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14. ABSTRACT
The Transformation Optics MURI team has continued to develop the theory, modeling and application of Transformation Optical (TO) media, as well as investigating related fabrication and materials issues necessary for implementing metamaterial based TO designs at infrared and visible wavelengths. Device concepts include ultra-wide field-of-view lenses; near-field magnifiers (or hyper-lenses); integrated photonic TO devices; plasmonic TO structures; and tapered waveguide analog TO devices. Of particular relevance is the development of quasi-

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ABSTRACT

The Transformation Optics MURI team has continued to develop the theory, modeling and application of Transformation Optical (TO) media, as well as investigating related fabrication and materials issues necessary for implementing metamaterial based TO designs at infrared and visible wavelengths. Device concepts include ultra-wide field-of-view lenses; near-field magnifiers (or hyper-lenses); integrated photonic TO devices; plasmonic TO structures; and tapered waveguide analog TO devices. Of particular relevance is the development of quasi-conformal (QC) optimization techniques that lead to more realizable TO designs, appropriate for the shorter wavelengths of interest. The QCTO approach has been demonstrated in the design of a flattened Luneburg lens, which can be realized using dielectric-only media, and has also been applied in the optimization of a multi-functional 'Janus' element that integrates simultaneous beam shifting and focusing operations within the same chip-scale footprint. Material and fabrication efforts have included the integration of gain media into metamaterial elements to offset absorptive losses, as well as a number of lithographic patterning techniques to achieve planar and bulk gradient and TO media operational at near- and mid-infrared wavelengths.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
04/27/2012	39	Yu-Ju Tsai, Stéphane Larouche, Talmage Tyler, Guy Lipworth, Nan M. Jokerst, David R. Smith. Design and fabrication of a metamaterial gradient index diffraction grating at infrared wavelengths, Optics Express, (11 2011): 24411. doi: 10.1364/OE.19.024411 276,662.00
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Optics Express, (10 2013): 0. doi: 10.1364/OE.21.026620
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09/15/2014 112 Antoine Moreau, David R. Smith, Cristian Ciraci?, J. Britt Lassiter. Quasi-analytic study of scattering from optical plasmonic patch antennas,
Journal of Applied Physics, (2013): 0. doi: 10.1063/1.4827185
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09/15/2014 113 Cristian Ciracì, Yaroslav Urzhumov, David R. Smith. Effects of classical nonlocality on the optical response of three-dimensional plasmonic nanodimers,
Journal of the Optical Society of America B, (09 2013): 0. doi: 10.1364/JOSAB.30.002731
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09/15/2014 114 Nathan Landy, David R. Smith. Two-dimensional metamaterial device design in the discrete dipole approximation,
Journal of Applied Physics, (07 2014): 0. doi: 10.1063/1.4891295
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09/23/2015 137 Evgenii E Narimanov, Zun Huang. Optical imaging with photonic hyper-crystals: Veselago lens and beyond,
Journal of Optics, (11 2014): 0. doi: 10.1088/2040-8978/16/11/114009
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Optical Materials Express, (06 2015): 0. doi: 10.1364/OME.5.001511
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09/23/2015 138 Evgenii E. Narimanov. Dirac dispersion in photonic hypercrystals,
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10/08/2015 140 John P. Barrett, Steven A. Cummer. Design and Full Characterization of Planar Active Magnetic RF Metamaterials,
IEEE Antennas and Wireless Propagation Letters, (12 2015): 0. doi: 10.1109/LAWP.2014.2388431
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10/11/2015 141 Cristian Ciracì, Xiaoshu Chen, David R. Smith, Sang-Hyun Oh. Nanogap-Enhanced Infrared Spectroscopy with Template-Stripped Wafer-Scale Arrays of Buried Plasmonic Cavities,
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10/11/2015 143 J. Britt Lassiter, Xiaoshu Chen, Xiaojun Liu, Cristian Ciracì, Thang B. Hoang, Stéphane Larouche, Sang-Hyun Oh, Maiken H. Mikkelsen, David R. Smith. Third-Harmonic Generation Enhancement by Film-Coupled Plasmonic Stripe Resonators,
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10/12/2015 142 Cristian Ciracì, Michael Scalora, David R. Smith. Third-harmonic generation in the presence of classical nonlocal effects in gap-plasmon nanostructures,
Physical Review B, (05 2015): 0. doi: 10.1103/PhysRevB.91.205403
373,929.00

11/18/2016 147 2. Nathaniel Kinsey, Akbar A. Syed, Devon Courtwright, Clayton DeVault, Carl E. Bonner, Vladimir I. Gavrilenko, Vladimir M. Shalaev, David J. Hagan, Eric W. Van Stryland, and Alexandra Boltasseva. Effective Third-Order Nonlinearities in Metallic Refractory Titanium Nitride Thin Films,
Optical Materials Express, ( ): 2395. doi:
1,019,912.00

11/18/2016 154 7. Ludmila J. Prokopeva and Alexander V. Kildishev. Expanding the theory of circular omnidirectional light concentrators to elliptic and spheroid designs,
Journal of Optics, ( ): . doi:
1,019,948.00

11/21/2016 136 J. Liu and E. Narimanov. Thermal hyperconductivity: Radiative energy transport in hyperbolic media,
PHYSICAL REVIEW B (Submitted), (10 2014): 041403-1. doi:
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11/21/2016 128 Viktoriia E. Babicheva, Mikhail Y. Shalaginov, Satoshi Ishii, Alexandra Boltasseva, and Alexander V. Kildishev. Finite-width plasmonic waveguides withhyperbolic multilayer cladding,
Optical Society of America, (11 2014): 9681. doi:
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11/21/2016 127 Paul R. West, James L. Stewart, Alexander V. Kildishev, Vladimir M. Shalaev, Vladimir V. Shkunov, Friedrich Strohkendl, Yuri A. Zakharenkov, Robert K. Dodds, and Robert Byren. All-dielectric subwavelength metasurfacefocusing lens,
Optical Society of America, (06 2014): 26212. doi:
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11/21/2016 152 Naresh Kumar Emani, Di Wang, Ting-Fung Chung, Ludmila J. Prokopeva, Alexander V. Kildishev, Vladimir M. Shalaev, Yong P. Chen, Alexandra Boltasseva. Plasmon resonance in multilayer graphene nanoribbons,
Laser & Photonics Reviews, ( ): 650. doi:
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11/21/2016 149 Jingjing Liu, Urcan Guler, Alexei Lagutchev, Alexander Kildishev, Oana Malis, Alexandra Boltasseva, Vladimir M. Shalaev. Quasi-coherent thermal emitter based on refractory plasmonic materials,
Optical Materials Express, ( ): 2721. doi:
1,019,923.00

11/21/2016 150 Rohith Chandrasekar, Naresh K. Emani, Alexei Lagutchev, Vladimir M. Shalaev, Cristian Ciracì, David R. Smith, Alexander V. Kildishev. Second harmonic generation with plasmonic metasurfaces: direct comparison of electric and magnetic resonances,
Optical Materials Express, ( ): 2682. doi:
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11/21/2016 151 Naresh Kumar Emani, Alexander V. Kildishev, Vladimir M. Shalaev, Alexandra Boltasseva. Graphene: A Dynamic Platform for Electrical Control of Plasmonic Resonance,
Nanophotonics, ( ): 214. doi:
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11/21/2016 148 Jingjing Liu, Urcan Guler, Alexei Lagutchev, Alexander Kildishev, Oana Malis, Alexandra Boltasseva, Vladimir M. Shalaev. Quasi-coherent thermal emitter based on refractory plasmonic materials,
Optical Materials Express, ( ): 2721. doi:
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11/21/2016 153 Ludmila J. Prokopeva, Evgenii E. Narimanov, Alexander V. Kildishev. Elliptic cylindrical pseudo-optical black hole for omnidirectional light absorber: comment,
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11/21/2016 155 H. Cang, A. Salandrino, Y. Wang, X. Zhang. Adiabatic far-field sub-diffraction imaging,
Nature Communications, ( ): . doi:
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11/21/2016 156 R. Zecca, P. T. Bowen, D. R. Smith, S. Larouche. Transformation optics simulation method for stimulated Brillouin scattering,
Physical Review A, ( ): . doi:
1,020,028.00

11/21/2016 157 G. Lipworth, N. W. Caira, S. Larouche, D. R. Smith. Phase and magnitude constrained metasurface holography at W-band frequencies,
Optics Express, ( ): 19372. doi:
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11/21/2016 158 Cristian Ciracì, Michael Scalora, David R. Smith. Third-harmonic generation in the presence of classical nonlocal effects in gap-plasmon nanostructures,
PHYSICAL REVIEW B, ( ): 205403. doi:
1,020,030.00

11/21/2016 159 X. Chen, C. Ciracì, D. R. Smith, S.-H. Oh. Nanogap-Enhanced Infrared Spectroscopy with Template-Stripped Wafer-Scale Arrays of Buried Plasmonic Cavities,
NanoLetters, ( ): 107. doi:
1,020,031.00

TOTAL: 121

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper
08/31/2011 38.00	Wenshan Cai, Vladimir Shalaev. Into the visible, Physics World, (07 2011): 30. doi:

TOTAL: **2**

Number of Papers published in non peer-reviewed journals:

(c) Presentations

DUKE UNIVERSITY:
1. “Metamaterial-Based Apertures Across the Spectrum”
Invited Colloquium
(CINT) Center for Integrated Nanotechnologies
Los Alamos National Laboratory
Los Alamos, New Mexico
January 7, 2016

2. “Metamaterials and Metasurfaces: Emerging Opportunities for Controlling Light with Structured Media”
Invited Talk
Waves and Structured Materials Workshop
UNC Charlotte
June 3, 2016

3. “Transitional Metamaterials Research”
META’16: The 7th International Conference on Metamaterials, Photonic Crystals and Plasmonics
Malaga, Spain
July 25 – 28, 2016

4. Holographic Metasurface Systems for Beam-Forming and Imaging
Invited Talk
SPIE Nanoscience + Engineering Symposium
San Diego, CA
August 28 – September 1

PURDUE UNIVERSITY:
Plenary/invited talks and short courses since August 2015:
1.(PLENARY) V. Shalaev, META15, the 6th International Conference on Metamaterials, Photonic Crystals and Plasmonics, New York City, NY, August 4-8, 2015
2.(PLENARY) V. Shalaev, Physics of Quantum Electronics Colloquium, PQE 2016, Jan 3-7, Snowbird, Utah
3.(INVITED) V. Shalaev, SPIE Optics and Photonics, San Diego, CA, August 9-14, 2015
4.(INVITED) V. Shalaev, Metacongress, Oxford, UK, September 6-11, 2015
5.(INVITED) V. Shalaev, OSA’s Incubator on Nonlinear Metamaterials, Washington, D.C., October 1-2, 2015
6.(INVITED) V. Shalaev, IEEE Photonics Conference, Reston, Virginia, October 4-8, 2015
7.(INVITED) V. Shalaev, Material Research Society Fall Meeting, Boston, MA, December 1-4, 2015
8.(KEYNOTE) A. Boltasseva, "Transparent conducting oxides and hard plasmonic ceramics for next-generation nanophotonics," META’15, the 6th International Conference on Metamaterials, Photonic Crystals and Plasmonics, City College of New York, New York City, NY, USA, August 4-7, 2015
9.(INVITED) J. Kim, N. Kinsey, A. Dutta, M. Ferrera, C. DeVault, I. Kitamura, A.V. Kildishev, V.M. Shalaev, A. Boltasseva, "Transparent Conducting Oxides as Plasmonic Component in Near Infrared," SPIE Optics and Photonics Congress, Metamaterials, Metadevices, and Metasystems conference, San Diego, CA, USA, 9-13 August 2015
10.(INVITED) J.C. Ndukaife, A.V. Kildishev, A.A.G. Nnanna, S.T. Wereley , V.M. Shalaev, A. Boltasseva, "Electro-thermoplasmonic Flow for Plasmon-Assisted Optical Trapping," SPIE Optics and Photonics Congress, Plasmonics: Metallic Nanostructures and Their Optical Properties XIII conference, San Diego, CA, USA, 9-13 August 2015
11.(INVITED) N. Kinsey, M. Ferrera, C. DeVault, J. Kim, A.V. Kildishev, V.M. Shalaev, A. Boltasseva, "Alternative Materials Lead to Practical Nanophotonic Components," SPIE Optics and Photonics Congress, Active Photonic Materials VII conference, San Diego, CA, USA, 9-13 August 2015
12.(INVITED) A. Boltasseva, "Refractory Plasmonic Materials for Practical Nanophotonics, Data Storage and Energy Conversion," National Academy of Engineering (NAE) U.S. Frontiers of Engineering (FOE) Symposium, National Academies’ Beckman Center in Irvine, California, USA, September 9-11, 2015
13.(INVITED) N. Kinsey, C. DeVault, J. Kim, M. Ferrera, V. Shalaev, A. Boltasseva, "Epsilon-Near-Zero Ultrafast Dynamics in Al-Doped Zinc Oxide at Telecommunication Wavelength," 9th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics: Metamaterials 2015, September 7-12, 2015, Oxford, UK
14.(INVITED) A. Boltasseva, "Practical Platform for Nanophotonics with Refractory Plasmonic Metal Nitrides and Transparent Conducting Oxides," Frontiers in Optics, San Jose, CA, USA, October 18-22, 2015
15.(INVITED) A. V. Kildishev and L. J. Prokopeva, Omnidirectional Light Concentrators-absorbers --- How to Make Their Core Flat? Progress in Electromagnetics Research Symposium PIERS 2015 Abstracts, 1 page, [Invited paper] Special Session "SC2: Transformation Optics", Prague, Czech Republic, July 06-09, 2015,
url:http://piers.org/piers2015Prague/submit/get_testpdf.php?status=valid&id=150205133026&pdffilename=150205133026.pdf.
16.(INVITED) A. V. Kildishev, L. J. Prokopeva, “Omnidirectional Concentrators and Absorbers: Trapping Light at any Angle”, 1 page, [Invited paper], Special Session: Geometrical techniques for controlling electromagnetic waves II, META’15, New York, July 2015;
url: http://metaconferences.org/ocs/public/conferences/9/pdf/3494.pdf.

