Design of Leaking Mode Free Hollow-Core Photonic Bandgap Fibers

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Abstract: An analytical design method of leaking mode free, large bandwidth, hollow-core all-silica Bragg fibers is reported that takes into account the effective refractive index change of the air layers caused by silica struts.

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1. Introduction

Photonic bandgap (PBG) fibers [1] are optical fibers that have unique optical properties compared to step-index and graded index fibers. Hollow-core (HC) PBG fibers are expected to have lower loss than total-internal-reflection-guiding fibers because of the lower absorption and Rayleigh-scattering of air compared to glass. The intensity threshold for nonlinearity can be several orders of magnitude higher for these fibers compared to silica-core fibers, which allows the propagation of high intensity laser pulses without significant spectral distortions [2]. The dispersion of these fibers is also unique and varies strongly across the bandgap [3, 4]. The shape of the dispersion profile of these fibers is similar to that of one-dimensional (1D) photonic bandgap structures or quarter-wave stacks [5] and two-dimensional (2D) PBG structures [6].

Present HC PBG fibers are not ideal for ultrafast laser applications: they exhibit limited bandwidth compared to the tunability range of Ti:sapphire lasers (670 nm to 1060 nm) and their dispersion varies with wavelength [7].

Some progress on producing ultrabroadband, all-silica PBG fibers, which have almost an octave bandgap, has already been made. The so-called all-silica Bragg fiber may exhibit a very wide bandgap if one only takes into account the alternating fused silica and air layers [8]. However, the realized fiber with the additional silica struts, which set the spacing between the silica rings, increases the effective refractive index of the low index cladding regions above unity. This small modification of the low index layer introduces plenty of interface-mode anti-crossing events [9] which rive the bandgap to many smaller ones and dramatically reduce the usable bandwidth. Some effort on broadening the usable bandgap has been made by searching for an optimum air-filling fraction of the fiber by changing the core size and the thickness of the first silica layer in a realistic HC PBG fiber [10] or introducing anti-resonant structures around the core [11]. Algorithms that are capable of such simulations – such as finite-element method (FEM), – are very time-consuming and ineffective in designing HC fibers when the optimum structure is maintained from transmission maps calculated in small steps and covering wide ranges of parameters.

In this paper our aim is to understand and describe the physical origin of the so called ”leaking modes” in all kind of PBG fibers including HC fibers with cylindrical or hexagonal fused silica cladding structures, or in any kind of PBG structures. We show that when meeting the so called quarter-wave condition requirement in the design at the center of the desired bandgap, the bandgap is free of leaking modes. Especially, we show that properly taking into account the contribution from the silica struts (which results in a few percent change in the effective refractive index of the air spacer layers) in all-silica Bragg fibers, one can construct structures exhibiting an ultra-large bandwidth (a few hundreds of nanometers). For 1D simulations, we use the well known transfer matrix method [5, 12] to describe the physical properties of the Bragg fiber. Later on, we apply the FEM for making simulation on the real, 2D structures including the effect of fine structures such as the fused silica struts.

We point out that two kinds of loss mechanisms are distinguished for HC PBG fibers. While ”leaking modes” are due to the high standing wave field in the air spacer layers and can be removed by correct design of the structure, ”surface modes” still appear in the silica struts due to symmetry concerns and cannot be described by 1D models.

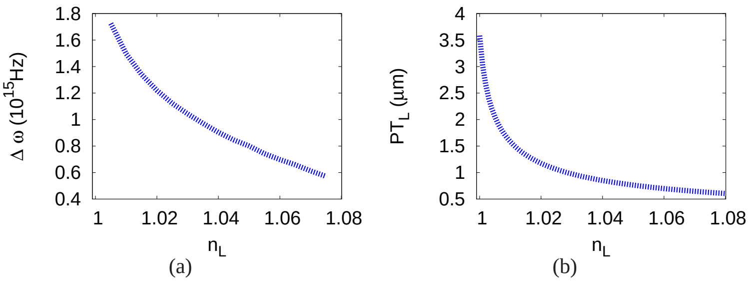


Fig. 1. (a) Computed bandwidth ($\Delta\omega$) of the bandgap for 1D quarter-wave structures as a function of the effective index of the low index layer (air spacer with support bridges) n_L at an angle of incidence of 86°, P polarized light, $n_H = 1.45$ is constant. (b) Computed physical thickness of the low index layer (PT_L) as a function of the effective layer indices when meeting the $\lambda/4$ condition at an angle of incidence $\Theta_o = 86°$.

2. Theory

The physical behavior of PBG structures can be well understood by investigating phase behavior of the electromagnetic waves partially reflected from the air/silica interfaces of the structure that add up to interfere. At a given wavelength high reflectance can be obtained when the partial waves meet in phase, i.e., the rays penetrating to different depths gain the same phase shift during propagation. A typical application of this idea in 1D is constructing low-dispersion dielectric high reflectors for femtosecond pulse lasers by using alternating high and low index dielectric layers with quarter-wave optical thicknesses [5]. In this case, the waves being partially reflected at the interfaces meet in phase upon reflection because of the $\pi/2$ phase shifts during both forth and back-propagation in the layers and the additional π phase shift at each air/silica interface. At oblique incidence, there are two facts that have to be considered: first, the effective refractive indices of the air layers change according to their angle of refraction and polarization of the electromagnetic wave (only p-polarization should be considered), secondly, the physical thicknesses of the layers have to be corrected by the cosine function of the angle of refraction in a given layer. The former fact results in, for instance, a considerable difference in the useful bandwidth as the function of the refractive index of the low index layer (and hence the angle of refraction), see Fig. 1 (a). The latter effect introduces a blue shift of the reflection band of such interference structures when they are tilted.

As a first approximation, photonic band gap fibers can be regarded as 2D dielectric high reflectors, in which the light propagates at grazing incidence. The ”angle of incidence” Θ_o can be derived from the real part ($\Re$) of the effective refractive index $n_{\text{eff}}(\lambda)$ of the structure using $\Theta_o = \arcsin(\Re(n_{\text{eff}}))$.

Since the phase delay during propagation and the phase shift upon reflection and transmission has to be calculated in the same way in the 1D and the 2D models, we use the 1D analogue of optical fibers for optimization. The physical thickness (D_i) of each layer (i) have to meet the $\lambda/4$ condition, similarly to standard quarter-wave dielectric high reflectors designed for oblique incidence (Θ_o) and λ_o central wavelength:

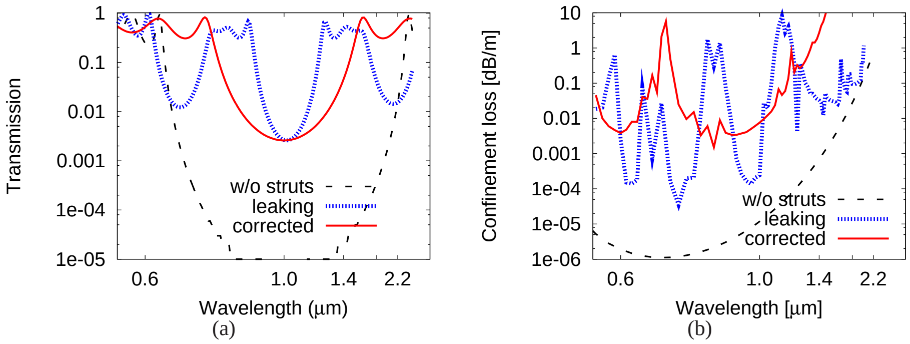
$$D_i = \frac{\lambda_o}{4}\frac{1}{n_i\cos(\Theta_i)}, \qquad (1)$$

where Θ_i are the refraction angles and n_i are the effective refractive indices of the different layers. During our investigations on HC Bragg PBG fibers, we have found that the effect of this equation is striking: the few percent change in the refractive index caused by the support bridges in the air layers dramatically changes physical layer thicknesses meeting the quarter-wave condition (see Fig. 1 (b)). As the following simulation results show, neglecting this slight modification of the effective refractive index results in interface-mode anti-crossing events which rive the bandgap to many smaller ones and dramatically reduce the usable bandwidth. However, choosing the physical layer thicknesses properly, we can easily eliminate the leaking modes. In our simulations, the index-rising effect of the support bridges (thickness ~ 50 nm) was estimated to be ~ 0.02. The appropriate Θ_i values are calculated by Snell’s law.

3. Results

In our numerical examples, designs comprising 3 silica-air layer pairs are presented which support bandgap guidance around 1 μm. 1D simulation results are shown in Fig. 2 (a). The ideal design in which the index rising effect of the support bridges in the air spacer layers is neglected is shown with a dashed line. When the small index rising effect of silica struts is taken into account but the spacer thickness is not corrected, leaking modes appear in the bandgap. This curve is shown with dotted line. The correct quarter-wave design exhibits a broad bandwidth free of leaking modes (shown with solid line) however, the bandwidth is reduced in agreement with Fig 1 (a).

Corresponding FEM calculation results are shown in Fig. 2 (b). The FEM simulation was carried out on an analogue structure consisting of a 6μm core, 3 alternating layers of silica and air, and 12 silica struts of 50 nm thickness in each air layer. The properly designed structure is free of ”leaking modes” however some perturbation due to still existing ”surface modes” can be observed.



(a) (b)

Fig. 2. (a) 1D computation results for transmission (corresponding to the loss of the fiber) as a function of wavelength for PBG structures of the following designs: $n_L = 1.00$ and $PT_L = \lambda_o/4/\cos(\Theta_0) = 3.584\mu$m, $\Theta_0 = 86°$, exhibiting a very wide bandgap (black dashed line), $n_L = 1.02$ and $PT_L = 3.584\mu$m with the leaking modes destroying the bandgap (blue dotted line), $n_L = 1.02$ and $PT_L = \lambda_o/4/1.02/\cos(\Theta_2) = 1.175\mu$m restoring the bandgap to some degree (red solid line), and (b) corresponding FEM results

As a conclusion, we can say that optical performance of HC Bragg fibers is extremely sensitive to the effect of support bridges between the concentric fused silica rings. In spite of the fact that they modify the effective refractive index of the air spacer layers by a few percent only, proper readjustment of physical thicknesses meeting the well known quarter-wave condition may require as high as 70% changes in these parameters. We found that this is typical for grazing incidence ($\Theta_o \sim 84$ to $87°$) in 2D and 1D photonic bandgap structures as well. A 2D finite element method and a 1D equivalent thin film analysis show, however, that leaking modes or mode anti-crossing events can be avoided by proper modeling and choice of the physical layer coefficients, when optical thickness of each layer is set to $\lambda_o/4$. The presented results and the applied numerical methods can be applied for modeling and design of all kinds of photonic bandgap fibers.

4. References

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