

# Impact of interstitial air holes on a wide-bandwidth rejection filter made from a photonic crystal fiber

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We have investigated the spectral properties of a band rejection filter made with a long-period fiber grating written in photonic crystal fiber that has interstitial air holes. Experiments showed that only one mode was coupled strongly to the fundamental core mode over a 600 nm spectral range. The central wavelength of the filter could be tuned over that range without being appreciably affected by any other mode. By using the multipole method, we found that the interstitial air holes of the photonic crystal fiber played a critical role in limiting the number of modes that could strongly interact with the fundamental mode and in obtaining well-separated resonance peaks. Excellent agreement between theory and experiment was obtained.

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Photonic crystal fibers (PCFs) have unique characteristics and controllable features that make them attractive in a number of applications.<sup>1–5</sup> A fiber coupler<sup>1</sup> and a long-period fiber grating<sup>2–4</sup> (LPG) are typical examples. LPGs have been studied mainly as gain-flattening filters<sup>5</sup> for an optical fiber amplifier, and this application extends to the field of optical coherence tomography.<sup>6</sup> Recently, we reported a LPG that was made with a solid-core PCF,<sup>7</sup> and we experimentally observed that only one strong LPG resonance peak was present over a 600 nm wide spectral range. We also observed that the resonance wavelength moved in the short-wavelength direction (exhibited a blueshift) as the grating periodicity increased. Petrovic *et al.*<sup>8</sup> observed the same blueshift with a LPG written in a commercial PCF. However, the cladding modes that they had suggested were involved in the mode coupling had a small amount of their power in the solid-core region. In general, a small amount of power in the core region implies a small overlap integral with the core mode, which makes it difficult to understand the strong resonant peaks of the LPG written in the PCF.

To understand the unusual spectral properties of the LPG written in PCF, we have carried out a theoretical analysis using the multipole method,<sup>9</sup> and in this Letter we report this analysis. We found that the interstitial air holes (ISAs) of the home-made PCF used for the experiment had to be included in the analysis to explain the presence of the strong and well-isolated resonant peak of the LPG written in the PCF. The theoretical analysis agrees well with the earlier experimental results,<sup>7</sup> within a 2% experimental margin of error when the ISAs are included.

The PCF used for the experiment<sup>7</sup> and modeled for theoretical analysis was fabricated with the stack-and-draw method.<sup>1</sup> The PCF had four layers of air holes and three layers of ISAs positioned among the

major air holes, as shown in the inset of Fig. 1. Due to our fabrication process, the holes in each layer had different sizes. The distance between the nearest-neighbor major air holes,  $\Lambda$ , was  $9.8 \pm 0.1 \mu\text{m}$ , and the air-filling factors, which were the ratios of the diameter of hole  $d$  to  $\Lambda$ ,  $d/\Lambda$ , for each layer were approximately 0.36, 0.35, 0.26, and 0.11 from inside to outside. The air-filling factors of the three ISA layers were approximately 0.08, 0.06, and 0.06 from inside to outside also. One of the ISAs in the innermost layer was absent because it was collapsed during the fabrication process. The outer shape of the PCF was almost hexagonal, and the average outer diameter was  $116 \mu\text{m}$ . The fiber was composed of fused silica glass (GE214) and was coated with a polymer that had a refractive index of 1.57. Figure 2 is a schematic of the PCF that is simplified for numerical analysis. The arrow in the figure indicates the absent ISA.

A LPG was formed by applying a periodic pattern of mechanical pressure on a side of the polymer-coated PCF that was placed between a grooved plate and a flat metal plate. The periodicity of the grating was adjusted by rotating the grooved plate. The

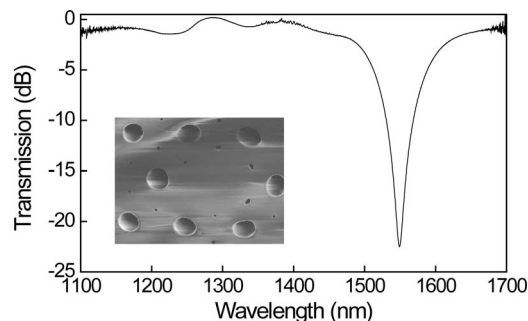


Fig. 1. Transmission spectrum of a LPG written in a PCF. The inset is a scanning electron microscope photograph.

