Slow Light Propagation in Annular Photonic Crystal Linear Waveguides

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***Abstract*-A linear waveguide defined in an annular photonic crystal is shown to guide light with low group velocities, irrespective of polarization. The guided modes are shown to exhibit an almost linear dispersion in the middle range of the normalized band structure, leading to very low group velocity dispersion.**

I. Introduction

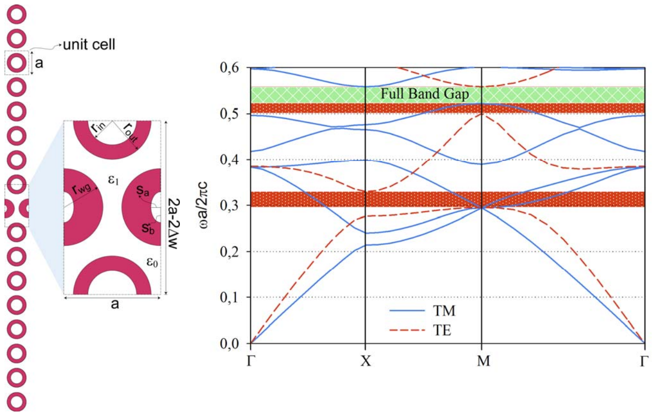
Propagation of light waves in photonic structures with low group velocities is required in many applications ranging from optical data storage and buffering to enhancement of optical nonlinearities [1,2].

Linear waveguides in photonic crystals are good candidates to achieve slow light propagation and on-chip integration of slow-light devices [2,3]. By carefully tailoring the band structure of a linear waveguide, it is possible to achieve slow-light propagation with group indices $n_g=v_g/c$ as low as 40-50, where $v_g=d\omega/dk$ is the group velocity of the guided wave and c is speed of light in vacuum [4-6]. However, group velocity dispersion (GVD), $\beta_2=d^2k/d\omega^2=d(v_g^{-1})/d\omega$, is an important entity limiting performance of a slow-light device [4-6]. Therefore, a design must take care of GVD, while minimizing group velocity.

Considering that most waveguides in two-dimensional (2D) photonic crystals guide only one polarization, it is desirable to design a linear waveguide that is capable of both polarization-insensitive guiding and facilitating slow-light propagation with low GVD. Annular photonic crystals, which are 2D structures to yield the maximum overlapping of the band gaps for transverse-electric (TE) and transverse-magnetic (TM) modes are good hosts for this purpose [7,8]. This study focuses on achieving low group velocity and group velocity dispersion by design of a linear waveguide in an annular photonic crystal.

II. Material and Computational Methods

Geometry and physical parameters of the linear waveguide are chosen such that the width of the so-called full band gap of the underlying square annular photonic crystal is maximized and overlapping of the guided even TE and TM modes within the gap is optimized [8]. The investigated structure is depicted on Fig. 1(a), where the unit cell is indicated and the waveguide region is enlarged. The physical parameters for the unit cell are $\varepsilon_1=13$, $r_{in}=0.251a$ and $r_{out}=0.396a$, where the lattice constant, a, is 0.730µm. Band structure computations are carried out via the Plane Wave Expansion Method (PWE) [9]. Band structure for the given parameters is presented on Fig. 1(b).



(a) (b)

Fig. 1-(a) The waveguide geometry to facilitate polarization-insensitive slow-light propagation, (b) band structrure of the indicated unit cell (dashed box) for the maximized full band gap.

The guide geometry is represented by the four parameters presented on Fig. 1(a) and these parameters are optimized by means of Simplex Algorithm to yield maximal overlap of the guided polarizations [8]. The search is based on minimizing the sum of squares in the difference of the normalized band structures of the guided modes [10]. The optimal parameter set is $\{r_{wg}, s_a, s_b, \Delta w\} = \{0.392a, 0.0899a, 0.156a, 0.0558a\}$.

Once overlap is achieved, variation of the group velocities, v_g, of the modes with respect to normalized wave number is obtained by differentiation. The GVD is also determined and plotted in the wavelength range of interest (1.32-1.40µm).

III. Results

Dispersion of the guided even modes within the full band gap is presented in Fig. 2. It is seen that the curves are flat at the edges of the wave number range, leading to very low group velocities. However, the most remarkable feature is almost linear variation in the mid k-range for both modes. The linear variation covers almost half of the k-range, where group velocity of the modes is around $c/13$ (c being the speed of light in vacuum). Although this value is large compared to the values reported in the literature, its significance lies in the polarization insensitivity. Furthermore, experience in the implementation of the Simplex Algorithm has shown that slope of dispersion curves are highly sensitive to variations in the semi major axes (s_a and s_b) of the core region of the guide. Actually, essentially flat bands leading to group velocities below $c/50$ for individual polarizations are observed by

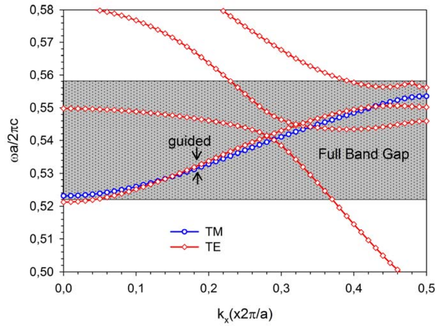
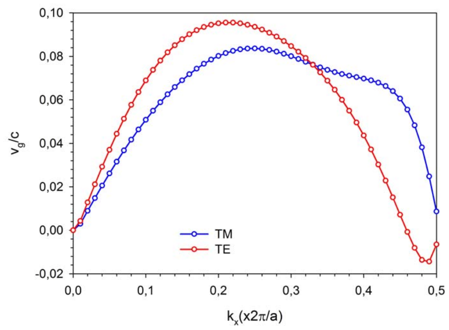


Fig. 2-Dispersion of the guided modes (indicated by arrows).

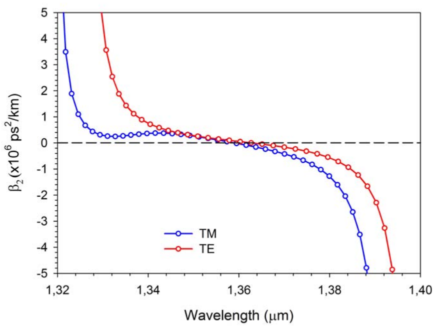
carefully adjusting these parameters. An effort is put on achieving optimal overlapping where low group velocities are maintained.

Fig. 3(a) presents the variation of group velocities of the modes with respect to normalized wave number. It is seen that v_g is always below $c/10$ and similar values of it is obtained for the TE and TM guided modes in mid k-range. The curves cross around k_x=0.30 and working with incident pulses around that point might lead to polarization-insensitive slow light propagation.

Group velocity dispersion, β_2, in the wavelength range of interest is presented in Fig. 3(b). Although very large values are observed at the two extremes, values very close to zero are obtained at the mid-range. This means transmission of signals almost without distortion, regardless of the polarization.



(a)



(b)

Fig. 3-(a) Variation of group velocity with respect to normalized wave number, (b) group velocity dispersion of the guided modes in the investigated wavelength range.

After achieving overlapping TE and TM modes with lower group velocities, Finite-DifferenceTime-Domain (FDTD) simulations will be run to demonstrate slow light propagation in the designed linear waveguide.

IV. Conclusion

Light propagation with low group velocity in a linear waveguide in an annular photonic crystal, irrespective of polarization, is investigated. TE and TM guided modes are found to be guided with group velocities around $c/13$ with almost zero GVD at the center of the investigated wavelength range. Possibility of reaching lower group velocities by varying the design parameters of the guide, while maintaining the overlap of the modes is discussed.

Acknowledgment

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