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Invited Paper

Nonreciprocal scattering by stacked nonlinear magneto-active semiconductor layers

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Abstract

The combinatorial frequency generation by the periodic stacks of magnetically biased semiconductor layers has been modelled in a self-consistent problem formulation, taking into account the nonlinear dynamics of carriers. It is shown that magnetic bias not only renders nonreciprocity of the three-wave mixing process but also significantly enhances the nonlinear interactions in the stacks, especially at the frequencies close to the intrinsic magneto-plasma resonances of the constituent layers. The main mechanisms and properties of the combinatorial frequency generation and emission from the stacks are illustrated by the simulation results, and the effects of the individual layer parameters and the structure arrangement on the stack nonlinear and nonreciprocal response are discussed.

Keywords: Semiconductor; Magnetic field; Periodic structure; Weak nonlinearity; Three-wave interaction; Combinatorial frequency generation

1. Introduction

Photonic crystals (PhCs) and metamaterials (MMs) have attracted continuous interest for over a decade owing to their unique functional capabilities and ubiquitous potential applications. While the focus was mainly on linear artificial media, nonlinear MMs and PhCs have recently been studied with the aim of improving efficiency of frequency conversion and harmonic generation, particularly, in THz and optical ranges [1–3]. Enhancement of nonlinear activity, achieved in MMs and PCs, was primarily rendered by the linear effects, such as dispersion and field localisation, whereas the nonlinearity itself was considered as an extrinsic parameter, the phenomenological constant of the constituent material. However, it appears that the actual response of nonlinear PhC and MM may significantly differ from that of the respective equivalent medium, especially, in magneto-active structures where several competing mechanisms of nonlinearity may coexist in the proximity of intrinsic resonances. Therefore, to adequately model the frequency mixing and harmonic generation phenomena in plasma-like MMs and PhCs, it is important to analyse them in a self-consistent manner, taking into account not only the field redistributions in the resonant elements [4,5] but also nonlinear dynamics of charges in the constituent elements [6].

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Stacked semiconductor layers and films represent an important class of MMs and PhC with a natural nonlinearity of the free-carrier current. Their nonlinear response is enhanced by coherent interactions of pump waves with carriers facilitated by the tailored frequency dispersion [6]. When semiconductor layers are also biased by external dc magnetic field, the nonlinear activity is further increased, and additionally both the linear and nonlinear responses become nonreciprocal, i.e. dependent on the direction of pump wave incidence [7]. Nonreciprocity in MMs and PhCs has recently been a subject of particular interest in the context of their applications in microwave and photonic devices [8–13]. The magneto-optical interactions can render the nonreciprocal response of linear [14–20] and nonlinear [21–22] structures. Also, stacks of semiconductor layers with mobile carriers exhibit strong magneto-optical activity and nonreciprocity in the presence of dc magnetic bias. In the linear regime, nonreciprocity of such periodic structures was explored in the past [23], while to the authors' knowledge, the *nonreciprocal nonlinear* response has not been studied, yet.

In this paper, we have investigated the effects of nonlinear scattering by a finite periodic stack of magnetically biased semiconductor layers with mobile carriers. A self-consistent boundary value problem, taking into account the dynamics of charges in the constituent semiconductor layers, is outlined in Section 2. A solution for the stack illuminated by pump plane waves of two tones, incident at dissimilar slant angles, is obtained in the approximation of three-wave mixing process [24]. The properties of combinatorial frequency waves emitted from the stacks are illustrated by the simulation results and discussed in Section 3. Main features of the nonreciprocal frequency mixing effects in the stacks of magneto-active semiconductor layered are summarised in Section 4.

2. Three-wave frequency mixing in semiconductor layers with magnetic bias

Let us consider a periodic stack of binary semiconductor layers biased by external dc magnetic field $\mathbf{H}_0$ pointing along the y-axis as shown in Fig. 1. The constituent layers of types a and b have thicknesses d_a and d_b and are of infinite extent in the $x0y$-plane. The stack of the total thickness $L = N\cdot(d_a + d_b)$ contains N unit cells and is surrounded by linear homogeneous medium with dielectric permittivity ε_r at $z \le 0$ and $z \ge L$.

The magnetised constituent semiconductor layers are represented as solid-state plasma with mobile charges. Then in a self-consistent formulation of the nonlinear scattering problem, Maxwell's equations are to be solved

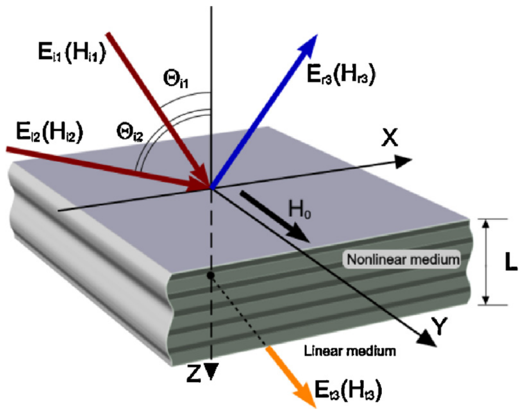

Fig. 1. Geometry of the problem.

simultaneously with the hydrodynamic and current continuity equations describing the charge dynamics

$$\mathrm{rot}\mathbf{H}_j = \frac{\varepsilon_{Lj}}{c}\frac{\partial \mathbf{E}_j}{\partial t} + \frac{4\pi}{c}\mathbf{j}_j, \quad \mathrm{rot}\mathbf{E}_j = -\frac{1}{c}\frac{\partial \mathbf{H}_j}{\partial t},$$

$$e\frac{\partial n_j}{\partial t} + div\mathbf{j}_j = 0,$$

$$\mathbf{j}_j = e(n_{0_j} + n_j)\mathbf{v}_j \quad \frac{\partial \mathbf{v}_j}{\partial t} + \nu_j\mathbf{v}_j + (\mathbf{v}_j\nabla)\mathbf{v}_j$$

$$= \frac{e}{m}\mathbf{E}_j + \frac{e}{mc}\mathbf{v}_j \times \left(\mathbf{H}_0 + \mathbf{H}_j\right), \quad (1)$$

where c is the speed of light in free space, e and m are the carrier charge and mass; subscript $j=a,b$ identifies constituent layers a and b in the unit cell; n_{0j} is the carrier concentration at equilibrium; ε_{Lj} is the lattice permittivity; ν_j is the collision frequency; $\mathbf{v}_j$, $\mathbf{j}_j$ and n_j are the velocity, current density and variable carrier concentration in each layer, respectively.

The stack is illuminated by a pair of TE or TM polarised pump waves of frequencies ω_1 and ω_2 incident at angles Θ_{i1} and Θ_{i2}, respectively. In general case the TE and TM waves are hybridised in the semiconductor layers and the scattered fields of both pump and combinatorial frequencies are cross-polarised. However, when the semiconductor layers are magnetised at $\mathbf{H_0}||0y$ and the incident TE waves have the field components E_y, H_x, H_z and TM waves have the field components H_y, E_x, E_z independent of the y-coordinate ($\partial/\partial y = 0$), the TE and TM waves refracted in the semiconductor layers remain orthogonal. The fields of such TE and TM waves satisfy Eq. (1) independently and can be analysed separately in the approximation of the velocity of charges much smaller than the speed of light. Inspection of Eq. (1) in the case of the TE polarised waves shows that the semiconductor layers remain reciprocal and linear. Therefore only the TM waves scattering by the stacks of