Report

INVOICE -IV th Period - Final Report

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Title

Parametric Interactions in One Dimensional Photonic Band Gap Structure

1. Summary

The aim of the work, is to study nonlinear parametric interactions, such as nonlinear frequency conversion and all-optical switching, in miniaturized photonic band gap materials. In particular, we wish to address highly efficient $\chi^{(2)}$ and $\chi^{(3)}$ processes in the short-wavelength range (less than 0.4 μm), and mid (3-5 μm) to far (8-12 μm) IR regions of the electromagnetic spectrum near the photonic band edge of one-dimensional photonic crystals. The work is performed in collaboration with the group of Dr. C. Bowden -Weapons Science Directorate -Missile Reaserach Development & Engineering Center -U.S. Army Aviation and Missile Command -redstone Arsenal, Al 35898-5000.

According to the previous reports related to the first 9 months of the contract, the work has been performed and continued following different activities, as described in technical report.

Technical Report

1. ***Parametric interactions in photonic band gap structures: applications to down conversion and up conversion. Third harmonic generation via chi(2) interaction.***

1a - High conversion efficiencies for parametric interactions in 1 D PBG structures have been predicted if the proper phase matching conditions are satisfied. Considering a three wave mixing process, and using our effective index model, we observed that phase matching conditions are satisfied in several different ways. This adds more flexibility in designing optimized real structures. We considered a down conversion process to generate a coherent IR field motivated by the apparent lack of cheap, compact, reliable laser sources in this wavelength range. We performed numerical simulations using a FFT-BPM method and we predicted conversion efficiencies one order of magnitude higher compared to those achievable with a bulk of the same length of the structure . The preliminary results presented in the previous reports have been improved selecting suitable materials to reach frequencies of 8, 10, 12 and 15 microns , starting from a parametric mixing of 1.2 and 1.5 microns. Selected materials are layers of AlGaAs/ Gaas . The calculations have been published on Optics Communication [1].

References

[1] M. Centini, M. Scalora, G. D'Aguanno, C. Sibilia, M. Bertolotti, M. J. Bloemer, C. M. Bowden, J.W. Haus "Efficient Nonlinear Infrared Parametric Generation in One-Dimensional Photonic Band Gap Structures", *Optics Communications,* vol. 189, pp. 135-142 (2001).

1-b -It has been completed the theoretical work on the third harmonic generation, specifically the case in which the fields have frequencies w, 2w and 3w respectively, with the initial condition of a single pump field at w. In this case we have two nonlinear processes involved: second harmonic generation and sum frequency generation, namely $\omega + 2\omega = 3\omega$. We note that is possible to simultaneously achieve exact phase matching conditions for both processes, leading to a new set of nonlinear, coupled differential equations, thus opening new research opportunities for both experimentalists and theorists alike. We found that the third harmonic generation process mediated by a chi(2) interaction can be some two orders of magnitude larger than bulk. These conditions are highly unusual, and cannot be achieved in a bulk medium due to the dispersive properties of the medium. Our simulations show that the pump field can be strongly depleted (at least 50%) in materials having chi(2)s of order 100 pm/V, and input intensities of order 1 Gw/cm^2 in structures only a few microns in length. These thresholds can be reduced with only modest increases in the number of periods, which increase the available density of modes. Last but not least, the effective coupling coefficients in the nonlinear polarization source terms are sensitive functions of the overlap integral of the fields inside the structure. This amounts to a new degree of freedom that can significantly influence the dynamics, depending on field tuning. This means that we can access a variety of conditions determined a new set of differential equations and that are impossible to achieve in ordinary bulk materials [2].