17.(INVITED) A. V. Kildishev, “Computational Nanophotonics: Designing Spaces for Light,” Invited Math Seminar Talk, Mathematics Department, Renssalaer Polytechnic Institute, New York, April 2016.

Presentations by students since August 2014:
1.Jongbum Kim, Nathaniel Kinsey, Aveek Dutta, Marcello Ferrera, Clayton DeVault, Ikuko Kitamura, Alexander V. Kildishev, Vladimir M. Shalaev, and Alexandra Boltasseva, "Transparent Conducting Oxides as Plasmonic Component in Near Infrared," SPIE Optics and Photonics Congress, Metamaterials, Metadevices, and Metasystems conference, San Diego, CA, USA, 9-13 August 2015
2.Justus C. Ndukaife, Alexander V. Kildishev, A.A.G. Nnanna, S.T. Wereley , Vladimir M. Shalaev, and Alexandra Boltasseva, "Electro-thermoplasmonic Flow for Plasmon-Assisted Optical Trapping," SPIE Optics and Photonics Congress, Plasmonics: Metallic Nanostructures and Their Optical Properties XIII conference, San Diego, CA, USA, 9-13 August 2015
3.Nathaniel Kinsey, Clayton DeVault, Jongbum Kim, Marcello Ferrera, Vladimir M. Shalaev, Alexandra Boltasseva, "Epsilon-Near-Zero Ultrafast Dynamics in Al-Doped Zinc Oxide at Telecommunication Wavelength," 9th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics: Metamaterials 2015, September 7-12, 2015, Oxford, UK

UNIVERSITY OF UTAH

1. META’2015 “Parallel transport design for gradient index lenses” (2015 August)
2. Metamaterials 2015 “Homogenization of metamaterials and effective medium models” (2015 September)

Number of Presentations: 25.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
08/31/2011	37	Sulochana Dhar, Talmage Tyler, Lin Luan, Matt Royal, Sabarni Palit, Nan Marie Jokerst. Integrated Photonics, Plasmonics, and Metamaterials, Proceedings of the International Symposium on Microwave and Optical Technology. 16-DEC-09, . : ,
09/01/2015	131	Ludmila Prokopeva, Naresh Emani, Jongbum Kim, Alexandra Boltasseva, Alex , Kildishev. Experimentally Fitted Time Domain Modeling of Graphene-Based Devices, Materials Research Society Spring Meeting. 06-APR-15, . : ,
09/23/2014	123	Steve A. Cummer, John P. Barrett. Design and Realization of Transistor-Embedded Active RFMetamaterials, International Union of Radio Science. 08-JAN-14, . : ,
09/23/2014	122	Alexander R. Katko, Steven A. Cummer. Transistor-Embedded Acousto-Optic and Nonlinear Metamaterials, International Union of Radio Science. 08-JAN-14, . : ,
09/23/2014	125	Allen M. Hawkes, Alexander R. Katko, Steven A. Cummer. A Microwave Metamaterial with IntegratedPower Harvesting Functionality, International Union of Radio Science. 08-JAN-14, . : ,

TOTAL: **5**

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
08/20/2012	59.00	Alexander K. Popov, Vladimir M. Shalaev. Nonlinear and active metamaterials, Metamaterials: Fundamentals and Applications IV. , San Diego, California, USA. : ,
08/29/2013	73.00	Mark D. Thoreson, Rasmus B. Nielsen, Paul R. West, Arian Kriesch, Zhengtong Liu, Jieran Fang, Alexander V. Kildishev, Ulf Peschel, Vladimir M. Shalaev, Alexandra Boltasseva, Allan D. Boardman, Nader Engheta, Mikhail A. Noginov, Nikolay I. Zheludev. Studies of plasmonic hot-spot translation by a metal-dielectric layered superlens, SPIE NanoScience + Engineering. 25-JUL-13, San Diego, California. : ,
08/29/2013	77.00	Naresh K. Emani, Ting-Fung Chung, Xingjie Ni, Alexander Kildishev, Yong P. Chen, Alexandra Boltasseva, Alexandra Boltasseva. Electrically Tunable Plasmonic Resonances with Graphene, CLEO: Applications and Technology. 14-JUN-13, San Jose, California. : ,
08/29/2013	78.00	Ludmila J. Prokopeva, Naresh K. Emani, Alexandra Boltasseva, Alexander Kildishev. TIME DOMAIN MODELING OF TUNABLE RESPONSE OF GRAPHENE, CLEO: QELS_Fundamental Science. 14-JUN-13, CLEO: QELS_Fundamental Science (2013). : ,
08/31/2011	34.00	Thomas Zentgraf, Jensen Li, Jason Valentine, Nicholas Tapia, Xiang Zhang . Transforming Integrated Optics, Frontiers in Optics. 24-OCT-10, . : ,
08/31/2011	33.00	M. D. Thoreson, J. Fang, Z. Liu, V. P. Drachev, A. V. Kildishev, V. M. Shalaev, A. Boltasseva. Progress in metal-dielectric composite superlenses, Proceedings of META'10 Conference. 22-FEB-10, . : ,
08/31/2011	32.00	R. B. Lielsen, P. West, A. Kriesch, Z. Liu, M. D. Thoreson, J. Fang, A. V. Kildishev, A. Boltasseva, U. Peschel, V. M. Shalaev. Studies of plasmonic hot-spot translation by a metal-dielctric layered superlens, Proceedings of SPIE Conference. 01-AUG-11, . : ,
08/31/2011	31.00	V. M. Shalaev, A. K. Popov. Nonlinear and active metamaterials, Proceedings of SPIE Conference. 03-AUG-11, . : ,
08/31/2011	30.00	Evgenii Narimanov , Igor Smolyaninov, Zubin Jacob. Spontaneous emission near hyperbolic metamaterials, Quantum Electronics and Laser Science Conference (QELS). 01-MAY-11, . : ,
08/31/2011	29.00	Harish Krishnamoorthy, Vinod Menon, Zubin Jacob, Evgenii Narimanov, Ilona Kretzschmar . Broadband Engineering of Quantum Dot Spontaneous Emission Using Flat Dispersion Metamaterial, Quantum Electronics and Laser Science Conference (QELS). 01-MAY-11, . : ,
08/31/2011	36.00	T. Tyler, G. Lipworth, J. Mock, N. Jokerst, D. Smith, Y. Tsai, S. Larouche. Metamaterial Blazed Gratings, Quantum Electronics and Laser Science Conference (QELS). 01-MAY-11, . : ,
08/31/2011	35.00	N. B. Kundtz, B. Sun, D. R. Smith, J. Hunt. Transformation optics compressed Rotman lens implemented with complementary metamaterials, SPIE Defense, Security and Sensing. 25-APR-11, . : ,
09/19/2014	15.00	Alessandro Salandrino, Hu Chang, Yuan Wang, Xiang Zhang. Sub-diffraction Imaging via Surface PlasmonDecompression, Conference on Lasers and Electro Optics. 08-JUN-14, . : ,

09/19/2014 17.00 Jingjing Liu, Amr M. Shaltout, Xingjie Ni, Vladmir M. Shalaev and Alexander V. Kildishev. Approximating Metasurfaces with Bianisotropic Tiles,
The Applied Computational and Electromagnetic Society. 23-MAR-14, . : ,

09/19/2014 16.00 Jingjing Liu, Amr M. Shaltout, Xingjie Ni, Vladmir M. Shalaev and Alexander V. Kildishev. Experimental validation of a new bianisotropic parameter retrieval technique using plasmonic metasurfaces made of V-shape antennas,
International Society for Optics and Photonics. 24-AUG-13, . : ,

09/19/2014 18.00 Ludmila Prokopeva, Naresh Emani, Alexander Kildishev and Alexandra Boltasseva. Tunable Pulse Shaping with Gated Graphene Nanoribbons,
Conference on Lasers and Electro-Optics. 08-JUN-14, . : ,

09/19/2014 19.00 Jieran Fang, Suprem R. Das, Ludmila J. Prokopeva, Vladimir M. Shalaev, David B. Janes, Alexander V. Kildishev. Time-domain modeling of silver nanowires-graphene transparent conducting electrodes,
The International Society for Photonics and Optics. 24-AUG-13, . : ,

09/19/2014 20.00 Jieran Fang, Suprem R. Das, Ludmila J. Prokopeva, Vladimir M. Shalaev, David B. Janes, and Alexander V. Kildishev. Time-domain Modeling of Silver Nano-net for Transparent Conducting Electrodes,
OSA Renewable Energy and the Environment Congress Tuscon, AZ. , . : ,

09/23/2014 24.00 John Barrett , Steven Cummer . Realization of Powered Transistor-Based Active Metamaterials,
Metamaterials 2013 Bordeaux France. 16-SEP-13, . : ,

09/23/2014 26.00 Ludmila Prokopeva, Alexander Kildishev. Efficient time-domain model of the graphene dielectric function,
International Society for Optics and Photonics. 24-AUG-13, . : ,

10/08/2015 39.00 J. P. Barrett, S. A. Cummer. Roadmap to electrically self-tuning metamaterials: Design and experimental validation,
2014 International Conference on Electromagnetics in Advanced Applications (ICEAA). 03-AUG-14, Palm Beach, Aruba. : ,

TOTAL: **21**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received	Book

TOTAL:

Received	Book Chapter
09/16/2013 95.00	Nathan Landy, Yaroslav Urzhumov, David R. Smith. Quasi-conformal approaches for two and three-dimensional transformation optical metamaterials, London: Springer-Verlag, (10 2013)

TOTAL: 1

Patents Submitted

PURDUE UNIVERSITY:
~~1. A. V. Kildishev and E. E. Narimanov~~
US 9,228,761 B2 Electromagnetic wave concentrator and absorber
January 5, 2016

DUKE UNIVERSITY:
1. David R. Smith, Nathan B Kundtz
Imaging Devices Based on Transformation Optical and Gradient Metamaterials

2. David R. Smith, Nathan B Kundtz, John D Hunt, Nathan I Landy
Extended Quasi-Conformal Transformation Optical Media for Electromagnetic and Optical Devices

3. David R. Smith, Yaroslav A Urzhumov, Kyoungsik Kim, Dongheok ShinBoadband electromagnetic transformation optical devices using elasto-electromagnetic smart metamaterials
iEdison Number = 2221101-13-0039

4. David R. Smith, Guy Lipworth
Lorentzian Constrained Holograms

Patents Awarded

PURDUE UNIVERSITY:
~~A. V. Kildishev and E. E. Narimanov~~
US 9,228,761 B2 Electromagnetic wave concentrator and absorberJanuary 5, 2016

Awards

Duke University:

1. David Smith, Recognized by ISI-Reuters as one of the "Highly Cited Researchers 2015," in the category of Physics.

PURDUE UNIVERSITY:

