Manipulating and Engineering of the Light using Nano-Structures and Optical Metamaterials

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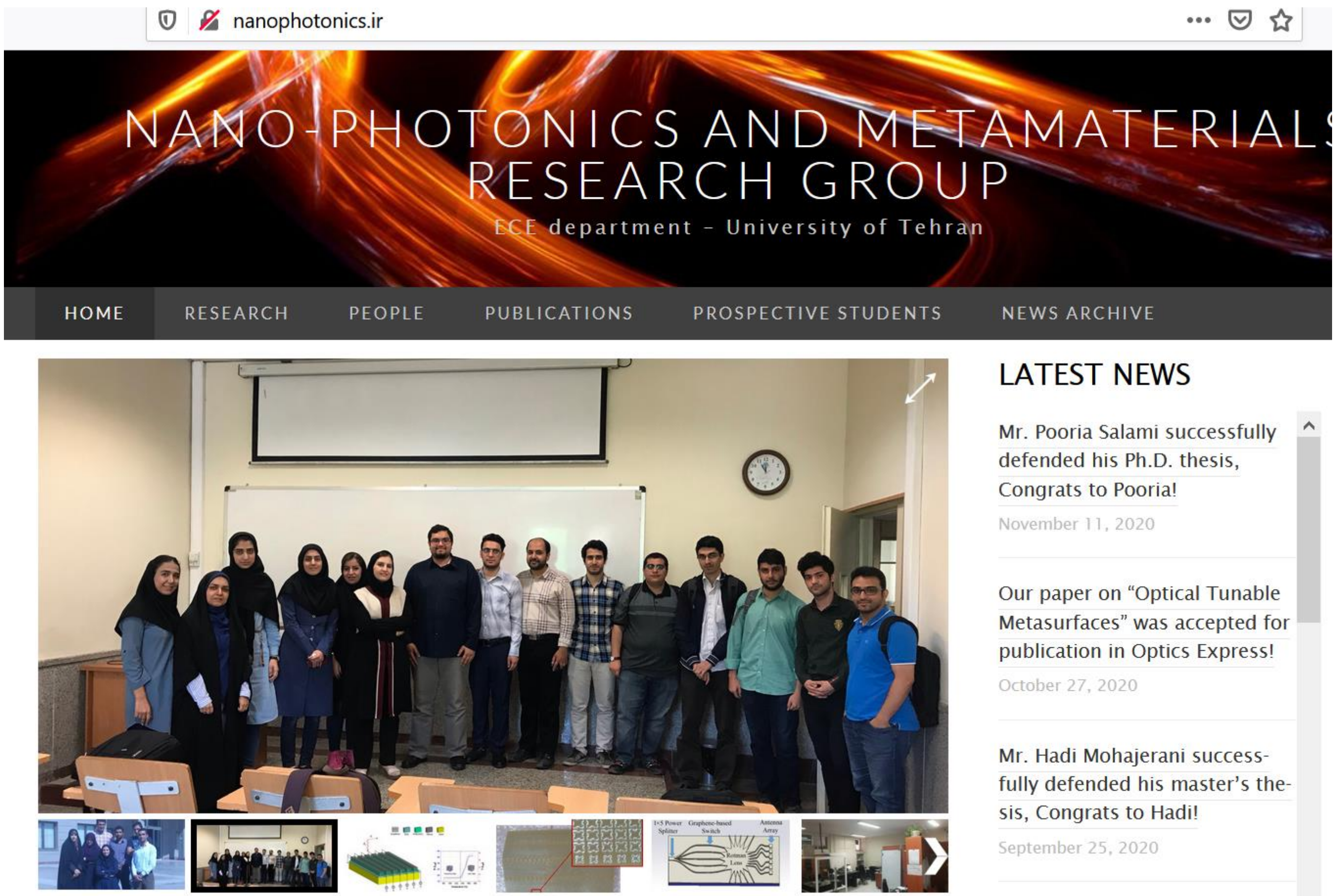
Thanks goes to my students in University of Tehran



Outline

- **Introduction to Metamaterials and Nano-Photonics**
- **Developing Integrated Photonic Devices for Next Generation High-Speed Wireless Communication Systems**
- **Efficiency-Enhanced Ultra-Thin Film Solar Cells using Nano-Structures and Metasurfaces**
- **Increasing the Resolution of Imaging Systems using Metasurfaces and Nano-Structures**
- **Invisibility Cloaks and Illusion using Metasurfaces and Nano-Structures**

Introduction to Metamaterials and Nano-Photonics

Maxwell Equations and the role of Electromagnetic Properties of Materials

$$\nabla \times E = -\frac{\partial(\mu H)}{\partial t}$$

$$\nabla \times H = \frac{\partial(\varepsilon E)}{\partial t} + J$$

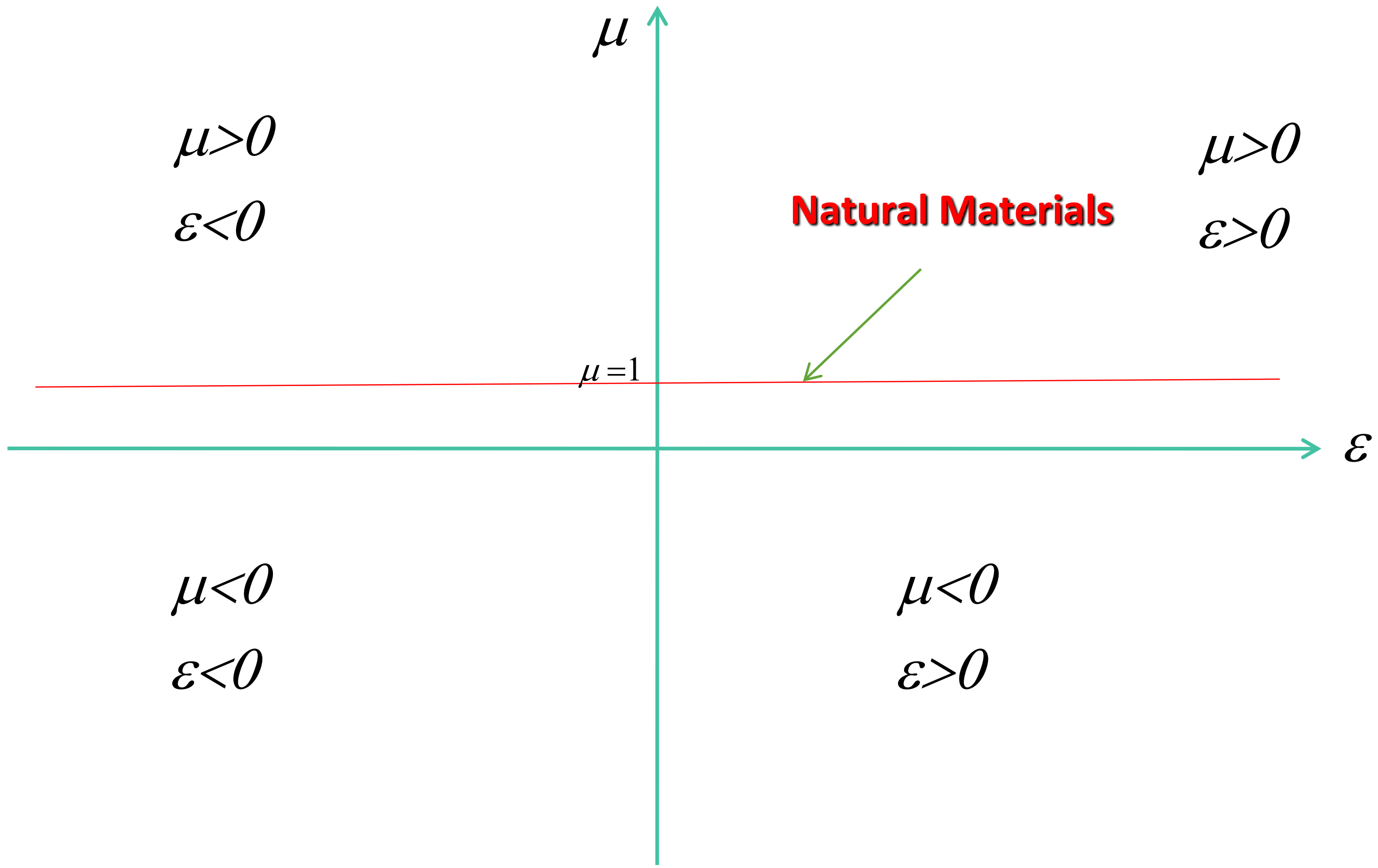
$$\nabla . \mu H = 0$$

$$\nabla . \varepsilon E = \rho$$

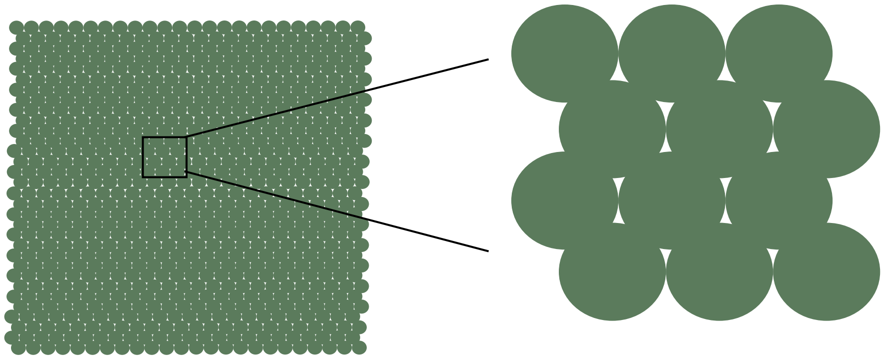
ε : Permittivity
μ : Permeability

When designing Electronic devices, ε and μ are dictated by the material you use in your device. And are positive.

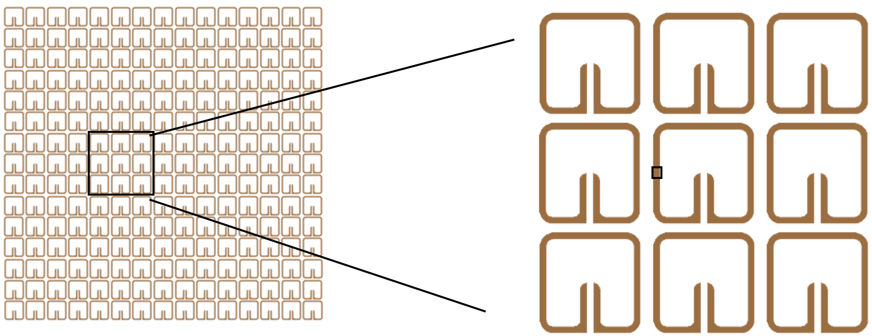
Different Configurations for Permittivity and Permeability



Definition of Metamaterials

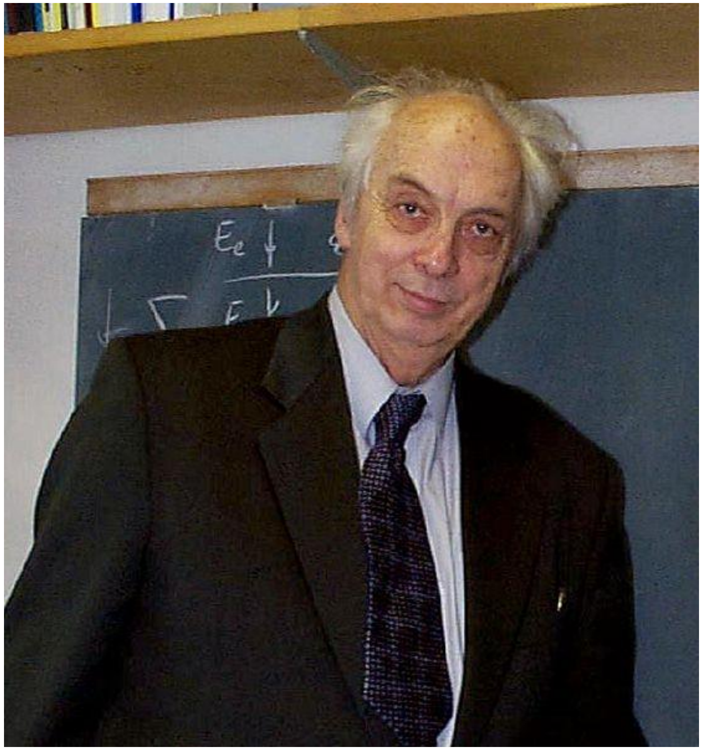


- **In natural materials permittivity and permeability are defined by molecules and atoms.**

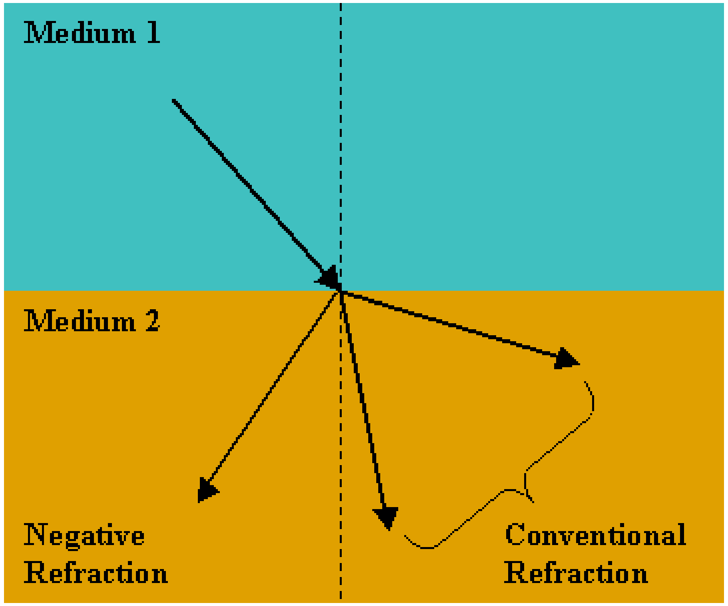


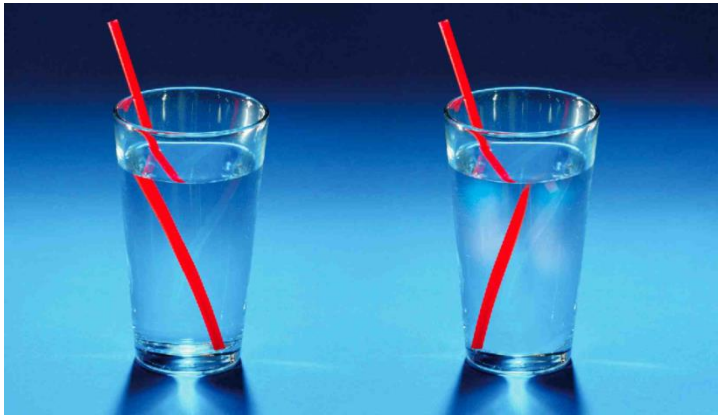
- **In metamaterials permittivity and permeability are defined by inclusions much smaller than the wavelength .**

What if we have negative ε and μ



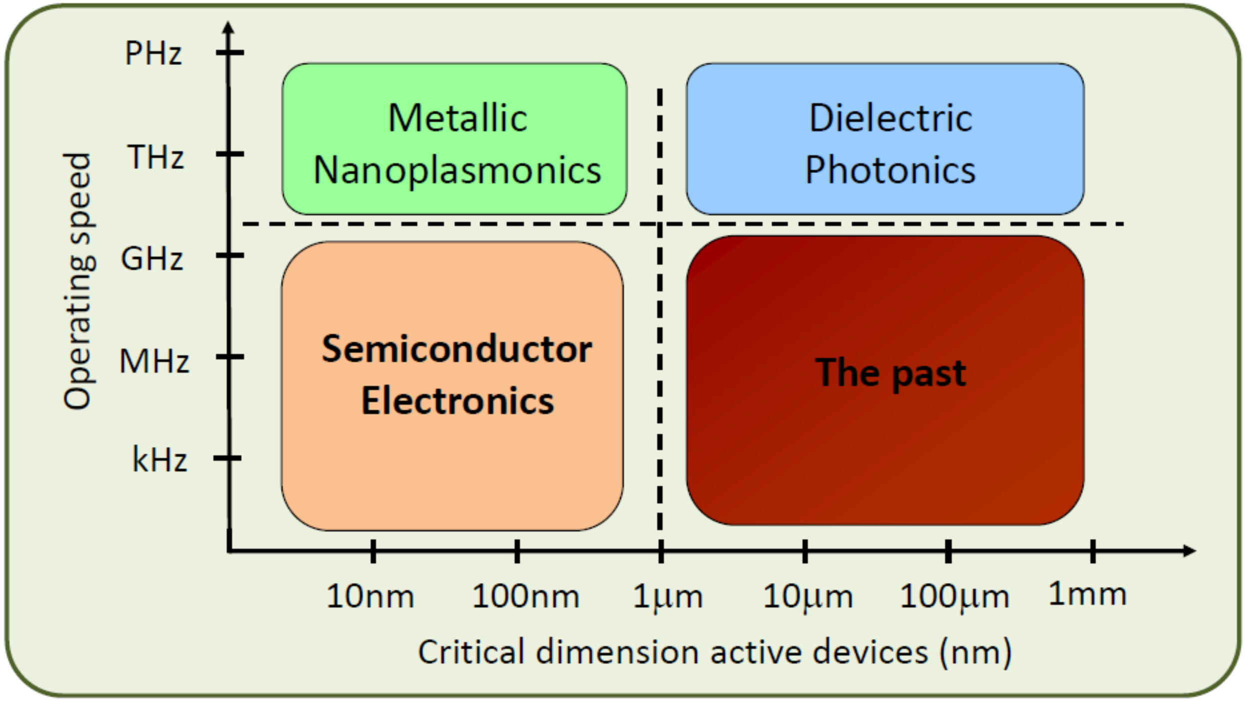
For the firs time, in 1967, Victor Veselago , a Russian Scientist, investigated the effects of a material with negative ε and μ on Electromagnetic waves, when radiating in such a media and found out very interesting and extraordinary behavior for such a material.





from: *Nature* 455, 299 (2008)

Why Nano-Photonics?



Plasmonics will enable an improved synergy between electronic and photonic devices

- Plasmonics naturally interfaces with similar size electronic components
- Plasmonics naturally interfaces with similar operating speed photonic networks

***R. Zia, et. al, Materials Today, 2006.**

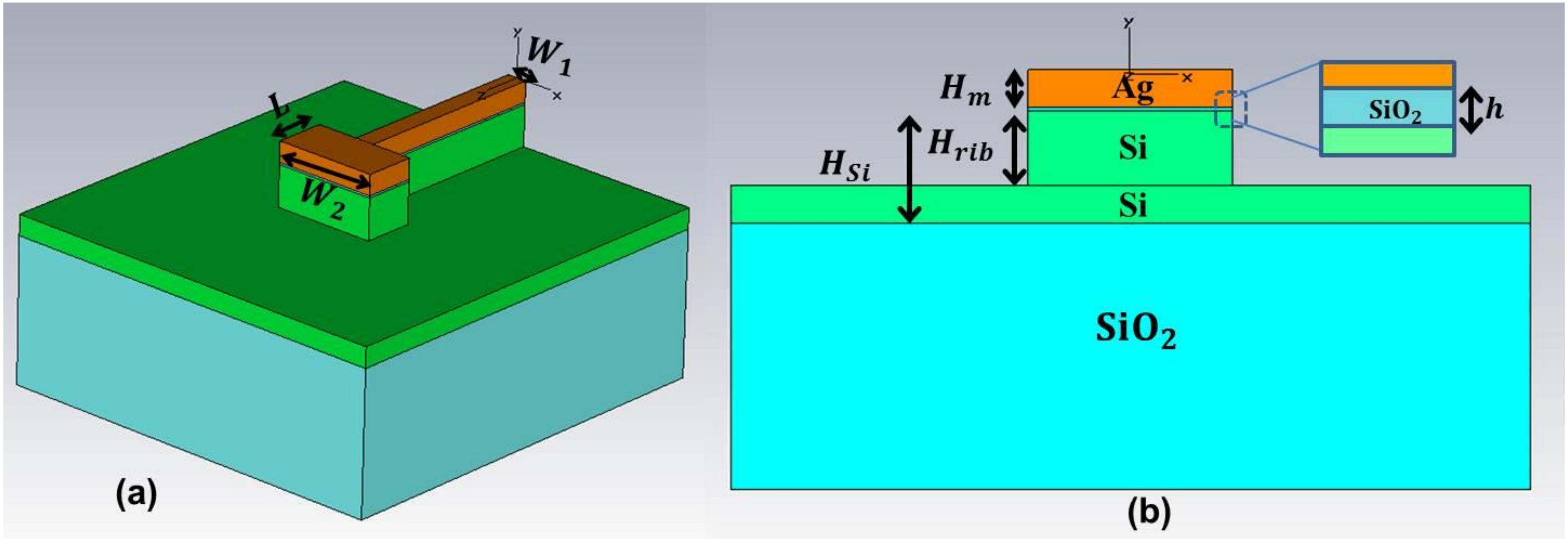
Developing Integrated Photonic Devices for Next Generation High-Speed Wireless Communication Systems

Manipulating Light by Nano-Antennas

Fig. (2): Different types of optical antennas written by electron beam lithography on Si wafers. We can see a dipole antenna (left), an asymmetric spiral antenna (center), and a patch antenna on a moving bridge (right). The physical mechanism for the transducer is a microbolometer for the left and righ antennas, and a MOM diode for the central one.

* **V**an Hulst, and et. al, “Antennas for light,” Nat Photon, 2011.

WaveGuide Fed Patch Antenna



Advantages:

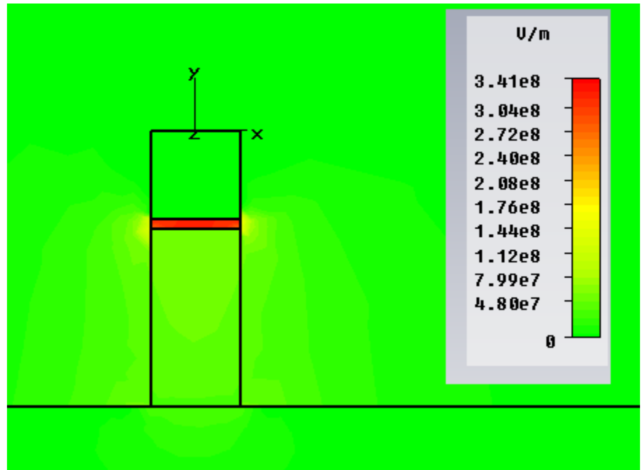
1) The antenna is matched, and therefore can be fed, with a hybrid plasmonic waveguide.

