Dispersion properties of high-contrast grating hollow-core waveguides

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We present unique dispersion characteristics of high-contrast grating (HCG) hollow-core waveguides and show that slow light can be facilitated using internal resonances developing inside the waveguide walls. In addition, we show a fast and precise method of inferring the dispersion information from the waveguide angular reflectivity spectrum. © 2010 Optical Society of America

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Waveguides with high phase dispersion are very beneficial for applications involving group-velocity manipulation, such as delay lines, interferometers and optical switches. Among the known techniques for obtaining slow-light waveguides based on phase dispersion are photonic crystal waveguides [1,2], coupled resonator optical waveguides (CROW) [3–5] and combinations thereof [6], all of which attract much attention owing to their enhanced dispersion characteristics. In the context of photonic crystal waveguides, the study of dispersion phenomena in structures involving leaky modes is an active area of research, whereby the dispersion properties have been studied both theoretically [7] and experimentally [8,9] in single-period [7] and dual-period [8] one- and two-dimensional [9] photonic crystal structures. However, as many slow-light waveguides involve exotic nanoscale designs, the ease of fabrication is often an issue. Additionally, these waveguides are susceptible to material nonlinearities, leading to undesirable effects on waveguide dispersion. A hollow-core waveguide that can efficiently slow the light because of resonant phase dispersion effects is therefore highly desirable. A hollow-core slow-light waveguide has an additional advantage when the core is filled with nonlinear gaseous or fluidic material for increasing light–matter interaction. Hollow-core waveguides are also beneficial for free-space coupling, because the core has no index contrast with free space.

Our group has previously proposed a novel hollow-core waveguide design based on HCGs [10], which are subwavelength gratings made of a high refractive index material (e.g., silicon) fully surrounded by air or a low-index medium. The HCG waveguide is schematically depicted in Fig. 1(a). HCGs, when properly designed, can be excellent broadband mirrors [11], providing reflectivity at least as high as and as broadband as a 40 layer distributed Bragg reflector (DBR). Therefore, guiding light between two parallel highly reflective HCGs can reduce the waveguide loss to unprecedented low values [10] while maintaining a high level of robustness against fabrication imperfections. For example, the waveguide design reported in [10] allows for HCG thickness tolerance of 30–40 nm, which is well above modern epitaxial specifications.

In this Letter, we present for the first time (to our knowledge) the unique dispersion characteristics of HCG waveguides that can lead to a large group index. This capability in hollow-core structures stems from an interesting feature of HCGs: an ability to develop internal resonances. The HCG resonance phenomenon was reported previously [12,13] in surface normal incidence configurations. However, uniquely in this work, the incident beam has a shallow, glancing incidence angle rather than surface normal to HCG. Leveraging the resonance in HCG cladding as a mechanism, we show a promising approach to obtain slow light that is based on the fact that the resonance coupling is direct, unlike most CROWs, which are based on evanescent resonance coupling. In addition, we demonstrate an easy and fast calculation technique capable of resolving the ω-k bands that is based on external reflectivity dips, without the need to simulate pulse propagation through the waveguide.

First, let us briefly describe the resonance mechanism of HCGs, a detailed description of which is available in [12–14]: As the wave is incident onto a grating, it excites several grating eigenmodes, which propagate outward toward the HCG output plane with different wavenumbers [13–15]. The phases accumulated by each mode while traversing through the HCG can be elegantly represented using the diagonal propagation matrix φ [15]. Upon reaching the HCG output plane, the modes either (i) leak...
outside, (ii) reflect, or (iii) couple into each other’s reflections. This can be represented by a reflection matrix $\rho$, the diagonal parts of which, $\rho_{ii}$, represent self reflections, while the off diagonal parts, $\rho_{ij}$, represent coupling into each other’s reflections [15]. By properly adjusting the thickness of the HCG, the phases accumulated by the modes can be matched in such a way that the outside leakage is canceled, and the energy is maintained inside through either reflection or mutual coupling. The mathematical condition for this is $\det[1 - (\rho \rho^T)] = 0$, $\rho$ being a unit matrix [13]. This equation is the multimode generalization of the well known Fabry–Perot resonance condition. Similarly to the resonators in CROW structures, HCG resonances are also accompanied by high phase dispersion, allowing efficient manipulation of waveguide group velocity.

The most intuitive way of obtaining $\omega-k$ characteristics of a waveguide is by simulating pulse propagation, using tools such as finite-difference time-domain (FDTD). The disadvantages of such approaches are long simulation time and/or precision trade-offs owing to finite spatial and spectral resolution. On the other hand, methods based on rigorous coupled-wave analysis (RCWA) of grating structures [16] rely on analytical solutions and thus are fast and precise. The main limitation of RCWA is that it is most suitable for calculating reflection of diffraction orders and typically does not provide direct information about waveguide modes. Therefore being able to infer waveguide $\omega-k$ characteristics from reflection spectra is necessary to leverage the advantages of RCWA. For the hollow-core waveguide, we can extract $\omega-k$ characteristics elegantly by simply sweeping the incident angles of a plane wave externally incident onto a waveguide (double stacks of HCG separated by core size $D$) at a given fixed frequency $\omega_i$ as shown in Fig. 1(b). We obtain a series of sharp resonant dips in the reflectivity versus angle plot. These dips represent the incidence angles for which a phase-matching condition with the waveguide mode is satisfied. The phase-matching condition dictates that the longitudinal wavenumber ($k_z$) of the incident wave must be identical to the longitudinal wavenumber ($k_z$) of the waveguide mode. Therefore, for a given frequency $\omega$, $k_z$ values of the guided modes can be obtained in a very rapid manner with high precision using the herein named swept-angle RCWA. The set of resonant incidence angles $\theta_{m}$, which are also shown in Fig. 1(b), can then be translated into the corresponding longitudinal wavenumbers $k_z = (\omega/c) \sin(\theta_{m})$, which represent the set of waveguide modes at frequency $\omega$. By repeating the same process for other frequencies, $\omega-k$ curves of the waveguide eigenmodes can be obtained.

It should be noted that, although very intuitive, the described method is of limited use for photonic crystal waveguides or even for traditional index-guided waveguides, since it cannot provide information on modes with phase velocity smaller than $c$ (along the $z$ direction). This is because for such modes, the profile along $\hat{x}$ is evanescent (in air) and thus the corresponding external incidence angles $\theta_{m}$ would have nonphysical imaginary values. Unlike photonic crystals and index-guided waveguides, the hollow-core HCG waveguide is uniquely suitable for the swept-angle RCWA method of inferring the $\omega-k$ relations. This is because in the case of HCG waveguide, modes with phase velocity smaller than $c$ are of no interest, since those modes propagate inside the HCG walls rather than inside the waveguide core, and their fields extend into the waveguide core only evanescently.

The $\omega-k$ curves of a typical HCG waveguide, inferred by the method described above, are presented in Fig. 2, which also includes a comparison to the simple hollow-core waveguide bound by perfect electric conductor (PEC) walls. The polarization of the HCG waveguide modes throughout this Letter is TE (i.e., field components are $E_y, H_x, H_z$). TM polarization produces similar results, but the HCG dimensions should be separately designed for each polarization. Figure 2(a) shows that at frequencies $\omega$ that are far from HCG resonance frequencies, there is no significant difference between HCG waveguide modes and PEC waveguide modes. The HCG waveguide mode condition is, in fact, a generalization of the PEC waveguide mode condition, accounting for the phase of the HCG: $k_D + \Phi_{HCG} = m\pi$, where $m$ is an integer representing the number of the mode and $\Phi_{HCG}$ is the reflectivity phase of HCG. According to this condition, the convergence between PEC waveguide modes and HCG waveguide modes is not surprising, since the phase of HCG away from resonance converges to a multiple of $\pi$, as shown in Fig. 2(b).

An interesting transition occurs as the frequency is swept up and reaches HCG resonance frequency: the $\omega-k$ curves of HCG waveguide modes (Fig. 1 solid curves) depart from the $\omega-k$ curves of PEC waveguide modes (Fig. 1 dashed curves) and downward toward the curves of lower PEC waveguide modes, eventually converging again. This transition can be explained by Fig. 2(b), which shows that the phase change accumulated by HCG through one resonance is $\pi$. Similarly, if the HCG has two resonances close to each other in frequency (each contributing a $\pi$ phase shift), as shown in Fig. 3, the waveguide exhibits a downshift of two modes (from third
to first, from fourth to second, etc.). Here, "close in frequency" means closer than the spectral window of a single mode downshift, $\Delta \omega$, which according to Fig. 2(a) is on the order of $\Delta \omega \sim 0.05 \pi c/\Lambda$ for the lowest modes. If the two resonances are separated further from each other, the double downshift will split into two single downshifts. The lowest modes [first in Fig. 2(a) and first and second in Fig. 3] do not have a PEC waveguide mode to downshift to. Instead, they downshift outside the escape cone, i.e., below the light line, and therefore are no longer detectable by the RCWA method described above. Downshifting below the light line means that as the frequency is swept up through the resonance, the energy of these lowest modes shifts gradually from the waveguide core into the HCG walls, until these modes become fully guided in the walls. The evolution of the $E$-field profile across the waveguide core, during the mode downshift process from the second mode to the first, is depicted in Fig. 2(c), using a ray optics approximation that takes into account the HCG reflectivity and phase. During the downshift, the mode profiles are shown to evolve from a double-peak antisymmetric profile to a single-peak symmetric profile. The diminishing magnitudes during the downshift are a result of the resonant dip in HCG reflectivity, as shown in Fig. 2(b). This dip in reflectivity causes part of the light to leak outside the waveguide, the most extreme case of which is at the resonance center, when the reflectivity drops to zero and thus the mode profile becomes identically null [horizontal line in Fig. 2(c)]. Identical null is the only function that is both symmetric and antisymmetric, and therefore no continuous downshift from antisymmetric to symmetric profile (or vice versa) can happen without it. Obviously, the tradeoff of group index versus loss (leakage), detectable by the diminishing magnitudes in Fig. 2(c), is a common tradeoff in many designs involving resonances. A clear slow-light design principle emerges from Fig. 2: The more closely spaced resonances the HCG wall has, the sharper the downshift, and the slower the group velocities that can be achieved. Using the paradigm of slow light facilitated by HCG phase dispersion, our collaborators have performed initial group-velocity optimizations for a TM polarization, predicting a group index of 7 over 15 nm optical bandwidth with propagation loss below 1 dB/mm [17].

In conclusion, in this Letter we presented for the first time (to our knowledge) the unique dispersion properties of the high-contrast grating hollow-core waveguide. We demonstrate a mode downshift phenomenon whereby, as a result of HCG resonance, the HCG waveguide modes shift from higher to lower PEC waveguide $\omega$-$k$ lines. We show a simple explanation of this phenomenon using the phase of the HCG and explain how slow light can be designed by placing multiple HCG resonances together. We also present a simple method to quickly and precisely infer the $\omega$-$k$ characteristics of the waveguide from external reflection calculations using swept-angle RCWA.

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