1.Vlad Shalaev, Honorary Doctorate from University of Southern Denmark, 2015

Graduate Students

NAME	PERCENT_SUPPORTED	DISCIPLINE
Clayton Devault	4	Electrical Engineering
Suresh Venkatesh	0	Electrical Engineering
Alex James W. Orange	0	Electrical Engineering
Rohith Chandrasekar	2	Electrical Engineering
Di Wang	5	Electrical Engineering
Jongbum Kim	3	Electrical Engineering
Naresh Sreenivas Viswanathan	0	Electrical Engineering
Siqi Wang	20	Materials Science and Engineering
Yang Xia	20	Materials Science and Engineering
Chengzhi Shi	1	Mechanical Engineering
FTE Equivalent:	**0.55**	
Total Number:	**10**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Xiangeng Meng	0.04
Xiaoze Liu	0.25
Marc Dubois	0.25
Sui Yang	0.20
FTE Equivalent:	**0.74**
Total Number:	**4**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
David R. Smith	0.04	No
Steven Cummer	0.00	
Nan Jokerst	0.00	
Vlad Shalaev	0.00	
David Schurig	0.02	
Xiang Zhang	0.02	
Alexandra Boltasseva	0.04	
Stephane Larouche	0.00	
Vlad Shalaev	0.13	No
Evengii Narimanov	0.02	No
FTE Equivalent:	**0.27**	
Total Number:	**10**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 2.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME	
Rohith Chandrasekar	
Sui Yang	
Total Number:	**2**

Names of other research staff

NAME	PERCENT_SUPPORTED
Alexei Lagoutchev	0.33
Xiangeng Meng	0.62
Yuan Wang	0.25
FTE Equivalent:	**1.20**
Total Number:	**3**

Sub Contractors (DD882)

1 a. University of Utah

1 b. 75 South 2000 East

Salt Lake City UT 841128930

Sub Contractor Numbers (c): 11ARO1066

Patent Clause Number (d-1): N/A

Patent Date (d-2):

Work Description (e): It is well known that imaging systems with either isotropic negative index or hyperbolic (

Sub Contract Award Date (f-1): 1/28/11 12:00AM

Sub Contract Est Completion Date(f-2): 1/27/16 12:00AM

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1 a. University of Utah

1 b. 1471 East Federal Way

Salt Lake City UT 841021821

Sub Contractor Numbers (c): 11ARO1066

Patent Clause Number (d-1): N/A

Patent Date (d-2):

Work Description (e): It is well known that imaging systems with either isotropic negative index or hyperbolic (

Sub Contract Award Date (f-1): 1/28/11 12:00AM

Sub Contract Est Completion Date(f-2): 1/27/16 12:00AM

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1 a. Purdue University

1 b. 155 South Grant Street

West Lafayette IN 479072114

Sub Contractor Numbers (c): 10ARO1047

Patent Clause Number (d-1): N/A

Patent Date (d-2):

Work Description (e): In this work, we design and study a metasurface that exhibits electric and magnetic resona

Sub Contract Award Date (f-1): 9/28/09 12:00AM

Sub Contract Est Completion Date(f-2): 1/27/16 12:00AM

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1 a. Purdue University

1 b. 610 Purdue Mall

West Lafayette IN 479072040

Sub Contractor Numbers (c): 10ARO1047

Patent Clause Number (d-1): N/A

Patent Date (d-2):

Work Description (e): In this work, we design and study a metasurface that exhibits electric and magnetic resona

Sub Contract Award Date (f-1): 9/28/09 12:00AM

Sub Contract Est Completion Date(f-2): 1/27/16 12:00AM

1 a. University of California - Berkeley

1 b. 2150 Shattuck Avenue, Room 313

Berkeley CA 947045940

Sub Contractor Numbers (c): 10ARO1049

Patent Clause Number (d-1): N/A

Patent Date (d-2):

Work Description (e): 1.Use theoretical and numerical studies to develop dialectric-based metamaterial systems

Sub Contract Award Date (f-1): 9/28/09 12:00AM

Sub Contract Est Completion Date(f-2): 1/31/16 12:00AM

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1 a. University of California - Berkeley

1 b. Sponsored Projects Office
2150 Shattuck Avenue, Suite 300

Berkeley CA 947045940

Sub Contractor Numbers (c): 10ARO1049

Patent Clause Number (d-1): N/A

Patent Date (d-2):

Work Description (e): 1.Use theoretical and numerical studies to develop dialectric-based metamaterial systems

Sub Contract Award Date (f-1): 9/28/09 12:00AM

Sub Contract Est Completion Date(f-2): 1/31/16 12:00AM

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1 a. North Carolina State University

1 b. 2701 Sullivan Drive
Admin Srvcs III, Box 7514

Raleigh NC 276957514

Sub Contractor Numbers (c): 10ARO1048

Patent Clause Number (d-1): N/A

Patent Date (d-2):

Work Description (e): See University of Utah/Dr. David Schurig. Dr. Schurig moved his lab to the University of

Sub Contract Award Date (f-1): 9/28/09 12:00AM

Sub Contract Est Completion Date(f-2): 1/27/11 12:00AM

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1 a. North Carolina State University

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Sub Contractor Numbers (c): 10ARO1048

Patent Clause Number (d-1): N/A

Patent Date (d-2):

Work Description (e): See University of Utah/Dr. David Schurig. Dr. Schurig moved his lab to the University of

Sub Contract Award Date (f-1): 9/28/09 12:00AM

Sub Contract Est Completion Date(f-2): 1/27/11 12:00AM

Inventions (DD882)

Scientific Progress

Please see Attached Final Technical Report

Technology Transfer

Inventions arising from this program have been disclosed and licensed to Intellectual Ventures, where they form part of the IV's portfolio of intellectual property. This portfolio has formed the basis for four existing startup companies: Kymeta (Redmond, WA), Evolv (Waltham, MA), Echodyne (Bellevue, WA) and Pivotal Communications (Bellevue, WA).

Transformation Optics MURI Annual Progress Report

Army Research Office

Technical Progress Report

Year 7, 2015-2016

A. COLLABORATIVE TEAM PROJECT: Second Harmonic Generation with Plasmonic Metasurfaces

Direct Comparison of Electric and Magnetic Resonances (Smith, Shalaev, Boltasseva, Kildishev) In this work, we design and study a metasurface, shown in Fig. A1, that exhibits electric and magnetic resonances to compare their contributions to SHG. We observe a stronger contribution to SHG from the electric resonance at the second harmonic than its magnetic counterpart at the fundamental wavelength, as shown in Fig. A2. While initial simulations using the hydrodynamic model were not able to fully capture the enhancement provided by the electric resonance, an effective $\chi^{(2)}$ model was able to do so. We find that effective $\chi^{(2)}$ model predicts stronger contribution from magnetic resonance, but use inhomogeneous broadening to explain experimental results, shown in Fig. A3.

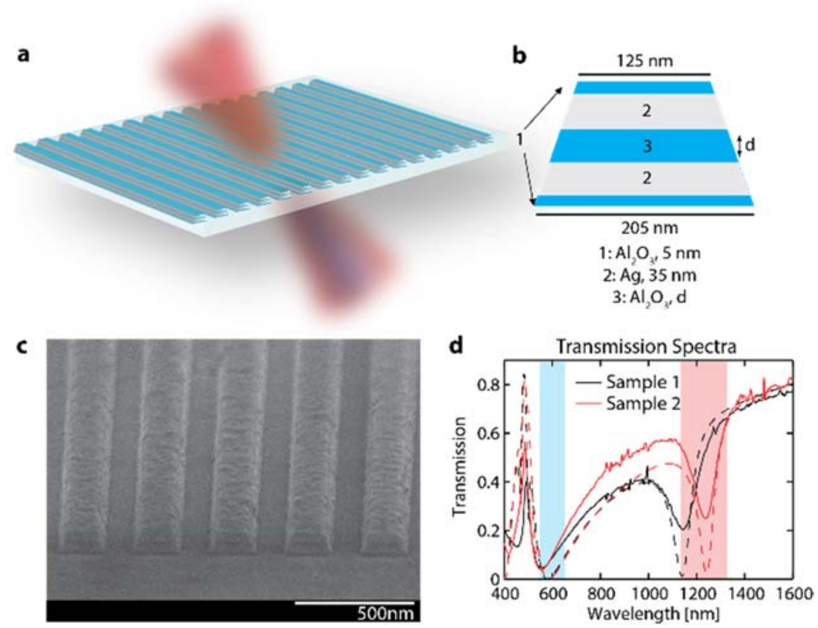


Figure A1. (a) 3D schematic of the metasurface consisting of coupled silver nanostrips gratings, (b) schematic of grating cross section, *d* = 19.5 nm for Sample 1 and 15 nm for Sample 2, (c) SEM image of metasurface, (d) Experimental (solid) and simulated (dashed) transmission spectra for Sample 1 and 2.

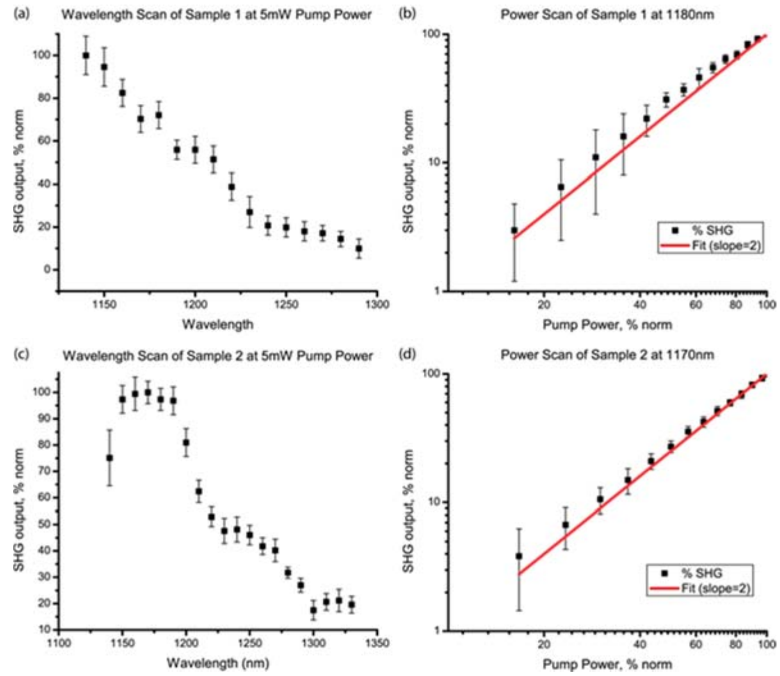


Figure A2. Experimental results for transmitted second harmonic output. (a),(c) Wavelength scans of Samples 1 and 2, the dotted red line shows magnetic resonance wavelength. (b),(d) Power scans of Samples 1 and 2.

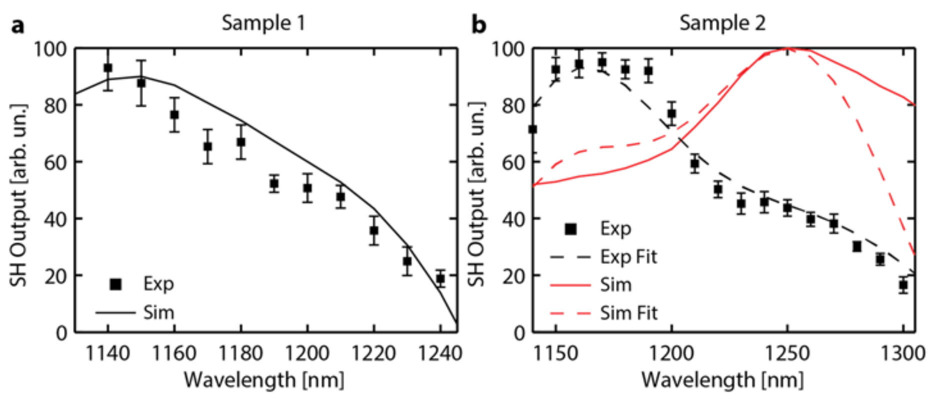


Figure A3. (a) Match of experiments (black squares) and finite-element simulations (black line) for Sample 1. b Finite-element simulations (shown in solid red) that do not account for roughness in the structure and show the magnetic resonance at 1250 nm to have stronger contribution to SHG than the electric resonance at 1140 nm. Due to the computational complexity of simulating roughness for 3D structures by finite-element methods, we use a simplified Gaussian model to account for roughness and confirm our experimental results. The Gaussian "roughness" model is first tested against the finite-element simulations (compare dashed red vs. solid red) and then applied to fit the experiments (compare dashed black vs. solid squares).

B. DUKE TEAM:

Holographic Metasurface (Smith) In this period, we have investigated the formation of a holographic metasurface at W-band (~100 GHz) using resonant, complementary metamaterial elements. A depiction of the entire experiment is shown in Fig. B1. Previously on this program we have investigated a number of different diffractive and holographic structures, as a means of implementing complex gradient structures that would eventually be required of transformation optical media. The goal of those designs was the use of artificial dielectric-like, non-resonant metamaterial structures that could be scaled ultimately to optical wavelengths. Using non-resonant "I-beam" and other artificial dielectric designs, holograms were created for the IR bands, including 10 μm and 1.5 μm.

