JOURNAL OF OPTOELECTRONICS AND ADVANCED MATERIALS Vol. 14, No. 3-4, March – April 2012, p. 371 - 375

Beam propagation and non-linear effects in photonic crystal optoelectronic devices

R.-F. STANCU[a,b*], P. STERIAN[a]
[a]*Academic Center for Optical Engineering and Photonics, Faculty of Applied Sciences, University "Politehnica" of Bucharest , Romania*
[b]*Optoelectronica-2001 SA, 409 Atomistilor Street, 077125 Magurele, Ilfov*

This paper investigates trough computer simulations the properties of photonic crystal optoelectronic devices regarding the beam propagation and nonlinear effects. Using Optiwave FDTD software, computer simulations were made for 2D photonic crystal micro-cavities and optical fibers. The results confirmed the theoretical data found in literature and generated important conclusions about the light transmission and nonlinear effects in the studied photonic crystal devices. It was shown that two important nonlinear effects in resonant micro-cavities are the optical bistability and harmonic generation, while in photonic crystal fibers, the influence of nonlinear effects seems not very significant.

(Recieved September 8, 2011;

Keywords: Photonic crystal, Micro-cavity, Fiber, Nonlinear effects

1. Introduction

The intensive research in advanced materials like photonic crystals led to the development of different advanced optoelectronic devices, like micro-cavities and photonic crystal fibers [1,10-11].

In this paper our main interest was to verify some theoretical considerations about the mathematical models, which describe the special properties and beam propagation through photonic crystal devices. Then, we highlighted the utility of FDTD method in 2D photonic crystal computer simulations to show the influence optical bistability, harmonic generation and other nonlinear effects in two types of photonic crystal devices: resonant micro-cavities and fibers. Results showed interesting facts about the above mentioned nonlinear phenomena and how they influence the beam propagation trough photonic crystal devices.

2. Theory

2.1. Photonic crystals

In 1991, E. Yablonovitch highlighted, through theory and experiments, the "photonic band gap" (PBG) materials, later known as photonic crystals.

Photonic crystals are defined as artificial periodic structures capable to forbid the electromagnetic field propagation in certain frequency bands on one, two, or even on all three spatial directions. [1]

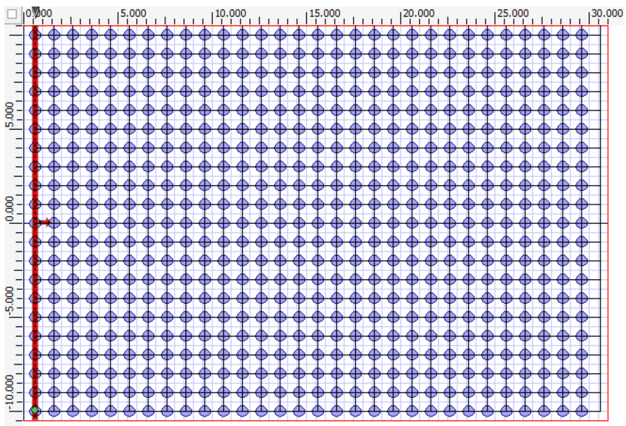

Fig. 1. 2D photonic crystal square lattice designed in Optiwave FDTD.

The most common known photonic crystal is the one made from a basic environment having an ε_{r1} electric relative permittivity, in which is introduced a matrix of cylinders (ε_{r2} electric relative permittivity). Consisting of a periodic succession of materials, the photonic crystals can be analyzed by the interaction between the electromagnetic waves and matter using the Maxwell equations. [2, 3] The equations that are used in determining the dispersion diagrams and the forbidden band gap structure of photonic crystals are:

$$\nabla \times \left(\frac{1}{\varepsilon_r(r)} \nabla \times H(r) \right) = \frac{\omega^2}{c^2} H(r) \quad (1)$$

$$\frac{1}{\varepsilon_r(r)} (\nabla \times [\nabla \times E(r)]) = \frac{\omega^2}{c^2} E(r) \quad (2)$$

The special quality of the photonic crystals to forbid the electro-magnetic field on all directions in specific spectral ranges offers the possibility to design different useful optoelectronic devices, like resonant micro-cavities, optical fibers and so on.

