Mimicking Frequency-mixing in Nonlinear Optical Negative-index Metamaterials: Unidirectional Raman Amplification and Shaping of Optical Pulses

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***Abstract*— The possibility of mimicking of huge enhancement of coherent nonlinear optical frequency-mixing processes, as predicted to occur in the plasmonic negative-index metamaterials, is investigated in Raman crystals. Negative dispersion of optical phonons, which ensures elastic waves with contra-directed phase and group velocities, plays a key role for such an analogy. A possibility to greatly enhance frequency conversion efficiency of stimulated Raman scattering is shown by making use of extraordinary properties of three-wave mixing of ordinary optical and backward elastic waves. Specific properties of the indicated nonlinear optical process in short-pulse regime are investigated and the possibility to eliminate such a fundamental detrimental effect as fast damping of optical phonons on the process concerned is shown.**

Keywords—nonlinear optics, three-wave nixing, negative-index metamaterials, optical phonons, stimulated Raman scattering, Raman amplifiers and oscillators

Physics and applications of negative-index metamaterials (NIMs) are being explored world-wide at a rapid pace. Current mainstream in fabricating of bulk NIM slabs relies on sophisticated methods of nanotechnology. Engineering strong fast quadratic nonlinear optical response by the plasmonic mesoatoms also presents a challenging goal not yet achieved. Extraordinary coherent nonlinear optical frequency-converting propagation processes predicted in NIMs has been simulated so far only in microwave frequency range. This paper proposes a different paradigm which employs spatial dispersion and allows one to mimic extraordinary nonlinear optical three-wave mixing (TWM) processes commonly attributed to NIMs in readily available crystals with strong Raman nonlinearity.

The possibility of huge enhancement of optical parametric amplification and frequency-shifted nonlinear reflectivity has been predicted through TWM in metamaterials, whereas one of the three coupled electromagnetic waves falls in the negative-index frequency domain [1]. The basic underpinning idea of this work is to replace the backward-wave electromagnetic mode by optical phonons, the elastic wave with negative group velocity, in order to achieve similar enhancement. Operation in short pulse regime is proposed to remove the severe detrimental factor imposed by fast phonon damping. Significant decrease of the required threshold intensity of fundamental radiation, as compared with that in the continuous-wave regime, is predicted down to that achievable by commercial lasers. Unparalleled properties of the proposed short-pulse process are numerically simulated and the possibility of huge enhancement of quantum conversion efficiency as well as of tailoring the duration and shapes of the generated and the transmitted fundamental pulses are predicted. Elaboration of the proposed concept allows one to utilize the revealed extraordinary features for creation of a family of unique photonic devices with advanced functional properties such as unidirectional optical amplifiers, filters, switches and cavity-free optical parametric oscillators. Basic requirements to the prospective crystals are discussed. Some of the examples can be found in [2].

[1] A.K. Popov and V.M. Shalaev, "Negative-index metamaterials: second harmonic generation, Manley–Rowe relations and parametric amplification," Appl. Phys. B Lasers Opt. vol. 84, 131–137 (2006).

[2] A. K. Popov, M. I. Shalaev, S. A. Myslivets, and V. V. Slabko, "Unidirectional amplification and shaping of optical pulses by three-wave mixing with negative phonons," Appl. Phys. A (Published on-line: November 2013). DOI 10.1007/s00339-013-8078-4

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