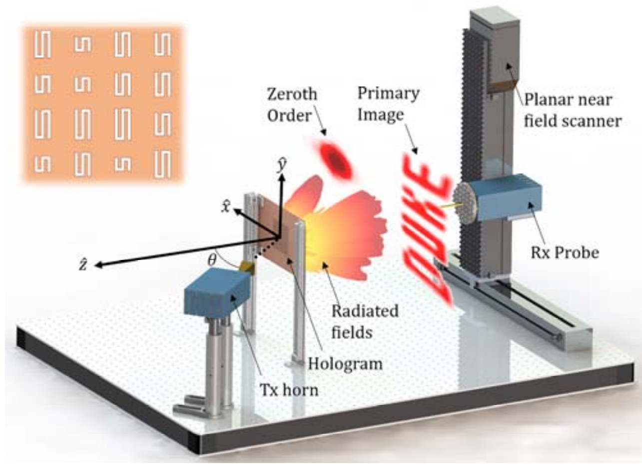


Figure B1. Illustration of an experiment to confirm a metasurface hologram at W-band frequencies. The microwaves are incident on the metasurface sample obliquely, as shown in the figure, with the transmitted fields scanned over an area using a W-band probe and 2D scanning equipment. From the fields measured over a plane, the fields can be propagated to the far-field where the hologram formation can be observed.

During the past several years, the emergence of metasurfaces has captured considerable attention. Metasurfaces make use of just a single layer of metamaterial elements to achieve functionality. Because only a single layer of metamaterial is used, the losses can be somewhat mitigated, allowing many types of functionality in a low-profile and easily fabricated device. To achieve an ideal diffractive element, it is necessary that phase shifts ranging from zero to 2π be controlled point-by-point throughout the medium. In the non-resonant metamaterial hologram, the phase shift was accessed by fabricating and bonding together many layers—up to 16. The phase shift, then, resulted from propagation through different zones of effective index. By contrast, a resonant metamaterial element modulates both the phase and amplitude of the transmitted wave, as illustrated in Fig. B2.

Each metamaterial element can be tuned by geometry to have a different resonance frequency ω_0. At the operating frequency, then, the phase and amplitude of each resonator will be different, taking on the possible values shown in Fig. B2. The resonance has the familiar Lorentzian form of

$$m(\omega) = A\frac{\omega_p^2}{\omega^2 - \omega_0^2 + i\gamma\omega} ,$$

which we have written as a complex, magnetic dipole moment, corresponding to the effective response of a complementary metamaterial element.

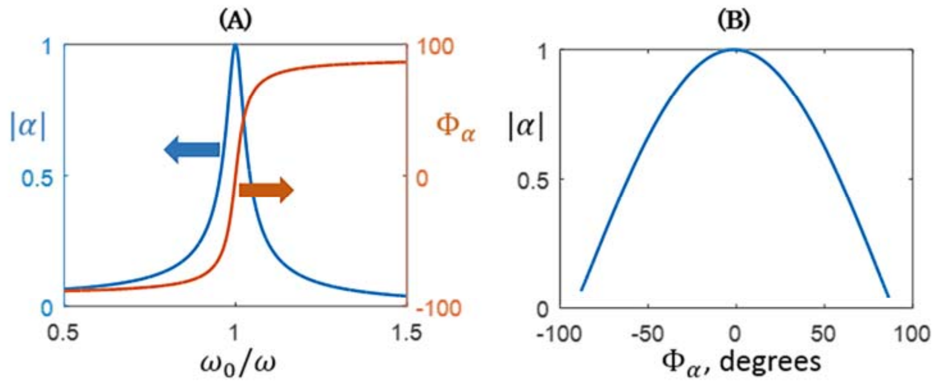


Figure B2. (Left) A resonant metamaterial element modulates both the amplitude (blue) and the phase (red) of the field incident. (Right) Because the resonance follows a Lorentzian form, the phase and amplitude are intrinsically linked together, with the amplitude falling off on either side of the resonance. While the resonator should be able to achieve phase advances between 0 to π, in reality the usable phase range is much less than that because of the lower amplitudes at the more extreme phase advances.

To form the metamaterial, a complementary meander line structure was used. The resulting metasurface is thus generally opaque, rejecting most of the incident microwaves, except at frequencies where the complementary meander lines are near resonance and radiate. The meander line structure was fabricated using an LPKF laser milling machine that was capable of producing feature sizes needed for operation at 100 GHz. The samples were formed from copper-clad circuit board materials (Rogers). Fig. B3 shows a photograph of the sample at varying magnifications. By varying the geometry of the meander line, the resonance frequency of each element could be set at any frequency within the W-band. By simulating many geometry variants, an interpolation could be created that provided the geometrical parameters needed to produce any phase shift at the design frequency of 100 GHz.

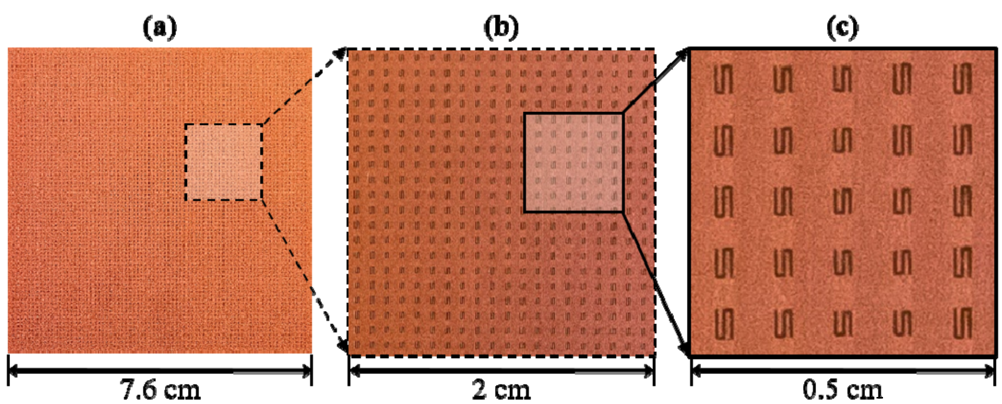


Figure B3. Photographs of the complementary metasurface hologram. The structure was fabricated using an LPKF laser milling machine, capable of producing the feature sizes needed for operation at 100 GHz. The resonance frequencies were controlled by changing various features of the meander line complementary structure.

The hologram was designed using standard techniques in which the known reference wave is interfered with the Fourier transform of the desired far-field image field pattern. In this case, the far-field hologram was meant to produce the word "DUKE." To design the hologram, the exact phase distribution was implemented assuming that the meander line elements would be used to form the actual sample. After creating this phase distribution, the Lorentzian constraint was introduced, and the amplitude at each phase point modified accordingly. Finally, the Gerchberg-Saxton algorithm was used to iteratively optimize the hologram. The phase and amplitude of the resulting hologram are shown in the first and second columns of Fig. B4, respectively. The final hologram, as measured, is shown in (i) of Fig. B4. The resulting hologram is not efficient, since the restricted phase range results in a significant amount of power being directed to the zeroth order diffracted beam, as indicated by the spot to the left of the figure. This effect was expected, and can be mitigated in future designs.

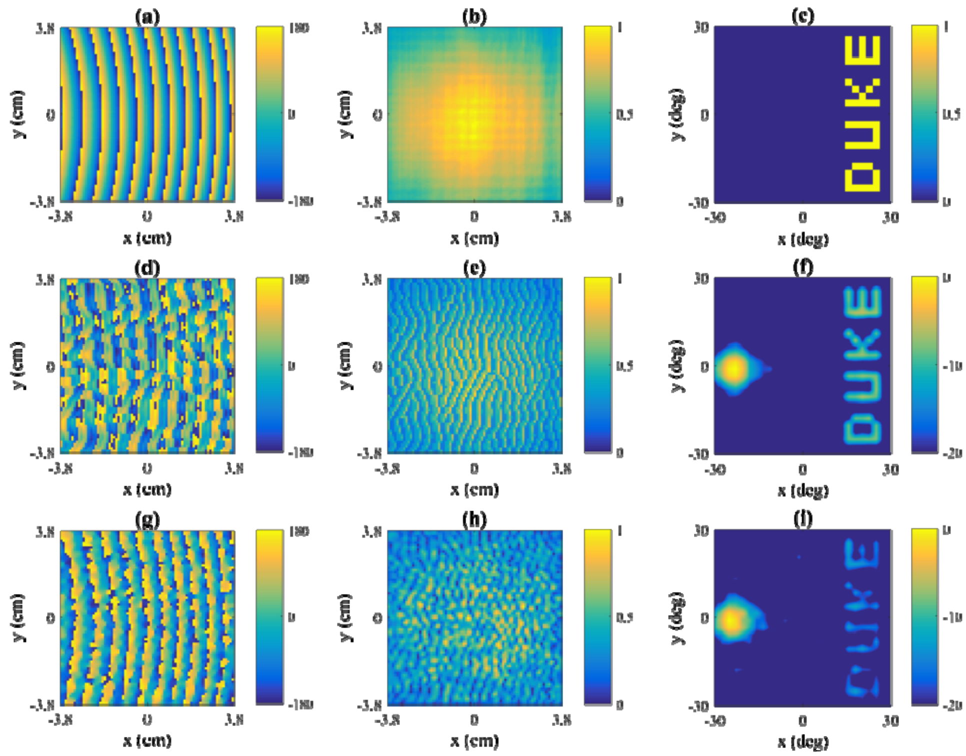


Figure B4. Fields at the hologram plane and far-field images. Phase (a) and magnitude (b) of the reference wave illuminating the hologram. Desired field pattern used in the GS algorithm (c). Phase (d), magnitude (e), and far-field pattern (f) of the simulated hologram generated by the GS algorithm. Measured and back-propagated phase (g) and magnitude (h) of the fabricated hologram and its experimental far-field pattern (i). Far-fields were computed as the Fourier transformed hologram fields. Simulations and measurements shown are reported at 92.5 GHz and 94.75 GHz, respectively.

In short, the metasurface hologram is interesting because it shows that a functional device can be designed with only a single layer of scattering medium. From the standpoint of TO, the experiment demonstrates the control over resonant metamaterial structures that can be obtained, since the hologram would not work if the phase relationships between the elements were not as designed. The holographic metasurface provides a useful testbed for metamaterial element design and confirmation.

Stimulated Brillouin Scattering Simulation using Transformation Optics (Smith) Brillouin scattering in\s a process in which optical waves are scattered by fluctuations in the density of a material. In the case of spontaneous Brillouin scattering, these density fluctuations are created by random thermal fluctuations in the material. In stimulated Brillouin scattering (SBS), two optical waves of slightly different frequencies interact to create a mechanical wave through electrostriction or other effects. Both optical waves scatter off this mechanical wave, exchanging energy. SBS is of technological interest since it can be used in amplifiers, to generate slow light, or frequency combs, amongst other things.

In recent years, there has been renewed interest in SBS since it was predicted—and experimentally confirmed—that Brillouin scattering can be enhanced by many orders of magnitude in nanoscale devices. This enhancement is due to a combination of surface electrostriction and radiation pressure. These effects are present at all dimensions, but are insignificant for macroscopic systems. For nanoscale systems, on the other hand, they can dominate.

Recently, we have been exploring the possibility to use metamaterials to design even more effective SBS devices. By properly designing a structured material such that it displays both optical and mechanical resonances, it should be possible to enhance SBS even further. One factor that has slowed down such efforts is the lack of an effective simulation approach. Indeed, the mechanical wave present in the material, which is an essential component of the SBS interaction, causes a movement of material points that must be accounted for in the optical simulations.

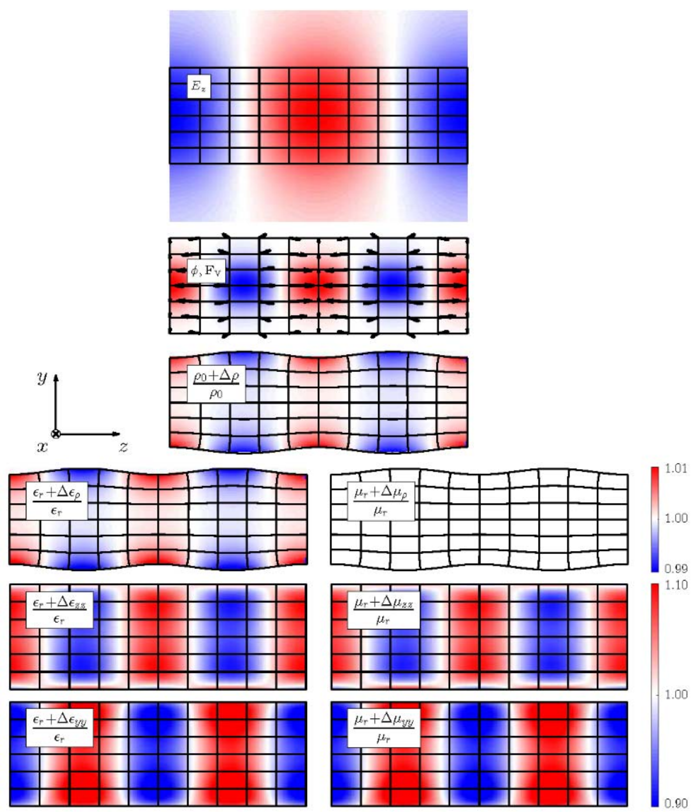


Figure B5. Schematic representation of the proposed approach to simulate SBS. Two contrapropagating optical waves (one represented in first row) give rise to an almost-standing wave (second row). This creates an optical potential, which gives rise to a mechanical force (color map and arrows in third row). The force creates a mechanical wave, with pressure fluctuations (fourth row). The pressure fluctuations change the permittivity of the material, but not the permeability for nonmagnetic materials (fifth row). Through the proposed transformation optics approach, the periodic movements of the material can be transformed in periodic variations of the permittivity and permeability in a fixed grid (sixth and seventh rows).

