Tailoring transparency of negative-index metamaterials with parametric amplification

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Abstract

The possibility of compensating losses in negative-index metatamterials doped by resonant four-level centers is shown based on quantum interference and extraordinary properties of parametric amplification of counter-propagating electromagnetic waves.

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1. Introduction.

It has been experimentally proven for the microwave analogs that negative-index electrodynamics enables the functionalities of the electronic devices previously unimaginable. Owing to the fact that the Maxwell equations are scalable, practically the same strategies can be used for the optical range. 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 causality principle, optical negative-index metatamaterials (NIMs) must be lossy. Absorption is generally recognized now as one of the most challenging problems that need 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]. Usually NI properties exist within certain frequency band, whereas the sample possesses ordinary, positive-index, properties outside this band. 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*. One possible approach 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 [2,3] originating from the non-symmetric current-voltage characteristics of its structural elements [4]. Herewith, we propose a different option which does not require strong nonlinear response of the building blocks of the NIMs. 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* [5]. 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-free lasing. However, they possess different advantages and offer different applications in photonics. We show that similar to that considered in [2], the processes under investigation exhibits 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. 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 [6-9] and of the $\chi^{(2)}$ – based OPA – in [2,3]. Recent experiments have shown exciting possibilities of crafting NIMs with nonlinear-optical response significantly exceeding that in ordinary crystals [10].

2. Laser-induced transparency and amplification associated with quantum interference and $\chi^{(3)}$-based OPA in doped double-frequency-domain NIM.

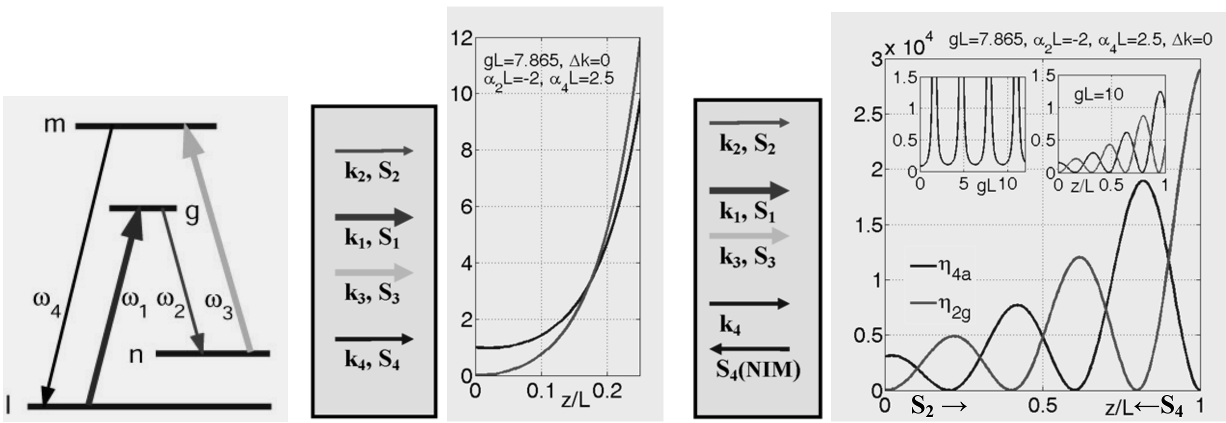
We consider OPA associated with resonant four-wave mixing (FWM) process depicted in Fig. 1a. Probe (signal) field at ω_4 is controlled by two driving fields at ω_1 and ω_3. This causes generation of the idler at $\omega_2 = \omega_3 + \omega_1 - \omega_4$, which may experience strong Raman amplification. An amplified idler contributes back to the signal through FWM process $\omega_4 = \omega_3 + \omega_1 - \omega_2$ and thus causes Raman amplification assisted OPA of the signal. Local optical parameters such as intensity-dependent refractive indices n_4 and n_2 and intensity-dependent absorption/amplification indices α_4 and α_2 as well as intensity-dependent $\chi^{(3)}_{4,2}$ can be tailored by changing intensity and resonance detuning of the control fields.

Maxwell's equations for scaled slowly varying amplitudes of the signal and idler fields take the form:

$$da_4 / dz = \pm i g a_2^* \exp[i\Delta k z] \mp (\alpha_4 / 2) a_4 \qquad (1)$$

$$da_2 / dz = i g a_4^* \exp[i\Delta k z] - (\alpha_2 / 2) a_2 \qquad (2)$$

Here, α_4 and α_2 are absorption or amplification (if $\alpha < 0$) indices, $\Delta k = k_1 + k_3 - k_4 - k_2$ is phase mismatch, g is OPA parameter proportional to $\chi^{(3)}_4 \chi^{(3)}_2 a_1 a_3$. Upper sign in (1) corresponds to PIM, lower – to NIM, where energy flow (Poynting vector) and phase velocity (wave-vector) are contra-directed.

