The 8th International Conference on Surface Plasmon Photonics (SPP8)

Plenary session

Date May 24, 2017
Time 09:00-09:45
Room International Conference Hall (4F)

Professor

Vladimir Shalaev
Purdue University, USA

Enabling Practical Nanophotonics with Plasmonics
Broadening the Applications Realm for Metasurfaces

Vladimir M. Shalaev
Purdue University, USA
Symmetry and Conservation

Emmy Noether

Symmetry \iff Conservation Law

Translational Symmetry \iff Conservation of Momentum
\[ k_{2x} = k_{1x} \]

Temporal Symmetry \iff Conservation of Energy
\[ \omega_1 = \omega_2 \]
Metasurfaces: Breaking Symmetry

Metasurface breaks translational invariance and introduces phase gradient

Complete control over transverse momentum

$A$

$n_i$

$\theta_r$

$dr$

$\Phi + d\Phi$

$n_t$

$\theta_t$

$B$

Ni et al, Science 335 (2012)

Seminal work on metasurfaces: Hasman, Capasso, Zheludev, Lalanne, Fainman/Levy, Tsai, Bozhevolnyi, Zhang, Smith, Atwater,…

N. Yu at al Science (2011)

Capasso’s Group
Thermophotovoltaics

Nanolaser/Spaser

Catalysis

Nanotweezer

Photodetectors

Ultrafast Control
Refractory Plasmonics

- Plasmonic metals
  - Low melting points
  - Soft
- Refractory metals
  - Lossy, non-plasmonic
- Transition metal nitrides
  - Mimic Au optical properties
  - High melting point
  - Hard materials

Transition Metal Nitrides can be the solution for high temperature applications

TiN outperforms Au and carbon in local heating applications

Urcan Guler *et al.* NL 13 (12) (2013)

Thermophotovoltaics: How it Works

Blackbody @ 1500° C
22% matches with PV cell response
Re-shape the emission for better match (53%)
36% of original BB radiation is emitted
64% of the energy is conserved

Current S/TPV Approaches


Photonic crystals

Arpin et al., Nature Comm. 4, 2630 (2013)

Efficiency 3.2%


Efficiency 6.8%

D. M. Bierman et al., Nat. Energy 1, 16068 (2016)
Refractory Metamaterials

Au TiN

Reliable Operation At 1500 °C
High Conversion Efficiency
High Power Density

T-dependent optical properties

Optical properties deviate at elevated temperatures

Custom built temperature dependent spectroscopic ellipsometer

Optical properties of TiN become comparable to Au and Ag at temperatures over 450° C

See also work by A. Zayats, J. Dionne, D. Norris, and Y. Sivan
T-Induced Deviations are Important

- Temperature of a plasmonic near field transducer in HAMR: 300-500 °C

Maximum field enhancement reduces by 50% and 17% in single crystalline and polycrystalline cases, respectively.

LSPR strength reduces with temperature

H. Reddy et al., ACS Photonics (2017)
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Plasmonic TiN for Water Splitting

GLAD for single-crystal TiO2 nanowires:
Broadband hot electron generation and transmission in TiN/TiO2
Rate of hot electrons with TiN colloids is 2x larger than with Au nanoparticles (broader absorption and Ohmic vs Shotcky contact)

TiN vs Au decorated TiO2 nanowires:

See also work by Halas and Norlander groups Moskovits group

S. Ishii et al ACS Photonics (2016)
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Ultrafast Control
Snowflake fractal (Au) metasurfaces for graphene photodetector

Broadband absorption and polarization insensitive response

J. Fang *et al* Nano Letters (2016)

2D materials for PV/PTE photodetectors: Halas/Nordlander, Atwater, Muller, Koppens groups
Graphene Photodetector with Fractal Metasurface

- Drain
- Graphene
- Fractal
- Plain Edge
- Source

Enhancement vs. Wavelength (nm):

- Absorption (%)
- 15
- 10
- 5
- 0
- 470 500 530 560 590 620 650

Normalized Photovoltage (a.u.) vs. Polarization Angle (°):

- Measurement
- Fit

Photovoltage (µV) vs. $V_{SD}$ (V):

- Power = 1 mW
- $\lambda$ = 514 nm
- Measurement
- Fit
Thermophotovoltaics

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Ultrafast Control
Plasmonic approach to achieve coherent optical sources at nanoscale

Spaser

Pump  Emission  Energy transfer

fluorophore  metal


Proof of Concepts

See also work by groups:
M. T. Hill, M. K Smit, CZ Ning
Y. Fainman
G. Shvets, C.-K. Shih, S. Gwo
S. Bozhevolnyi, R. Quidant
D. J. Norris
J. B. Khurgin
N. Zheludev
T. Odom
M. P. van Exter