2.2. Photonic crystal micro-cavities

A photonic resonator is made by modifying the crystal's structure in certain region. In the resonant cavity design we have to take in consideration the fact that it must admit frequency modes placed in the forbidden band gap. There is no simple mathematical procedure to realize this, but the cavities geometry can be repeatedly switched until the desired result is obtained.

In the case of photonic crystal micro- cavities, FDTD and PWM can be combined o obtain clear conclusions about them. So, with PWM the cavity modes can be evaluated, and after that, the resulting data can be used in FDTD to obtain the field maps and calculate precisely the frequency for each mode. [4, 5]

Another important element that must be determined is the cavity quality factor, noted with Q. The idea is to have a qualitative image on each mode's lifetime regarding the side length. The quality factor is a physical measure that compares the frequency at which one system oscillates with the rate of energy dissipation. For example, a big value of Q corresponds at a small dissipation rate in comparison with the oscillation frequency. Also, a small value of Q will correspond at a high dissipation rate. [2, 3]

2.3. Photonic crystal fibers

The use of a 2D photonic crystal as cladding of an optical fiber is possible by choosing as core a material that has a higher refractive index than the cladding. A good example of such structure is the photonic crystal fiber made out of a solid core surrounded by a triangular lattice of air cells. Those fibers are known as index-guiding photonic crystal fibers and are able to transmit light by total internal reflection. Other types of photonic crystal fibers are the hollow core ones. [6,7]

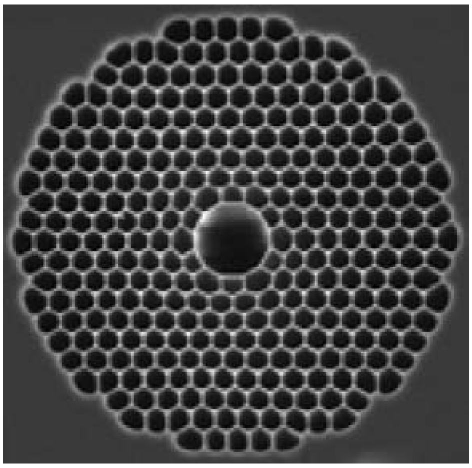

Fig. 2. Hollow core photonic crystal fiber [6]

2.4. Perturbation theory

If a material is only weakly linear, then there will be a small $\Delta\varepsilon$ shift in the dielectric function, that is proportional with the field's amplitude, either with its intensity. The perturbation theory is almost exact for many applications concerning optical nonlinearities, because the maximal changes in the refractive index value are usually lower than 1%. The results become interesting when perturbations are accumulating for a long period of time. Let's consider the condition applied to the electric field:

$$\nabla \times \nabla \times E(r) - \left(\frac{\omega}{c}\right)^2 \varepsilon(r) E(r) \qquad (3)$$

Because we are interested about the $\Delta\varepsilon(r)$ shifts, by applying the perturbation procedure on the last expression, we get a simple shifting relation for the $\Delta\omega$ frequency that results for a small $\Delta\varepsilon$ perturbation of the dielectric function

$$\Delta\omega = -\frac{\omega}{2}\frac{\int d^3 r \Delta\varepsilon(r)|E(r)|^2}{\int d^3 r \Delta\varepsilon(r)|E(r)|^2} + O(\Delta\varepsilon^2) \qquad (4)$$

In this equation, ω and E represent the frequency and profile modes for a perfect linearity and a ε dielectric function without losses. [2]

3. Optical bistability and harmonic generation in photonic crystal micro-cavities

In linear state, the light is transmitted through input and output channels by using a resonant tunneling process. Thus, we suppose that the input and output channels are two monomode waveguides, the rate between the output and input power being characterized by a Lorentz form:

$$\frac{P_{out}}{P_{in}} = \frac{1}{1 + \left(\frac{\omega - \omega_c}{\Gamma}\right)^2} \qquad (5)$$

where Γ represents the resonant width. From here, the resonant quality factor Q can be determined: $Q = \omega_c / 2\,\Gamma$.

Let's take in consideration when the linear state is changed by introducing, through physical mechanisms, the nonlinear response in the optical resonator. Let's consider that the nonlinearity in the system is introduced by a Kerr type material placed inside the resonator. It can be shown rigorously, by using perturbation theory argum-ents, that this nonlinear dependence can be written in a Lorentz form as follows:

$$\frac{P_{out}}{P_{in}} = \frac{1}{1 + \left(\frac{P_{out}}{P_o} - \Delta\right)^2} \qquad (6)$$

where P_0 is the so called cavity power characteristic, and Δ is the normalized frequency by the resonant width, $\Delta = (\omega_c - \omega_p)/\Gamma$.

