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Tunable Leaky Loss Properties of Photonic Bandgap Fibers*

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Abstract: Loss properties of photonic bandgap fibers were theoretically investigated by using the vector plane-wave expansion method and the vector finite element method. The tunable PBGFs are composed by filling high index material in the air holes of index-guiding photonic crystal fibers. The wavelength dependence of leaky loss and group velocity dispersion has been illustrated. The leaky loss in the tunable properties of photonic bandgap fibers is strongly depended on the refractive index of filled material due to the photonic bandgap effect.

Key words: Photonic crystal fibers; Photonic bandgap fibers; Leaky loss

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0 Introduction

Photonic crystal fibers (PCFs) have become more attractive in the optical field recently due to their unique properties, such as endless single mode guiding[1], tailorable group velocity dispersion[2] and high nonlinearity[3-5]. According to their guided mechanisms, PCFs are generally divided into two kinds: index-guiding PCFs, which guide light by total internal reflection between a high-index core and air-hole cladding, and photonic bandgap fibers (PBGFs), which confine the light in the vicinity of the core due to the photonic bandgap (PBG) effect of photonic crystal cladding. Recently, novel PBGFs obtained by filling high index material in PCFs have been demonstrated. T. P. White, et al. presented their work on guidance of PBGFs consisting of high refractive index cylinders embedded in a low index background using full vector multipole method[6]. Later, Bise, et al. demonstrated a tunable PBGF, which was obtained by filling high index fluid in PCFs, and adjusting the temperature can spectrally shift the resulting bandgaps[7]. Recently, electrically tunable liquid-crystal- filled PCFs have been demonstrated by M. W. Haakestad and Du et al[8-9]. The theoretical analysis for the characteristics of tunable PBGFs with varying of index filled material based on PBG theory had been illustrated by C. Zhang, et al[10-11].

In this work, the theoretical analysis of the tunable PBGFs is presented. These PBGFs are composed by filling high index material in the holes of index-guiding PCF. By means of plane-wave expansion (PWE) method, the PBG maps have been found; furthermore, the shifting of PBG has been investigated when the refractive index of the filled material is varied. The wavelength dependence of leaky loss and group velocity dispersion (GVD) of fundamental modes in the PBGFs have been investigated using a full-vector finite-element method (FEM) with anisotropic perfectly matched layers (PMLs). Moreover, we demonstrate the characteristics of fundamental mode can be tunable by changed refractive index of filled material. The tunable loss properties at 1 550 nm can be realized based on this PBGFs.

1 Modeling and theory

The structure of the PBGF is shown in Fig. 1, which has a silica core surrounded by 6 periods of air holes arranged in triangular lattice. The defining

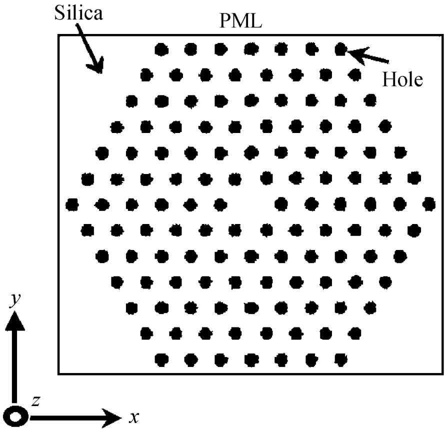

Fig. 1 Cross section of the microstructure fiber

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parameters of the structure are the lattice constant Λ, *the air holes diameter* $r=0.23\Lambda$. The refractive index of silica is assumed to be filled by high refractive index liquid crystal material, whose refractive index n_f could be tuned by electric field and vary between from 1.6 to 1.7 in our case.

The photonic band structure of the PBGF is calculated by using full-vector PWE method. The basis of full-vector PEW method is the vectorial wave equation for magnetic field $\boldsymbol{H}(\boldsymbol{r})$ as an eigenvalue problem

$$\nabla\times\{\varepsilon^{-1}(r)\nabla\times\boldsymbol{H}(\boldsymbol{r})\}=k_0^2\boldsymbol{H}(\boldsymbol{r}) \tag{1}$$

where $\varepsilon(r)$ represents the dielectric constant, k_0 is the free-space wave number. The eigenfrequencies and eigenfunctions are computed by resolving the equations with periodic boundary conditions using preconditioned conjugate-gradient minimization of the block Rayleigh quotient in a planewave basis[12].

To evaluate leakage losses and to enclose the computational domain without affecting the numerical solution, a full-vector FEM using anisotropic PMLs as absorbing boundary conditions has been introduced. From Maxwell's equations the following vectorial wave equation is derived[13]

$$\nabla\times([s]^{-1}\nabla\times\boldsymbol{E})-k_0^2\varepsilon[s]\boldsymbol{E}=0 \tag{2}$$

where $\boldsymbol{E}$ is the electric field vector, $[s]$ is the PML matrix, and $[s]^{-1}$ is an inverse matrix of $[s]$.