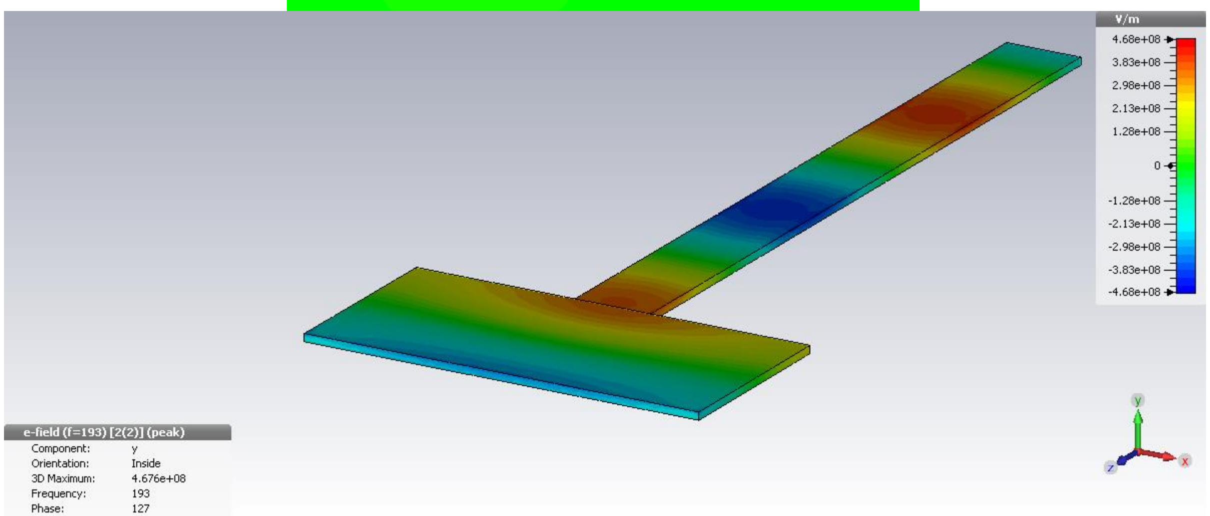
2) The antenna design, is CMOS compatible, and therefore can be integrated with other elements in an opto-electronic circuit.

***Yousefi, et al, Optics Express, No. 16, 2012.**

JOHNS HOPKINS UNIVERSITY

Waveguide Fed Patch Antenna: Field Distribution





***Yousefi, et al, Optics Express, No. 16, 2012.**

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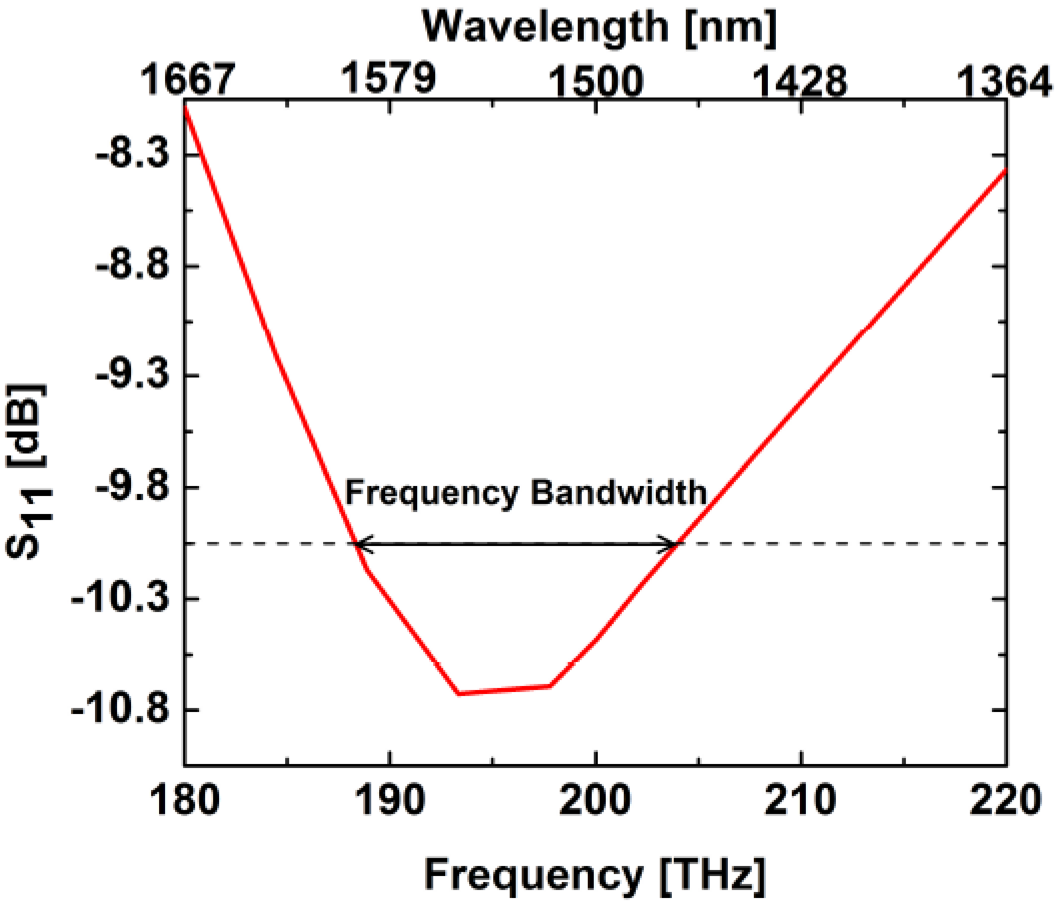
Waveguide Fed Patch Antenna: Characteristics

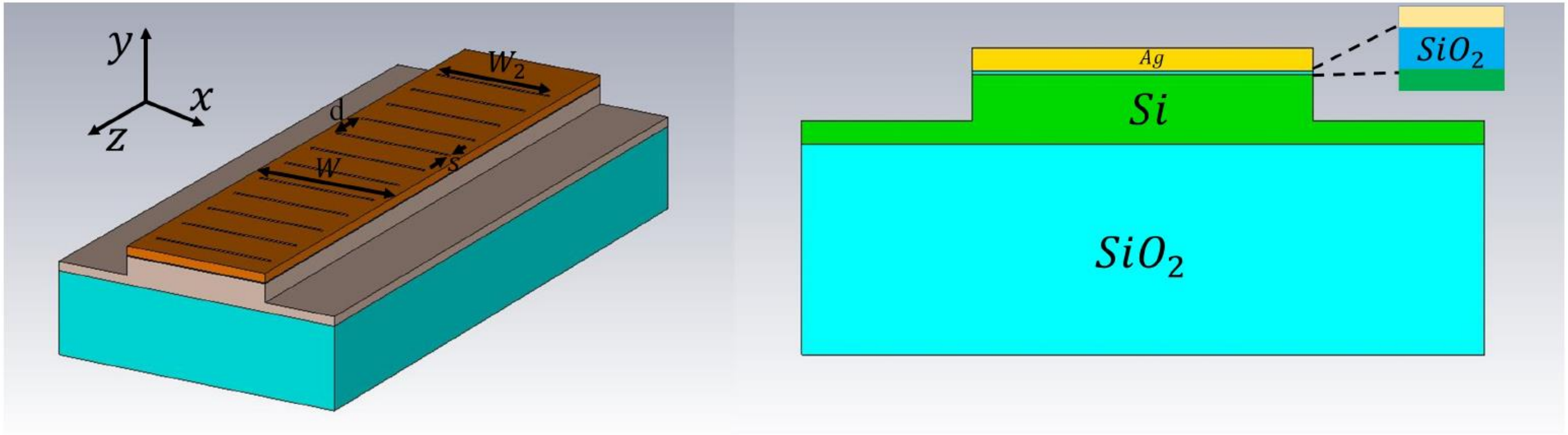


The bandwidth is 15.6 THz, or 8% corresponding to the wavelengths of 1463 nm-1580 nm, covering all the standard optical communication bands of S and C.

***Yousefi, et al, Optics Express, No. 16, 2012.**

Johns Hopkins University

Increasing directivity by designing leaky wave nano-antennas



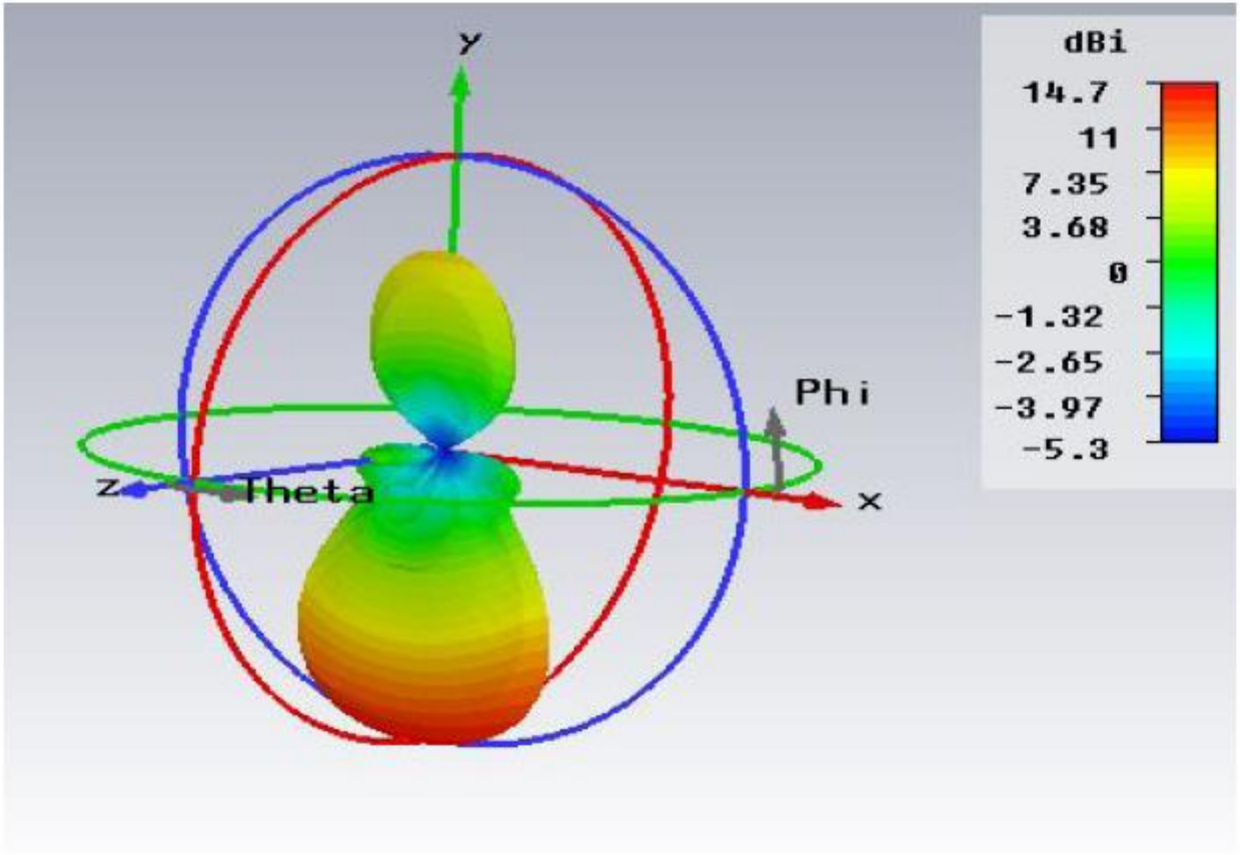
$$E_y = \sum_{n=-\infty}^{\infty} E_{y,n} e^{-jK_{z,n} z}, K_{z,n} = j\alpha + \beta_{z,0} + 2n\frac{\pi}{d}$$

$$|real\left(K_{z,-1}\right)| < \beta_0, \left|n_{eff} - \frac{2\pi}{d}\right| < \beta_0$$

*** Yousefi, Progress in Electromagnetic Research Letters, 2014.**

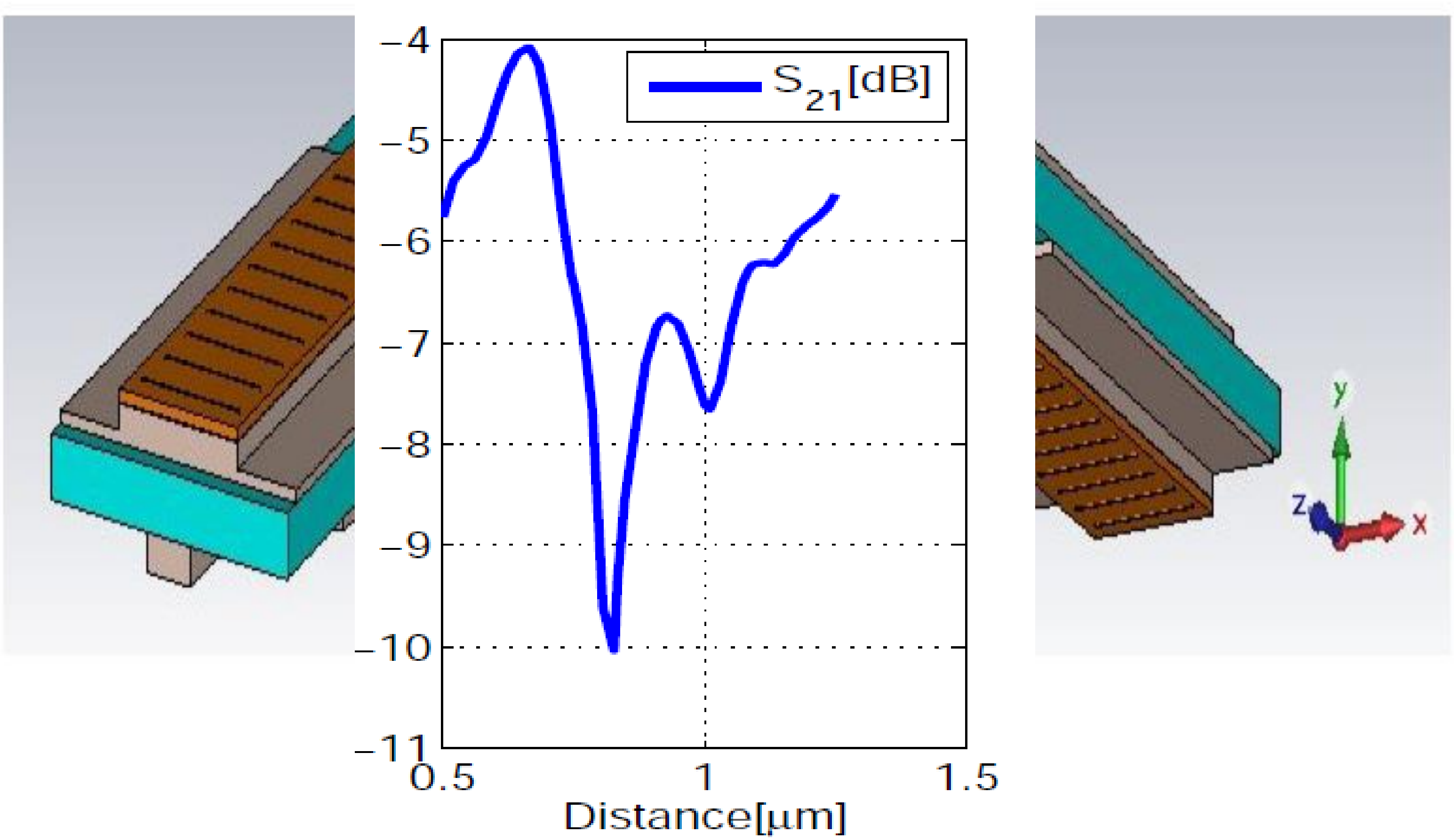
Johns Hopkins University

Increasing directivity by designing leaky wave nano-antennas



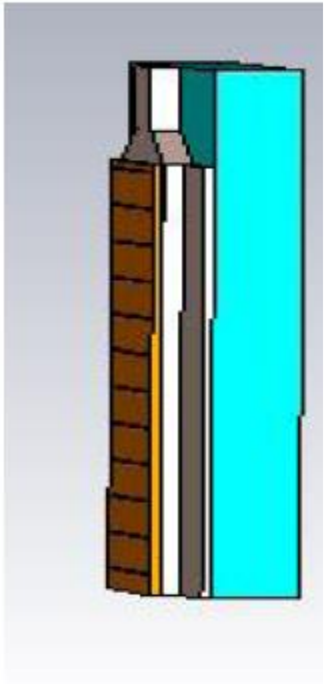
* **Yousefi, Progress in Electromagnetic Research Letters, 2014.**

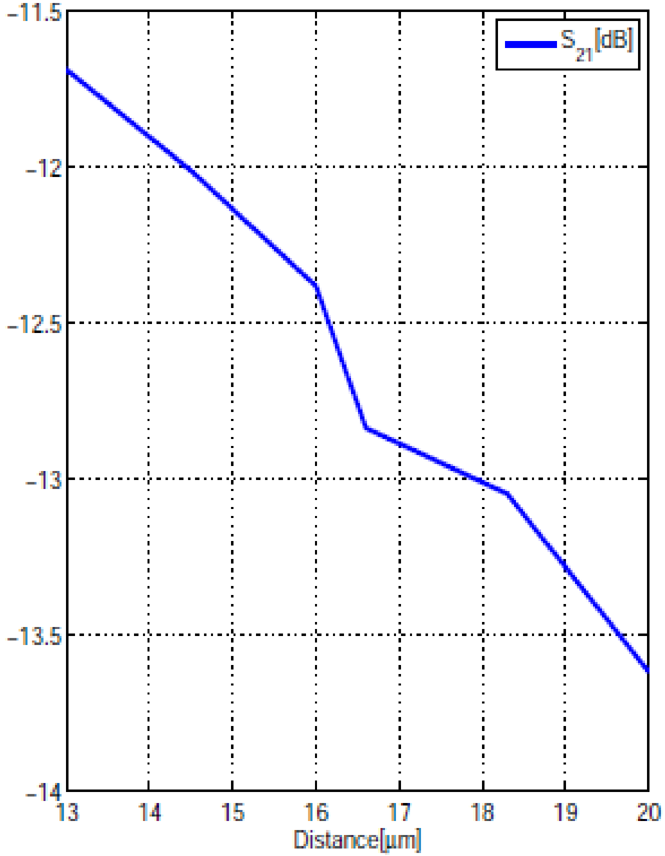
Inter- and Intra-chip Optical Link Using a Hybrid Plasmonic Leaky Wave Nano-antenna

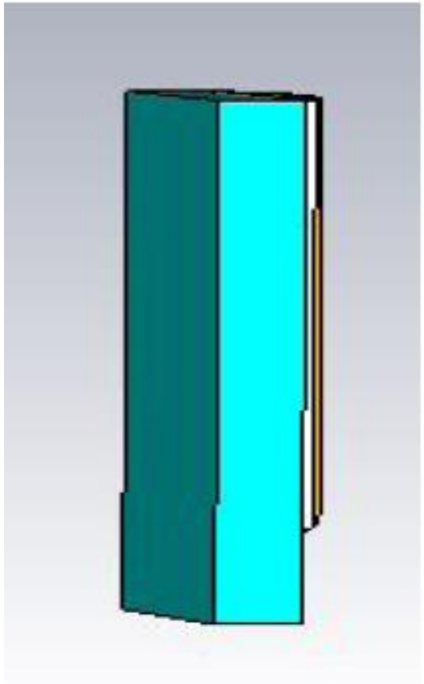


*Ebrahimi, Yousefi, Optics Communications, 2017.

Inter- and Intra-chip Optical Link Using a Hybrid Plasmonic Leaky Wave Nano-antenna

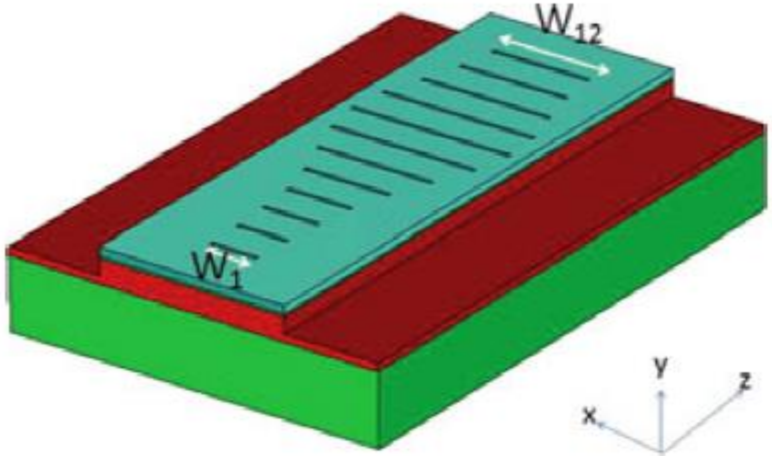






*Ebrahimi, Yousefi, Optics Communications, 2017.