To sustain this point of view, we considered the structure represented in figure 2. It is made from a photonic crystal that is comprised out of high electrical permittivity cells ($\varepsilon_r = 12$), introduced in a low value electrical permittivity dielectric material ($\varepsilon_r = 2$). A defect was introduced in the center of the structure by a slight growth of one of the cell's dimension (0.5a from 0.3a, in this case a = 1µm. This central defect was symmetrically coupled with two waveguides. If we suppose that the central cell is made from a nonlinear Kerr material, this structure can be considered to show bistability properties: if a wave is transmitted through the waveguide, the relation between the input-output will show bistability, in case the external illumination frequency and the resonant cavity are big enough. This is confirmed by the numerical calculus represented in figure 3, in which results obtained from the perturbation theory and nonlinear FDTD methods are compared. In this case we took $\Delta = 4$. Even if the quality factor Q is only 500, similar cavities can be designed for a much higher factor, while the light is confined in regions that are under the wavelength dimensions, something that can't be obtained directly by conventional Fabry-Perot devices.

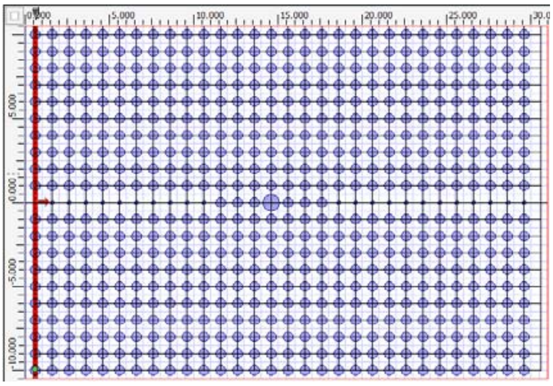

Fig. 3. Optical resonator coupled with two waveguides, made by enlarging the central PBG cell at 0.5a dimension, the other lattice cells having 0.3a dimension. The photonic structure was made using a basic environment having ε_r=2, in which a lattice of ε_r = 12 PBG cells was introduced

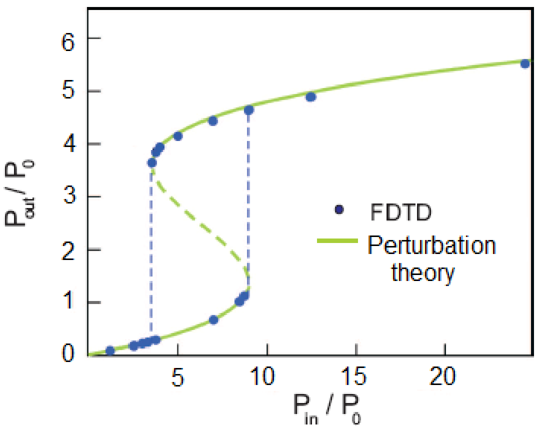

Fig. 4. The dependence of output power on input power simulated in FDTD

The nonlinear optical process can determine the harmonic generation in which the light at a certain frequency is converted into light having a multiplication of frequency: for example, a Kerr nonlinearity $\chi^{(3)}$, in which the material's polarization is proportional with E^3, that leads to a 3ω generation starting from ω.

In harmonic generation we can define the modal volume that reflects the spatial expansion and the mode intersection at the ω and 2ω frequencies. An efficient coupling coefficient that controls the harmonic conversion is inversely proportional with this value and it can be precisely defined using the perturbation theory. The advantage of using photonic crystals in this context is that they permit simultaneously obtaining high values for Q and confinement in small modal volumes.

Even if is clear that the double resonance could improve harmonic generation, it is not clear if 100% conversion can be obtained. If in the cavity a significant energy is accumulated at both ω_1 and ω_2, the frequency difference generation results in conversion from ω_2 to ω_1.

As it was observed in the case of bistability, when a cavity is pumped from one side, light can be reflected or it can go forward on another channel, the 100% appearing when the extinction rates in the cavity on both channels are identical. In case of harmonic generation, we considered a cavity with a single input/output channel that can operate at two frequencies: ω_1 is pumped from an entrance channel, the light is being either reflected, either is escaping to ω_2.

The rate of conversion depends on the power. If the power is too low, then the nonlinear conversion rate is low, and all the light is reflected to ω_1. If the power is to high, the rate of nonlinear conversion is also high, and so all the harmonic light escapes to ω_1. Between the two extremes there is a critical power P_0 when the rates are equal, and 100% of the entrance power is converted and escapes to ω_2. This evaluation was made considering the absence of other types of losses.

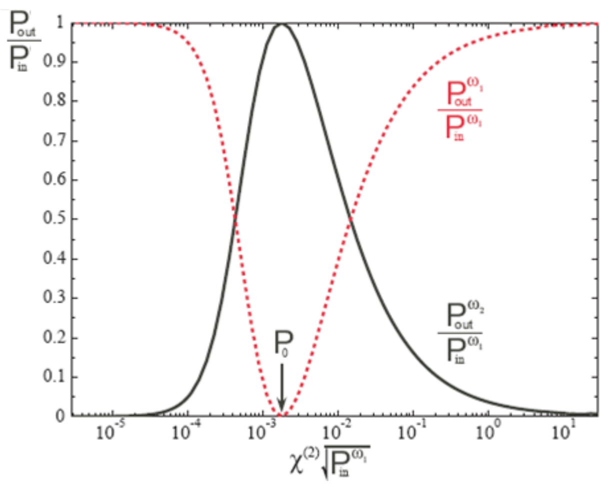

Fig. 5. Conversion efficiency made for $\omega_1 = 0.5\ 2\pi c/a$, $Q_1 = 10^5$, $Q_2 = 2\ Q_1$, $1/V_{HG} \approx 10^{-5} a^{-3}$, where a=1µm is the photonic crystal lattice constant

4. Nonlinear effects in photonic crystal fibers

The photonic crystal fibers are a class of optoelectronic devices useful in low loss transmission of optical pulses that have a certain wavelength. The optical modes o such devices are found in discrete bands. The band structure in photonic crystal varies with the chosen structural geometry.

By using FDTD method photonic crystal fibers were designed. Unlike the classical optical guides, in which the modeling was done by constructing an optical channel of certain length, by placing an electromagnetic radiation source at one end and the simulation of one wave pass through the whole system, in the case of photonic crystal fibers a system was elaborated in which we suppose the electromagnetic field already in the fiber and we verify its behavior in time, without introducing any other light sources.

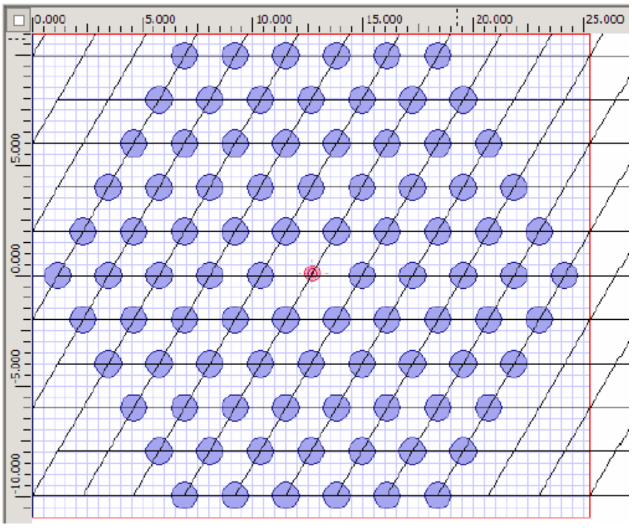

Fig. 6. Photonic crystal fiber design in Optiwave FDTD.

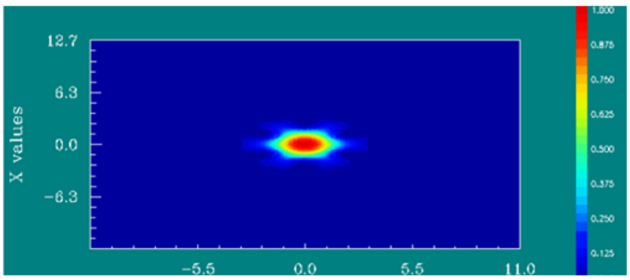

Fig. 7. Distribution of propagation modes in the designed fiber.