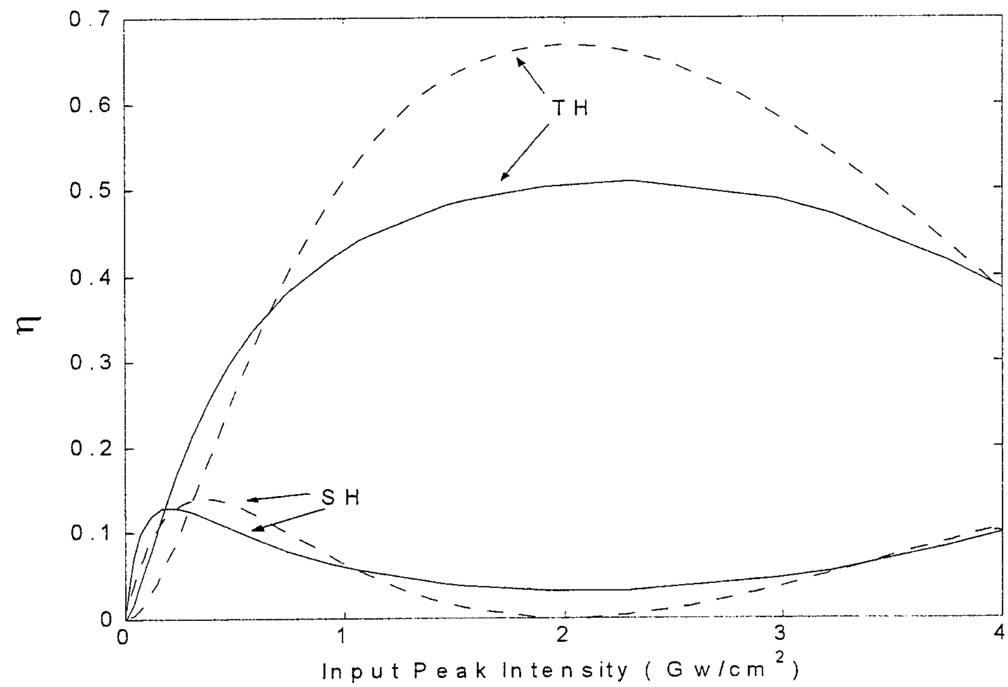

Figure 1. Second and third harmonic conversion efficiency as a function of the pump peak intensity for the PBG structure (solid line) and an ideal case of a plane propagating in a phase matched bluk medium (dashed line) of the same length and nonlinear coefficient.

References

[2] M. Centini, G. D'Aguanno, M. Scalora, C. Sibilia, M. Bertolotti, M. J. Bloemer, C. M. Bowden, "Simultaneously Phase-Matched Pulsed Second and Third Harmonic Generation in One-Dimensional Photonic Band Gap Structures", submitted to *Phys. Rev. E*.

1-c It has been designed a layered structure of AlGaAs/Al2O3 to study second harmonic generation process and parametric interaction in the region of 0.775 microns- 1.55 microns . The structure has been realized in the Institut de Micro-Optoélectronique (IMO) -Ecole Polytechnique Fédérale de Lausanne (EPFL). Comparison among experiments and theory in the linear regime have been done. Nonlinear frequency conversion has been measured with ρ pulses at 1.55 μm. a second harmonic generated signal has been detected.

The estimated conversion efficiency is of the order of 10^{-4} for an input peak intensity of 80 MW/cm^2. These experiments have been performed in Paris at CNET-CNRS, lab. of Dr. A. Levenson. The same experiment will repeated at University of Roma with a more powerful source at the same wavelength of 1.55 μm and with a larger pulse (5ps).

This work will be matter of publication.

This work has been originated by the theoretical and preliminary experimental studies on nonlinear frequency conversion [3].

References

[3] G. D'Aguanno, M. Centini, M. Scalora, C. Sibilia, Y. Dumeige, P. Vidakovic, J.A. Levenson, M.J. Bloemer, C.M. Bowden, J.W. Haus, M. Bertolotti, "Photonic Band Edge Effects in Finite Structures and Applications to $\chi^{(2)}$ Interactions", *Phys. Rev. E*, vol. 64, p. 016609 (2001).

[4] M. Scalora, M.J. Bloemer, C.M. Bowden, M. Centini, G. D'Aguanno, C. Sibilia, M. Bertolotti, "Choose your color from the photonic band edge: Nonlinear frequency conversion .....", *Opt. Photon. News*, vol 12, p. 38 (2001).

[5] Y. Dumeige, P. Vidakovic, S. Sauvage, I. Sagnes, J.A. Levenson, C. Sibilia, M. Centini, G. D'Aguanno, M. Scalora, "Enhancement of Second Harmonic Generation in 1-D Semiconductor Photonic Band Gap", *Appl. Phys. Lett.*, vol. 78, p. 3021 (2001).

1-d It is in progress the development of a new theoretical model to study nonlinear refraction in quadratic nonlinear periodical structures.

