Index Modulation of Transient Grating in Nonlinear Medium

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ABSTRACT

A transient chirped grating structure is formed by beam interferences in nonlinear photonic crystal waveguide. Pulse propagation in nonlinear transient grating media is investigated and its impact on the transmission dynamics is explored. The grating may not be stationary propagating but anharmonically oscillating. Thus, effective modification of the refractive index needs to be evaluated in detail.

Keywords: Gratings; Dynamic gratings

1. INTRODUCTION

Gratings in photonics devices are indistinguishable tools for light manipulations [1].The gratings are composed of the spatial modulation of n, ε or χ. Permanent gratings are used in the most of the studies so far. The interaction between pump and probe is widely investigated in linear and nonlinear steady grating structures [2,3]. Previous studies have focused on the detecting diffracted waves from grating by applying a third probe or self diffraction of inducing light wave especially the stationary grating [59]. Differently from the permanent grating, the transient grating is occurred as long as the light source is applied. Then, it has disappeared when the induced light is switched off in the transient or dynamic gratings. Besides, common transient grating structure can be assumed quasi-stationary because of the maxima and minima nodes are neither oscillate nor propagate. The grating does not change during the propagation of probe signal. The grating amplitude decays without oscillation when the light source is switched off [1]. Additionally, non-instantaneous case is called different phenomena in the literature and cannot be easily described as a modification of refractive index. Its effect is called Raman, and is not considered to be a part of the Kerr effect. Such grating system is a time variant system and must be modeled as Raman [5,1,6]. Hence, a transient chirped grating structure that is formed by interferences of oblique incident laser beams in nonlinear photonic crystal (PhC) waveguide is considered. That kind of gratings are not propagating in the direction of grating axis (along waveguide) but it may travel in the transverse direction, and its fields anharmonically oscillate due to material dispersive Raman nonlinearity [7,8,9]. Thus, the effective refractive index is affected from the variation of interference fields. In this study reflection and transmission properties have been observed with a third probe beam propagation through the grating. Moreover, light propagation in grating with temporal and spectral characteristics is considered. Index variation is investigated in terms of the time variation of interference field and energy in nonlinear medium.

2. STATIONARY AND TRANSIENT GRATING

In general, an interference grating structure can be generated in a third order (Kerr type) nonlinear waveguide by exposing the intensity distribution of the interference. When the beams interference occurs at the y=0 plane, a stationary grating pattern is created. The grating period, along the *x*-direction, depends on the interference beam angle, the writing beam wavelength, and the interference plane (y). As simulation geometry pictured in Fig.1, there is a hexagonal PhC structure with air holes into linear polymer substrate. One row of holes is removed to make a gap where nonlinear Kerr type line defect waveguide placed. The radius of the rods is chosen 0.2a, the waveguide width $a\sqrt{3}/2$ and the refractive index of background Silicon Dioxide (SiO_2) and the nonlinear material, Methyl Red (MR) doped Polyvinyl Alcohol (PVA) are 1.46 and 1.488 respectively. The lattice constant 'a' is in unit of μm and all the values in the simulation are normalized with μm. Since c = 1 in Meep units, *a* (or *a* / c) is our unit of time as well. For example, normalized frequency f corresponding to λ = 1.53μm is calculated as f=1/1.53 = 0.65 for *a* = 1μm. Third order nonlinear coefficient

