Antiresonant reflecting photonic crystal optical waveguides

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We propose a simple analytical theory for low-index core photonic bandgap optical waveguides based on an antiresonant reflecting guidance mechanism. We identify a new regime of guidance in which the spectral properties of these structures are largely determined by the thickness of the high-index layers and the refractive-index contrast and are not particularly sensitive to the period of the cladding layers. The attenuation properties are controlled by the number of high/low-index cladding layers. Numerical simulations with the beam propagation method confirm the predictions of the analytical model. We discuss the implications of the results for photonic bandgap fibers. © 2002 Optical Society of America

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Photonic bandgap (PGB) optical waveguides have attracted significant interest in the past few years.[1] This interest was greatly motivated by recent progress in the fabrication of these structures in a fiber geometry.[2–4] So-called microstructured photonic crystal optical fibers (MOFs) typically incorporate a low-index core region surrounded by a hexagonal array of air holes in the cladding region that run along the length of the fiber.[3] These fibers are very promising candidates for novel optical fiber and photonic device designs. Typically, MOFs rely on one of the following guidance mechanisms: total internal reflection or PBG guidance. The former mechanism is similar to the usual step-index fiber in which the refractive index of the core is larger than that of the cladding. The latter mechanism guides light in a low-index core through Bragg reflections off high- and low-index periodic layers in the cladding. One of the key signatures of this mechanism of guidance has been a spectral response that is approximately periodic with frequency,[3] interpreted as being higher-order PBGs. In this Letter we show that, when the lattice constant of the PBG waveguide is larger than the optical wavelength and the index contrast is high, the spectral characteristics of the waveguide can be governed by the thickness of the first high-index layer rather than the lattice constant. In other words, a periodic spectral response is not necessarily a signature of a PBG effect but rather is a simple resonant effect associated with high-index contrast regions. We show that the spectral properties of such PBG optical waveguides can be described analytically by use of a so-called antiresonant reflecting optical waveguide (ARROW) model.[5] We suggest that it is useful to differentiate between ARROWs[5] and Bragg waveguides[6] to describe PBG structures such as MOF.

Three geometries of PBG optical waveguide, including the characteristic dimensions, are shown in Fig. 1. Figure 1(a) shows a one-dimensional (1D) layered structure consisting of a low-index silica core surrounded by an array of high- and low-index layers, Fig. 1(b) shows a concentric ring structure, and Fig. 1(c) shows a MOF with air holes filled with high-index oil.

The standard beam propagation method was used to calculate the transmission spectra for the structures shown in Fig. 1. We found that numerical simulations for the structure in Fig. 1(c) were very time consuming, so we limited our numerical study to the first two structures in Fig. 1. The simulations used the beam propagation method in the scalar limit and assumed a launch condition of a Gaussian beam with a diameter of 8 μm, as shown in Fig. 1(a). We calculated the spectral response by integrating the power at the end of the waveguide within the core region and normalizing it to the integrated input power (in our case everything is launched in the core). Figure 2(a) shows the calculated spectral responses of two 1D waveguides with parameters as follows: $n_1 = 1.4$; $n_2 = 1.8$; $\Lambda = 5.000$ μm, 5.300 μm, and 5.642 μm, where $\Lambda = d + b$ is a lattice constant; $d = 3.437$ μm is the thickness of the high-index layer and is fixed in this example; b is the thickness of the low-index layer; $a = 4\Lambda - d$; the waveguide length is 5 cm. The insets show the fundamental mode profiles for different wavelengths. Note that for the wavelengths $\lambda > \Lambda$ the positions of the spectral minima change with lattice constant Λ as expected in a periodic Bragg structure. Figure 2(b) shows the short-wavelength part of the spectrum, which can be roughly defined as $\lambda < \Lambda$ (a rigorous condition is derived below).

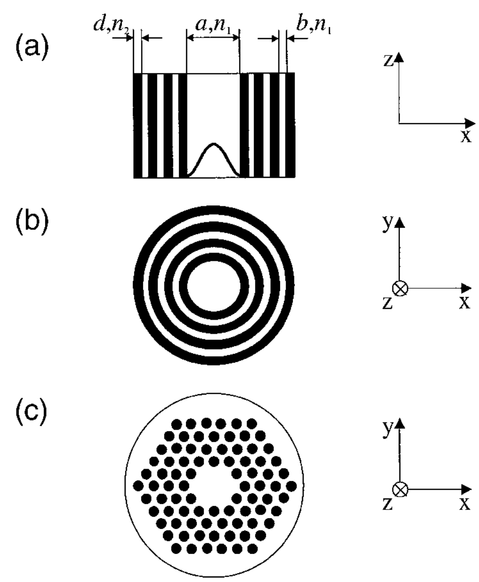

Fig. 1. Schematics of (a) a 1D ARROW structure, (b), its 2D equivalent, and (c) a microstructured optical fiber.