Noginov, Shalaev, Wiesner groups

Xiang Zhang group
Active metasurfaces for lasing: Highly directional spasing hole array

Room temperature, single-mode lasing

Meng et al., Laser & Photonics Reviews 8, 896-903 (2014)
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Plasmon Nano-Optical Trapping


Nano letters (2012) (Dionne group, Stanford)


Trapping single Protein

Nano letters (2011) (Gordon group, Univ Victoria)

See also works from the groups of: Kenneth Crozier (U Melbourne), Lambertus Hesselink (Stanford), Kimani Touissaint (UIUC), Xiang Zhang (UC Berkeley) and Yasuyuki Tsuboi (Osaka, Japan)
Hybrid Electrothermalplasmonic Nanotweezer (HENT)

Addresses the *long-standing* challenge to rapidly load a plasmon trap

Fast and precise delivery to plasmonic hotspots

High resolution nanoparticle trapping

Ability to immobilize trapped object

Directed Spatially Selective Self (DS³) Assembly

A scheme for high throughput parallelized assembly of nanodiamonds on nanophotonic structures

J. Ndukaife et al Manuscript in Preparation
100 nm Nanodiamonds are positioned on each nanoantenna and not in the space between!
Thermophotovoltaics

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Ultrafast Control
TCOs are Metallic Semiconductors

Large free-carrier concentrations make TCOs metallic

- Dopants: Aluminum, Indium, Gallium
- Concentrations of $10^{21} \text{ cm}^{-3}$
- Defect Centers: Hydrogen, Oxygen, Zinc

Wide bandgaps reduce visible absorption

- Bandgaps $> 3\text{eV}$
- Transparent over visible spectrum

see work by groups:
H. A. Atwater
O. L. Muskens
M. Brongersma
V. J. Sorger
M. A. Noginov
C. B. Murray
D. J. Milliron
R. P. H. Chang
M. Wegener
S. Franzen
T. W. Odom
A. Lavrinenko
S. Sadofev/Benson group
Switching with TCOs

Dynamic/active control of TCO’s carrier concentration i.e. plasma frequency:

- Electrical bias for injection of additional free-electrons e.g. MOS-type devices
- Optical pumping via the redistribution and/or addition of conduction electrons
- Post-deposition thermal annealing for thermal activation of donor defects
- Structural, opto-mechanical coupling

See also work of Atwater, Boyd, Muskens, Brongersma, Zheludev, Dal Negro, Odom, Ketterson, Chang, Sadofev/Benson and others

J. Kim et al., IEEE JSTQE 19, 4601907 (2013)
M. Abb et al., Nano Lett. 11, 2457 (2011)
H.W. Lee et al., Nano Lett. 14, 6463 (2014)
Kerr Nonlinearity in AZO at ENZ point

\[ n = n_0 + \Delta n = n_0 + n_2 I \]

\[ n_2 = n_{2r} + i \beta_2 \sim \frac{\chi^{(3)}}{n_0} \]

Kerr index is dependent on refractive index
- \( n_2 \sim \chi^{(3)}/n_{\text{probe}} \)

Pump-Probe Configuration
- 785 nm Pump
- Broadband NIR Probe: 1150-1550 nm
- \( \chi^{(3)}(\omega_{\text{pump}}; \omega_{\text{probe}}) \)

See also work by Boyd group
Light-induced refractive index changes of the order of unity

Feasibility of dynamic light-induced metasurfaces/gratings by using shaped beams

Caspani, et al. PRL (2016)
see also work by Boyd, Science (2016)
Interband Dynamics in TCOs

Interband excitation promotes additional electrons into the conduction band, *blue-shifting* the plasma frequency.

Fast recombination of free-carriers through band-gap vacancy/impurity states (Shokely-Reed Hall mechanism)

UV 262 nm pump induces large and sub-picosecond modulation in Al:ZnO thin films

Intraband Dynamics in TCOs

Conduction electrons absorb low-energy pump and equilibrate to a new Fermi distribution; plasma frequency is *red-shifted*

Fast relaxation because of anomalously large difference in electron and lattice heat capacities (slow lattice $dn/dT$ doesn’t contribute much)

NIR 787 nm pump also induces large and sub-picosecond transients in Al:ZnO thin films

Simultaneous Nonlinearities

Engineered nonlinearities by controlling the delay between the two pumps


Feasibility of dynamic light-induced metasurfaces/gratings by using shaped beams
Ultrafast Metasurface Cavity

Optical pumped nanocavity incorporating Al:ZnO for ultrafast tunability

15 nm wavelength shift corresponding to a %100 change in transmission

Ultrafast recombination time < 1 ps (pump 787 nm)

In collaboration with Heriot Watt (Marcello Ferrera) and former student Jongbum Kim
Metasurface Embedded Design