This year, we have finalized our work to develop an approach to simulate such processes. This approach, illustrated in Figure B5, relies on replacing the mechanical wave in the material by a periodic variation of the permittivity and the permeability through transformation optics. It leads to three coupled partial differential equations (two for the optical waves and one for the mechanical wave). Our approach is very general and can be applied to any geometry, and many simulation approaches. We have implemented it in COMSOL, a commercially available finite element method software, which allows one to modify the differential equations that are solved.

We have compared our approach to the results of established analytical approaches for two simple cases: a bulk material and a nanoscale waveguide. As shown in Figure B6, in the case of the bulk material, our approach agrees perfectly with the theory. In the case of the waveguide, there are small differences. We attribute those differences to limitations of the theory, which is inherently mono-modal, while our approach considers all the modes present in the waveguide.

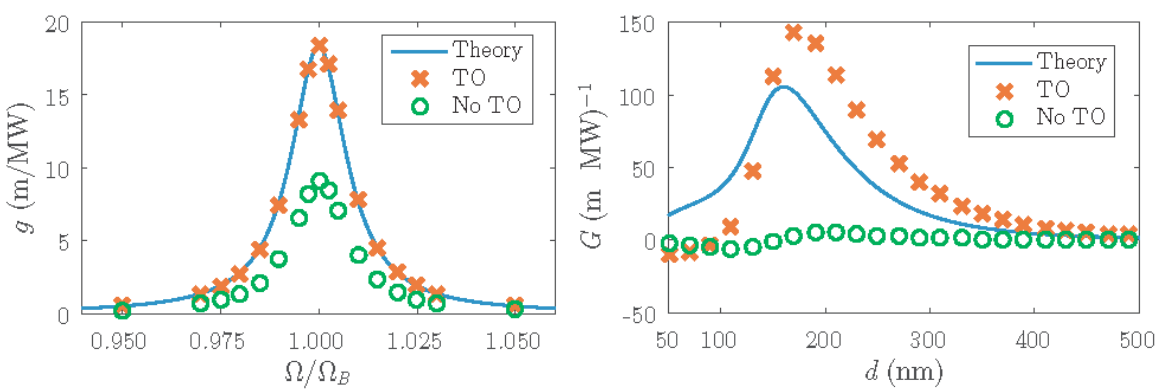


Figure B6. Comparison of the results of our approach and analytical theory for a bulk uniform material (left) and a 2D waveguide (right). Simulations without implementing our approach give results that are significantly different from the theory, while results obtained with our approach are almost identical to it.

Lattice-Transformed Metamaterials (Smith) Transformation optics is a powerful design approach that allows one to design devices with exceptional properties, such as invisibility cloaks. However, it has proven difficult to fabricate many of the devices, since the properties required by the transformation often are highly anisotropic and include a magnetic response. They also sometimes require permittivity and/or permeability below one, or even negative.

The typical approach to realize devices designed by transformation optics is to take the properties and discretize them on a regular grid, either in Cartesian, cylindrical, or spherical coordinates. In this approach, the properties of every element on the grid may be different, following the symmetry of the transformation. This year, we have studied a new approach which consists in placing a series of identical elements on an original grid, and then deforming this grid according to the desired transformation.

The effect of the transformed lattice of identical elements and the effective properties predicted by transformation optics are almost identical. This approximation is only valid if the elements remain distant enough to avoid near-field effects, while remaining close enough for the pseudo-static approximation to be valid. We have also shown that this approximation is better when the effective permittivity of the starting material is high.

Figure B7 shows our approach applied to the two-dimensional transformation $z' = z^2$, where $z = x + iy$. It clearly demonstrates that the device made of a transformed lattice of identical elements acts almost identically to a device made of a continuous material with the permittivity calculated according to the same transformation.

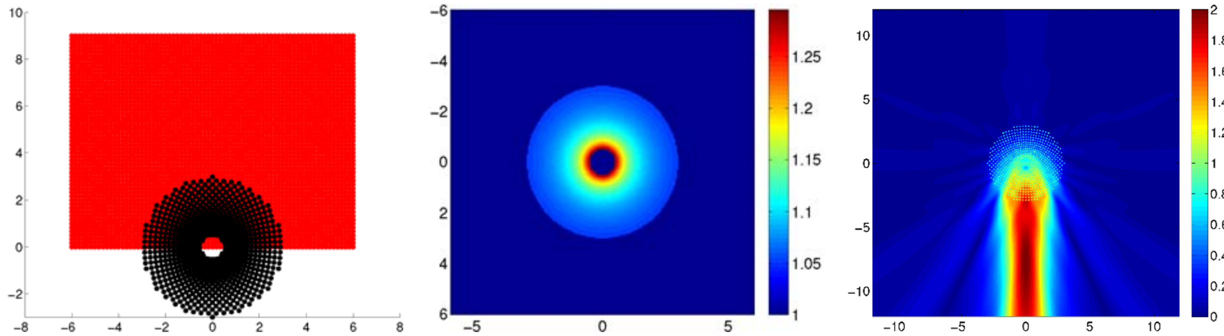


Figure B7 Transformation of a series of polarizable elements on s square lattice into a circular element (left), the approximate permittivity, as predicted by the transformation (center), and field scattered by the device (right).

C. PURDUE TEAM:

Effective Third-Order Nonlinearities in Metallic Refractory TiN Thin Films (Boltasseva, Shalaev) Plasmonics and metasurfaces offer the potential for dramatic field confinement and enhancement which may be critical for nonlinear optics. In recent years, many works have studied the potential of metallic metasurfaces to provide nonlinearities. However, many of these demonstrations were limited by the plasmonic materials deformation under the high optical intensity generated through the confinement of light. As a potential solution to this problem we propose TiN, a gold-like plasmonic ceramic which a melting point above 2900°C, which has been shown to possess a damage threshold at least 1 order of magnitude larger than gold films of a similar thickness.

Using the Z-scan technique, we investigate the intensity dependent refractive index and absorption in this material at 780 nm and 1550 nm. At 1550 nm (Fig. C1) we find a saturation intensity of I_{sat} = 530 GW/cm^2 which when expanding to the first order with $\alpha(I) \approx \alpha_o - (\alpha_o/I_{sat})I = \alpha_o + \alpha_2 I$, results in an average value of $\alpha_2 = -6.6 \times 10^{-9}$ m/W.

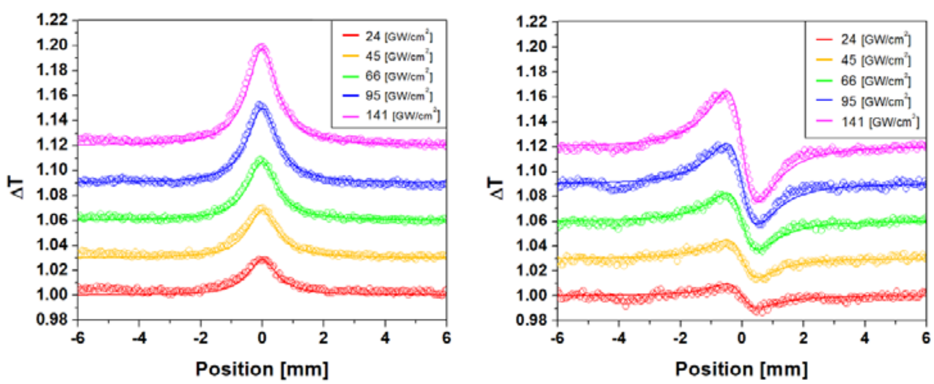


Figure C1. Compilation of the a) open aperture and b) closed aperture Z-scan curves for several different intensities at 1550 nm. Experimental results are shown with symbols and the fitted curves are depicted with a solid line.

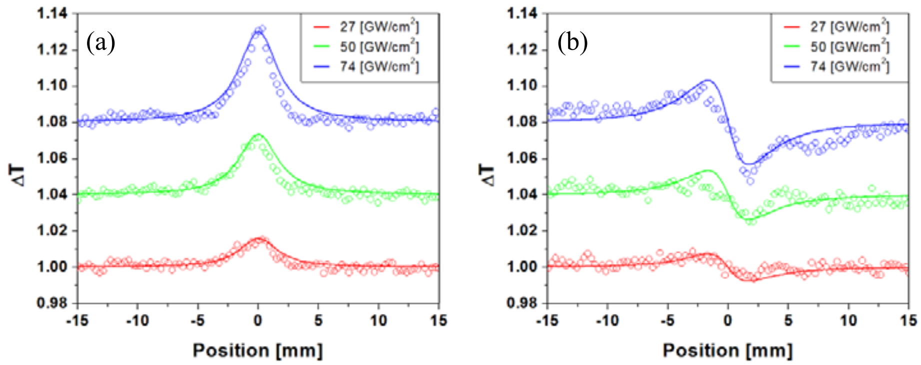


Figure C.2. Compilation of the a) open aperture and b) closed aperture Z-scan curves for several different intensities at 780 nm. Experimental results are shown with symbols and the fitted curves are depicted with a solid line.

Likewise, fitting the closed aperture experimental data, an $n_2 = 3.7 \times 10^{-15}$ m^2/W is extracted which together correspond to a complex third-order susceptibility of $\chi_{\mathrm{eff}}^{(3)} = 5.9 \times 10^{-17}$ - i1.7×10^{-16} m^2/V^2. At 780 nm (Fig. C.2), we find saturation intensity of $I_{\mathrm{sat}} = 510$ GW/cm^2 or $\alpha_2 = -6.8 \times 10^{-9}$ m/W. For the closed aperture experimental data, an $n_2 = 1.3 \times 10^{-15}$ m^2/W is extracted which together correspond to a complex third-order susceptibility of $\chi_{\mathrm{eff}}^{(3)} = 5.9 \times 10^{-17}$ - i1.7×10^{-16} m^2/V^2. Although a direct comparison of the nonlinearities with other materials is difficult due to varying experimental parameters, we note that TiN exhibits nonlinearities which are comparable to those found in gold and silver. We also note than unlike gold, TiN exhibits saturable absorption up to 780 nm which may be useful for applications in intensity selective mirrors. Coupled with a damage threshold which is at least 1 order of magnitude larger than gold, TiN is shown to be a promising material for future metal-based nonlinear optics.

Plasmonic Resonance in Single- and Double-Layer CVD Graphene Nanoribbons (Boltasseva, Kildishev, Shalaev) Single layer graphene (SLG) nanostructures have been shown to support electrically tunable surface plasmon resonances with large wave localization (λ_0/λ_p ~100) in the mid-infrared range. At present there is a critical need to drive the plasmonic resonance of SLG nanostructures into near-infrared wavelengths, and to increase the relatively small strength of plasmonic resonance for realization of practical devices.

Theoretical and experimental studies of AB-stacked bilayer graphene predict an enhanced optical conductivity due to strong interlayer coupling, which is expected to allow double-layer graphene to support plasmonic resonances at smaller wavelengths than SLG. In this paper we report our study of plasmon resonance in nanopatterned single layer graphene nanoribbon (SL-GNR), double layer graphene nanoribbon (DL-GNR) and triple layer graphene nanoribbon (TL-GNR) structures. We use infrared microscopy measurements to verify the existence of electrical tunable plasmons in such stacked multilayer GNRs. We find that the strength of the plasmonic resonance increases in DL-GNR when compared to SL-GNRs. However, we do not find a further such increase in TL-GNRs compared to DL-GNRs. We carried out computationally inexpensive full wave simulations using surface-current-based finite element technique to validate and fit experimental results and extract the carrier scattering rate as a fitting parameter. The numerical simulations show remarkable agreement with experiments for unpatterned SLG sheet, and a qualitative agreement for patterned graphene sheet.

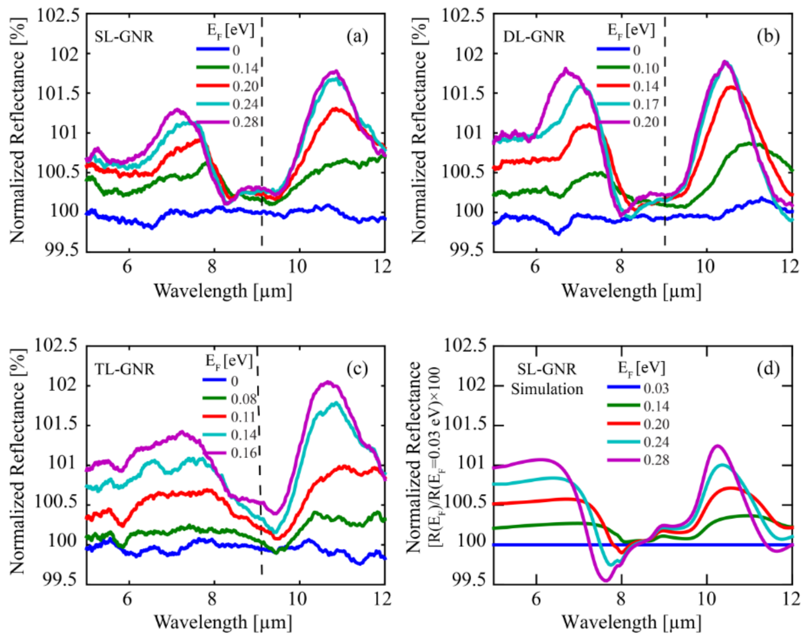


Figure C3. Modulation of IR reflectivity of GNRs fabricated on Si/SiO2 substrate as a function of Fermi energy (EF) of graphene; the vertical dashed lines indicate the peak of SiO2 optical phonon. The SL-GNR, DL-GNR and TL-GNR samples were fabricated by transferring and stacking CVD grown graphene sheets, followed by EBL and oxygen plasma patterning. The reflectance from GNRs was measured using Fourier Transform Infrared Spectroscopy (FTIR), with a microscope accessory (Nicplan IR Scope, 15X, NA 0.58 Reflectochromat objective). The incoming beam was polarized with electric field perpendicular to ribbons using a wire grid polarizer to excite transverse magnetic modes in GNRs. Panels (a) - (c) show measured reflectance on SL-GNRs, DL-GNRs and TL-GNRs respectively. The measured data were normalized to the reflectance at the charge neutral point in our experiments. The width and period of GNRs were fixed at 50 nm and 150 nm respectively. (d) 2D full wave FEFD simulations of SL-GNRs with COMSOL Multiphysics using a surface current model for graphene; simulations performed at 0° to 35° angles (corresponding to NA = 0.58) of incidence with 5° spacing were averaged to obtain the curves shown here. The Fermi energy for each sample was calculated using a uniform charge approximation that does not take into account the screening and interlayer coupling effects.

Quasi-Coherent Thermal Emitter based on Refractory Plasmonic Materials (Shalaev,Boltasseva,Kildishev)

The thermal emission of refractory plasmonic metamaterial – a titanium nitride 1D grating – is studied at high operating temperature (540 °C). By choosing a refractory material, we fabricate thermal gratings (shown in Fig. C.4) with high brightness that are emitting mid-infrared radiation centered around 3 μm. We demonstrate experimentally that the thermal excitation of plasmon-polariton on the surface of the grating produces a well-collimated beam with a spatial coherence length of 32λ (angular divergence of 1.8°) which is quasi-monochromatic with a full width at half maximum of 70 nm. These experimental results show good agreement with a numerical model based on a two-dimensional full-wave analysis in frequency domain.

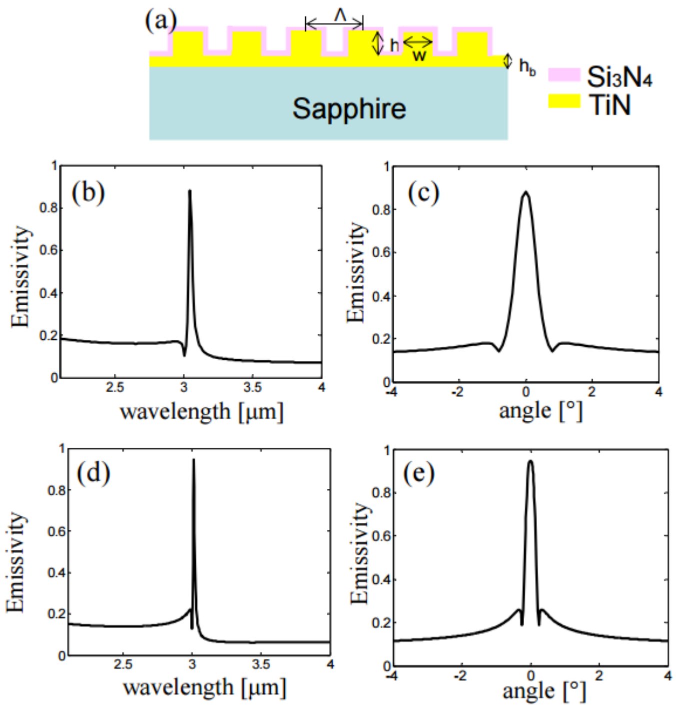


Figure C4 (a) Schematics of the TiN grating structure.Calculated emissivity of a TiN grating as a function of wavelength, along surface normal (b) and emission angle at the wavelength of 3.05 μm (c) . The grating parameters: period, Λ = 3 μm, filling factor, $q = w/ \Lambda = 0.537$, height, h = 100 nm, and TiN under layer thickness h_b = 50 nm. Same dependencies for reference Au grating with identical geometry: as a function of wavelength (d) and emission angle (e) at the wavelength of 3.013 μm.

Figure C4. shows the calculated emissivity of the grating along surface normal for ppolarization (E-field is in the incidence plane), as only p-polarized waves are coupled to surface plasmons in 1D metal gratings in the direction perpendicular to gratings lines. The TiN grating with a period Λ of 3 μm, a groove height h of 100 nm, and a filling factor (q = w/ Λ) of 0.537 was modelled with 40-nm silicon nitride cover layer on top, which was used in experiment to prevent oxidation of TiN at elevated temperatures. The schematic of the sample is shown in Fig. 7(a). Figure 7(c) indicates that at the wavelength of 3.05 μm, the calculated directionality of the p-polarized emission has a divergence angle of mere 0.7°. This is a signature of the spatial coherence of the source. The TiN grating structure theoretically yields a thermal emission with a spatial coherence length / 82 cl = Δ= λ θ λ and a quality factor Q = Δ= λ λ / 87 (Δ = λ 35 nm). For comparison, we compute the gold structures under the same geometry with permittivity approximated by Johnson-Christy model with a loss factor of three [23]. The calculated emissivity of the gold grating as a function of wavelengths and angles are shown in Fig. C4 (d, e).

Figure C5(a) shows the SEM image of the TiN grating with a 40 nm thick SiN anti-oxidation layer, which was fabricated using a top-down approach. Fig. C5(b) shows the control sample, which as an Au grating with similar geometry. Figure C5(c) shows the damaged Au sample after heating to 540° C. Figure C5(d) shows the experimental setup.

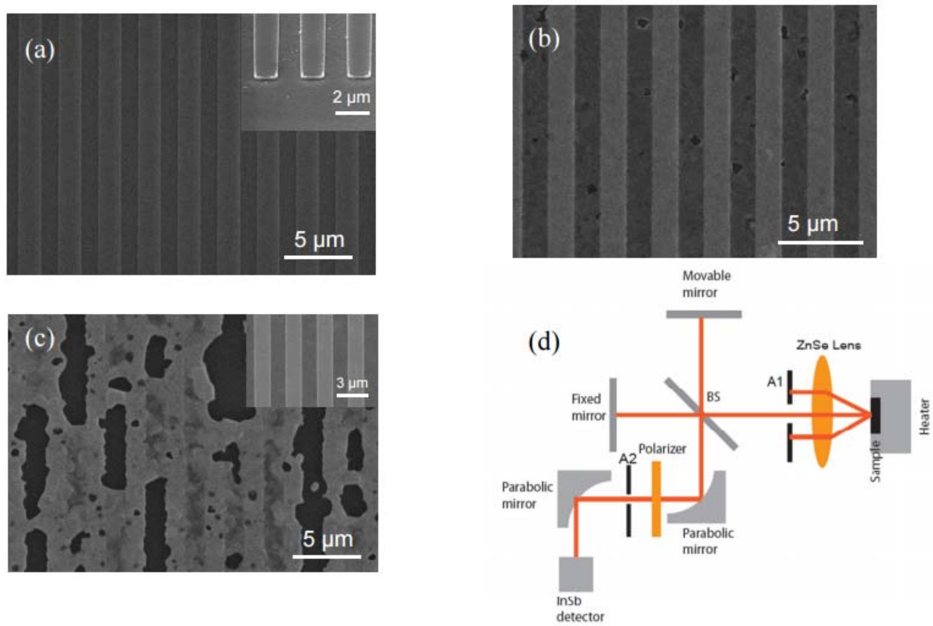


Figure C5. (a) SEM image of the TiN grating after heated up to 540°C for 32h, the inset shows the tilted view. (b) SEM image of the Au grating after heated up to 400°C for 25h. (c) SEM image of the Au grating after heated up to 540°C for 8h, the inset shows the original structure. (d) Schematic of the experimental setup for thermal emission measurements of TiN grating. BS: KBr beamsplitter, A1,A2: iris apertures.

Fig. C6(a) shows the measured emissivity in the direction normal to the surface. Theoretically the grating with a pitch size of 3 μm is shown to have a high emissivity at 3.05 μm. Experimentally we measured a narrow peak at the wavelength of 3.06 μm with full width at half maximum equal to 70 nm corresponding to a Q factor of 43. The measured wavelength profile is the integrated emission from the TiN grating over the detection angle of 1.35° normalized by the emission from blackbody reference. The simulation followed the experimental setup with averaging of the emissivity over the same angular range. Thus TiN grating appears to yield a narrow-band emission with a spatial coherence length / 32 *cl* = Δ= *λ*θ*λ* (angular divergence of 1.8°) as shown in Fig. C.6(b). The reduced efficiency of the measured emission peak is due to the increased loss factor of Drude damping term of the material at elevated temperature. The increased loss factor inherently broadens and lowers down the emission peak. We also measured the emissivity of planar unpatterned region to be 0.12 which is slightly higher than the theoretical calculation 0.08. The slight deviation is attributed to increased loss factor of TiN and surface roughness inherent in nanofabricated samples.

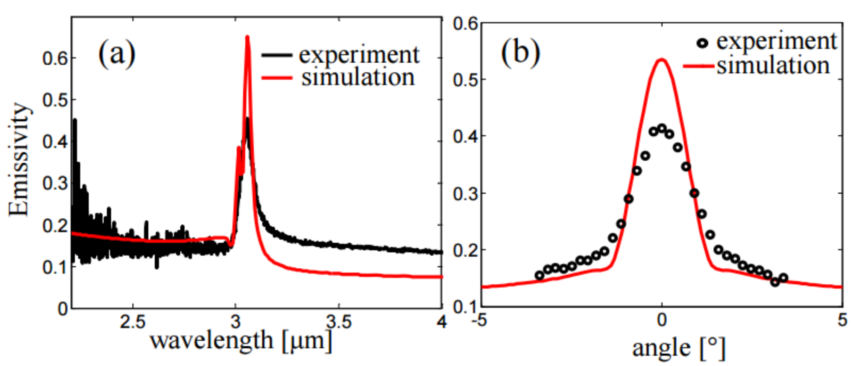


Figure C6. (a) Measured and calculated emissivities as a function of the wavelength for emission angle θ = 0° at 540 °C. (b) Angular profile of emissivity at the wavelength of 3.06 μm vs. calculation

Expanding the theory of circular omnidirectional light concentrators to elliptic and spheroidal designs (Kildishev) We propose a new class of GRIN omnidirectional light traps, giving shape flexibility to our previous circular design. New theoretical prototype of the device has elliptic profile with eccentricity being a flexible parameter. The ideal version of this design traps light to geometric locus of zeroth elliptic component, which corresponds to a strip as wide as distance between foci (in case of elliptic cylinder), line between foci (in case of prolate spheroid), or a disk with diameter joining foci (in case of oblate spheroid). These designs expand the realistic form factor of the absorbing element from circular cylinder and sphere (in previous circular design) to strip, pill and button with some finite thickness. The new elliptically flattened designs bring the opportunity to use the existing planar semiconductor technology for absorbing elements. Our theoretical analysis of ray trajectories proved omnidirectional trapping for both designs—elliptic cylinder and spheroids. Our full-wave finite element simulations for cylindrical case showed that the trapping shell with inserted absorbing core, while obviously suffering from some scattering and diffraction, did preserve the omnidirectional property, and that focused GBs follow paths predicted by ray tracing analysis. Detailed analyzes of performance, absorption efficiency, and their dependence on parameters will be published elsewhere. Omnidirectional cylindrical lenses and microlenses and their extension to prolate or oblate spheroidal lenses are important in non-imaging applications, including efficient mobile photovoltaic cells and multicolor IR sensing