Controlling Side Lobe in leaky Wave Plasmonic Antennas



$$P(z) = |B|^2 e^{[-2\int_0^z \alpha(\zeta)d\zeta]}$$

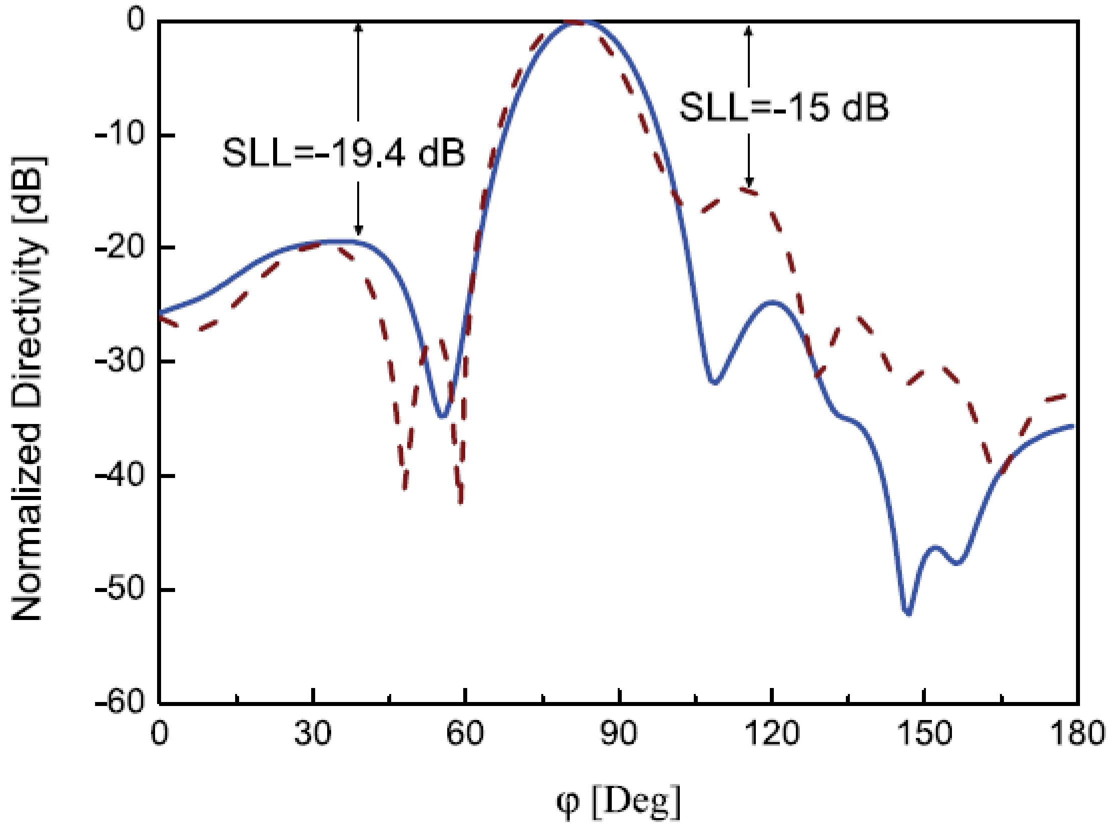
$$\frac{1}{P(z)}\frac{dP(z)}{dz} = -2\alpha(z).$$

$$P(z) = P_{IN} - \int_0^z |A(\zeta)|^2 d\zeta - \text{LOSS}(z).$$

$$\text{LOSS}(z) = \left[\frac{MTL}{MTR}\int_0^L |A(\zeta)|^2 d\zeta\right]\frac{z}{L}$$

*Panahi, Yousefi, et al, *Journal of Lightwave Technology*, 2015.

Controlling Side Lobe in leaky Wave Plasmonic Antennas



***Panahi, Yousefi, et al, *Journal of Lightwave Technology*, 2015.**

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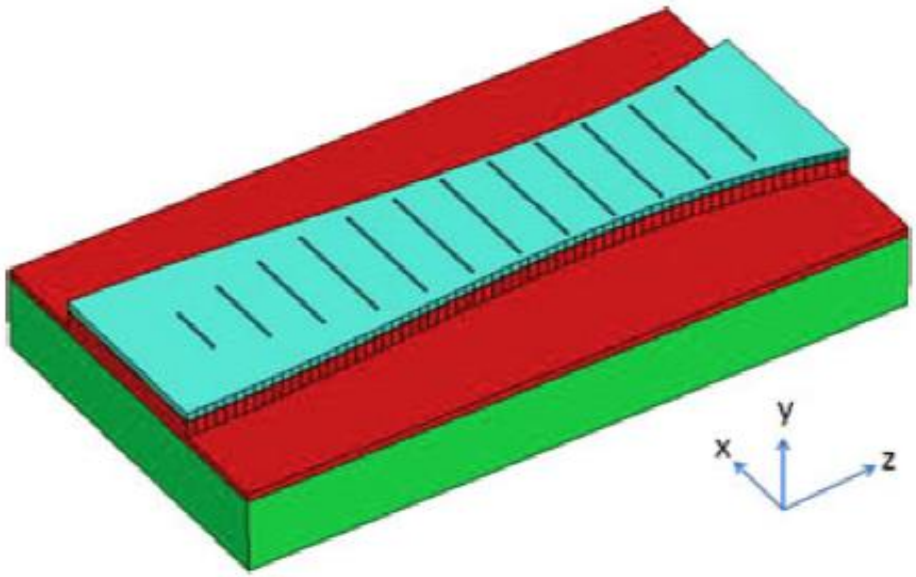
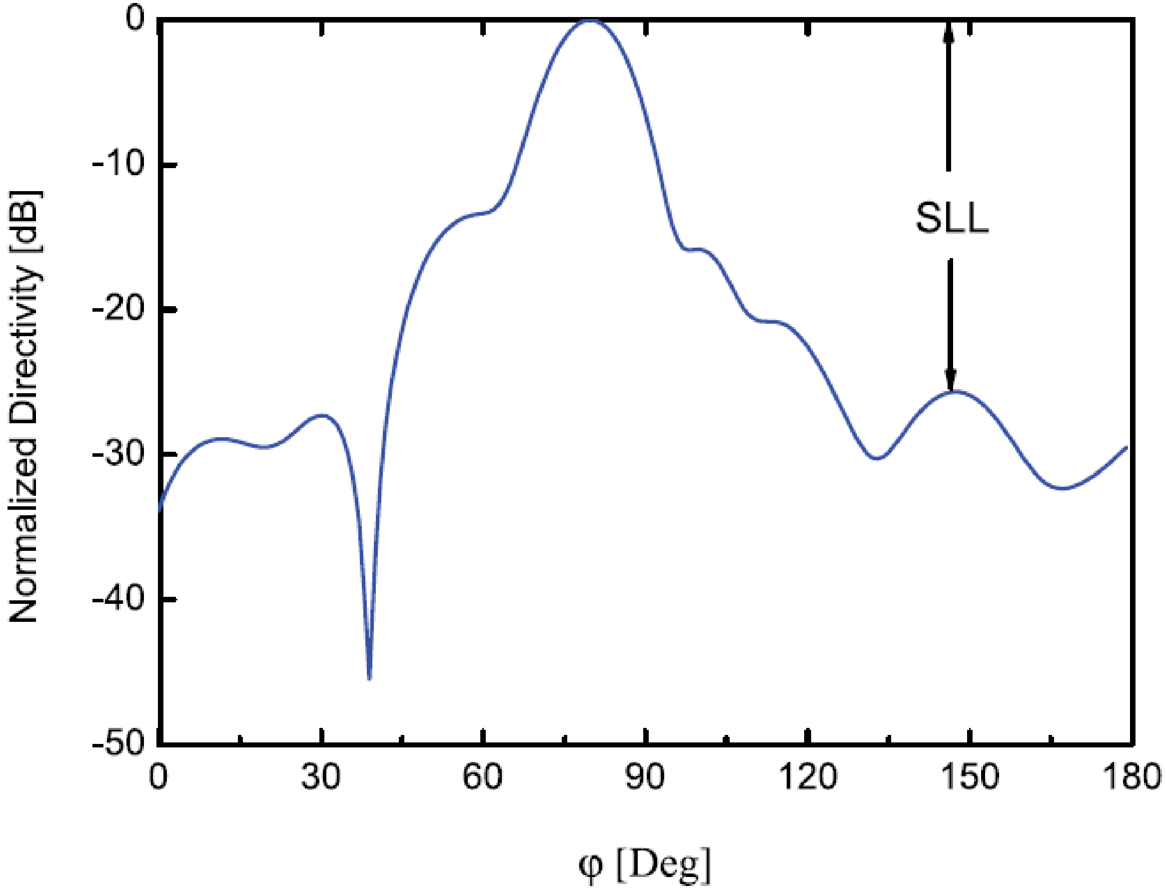


Fig. 13. Optical antenna designed with wall tapering.

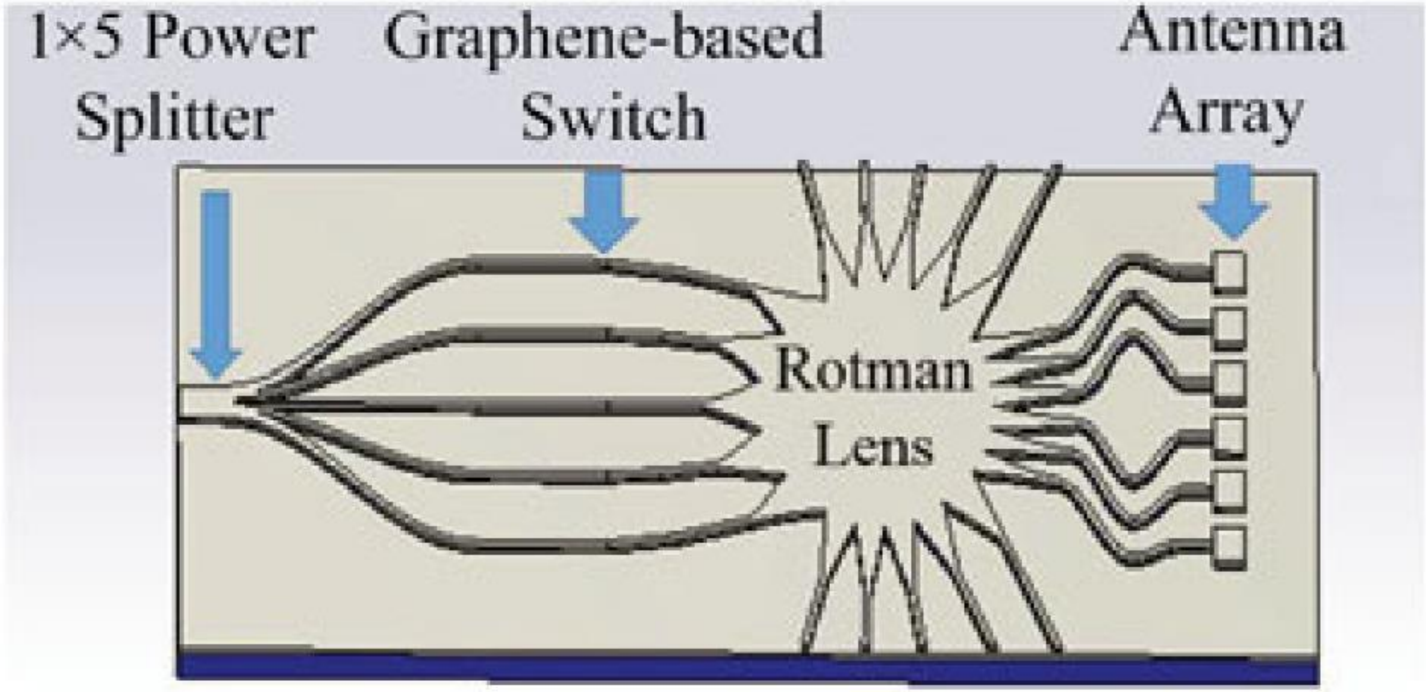
*Panahi, Yousefi, et al, *Journal of Lightwave Technology*, 2015.

Controlling Side Lobe in leaky Wave Plasmonic Antennas



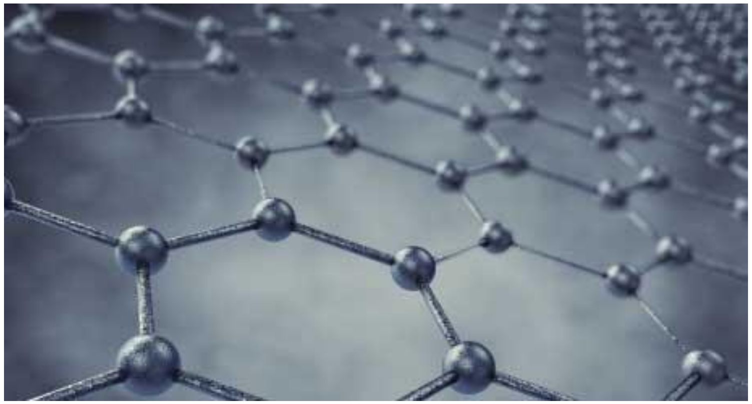
*Panahi, Yousefi, et al, *Journal of Lightwave Technology*, 2015.

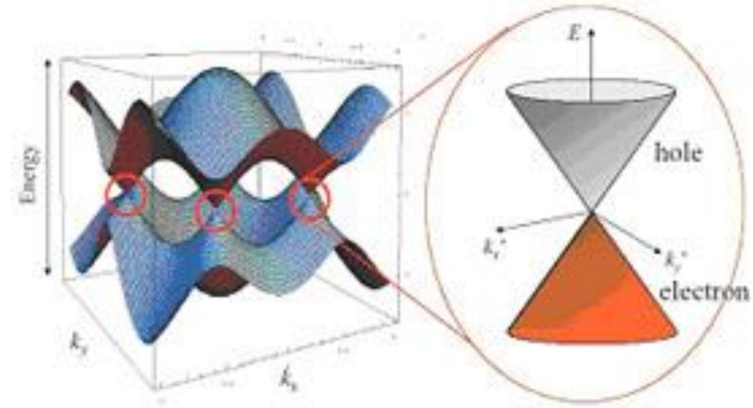
Integrated Optical Phased Array Nano-Antenna System Using a Plasmonic Rotman Lens



* Ashrafi, Yousefi, et al, *Journal of Lightwave Technology,* 2016.

Introduction to Graphene





- Graphene is one of the crystalline forms of carbon in which, carbon atoms are arranged in a regular hexagonal pattern.
- The electrons in graphene behave like massless Dirac-Fermions, which results ir the extraordinary properties, including supporting plasmonic waves at THz frequencies.
- In absence of magnetic field, graphene conductivity can be estimated by Kubo formula

$$\sigma(\omega,\mu_C,\gamma,T)=\frac{je^2(\omega-j2\gamma)}{\pi\hbar^2}\left\{\frac{1}{(\omega-j2\gamma)^2}\times\int_0^\infty\left(\frac{\partial f_D(\varepsilon)}{\partial\varepsilon}-\frac{\partial f_D(-\varepsilon)}{\partial\varepsilon}\right)d\varepsilon+\int_0^\infty\frac{f_D(\varepsilon)-f_D(-\varepsilon)}{(\omega-j2\gamma)^2-4(\varepsilon/\hbar)^2}d\varepsilon\right\}$$

*** A. Fallahi , et al, Physical Review B, 2012.**

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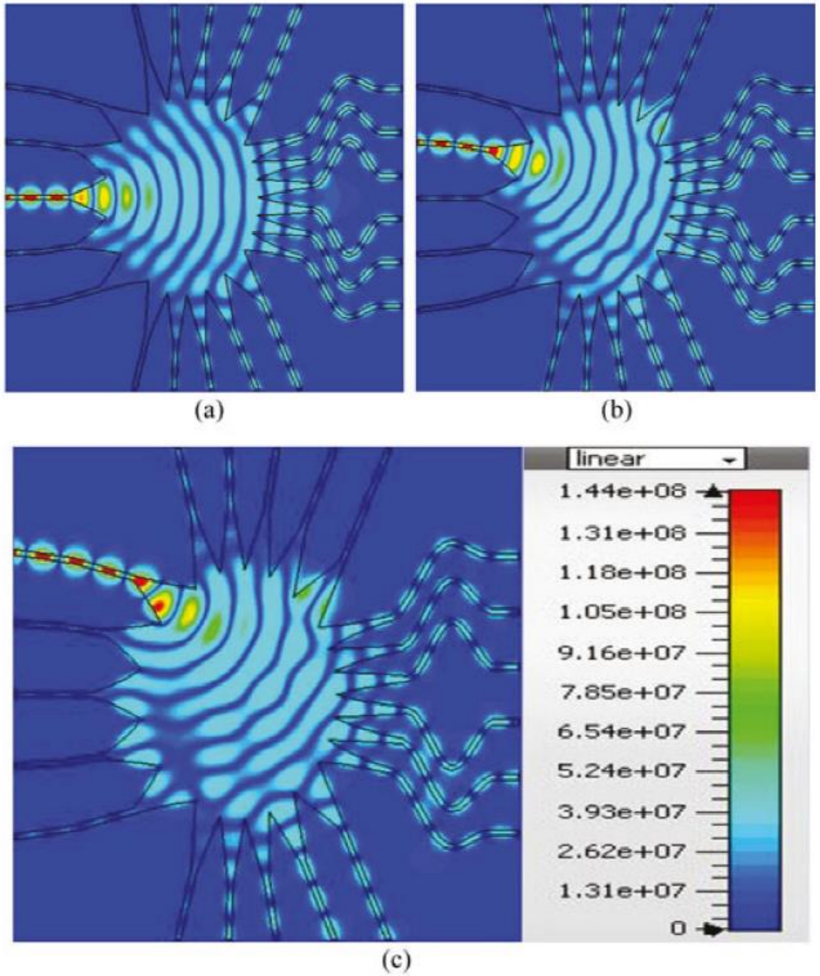
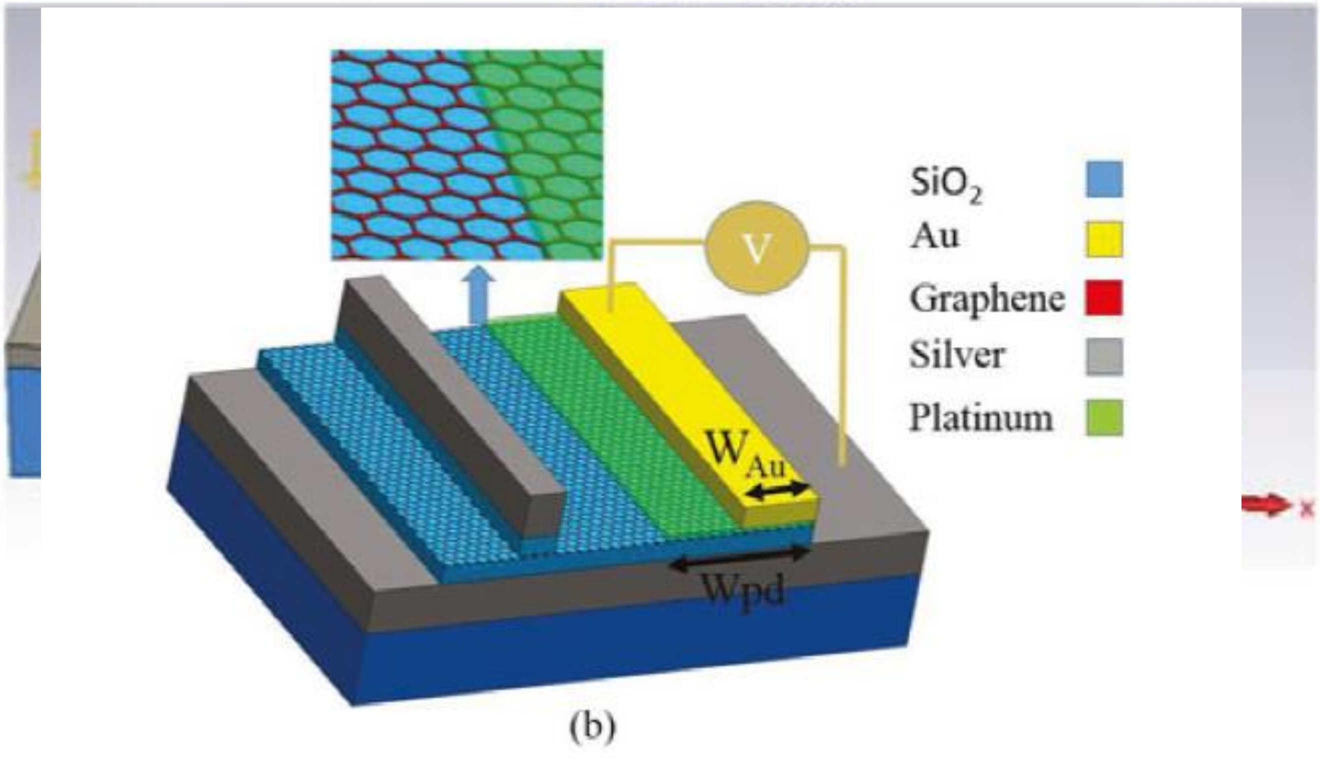


*** Ashrafi, Yousefi, et al, *Journal of Lightwave Technology,* 2016.**

Graphene based Switch



* Ashrafi, Yousefi, et al, *Journal of Lightwave Technology,* 2016.

