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Artificial Second Order Non-Linearity in Photonic Crystals.

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ABSTRACT

We describe a technique for obtaining effective second order non-linearity χ^2 in non centro-symmetric Photonic Crystal made from centro-symmetric materials (e.g. glass, Ge or Si). The effect is based on the electric quadrupole transition, strong electromagnetic mode deformation and different contributions to the volume polarization from different parts of the photonic crystal[1].

INTRODUCTION

Many new application based on different physical phenomena are feasible now with the help of photonic crystals. Possibility to design photonic density of states and spatial electromagnetic modes structure open new ways for creation of materials with extraordinary optical properties.

The second order nonlinear materials are highly required both for fundamental research and for industrial applications. Unfortunately there are many constrains that limit the choice of such materials: the value of χ^2 should be reasonably high, absorption in required spectrum should be low, high damage threshold is required and finally to possess second order non-linearity the materials has to be non-centro-symmetric. The latter immediately eliminates all amorphous materials (like glass or Silicon) and crystals from 11 of 32 symmetry classes. Hence the technology that allows fabrication of non-linear materials from previously unsuitable centro-symmetric substrates can significantly enlarge the material choice for non-linear optics.

A local second order polarization $P^{(2)}$ exists even in centro-symmetric materials due to the higher than dipole electromagnetic transitions[2]. The asymmetry of the electromagnetic field spatial mode leads to quadrupole transition, while dipole transition is based on the asymmetry of the electron wave function. The second order polarization corresponding to a quadrupole transition is:

$$\vec{P}_Q^{(2)} = Q \vdots \vec{E}\nabla\vec{E} \qquad (1)$$

where Q is a fourth-order tensor. Generally the volume contribution of eq. (1) polarization vanishes, due to periodicity of electromagnetic mode and gradient dependence of quadrupole transition polarization. However the result in properly designed photonic crystals can be quite different.

Integration of eq. (1) over the volume in dielectric/air photonic crystal can be different from zero due to not equal contribution to volume polarization from different parts of the crystal. The polarization of the air regions can be totally neglected due to low electron density. Constructing photonic crystal in such a way that in dielectric part the quadrupole polarization has one sign and in the air the opposite, effective "structural" volume polarization can be obtained. The required symmetry breaking is introduced on the macroscale of the photonic crystal unit cell, contrary to atomic scale asymmetry in ordinary non-linear materials. Electromagnetic mode inside photonic crystal can be highly modulated[3], leading to large $\nabla\vec{E}$ term.

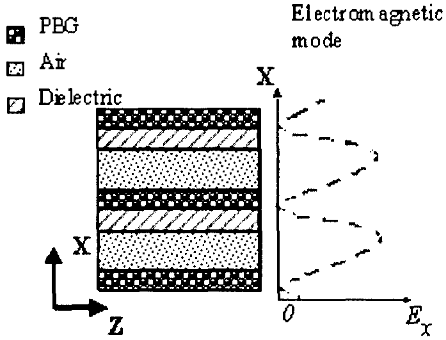

Figure 1: Array of waveguides in Photonic Band Gap Crystal. The electromagnetic mode with frequency inside the gap is strongly modulated in this structure.

The theoretical analysis leads to the following estimation for effective second order susceptibility $\chi^{(2)}_{str}$ induced by quadrupole effect:

$$\chi^{(2)}_{str} = \frac{d}{\lambda}\eta\beta_{overlap}\chi^{(2)}_{real} \qquad (2)$$

where d is characteristic interatomic dimension, λ is radiation wavelength, η is numerical coefficient (generally ≥ 10) that indicates the difference between dipole and quadrupole transition matrix elements, $\beta_{overlap}$ (generally ≈ 1) depends on eletromagnetic modes structure inside the photonic crystal and $\chi^{(2)}_{real}$ is some characteristic value for ordinary second order susceptibility. From previous experiments on the surface non-linear effects in Si and Ge, it is possible to estimate that $\chi^{(2)}_{str}$ in photonic crystals made from these substrates can be comparable with second order susceptibilities of ordinary non-linear materials. This result (2) is valid for both 2D and 3D properly designed photonic crystals[1].

Photonic crystals with strong spatial modulation of electromagnetic field are the preferred structures for the proposed method. In photonic crystal strong modulation can be obtained due to spatial photon density of states modification by defects incorporating or due to initially modulated electromagnetic mode[3]. We will concentrate on specific structure: the photonic crystal that consists of periodic defects lattice in the Photonic Band Gap environment. A single defect in PBG environments can possess localized modes for frequencies inside the gap. This means that for such frequencies in periodic lattices of defects, the mode might not be localized, but strongly modulated. This structure, in our opinion, should provide the maximum effect and its fabrication is feasible.

The defects should be asymmetric and possess dielectric/air structure. In this case maximum volume contribution of polarization (after integration of eq. 1) can be obtained. In our opinion the hollow cavities, partially filled with the substrate's material, are the best candidates for the proposed method.

RESULTS

The specific case of Optical Parametric Oscillations (OPO) in array of air waveguides inside Photonic Band Gap Crystal was numerically and theoretically studied. The mode modulation in such structure achieved due to lower photon state density in PBG environment and strong light confinement inside the waveguides. The required break of symmetry was introduced by partial dielectric filling of the waveguides (see Figure 1).

The numerical simulation of light propagation in such structure (see Figure 2) clearly shows that asymmetric modulated mode can be achieved leading to non-vanishing bulk quadrupole polarization. The analysis of the obtained results[1] proves that the prediction (2) is valid.

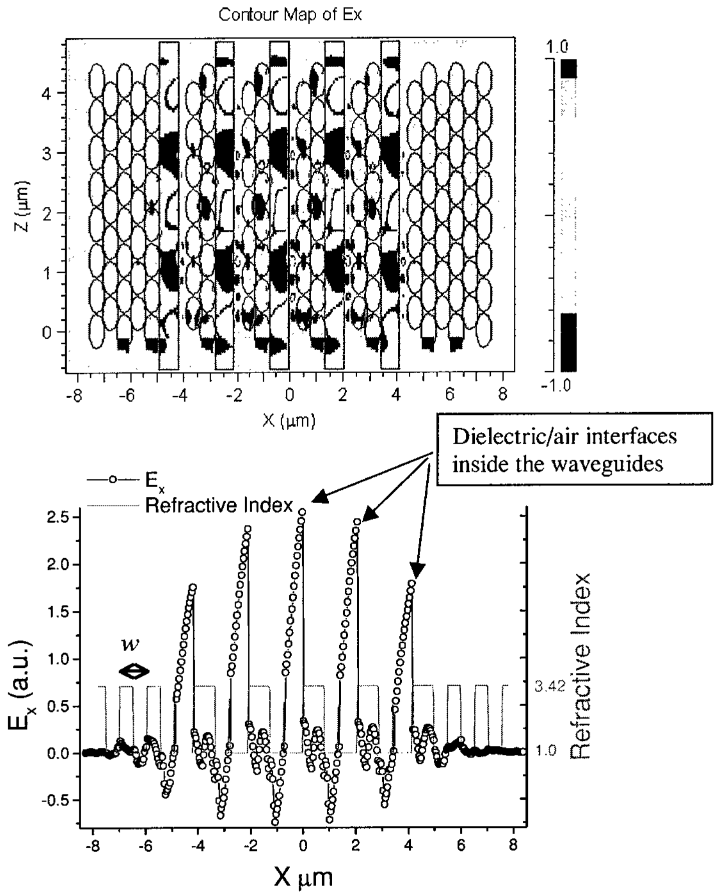

Figure 2: Numerical FDTD simulation results for TE electromagnetic mode propagation in waveguide array in 2D PBG crystal. PBG is a hexagonal array of holes in Si substrate (lattice constant *a=0.6 μm, r/a = 0.48*). Waveguides are obtained by removing of the array of the unit cells and separated by the single unit cell. They are partially air filled (*w = 0.7 μm*). It leads to asymmetric mode structure. The simulation was performed with FullWave commercial software.

DISCUSSION

The proposed non-linearity is the intrinsic property of photonic crystals. Indeed the spatial mode modulation can be achieved without PBG, but it is extremely difficult to create an asymmetric dielectric/air high-Q resonator. All ordinary resonators (waveguides, spheres or microdisks) are highly sensitive to any geometrical or refractive index perturbations. Defects in PBG environment are much more robust and flexible resonators, which can accomplish the task. Not surprisingly the guiding of light in air was accomplished with the help of photonic crystals[4], by creation a defect in PBG environment or by "SuperMirror" waveguide.

For efficient non-linear process phase matching conditions have to be satisfied. Otherwise the signal from different points along propagation will be in destructive interference. Generally in most ordinary non-linear materials this condition can be influenced only by change of the propagation direction. Another method is achieving artificial phase matching by periodic modulation of the sign of non-linear tensor coefficient. It can be done e.g. in ferroelectric crystals using periodic poling. In non centro-symmetric Photonic Crystals modulation of the non-linear coefficient can be introduced during fabrication by inversion of unit cell structure (see Figure 3).

Integrated optics is one of the possible future applications for structural $\chi^{(2)}_{str}$ materials. Broad use of ordinary non-linear materials in integrated optics is limited due to incompatibility of different processes and high production price. Creation of effective non-linearity from wafer's substrate itself can solve these problems.

The current attenuatiation losses in 2D waveguides are high, due to radiation losses in the third direction. It is a technical (not fundamental) problem to the implementation of the proposed method by this technology, as well as for the entire 2D technology itself. There is a great effort by many groups to bring these losses to the level of ordinary integrated optics (sub cm-1). The problem of losses is much less crucial in photonic crystal fibers and 3D photonic band gap waveguides due to all 3D confinement of the propagating light. Also some extremely deep 2D Si photonic crystals[5] may be suitable for checking the proposed concept.

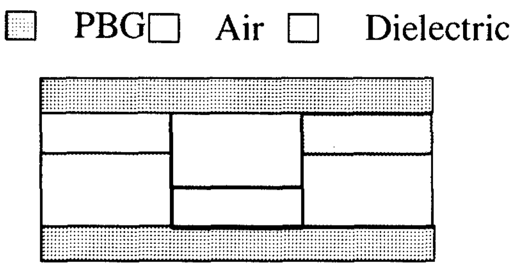

Figure 3: Unit cell inversion in non-centro-symmetric photonic crystal may be used for Quasi Phase Matching

CONCLUSION

It was shown that properly designed photonic crystals from centro-symmetric materials (glass, Si or Ge) can posses effective second order non-linearity of the same order as ordinary non-linear materials.

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