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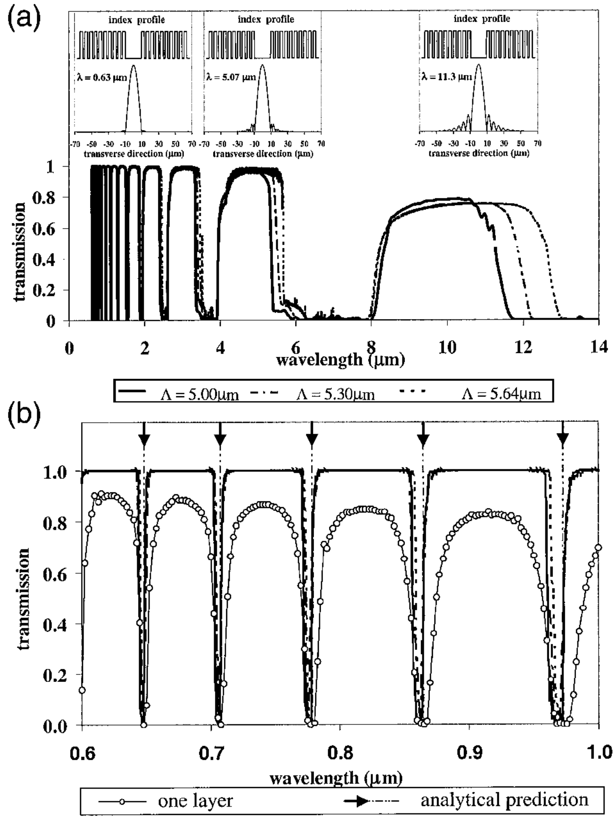

Fig. 2. Calculated transmission spectra for 1D 10-layer structures over the ranges (a) 0.6–15 μm and (b) 0.6–1 μm. Insets, fundamental mode profiles for three different wavelengths. The straight lines in (b) correspond to analytical predictions from Eq. (1), and the curves with open circles correspond to a one-layer structure.

Interestingly, for the shorter wavelengths, in our simulations we observed no significant change in the position of spectral minima when we changed the period of the PBG optical waveguide, or even if we removed all but one of the cladding layers, as shown in Fig. 2(b). This result certainly contradicts our expectations based on the Bragg reflection mechanism of guidance, in which the period would be an extremely important parameter. In a search for an explanation of the spectral properties of PBG optical waveguides in this regime, we propose the following.

Since $n_1 < n_2$, total internal reflection does not occur at the core–cladding interface, and therefore no guided modes can propagate in the low-index core of any of the three structures described above. However, these structures would support leaky-mode propagation.[7] Figure 3(a) shows an example of a leaky-mode waveguide, often called a hollow waveguide. This infinite cladding structure generally is very lossy, and the loss scales with the wavelength and the core size as $\sim\lambda^2/a^3$.[8] Note that a cylindrical waveguide with an infinite cladding is generally even more lossy than its planar counterpart. However, we note that, even for the mode with lowest attenuation, the ratio of the loss coefficient in cylindrical and in planar geometries is ≈ 1.5.[7,8] To reduce the propagation losses, we add high-index layers providing additional confinement in the core region as a result of antiresonant reflection in the cladding layers. One- and two-layer ARROWs are shown in Figs. 3(b) and 3(c).

The principle of the ARROW waveguide can be understood by consideration of Fig. 4, which shows two different wavelengths propagating in the center core of a waveguide formed by a low-index core surrounded by two high- and low-index cladding layers. The wavelengths corresponding to the minima of the transmission coefficient are referred to as resonant wavelengths, and the wavelengths corresponding to high transmission parts of the spectrum are called antiresonance wavelengths. This terminology is motivated by the fact that high transmission originates from the antiresonant nature of the individual cladding layers with respect to the transverse propagation constant. Each layer can be considered a Fabry–Perot- (FP-) like resonator. Narrowband resonances of this FP resonator correspond to transmission minima for the light propagating in the core, or resonant wavelengths of the low-index core waveguide. Wide antiresonances of the FP resonator (wavelengths experiencing low leakage as a result of destructive interference in the FP resonator) correspond to a high transmission coefficient for the low-index core waveguide. The lower plot in Fig. 4 shows the transmission spectrum of this waveguide. Note that in the antiresonance regime the transmission coefficient is high but not exactly 100%. This coefficient is due to

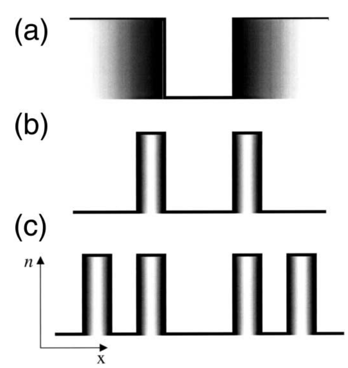

Fig. 3. Schematics of (a) a hollow waveguide, (b) a one-layer ARROW structure, and (c) a two-layer ARROW structure.