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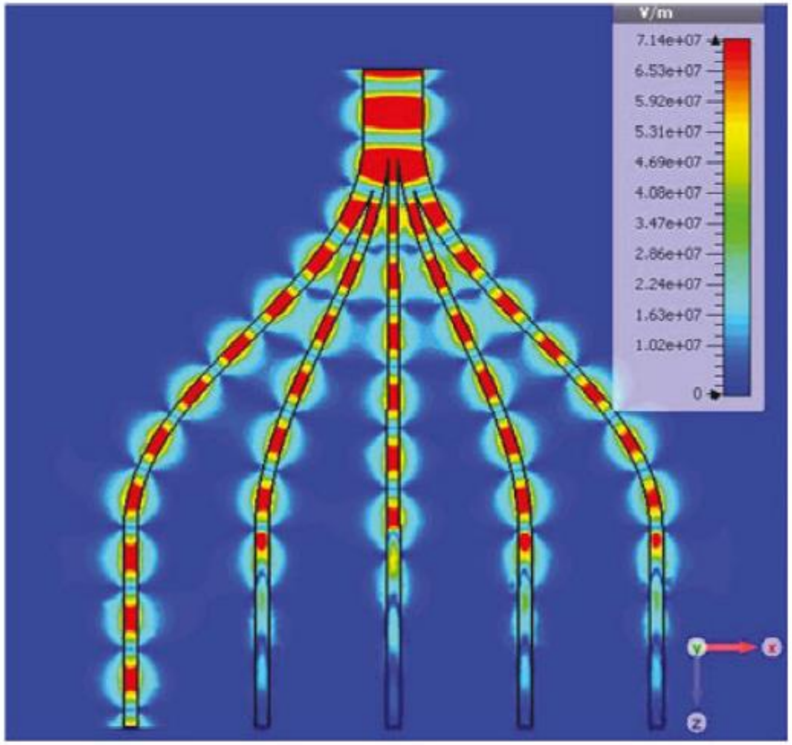
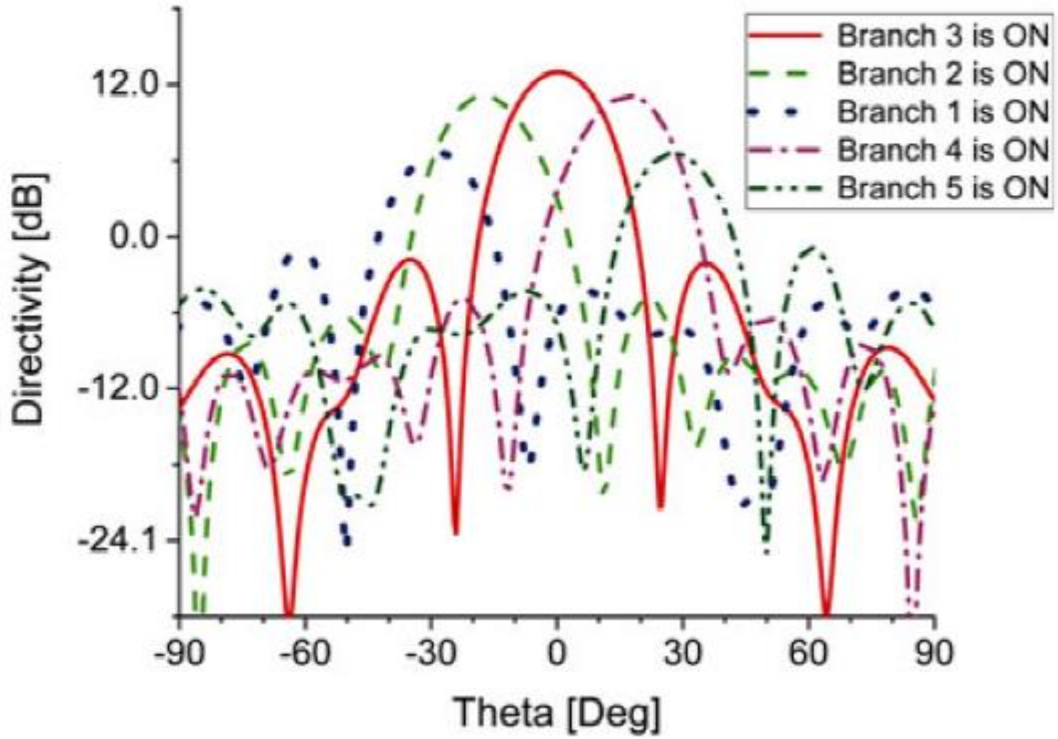


* Ashrafi, Yousefi, et al, *Journal of Lightwave Technology,* 2016.

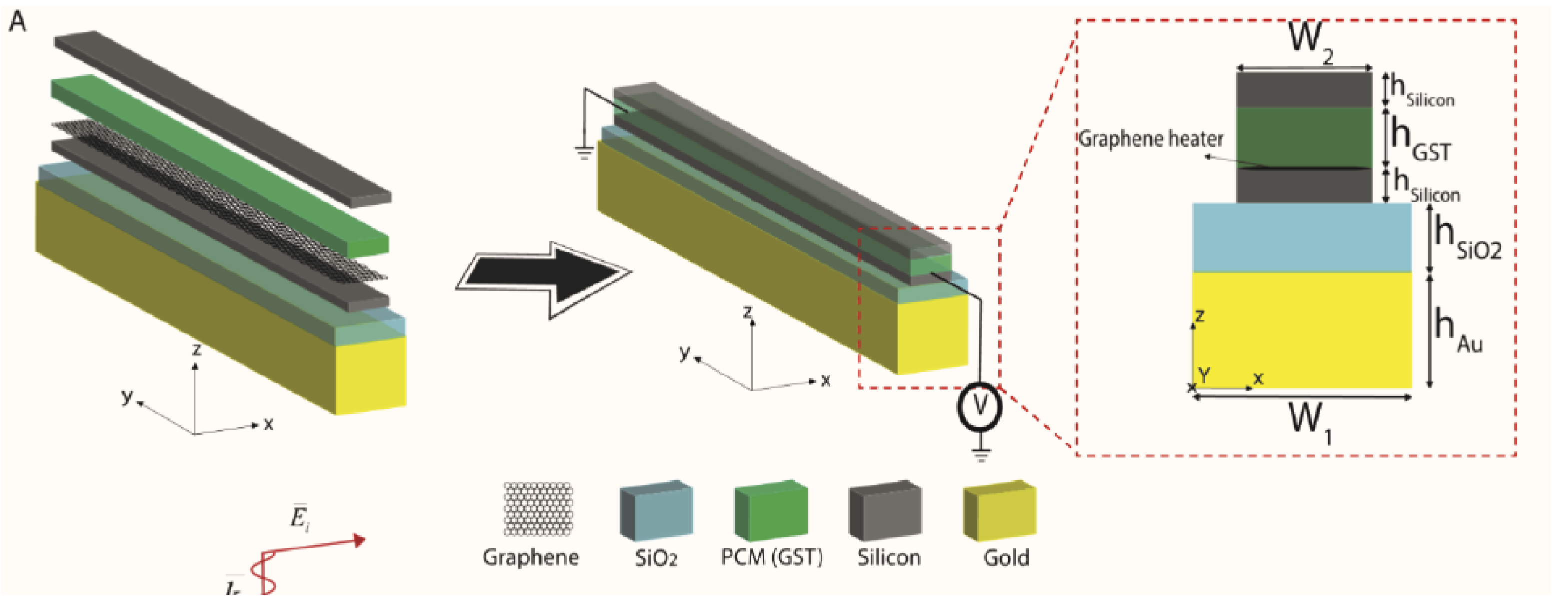
Integrated Optical Phased Array Nano-Antenna System Using a Plasmonic Rotman Lens



Active branch	Main lobe angle (deg)	Directivity (dB)
1	−29	6
2	−15	10.8
3	0	12.1
4	+15	10.8
5	+29	6

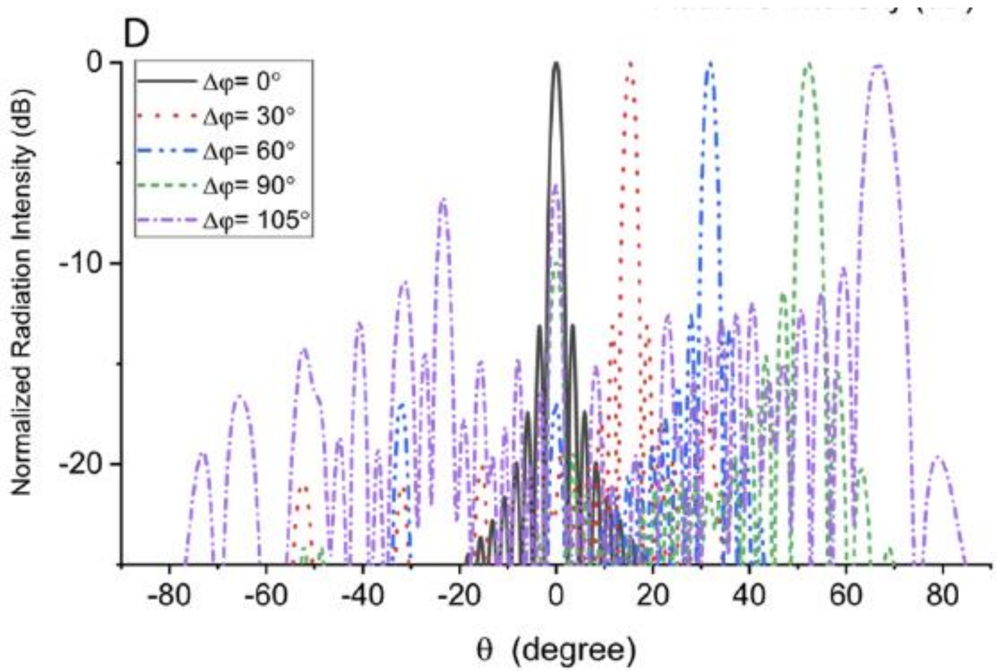
* **Ashrafi, Yousefi, et al, *Journal of Lightwave Technology,* 2016.**

Optical Beam Steering using Tunable Metasurfaces



* **Abed, Yousefi, *Optics Express,* 2020.**

Optical Beam Steering using Tunable Metasurfaces



* **Abed, Yousefi, *Optics Express,* 2020.**

Optical Switches based on Hypebolic Metamaterials

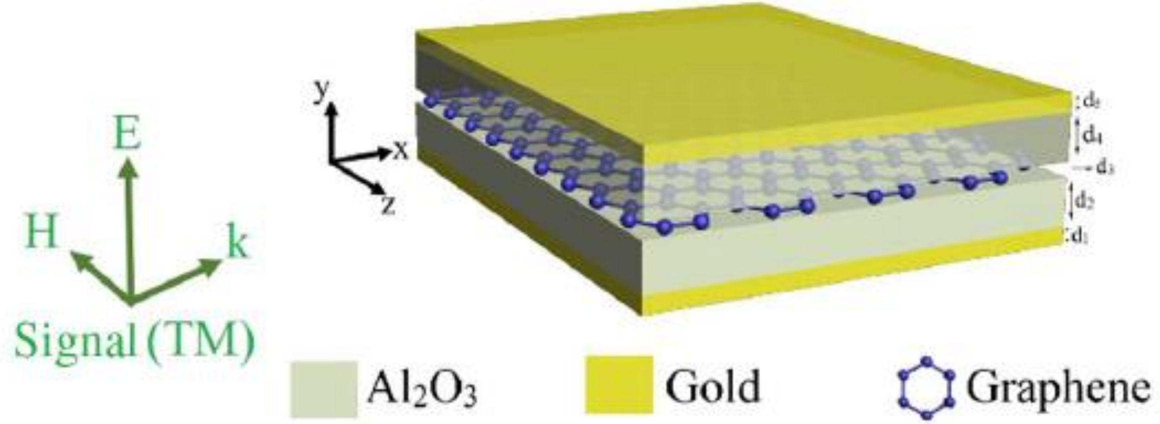


Fig. 1. Unit cell of a HMM that is periodic in the y-direction.

*** Moravvej-Farshi, Yousefi, and etc, APPLIED OPTICS, 2015.**

Optical Switches based on HMM Struc

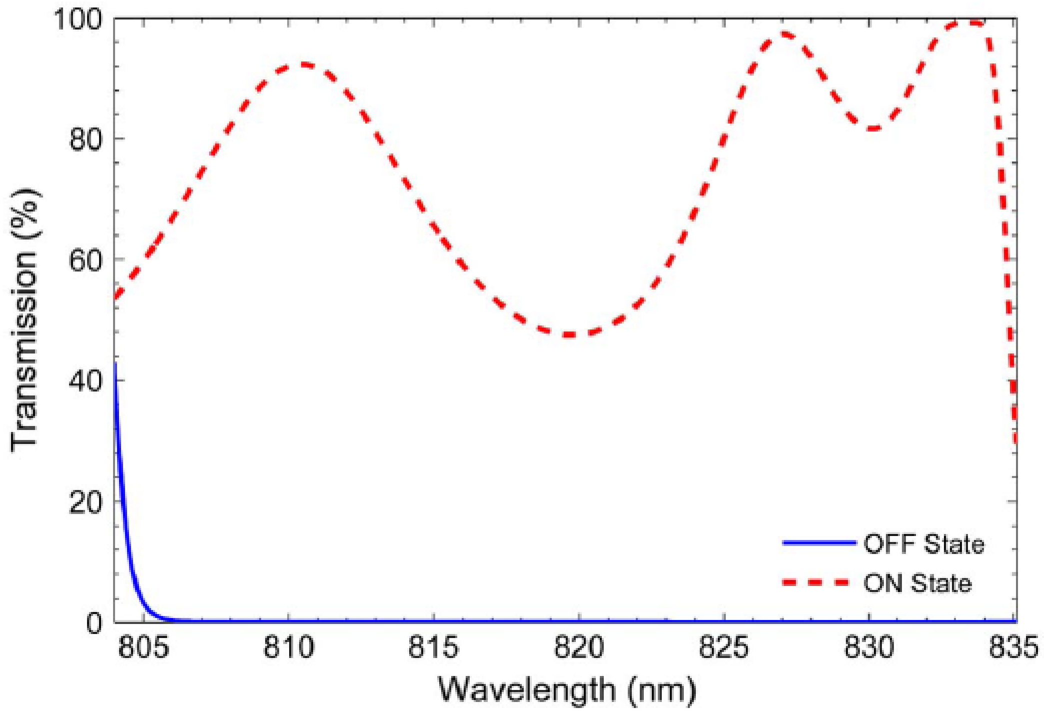
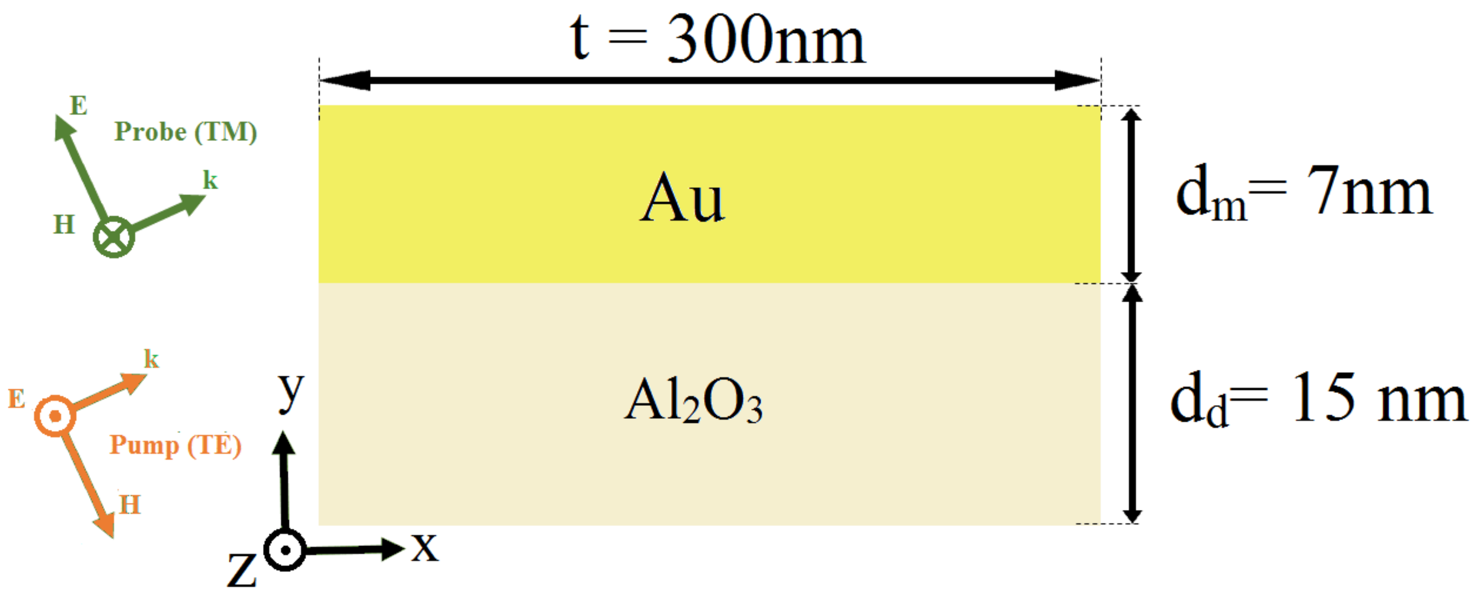


Fig. 9. Transmission spectra for the switchable HMM medium with 7-nm Cu and 10-nm Si in OFF ($\mu_C = 1$ eV) and ON ($\mu_C = 0.96$) states.

*** Moravvej-Farshi, Yousefi, and etc, APPLIED OPTICS, 2015.**

All Optical Switching by HMM Structure

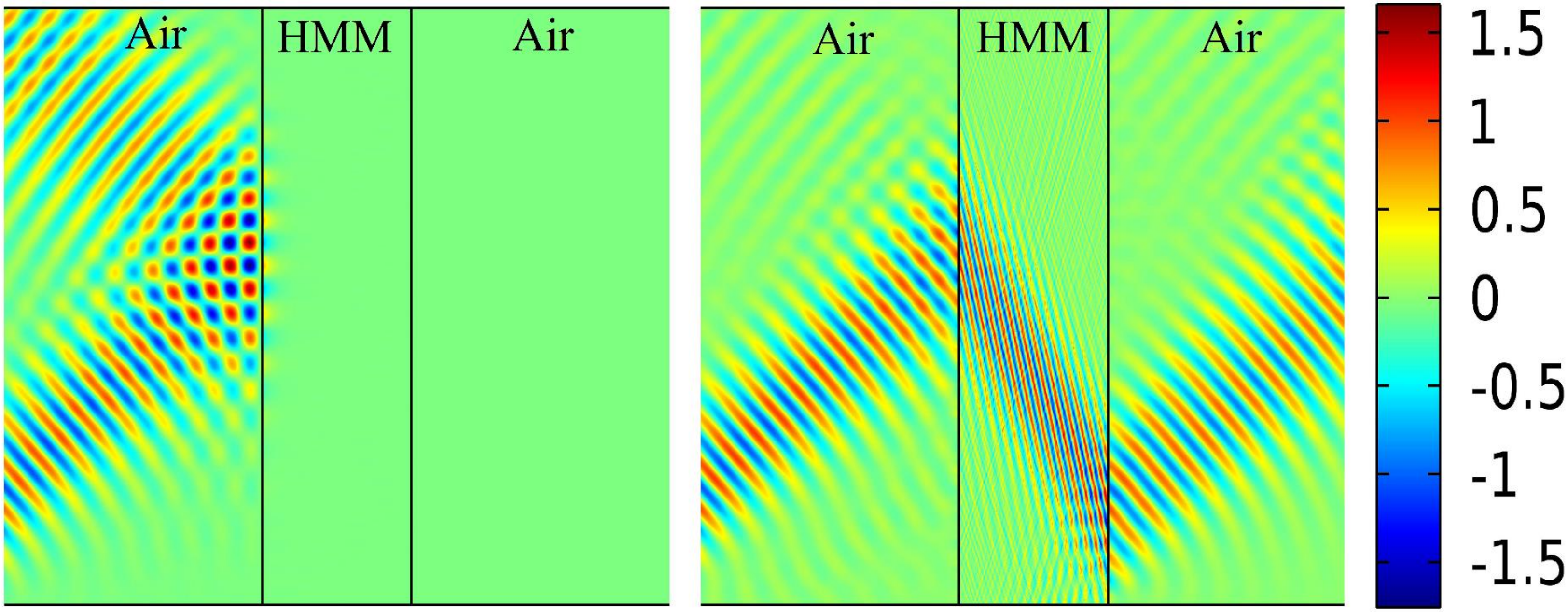
- Unit cell of the proposed HMM structure



$$\varepsilon_{\parallel} = \frac{\varepsilon_d d_d + \varepsilon_m d_d}{d_m + d_d}, \qquad \varepsilon_{\perp} = \left(\frac{\varepsilon_m^{-1} d_m + \varepsilon_d^{-1} d_d}{d_m + d_d} \right)^{-1}$$

*** Moravvej-Farshi, Yousefi, and etc, JOSA B, 2015.**

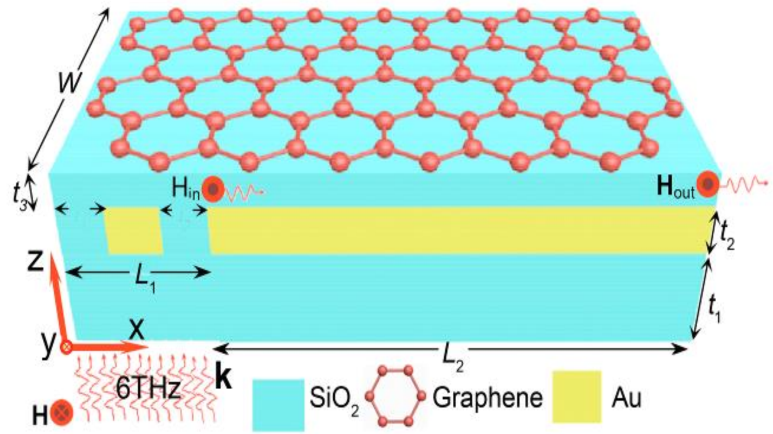
Numerical Results and Discussion



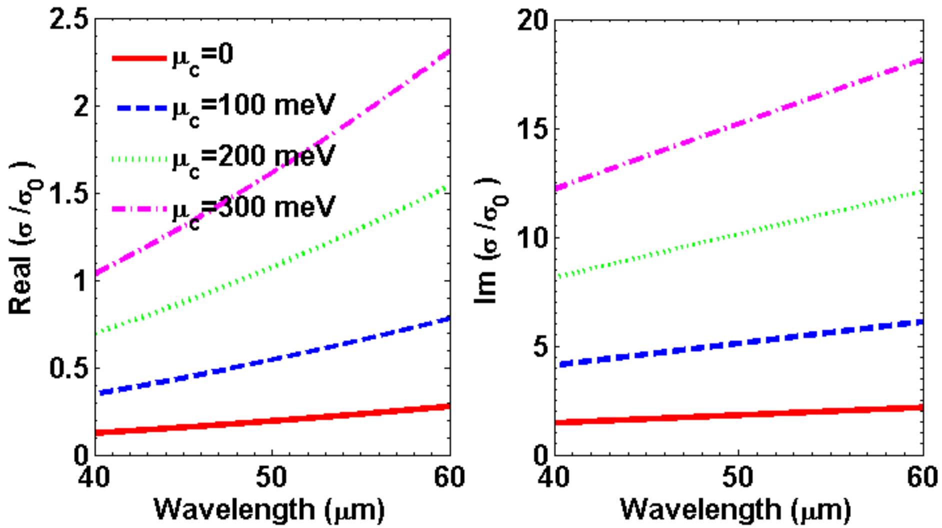
without the pump signal (OFF state) with pump signal (ON state)