2 Analysis

Fig. 2 shows the bandgaps of the perfect PBGF's cladding pattern by using the PWM. The refractive index of filled material is assumed to be 1.65, which is very close to the refractive index of liquid-crystal. The diagram reveals the existence of two PBGs and the silica line ($n_{\mathrm{eff}}=1.444$) crossing fundamental and secondary gap regions. According to waveguide theory, the core guided modes exist in the fibers only when the modal effective index locates in the PBGs and below the silica line.

The guided modes in the PBGFs are simulated by use of the vector finite element method with anisotropic PMLs. One-quarter was used to investigate according to the symmetrical structure of MFs to reduce the time of calculation. The effective index for fundamental core guided modes as a function of normalized wavelength is illustrated in Fig. 2. The dispersion curves of the fundamental mode exist in both PBG regions with two discrete frequency bands . For both frequency bands, the fundamental modes cut off in short wavelength because the modal effective index is close to the refractive index of silica, whereas, they cut off in long wavelength because the modes outside the PBG regions. The normalized wavelength of the two bands is 0.34～0.49 and 0.57～1.18, respectively.

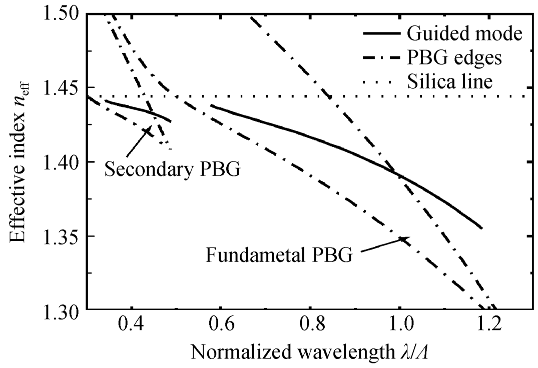
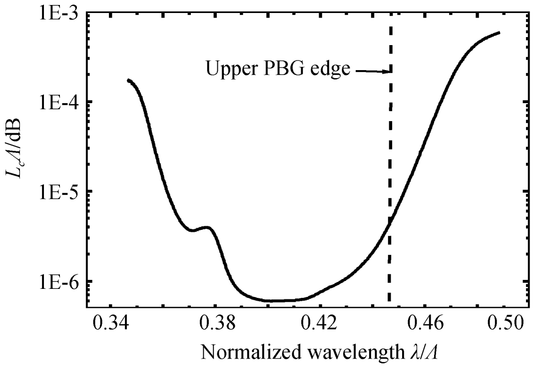
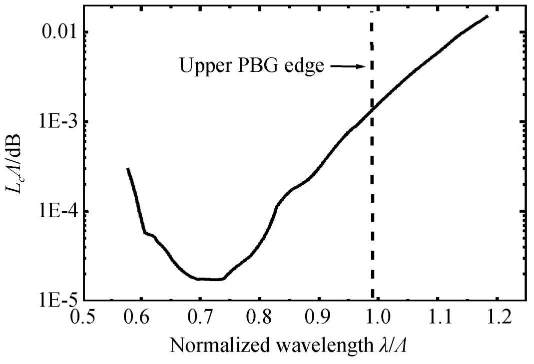


Fig. 2 Effective index of PBG edges and defect mode in the PBGF

Fig. 3 shows the wavelength dependence of normalized leaky loss for the PBGF. As expected, the leaky loss becomes minimum around the center of PBG and increases as approaching the band edges. The phenomenon ascribes that the mode fields are confined in the core of fiber when the modes appear around the center of PBG, but they enlarge to the cladding rapidly when the modes are close to the edges of PBG. Moreover the leaky loss in fundamental gap is larger than that in secondary



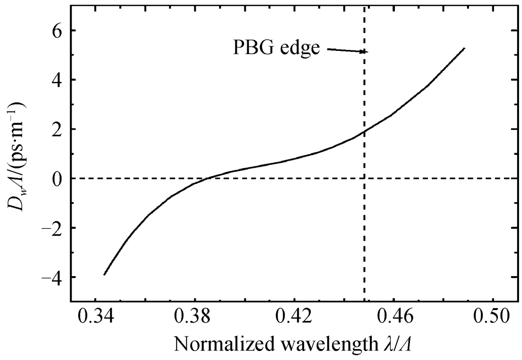
(a)Secondary gap



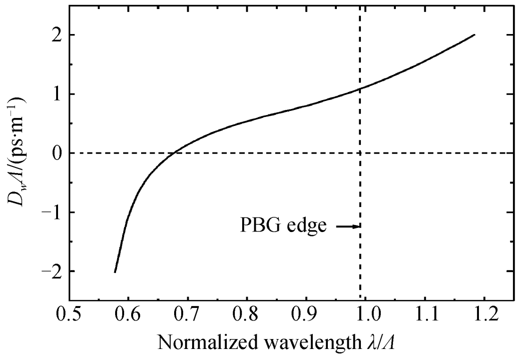
(b)Fundamental gap

Fig. 3 Normalized leaky loss versus normalized wavelength gap. According to Fig. 3, the leaky loss increases rapidly though the modal dispersion curves extend to outside of the upper bandgap edges.

