Optical Functionalities on Demand: from metamaterials to metadevices

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www.nanophotonics.org.uk

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www.nanophotonics.sg
The 1st Photonic Revolution

Global Telecommunications

Optical Data Storage

Laser medicine

Laser manufacturing
The Next Photonic Revolution: Metamaterials

Web of Science Publications: Metamaterials

- 1962
- 1969
- 1975

- 10,000
- 1,000
- 100
- 10
- 1

Years:
- 2000
- 2001
- 2002
- 2003
- 2004
- 2005
- 2006
- 2007
- 2008
- 2009
- 2010
- 2011
- 2012
- 2013

Bars represent:
- Metamaterials
- Laser
Metamaterials = Negative Index Media & Superlens?

Metamaterials = Invisibility & Cloaking?
Metamaterial is a manmade media with all sorts of unusual functionalities that can be achieved by artificial structuring smaller than the length scale of the external stimulus.


Metamaterials are manmade media with electromagnetic properties on demand
Metamaterials: electromagnetic properties on demand

- Natural Solid
- Electromagnetic Metamaterial
- Active/nonlinear medium
- Electromagnetic Metamaterial
- Reconfigurable metamaterial
- “Quantum” Metamaterial
- Plasmonic Resonators
- Superconducting quantum devices

Atoms
1st Metamaterial (J. Bose, 1898)

"In order to imitate the rotation by liquids like sugar solutions, I made elements of "molecules" of twisted jute..."
L. D. Landau, E. M. Lifshitz, and L. P. Pitaevskii (1962): “... there is certainly no meaning in using the magnetic susceptibility from optical frequencies onwards and ... we must put $\mu = 1$."

Method for increasing the permeability of artificial dielectrics

Negative Permeability and Permittivity ("left-handed")

Negative refraction due to chirality $\sim \text{Im} \{ m_{kn} d_{nk} \}$

S. A. Schelkunoff & H. T. Friis
Antennas Theory and Practices. J. Wiley & Sons, 1952

D. R. Smith, W. J. Padilla ... S. Schultz, PRL (2000)

Tretyakov (2003)
Pendry (2004)
Rogarcheva... Zheludev PRL. (2006)
Plum .... Zheludev, PR B (2009)
Impact of Metamaterials on Fundamental Physics #2
Reciprocal Asymmetric Transmission

Birefringence | Optical Activity | Faraday effect

Forward

Reversed

Asymmetric transmission
Reciprocal effect!

Planar Chiral Metamaterial

>30 papers

Fedotov ... Zheludev. PRL (2006)
Impact of Metamaterials on Fundamental Physics #3
Toroidal Dipole

Magnetic Multipoles
(Transverse currents)

Electric Multipoles
(Charges)

Toroidal Multipoles
(Radial Currents)

Zeldovich. Sov. Phys. JETP (1953)

Toroidal dipole
Magnetic dipole
Electric quadrupole
Magnetic quadrupole

Bacteriophages
Proteins

>25 papers (and grows fast)

Kaelberer ... Zheludev Science (2010)

Power Scattered

10^23
10^22
10^21
10^20
10^19
10^18

14.5 15.0 15.5 16.0 16.5 17.5

Frequency (GHz)
Designing Resonances: EIT & Fano resonances

Electromagnetic Induced Transparency & stopped light in Atoms

- Pump
- Δ₂
- Δ₁
- γ
- Probe

Plasmonic EIT

Zhang ... Zhang. PRL (2008)
Liu ... Giessen. Nat. Mat (2009)

Controlling EIT


Electromagnetic Induced Transparency & stopped light in Metamaterials

Slow light

Papasimakis, Fedotov, ... Zheludev
PRL (2007 & 2008)
Luk’yanchuk, Zheludev .... Nat. Mat. (2010)

> 400 papers
Sharp resonances in superconducting metamaterials

Array of halls in high-$T_c$ superconductor YBCO, $Q>60$

Spiral meta-molecule in supercond. niobium

Wavelength over size >700

Tsiatmas ... Zheludev. APL (2010)

Kurter ... Anlage

>30 papers
Sensor Metamaterials

Hydrogen Palladium Sensing
- Tittl, ... Giessen
  Nano Letters (2011)