*** Moravvej-Farshi, Yousefi, and etc, JOSA B, 2015.**

Subwavelength Graphene-Based Plasmonic THz Integrated Devices

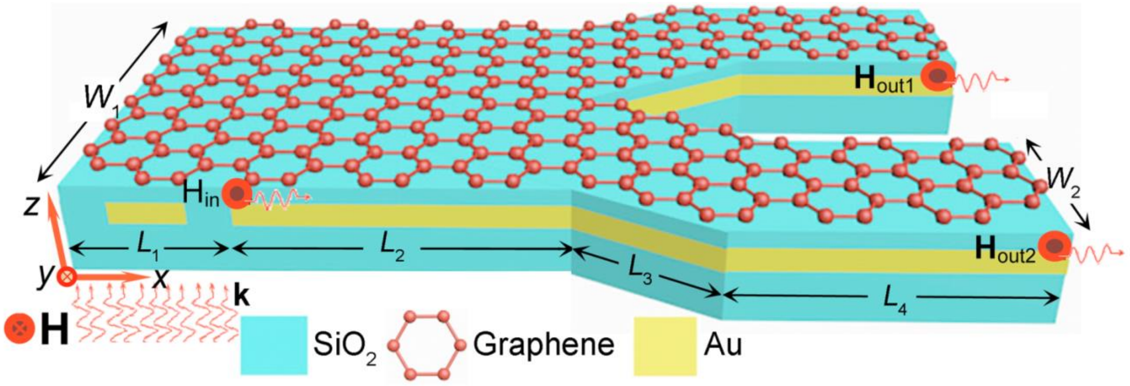


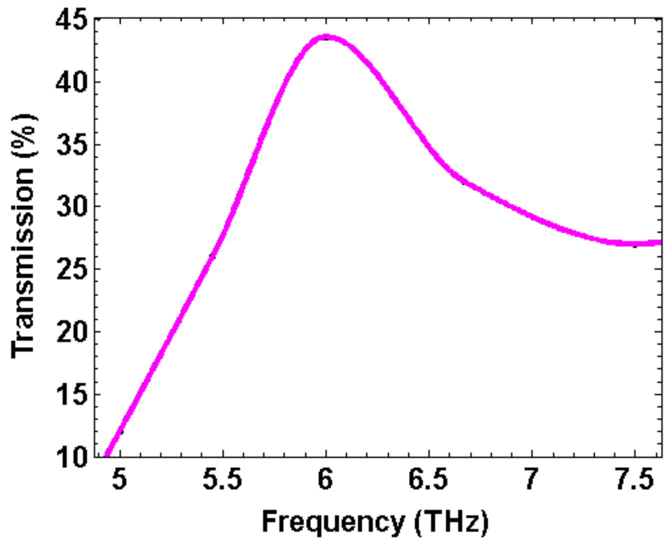
Structure Layout

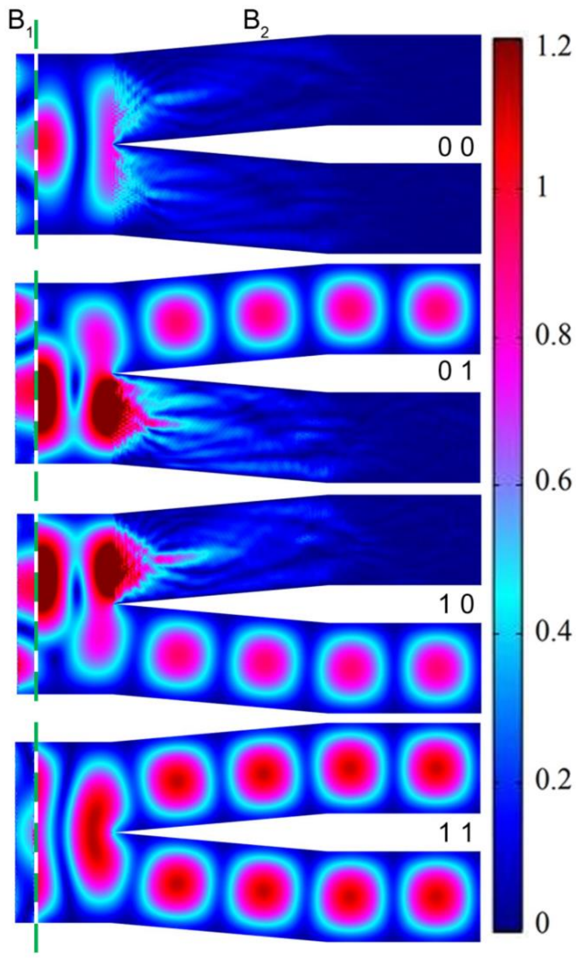


* Yarahmadi, Moravej, Yousefi, IEEE Transactions on THz Technology, 2015.

Subwavelength Graphene-Based Plasmonic THz Y-Branch Switch

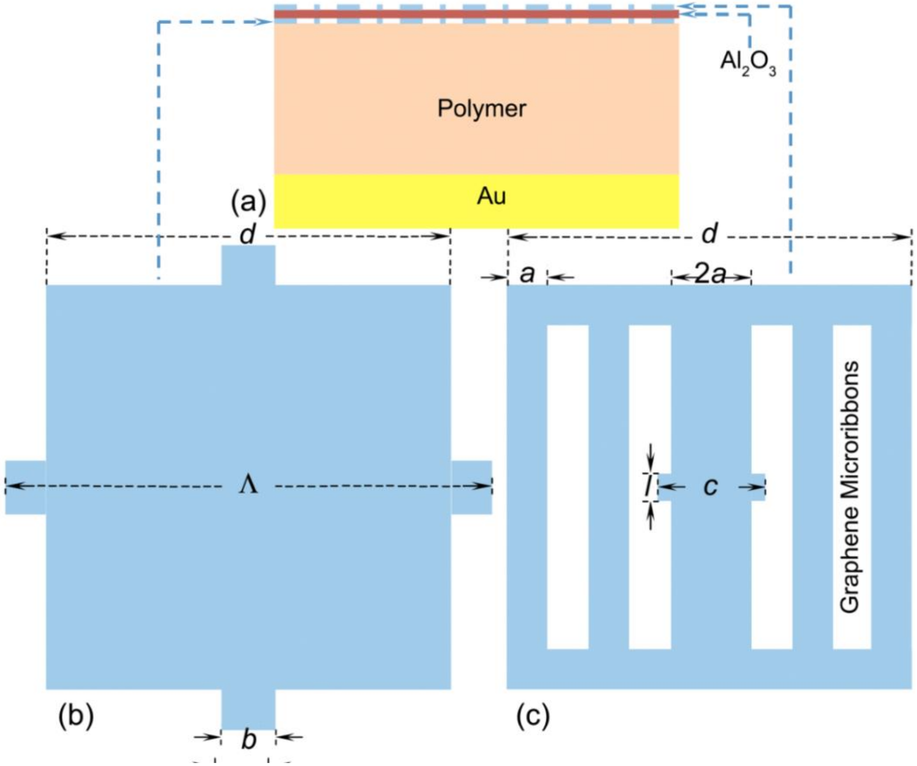






* Yarahmadi, Moravej, Yousefi, IEEE Transactions on THz Technology, 2015.

Tunable THz Perfect Absorber Using Graphene-Based Metamaterials



Structure Dimensions:

Λ=15 μm

a = 0.5 μm

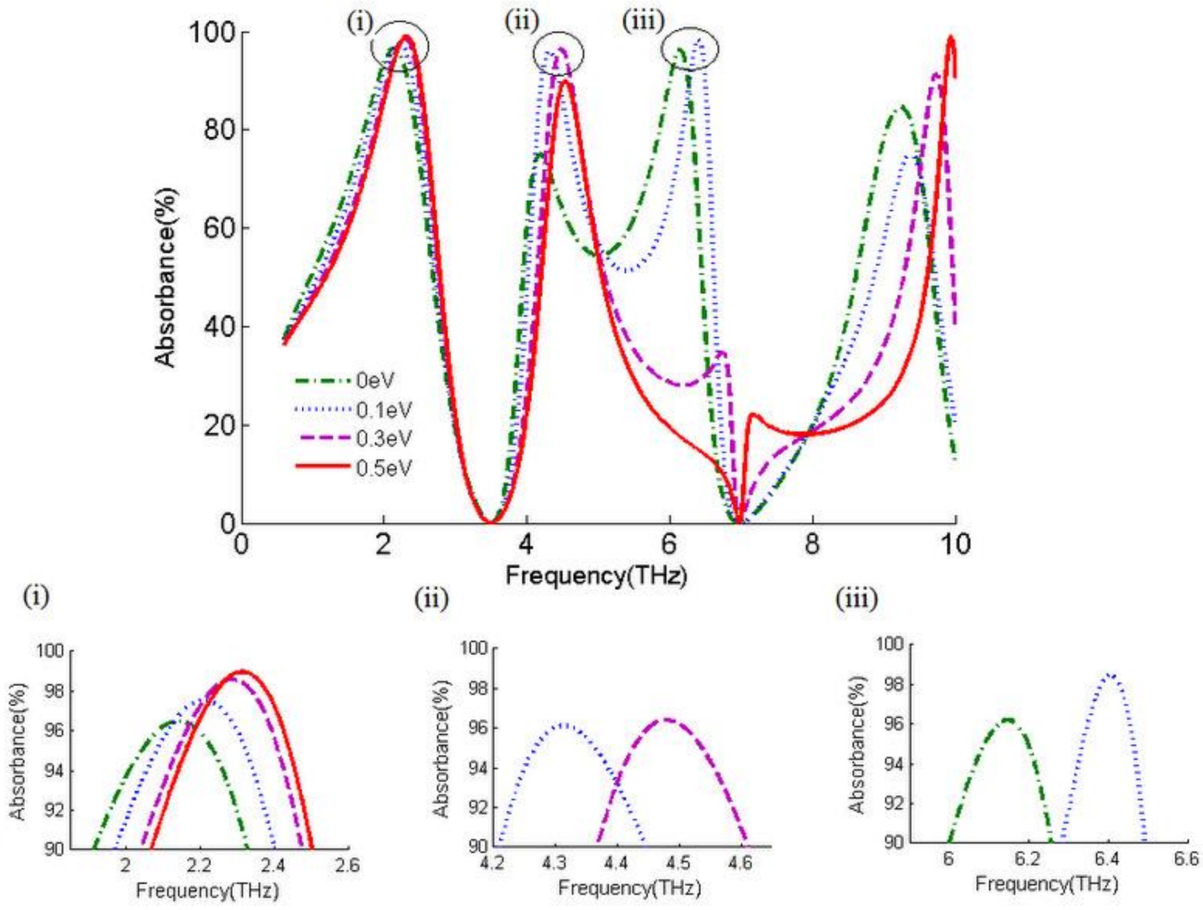
b = 2 μm

c= 2 μm

d= 12 μm

*** Faraji, Moravej, Yousefi, Optics Communications, 2015.**

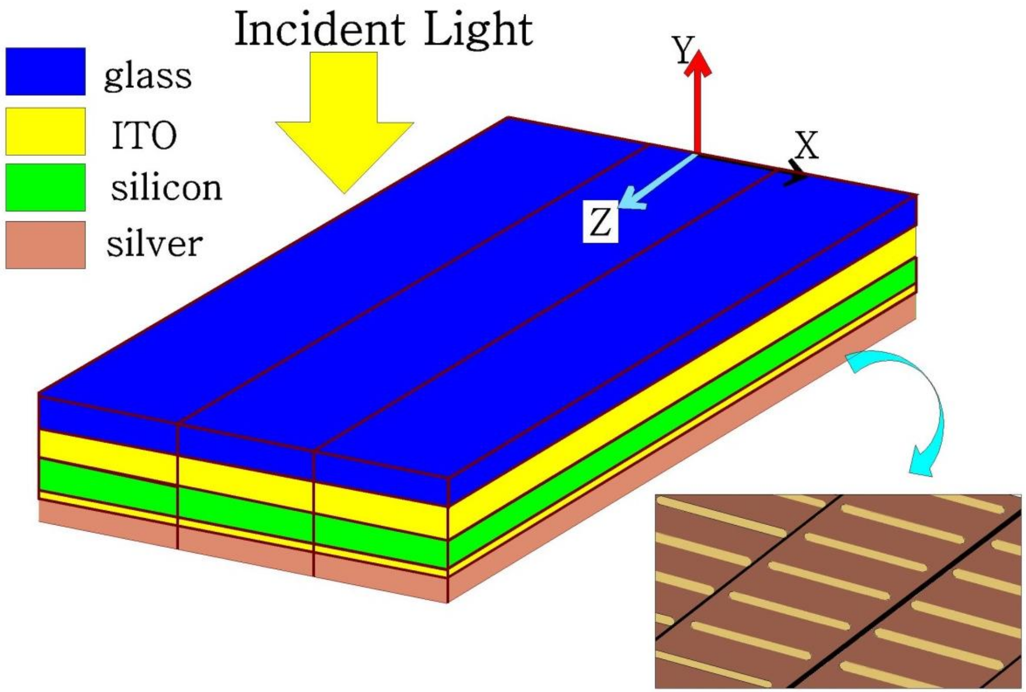
Tunable THz Perfect Absorber Using Graphene-Based Metamaterials

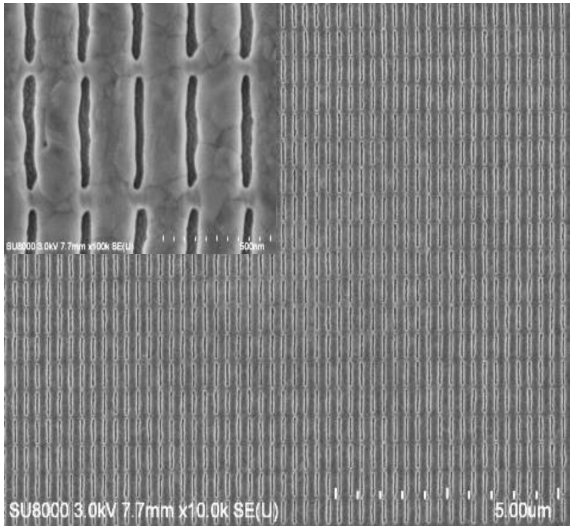


*** Faraji, Moravej, Yousefi, Optics Communications, 2015.**

Efficiency-Enhanced Ultra-Thin Solar Cells using Nano-Structures and Metasurfaces

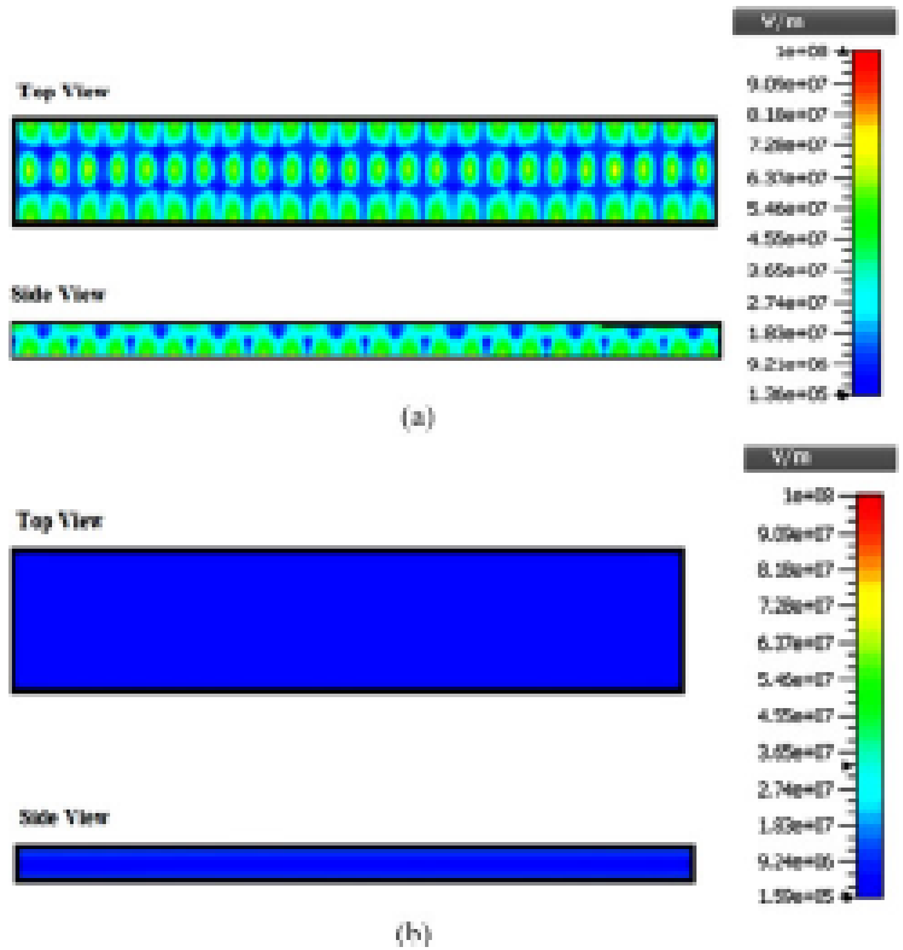
Enhanced Thin Solar Cells Using Optical Nano-Antenna Induced Hybrid Plasmonic Travelling-Wave





*Taghian, Ahmadi, Yousefi, *Journal of Lightwave Technology,* 2016.

Enhanced Thin Solar Cells Using Optical Nano-Antenna Induced Hybrid Plasmonic Travelling-Wave



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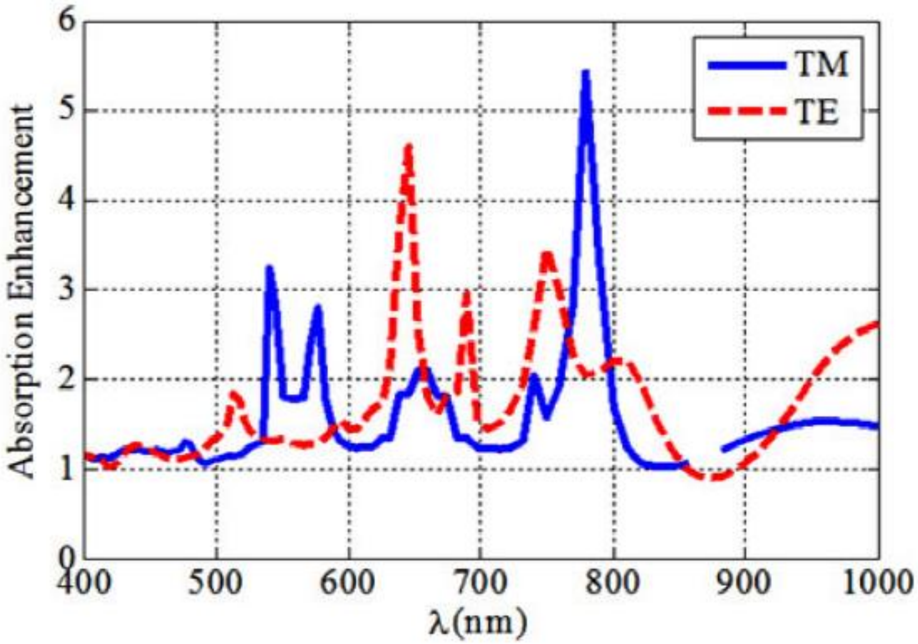
Enhanced Thin Solar Cells Using Optical Nano-Antenna Induced Hybrid Plasmonic Travelling-Wave



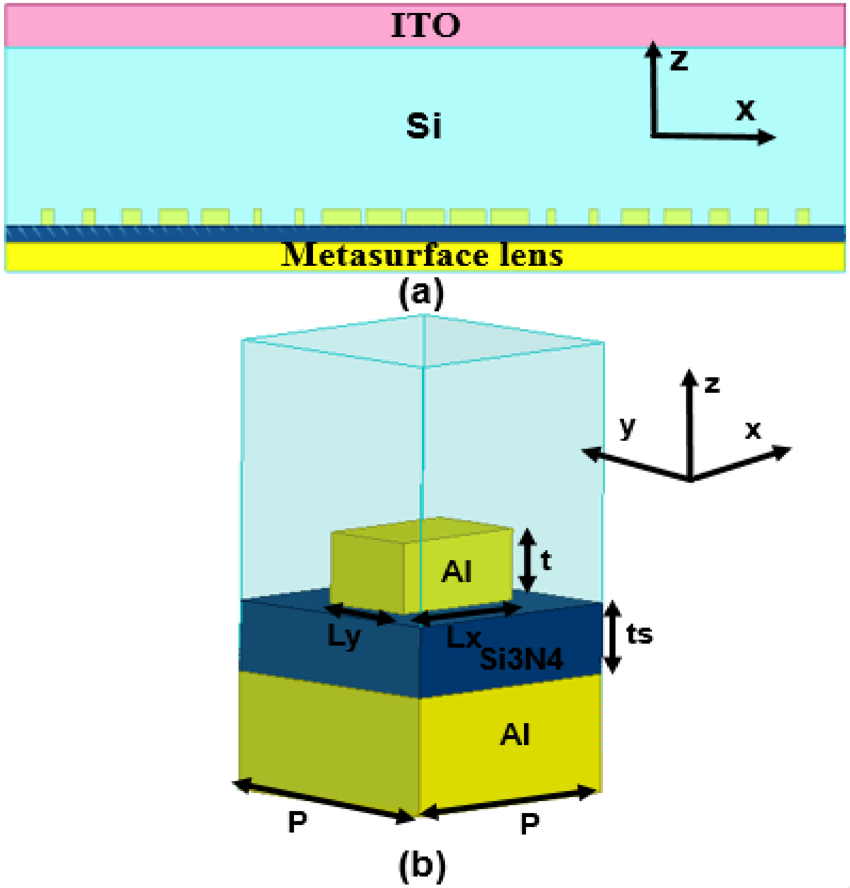
$$A(\lambda) = \omega \mathrm{Im}(\varepsilon(\omega)) \int_v |E|^2 dv$$

Fig. 9. Absorbance enhancement in the active layer of thin film solar cell for TM and TE light polarization.

The short circuit current is numerically calculated, and the results show that it is increased for both TM and TE polarizations by a factor of 1.4 and 1.3, respectively.

