Realization of Single-Moded Broadband Air-Guiding Photonic Bandgap Fibers

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***Abstract*—In this letter, we propose a novel type of air-guiding photonic bandgap fiber, which exhibits an effectively single-mode operation with a low confinement loss over a wide wavelength range, extended from 1460 to 1840 nm. For several realistic structural parameters, the wavelength dependence of the dispersion as well as the confinement loss properties are investigated through a full-vector modal solver based on the finite-element method. In particular, we optimize the structure so as to exhibit the following performance: effectively single-mode operation from 1460 to 1840 nm, with corresponding confinement loss of the fundamental air-guided mode of 8.8×10^{-5} dB/km, and enhancement of the confinement loss of the higher order mode of 43 dB/m for ten-ring structure.**

***Index Terms*—Photonic bandgap fiber (PBGF), photonic crystal fiber.**

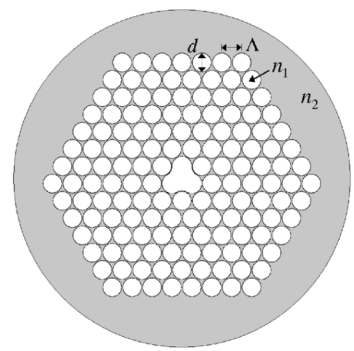

Fig. 1. Cross section of the proposed PBGF, where d is the diameter of air holes, Λ is the distance between adjacent air holes, and $n_1 = 1.0, n_2 = 1.45$ are the refractive indexes of air and silica, respectively.

I. Introduction

RECENTLY, photonic bandgap fibers (PBGFs) have gathered much attention because of the novel way of guiding light. In PBGFs, the cladding is usually composed of a periodic arrangement of air and silica, by incorporating a "nonperiodic" defect into the structure. Thus, the light propagates in the defected region known as the core, by the photonic bandgap (PBG) effect [1], [2]. Because the refractive index of the core is lower than that of the cladding, it is possible to guide light in air [3]–[14]. In air-guiding PBGFs, an optimization of the cladding structure has been investigated so far to obtain a large communication bandwidth as well as low confinement loss properties [10]–[13]. It is a necessary requirement for air-guiding PBGFs that a photonic crystal cladding structure exhibits PBGs covering the β/k values equal or less than one (where β is the propagation constant and k is the wavenumber in free space). In general, for air-guiding PBGFs, because the dispersion curve of the fundamental air-guided mode appears near the air line in the PBG, the spans of the air line over the PBG regions can be considered as the available transmission band. It is known that the triangular lattice cladding, which is commonly used in practical realization of PBGs, exhibits large spans when the air-filling fraction (AFF), which depends in a square fashion on the normalized air hole diameter by a pitch constant, is increased. The bandgap size of the triangular lattice with large AFF is sufficient; however, the telecommunication window over which single-mode can be achieved, is reduced considerably, because the air-core region is generally constructed by removing 7 or 19 air holes, leading to the existence of higher order modes [4]. Though a particular core shape has been proposed to prevent not only surface modes but also higher order modes from being guided [14], the main drawback is the feasibility of such core shape.

In this letter, we propose a novel type of PBGF, whose core is realized by removing only three air holes. For several realistic structural parameters, the wavelength dependence of the dispersion as well as the confinement loss properties is investigated through a full-vector modal solver based on the finite element method (FEM) [15]. We show that the proposed fiber exhibits an effectively single-mode operation with a low confinement loss for a wide wavelength range extended from 1460 to 1840 nm and, in particular, we prove that the broadband single-mode operation and low confinement loss are consistent between each other in the proposed air-guiding PBGF.

II. Single-Mode Operation of Air-Guiding PBGFs

Fig. 1 shows the cross section of the proposed PBGF, where d stands for the diameter of the air holes, Λ is the distance between adjacent air holes, and $n_1 = 1.0, n_2 = 1.45$ are the refractive indexes of air and silica, respectively. In contrast to conventional triangular-type air-guiding PBGF, the defected core of the proposed PBGF is formed by removing only three air holes and smoothing the resulting core edges. Because the defected core surface does not intersect with the silica material where bulk mode has high intensity, no surface modes exist in such core types [14].