Non-specific Protein Sensing
- Xu, Xiong.
  Nanoletters (2011)

Specific streptavidin prot. sensor
- Xiaojun Wua, ... Li Wang
  Biosensors and Bioelectronics (2013)

Strain sensors for orthopaedics
- Melik, ... Demir

Glucose sensor
- N. Liu, ... Giessen et.
  Nano. Lett. 2010;
  Wang, ... Zhao
  APL (2013)

Blood pressure monitoring with metamaterial antennas
- Noh ... Kim
  Electr. Lett. (2014)
Designing Anisotropy & birefringence

Epsilon zero metamaterials

Wave guiding in Epsilon zero MMs & Metatronics

Silveirinha ... Engheta. PRL (2006)
Elser, ... Narimanov. APL (2006)
Noginov, ... Narimanov. APL (2009)
Pollard .... Podolskiy. PRL (2009)

Zero-index waveguides


Isoindex (index zero-crossing) metamaterials

Silveirinha ... Engheta. PRL (2006)

Mass ... Polman, Nat. Phot. (2013)

Zheludev, Plum, Fedotov. APL (2011)

Optical ENZ

Negative-index in waveguides

(λ - λ₀)/Δλ

Isoindex spectral filter

Dielectric permittivity

ε₁

ε₂

Zero ε point

Wavelength

Epsilon zero metamaterials

Wave guiding in Epsilon zero MMs & Metatronics

Negative-index in waveguides


Zero-index waveguides
Silveirinha ... Engheta. PRL (2006)


Optical ENZ
Controlling polarization: chirality

The Born-Kuhn Molecular model (1915)


Meta-materials APL (2000)

Decker ... Wegener (2007)

Rotatory power orders of magnitude stronger than in natural media!

Optical “Stereo” Metamaterials

Extrinsic Chirality

Metamaterials” Circular polarizers

700 nm

Plum ... Zheludev. APL (2007)

Plum ... Zheludev PRL (2009); APL (2008)

Gansel ... Wegener. Science (2009); APL (2012)
Controlling boundary conditions: Perfect absorber

“Amplification” of absorption with metamaterials

Amplified losses

-38dB, 9 GHz

Fedotov .... Zheludev. PR-E (2005); APL (2006)

“Total” absorption with metamaterials

Zhang ... Zheludev NPG Light (2012)

>200 papers

Schwaneckeb... Zheludev J. Opt. (2007)

Light-Harvesting metamaterials: thermal detectors & bolometers

Transmission

Frequency, $\nu$ (GHz)

Sensitivity (V/W)

NEP = $0.3 \text{ nW Hz}^{-1/2}$

$200 \mu m$

Enhanced optical Bolometer

Niobium on Sapphire

Superconducting Meta- Bolometer

NEP = $1 \text{ nW Hz}^{-1/2}$

NEP = $10 \text{ nW Hz}^{-1/2}$

Infrared Detection with cantilever pixels deflection

Tao, ... Padilla, Averitt. Opt. Exp. 2011

Niesler ... Wegener. APL (2012)

Savinov... Zheludev Super. Sci. & Tech. (2013)

Tao, ... Padilla, Averitt. Opt. Exp. 2011
Tailoring emission lines with metamaterials

Control of thermal radiation with metamaterials

Liu ... Padilla. PRL (2011)

Tuneable plasmonic emission in reconfigurable MM

Adamo ... Zheludev. CLEO-Europe (2013)
New Materials for metamaterials

IR magnetic response in Te metamaterial
- Ginn, Brener ... Sinclair. PRL (2012)

Graphene metamaterial
- Papasimakis ... Zheludev, de Abajo NPG Light (2013)

Negative refraction in conductive oxide metamaterial

Silicon metamaterial
- Zheng ... Zheludev. OPT Exp. (2013)

TiN-based metamaterial: enhanced emission
- Naik ... Boltasseva. TBP (2013)

Visible and UV metamaterials from topological insulator
- Ou, So, ... Zheludev Arxive (2013)
CTNs & Graphene in metamaterials