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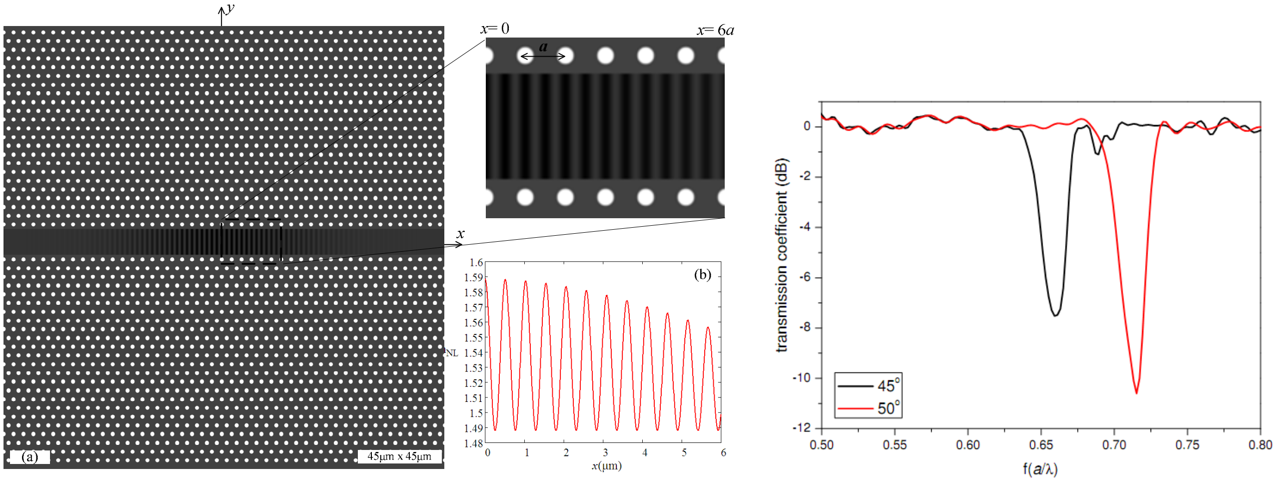
(n_2) is taken as $2\text{x}10^{-9}$ cm^2/W. Using PhC with nonlinear waveguide has two main advantages. First; the light can be confined narrower region of interest and nonlinearity can effectively be harvested. Second; the necessary interference geometries can be obtained easily in PhC structures that light manipulation needed more. For simplicity, in this work, two-dimensional Gaussian beams interference geometry (two beams are in the same plane) has been considered. After the coordinate transformation and the first order approximation, complex Gaussian beam equation can be written as follows [10];

$$U(x) = \left(\frac{A}{\left(L + y\cdot\cos(\theta) - x\cdot\sin(\theta) + i\cdot z_0\right)}\right)\times\exp\left[-ik\left(L + y\cdot\cos(\theta) - x\cdot\sin(\theta)\right)\right]$$
$$\times\exp\left[\frac{-1}{2\left[L + y\cdot\cos(\theta) - x\cdot\sin(\theta + i\cdot z_0)\right]}\cdot ik\left[\left(x\cdot\cos(\theta) + y\cdot\sin(\theta)\right)^2\right]\right] \tag{1}$$

Where z_0 is Rayleigh range, θ is incidence angle, L is the axial distance from minimum waist of beam to interference plane and A is constant. Interference (intensity) equation will be in the following equation.

$$I(\mathbf{r},t) = \left|U_1(\mathbf{r},t) + U_2(\mathbf{r},t)\right|^2 \tag{2}$$

According to the interference equation, there are two terms that make the refractive index profile different than the uniform grating. The first term is an amplitude modulation (envelope) that diminishes exponentially and the second term is a pitch modulation that modifies the grating period. The grating length is bounded with the envelope function of the interference equation. Index deviation is come from standing wave form of intensity. Effective change in refractive index Δn for a plane wave with time-average intensity (I) travelling through an instantaneous homogeneous Kerr material is defined as $\Delta n = n_2 I$. It is expected to incremental refractive index change of the medium in accordance with intensity profile depending on optical property of the material as shown in Fig 1. Bragg frequency is estimated from expected index profile along the grating x-axis using the Bragg condition $\lambda_B = 2\Lambda\bar{n}$, where $\bar{n}$ is effective index, Λ is Bragg period. Transfer matrix method (TMM) based on discretization the grating structure in subsections is used to estimate the Bragg frequency as shown in Fig. 2. Transfer matrix is defined for each part and Bragg frequency is obtained. Finite Difference Time-Domain Method (FDTD), which are developed by MIT photonic research group, are used to analyze the device characteristics [11].On the other hand, the simulation platform MEEP supports only instantaneous Kerr nonlinearity case. Meep supports dispersion media like Lorentz and Drude separately.



