Efficient antiguiding without omnidirectional reflectors

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Abstract: Reflector omnidirectionality is not always necessary for efficient anti-guiding of arbitrary polarized modes in low-index core photonic band gap waveguides. In some regimes "low" and "high" index-contrast reflectors can confine "bad" TM polarization equally well.

OCIS codes: 310.2790 Guided waves; 230.1480 Bragg reflectors

1. Introductrion

Anti-guiding waveguides such as hollow Bragg fibers [1, 2], microstructured fibers [3, 4] and multi-layer planar waveguides [5, 6] are able to guide light through the gaseous or low refractive index cores, achieving radiation confinement by a surrounding photonic crystal reflector. Hollow core fibers promise low transmission losses at almost any wavelength for high power guidance, as well as efficient guidance through low refractive index liquid cores for biological sensing and chemical characterization applications [7]. In [8] omnidirectional (OD) reflector was described stating that a high index contrast planar periodic reflector can be designed to completely reflect an incoming light in a certain frequency range for any angle of incidence and any state of polarization. It is frequently believed that to enable efficient anti-guiding of both polarizations (TM being most problematic) an OD reflector is needed as a part of a waveguide design. Although a good counterexample is a hollow silica based microstructured fibers that guide with non OD reflectors, the question of anti-resonant waveguide guiding efficiency as a function of core and reflector indexes in an interesting one. In large core 2D waveguides and Bragg fibers ray picture of guiding is applicable where a well defined incidence angle onto a reflector can be assigned to a core mode propagating by consecutive reflections from a PBG mirror. In this regime, to guarantee low loss guiding it is necessary to design an efficient reflector for all polarizations, but only a narrow range of incidence angles around an effective incidence angle of a core mode. This design condition is considerably less restrictive than that of an OD reflection leading to some regimes when "low" and "high" index contrast reflectors can confine both polarizations equally effective.

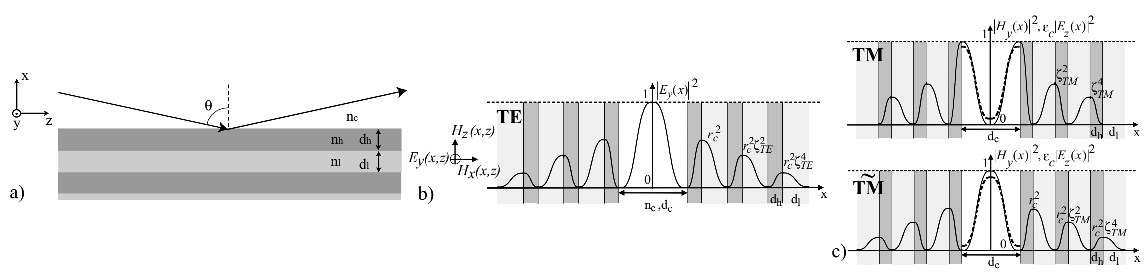

Fig. 1. a) planar PBG reflector ; planar hollow PBG waveguide and fundamental b) TE c) TM, $\tilde{TM}$ modes

2. Efficient guiding of both polarizations in low refractive index core waveguides

We consider performance of reflectors made of a periodic sequence of dielectric layers which is the case in Bragg fibers and planar waveguides. In Fig. 1(a) schematic of a reflector made of a periodic sequence of high n_h and low n_l refractive index layers of thicknesses d_h and d_l is presented. Refractive index of a material above the reflector (core material) is n_c. The angle of radiation incidence is fixed and equal to θ. Transfer matrix theory can be used to relate electromagnetic fields in adjacent layers. It concludes that for a given frequency ω and a fixed angle of incidence θ a quarter wave stack with thicknesses $d_h k_x^{n_h} = d_l k_x^{n_l} = (2p+1)\pi/2$, $k_x^n = \omega\sqrt{n^2 - n_c^2 sin^2(\theta)}$ maximizes reflection for both TE and TM polarizations. For such an optimal reflector, field decay rate per reflector bilayer (reflector efficiency) is given by a factor ζ, which for TE polarization (electric field is parallel to the reflector plane) is $|\zeta_{TE}| = k_x^{n_l}/k_x^{n_h}$. Thus, in a bilayer j field intensity is $\sim \zeta^j$. In Fig. 2(a) schematic of a TE filed decay rate is presented featuring monotonically increasing reflector efficiency for oblique angles of incidence. Reflection of TM polarization (magnetic field is parallel to the reflector plane) is more challenging, and depending upon the value of a core index two cases are