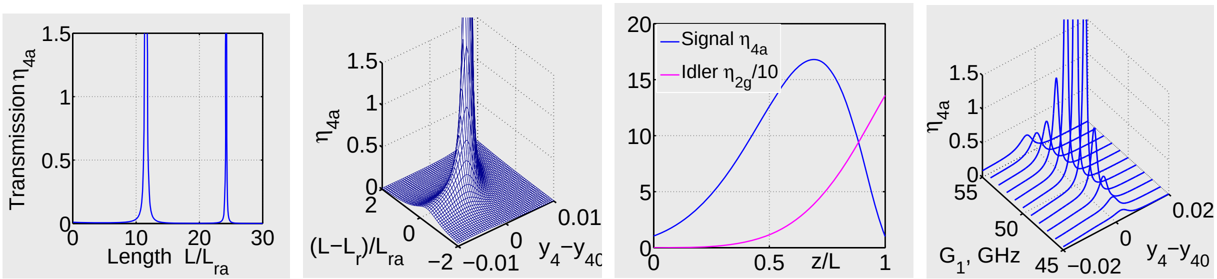


(a) **(b)** **(c)** **(d)** **(e)**

Fig. 1. Schemes of quantum control - (a); of phase-matched wave propagation in PIM - (b); amplification of the signal (the upper plot) and generated idler (lower plot) along the PI slab – (c); phase-matched coupling configuration in a slab with negative refractive index at ω_4 and positive at all other frequencies – (d); resonances in the output of the backward signal wave at z=0 – [the upper left inset in (e)], intensity distribution of the signal entering the slab at z=L (main plot with maximum about $z/L \approx 0.8$) and of the idler entering the slab at z=0 (main plot with minimum about $z/L \approx 0.8$), many-order changes in the amplitudes at small changes of the OPA parameter [the upper right inset in (e)].

Figure 1 displays drastic differences between FWM-based OPA in absorbing phase-matched PI and in double-domain NI slabs. Coupling geometry and evolution of the signal and the idler along the ordinary, positive-index (PIM), slab is shown in Figures 1 (b) and (c). In NIM, at co-directed wave-vectors, energy flow for signal is contra-directed. Figure 1(e) shows cardinal changes in the spatial behavior of the coupled contra-propagating waves that stems from backwardness of one of them. It is most explicitly seen for the case of transparent slabs. In transparent phase-matched PIM ($\alpha_4 = 0$, $\alpha_2 = 0$, and $\Delta k=0$), the amplification coefficient for the signal, $\eta_{4a} = |a_4/a_{40}|^2$, and efficiency of its conversion to idler, $\eta_{2g} = |a_2/a_{40}|^2$, grow as exp(2gz), whereas for backward waves in NIM signal varies along the slab as $\eta_4 = |\cos(gz)/\cos(gL)|^2$ [11]. The latter equation depicts strong resonance dependence on gL and the behavior similar to the distributed feedback. When $gL \to (j+1)\pi/2$, the output signal $\eta_4 \to \infty$ at z=0, which indicates cavity-free oscillation threshold.

Herewith, we have investigated a model of four-level centers embedded into the host slab that possess intrinsic negative refraction index and 1% transmission at ω_4. Optical transition's HWHM for the embedded centers were selected in the range of $\Gamma_{ij} \sim 10^{12}$ s^{-1}, for Raman transitions ~ 10^{10} s^{-1}, and the energy level lifetimes ~ 10^{-8} s. The results of the numerical simulations are shown in Fig. 2. Here, $L/L_{ra} = \alpha_{40}L$ is slab thickness scaled to the resonant absorption length, $\Omega_1 = \omega_1 - \omega_{gl}$, etc., are resonance detunings, $y_4 = \Omega_4/\Gamma_{ml}$; $G_{1,2} = E_{1,2}d_{ij}/2\hbar$ are coupling Rabi frequencies. For typical optical transitions, the magnitudes $G \sim 10^{12}$ s^{-1} correspond to control field intensities I ~ (10÷100) kW/(0.1mm)^2 Optimum resonance frequency detunings appear in the range of $|\Omega i|/\Gamma ml \approx 1 \div 3$, and optical thickness for the signal in the resonance maximum – about $L/L_{ra} \approx 11$.



(a) (b) (c) (d)

Fig.2. Compensating losses in NIM doped by resonance four-level centers by two control lasers. (a) – output signal at z=0; (b) strong resonance dependence on product of concentration of the centers and the slab thickness and on the probe field frequency; (c) – distribution of the signal (the plot with maximum) and of the idler; (d) – dependence of the signal transmission on its frequency and on the intensity of one of the control field.

Particularly, Fig.2 was computed for G_1=G_3= 50 GHz, Ω_1= Ω_3 = 2.5 Γ_1, which corresponds to $y_4(max)\approx 1.3$, $L/L_{ra} = \alpha_{40}L \approx 11.5$, $g/\alpha_{40} \approx 0.21$. Assuming resonance absorption cross-section $\sigma_{ra} \sim 10^{-16}$ cm^2, which is typical for dye molecules, and concentration of the centers $N \sim 10^{19}$ cm^{-3}, we obtain $L_{ra}^{-1} = \alpha_{ra} \sim 10^3$ cm^{-1}, and required slab thickness in the range $L \sim (10 \div 100)$ µm.

3. Conclusions

We propose compensation of losses in optical NIMs through tailored embedded optical nonlinearities. We have explored the features of FWM-based OPA in such composite metamaterial with negative refractive index at the frequency of the signal field and positive index for all other three coupled waves. Strong nonlinear optical response of the composite is primarily determined by the embedded resonant four-level centers. In addition, we have shown the opportunities of quantum control of the local optical parameters, which employs constructive and destructive quantum interference tailored by two auxiliary driving control fields. The features of narrow-band frequency-tunable transparency window in the negative index frequency domain, cavity-free generation of the entangled counter-propagating photons, and the feasibilities of quantum switching in the NIMs were numerically simulated.

4. Acknowledgement

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