Compensating losses in positive- and negative-index metamaterials through nonlinear-optical quantum switching

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Optical negative-index metamaterials (NIMs) form a novel class of artificial electromagnetic materials that promise revolutionary breakthrough in photonics and became possible due to fast developments in nanotechnology. Particularly, this is in regard to 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, NIMs must be lossy. Absorption is generally recognized now as one of the most challenging problems that needs to be addressed for numerous 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 materials that provide amplification due to population inversion. Herewith, we propose alternative means of compensating losses, producing full transparency, or amplification, or even cavity-free optical oscillation in NIMs. The underlying physical mechanism essentially stems from constructive and destructive nonlinear interference effects (NIE) in the embedded resonant centers, like ions or molecules, controlled by two light beams with frequencies outside the negative-index domain. The proposed scheme of quantum control involves interference between resonant Raman-like and optical parametric amplification (OPA)-like quantum pathways [1] (and references therein), but does not rely on a coherent population trapping-type of excitation commonly employed in double-Λ schemes of quantum control [2]. We also show that the propagation features of the signal (probe) wave become dramatically different in NIM compared with its counterpart in natural crystals. Counterintuitive features of nonlinear-optical processes under investigations originate from opposite directions of the energy flow and the phase velocity, which is inherent to electromagnetic waves propagating in NIMs [3–7]. The possibility of compensation of losses and generation of counter-propagating entangled right- and left-handed photons controlled by an external laser has been predicted in such materials, even in a cavity-free regime, based on the extraordinary geometry and features of off-resonant OPA in NIMs [6, 7]. Here, we have used for numerical simulations a solution for the set of coupled density-matrix and Maxwell's equations [1] and the double-Λ model for inhomogeneously broadened optical transitions in Pr:YSO [2], which exhibits very long spin coherence relaxation time in the ground electronic state.

Thus, we have shown the possibilities of compensation of strong losses in negative- and positive-index materials by two laser beams as well as of wavelength-selective frequency-tunable narrow-band filtering. Such feasibility of quantum switching from strong absorption to amplification via transparency is possible due to NIE-accompanied resonant Raman-like and OPA-like processes in doped metamaterials. A possibility of generation of counter-propagating entangled right- and left-handed photons in doped NIMs in cavity-free regimes is investigated too. An illustration of the possibilities offered by such a scheme of quantum control through NIE and the feature of such processes in ordinary positive-index materials doped by Pr^{3+} is given below (Fig. 1).

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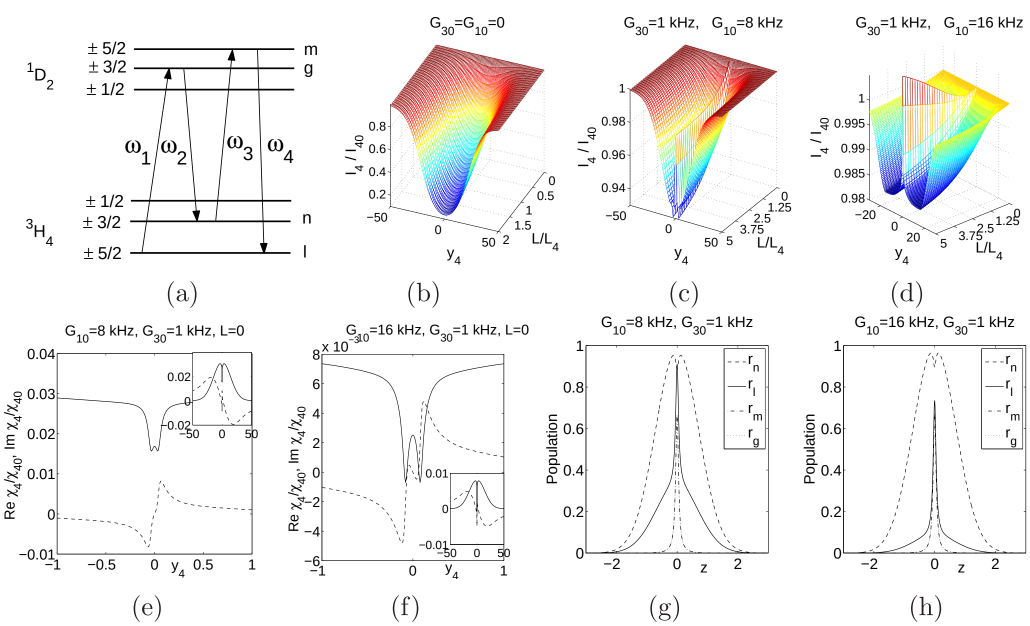

FIG. 1: Quantum switching from strong absorption to amplification in a doped solid. I_{40} is the signal intensity at the medium entrance, y_4 is its frequency detuning from the transition center scaled to the transition homogeneous half-width, L/L_4 is the propagation length scaled to the original resonant absorption length for this transition, G_{i0} is the coupling Rabi frequency for the control field at the medium entrance, G_i is its local magnitude inside the medium slab. Both control fields, at ω_1 and at ω_3, are tuned to the resonance center of the corresponding transitions. (a): Energy-level diagram. $E_{1,3}$ – control, E_4 – probe, E_2 – generated idler fields. (b): Absorption at control fields turned off. (c) - (d): Switching from absorption to amplification via transparency at different intensity of the control fields. In (c), the transparency at L/L_4=5, y_4=0 is equal to 1.008. (e) and (f): Spectral structures created by the control fields in the absorption (solid line) and refractive (dash line) indices at the medium entrance; (e) corresponds to (c) and (f) – to (d). Broader scans are displayed at the insets. (g) and (h): Holes and peaks created in the population distribution over the energy shifts δE for inhomogeneously broadened levels; z=$\delta E/\Delta E$ and ΔE is the half-width of the inhomogeneous broadened levels. The populations of levels r, l and m are multiplied by 20. The feasibility of manipulating population difference at the spin transition ln is seen.