***Taghian, Ahmadi, Yousefi, *Journal of Lightwave Technology,* 2016.**

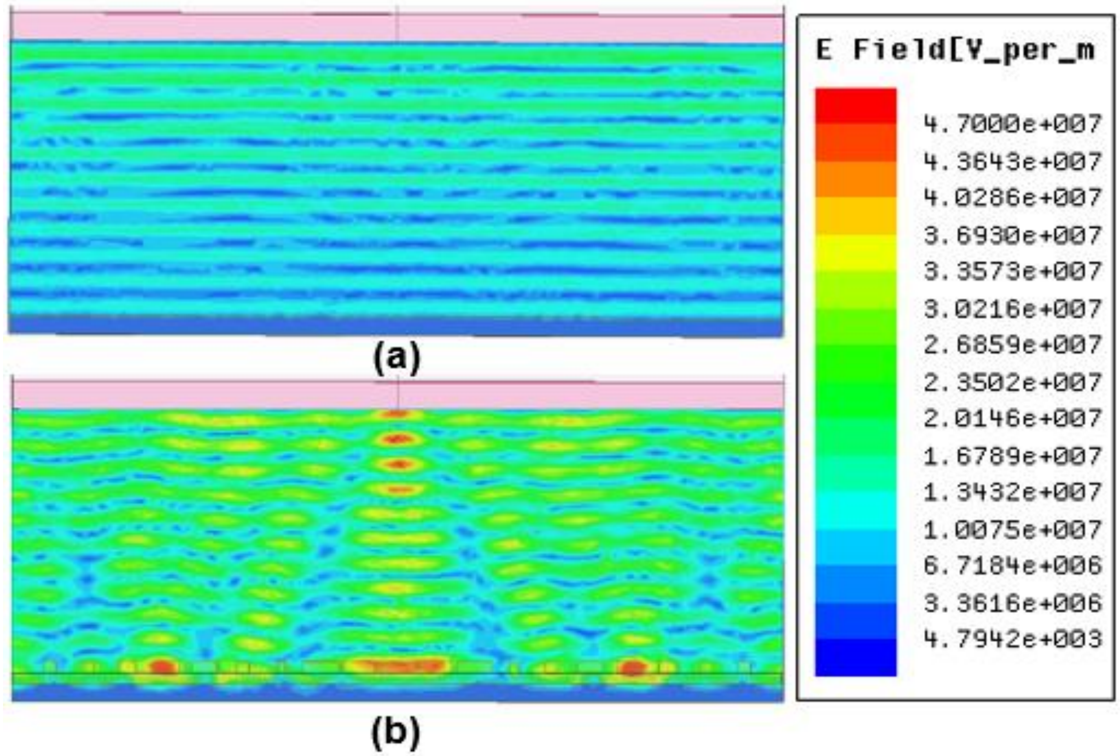
Absorption Enhancement in Thin-Film Solar Cells using an Integrated Metasurface Lens



$$\sin\theta_r - \sin\theta_i = \frac{\lambda}{2\pi n_i}\frac{d\Phi(x)}{dx}$$

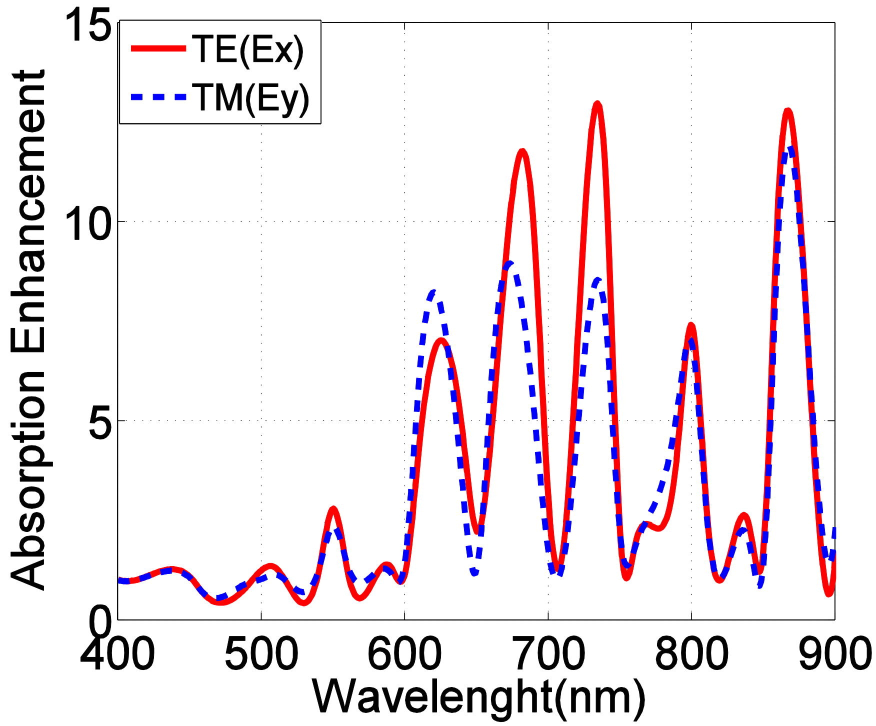
*Shameli, Yousefi, Journal of Optical Society of America B, *2018.*

Absorption Enhancement in Thin-Film Solar Cells using an Integrated Metasurface Lens



Shameli, Yousefi, Journal of Optical Society of America B*, 2018.

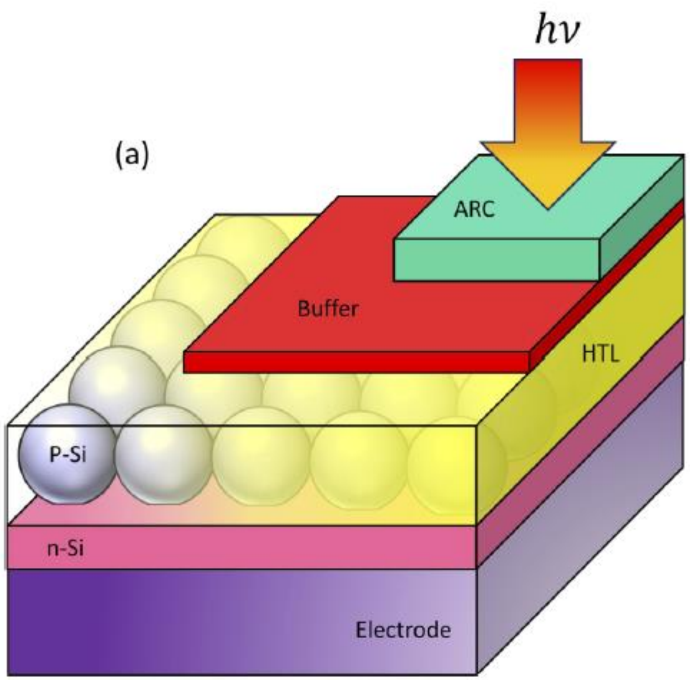
Absorption Enhancement in Thin-Film Solar Cells using an Integrated Metasurface Lens

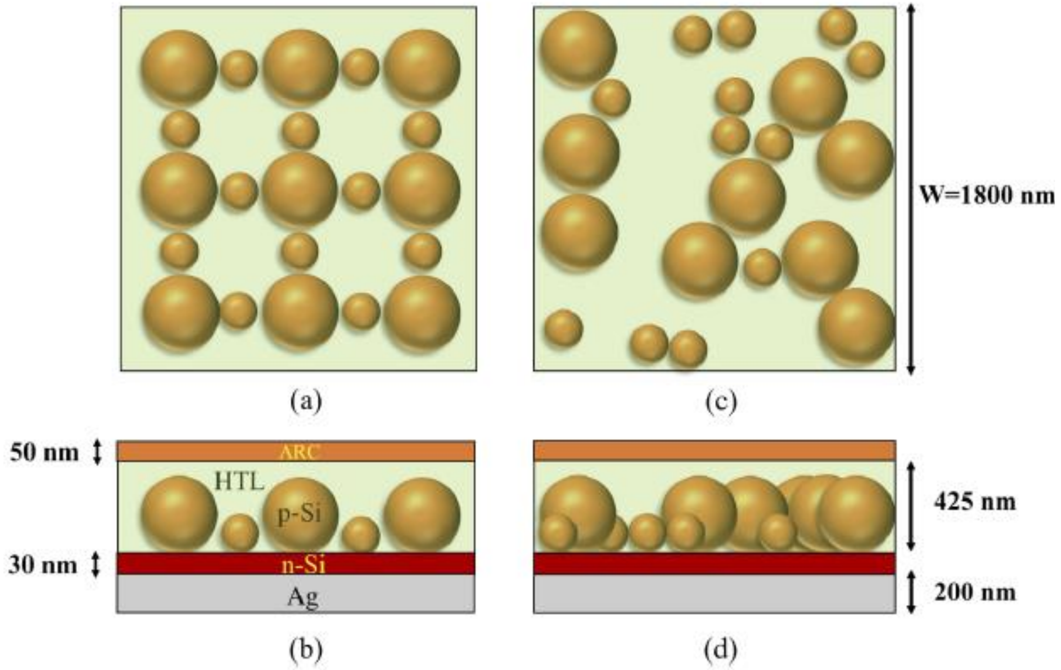


The short circuit current is numerically calculated, and the results show that it is increased for by a 47%.

Shameli, Yousefi, Journal of Optical Society of America B*, 2018.

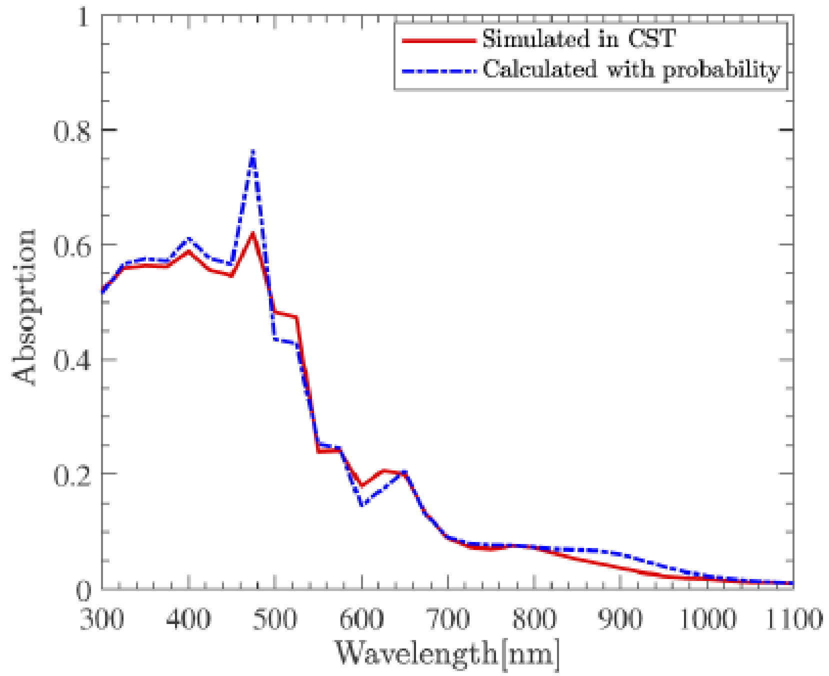
Distributed silicon nanoparticles: an efficient light trapping platform toward ultrathin-film photovoltaics





Shameli, Mirnaziry, Yousefi, Optics Express, *2021.*

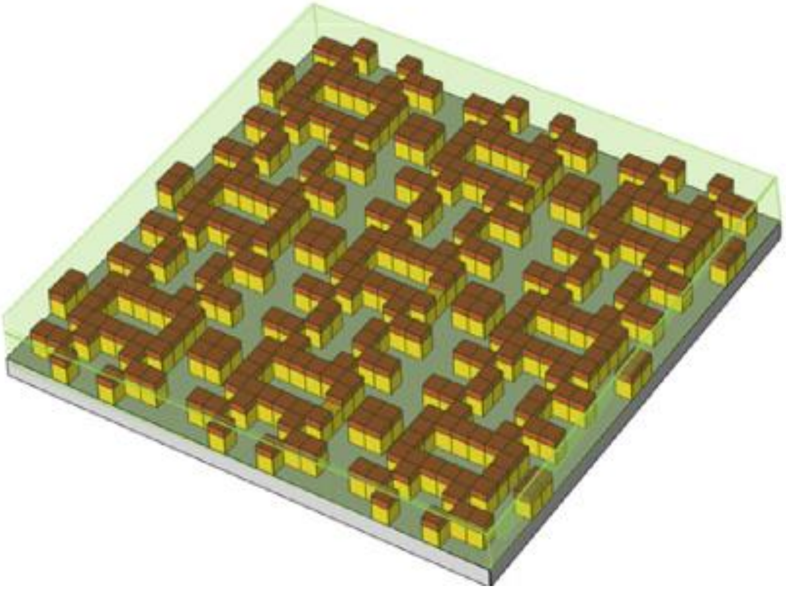
Distributed silicon nanoparticles: an efficient light trapping platform toward ultrathin-film photovoltaics

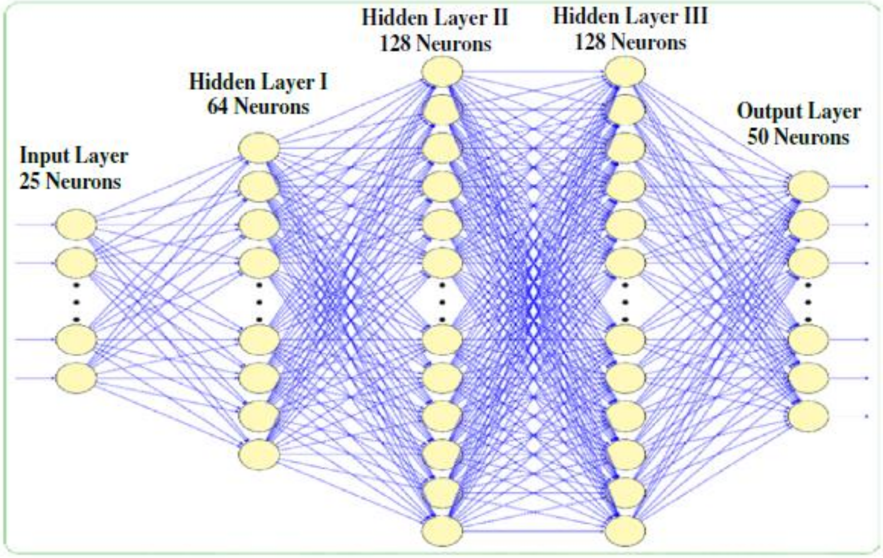


The average of photo-current enhancement for random solar cells were 2.56 and 2.44 for TM and TE polarizations, respectively.

Shameli, Mirnaziry, Yousefi, Optics Express, *2021.*

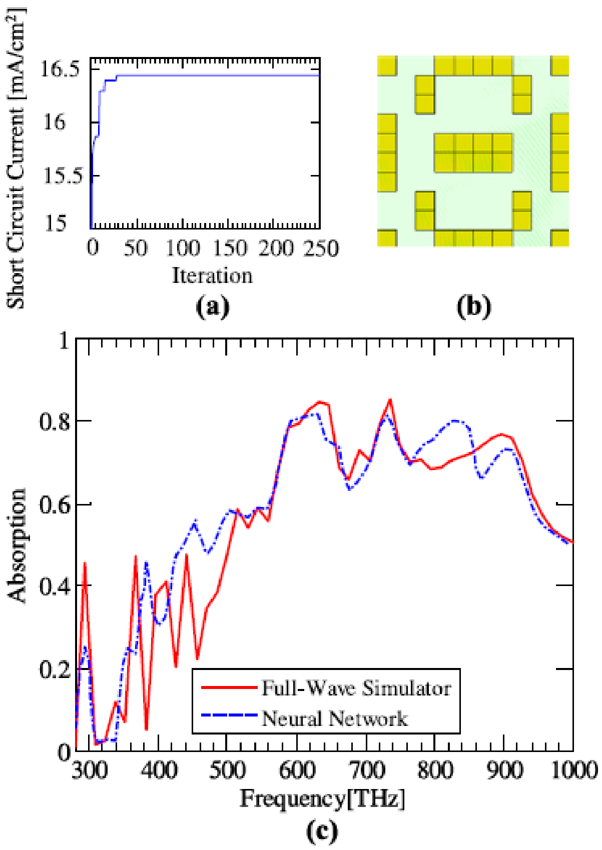
Using Neural Networks to Optimize the Metasurfaces for Light Absorption





Shameli, Fallah, Yousefi, JOSA B, 2021.

Using Neural Networks to Optimize the Metasurfaces for Light Absorption



The numerical results showed that the optimum solar cell provides a short circuit current that is 2.47 times higher than a simple solar cell containing the same amount of crystalline silicon, when the light is normally incident to the cell.

Shameli, Fallah, Yousefi, JOSA B, 2021.

Increasing the Resolution of Imaging Systems using Metasurfaces and Nano-Structures

Far-Field Imaging Beyond the Diffraction Limit using Nano-Structures

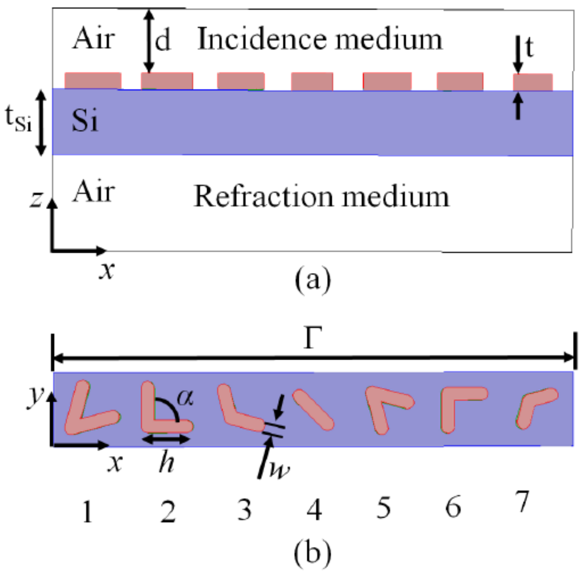


Fig. 2: The metasurface elements used to provide phase discontinuity (a) Side view and (b) Top view.

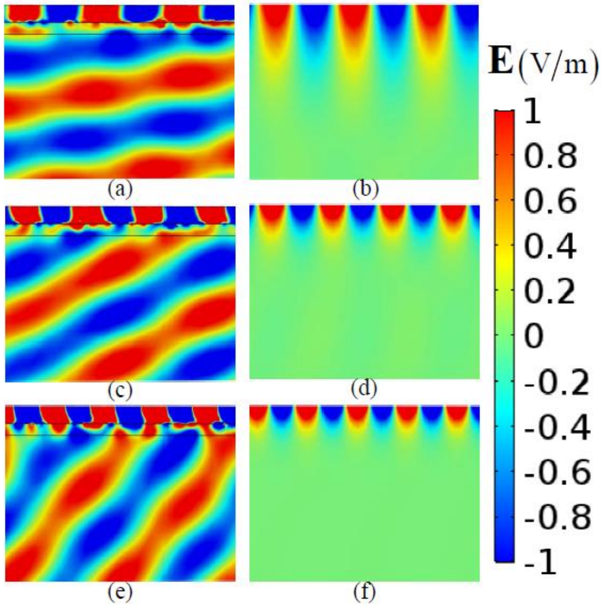


Fig. 3: Normalized electric field, due to the TM-polarized plane wave incident, (a,c,e) in the presence of the metasurface, and (b,d,f) without the metasurface, for (a,b) $k_T = 1.1k_0$, (c,d) $k_T = 1.4k_0$, (e,f) $k_T = 1.7k_0$.

***Salami, Yousefi, *Journal of Light Wave Technology,* 2019.**

Far-Field Imaging Beyond the Diffraction Limit using Nano-Structures

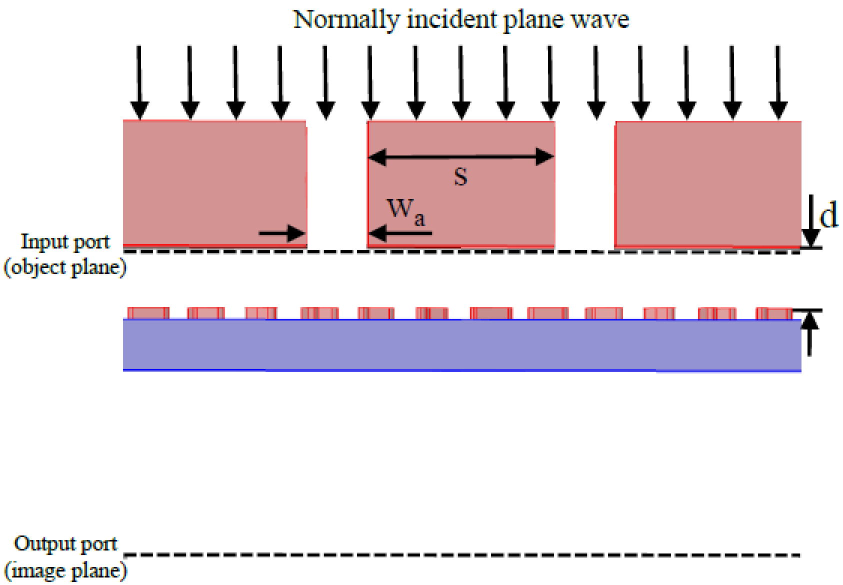
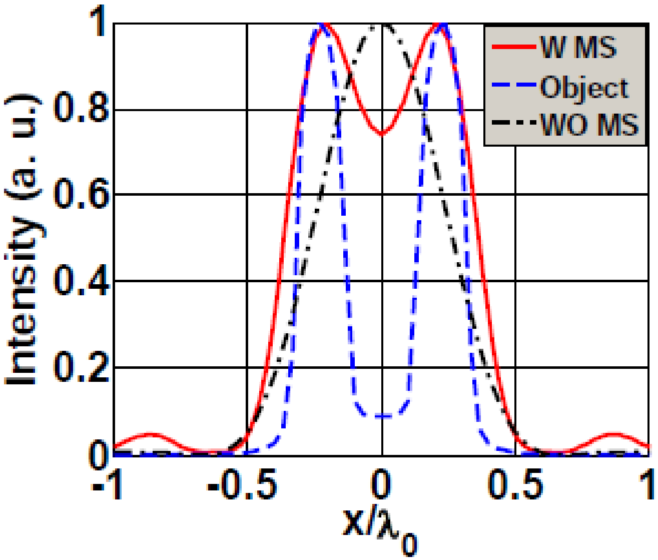


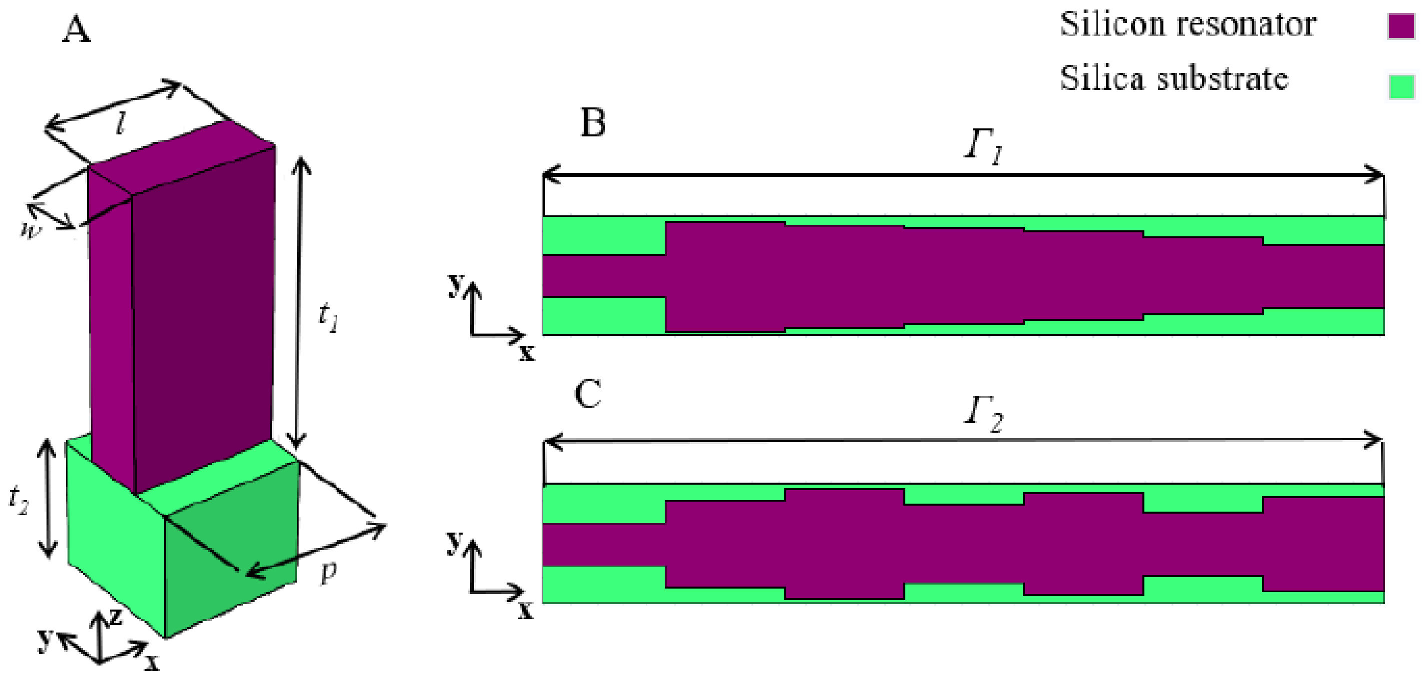
Fig. 9: The object with subwavelength features.