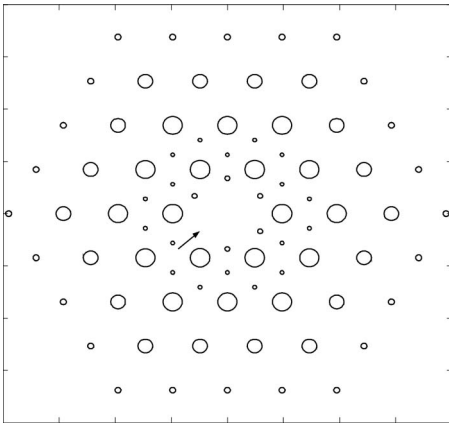


Fig. 2. Numerical model of the air-hole geometry. There are four major layers of air holes and three ISA layers. Additionally, there is one missing ISA, as indicated by the arrow.

phase-matching condition is well known as  $[n_{\text{eff}}^{(f)}(\lambda) - n_{\text{eff}}^{(m)}(\lambda)]\Lambda_g = \lambda$ , where  $\Lambda_g$  is the grating period and  $n_{\text{eff}}^{(f)}(\lambda)$  and  $n_{\text{eff}}^{(m)}(\lambda)$  are the effective indices of the fundamental core mode and the  $m$ th-order (cladding) mode, respectively. Generally, the effective index of a waveguide depends on wavelength  $\lambda$ . Figure 1 shows one of the measured transmission spectra of the LPG written in the home-made PCF, centered near 1550 nm. It shows that there is only one resonant peak over a 600 nm wavelength span from 1100 to 1700 nm. As the grating periodicity was increased, the resonant peak moved toward shorter wavelengths. At a grating period of 653.3  $\mu\text{m}$ , the resonance wavelength was 1648.7 nm. However, at a period of 905.5  $\mu\text{m}$ , the wavelength decreased to 1151.3 nm. Only one strong resonant peak was observed even when the resonance wavelength shifted over a 500 nm span with a change in the grating's periodicity.

To determine the possible cladding modes into which the fundamental core mode could be strongly coupled through the LPG, we used the multipole method. First, the effective indices of the core and cladding modes of the PCF were calculated and the field profile of each mode was obtained. Then, the power portion of each mode in the core region was calculated. The core region of the PCF was defined as the one where 95% of the fundamental core mode's power was confined. Finally, the mode most suitable for explaining the experimental result was selected.

In Fig. 3, the power portions of the cladding modes were calculated at a wavelength of 1.55  $\mu\text{m}$  and plotted as a function of  $[n_{\text{eff}}^{(f)}(\lambda) - n_{\text{eff}}^{(m)}(\lambda)]/\lambda$ . Since the effective index of a higher-order mode has a smaller value, in general, the cladding-mode order increases monotonically along the horizontal axis of the figure. Further, the phase-matching condition says that the inverse of the value in the horizontal axis equals the grating periodicity.

For comparison, the case with an ideal PCF that has no ISAs was calculated at the same wavelength and plotted in Fig. 3(a). There were 37 cladding modes that had power portions above 1% and 16

modes above 10%, where degenerate modes were counted. However, for the PCF with the ISAs, as shown by Fig. 3(b), only 7 modes had power portions above 1% and only 3 had portions above 10%. Since the mode coupling is proportional to the overlap integral between modes, this numerical analysis leads us to say that the ISAs are effective in limiting the number of cladding modes that can strongly couple to the fundamental mode and hence the number of resonant peaks in the LPG spectrum.

