

## Nonlinear-optical Negative-index Metamaterials: Extraordinary Properties and Applications

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(Received 19 May 2013; published online 31 August 2013)

The principles of nanoengineering of metamaterials which support optical electromagnetic and elastic waves with negative group velocity are described. Extraordinary properties of nonlinear-optical energy transfer between contra-propagating short pulses of electromagnetic and elastic waves are investigated and prospective unique photonic devices are discussed.

**Keywords:** Nonlinear optical negative-index metamaterials, Backward electromagnetic and elastic waves, Nonlinear energy exchange between ordinary and backward waves, Second harmonic generation and frequency mixing, Photonic devices.

PACS numbers: 78.67. – n, 42.65.Ky, 42.65.Dr, 42.79.Fm, 42.79.Nv

### 1. INTRODUCTION

Optical negative-index materials (NIMs) form a class of electromagnetic media that promise revolutionary breakthroughs in photonics. The possibilities of such breakthroughs originate from backwardness, the extraordinary property that electromagnetic waves (EMWs) acquire in NIMs. Unlike in ordinary, positive-index materials, the energy flow,  $\mathbf{S}$ , and the wave-vector,  $\mathbf{k}$ , become counter-directed in NIMs that determines their unique linear and nonlinear optical (NLO) propagation properties. Backward waves (BW) are also referred to as waves with negative group velocity. Usually, NIMs are nanostructured metal-insulator composites with a special design of their building blocks at the nanoscale that enables negative optical magnetism. Metal component imposes strong absorption of optical radiation in NIMs, which presents a major obstacle towards their numerous prospective exciting applications. Extraordinary features of coherent NLO frequency conversion processes in NIMs, which stem from wave-mixing of ordinary and backward electromagnetic waves (BEMWs), and the possibilities to apply them for compensating the outlined losses have been shown in [1-5] (for a review, see [5,6] and references therein). Most remarkable feature is appearance of distributed feedback NLO behavior. It allows sharp, resonance type, increase of the conversion efficiency as function of the product of strength of the input EM field and the slab thickness, which is in strict contrast with the commonly known exponential growth in ordinary PI materials. Essentially different properties of three-wave mixing (TWM) and second harmonic generation (SHG) have been shown [3, 5, 6].

### 2. RESULTS AND DISCUSSIONS

In this work, novel concepts of NLO photonic materials are proposed, which support negative group velocity

of EM or elastic waves and lay outside of current mainstream in fabricating plasmonic-based NIMs. They concern with the materials that support electromagnetic or vibration waves with negative group velocity. Energy flux,  $\mathbf{S}$ , and wave vector,  $\mathbf{k}$ , become counter-directed in a media with negative dispersion  $\partial\omega/\partial k < 0$ , which is seen from the equation  $\mathbf{S} = \mathbf{v}_g U$ , where  $U$  is energy density,  $\mathbf{v}_g = \text{grad}_{\mathbf{k}}\omega(\mathbf{k})$ . Such NLO materials enable greatly enhanced coherent NLO energy exchange between ordinary and BWs as applied to SHG, TWM- and four-wave mixing processes. Two different classes of materials which support BWs are proposed and will be described: metamaterials with specially engineered spatial dispersion of the nanoscopic building blocks, such as standing carbon nanotubes [7], and crystals that support optical phonons with negative group velocity [8]. The possibility to employ ordinary, readily available crystals instead of plasmonic NLO NIMs is justified. Plasmonic NIMs are challenging to engineer that requires sophisticated techniques of nanotechnology. We show that extraordinary NLO frequency-conversion propagation processes attributed to NIMs can be mimicked in the proposed fully dielectric materials. We also show that the detrimental effects of strong losses caused by fast optical phonon damping can be eliminated in the short-pulse regime. Comparative analysis is given.

Fig. 1a depicts metamaterial slab that can be viewed as a wave guide formed by a metal plate (bottom) and by air (top) tampered by carbon nanotubes. Fig. 1b shows two modes supported by the metamaterial (waveguide). Frequency  $f_1$  correspond to positive and  $2f_1$  – to negative group velocities, both propagate with the same phase velocity. The latter indicates the possibility of phase matching of SHG.

Fig. 2 depicts dispersion of optical phonons  $\omega_s(k_s)$ , such as in calcite, and phase matching of ordinary, co-propagating fundamental ( $l$ ) Stokes ( $s$ ) and backward elastic wave ( $v$ ). Here,  $S_i$  are energy fluxes and  $k_i$  are wave vectors.

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Fig. 3a (solid line) shows quantum conversion efficiency of stimulated Raman scattering (TWM) in the case of contra-propagating phase-matched ordinary Stokes and backward phonon waves. Dashed line shows alternative option of phase-matched co-propagating Stokes and phonon waves, which correspond to standard SRS process. Great enhancement of the efficiency is explicitly seen in the first case. The possibility to tailor of duration and shape of the output pulses is seen.

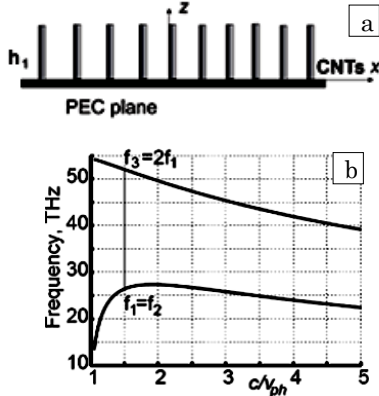


Fig. 1 – (a) “Nanoforest” made of carbon nanotubes and (b) phase matching of backward SH and ordinary fundamental EM waves propagating along axis  $x$

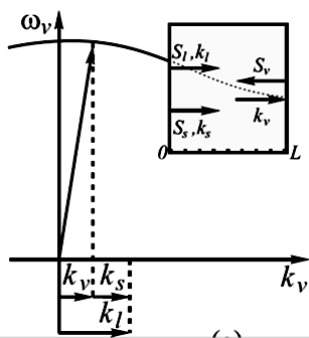


Fig. 2 – Negative dispersion of optical phonons and phase matching of ordinary fundamental ( $l$ ), Stokes ( $s$ ) and backward contra-propagating phonon ( $v$ ) waves

3. CONCLUSIONS

In the conclusions, alternative approach to fabricating nanostructured metamaterials that enables coexistence of ordinary and backward optical electromagnetic waves is proposed. The possibility of conversion of ordinary EMW to the contra-propagating BEMW at its doubled frequency is shown. Such metaslab can be viewed as a *frequency-doubling* NLO microscopic *metamirror*

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and optical data-processing chip. Especially interesting unparallel properties appear attributed to short pulse regime. A class of readily available crystals is proposed that allows mimicking extraordinary NLO propagation processes commonly associated with plasmonic negative-index metamaterials. Here, optical phonons with negative group velocity are proposed to replace EMW in the frequency domain of negative refractive index. The possibility to greatly enhance Raman amplification and to eliminate the detrimental effect of phonon damping is shown making use of short pulse regime. The concepts of *unique ultracompact photonic devices* such as data processing chips, microscopic modulators, amplifiers, oscillators and nonlinear-optical sensors are discussed.

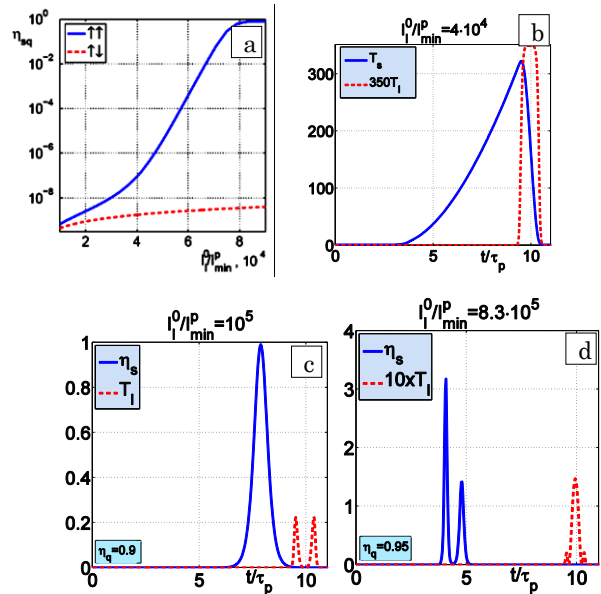


Fig. 3 – (a) Quantum conversion efficiency vs. energy of femtosecond pump pulses. Solid line – in the proposed coupling scheme, dashed line – standard coupling scheme. (b)-(d) Changes in the shapes of generated Stokes (solid line) and transmitted fundamental (dash line) output co-propagating pulses with the increase of energy of the input fundamental pulse.  $\eta_q$  is corresponding conversion efficiency,  $\tau_p$  – duration of the input fundamental pulse

ACKNOWLEDGEMENTS

This work was supported in parts by the Air Force Office of Scientific Research (Contract No FA950-12-1-298), by the National Science Foundation (Grant No ECCS-1028353), by the Academy of Finland and Nokia through the Center-of-Excellence program, by the Russian Federal Program on Science, Education and Innovation (Contract No 14.A18.21.1942), and by the Presidium of the Russian Academy of Sciences (Grant No 24-31).

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