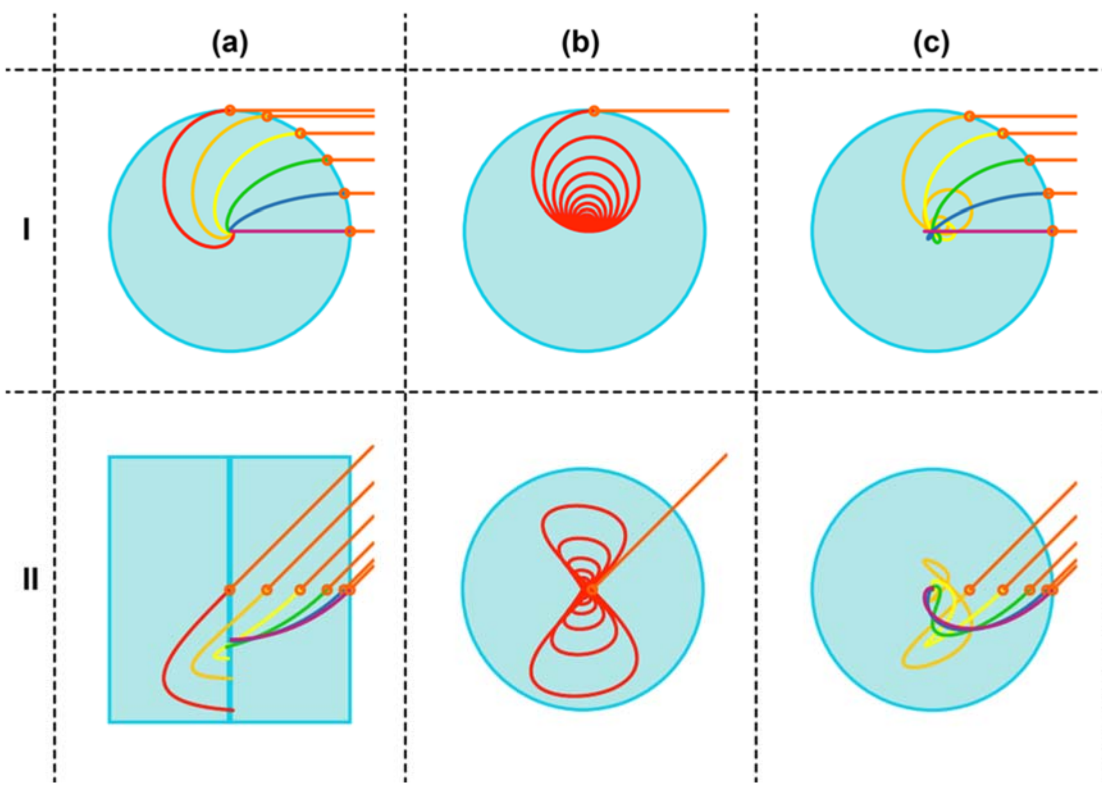


Figure C7. Circular case (cylinder or spherical), p = 2, $\beta = \pi/4$. Rows: I—xz-plane, II—xy-plane. Columns: (a) circular cylinder, (b) sphere, ray close to tangent, (c) sphere, non-tangent rays.

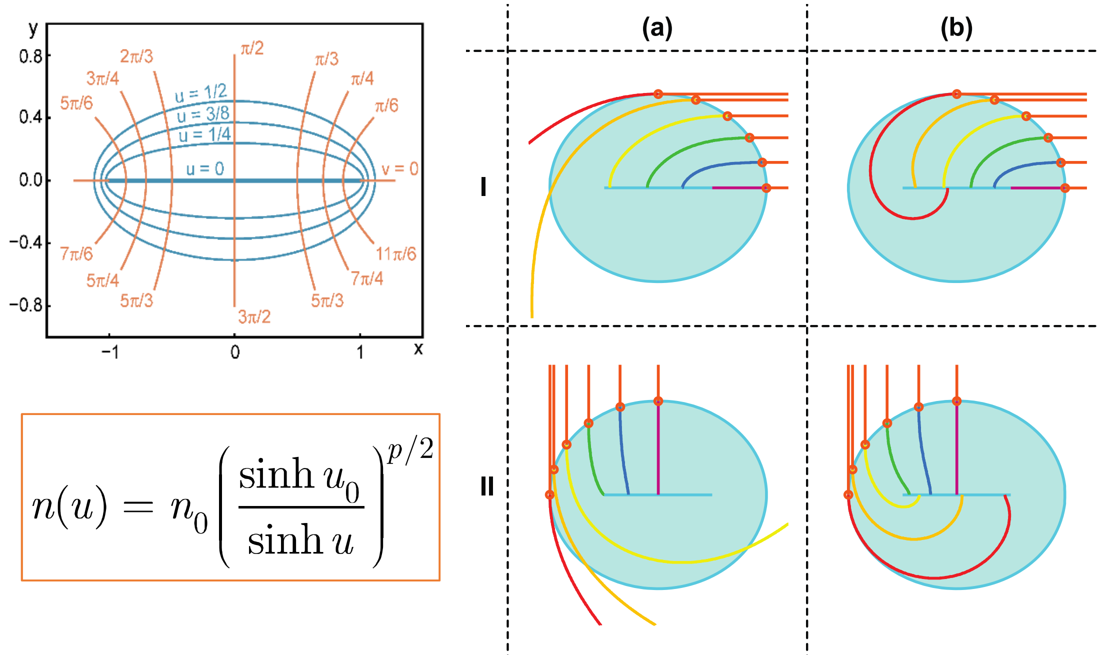


Figure C8. Elliptic cylinder. Rows: I—α = 0°, II—α = π/2. Columns: (a) $-p$ = 1 (absorption efficiency 80%-93%), (b) $-p$ = 2 (100% efficiency)

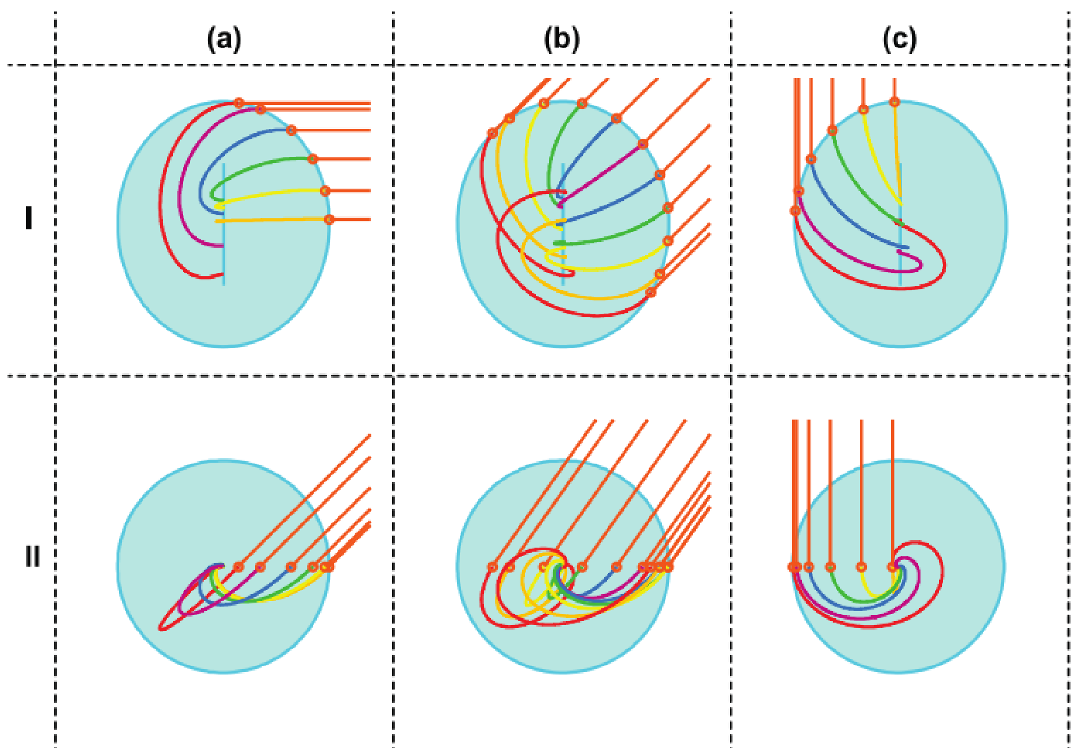


Figure C9. Prolate spheroid. Rows: I—xz-plane, II—yz-plane. Columns: (a) α = 0°, (b) α = 45°, and (c) α = 90°.

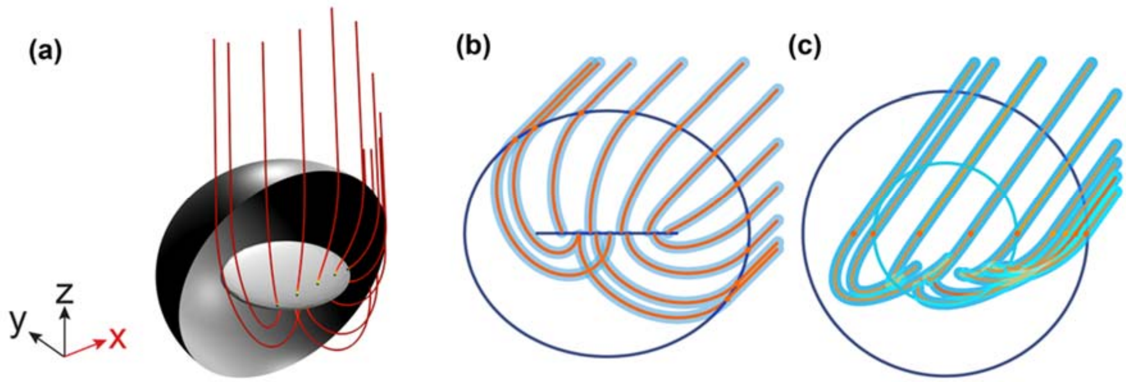


Figure C10. Oblate spheroidal concentrator. Comparison of ray tracing results obtained by our semi-analytical method (SAM) and by the Ray Optics module of COMSOL Multiphysics (COMSOL). Ray incidence considered is α = 45° and β = 45°. (a) Ray-tracing results from COMSOL. (b), (c) Perfect fit between SAM and COMSOL results shown in two projections: (b) shows xz-projection, while (c) shows xy projection. Thick blue lines depict the traces obtained from COMSOL, thin orange lines show SAM results. (The blue lines are intentionally shown thicker to make them visible, otherwise all the traces would completely overlap.)

D. BERKELEY TEAM

“Janus” optical device Employing the transformation optics methodology, we have successfully designed and demonstrated a “Janus” optical device which possesses simultaneously multiple functions within one single optical element. This opens up a new door to achieving compact and high-speed integrated photonic systems. In addition, we introduce the transformational plasmonics concept to efficiently manipulate the propagation of surface plasmons, by only modifying the dielectric material properties adjacent to a metal.

Transformational plasmonic devices We successfully demonstrated transformational plasmonic devices, including a plasmonic Luneburg lens to focus surface plasmon polaritons and a plasmonic Eaton lens to bend surface plasmon polaritons. Our approach has the potential to achieve low-loss functional plasmonic elements with a standard fabrication technology based on grey-scale electron-beam lithography and is fully compatible with active plasmonics. Furthermore, this method provides a scheme with which to realize more complex two-dimensional plasmonic elements using transformation optics.

Carpet cloak for visible light Invisibility carpet cloak has been realized in the infrared region using a silicon waveguide platform. At shorter wavelengths, however, devices reported so far suffer from significant scattering from surfaces within a unit cell as the feature sizes become comparable to wavelength. We demonstrate a visible light carpet cloak device made of silicon nitride on a specially prepared nanoporous silicon oxide with very low index. The fabricated device demonstrates wideband invisibility throughout the visible spectrum with low loss. This silicon nitride on low index substrate can also be a general scheme for implementation of transformation optical devices at visible frequencies.

“Photonic Blackhole” using transformation optics By using transformation optics, it is possible to attract photons to a central point in the system, similar to the celestial blackhole phenomenon. The optical device for this purpose, known as the Photonic Blackhole will be able to force the flow of optical energy toward its central “core.” The metamaterial is designed to transform the space in which light propagates, so that the optical waves, incident within the event horizon of the device, would automatically spiral and finally arrive at the core. We have developed the nanofabrication processes to implement the design using electron beam lithography and high aspect ratio dry etching.