(a) (b)

Figure 1. (a) Realistic index grating profile embedded into PhC b) Transmission coefficient for two different incidence angle

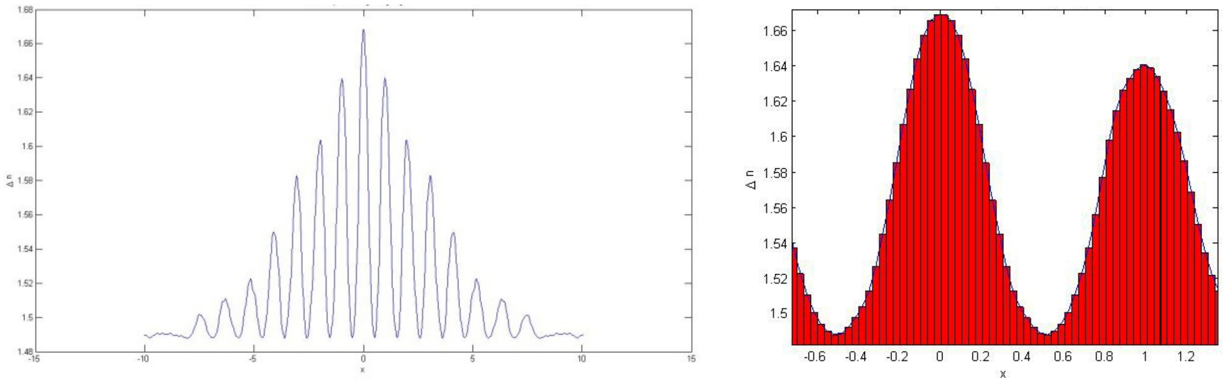


Figure 2. Estimated index profile (left figure) and Discrete Samples of TMM in one period of grating (right figure)

Transient chirped grating structures formed by Gaussian beam interferences in nonlinear photonic crystal waveguide is depicted in Fig. 3. The way to deliver the interfering beams into the nonlinear waveguide is through the bulk of PhC. Propagation modes are obtained from bulk PhC band structure graphs thus the possible interference angles of the beam are delimited. Interference of beams and corresponding electric field profile in interference region are pictured in the Fig . 4.

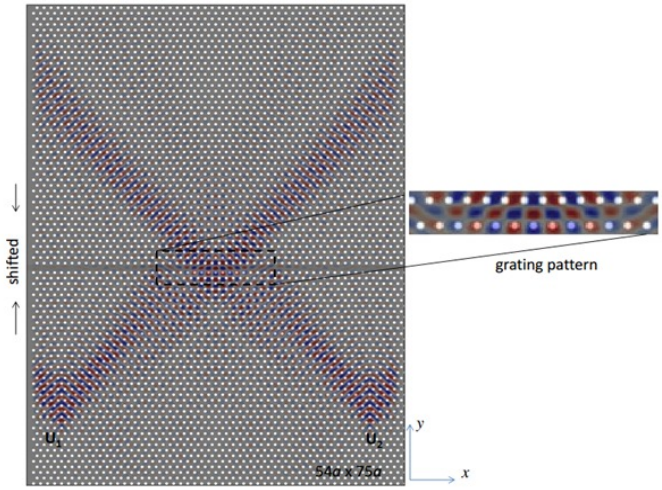


Figure 3. Gaussian beams (Hz polarized) interference pattern in PhC structure (54a x 75a), (U1, U2 are identical and incident angle and frequency are taken θ=45º, λ=1.053 µm)

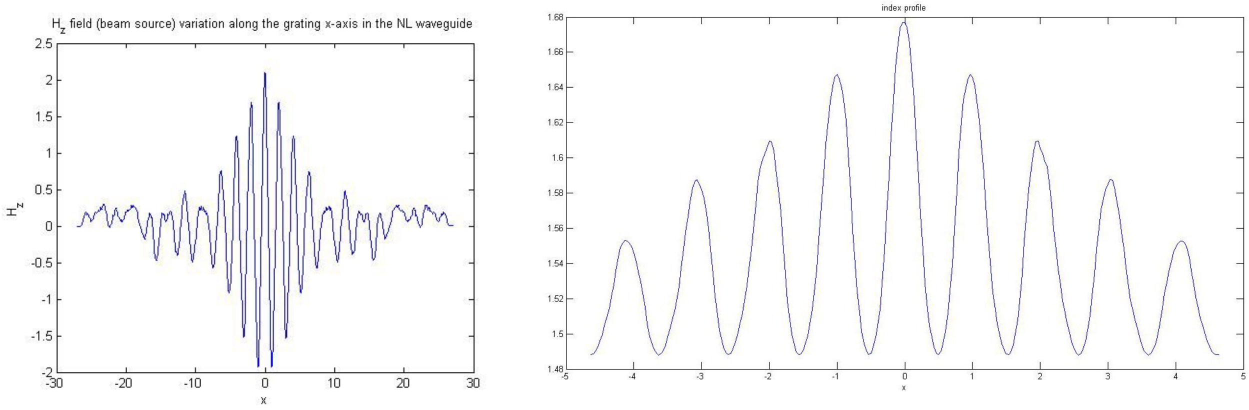


Figure 4. Electric field variation and expected index profile along the grating *x*-axis in PhC nonlinear simulation