*Salami, Yousefi, *Journal of Light Wave Technology,* 2019.



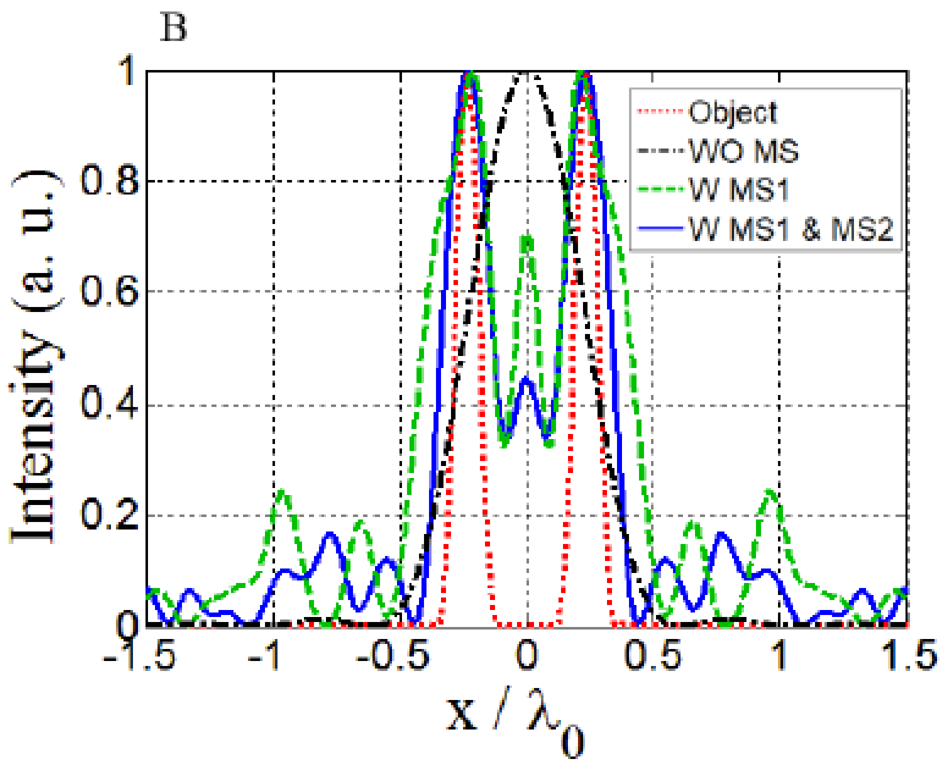
$$s = \frac{\lambda_0}{3.4}$$

Far-Field Imaging Beyond the Diffraction Limit using Nano-Structures



Akbari, Salami, Yousefi, ***Optics Express,*** **2022.**

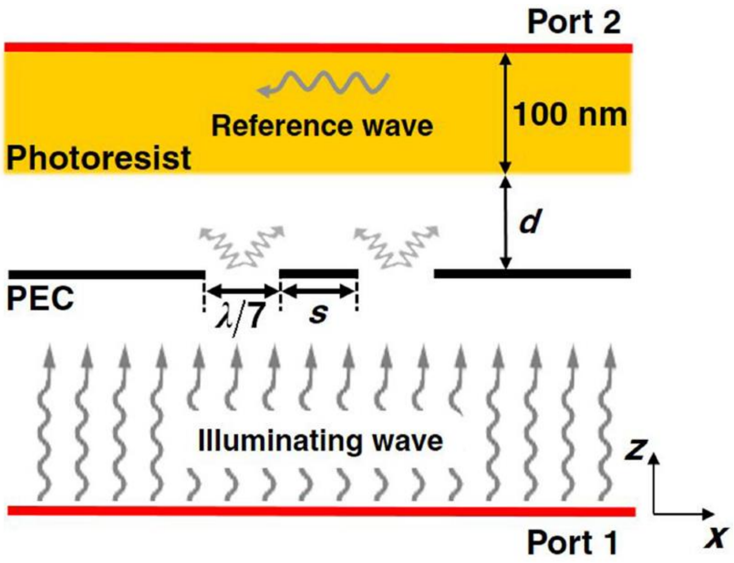
Far-Field Imaging Beyond the Diffraction Limit using Nano-Structures

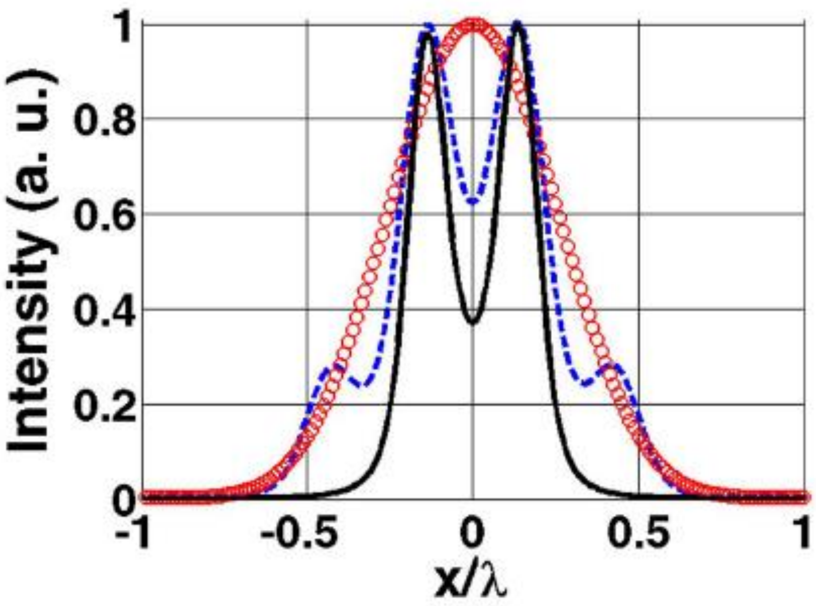


$$s = \frac{\lambda_0}{5}$$

Akbari, Salami, Yousefi, *Optics Express,* 2022.

Far-Field Imaging Beyond the Diffraction Limit using Nano-Structures

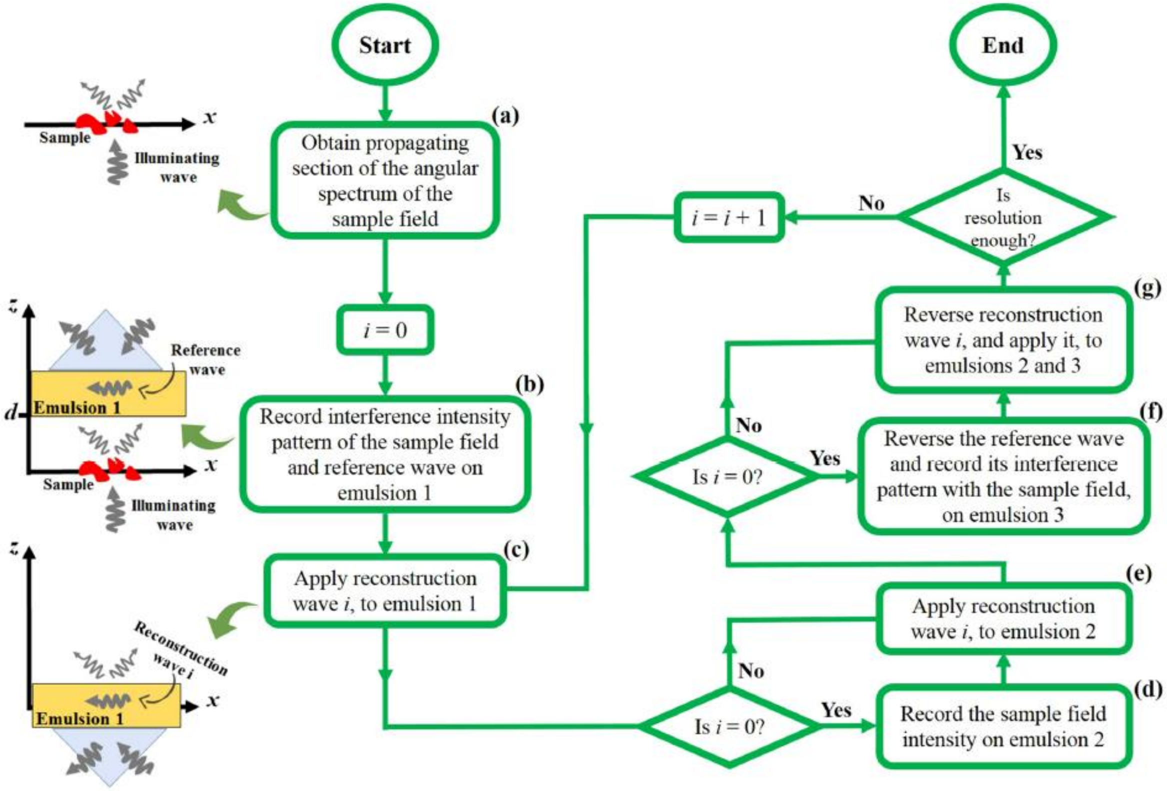




$s = \frac{\lambda_0}{7}$

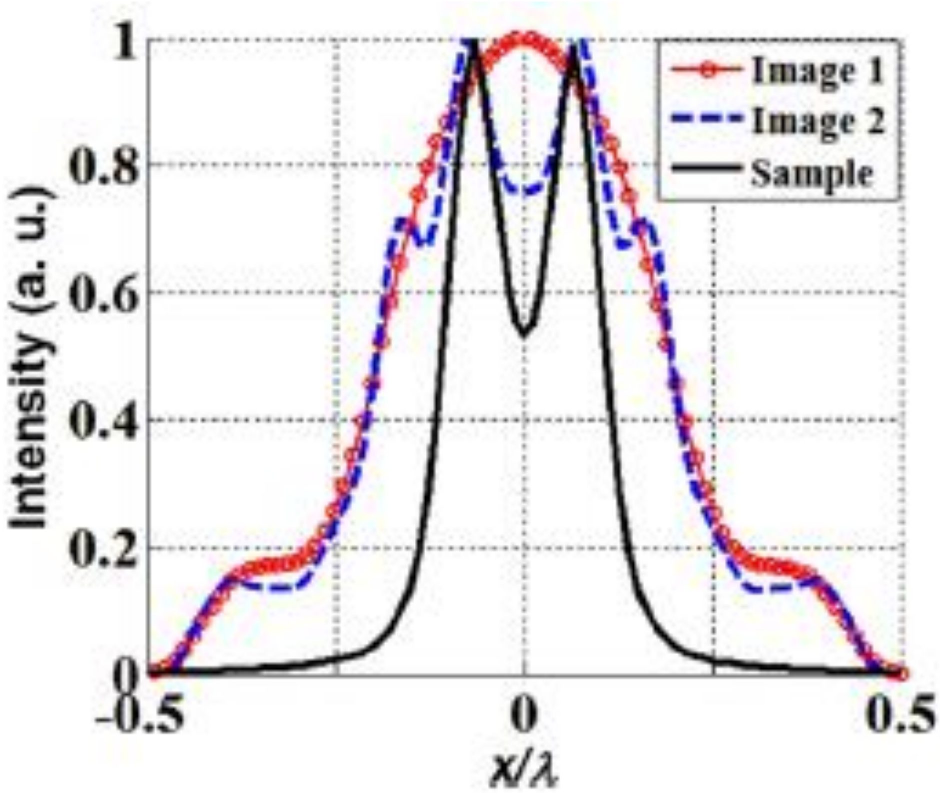
*Salami, Yousefi, *Journal of Light Wave Technology,* 2020.

Super-resolution far-field sub-wavelength imaging using multiple holography



Salami, Yousefi, *JOSA B,* 2021.

Super-resolution far-field sub-wavelength imaging using multiple holography

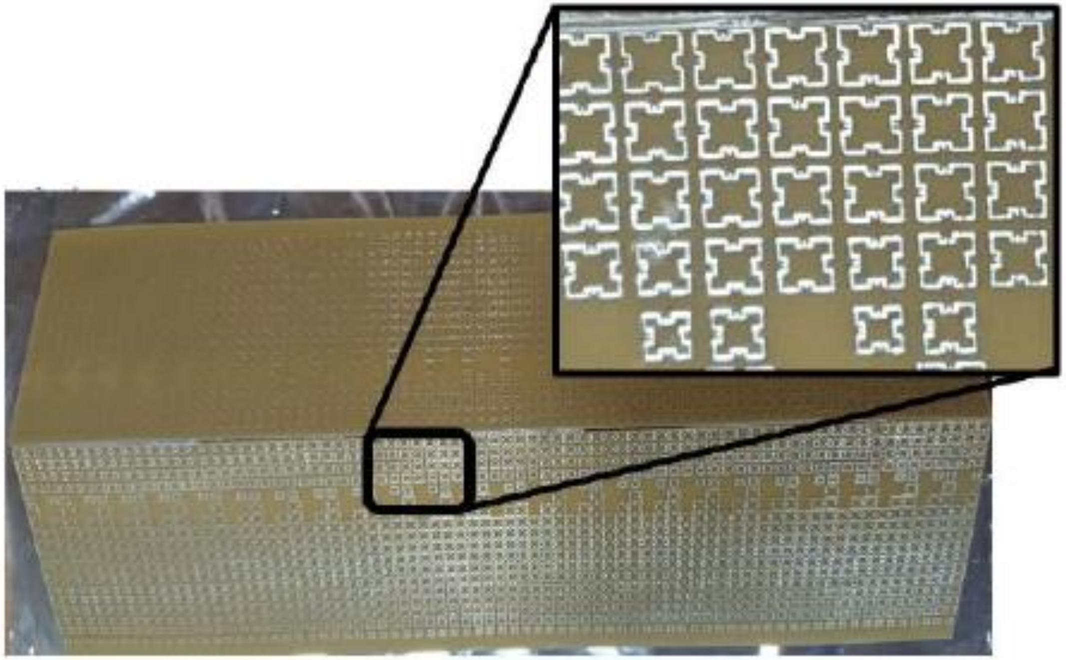


$$s = \frac{\lambda_0}{14}$$

Salami, Yousefi, *JOSA B,* 2021.

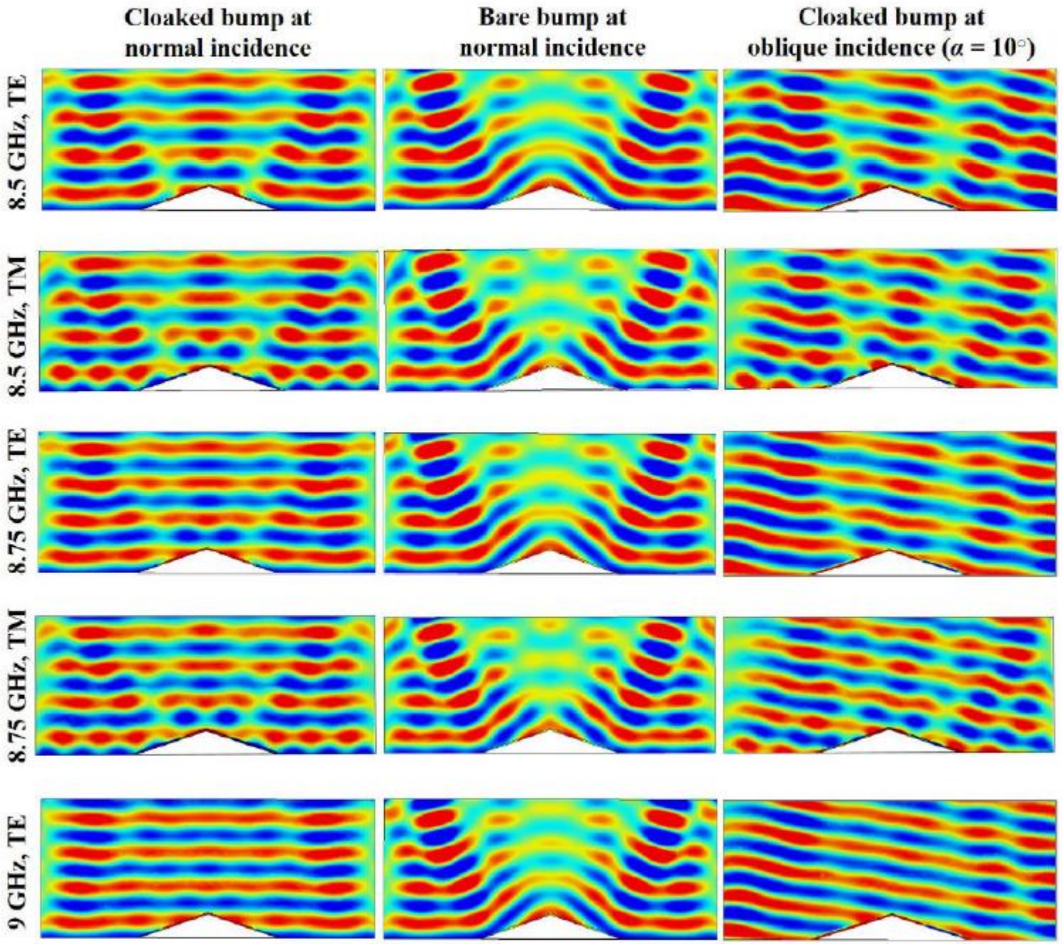
Invisibility Cloaks and Illusion using Metasurfaces and Nano-Structures

Wide-band Polarization-independent Metasurface-based Carpet Cloak



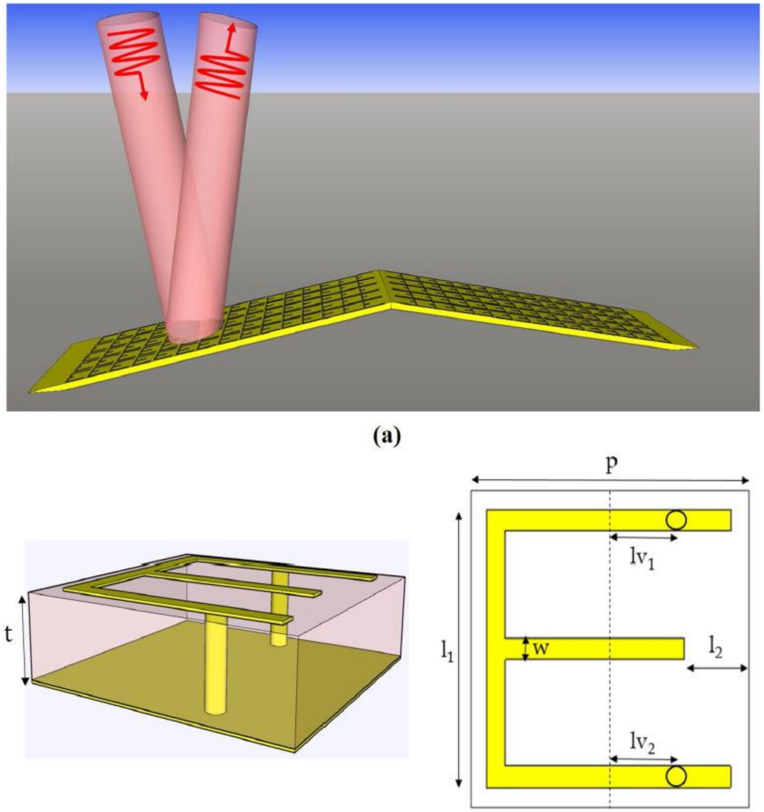
Salami, Yousefi, *IET Microwaves, Antennas & Propagation,* 2020.

