Gaussian pulse mixing by nonlinear photonic crystals

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Abstract

The properties of mixing and scattering of two non-collinear Gaussian pulses with different centre frequencies and lengths, incident on the finite nonlinear periodic layered dielectric structures, have been analysed. It is shown that at the backward emission grows with the number of layers and can reach the level of the forward emission in the direction of combinatorial frequency scattering.

1. Introduction

The physical phenomena associated with pulse generation, transmission and processing in functional devices always attracted strong interest. Pulsed signals in continuous media have been a subject of major developments in microwaves and optics over the last fifty years. Emergence of photonic crystals and metamaterials opened new avenues for manipulating pulsed signals in novel mm-wave, THz and optical devices. Nonlinear effects in the artificial media and their applications to pulse assisted harmonic generation and waveform control with the aid of nonlinear photonic crystals (NPC) and metamaterials with quadratic and cubic nonlinearities have recently attracted increasing attention, see, e.g. [1]-[4]. It has been demonstrated that the dispersion and nonlinearity engineering enables modification of pulse shape and control of the nonlinear wave interaction. The earlier developments have been primarily concerned with the extreme cases of the very short or very long pulses, non-commensurate with the characteristic scales of the finite structures. However the problems of multiple pulse interactions and mixing in the commensurate structures still remain scarcely studied and scantly understood.

In this work, the process of mixing two Gaussian pulses of dissimilar frequencies obliquely incident on the nonlinear periodic structure of finite thickness is explored. The closed form solutions have been obtained and analysed in both extreme cases and in the instances, when the incident pulses interact at the scale commensurable with structure periodicity. Impact of the dispersion on nonlinear response and shape of the scattered waveform has been examined. It is demonstrated that broad spectral content of the input pulses expedites the phase and frequency synchronism and improves efficiency of the frequency conversion, especially at the EBG edges.

2. Nonlinear scattering by layered periodic structure

Let two Gaussian pulses with different central frequencies ω_{01} and ω_{02} be incident at angles Θ_{i1} and Θ_{i2} on a finite NPC formed by two alternating dielectric layers of thicknesses d_1 and d_2 as shown in Fig. 1. The stack of layers of total thickness $L=N\cdot(d_1+d_2)$ contains N periods and is surrounded by homogeneous linear medium with dielectric permittivity ε_a at $z\le 0$ and $z\ge L$. The NPC constitutive layers have 6mm class of anisotropy and are characterised by the tensors of linear dielectric permittivity $\hat{\varepsilon}_j=\left(\varepsilon_{xx},\varepsilon_{xx},\varepsilon_{zz}\right)$ and a second-order nonlinear susceptibility tensor $\hat{\chi}_j$, j=1,2. We assume that nonlinearity is weak and the structure is isotropic in the *x*-*y* plane. Therefore the incident waves of the TE and TM polarisations with the fields independent of the *y*-coordinate ($\partial/\partial y = 0$) can be treated separately. Only the case of TM-polarization is discussed here, whilst the TE waves, unaffected by the anisotropy of $\hat{\chi}_j$, are analysed similarly.

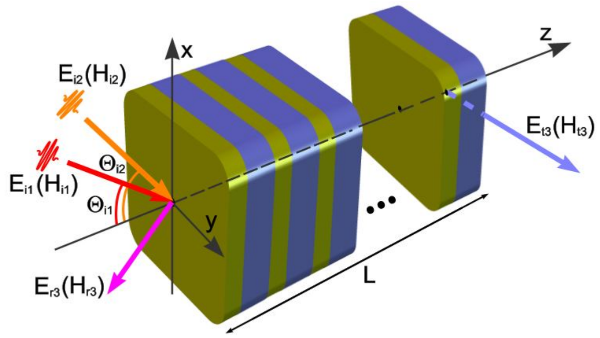

Fig.1: Geometry of the problem.

The characteristics of the scattered pulses, generated in the mixing process associated with the second order nonlinearities of the layers, have been obtained by the modified transmission matrix method. In the approximation of weak nonlinearity, the original nonlinear problem has been reduced to the solution of the linear inhomogeneous wave equations for the fields in each layer [5]. The total field in each nonlinear layer is obtained in the form of spectral integrals over frequencies ω and ω' containing the 6 planar waves with the longitudinal wavenumbers $k_{zLj}^{1,2}(\omega) = \pm\sqrt{\left(\omega^2/c^2 - \left[k_x^{1,2}(\omega)\right]^2/\varepsilon_{zzj}\right)\varepsilon_{xxj}}$ and $k_{zLj}^{\pm}(\omega,\omega') = \pm\left[k_{zLj}^{1}(\omega') \pm k_{zLj}^{2}(\omega-\omega')\right]$ where $k_x^{1,2}(\omega) = \omega\sqrt{\varepsilon_a}\sin\Theta_{i1,2}/c$, c is the free space speed of light and j = 1, 2 denotes the respective constituent nonlinear layer in the unit cell.

The obtained solution provides an insight in the properties of the TM wave scattering by the NPC illuminated by a pair of Gaussian pulses of different central frequencies $\omega_{01,02}$ incident at angles $\Theta_{i1,2}$ and enables the detailed analysis of the of the main characteristics of the pulse mixing process.