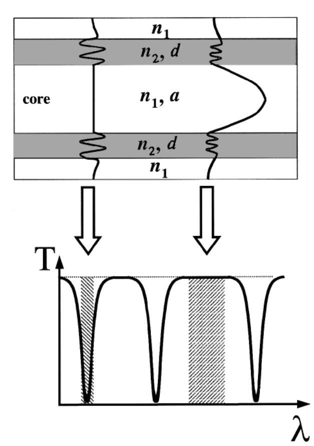

Fig. 4. Schematic of (top) the ARROW structure and (bottom) its transmission spectrum.

imperfect reflections off the low-high index interfaces. Usually, low-order modes propagate with glancing angles with respect to the interface, and therefore the reflection is quite high and the loss is low, whereas higher-order modes are more lossy because they have larger incident angles.

Let us first consider a 1D waveguide with just one high- and one low-index layer, shown in Fig. 4. At wavelengths that satisfy $k_{ex}d = \pi m$, $m = 1, 2, \ldots$, where k_{ex} is the propagation constant, a standing wave is formed in the high-index layers. For all other wavelengths, antiresonant reflection takes place, and light is confined in the core. Figure 2(b) shows that even a structure with a single high-index layer exhibits a periodic spectral response. As we add more high- and low-index layers to the structure in Fig. 1(a), the leakage rate decreases significantly without changing the position of the transmission minima, as shown in Fig. 2(b).

Simple derivations lead to the following relationship between the position of the dips of the spectrum and the parameters of the waveguide, n_1, n_2, and d, assuming $\lambda/a \ll 1$:

$$\lambda_m = \frac{2n_1 d}{m}[(n_2/n_1)^2 - 1]^{1/2}, \quad m = 1, 2, \ldots. \tag{1}$$

If all high-index layers are identical and they are in resonance with one another, i.e., the condition $k_{ex}d = \pi m$ is satisfied, then light escapes in the direction perpendicular to the core. These resonant wavelengths correspond to narrow transmission spectrum minima. This phenomenon can also be described in terms of resonant tunneling. Note that Eq. (1) does not include any dependence on the waveguide core size (assuming that $\lambda/a \ll 1$) or low-index layer thickness ($b \ll a$ in our case). This suggests that the positions of the spectral minima do not rely on the periodicity of the cladding. Equation (1) can be used to predict the positions of spectral minima found numerically and shown in Fig. 2(b).

Antiresonant reflection for a given d reaches the maximum value for the optical wavelengths that satisfy the following condition:

$$\lambda_l = \frac{4n_1 d}{(2l + 1)}[(n_2/n_1)^2 - 1]^{1/2}, \quad l = 0, 1, 2, \ldots. \tag{2}$$

In general, we should introduce another antiresonance condition for the optimum thickness of the low-index layer:

$$b = (2l + 1)\frac{a}{2}, \quad l = 0, 1, 2, \ldots. \tag{3}$$

However, for $b \ll a$, so that the low-index layers are too narrow to support any modes by themselves, these layers are always antiresonant, and condition (3) can be neglected.

At longer wavelengths,

$$\lambda/d > 2\sqrt{n_2^2 - n_1^2}, \tag{4}$$

the standing-wave effect does not occur, defining a limit for the validity of the ARROW waveguide model. For our parameters, $\lambda = 2d(n_2^2 - n_1^2)^{1/2} \approx 7\ \mu m$. At shorter wavelengths ($\lambda < 7\ \mu m$ in our example), the fundamental mode is very well confined by the ARROW mechanism [see the insets in Fig. 2(a)]. At longer wavelengths ($\lambda > 7\ \mu m$ in our example), the mode profile shows a typical structure that was previously reported for Bragg fibers.[6] Finally, we note that Eqs. (1)–(4), originally derived for the 1D structure in Fig. 1(a), can be readily applied to predict the spectral features of the ring structure in Fig. 1(b). However, these equations should be modified for the MOF in Fig. 1(c). We will follow up on this in future publications.

In conclusion, we have demonstrated a regime in which the guiding properties of PBG optical waveguides are governed primarily by antiresonant reflection from multiple cladding layers. In this regime the transmission spectrum of the PBG structure is determined by the index contrast and the thickness of the first high-index layer rather than the lattice constant. The leakage rate, however, depends on the number of cladding layers and decreases with an increasing number of layers. We presented an analytic model based on an antiresonant reflection guidance mechanism that offers simple design rules for novel PBG-structure-based devices and transmission fibers.

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