2. Chirped pulses propagation trough 1D photonic band gap structures.

It has been concluded the comparison among theory and experiments for the photonic band gap structures as delay lines in presence of a chirped pulse. The mechanism used takes advantage of the slowing down of the electromagnetic field when tuned at frequencies near the band gap. This effect is due to field's self-interference and multiple reflections inside the structure. The delay time of the transmitted pulse with respect a similar pulse that has propagated i for the same distance is calculated using the matrix transfer method. The results are in good agreement with the experimental data obtained using Fourier limited pulses. Later we noticed that for a chirped pulse the delay times were significantly different compared to the delay times predicted for Fourier transform limited pulses. Using an effective medium picture that we developed, we found two separate contributions to the total, predicted delay time: the first term is due to interference and field's localization; the second is due to pulse reshaping. Reshaping occurs as a result of an unusual coupling effect, which ties the amount of chirp to the dispersive properties of the structure. Specifically, this term is proportional to the product of the chirp coefficient by the derivative of the natural logarithm of the transmission function. The result is that reshaping can account for a delay that is of the same order of magnitude as the delay that arises from first term, and can be positive or negative, depending on the frequency where the field is tuned. This can result in superluminal group velocities, tunable delays on the order of 100ps, and high transmission. These unusual circumstances are consistent with relativistic predictions, because we also predict that energy velocities will remain subluminal according to the formula: $v_e=v_g*T$. This means that even if the observed group velocity is superluminal, energy (and hence information) transport remains well into the relativistic domain. Experiments have been performed using a 450 μm GaAs sample, and a semiconductor, near-IR laser, emitting between 1500 and 1600 nm. Once again experiments agree well with theoretical predictions. The analysis on chirped pulses comes from a more general approach of pulse propagation in PBG, which has been analysed during the first part of the contract and as described in the ref. [6].

References

[6] G. D'Aguanno, M. Centini, M. Scalora, C. Sibilia, M.J. Bloemer, C.M. Bowden, J.W. Haus, M. Bertolotti, "Group velocity, Energy Velocity and Superluminal Propagation in Finite Photonic Band Gap Structures", *Phys Rev. E*, vol. 63, p- 036610 (2001).

3. Research activity directed toward understanding the theoretical aspects related to linear and nonlinear optical properties of photonic band gap (PBG) materials - Guided wave geometry.

It has been concluded the theoretical study on PBG in $LiNbO_3$. In fact we investigated the realization of a photonic band-gap (PBG) structures in a proton exchanged (PE) $LiNbO_3$ planar waveguide for SHG purposes. The use of a PBG structure in SHG processes can significantly enhance the conversion efficiency tuning the fundamental field at the band edge transmission resonance (BER), where the density of modes (DOM) is maximum and reaching the phase-matching condition through an effective index model 0. The PBG structure is reproduced through the introduction of a linear grating whose period is chosen to tune the fundamental field at BER. The PE technique is preferred since it allows reaching a high index contrast between film and substrate: this sets an upper limit to the linear coupling constant, which corresponds to the index contrast between different layers in a bulk one-dimensional PBG structure. The equivalent index contrast achievable in the waveguide case is at least an order of magnitude smaller than the one achievable in bulk: we showed that the use of the sole linear grating is not sufficient to obtain both high DOM and phase-matching of a SHG process 0. Choosing the linear grating's period to satisfy the BER tuning condition, a further means to reach phase-matching is necessary and in this paper the quasi-phase-matching scheme is considered. In this way an enhancement in the conversion efficiency of at least an order of magnitude, respect to a same length phase-matched device, is readily achievable, and an even better result can be obtained if the linear grating is etched on a material with a refractive index greater than the $LiNbO_3$ one. The conversion efficiency, normalized to the one achievable in a quasi-phase-matched device of the same length, may be expressed by the following:

$$\eta^+ = \eta^- \underset{N>>1}{\cong} K_{NL_1}^2 \frac{A^2}{4}\left(\frac{NK_{L_1}}{\beta_{FF}}\right)^4 (N\Lambda_L)^2 \propto N^6 \qquad \text{i)}$$

where the apices $^{+,-}$ stands for forward and backward propagation respectively, K_{NL_1} and K_{L_1} are the nonlinear and linear coupling constant, β_{FF} is the propagation constant of the fundamental field and N is the number of periods of the linear grating. In equation i) the DOM gives the N^4 dependence, a result already known in the bulk case 0, while the phase-matching condition brings a N^2 dependence. In Figure 1 the plot of equation i) is shown in a sample case.