Fig. 2 shows the modal dispersion curves of guided modes as a function of the wavelength for the proposed PBGF, where the structural parameter of $d/\Lambda = 0.96$ was chosen. The shaded region represents the PBG region calculated by using FEM, provided that the number of cladding rings tends to infinity. The solid and dashed curves represent the effective indexes of the fundamental and second-order modes, respectively. The second-order modes are consisting of four modes: two

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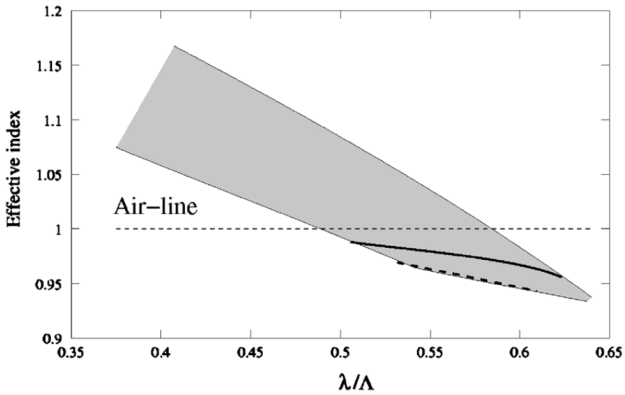

Fig. 2. Dispersion curves for the proposed PBGF with $d/\Lambda = 0.96$. The shaded region represents the PBG provided that the number of cladding rings is infinite. The solid and dashed curves represent the effective indexes for the fundamental and second-order modes, respectively.

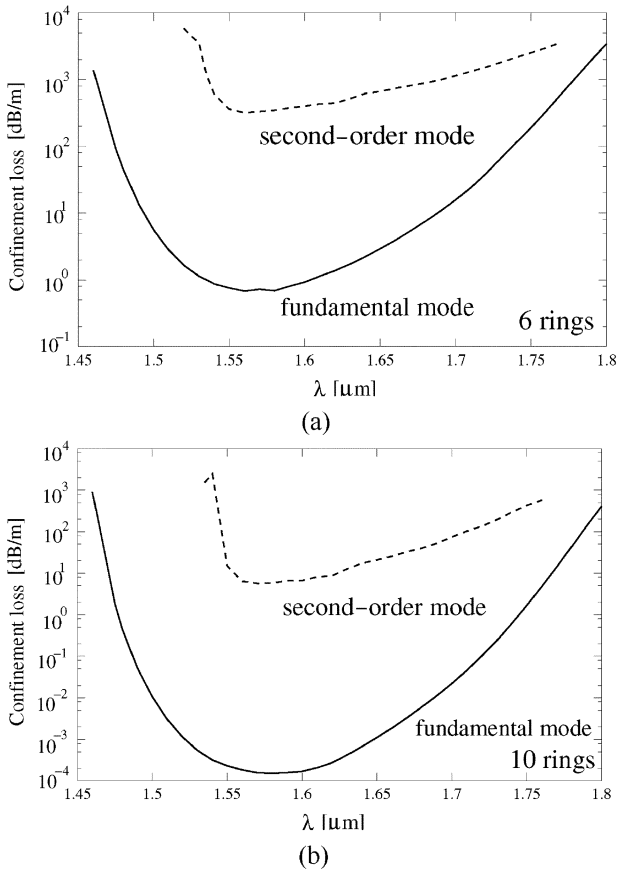

Fig. 3. Confinement losses of the proposed PBGF with (a) six rings and (b) ten rings, where $d/\Lambda = 0.96$ and $\Lambda = 2.89$ μm. The solid and dashed curves represent the confinement losses for the fundamental and second-order modes, respectively.

HE_{21}-like modes, a TE_{01}-like mode, and a TM_{01}-like mode, as in conventional optical fibers. Here, only the HE_{21}-like mode is shown as the second-order mode because the effective indexes of the TE_{01}-like mode and the TM_{01}-like mode were found to be close to those of HE_{21}-like mode. The fundamental mode stays nicely in the PBG region and, on account of the small core diameter; the higher order mode on the other hand is driven near the edge of the PBG region. Fig. 3(a) and (b)

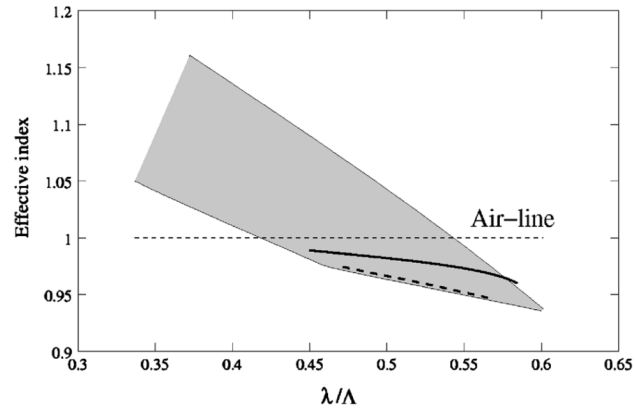

Fig. 4. Dispersion curves for the proposed PBGF with $d/\Lambda = 0.98$. The shaded region represents the PBG provided that the number of cladding rings is infinite. The solid and dashed curves represent the effective indexes for the fundamental and second-order modes, respectively.

shows the wavelength dependence of the confinement loss of the PBGF with six and ten air-hole rings, respectively, where $d/\Lambda = 0.96$ and $\Lambda = 2.89$ μm. The confinement loss of the second-order mode is about three orders of magnitude larger than that of the fundamental mode for a six-ring fiber, and five orders of magnitude larger for a ten-ring fiber. As a result, we could say that the fiber with a total number of ten air-hole rings and structural parameters of the cladding of $d/\Lambda = 0.96$ and $\Lambda = 2.89$ μm can operate as effectively single-moded over a wide wavelength range.

To realize a much broader transmission band with the proposed fiber, we increase the air-hole size up to $d/\Lambda = 0.98$. When d/Λ is increased, the PBG region is shifted to shorter wavelengths (leftward), and the pitch required to set the midgap wavelength λ_c in the telecommunication window (e.g., $\lambda_c = 1.55$ μm) becomes larger. There is a worry that this fiber may support higher order modes because the core diameter normalized by the wavelength becomes larger due to the necessity of setting a large pitch. In spite of this worry, the fiber drives the higher order mode again near the edge of the PBG region though the fundamental mode exists in the middle of the PBG region, as shown in Fig. 4. Fig. 5(a) and (b) shows the wavelength dependence of the confinement loss with six and ten air-hole rings, respectively, where $d/\Lambda = 0.98$ and $\Lambda = 3.23$ μm. Though the confinement loss of the fundamental mode becomes lower as expected, the confinement loss of the second-order mode is as large as that of the fiber with a normalized structural parameter of $d/\Lambda = 0.96$. The reason for this is that the bandgap shape (shaded region) for the structural parameter of $d/\Lambda = 0.98$ penetrates less beyond the air line in comparison to the case of $d/\Lambda = 0.96$ in the PBG region. The confinement loss of the second-order mode is about five orders of magnitude larger than that of the fundamental mode for a six-ring fiber, and nine orders of magnitude larger for a ten-ring fiber. As a conclusion, we can fairly say that the fiber with ten air-hole rings and structural parameters of $d/\Lambda = 0.98$ and $\Lambda = 3.23$ μm has low confinement loss of the fundamental mode and can operate as an effectively single-moded over a wide wavelength range extended from 1460 to 1840 nm.

Fig. 6 shows the d/Λ-dependence of the confinement loss for the ten-ring fiber at 1.60 μm, where each of the pitches of the

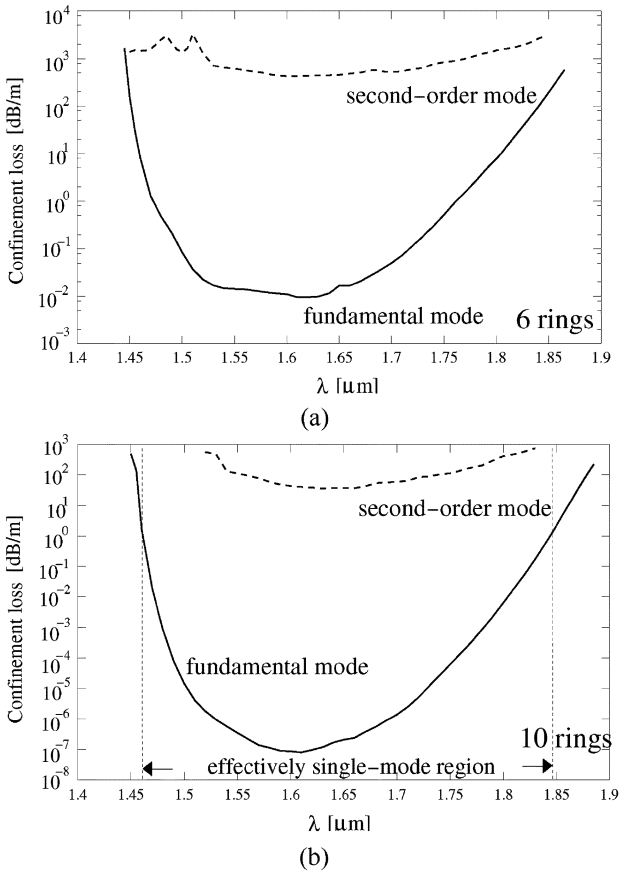

Fig. 5. Confinement losses of the proposed PBGF with (a) six rings and (b) ten rings, where $d/\Lambda = 0.98$ and $\Lambda = 3.23$ μm. The solid and dashed curves represent the confinement losses of the fundamental and second-order mode, respectively.

structure is selected to set the central wavelength of the PBG region at a wavelength of $\lambda_c = 1.55$ μm. There is a general idea that a conventional PBGF with triangular lattice tends to be a multimode fiber as the value of d/Λ increases. However, contrary to the idea, due to the fact that the confinement loss of the fundamental mode gets lower and that of the second-order mode being almost constant as increasing the value of d/Λ, the broadband single-mode operation and low confinement loss are consistent between each other in the proposed air-guiding PBGF.

III. Conclusion

A novel type of PBGF, whose core is realized by removing three air holes, has been proposed. We have analyzed the spectral dependence of the dispersion as well as the confinement loss and we have identified its optimized structural parameters. We have particularly shown that the proposed PBGF exhibits an effectively single-mode operation with a low confinement loss over the wavelength range extended from 1460 to 1840 nm.

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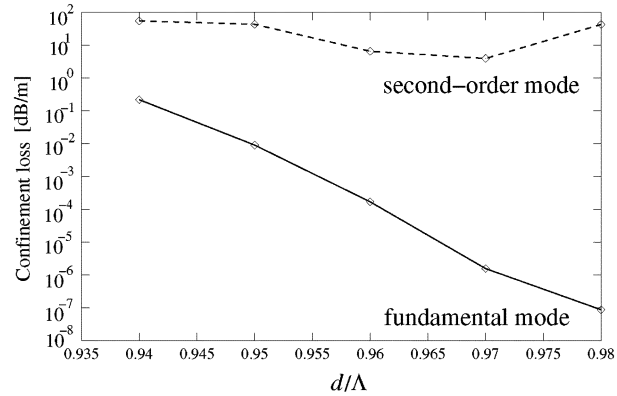

Fig. 6. Dependence on d/Λ of the confinement loss for the ten-ring fiber at wavelength of 1.60 μm, where each of the pitches of the structure is selected to set the central wavelength of the PBG region at $\lambda_c = 1.55$ μm. The solid and dashed curves represent the confinement losses of the fundamental and second-order mode, respectively.

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