Cavity Sample with Al:ZnO layer

- Aluminum Oxide (Passivation)
- Silver (Top mirror)
- Aluminum Oxide (Spacer)
- Ga:ZnO
- Aluminum Oxide
- Silver (Bottom mirror)

- $P = 125 \text{ nm}$
- $W$
- $30 \text{ nm}$
- $24 \text{ nm}$
- $210 \text{ nm}$
- $30 \text{ nm}$
- $70 \text{ nm}$
- $25 \text{ nm}$
- $24 \text{ nm}$

- $\Delta \lambda = 15 \text{ nm}$
- $\Delta \lambda = 20 \text{ nm}$
- $\Delta \lambda = 25 \text{ nm}$

In collaboration with Heriot Watt (Marcello Ferrera) and former student Jongbum Kim
Time-Gradient Metasurface

Non-reciprocal metasurfaces

Breaking translation symmetry and momentum conservation

\( \sqrt{k_x^2 + k_y^2} = \frac{\omega}{c} \)

Breaking temporal symmetry and energy conservation

Photonic TIME crystals
space-time duality in Maxwell Eqs
-> forbidden k-zones
$w^2 = w_p^2 + k^2c^2$

- $w$ changes are on same order as change of $\omega_p$ ($\sim 135$ nm), which occurs over time scale of 100-150fs
- Time inside AZO $\sim 20$ fs, $\Delta \lambda \sim 15 - 20$ nm

$k$ is fixed, $w$ changes with $w_p$
Frequency-Array Metasurface

Conventional Phase-Array Metasurface

Frequency-Array Metasurface

Electro-optical modulators (L.C, LiN, gate-tunable MS)

\[ E = \sum_{n=-N}^{N} \frac{e^{i(\omega_n t - k_n |r - r_n|)}}{\sqrt{|r - r_n|}} \]

\[ d = 750 \text{ nm} \quad \lambda_0 = 1.5 \mu\text{m} \]

with Amr Shaltout and Mark Brongersma

\[ \Delta \omega = 2\pi \times 100 \text{ GHz} \]
time of angular steering (~10ps) is comparable to propagation time of light.

-> light beam is curved

Similar to curved water stream when rotating fast a water horse.
Phase Gradient Metasurface

\[ \phi = k_0 \left( f_c - \sqrt{f_c^2 + x^2} \right) \]

\[ \phi = k_0 \sin(\theta) x \]

\[ \phi = k_0 \left( f_c - \sqrt{f_c^2 + x^2} \right) + \frac{k_0}{k_0 \sin(\theta) x} \]
Experimental Observation

Cylindrical lens \( f_c = 1 \text{ cm} \)

2.5 ps pulses @720nm

Microscope Objective

Streak camera

Graphs showing intensity vs. angle and time vs. angle.
Application of Metasurfaces

Broadening the Application Realm

Thermophotovoltaics

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Photodetectors

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Nanotweezer

Ultrafast Space-Time Control
Future Applications

**FLAT/WEARABLE OPTICS**

- Reconfigurable lenses
- Dynamic holograms
- Beam steering
- Novel light sources
- Dynamic signal routing
- Ultra-fast, active devices
- Harsh-environment sensors
- Wearables/googles
- Augmented reality
- Wearable sensors
- Ultrafast space-time light modulators
TEAM AND SUPPORT

Students
- Justus Ndukaife
- Aveek Dutta
- Sajid Choudhury
- Krishnakali Chaudhuri
- Harsha Reddy
- Deesha Sha
- Soham Saha
- Samuel Peana
- Zhuoxian Wang
- Clayton DeVault
- Oksana Makarova

Collaborations
- Prof. A. Boltasseva (Purdue)
- Prof. A. Kildishev (Purdue)
- Prof. N. Engheta (UPenn)
- Prof. A. Alu (UTexas Austin)
- Prof. M. Brongersma (Stan.)
- Prof. M. Ferrera (Heriot-Watt)
- Prof. D. Faccio (Heriot-Watt)
- Prof. A. Urbas (AFRL)
- Prof. E. Van Stryland (CREOL)
- Prof. T. Norris (UofMich)

Postdocs
- Dr. Urcan Guler
- Dr. Simeon Bogdanov

Former members
- Prof. G. Naik (Rice)
- Prof. N. Kinsey (VCU)
- Dr. S. Ishii (NIMS)
- Dr. N. Emani (DSI)
- Dr. P. West (Intel)
- Dr. J. Kim (U. Maryland)
- Dr. X Meng (Qilu Tech U)

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THANK YOU!

Nature Photonics News&Views Highlight

In search of new materials

NATURE PHOTONICS | VOL 5 | MARCH 2011

MATERIALS SCIENCE

Low-Loss Plasmonic Metamaterials

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shalaev@purdue.edu