The numerical results of GVD of the fundamental mode in the two bandgap regions of the PBGFs are shown in Fig. 4. The GVD in either bandgap exhibit the same qualitative behavior: (a) the GVD is strongly wavelength dependent; (b) it goes from negative values at shorter wavelengths to positive values at longer wavelengths; (c) it increases rapidly near the upper band edge and decreases rapidly near the lower band edge; (d) it crosses zero point within the low loss window. Whereas the dispersion slope around the center of fundamental gap is larger than that of the secondary gap.



(a)Secondary gap



(b)Fundamental gap

Fig. 4 Normalized GVD for fundamental mode as a function of normalized wavelength in secondary and fundamental gap region of the PBGFs

Fig. 5 shows the effective indexes of the fundamental modes for Λ=3.38 μm, and n_f=1.60 and 1.70 together with the PBG edges as a function of wavelength in the second PBG. With the increasing of n_f, the increase of the effective index for PBG edges is rapider than that for guided modes. This result means the relative position of dispersion curves between guided modes and PBG edges is changed with the variety of n_f. For example, at λ=1 550 nm, the guided modes, which locate outside the PBG region when n_f = 1.6, locate inside the PBG region when n_f=1.70.

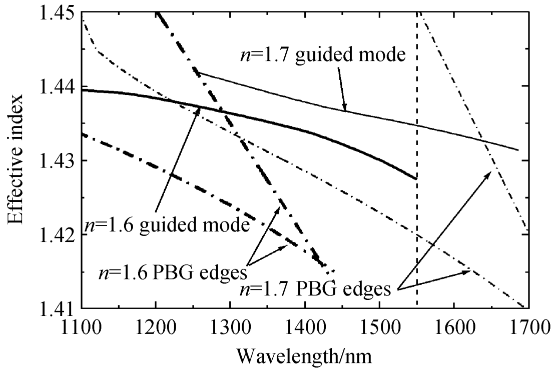


Fig. 5 Modal effective index versus wavelength when refractive index of filled material n_f is 1.6 and 1.7 in second PBG

Therefore, for a fixed normalized wavelength, the guided properties of the PBGFs may be changed obviously with the variety of n_f. Fig. 6 shows effective index and leaky loss of fundamental mode as a function of the refractive index for filled material n_f at λ=1 550 nm. With the increase of n_f from 1.60 to 1.70, the dispersion curve of fundamental modes comes into PBG region, the leaky loss decrease rapidly from 400 dB/m at n_f= 1.60 to 0.3 dB/m at n_f=1.67. As a result, the tunable loss could be realized by varying n_f.

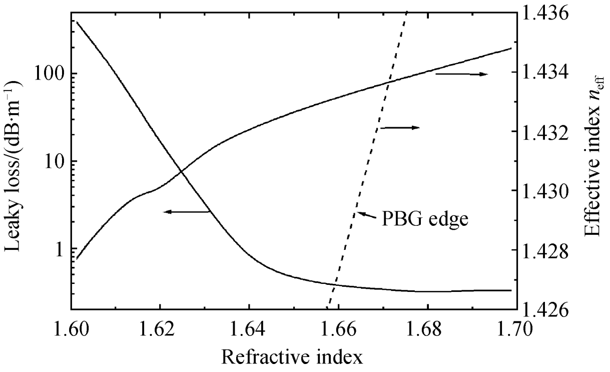


Fig. 6 Effective index and leaky loss of fundamental mode as a function of the refractive index for filled material n_f at λ=1 550 nm

3 Conclusion

In conclusion, tunable photonic bandgap fibers (PBGFs) were theoretically investigated by using the vector plane-wave expansion method and the vector finite element method with anisotropic PMLs. The leaky loss in the tunable PBGFs can be strongly depended on the refractive index of filled material, which can be tunable by themal and electrically field. The tunable loss properties at 1 550 nm can be realized based on this PBGFs.

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可调光子带隙光纤的泄漏损耗特性研究

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摘　要：通过向折射率引导型光子晶体光纤的空气孔中填充可调的高折射率的材料可以获得带隙可调的光子带隙光纤. 本文采用矢量平面波展开法与矢量有限元法对可调光子带隙光纤的泄漏损耗特性进行了理论研究. 研究表明，这种可调光子带隙光纤的光子带隙效应使其泄漏损耗与填充材料的折射率有很强的依赖关系，同时给出了光子带隙光纤的泄漏损耗和群速度色散与归一化波长的关系.

关键词：光子晶体光纤；光子带隙光纤；泄漏损耗

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