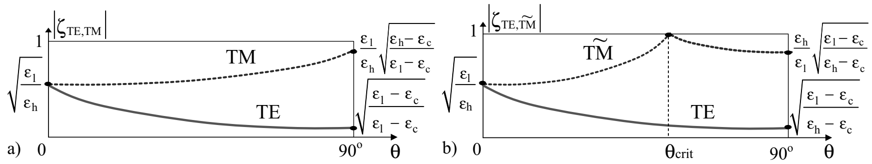

Fig. 2. Radiation decay rates into the reflector optimized for incidence angle θ a) $\epsilon_c < \epsilon_{crit}$ b) $\epsilon_c > \epsilon_{crit}$.

possible. If $\epsilon_c < \epsilon_{crit}$ (TM regime), where $\epsilon_{crit} = \epsilon_h\epsilon_l/(\epsilon_h + \epsilon_l)$ one finds that $|\zeta_{TM}| = (\epsilon_l k_x^{n_h})/(\epsilon_h k_x^{n_l})$ which is presented in Fig. 2(a). While reflection of TM polarization is worse than reflection of TE polarization, nevertheless, for any angle of incidence one can still design a reflector that reflects both polarizations. If $\epsilon_{crit} < \epsilon_c < \epsilon_l$ ($\tilde{TM}$ regime), then $|\zeta_{TM}| = (\epsilon_h k_x^{n_l})/(\epsilon_l k_x^{n_h})$ which is plotted in Fig. 2(b). As before, reflection of TM polarization is worse than reflection of TE polarization, moreover, there exists an incidence angle $\theta_{crit} = sin^{-1}(\epsilon_{crit}/\epsilon_c)$ for which it is impossible to design an efficient reflector as $|\zeta_{TM}(\theta_{crit})| = 1$. We now consider performance of reflectors for oblique incidence angles $\theta \sim 90^o$, $k_z \sim \omega n_c$ which is relevant for modal propagation in large core planar waveguides Fig. 1(b), and Bragg fibers with $d_c \gtrsim 10\lambda$. To characterize anti-guiding efficiency of a large core waveguide, in Fig. 3(a) we present universal contour plots of the radiation decay rates into the reflector for TE and TM polarizations as functions of the relative multilayer indexes (normalized by n_c). Note, that for TM polarization there are two distinct regions of phase space denoted on Fig. 3(a) as TM when $\epsilon_c < \epsilon_{crit}$, and $\tilde{TM}$ when $\epsilon_{crit} < \epsilon_c < \epsilon_l$. In each of the regions one finds contour lines of material parameters corresponding to the same field decay rate. For example, a polymer based "low" index contrast reflector $n_l = 1.414$, $n_h = 1.6$ anti-guiding (in the $\tilde{TM}$ regime) in a liquid core $n_c = 1.32$ will have the same TM field decay rate of ~ 0.72 per bilayer as a "high" index contrast OD reflector with indexes $n_l = 1.414$, $n_h = 2.5$ guiding (in the TM regime) in the air $n_c = 1$ or liquid $n_c = 1.32$.

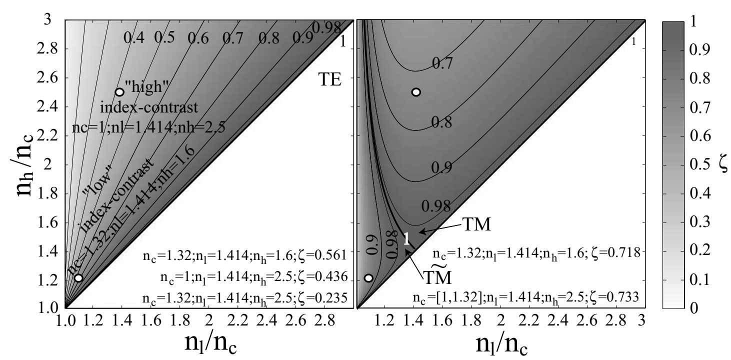

Fig. 3. Field decay rates into the optimal reflector at $\theta \sim 90^o$

Finally, we comment on field distribution in fundamental modes of a low core index planar waveguide with $d_c k_x^{n_c} = \pi$. In Fig. 1(b) electric field of a TE polarized mode is shown, where $r_c \simeq \lambda/d_c$. Starting with this field distribution it can be demonstrated that modal radiation and material absorption losses scale as d_c^{-3} (similar scaling is observed for TE_{0n} modes of Bragg fibers). For TM polarized modes two cases are possible. In Fig.1(c) magnetic (solid curve) and electric (dotted curve in the core) fields are presented, where $|E_z^{core}(x)| \ll |E_x^{core}(x)| \simeq |H_y^{core}(x)|/n_c$. In TM regime field content in the core is considerably different from that in the TE case, leading to d_c^{-1} scaling of transmission losses with a core size (similar scaling is observed for HE, EH modes of Bragg fibers). In $\tilde{TM}$ regime electric field distribution in the core becomes similar to that of a TE case, thus leading again to a d_c^{-3} dependence of transmission losses even for a TM polarized mode! This analytical result for planar reflectors has been also confirmed for Bragg fibers.

3. References

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