Metamaterial absorption, %

λ_{22}

Plasmonic resonance

λ_p

δ_{pe}

λ_{11}

Excitonic resonance

CNTs absorption, %

λ

Plasmonic & Excitonic absorption lines

Modulating graphene properties by carrier injection

Fermi Level

n-doping pristine graphene

p-doping

Modulating graphene properties by carrier injection

T = 1.14ps

T = 1.27ps

carrier-recombination

graphene

carrier-phonon

carrier recombination

X 20

T = 1.14ps

T = 1.27ps

pump-probe delay (ps)

Lee, ... Min. Nat. Mat. (2012)

Nikolayenko... Zheludev

PRL (2010)

Nikolayenko... Zheludev

APL (2012)

Carbon Nanotubes

500nm

Graphene

470nm

Carbon Nanotubes

Graphene

Nikolayenko... Zheludev

PRL (2010)

Nikolayenko... Zheludev

APL (2012)

Lee, ... Min. Nat. Mat. (2012)
Ultrafast switching with metamaterials

Gold Metamaterial


Fluence [J/cm²] x Relax. time [s] = 10^{-18} J x sec / cm²

>40 papers

Wurtz ... Zayats. *Nature Nanotech.* (2011)

Padilla ... *PRL* (2006)
Chen ... *Opt. Lett.* (2007)
Dani... *Nano Lett.* (2009)
Nonlinear optical activity in metamaterial: 10^7 times stronger than natural media


FOM ~ 10^{-11} deg·cm/W

2012: Giant nonlinear optical activity in a plasmonic metamaterial
Quantum Optics of Metamaterials: Single Photon gate, multi-THz bandwidth

Quanta from heralded photon source

50:50

Mirror

Plasmonic metamaterial

Standing wave

( interference of the wave function )

Ultrafast:

Fang, Tseng, Ou, MacDonald, Tsai & Zheludev

APL 104, 141102 (2014)

Ultrathin 50nm free-standing plasmonic metamaterial absorber
Phase Change Metamaterials & Optical memory

Chalcogenide Glass Technology

Re-Writable CD  Samsung PCh Memory

Electrical THz frequency tuning

All-optical, non-volatile, bidirectional switching

Writing Optical Pulse 660nm 100 ns, 0.1 mW/µm²

Arasing Optical pulse 660nm 50 ns, 0.25 mW/µm²

Quantum effects in MM >300 pps
Light in a fibre loop

Quantum Metamaterials
Superconducting wire loop

YBCO metamaterial

Quantized magnetic flux
Quantized canonical momentum

Flux in the ring, $\Phi$
$h/e$
$h/2e$
External Flux $\Phi_{ext}$

Quantum Exclusion zone
Flux quantum

Conventional SR metamaterial
High intensity
Low intensity

Different resonance frequencies


Quantum SCQID Metamaterial

Trepanier ... Anlage, 2013
Du, Chen, Li, 2006
Lazarides & Tsironis, 2007
Metamaterials and LC devices

Polarizer
ITO glass
Alignment layer
RGB Filter
Polarizer
ITO glass

Buchnev ... Zheludev, Fedotov Opt. Exp. (2013)
Minovich ... Kivshar APL (2012)
Zhao... Zhang. APL (2007).

Microwave
Optical

Metamaterial as polarizer, transparent electrode and alignment layer

Transmittance, %
Wavelength, μm

>50 papers

0 V
1.0 V
1.2 V
1.5 V
7.0 V
2.0 V
6.0 V

>50 papers
EO & MO modulation with metamaterials

THz modulation in metamaterial: carrier injection

- Chen... Aweritt Nature (2006)
- Chan... Mittleman APL (2009)

Magnonic Metamaterial Waveguide

- Magnetic field
- YIG
- RF

EO Superconducting Metamaterial

- Incident radiation
- Control current
- Self-induced H

Electrochemical Modulation MM

- Stenning... Zheludev Opt. Exp. (2013)

>100 papers
Control of Spontaneous Emission with MMs & “Lasing Spaser”

Enhanced Emission

Tanaka… Zheludev. PRL (2010)

Purcell factor > 100 !


“Hyperboloc” Dye Dielectric @ metal stack


Enhanced Emission

Tanaka… Zheludev. PRL (2010)

Purcell factor > 100 !


“Hyperboloc” Dye Dielectric @ metal stack


Enhanced Emission

Tanaka… Zheludev. PRL (2010)

Purcell factor > 100 !