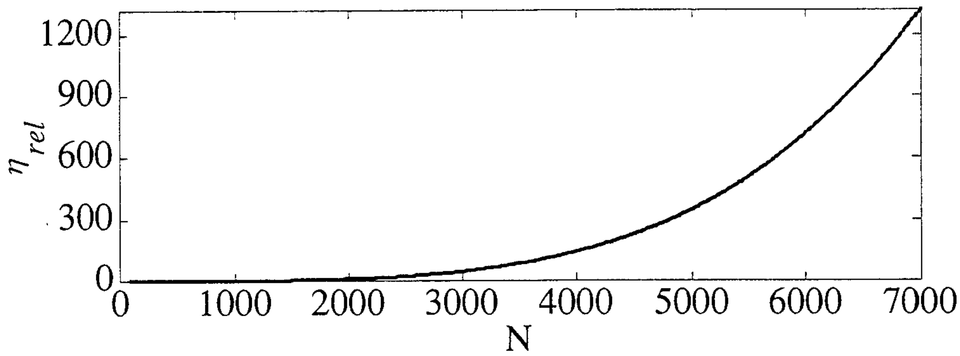

FIGURE 1. Relative conversion efficiency as a function of the number of periods for a waveguide 440 nm deep, and a linear grating etched directly onto the $LiNbO_3$ film on an additional layer 100 nm thick.

The upper limit to equation i) is set by the transmission band-edge resonance linewidth which decreases with the number of periods according to a N^3 dependence. In the case of Figure 1, a relative conversion efficiency equal to 75 is reached when the FWHM of the transmission resonance is equal to 3 GHz.

It has been the modellization of a guided geometry to be experimentally realized and tested. It has also been concluded the analysis of a geometry based on the enhancement of SH from Cerenkov effect in protonic exchange -LiNbO3. Large enhancement due to band edge resonance has been found.

This work will be soon submitted for a publication.

References

[1] M. Centini, C. Sibilia, M. Scalora, G. D'Aguanno, M. Bertolotti, M. J. Bloemer, C. M. Bowden, I. Nefedov, "Dispersive properties of finite, one-dimensional photonic band gap structures: applications to nonlinear quadratic interactions", *Phys. Rev. E*, vol. 60, pp. 4891-4898, 1999.

[2] C. H. Tang, P. B. Bey, "Phase matching in second-harmonic generation using artificial periodic structures", *IEEE J. Quantum Electron.*, vol. 9, pp. 9-17, 1973.

[3] G. D'Aguanno, M. Centini, C. Sibilia, M. Bertolotti, M. Scalora, M. J. Bloemer, C. M. Bowden, " Enhancement of $\chi^{(2)}$ cascading processes in one-dimensional photonic bandgap structures", *Opt. Lett.*, vol. 24, pp. 1663-1665, 1999.

[4] D.Pezzetta, C.Sibilia, M.B[illegible]lotti, J.Haus, M.Scalora, M.Bloemer[illegible]Bowden "Photonic band gap structures in nonlinear guided waves: Application to second harmonic generation", *JOSA B*, August 2001.

APPENDIX

During the year of the project we have

-Established some criteria for nonlinear frequency generation in 1D PBG in the short wavelength regions and in the IR region and to give a project of layered configuration for frequency conversion .

-Structure of AL2O3/AlGaAs has been realized and experimentally measured.

-Studies the guided wave propagation in a geometry simulating 1-d PBG

(see list of publications)

Next objectives

(1) To experimentally demonstrate efficient generation in the blue spectral region and in the far I.R. spectral region.
(2) To experimentally demonstrate the guided wave enhancement of frequency at 1.55 micron.
(3) For all the frequencies range of interest (u.v. and IR) we theoretical analysis to increase the efficiency of quadratic and cubic nonlinear optical interaction in one-dimensional (1D) photonic band-gap (PBG) structures through phase matching and local field enhancement with particular attention to the pulse propagation , with the objective of analyzing in detail the role of the group velocity mismatch among different pulses to optimize the conversion efficiency .

List of publications under ERO – University of Rome contract (2000- 2001)

[1] M. Centini, M. Scalora, G. D'Aguanno, C. Sibilia, M. Bertolotti, M. J. Bloemer, C. M. Bowden, J.W. Haus "Efficient Nonlinear Infrared Parametric Generation in One-Dimensional Photonic Band Gap Structures", *Optics Communications,* vol. 189, pp. 135-142 (2001).

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[3] G. D'Aguanno, M. Centini, M. Scalora, C. Sibilia, Y. Dumeige, P. Vidakovic, J.A. Levenson, M.J. Bloemer, C.M. Bowden, J.W. Haus, M. Bertolotti, "Photonic Band Edge Effects in Finite Structures and Applications to $\chi^{(2)}$ Interactions", *Phys. Rev. E*, vol. 64, p. 016609 (2001).

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[6] D.Pezzetta, C.Sibilia, M.Bertolotti, J.Haus, M.Scalora, M.Bloemer, C.Bowden "Photonic band gap structures in nonlinear guided waves: Application to second harmonic generation", *JOSA B*, August 2001.

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