Metasurfaces

Review:
A.V. Kildishev, A. Boltasseva, V.M. Shalaev,
Planar Photonics with Metasurfaces, Science 339, 6125 (2013)

Early and seminal work on metasurfaces:
E. Hasman, F. Capasso, ...
Symmetry and Conservation

Emmy Noether

Translational Symmetry $\iff$ Conservation of Momentum

$k_{2x} = k_{1x}$

Temporal Symmetry $\iff$ Conservation of Energy

$\omega_1 = \omega_2$
Generalized Snell’s Law (Capasso group)

For reflection
\[ \sin \theta_r - \sin \theta_i = n_i^{-1} k_0^{-1} \nabla \Phi \]

For refraction
\[ n_t \sin \theta_t - n_i \sin \theta_i = k_0^{-1} \nabla \Phi \]
Broadband Light Bending

Operating at 1–1.9µm

Ni et al, Science 335 (2012) (Shalaev group)
Meta-lens and Meta-holograms

Ni et al, LSA 2,  e72, (2013)

See also:

Meta-lens:
- Aieta et al., Nano Lett. 12, 4932 (2012) (Capasso group)

Meta-holograms:
- S. Larouche et al., Nat. Mat. 11, 450 (2012) (D Smith group)
- Zheng et al, Nat Nanotechnology 10, 308 (2015) (Guixin Li, Zentgraf, S Zhang groups)

Bozhevolnyi group:
Gap plasmons for metasurfaces
**Metasurface optical devices**

**Huygens’ surfaces**

![Huygens' surfaces diagram]


**CD Spectrometer**

![CD Spectrometer diagram]

A. Shaltout et al., *Optica* 2015

**Dielectric Metasurface Lens**

![Dielectric Metasurface Lens diagram]


**Color Hologram**

![Color Hologram diagram]

**Nanocavity**

![Nanocavity diagram]

**Active metasurface for lasing**

![Active metasurface for lasing diagram]

X. Meng et al, LPR (2014)

**SHG with metasurfaces**

![SHG with metasurfaces diagram]

R. Chandrasekar et al, OMEX (2015)

**Broadband Optical Rotator**

![Broadband Optical Rotator diagram]


**Antenna on ENZ**

![Antenna on ENZ diagram]

ENZ layer
Time-Gradient Metasurfaces
Space-Time Metasurfaces

Space-gradient metasurfaces relaxed Snell relation.
Time-gradient Metasurfaces enable new effects:
- Non-reciprocal Snell relation
- Doppler-like wavelength shift
- Energy exchange with light

See also non-reciprocal EIT effect: Hadad et al, “Space-time Gradient metasurfaces”, PRB 92(10), 2015.
TCOs as Metallic Semiconductors

Large free-carrier concentrations make TCOs metallic

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

Wide bandgaps reduce visible absorption

- Bandgaps > 3eV
- 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
Kerr Nonlinearity in AZO at ENZ point

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

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

Kerr index is dependent on refractive index
- \[ n_2 \sim \frac{\chi^{(3)}}{n_{probe}} \]

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

See also work on ITO by Boyd group, Science (2016)

Collaboration with Hariat-Watt Univ.
Optical Kerr Effect in AZO at ENZ point

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 on ITO by Boyd group, Science (2016)

see also work by H. Atwater, M. Brongersma, Muskens
Metasurface sub-λ Cavity with Ultrafast Switching

Optical pumped nanocavity incorporating Ga: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 Uni and former student Jongbum Kim
4D Photonics with Space-Time Metasurfaces

Non-reciprocal time-varying metasurfaces

\[ \Delta p_x = \hbar (\Delta k_x) = \hbar \frac{\partial \psi_{ms}}{\partial x} \]

symmetry and momentum conservation

(a)

[Diagram showing the relationship between k_x and k_y with \( \sqrt{k_x^2 + k_y^2} = \frac{\omega}{c} \)]

\[ \Delta E = \hbar (\Delta \omega) = -\hbar \frac{\partial \psi_{ms}}{\partial t} \]

symmetry and energy conservation

(b)

[Diagram showing the relationship between \( k_x \) and \( \Delta \omega/c \)]

Photonic TIME crystals
space-time duality in Maxwell Eqs
-> forbidden k-zones

Shaltout et al (see also work by Halevi)

What we discussed today

Metamaterials:

- Electrical metamaterials (plasmonics) for nanophotonics
- Magnetic metamaterials and negative refractive index
- Metamaterials for super-resolution
- Optical cloaking
- Metasurfaces