“Hyperboloc” Dye Dielectric @ metal stack

Free-electron driven metamaterial light sources

Laser conditioned fibre

FIB Plato Preparation

Metamaterial Arrays

700nm uy=176nm

750nm uy=176nm

800nm uy=176nm uy=160nm

reference grating

Adamo ... Zheludev PRL (2012)
So ... Zheludev TBP(2014)
Reconfigurable metamaterials: nanoscale forces

Random access metamaterial (RAMM)

Differential thermal expansion

Cooling

Heating

Ampere Force

Lorentz-Laplace force

Optical Forces

Coulomb Force

>70 papers
THz MEMS reconfigurable Metamaterials

- Tunable anisotropy
- Terahertz var. waveplates
- Tunable filters
- Polarimetry


Human Hair

Elastic SiN membrane

1 mm x 1mm

Reconfigurable metamaterials

Giant Electro-optic Effect:
Ou, Plum ...Zheludev. Nat. Nanotech (2013)

Giant Optical Nonlinearity
Joule reconfigurable metamaterial

Elastic SiN membrane

Disconnected bridge

Joule Heating

Nanoscale meta-molecule

Connected bridge

Broken loop

Elastic bridge design

25μ x 15 μ

Terminal B

Terminal A

Gold Si₃N₄

Ou, Valente, Plum ... Zheludev. CLEO-Europe (2013)
Lorentz-Laplace reconfigurable metamaterials

\[ F = IL \times B \]

Ou, Valente, Plum ... Zheludev. CLEO-Europe (2013)

Different Currents (few mAs)

Transmission Change, %

30µ

RPM in micro spectrometer

RPM with contact wires on wafer
Coulomb reconfigurable metamaterials

Mass ~ 0.5 pg (pico-gram)

> 70% change in transmission/reflection

EO coefficient 5 orders of magnitude stronger than in LiNbO₃

Off

On

Ou, Plum ...Zheludev
Nat. Nanotech (2013)
Reconfiguring metamaterials with light

Plasmonic Reconfigurable metamaterial

Dielectric Reconfigurable metamaterial

Out of plane
In plane
Narrow bridge
Wide bridge

Frequency, MHz

ΔT/T, %

2.0 MW/m²
1.4 MW/m²
1.0 MW/m²
0.8 MW/m²
0.4 MW/m²
0.2 MW/m²

Zhang, Macdonald, Zheludev
NPG Light: Science and Applications (2013)
Size matters

Weak elastic force at the nanoscale

Hooke's force
\[ F \sim k \Delta x \sim r^2 \]

High natural frequencies at the nanoscale

Mechanical resonance
\[ \omega_0 \sim (k/m)^{1/2} \sim 1/r \]

Mechanical Resonance Frequency

CPU Technology

Intel 386
Intel 486
Intel Pentium
Intel Pentium II
Intel Pentium III
Intel Pentium Dual-Core
Intel Core i7

Scale, µm

Frequency, MHz
Randomly Reconfigurable Metamaterials

1D Randomly reconfigurable metamaterial

2D Randomly reconfigurable metamaterial

Magnetic field

Lorentz force
"In fact, the only remaining unused dimension in fiber telecommunication networks is space..." Nikia-Siemens

Where future “killer applications” may come from?

Tuneable Lasing Spaser

Space Division Multiplexing in fiber networks

Mobile dynamic 3D display

Random Access Metamaterial Spatial Mode Multiplexer/Demultiplexer

Random Access Metamaterial

Multicolour laser or lasing spaser

Smart Phone

Dynamic Holographic Image

Multimode fiber

Pump beam

Gain medium

Light out (Lasing beam)
Conclusions

- Research on metamaterials is rewriting optics textbooks as we know them
- Metamaterials is emerging enabling technology in all applications of light
- Main technology drivers for developing metamaterials are:
  - Telecoms (reduction of energy consumption and increase of bandwidth)
  - Energy conversion and re-distribution
  - Sensors
  - Light sources
  - Cognitive & Data processing systems?
- Metamaterials - >> Metadevices - >> Metasystems

From metamaterials to metadevices
Zheludev & Kivshar.
Chiral Fractal Metamaterial

Southampton University Mountbatten Building
THANK YOU!

The talk may be found at: