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14. ABSTRACT

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as of 10-Jul-2018

Agency Code:

Proposal Number: 65605PH

Agreement Number: W911NF-14-1-0619

INVESTIGATOR(S):

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Report Date: 14-Dec-2017

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Final Report for Period Beginning 15-Sep-2014 and Ending 14-Sep-2017

Title: Coherent Nonlinear Nanophotonics

Begin Performance Period: 15-Sep-2014

End Performance Period: 14-Sep-2017

Report Term: 0-Other

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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees:

STEM Participants:

Major Goals: Contemporary nonlinear optics grounds itself on the concept of electromagnetic waves with CO-DIRECTED phase velocity and energy flux which is typical for all natural isotropic materials. A majority of widely used linear and nonlinear photonic devices exploit this concept. The advent of the nanotechnology has made possible the creation of the metamaterials that enable generation of the electromagnetic waves with CONTRA-DIRECTED energy flux and phase velocity that are referred to as BACKWARD electromagnetic waves. Such uncommon property has opened novel avenues in linear geometrical optics towards the extraordinary applications such as the subwavelengths resolution, the clocking of objects, etc. Similar revolutionary breakthroughs are anticipated in COHERENT nonlinear optics where matching of phase velocities of the CONTRA-PROPAGATING coupled waves plays a crucial role. A MAJOR GOAL of this project was the exploration of such possibilities. It was aimed at the studies towards the basic principles of nanoengineering of the prospective metamaterials and at the investigations of the particular properties of the second harmonic generation, parametric amplification, switching, changing the propagation direction and frequencies of pulses of the entangled photons by making use of the backward light waves in the proposed metamaterials. The outcomes should pave the pathways to the novel extraordinary possibilities to control the light waves.

Accomplishments: We have shown that a deliberately engineered dispersive metamaterial slab can enable the coexistence and phase matching of ordinary fundamental and contra-propagating backward second harmonic electromagnetic waves. Energy flux and phase velocity are contra-directed in the backward waves, which is the extraordinary phenomenon that gives rise to unique nonlinear optical propagation processes. We have demonstrated that frequencies, phase, and group velocities, as well as the losses inherent to the guided electromagnetic modes supported by such metamaterial, can be tailored to maximize the conversion of frequencies and to reverse the propagation direction of the generated second harmonic wave. Such a possibility, which is of a paramount importance for nonlinear photonics, is proven using a numerical model describing the hyperbolic metamaterial made of carbon nanotubes standing on the metal surface. Extraordinary properties of the backward-wave second harmonic generation in the reflection direction and of the corresponding frequency doubling meta-reflector in the THz are investigated with a focus on the pulsed regime. Most important details can be found in our paper recently published in ACS Photonics, 2017 (uploaded).

We have proposed the metamaterial that supports a mixture of three or more normal and backward electromagnetic modes with equal co-directed phase velocities and mutually contra-directed energy fluxes. This enables extraordinary three-wave mixing, greatly enhanced optical parametric amplification, and frequency-changing generation of entangled photons in the reflection direction. Proof-of-principle numerical simulations of such processes have been presented based on the example of the wave-guided terahertz waves contra-

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propagating in the metaslab made of carbon nanotubes. Most important details can be found in our paper recently published in Optics Letters, 2017 (uploaded).

We have shown that the opposite direction of phase velocity and energy flux in backward waves gives rise to extraordinary transient processes due to greatly enhanced optical parametric amplification and frequency up- and down-shifting nonlinear reflectivity. The differences are illustrated through comparison with the counterparts in ordinary, co-propagating settings. Most important details can be found in our paper published in Optics Letters, 2016 (uploaded).

One of the important outcomes of the project is the proposed approach which is fundamentally different from the current mainstream in engineering the negative-index metamaterials. We have shown that the model of the proposed metamaterials employed in our simulations can be generalized and applied to nanoengineering the metamaterials made of nanostructures of different shapes, architectures, and materials. Such subsequently advanced metamaterials would support the coexistence of the tailored positive and negative dispersion of the guided electromagnetic waves while providing their phase matching and decreased losses in novel broad frequency ranges.

Theoretical studies and numerical simulation were employed to achieve the stated goals. Nonlinear partial differential equations were used to investigate nonlinear optical propagation processes in the proposed metamaterials with focus on the pulsed regimes.

The outlined accomplishments demonstrate novel pathways to manipulating light and to the creation of miniature nonlinear photonic devices with extraordinary properties operating through extended frequency bands.

Training Opportunities: As the research progressed, the results were discussed with graduate and PhD students and presented on the Purdue University website.

Results Dissemination: Results were disseminated through publications in leading topical journals, open electronic archives, talks at numerous international conferences and seminars for graduate and PhD students, and on the Purdue University website.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI

Participant: Alexander K Popov

Person Months Worked: 5.00

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Funding Support:

CONFERENCE PAPERS:

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Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: OWTNM 2015, Optical Wave and Waveguide Theory and Numerical Modelling Workshop
Date Received: 18-Aug-2016 Conference Date: 17-Apr-2015 Date Published:
Conference Location: City University, London, UK
Paper Title: Phase Matching and Frequency Mixing of Contra-propagating Electromagnetic Pulses in the
Waveguide Tampered by Carbon Nanoforest
Authors: A. K. Popov, S. A. Myslivets, A. V. Kildishev, A. O. Korotkevich
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2015 Summer Topicals Meeting Series
Date Received: 18-Aug-2016 Conference Date: 13-Jul-2015 Date Published:
Conference Location: Nassau, Bahamas
Paper Title: Coherent Nonlinear-Optical Signal Processing in Spatially Dispersive Plasmonic Metamaterials
Authors: A. K. Popov, S. A. Myslivets, A. V. Kildishev, A. O. Korotkevich
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: META'15, the 6th International Conference on Metamaterials, Photonic Crystals and
Plasmonics
Date Received: 18-Aug-2016 Conference Date: 04-Aug-2015 Date Published:
Conference Location: New York, NY, USA
Paper Title: Phase Matching and Tree-wave Mixing of Contra-propagating Light Pulses in Negatively Dispersive
Metamaterials
Authors: A. K. Popov, S. A. Myslivets, A. V. Kildishev, A. O. Korotkevich
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Frontiers in Optics: The 99th OSA Annual Meeting and Exhibit/Laser Science XXXI
Date Received: 18-Aug-2016 Conference Date: 18-Oct-2015 Date Published:
Conference Location: Rochester, NY, USA
Paper Title: Frequency Conversion of Short Optical Pulses in Negatively Spatially Dispersive Metamaterials
Authors: A. K. Popov, S. A. Myslivets
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2015 CLEO Pacific Rim Conference
Date Received: 18-Aug-2016 Conference Date: 24-Aug-2015 Date Published:
Conference Location: Busan, Korea
Paper Title: Second Harmonic Generation and Shaping of Contra-propagating Light Pulses in Negatively
Dispersive Metamaterials
Authors: A. K. Popov, S. A. Myslivets, A. V. Kildishev, A. O. Korotkevich
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: ETOPIIM 10, Tenth International Symposium on Electrical, Transport, and Optical Properties
of Inhomogeneous Media
Date Received: 18-Aug-2016 Conference Date: 21-Jun-2015 Date Published:
Conference Location: Neveh Ilan, Israel
Paper Title: Coherent Nonlinear Optical Transport Processes in Spatially Negatively Dispersive Metamaterials:
extraordinary and counterintuitive (Invited Talk)
Authors: Alexander Popov
Acknowledged Federal Support: **Y**