In Fig. 3(b), point  $p$  indicates that we can have a very strong resonant peak at 1.55  $\mu\text{m}$  with a proper choice of the grating period, in this case 685  $\mu\text{m}$ . The inverse of the corresponding horizontal axis is indicated by the vertical line. With shorter grating periods, at the same wavelength, we can have resonance peaks indicated by points  $q$  and  $r$ , but their coupling strength will be much weaker than at point  $p$ . We note that the breakage of the sixfold symmetry of the PCF due to the missing ISA will cause a small birefringence of approximately  $10^{-7}$ – $10^{-5}$  that leads to the visible mode pairs at points  $p$  and  $q$ . We estimate that it would require an experimental length of at least 9 cm to separate the modes in the pair, but our experiment was done with only a 1.5 cm long grating.

The effective indices of the PCF modes were calculated as a function of wavelength, and the corre-

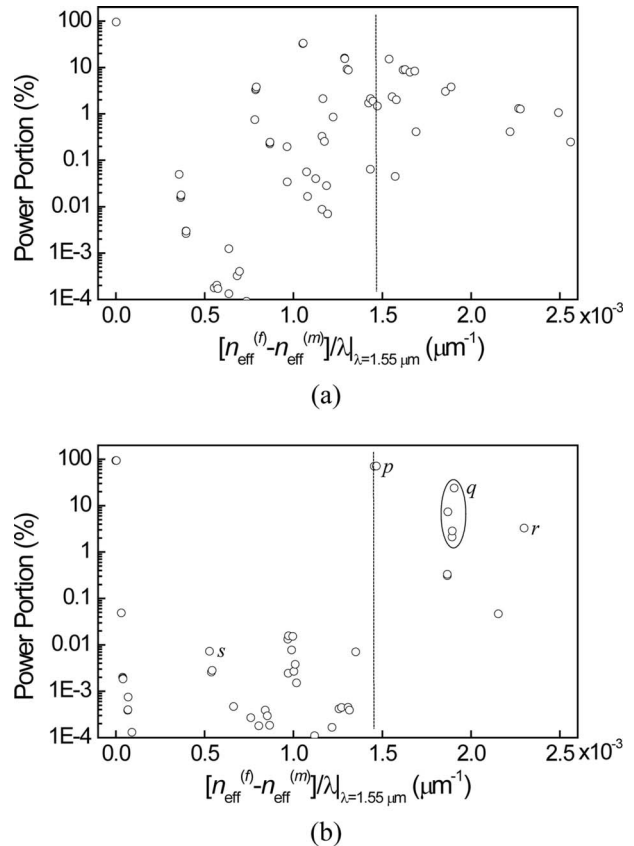


Fig. 3. Power portions of the modes calculated at  $\lambda = 1.55 \mu\text{m}$  and plotted in terms of the normalized effective index difference  $[n_{\text{eff}}^{(f)} - n_{\text{eff}}^{(m)}]/\lambda|_{\lambda=1.55\mu\text{m}}$  (a) without and (b) with the ISAs. The vertical line indicates the grating period at which point  $p$  has a resonant peak at a wavelength of 1.55  $\mu\text{m}$ .

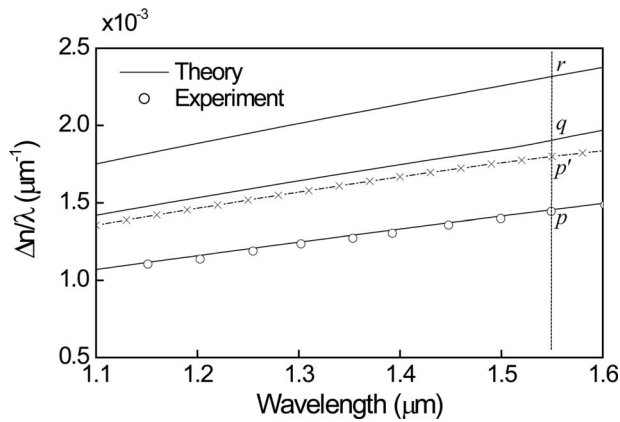


Fig. 4. Phase-matching curves plotted in terms of wavelength  $\lambda$ . The open circles are the experimental data measured with different grating periods, and the solid lines are the tracks of the points in Fig. 3(b) calculated at different wavelengths. The points crossed by the vertical line correspond to the points in Fig. 3(b).

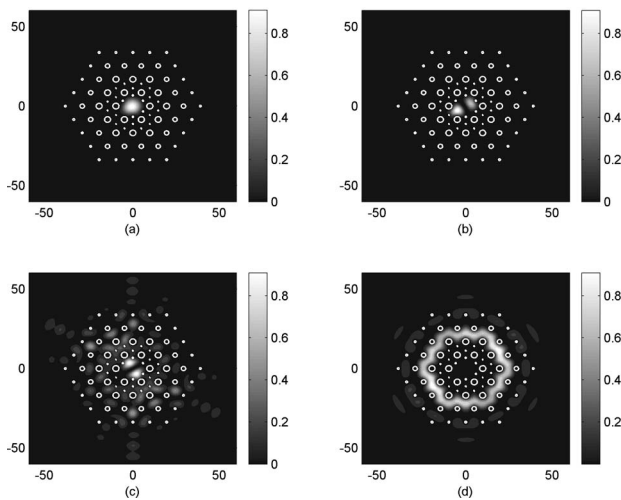


Fig. 5. Absolute values of the longitudinal component of the Poynting flux calculated at  $1.55 \mu\text{m}$  for (a) the fundamental core mode, (b) one of the two nearly degenerate modes at point  $p$ , (c) the largest modes at points  $q$ , and (d) the mode at point  $s$  in Fig. 3(b). The white circles are the air holes of the PCF.

sponding phase-matching condition for a LPG coupling was plotted in Fig. 4. In the figure, the inverse of the vertical axis is the grating period that is necessary to have a resonance peak at the corresponding wavelength indicated on the horizontal axis. The lines show how the points in Fig. 3(b) change as the wavelengths at which the effective indices are calculated change. The crossing points connected by the vertical line in the figure correspond to points  $p$ ,  $q$ , and  $r$  of Fig. 3(b). With Fig. 4, we can clearly see that, with a grating period of  $685 \mu\text{m}$  ( $\Delta n/\lambda = 1.46 \times 10^{-3}$ ), we will have a resonant peak at  $1.55 \mu\text{m}$ , corresponding to point  $p$  in Fig. 3(b), but the next-nearest resonance peak happens around  $1.1 \mu\text{m}$ . Further, we can see that a larger grating periodicity gives a shorter resonant wavelength. The line labeled  $p'$  in Fig. 4 shows what will happen to point  $p$  when there is no

missing ISA. We can see that there is an appreciable change in the grating period or in the resonant wavelength, which means that the effective indices of the cladding modes depend sensitively on the exact distribution of the ISAs.

In Fig. 5, we show the absolute values of the longitudinal Poynting flux for the fundamental core mode [Fig. 5(a)], one of the two nearly degenerate modes corresponding to point  $p$  [Fig. 5(b)], the mode with the largest power portion at points  $q$  [Fig. 5(c)], and finally the mode corresponding to point  $s$  [Fig. 5(d)]. The field profiles of Figs. 5(b) and 5(c) are similar to that of the first higher-order mode of a conventional step-index fiber. Each mode has an appreciable portion of its power located in the core region; however, it is ambiguous as to whether we should call this mode a core mode or a cladding mode. Figure 5(d) shows that the field profile is a ring shape. Its power is located mainly outside the core region, thus the mode coupling with the core mode is inevitably small.

In conclusion, we have explained the unusual spectral properties of a long-period grating written in photonic crystal fiber. Our experimental observation and theoretical analysis indicate that the interstitial air holes of a PCF suppress many modes and leave only a few well-separated modes that have large power portions in the solid-core region, and thus lead to a strong and well-isolated LPG resonance peak over a wide wavelength range. The results also suggest that it is possible to use air holes with different sizes—and, in particular, to take advantage of ISAs—to engineer structures that cannot be obtained with air holes that have the same size.

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