3. Results and discussion

To illustrate the properties of pulse mixing, two Gaussian pulses with dissimilar central frequencies $\omega_{01} = 4.195\times10^{13}\ s^{-1}$ and $\omega_{02} = 2.158\times10^{13}\ s^{-1}$, and the pulse durations $\tau_1 = 500$ fs and $\tau_2 = 120$ fs, incident at oblique angles Θ_{i1} =15° and Θ_{i2} = 40° on the finite NPC, have been analysed numerically at the following parameters of the nonlinear layers: d_1=0.001 mm, $\varepsilon_{xx1} = 5.382$, $\varepsilon_{zz1} = 5.457$, $\chi_{xxz1} = 2.1\times10^{-7}$, $\chi_{zxx1} = 1.92\times10^{-7}$, $\chi_{zzz1} = 3.78\times10^{-7}$; d_2=0.004 mm, $\varepsilon_{xx2} = 1.4$, $\varepsilon_{zz2} = 2.6$, $\chi_{xxz2} = 2.82\times10^{-8}$, $\chi_{zxx2} = 2.58\times10^{-8}$, $\chi_{zzz2} = 8.58\times10^{-8}$. The surrounding media have the permittivity $\varepsilon_a = 1$. The frequencies $\omega_{01,2}$ and incidence angles $\Theta_{i1,2}$ have been chosen identical to those used in [5] for the analysis of the plane wave mixing by a single nonlinear layer in order to enable a consistent comparison of the nonlinear interactions in the two structures.

The efficiency of the pulse mixing process is influenced by several interrelated factors. These include the phase synchronism of the central frequencies in the three-wave mixing process ($\omega_3 = \omega_{01} + \omega_{02}$), disparity and dispersion of the reflection coefficients of the incident pulses, and the layer parameters which determine the band structure of the photonic crystal. As shown in [5], these parameters cannot be chosen independently even for a single layer. In the NPC case, the pulse interactions become more intricate due to complex dispersion and temporal confinement of the interacting waveforms. For example, it has been found that the increase of the number of the layers in the NPC has a distinctive effect on intensity of mixing products emitted in forward and backward directions. Fig. 2, 3 illustrate the time dependencies of the field intensity $\left|H_{yr3,t3}\right|^2$ scattered in the directions corresponding to emission of the combinatorial frequency ω_3. It can be observed that these bursts of emission are substantially shorter than the incident pulses and broaden when the number of the periods N increases. Moreover, the intensity of backward emission $\left|H_{yr3}(t)\right|^2$ grows with N at a higher rate and becomes nearly the same as that for $\left|H_{yt3}(t)\right|^2$ at N=8: $\left|H_{yr3}\right|^2/\left|H_{yt3}\right|^2 \approx 0.06$ at N=3 and $\left|H_{yr3}\right|^2/\left|H_{yt3}\right|^2 \approx 1$ at N=8. Efficiency of the pulse mixing has been further enhanced by altering the structure parameters by matching the central frequencies of both pump pulses with the NPC bandgap edges.

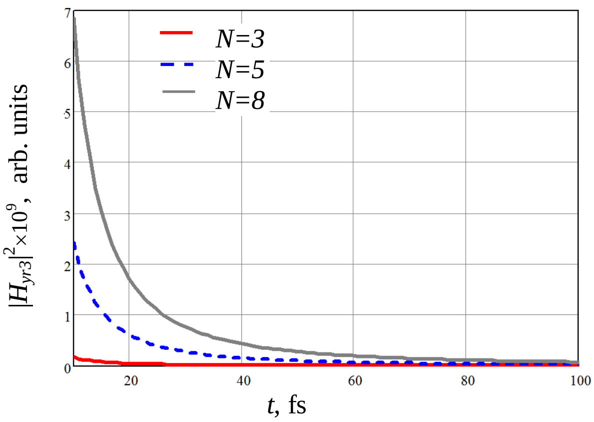

Fig.2: Intensity of the field radiated in the backward direction from nonlinear photonic crystal at x=z=0.

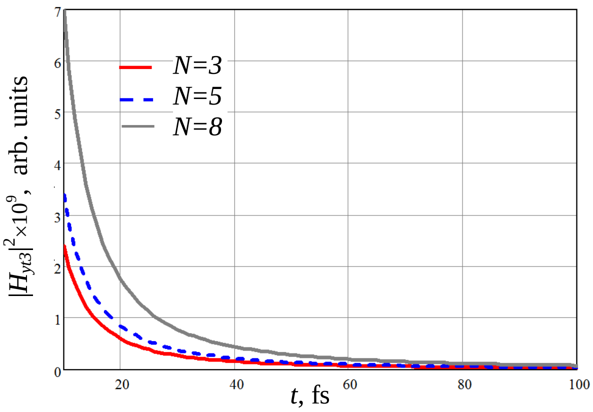

Fig.3: Intensity of the transmitted wave radiated from the nonlinear photonic crystal in the forward directions of the z-axis at the x=0 and $z=N\cdot(d_1+d_2)$.

4. Conclusions

The properties of Gaussian pulse mixing and scattering by the finite NPC have been examined. The features of the reflected and refracted waveforms and effects of the structure parameters and length of the incident pulses on the mixing process are analysed. The detailed discussion of the phenomenology and parametric study will be provided in the presentation.

Acknowledgments

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