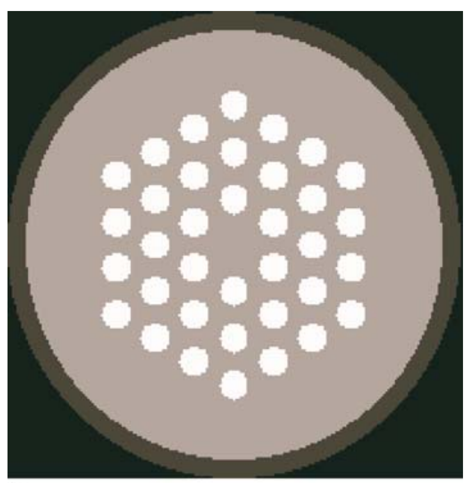
1 Introduction

In recent years, photonic crystal fibers (PCFs) have attracted significant attention because of their unusual optical properties and their great potential for important applications [1–3]. A PCF consists of a fused silica core surrounded by an ordered array of cylindrical air holes running along its length. The air holes form a low-index cladding around the solid core in which the light is guided by modified total internal reflection, and therefore these typical fibers are often referred to as index-guiding photonic crystal fibers (IGPCFs) [1]. IGPCFs exhibit many unusual properties such as endlessly single mode [4], highly tunable dispersion [5], and easily controllable effective mode area [6] for linear [7] and nonlinear [8, 9] applications and so on.

It was often found in the fabrication process for PCFs that interstitial air holes (IAHs) might be produced from the common stack-and-draw process [10–12]. There have been reports on the influence of these IAHs on the photonic bandgap (PBG) properties of PCFs. J. Broeng et al. have proposed a new design of photonic crystal fibers based on the modified triangular and hexagonal structure [13]. Yanfeng Li et al. have studied honeycomb photonic bandgap fibers (HPBFs) with and without interstitial air holes [14]. It is found that the bandgap width of HPBFs is enlarged by the IAHs and that at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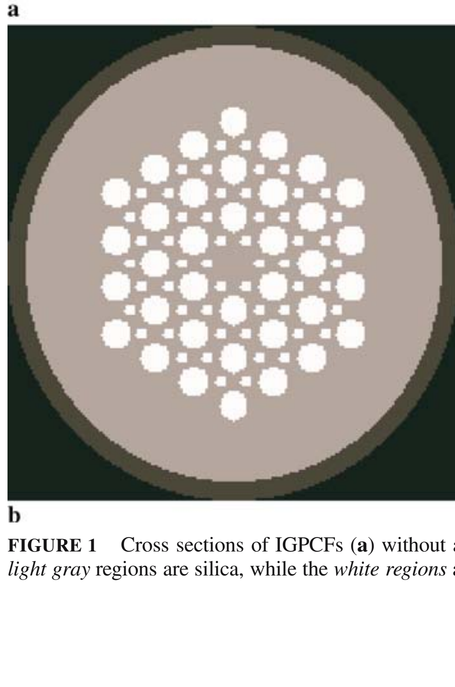
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FIGURE 1 Cross sections of IGPCFs (**a**) without and (**b**) with IAHs. The *light gray* regions are silica, while the *white regions* are air

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the same moderate air-filling fraction HPBFs with IAHs can shift the position of the largest PBGs and produce more uniform PBGs in comparison with HPBFs without IAHs. Similarly, one can expect that the basic properties of IGPCFs can be influenced by the interstitial air holes, which often remain in the fiber cladding after drawing. From a manufacturing point of view, it is very important to learn the extent to which these IAHs can affect the basic modal properties of IGPCFs such as mode area, confinement loss, nonlinear coefficient, and dispersion.

Cross sections of IGPCFs with and without IAHs are schematically shown in Fig. 1. The light gray regions are silica, while the white regions are air. The cross section of IGPCFs without IAHs is schematically shown in Fig. 1a, and that of IGPCFs with IAHs is schematically shown in Fig. 1b. The interstitial air holes are located at midpoint between three nearest holes in the triangular lattice (see Fig. 1b) and are caused by the stacking and drawing fabrication technique used for PCFs. These interstitial air holes cause a modification of the triangular crystal lattice of the cladding.

In this paper, we have numerically studied the basic properties of IGPCFs with and without IAHs by the multipole method [15, 16]. The IAHs were shown to favorably decrease the confinement loss and the effective mode area of IGPCFs, and simultaneously increase the nonlinear coefficient in the IGPCFs. In addition, at the same air hole diameter d and pitch Λ, IGPCFs with IAHs can shift the position of the zero-dispersion wavelengths to the shorter wavelengths and generate more flattened group-velocity dispersion in the region of anomalous dispersion.

2 Numerical results and discussion

In this paper, we have simulated the mode field, confinement loss, effective mode area, nonlinear coefficient and the chromatic dispersion of IGPCFs with and without IAHs using the multipole method [15, 16]. The multipole method yields both the real and the imaginary parts of the mode propagation constant; the former being associated with the dispersion of PCFs, and the latter giving the confinement loss associated with the finite extent of the MOF's set of confining inclusions. In the numerical simulation, we use CUDOS MOF UTILITIES software, which was programmed by B.T. Kuhlmey of the University of Sydney [15, 16].

In the numerical simulation, we adopt the lattice pitch $\Lambda = 2.5\,\mu$m, the diameters of IAHs $d_1 = 0.5\,\mu$m, while the ratios of air hole diameter to pitch d/Λ are 0.5, 0.6, 0.7 and 0.8, respectively. To clarify whether the change in the optical properties in the presence of interstitial holes is due to simply change in air-filling fraction or not, the optical properties of the PCF without interstitial holes but having the same air-filling fraction as the PCF with interstitial holes have been simulated. Accordingly, the ratios of air hole diameter to pitch d/Λ are 0.57, 0.66, 0.75 and 0.84, respectively.

We first compute the light intensity distributions for a fundamental mode in two PCF structures with the same lattice pitch $\Lambda = 2.5\,\mu$m and the same $d/\Lambda = 0.6$, and the wavelength λ equal to $1.55\,\mu$m. The mode field diagram is given in Fig. 2 for a PCF without (a) and with (b) IAHs, where the diameter d_1 of IAHs is $0.5\,\mu$m. As shown in Fig. 2, the mode field in IGPCFs with IAHs is more localized in the fiber core than in IGPCFs without IAHs.

Figure 3 shows the confinement loss L of IGPCFs as a function of wavelength λ. In Fig. 3, those curves with sign J denote the results of PCFs with IAHs, namely $d/\Lambda = 0.5$,J denotes the result of PCFs with IAHs, while $d/\Lambda = 0.5$ denotes the result of PCFs without IAHs, and the $d/\Lambda = 0.57$ denotes the result of PCFs without IAHs but having the same air-filling fraction with $d/\Lambda = 0.5$,J, and the same applies to Figs. 4–7. From Fig. 3 we can observe that the IAHs could favorably decrease the confinement loss in IGPCFs, especially for the structures with lower d/Λ or in the region of the shorter wavelengths.

In Figs. 4 and 5 we illustrate the effective mode area S and the nonlinear coefficient γ as a function of wavelength λ, respectively. Similarly, IGPCFs with IAHs result in the smaller effective mode area and the increased nonlinear coefficient. At the same air-filling fraction the effective mode area of IGPCFs with IAHs is smaller than IGPCFs without IAHs.

In Fig. 6 we have illustrated the chromatic dispersion D of IGPCFs as a function of wavelength λ. Figure 6b shows a magnified view of a part of the curves in Fig. 6a. From Fig. 6a, it can be realized that IAHs make group-velocity dispersion more flattened in the region of anomalous disper-

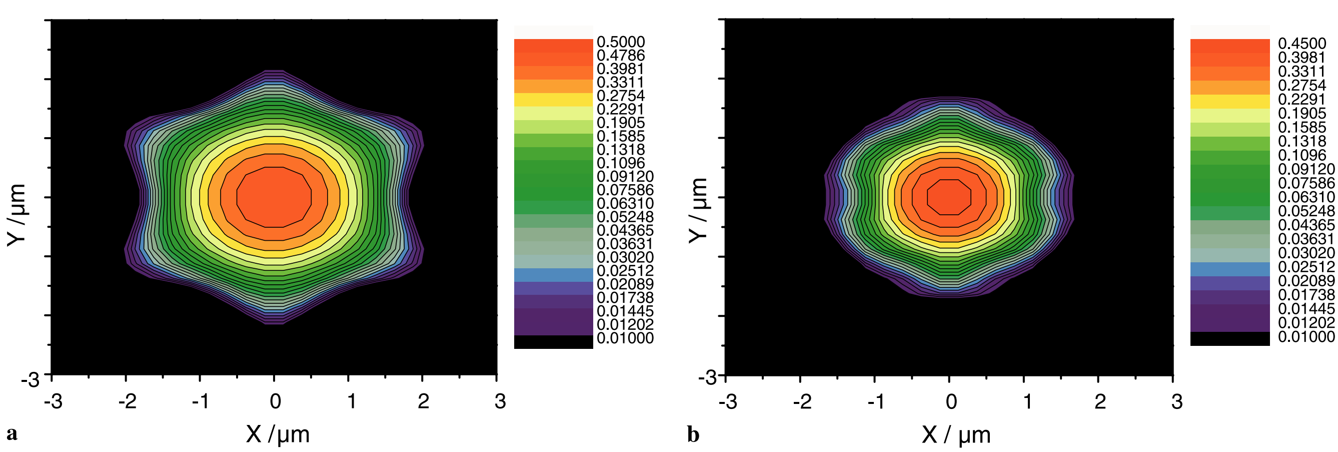

FIGURE 2 Light intensity distributions for a fundamental mode in two PCF structures with the same lattice pitch $\Lambda = 2.5\,\mu$m and the same $d/\Lambda = 0.6$, and the wavelength equal to $\lambda = 1.55\,\mu$m: (**a**) without and (**b**) with IAHs. The diameters d_1 of IAHs is $0.5\,\mu$m

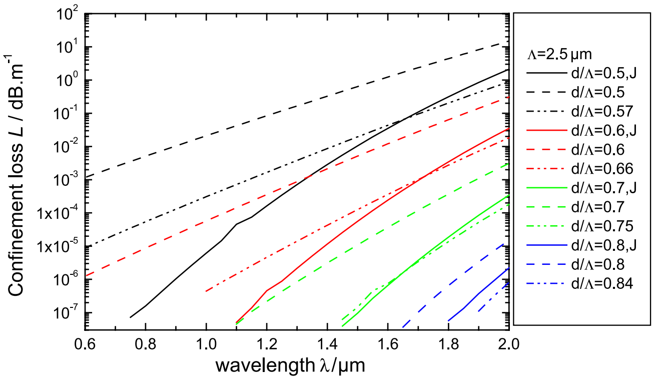

FIGURE 3 The confinement loss L of IGPCFs as a function of wavelength λ

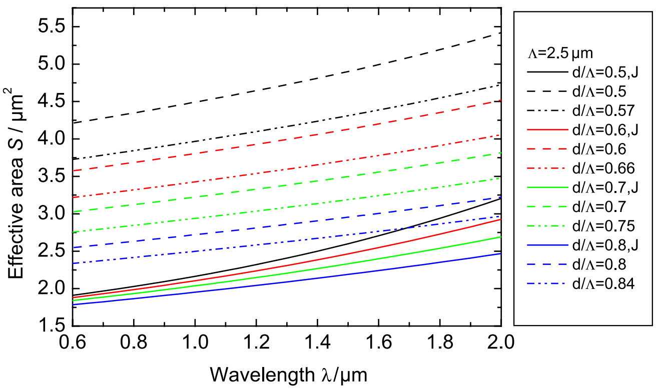

FIGURE 4 The effective mode area S of IGPCFs as a function of wavelength λ

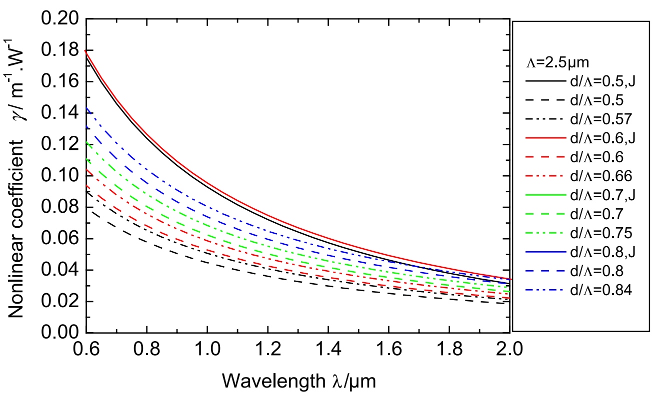

FIGURE 5 The nonlinear coefficient γ of IGPCF as a function of wavelength λ

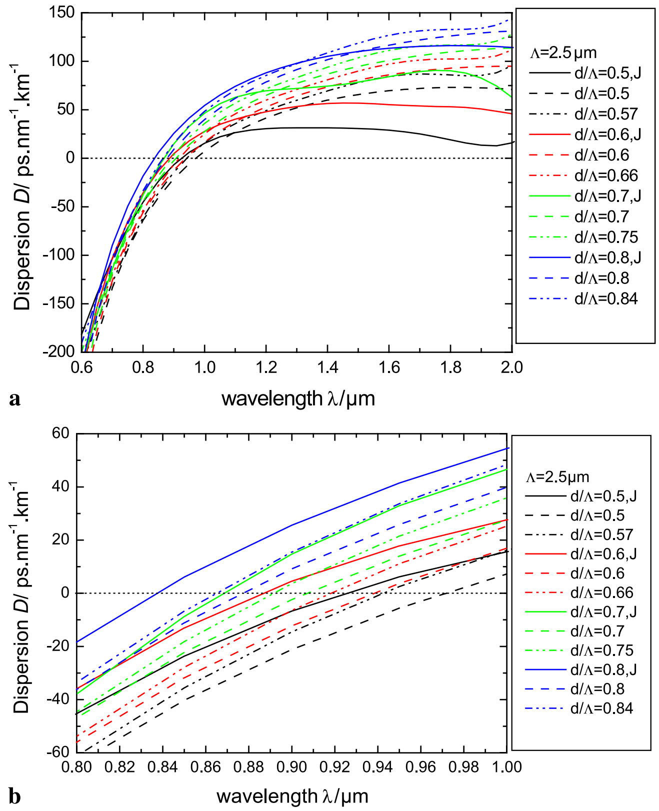

FIGURE 6 The dispersion D of IGPCFs as a function of wavelength λ. (**b**) shows a magnified view of a section of the curves in (**a**)

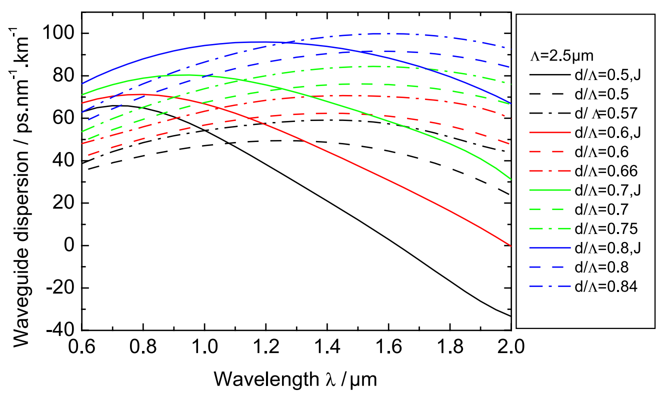

FIGURE 7 The waveguide dispersion of IGPCFs as a function of wavelength λ

sion. The issue of designing PCFs with flattened dispersion has been addressed both theoretically [17, 18] and experimentally [19]. What is different here is that the flattened dispersion is just induced by the addition of IAHs, not by tuning the diameter d of the air holes. As can be seen, the dispersions differ a lot in PCFs with and without IAHs but at the same air-filling fractions. This shows that the role of IAHs is not the same as simply increasing the air-filling fraction. Figure 6b shows that the position of the zero-dispersion wavelengths in the IGPCFs with IAHs can be shifted to shorter wavelengths than that of IGPCFs without IAHs. Even if at the same air-filling fractions the zero-dispersion wavelengths of the IGPCFs with IAHs are smaller than the IGPCFs without IAHs.

The above results can be explained qualitatively as follows [20, 21]: The light field backscattered from the PCFs cladding air holes is generally spatially coherent and the presence of a large number of IAHs increases the interference intensity of multiple scattering, which further increases the confinement of the light propagated in the fiber core, as in Figs. 2 and 3, where stronger mode confinement is clearly seen. According to the equation $\gamma \propto 1/S$, the decrease in effective mode area S results in the increased nonlinear coefficient γ, as demonstrated in Figs. 4 and 5. This can also be understood by noting that the IAHs are located in such a way that the leakage of light through the silica bridges between the regular air holes is effectively blocked. In terms of influence on the dispersion, the role of the IAHs is larger and more significant than simply increasing the total air-filling fraction, as we illustrate in Fig. 7, where we show that the the waveguide dispersion is modified by the IAHs. Thus, it can be seen that due to the strongly modified waveguide dispersion, the total dispersion can be altered as shown in Fig. 6.

3 Conclusion

We have numerically investigated the basic properties of index-guiding photonic crystal fibers with and without interstitial air holes by the multipole method. The interstitial air holes were shown to favorably decrease the confinement loss and the effective mode area of IGPCFs while simultaneously increasing the nonlinear coefficient in the IGPCFs. On the other hand, the IAHs can beneficially make the group-velocity dispersion more flattened in the region of anomalous dispersion, even though at the same air-filling fraction the zero-dispersion wavelengths of the IGPCFs with IAHs are smaller than the IGPCFs without IAHs. The interstitial air holes were shown to have an important impact on the basic properties of index-guiding photonic crystal fibers.

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