Routing surface plasmons with self-accelerating beams Transforming the flow of surface plasmon polaritons (SPPs) at a subwavelength scale paves the way for ultra-compact integrated optical circuits. Traditional plasmonic elements based on either structuring metal surfaces or placing discrete dielectric structures on metal surfaces rely on fabricated permanent structures which are difficult to reconfigure. We have demonstrated a novel approach for dynamically routing SPPs in real-time with plasmonic self-accelerating beams based on nondiffracting wave-packets. By introducing nondiffracting Airy beams into plasmonics, SPPs can be guided along metallic interface without any physical waveguide structures.

Metasurfaces for manipulating surface plasmons So far, almost all studies on metasurfaces have been focusing on manipulating propagating waves. In contrast, only a few of them have been devoted to employing metasurfaces to control near-field waves, such as surface plasmons. We demonstrate that one-dimensional metallic gratings, a simple metasurface with practically feasible geometries, are capable of tailoring the dispersion, and thus the propagation characteristic of surface plasmons in an unprecedented manner. As a result, normal, non-divergent and anomalous diffraction are achieved as surface plasmons propagate along the metasurface. In particular, arising from the hyperbolic constant frequency contour, surface plasmons undergo negative refraction as they propagate from a flat metal surface to a metasurface.

One-way cloaking via parity-time symmetric transformation optics By introducing the PT symmetric optical potentials into transformation optics, we have proposed a new scheme to realize the one-way invisibility cloak. Since the transformed PT symmetric potentials provide a specific unidirectional wave vector, unidirectional light reflection and scattering are expected to occur when the phase matching condition is approximately satisfied, while light incident from the other direction propagates through the potentials without any perturbation. Therefore, the concealed object is cloaked depending on incident directions of light.0Moreover, we show that the enhanced backward scattering from the transformed PT symmetric potentials can be engineered to demonstrate a one-way optical illusion of the concealed object.

Super resolution imaging with transformation optics We explored a new approach to utilize an additional freedom, i.e. phase of surface plasmon polaritons, to remarkably improve the imaging resolution through a transformation optics scheme. We put forward a strategy to overcome the refractive index limitation of natural materials by harnessing a geometry-mediated decompression of plasmon polaritions. The idea is to adiabatically expand the SPP wavelength while preserving phase information, in order to form a pre-magnified image object that could be observed in far-field. This is achieved as a consequence of the varying distance between the two metallic surfaces which causes the gap SPP to adiabatically turn into a single-surface SPP. Our design demonstrates that by utilizing the transformation optics and abandoning global wavelength in favor of a spatial grid of variable wavelengths would provide a means to extend the domain of geometrical optics to a deep sub-wavelength scale.

E. UNIVERSITY OF UTAH TEAM

Transformation Optics Design of a Planar Near Field Magnifier for Sub-wavelength Imaging It is well known that imaging systems with either isotropic negative index or hyperbolic (indefinite) media under certain conditions can achieve super-resolution. However, achieving sub-diffraction limited imaging along with magnification can be challenging. In this article, we design, simulate and evaluate the performance of planar near-field magnifier lenses capable of achieving super-resolution based on transformation optics design principles. Specifically, we use a grid-relaxed transformation that results in material properties that are more amenable to implementation. We discuss the possible design choices in terms of material properties, adverse effect of loss tangent on such magnifier, effect of magnification factor and other design constraints that are associated with such magnifying super-resolution lenses. We also present a complete 3D simulation of a planar near-field magnifier (with magnification = 3×) based on cylindrical harmonic decomposition and 2.5D technique and evaluate its imaging perfor-mance with a standard resolution target. We investigate and propose a potential path to achieve higher magnification factors using transformation optics design.

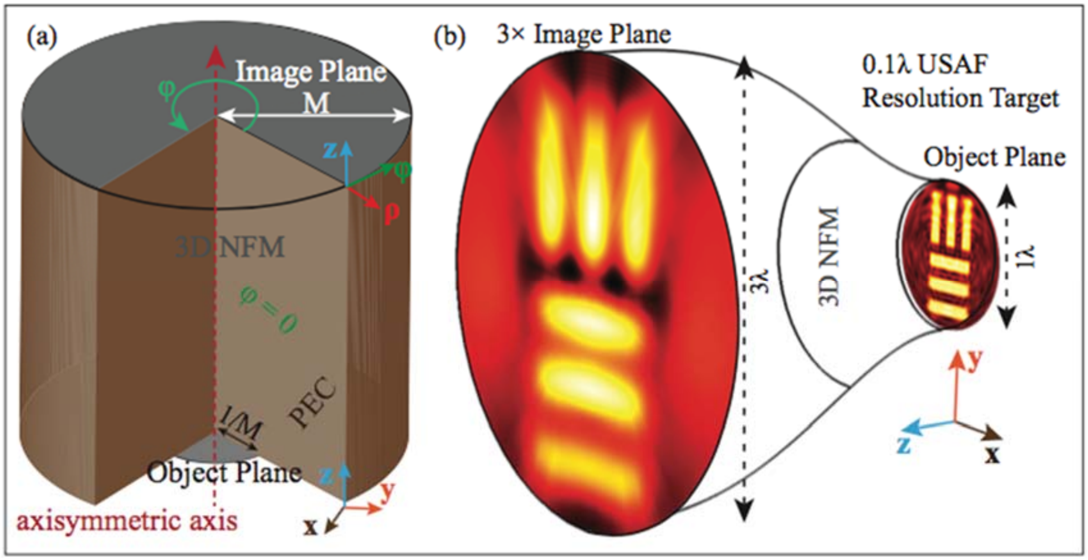
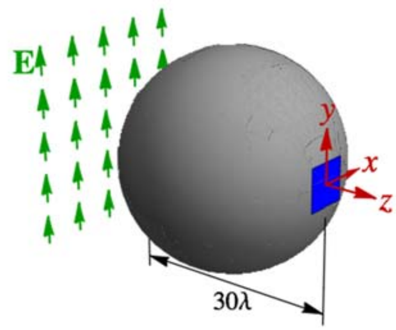


Figure E1. (a) Shows the perspective section view of a 3D NFM, which is the axial revolution of a 2D planar NFM in (ρ', $\varphi = 0$, z') plane. Axisymmetric axis is shown in dotted red line. The material property tensors correspond to that of anisotropic bilayer. (b) Shows the object plane transverse electric field norm and 3× magnified image plane transverse electric field norm. A 0.1 λ USAF resolution target was chosen for this demonstration.

Controlling the Twisting of Light The usual paradigm for transformation optics relies on the form invariance of Maxwell's equations un-der a holonomic transformation. In this case, Maxwell's equations are unchanged, but the permittivity and permeability tensors that appear in the constitutive relations undergo a modification. The practical use of this piece of mathematics arises from the reinterpretation of these transformed material property tensors as real material properties in a flat space. One can expand these ideas to a broader paradigm to include anholonomic transformations which are intrinsically connected to bianisotropic material proper-ties. Anholonomic transformations are not derivable from coordinate transformations. However, the torsion tensor is a geometrically intuitive object that can describe an anholonomic transformation. Geometrically, the torsion describes the twisting of space as one moves along a curve. This twisting offers direct control over polarization rotation as a wave propagates along a trajectory. Visualizing this twisting is a fairly intuitive way to design a polarization manipulating device, much more so than the direct specification of the chiral material properties.



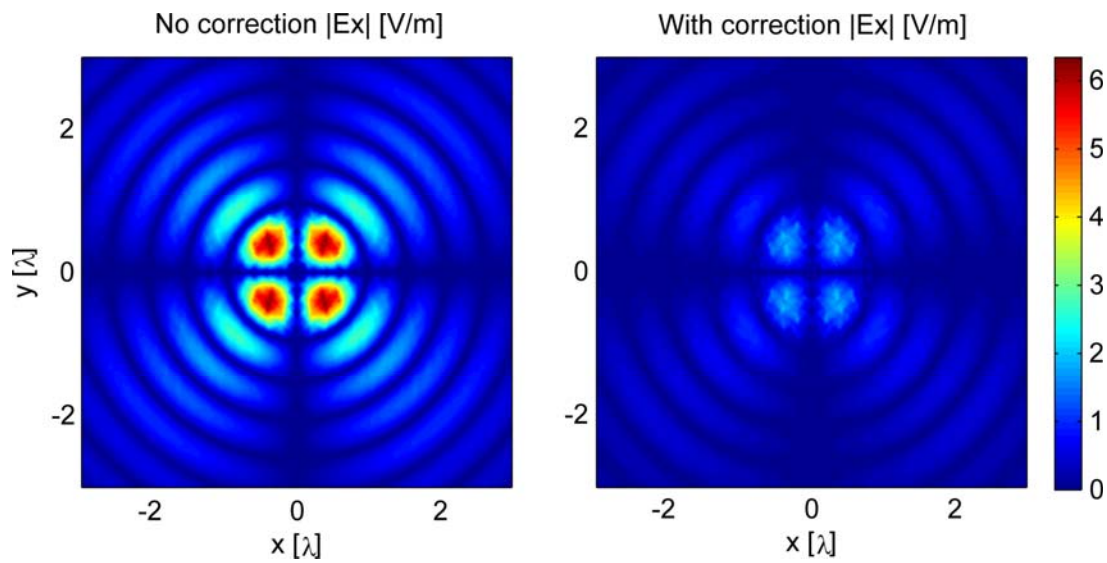


Figure E2. Shows the magnitude of E_x component at z = +15 lambda (xy-plane containing the focal point) for without and with chiral correction for an incident y-polarized plane wave of 1 V/m.

Quantitative metamaterial property extraction We examine an extraction model for metamaterials, not previously reported, that gives precise, quantitative and causal representation of S-parameter data over a broad frequency range, up to frequencies where the free space wavelength is only a modest factor larger than the unit cell dimension. The model is comprised of superposed, slab-shaped response regions of finite thickness, one for each observed resonance. The resonance dispersion is Lorentzian and thus strictly causal. This new model is compared with previous models for correctness likelihood, including an appropriate Occams factor for each fit parameter. We find that this new model is by far the most likely to be correct in a Bayesian analysis of model fits to S-parameter simulation data for several classic metamaterial unit cells.

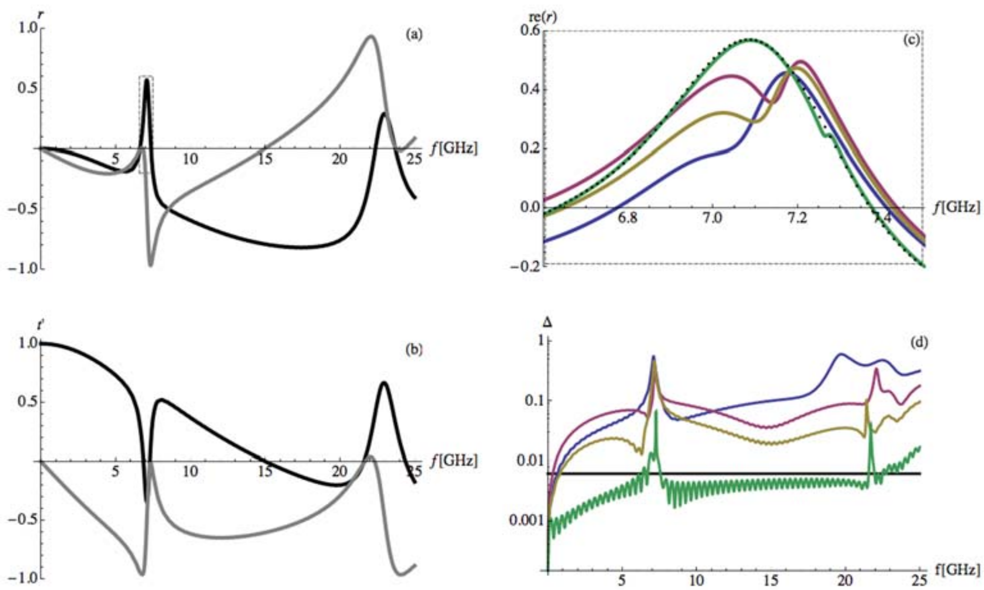


Figure E3. Microwave cloak unit cell. From simulation, the real and imaginary part of the (a) reflection coefficient and (b) transmission coefficient. (c) Best global fits of the four models to the simulated data (black dots). The narrow range of frequencies displayed is indicated by the dashed box in (a). The models are shown in: green (multi-thickness), yellow (single thickness), red (thin sheet) and blue (homogeneous). (d) The combined residuals, with the same color scheme.