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Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Tri-Service Metamaterials Review
Date Received: 18-Aug-2016 Conference Date: 17-Nov-2014 Date Published:
Conference Location: Duke University, USA
Paper Title: Nonlinear Optics in Spatially Negatively Dispersive Metamaterials: Extraordinary and Counterintuitive
Authors: Alexander Popov
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 17th International Conference Laser Optics 2016
Date Received: 18-Aug-2016 Conference Date: 27-Jun-2016 Date Published: 27-Jun-2016
Conference Location: Saint Petersburg, Russia
Paper Title: Extraordinary time-dependent processes in the parametric interaction of counter-propagating waves
Authors: V.A. Tkachenko, A.K. Popov, S.A. Myslivets, V.V. Slabko
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Tri-Service Metamaterial Review
Date Received: 14-Dec-2017 Conference Date: 07-Nov-2016 Date Published:
Conference Location: Arlington, VA
Paper Title: Negatively spatially dispersive metamaterials: extraordinary transients in the parametric amplification and nonlinear reflectivity
Authors: Alexander K. Popov
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: ICONO/LAT 2016 – International Conference on Coherent and Nonlinear Optics (ICONO 2016)/ International Conference on Laser, Applications and Technologies (LAT 2016)
Date Received: 14-Dec-2017 Conference Date: 26-Sep-2017 Date Published:
Conference Location: Minsk, Belarus
Paper Title: Parametric amplification with backward waves: Pulse shapes
Authors: Vitaly V. Slabko, Victor A. Tkachenko, Alexander K. Popov, and Sergey A. Myslivets
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: International Conference on Nano-photonics and Nano-electronics (ICNN2017)
Date Received: 14-Dec-2017 Conference Date: 18-Apr-2017 Date Published:
Conference Location: Yokohama, Japan
Paper Title: Backward-wave Phase-matching in Spatially Dispersive Metamaterials
Authors: Alexander Popov, Igor Nefedov, and Sergey Myslivets
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Purdue Quantum Center Workshop on Coherent Effects in Physics and Chemistry
Date Received: 14-Dec-2017 Conference Date: 28-Apr-2017 Date Published:
Conference Location: Purdue University, West Lafayette, Indiana.
Paper Title: Coherent Nonlinear Optical Propagation Processes in Hyperbolic Metamaterials
Authors: Alexander K. Popov
Acknowledged Federal Support: **Y**

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Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: PIERS 2017, Progress In Electromagnetics Research Symposium
Date Received: 14-Dec-2017 Conference Date: 22-May-2017 Date Published:
Conference Location: St Petersburg, Russia.
Paper Title: Extraordinary Transient Nonlinear-optical Processes on the Spatially Dispersive Metasurfaces
Authors: Alexander K. Popov, V. V. Slabko, V. A. Tkachenko, and S. A. Myslivets, ``Extraordinary Transient Nonl
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: International Workshop on Novel Optical Materials and Applications (NOMA2017)
Date Received: 14-Dec-2017 Conference Date: 04-Jun-2017 Date Published:
Conference Location: Cetraro, Italy.
Paper Title: Enhancing coherent nonlinear optical coupling in hyperbolic metanowaveguides
Authors: Alexander K. Popov, Vitaly V. Slabko, Victor A. Tkachenko, and Sergey A. Myslivets
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: International Symposium Days of Diffraction
Date Received: 14-Dec-2017 Conference Date: 19-Jun-2017 Date Published:
Conference Location: St. Petersburg, Russia
Paper Title: Frequency mixing of guided electromagnetic waves in hyperbolic metamaterials
Authors: A. K. Popov, V. A. Tkachenko, , V. V. Slabko, . S. A. Myslivets, and I. S. Nefedov
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Progress In Electromagnetics Research Symposium (PIERS)
Date Received: 14-Dec-2017 Conference Date: 19-Nov-2017 Date Published:
Conference Location: Singapore
Paper Title: Effects of Losses and Phase Mismatch on Transient Processes in Optical Parametric Amplification
through Three-wave Mixing of Ordinary and Backward Electromagnetic Waves
Authors: Viktor A. Tkachenko, Aleksey S. Tsipotan, Sergey A. Myslivets, Vitaly V. Slabko, and Alexander K. Popc
Acknowledged Federal Support: **Y**

Nothing to report in the uploaded pdf (see accomplishments and attached reprints of the papers).