Nonlinear optical switching from lossy to amplifying negative-index metamaterials

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Abstract: Extraordinary properties of parametric amplification and of quantum interference which enable compensation of losses and of cavity-free generation of counter-propagating entangled right- and left-handed photons controlled by an external laser are investigated.

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1. Introduction. Optical negative-index metamaterials (NIMs) form a novel class of electromagnetic materials that promise revolutionary breakthrough in photonics. Particularly, this regards with signal and information processing capabilities and novel concepts of elemental and integrated optical components and devices, which enable smart, adaptive and reconfigurable sensing and image processing. However, to satisfy the casuality principle, optical negative-index metatamaterials (NIMs) must be lossy. Absorption is generally recognized now as one of the most challenging problems that needs to be addressed for practical applications of these revolutionary artificial electromagnetic materials. Significant efforts of the NIM's community are currently applied towards compensating losses by the amplifying centers embedded into NIM host material that provide amplification owing to population inversion.[1] Herewith, we propose alternative means of compensating losses, producing a *full transparency, or amplification, or even cavity-free optical oscillation in NIMs.* The underlying physical mechanism is optical parametric amplification (OPA) controlled by the electromagnetic waves with the frequencies outside the negative-index domain (NID), which provides the loss-balancing OPA inside the NID. We also predict the possibility of generation of *entangled pairs of counter-propagating right- and left-handed photons.* We have investigated two alternative approaches. One is to tailor the optical properties of NIMs with the control laser without a change of the composition and structure of the material. The indicated opportunity relies on quadratic nonlinearity of a NIM due to the non-symmetric current-voltage characteristics of its structural elements.[2] Another option does not require strong nonlinear response of the building blocks of the NIM. Instead, it employs embedded four-level centers and the methods of *quantum control* attributed to strong resonant four-wave coupling with such centers and to *quantum interference*.[3] Whereas both options enable compensation of losses and offer the possibilities of flexible switching from strong absorption to transparency and further to inversionless amplification and cavity-less lasing, they possess different advantages and offer different applications in photonics. We show that both of the investigated processes exhibit extraordinary counter-intuitive properties as compared to those known from the textbooks. This is because opposite directions of energy flow and phase velocity of light in the NI frequency domain. First optical NIMs were created in 2005, and nonlinear optics in the NIMs still remains the less developed area of electromagnetism. Unusual features of second harmonic generation (SHG) in NIMs were predicted in,[4–6] and of OPA - in.[6,7] First experiments on SHG in NIMs were reported in.[8]

2. Laser-induced transparency, OPA and OPO associated with quadratic nonlinearity of a NIM. Typical specific features of compensating losses in NIMs by means of OPA are illustrated below in Fig. 2, (a), (c), (e) and (f), for the simplest case of three-wave mixing process associated with the quadratic nonlinearity of the host material. It shows strict contrast with the corresponding typical dependence intrinsic to the similar process in a positive index material [Fig. 2, (b) and (d)]. Here, we assume that a left-handed wave at ω_1 falls in a NID and travels with its wavevector $\mathbf{k}_1$ directed along the z-axis [Fig. 2, (a)]. Then its energy-flow $\mathbf{S}_1$ is directed against the z-axis. We also assume that the sample is illuminated by a higher-frequency wave traveling along the axis z. The frequency of this radiation ω_3 falls in a PID. The two coupled waves with *co-directed* wavevectors $\mathbf{k}_3$ and $\mathbf{k}_1$ create a difference-frequency generated (DFG) idler at $\omega_2 = \omega_3 - \omega_1$, which is in a PID. The idle wave contributes back into the wave at ω_1 through three-wave coupling and thus enables OPA at ω_1 by converting the energy of the pump field at ω_3. Thus, the process under consideration involves a three-wave mixing with *all wavevectors directed along* z. Note that the energy flow of the signal wave, $\mathbf{S}_1$, is directed against z, i.e., it is directed *against* the energy flows of the two other waves, $\mathbf{S}_2$ and $\mathbf{S}_3$. Such a coupling scheme is in contrast with the conventional phase-matching scheme for OPA [Fig. 2, (b)]. The Manley-Rowe relations, which follow from the Maxwell's equations at absorption