3. DYNAMIC GRATING PROPERTIES

To observe the nonlinear effect on the pulse propagation and grating, control beams are taken identical and applied to instantaneous Kerr nonlinear waveguide with contra propagating and input signal is monitored at the center of the waveguide as depicted in Fig. 5. In order to take into account of anharmonic effect, time variation of field and intensity/energy in waveguide grating which is formed by different pump (control signal) configuration into the instantaneous Kerr nonlinear medium are examined. Bragg period is seen from interference patterns and fundamental Bragg frequency can be estimated from average index change before the simulation as the following. When two control beam with amplitude coefficient A=2 (a.u) is applied, average index change is calculated as 0.12 for the Kerr coefficient (n_2) and average power are 0.2 (a.u) and 0.5 (a.u) respectively. Fundamental Bragg wavelength is calculated as 1.608 (f_B=0.6218 c/*a*). Pump (control) signal is taken Hz polarize (TM) Gaussian pulse and defined as mode profile at center frequency 0.650019c/*a*. Probe (input) signal is taken Ez polarize (TE) continuous wave (cw). Bragg frequency is searched in the input frequency range between 0.56 c/*a*-0.68c/*a*. Input signal is also given as mode profile at each frequency. Simulation should be run 153 time units for 100 periods (100/f).

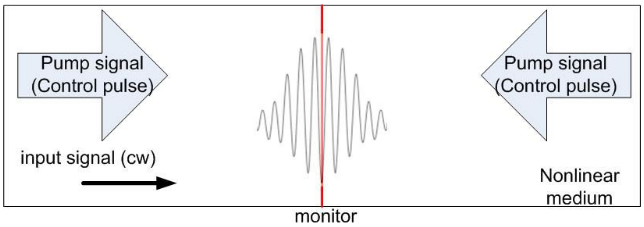


Figure 5. Monitoring the interference pump signal and the probe signal in instantaneous Kerr nonlinear medium

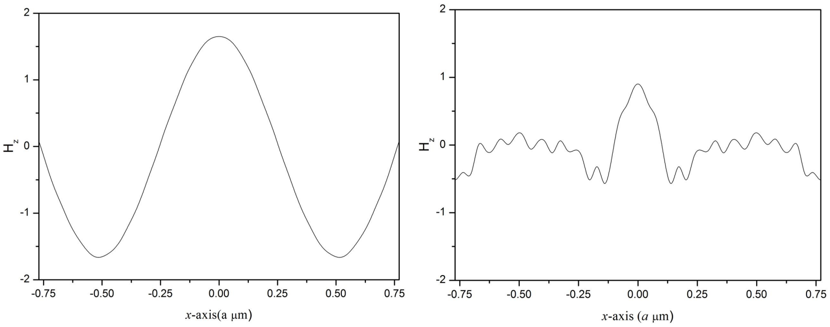


Figure 6. Anharmonic time variation of interference of contra propagating field without (left figure) and with (right figure) nonlinearity

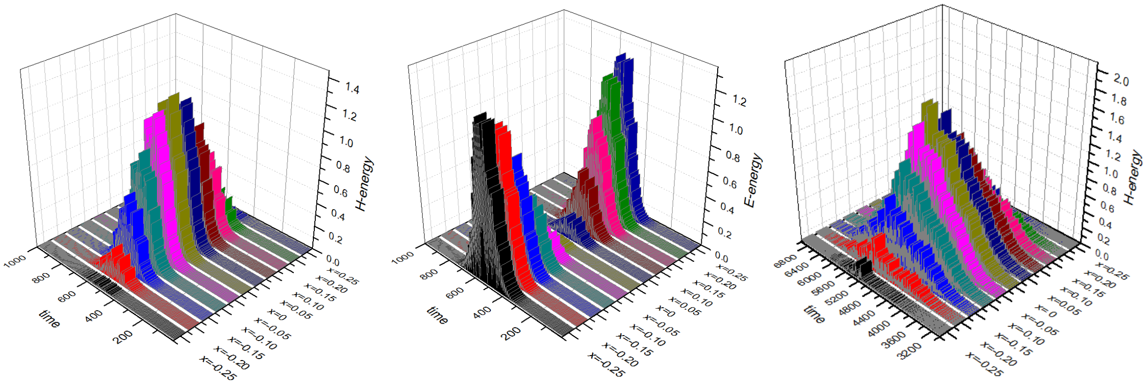
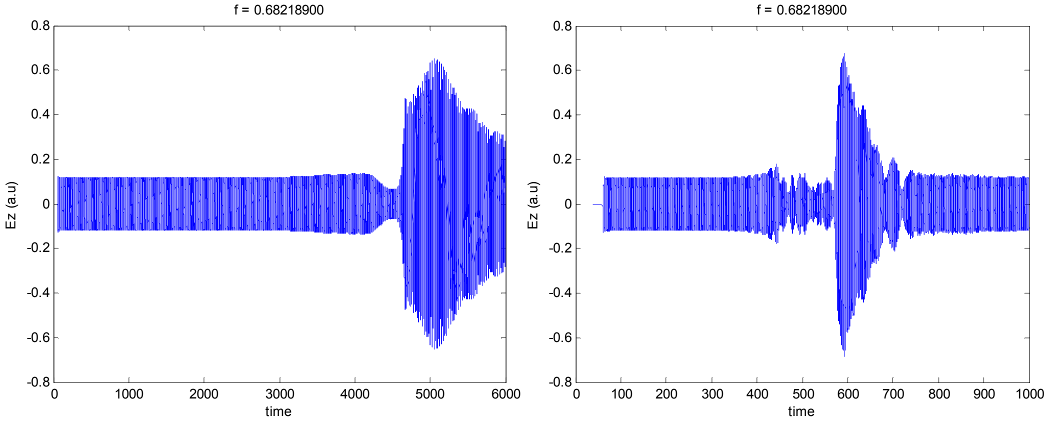


Figure 7. H/E energy variation of one cycle of grating for pulse width 0.01, and 0.001 respectively.

Index variation form is assumed like the energy profile along the waveguide. Hence, H-energy, E-energy are monitored for different pulse width (df=0.01, 0.001) and along the grating *x*-axis position between $\boldsymbol{-0.25a \leq x \leq 0.25a}$ in one period of grating and one period of driven frequency in the Fig. 7.

If the control pulse with high intensity is applied, material properties (index and absorption) are changed by the interference field intensity. That kind of laser induced transient grating may not be propagating but anharmonically oscillating as shown in Fig. 6. Thus, the effective refractive index is rather different than the harmonic fields. The index modulation is highly affected from the relation of the pulse duration and nonlinear relaxation time. If the relaxation time is longer than pulse, the index modulation can be assumed to follow the envelope of intensity [9]. Because of the refractive index variation follows the control pulse intensity shape; different part of signal is faced to different index value. Only a small part of the control signal is matched with the estimated Bragg frequency. Naturally, the stop level obtained from simulation result is very low. When the pump pulse reaches at waveguide, probe signal around the Bragg frequency dramatically changes as shown in Fig 8. Attenuation occurs at different frequency for pump pulse frequency width. The attenuation period is too short and signal level is increases soon after. Reflectivity decreases but oscillates after the pump signal passes.



(a) (b)

Figure 8. TM mode (Ez) continuous wave probe (input) signal variation under the TE mode (Hz) pump (control) pulse signal with different frequency width a) df=0.001 b) df=0.01

4. CONCLUSION

The index modulation is highly affected from the pulse duration in nonlinear medium. The grating makes oscillation anharmonic and average intensity different then the harmonic case. Because of the refractive index variation follows the control pulse intensity shape; different part of signal is faced to different index value. So Bragg frequency is continuously altered. Hence, modification of the refractive index needs to be evaluated apart from the linear case and time variation effect should be considered especially in material dispersive Raman nonlinearity medium. Perhaps the best way to characterize the grating and the associated index modulation can be achieved by means of assessing the its reflectiveness.

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