For a wavelength having the testing value of 1300 nm, 95% efficiency was measured for the designed fiber. Also, 3.5% of the total energy escapes outside the area of interest was noticed.

In both the optical fiber and dielectric core, there is a λ/a for which the effective area A_{ef} is minimized; for a hollow core fiber, $A_{ef} \approx 10.5\ (\lambda/2n)^2$ at $\lambda/a \approx 1.37$ ($k_z a/2\pi \approx 1.0$), and for the one with dielectric core, $A_{ef} \approx 4.02\ (\lambda/2n)^2$ at $\lambda/a \approx 1.46$. The reason why there is an optimum is the following: as λ is higher than a, the core is seen as a small perturbation, having large mode area and a reduced guidance. If λ is too low, then multiple wavelengths can propagate through the solid core. We observed that in the limit of $\lambda \ll a$, A_{ef} is close to a constant that is sometimes lower than the core area. This is in correspondence with the asymptotic prediction of limit scaling, which indicates that there has to be a fixed field pattern for low λ values.

By contrast, a standard Si mono-mode fiber, with an effective area of 50-80 μm^2 at λ=1.55 µm, or 175-280 $(\lambda/2n)^2$, and certain high nonlinear silica fibers have the A_{ef} around 10 μm^2 = 35 $(\lambda/2n)^2$. These high effective areas are translated directly in high power demands for nonlinear devices. Their nonlinear applications are further more limited by the drastic modifications of group velocity dispersion in low contrast waveguides. Thus, the nonlinearities in photonic crystal fibers are much lower, those fibers having the capacity to transmit long distance signals without nonlinear effects, like the signal crossover on different frequency channels [8-10].

5. Conclusions

The photonic crystal micro-resonators offer a unique light confinement mechanism, offering a combination of high quality factors and small modal volumes. This puts a lot of nonlinear processes in a new operating regime. For example, we have shown that optical bistability is strongly amplified in these systems. Also, the second or even third harmonic generation can be realized to operate with high efficiencies, at both input and output frequencies, in particular with 100% efficiency for low powers.

Also, we have shown that nonlinear effects in photonic crystal fibers are much lower, those fibers having the capacity to transmit signals on long distances without being influenced by nonlinear effects, like the signal crossover on different frequency channels.

In conclusion, all these nonlinear phenomena can offer the possibility of designing innovative and totally optical devices, of signal processing, operating at lower powers and switching times than in the case of classical nonlinear devices. These properties, combined with some key characteristics of the devices, like the micrometric dimensions and high integration possibilities, can make the photonic crystal cavities and optical fibers some of the most important pieces in developing integrated photonic technologies.

References

[1] Eli Yablonovitch, Physical Review Letters **58**(20), 2059 (1987).
[2] John D. Joannopoulos, Steve G. Johnson, Joshua N. Winn, Robert D. Meade, „Photonic crystals. Molding the flow of light." – Second Edition, Princeton University Press, New Jersey, SUA, 2008.

[3] Ninulescu, V.& Sterian, A. R. Dynamics of a Two-Level Medium Under the Action of Short Optical Pulses, Lecture Notes in Computer Science, LNCS **3482**, 635-642, Gervasi, O.et al. (Eds), Springer – Verlag, (2005), Berlin, Heidelberg. (2005).
[4] Lazăr Bogdan, Paul Sterian, Proceedings of SPIE, **5,** 631 (2007).
[5] Steve G. Johnson, „Computational Photonics. Frequency and Time Domain Methods", MIT Applied Mathematics, 2009
[6] Federica Poli, Annamaria Cucinotta, Stefano Selleri, „Photonic Crystal Fibers", Springer, Olanda, 2007
[7] http://www.rp-photonics.com/ photonic_crystal_fibers.html
[8] M. Dima, M. Dulea, D. Aranghel et al., Optoelectron. Adv. Mater. – Rapid Commun. **4**(11), 1840 (2010).
[9] C. Iliescu, M. Avram, B. Chen, et al., J. Optoelectron. Adv. Mater. **13**(2-4), 387 (2011).
[10] D. Mihalache, J. Optoelectron. Adv. Mater.. **13**(9), 1055 (2011).
[11] Stancu, R.F., Sterian, P., Optoelectron. Adv. Mater. – Rapid Comm. **4**(12), 2114 (2010).

*Corresponding author: radu_florin_stancu@yahoo.com