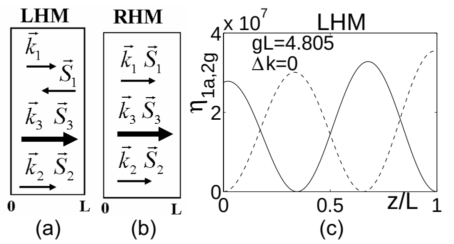

Fig.1

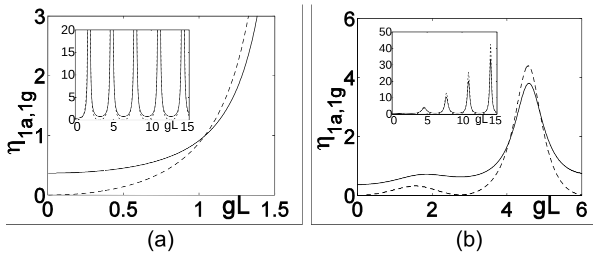

Fig.2

Fig. 1. (a)-(d): The difference between OPA processes in NIMs and PIMs. (a) and (b) – phase matching schemes, (c) and (d) – a typical difference in the signal (the solid line) and the idler (the dashed line) spatial intensity distributions. (c): $\alpha_1 L = 1$, $\alpha_2 L = 1/2$.

Fig. 2. Output amplification, η_{1a} (the solid line), and the DFG factor η_{1g} (the dashed line) for the backward wave at z=0. (a) $\Delta k = 0$. (b) $\Delta kL = \pi$. (a) and (b): $\alpha_1 L = 1$, $\alpha_2 L = 1/2$.

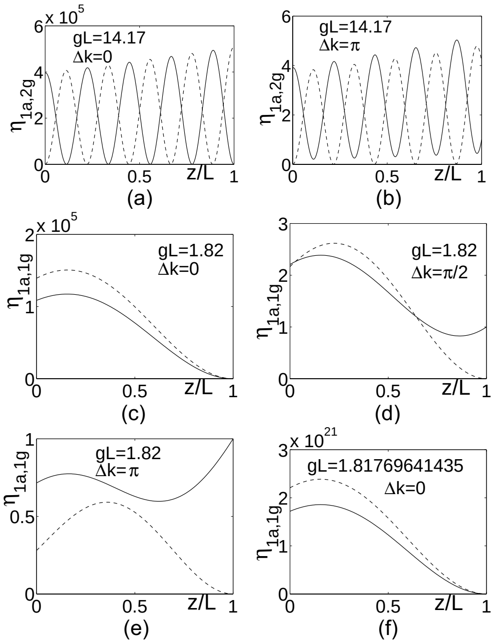

Fig. 3. The amplification factor for the negative-index signal $[\eta_{1a}(z) = |a_1/a_{1L}|^2$; the solid lines in (a)-(f)], the conversion factor for the signal $[\eta_{1g}(z) = |a_1/a_{20}^*|^2$; the dashed lines in (c)-(f)]; and the conversion factor for the positive-index idler $[\eta_{2g}(z) = |a_2/a_{1L}^*|^2$; the dashed lines in (a) and (b)] for various Δk and gL. $\alpha_1 L = 1$, $\alpha_2 L = 1/2$.

indices $\alpha_1 = \alpha_2 = 0$, have the form:

$$d\left[(S_{1z}/\hbar\omega_1) - (S_{2z}/\hbar\omega_2)\right]/dz = 0, \quad d\left[\sqrt{\mu_1/\epsilon_1}(h_1^2/\omega_1) + \sqrt{\mu_2/\epsilon_2}(h_2^2/\omega_2)\right]dz = 0. \qquad (1)$$

Equation (1) describes the creation of pairs of *entangled counter-propagating photons* $\hbar\omega_1$ and $\hbar\omega_2$; it takes into account the opposite signs of the corresponding derivatives with respect to z. The equation predicts that the *sum* of the terms proportional to the squared amplitudes of the signal and idler remains constant through the sample, which is in contrast with the requirement that the *difference* of such terms is constant in the case of a PIM. Equations for slowly varying amplitudes reveal unusual spatial properties for the three-wave mixing process inside a LHM [c.f., Fig. 1,(c) and (d)], which depends on the product gL and on phase mismatch Δk (Fig. 3). Here, g is the factor proportional to the product of squared nonlinear susceptibility and the intensity of the pump field. A *strong resonance dependence of the output intensity of the left-handed wave on the factor gL* [Fig. 2, (a)and (b) and Fig. 3] indicates that unless the pump *intensity and the phase matching are appropriately optimized*, the maximum of the amplitude of the left-handed wave may occur inside rather than on the output edge of the slab [Fig. 3, (a) and (b)]. The OPA can *not only fully compensate for absorption but even turn into oscillations* when the intensity of the control field reaches values given by a periodic set of increasing numbers [Fig. 2, (a), (b)].

The important advantage of the backward SHG, OPA, and OPO in NIMs investigated here is the distributed feedback, which is inherent to such scheme and enables oscillations without a cavity. In NIMs, each spatial point serves as a source for the generated wave in the reflected direction, whereas the phase velocities of all the three coupled waves are co-directed. For a more detailed consideration see ref.[6,7]

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