Wide-band Polarization-independent Metasurface-based Carpet Cloak

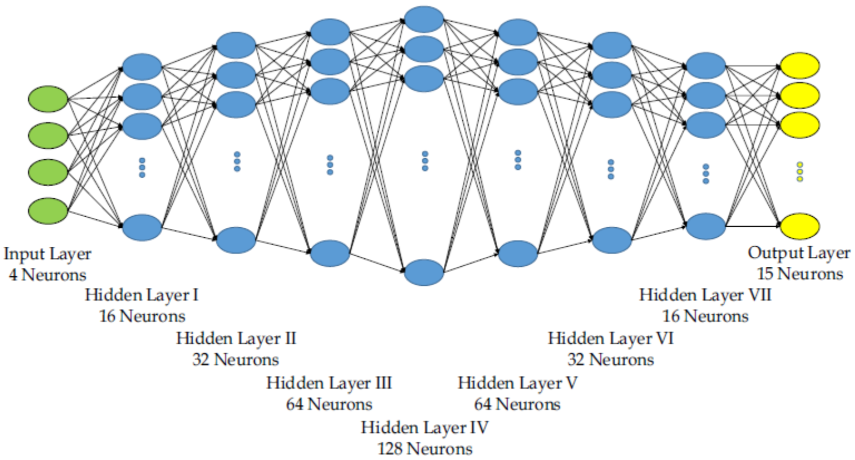


Salami, Yousefi, *IET Microwaves, Antennas & Propagation,* 2020.

Developing a Carpet Cloak Operating for a Wide Range of Incident Angles using a Deep Neural Network and PSO Algorithm

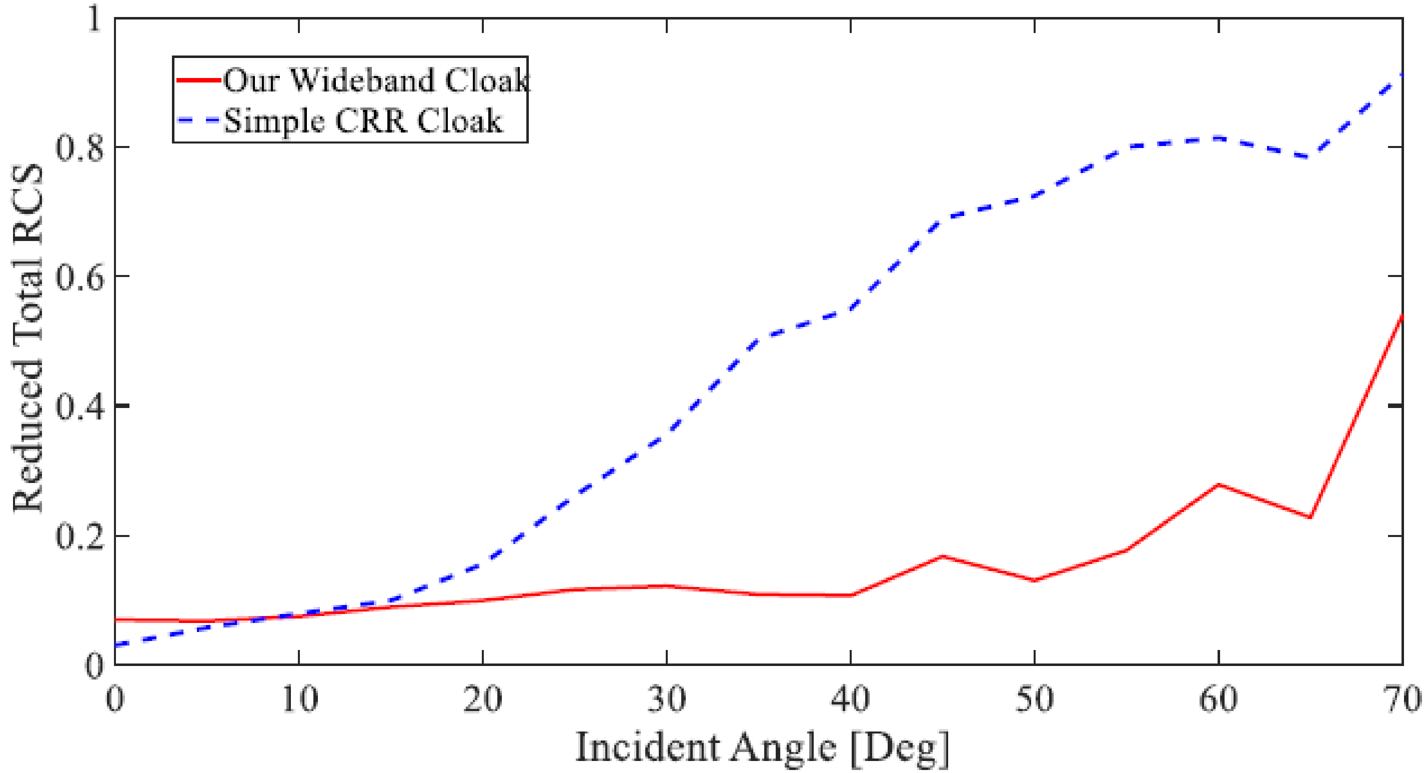


(a) (b) (c)



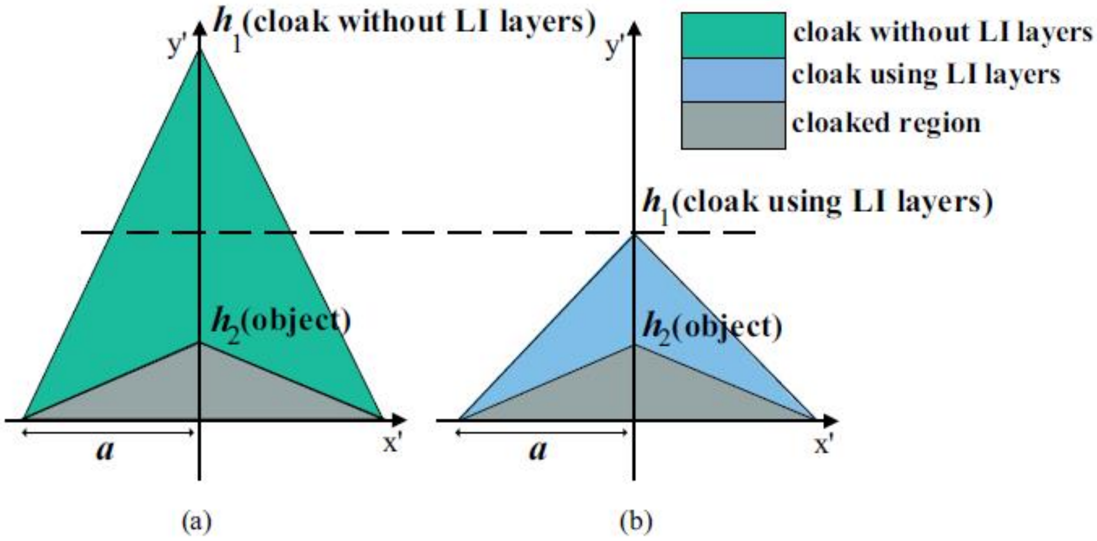
Fallah, Kalhor, Yousefi, *Scientific Reports*, 2023.

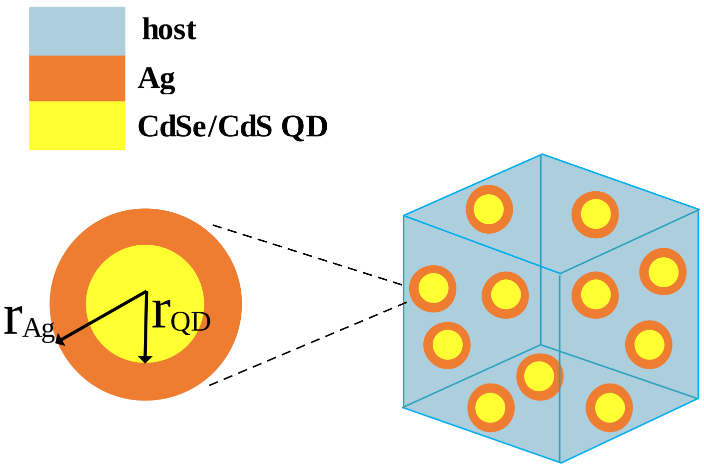
Developing a Carpet Cloak Operating for a Wide Range of Incident Angles Using a Deep Neural Network and PSO Algorithm



Fallah, Kalhor, Yousefi, *Scientific Reports,* 2023.

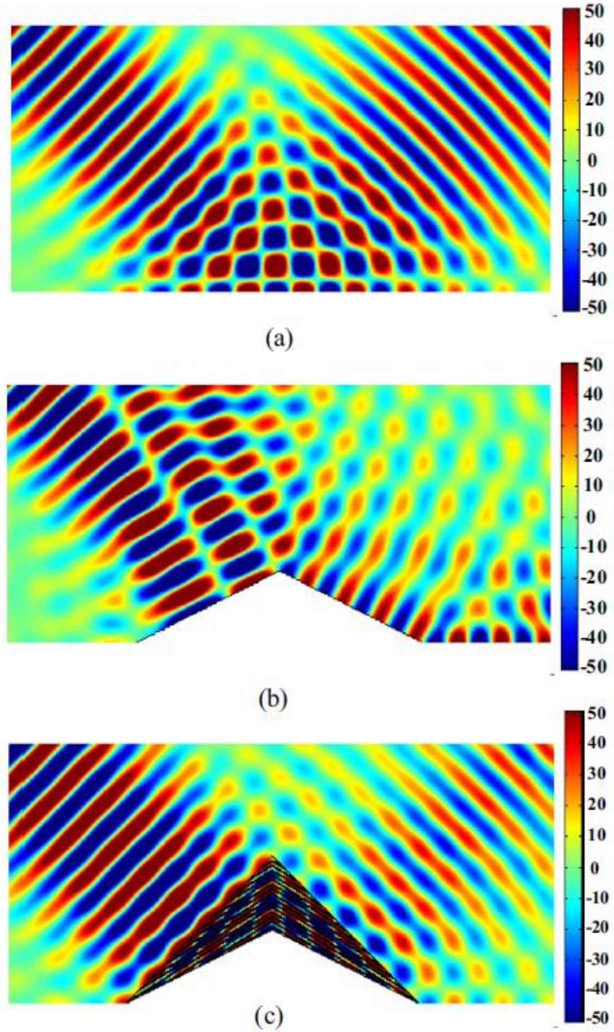
Low profile multi-layered invisibility carpet cloak using quantum dot core–shell nanoparticles

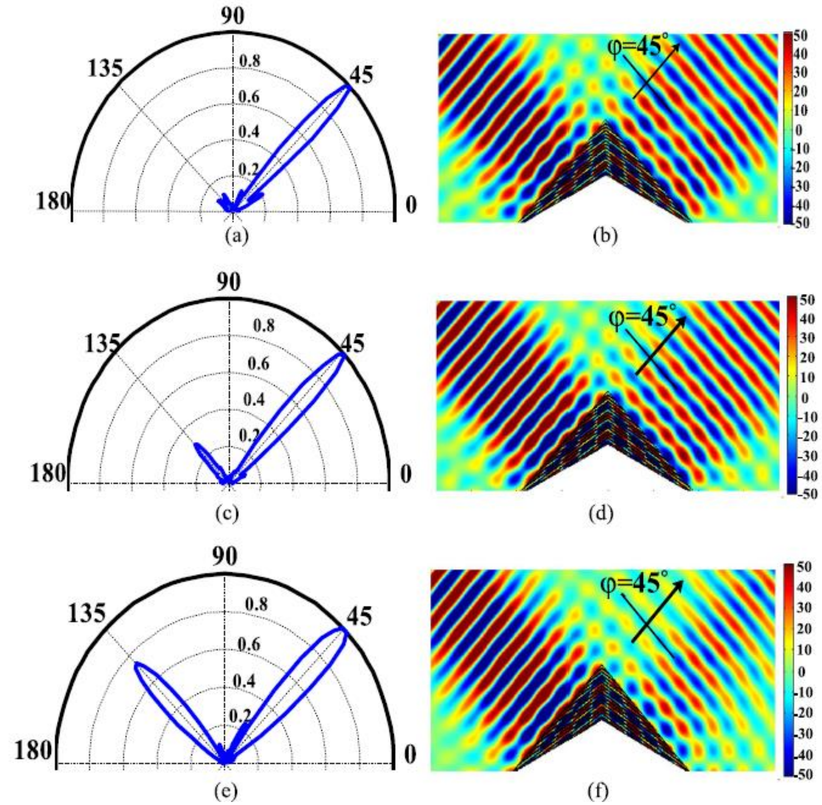




Monemian, Yousefi, *Scientific Reports, 2023.*

Low profile multi-layered invisibility carpet cloak using quantum dot core–shell nanoparticles

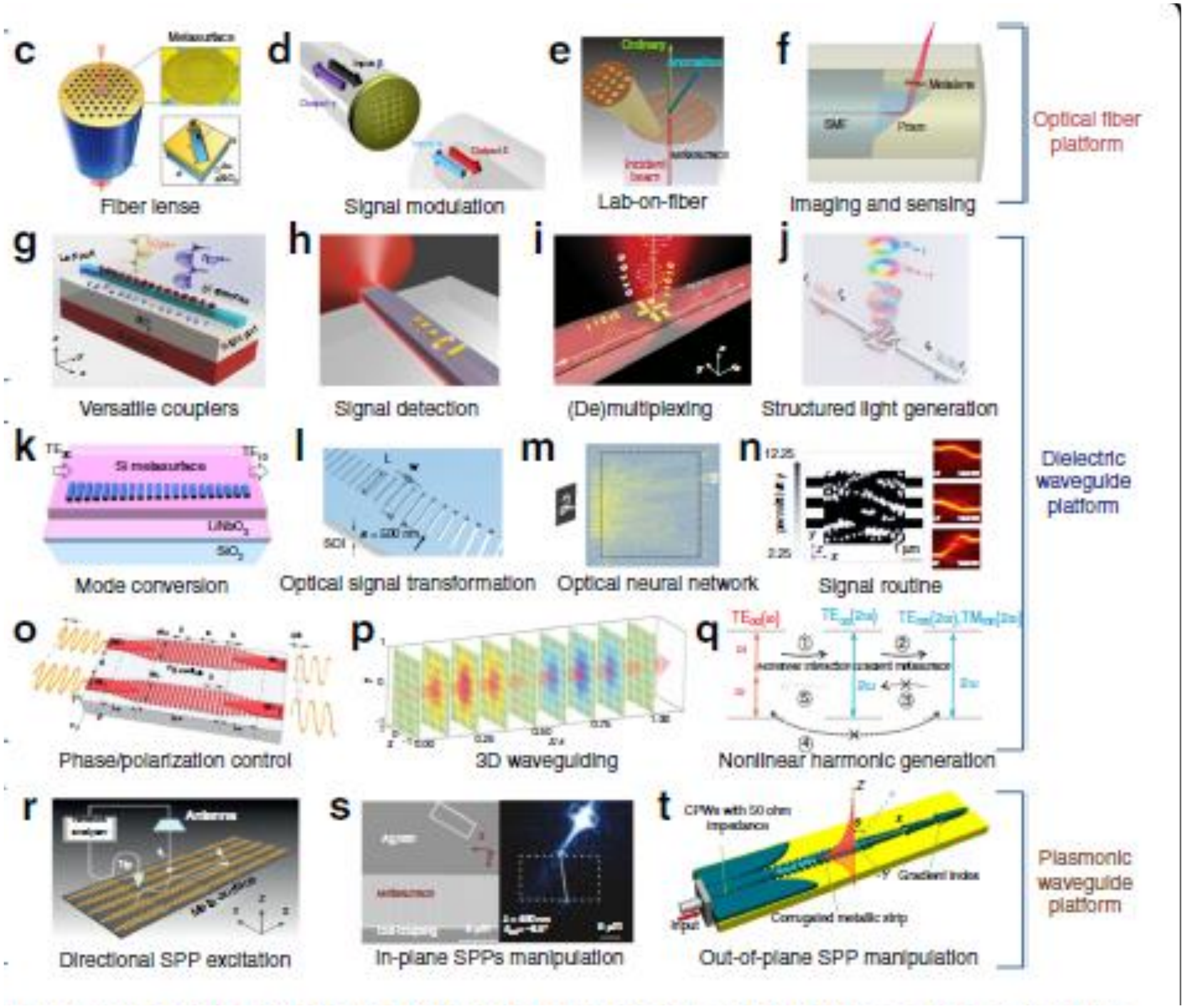




Monemian, Yousefi, *Scientific Reports, 2023.*

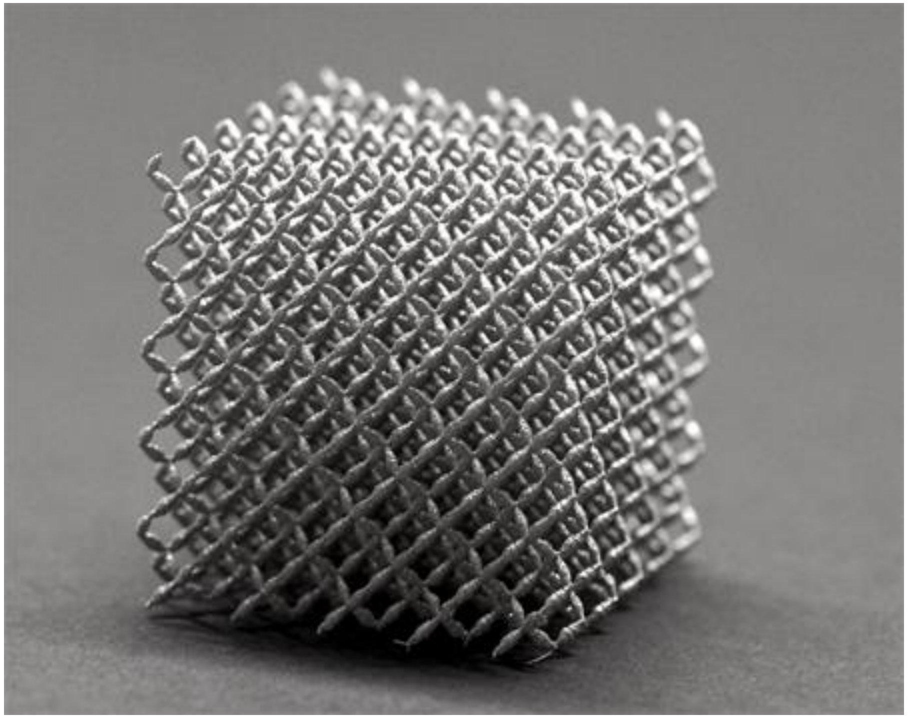
Future Research Directions

Integrated Metasurfaces or Meta-Waveguides



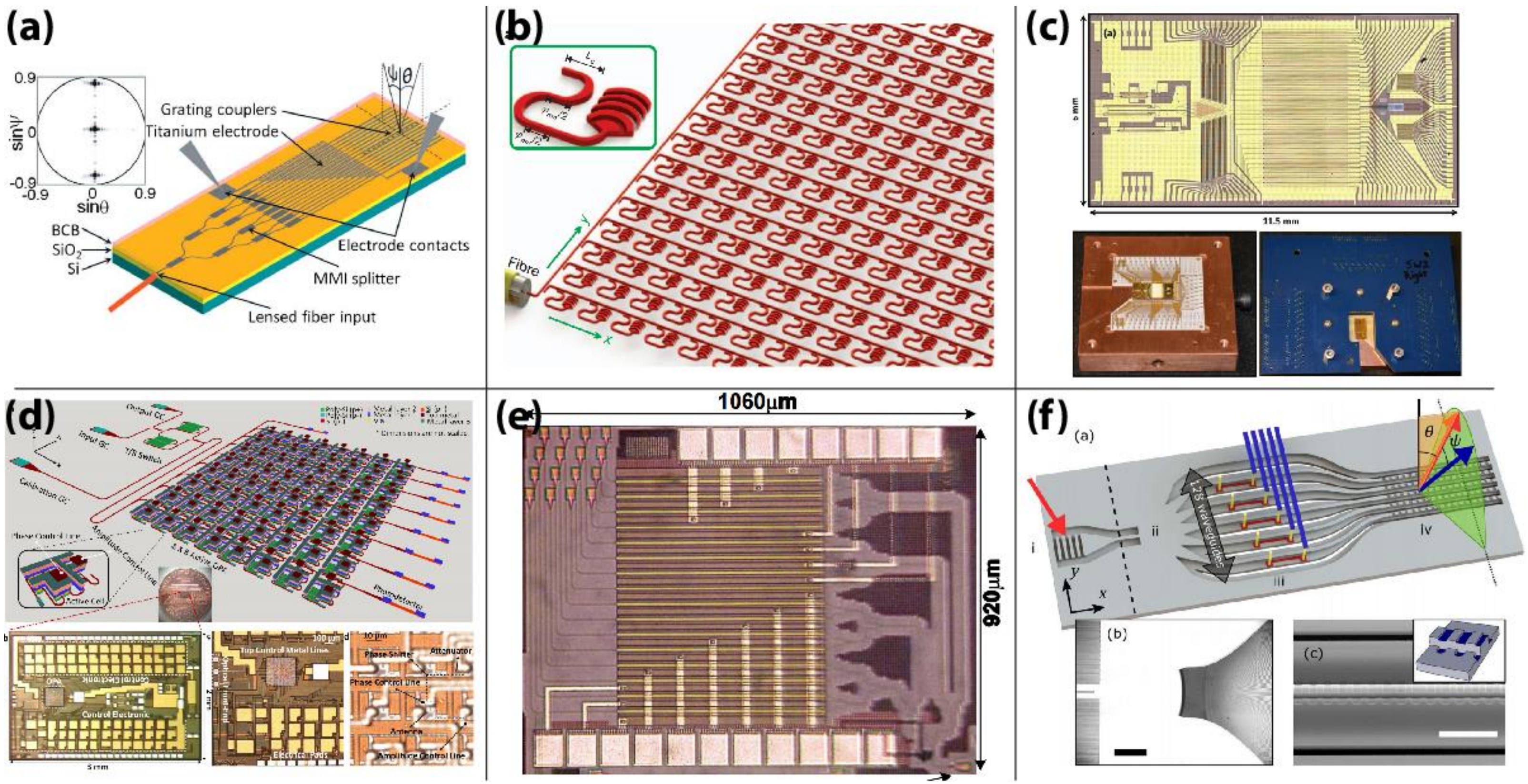
Meng et al. Light: Science & Applications, 2021.

Metamaterials Fabricated by 3D-Printers



Tim Palucka, *Applied Physics Letters*, 2017

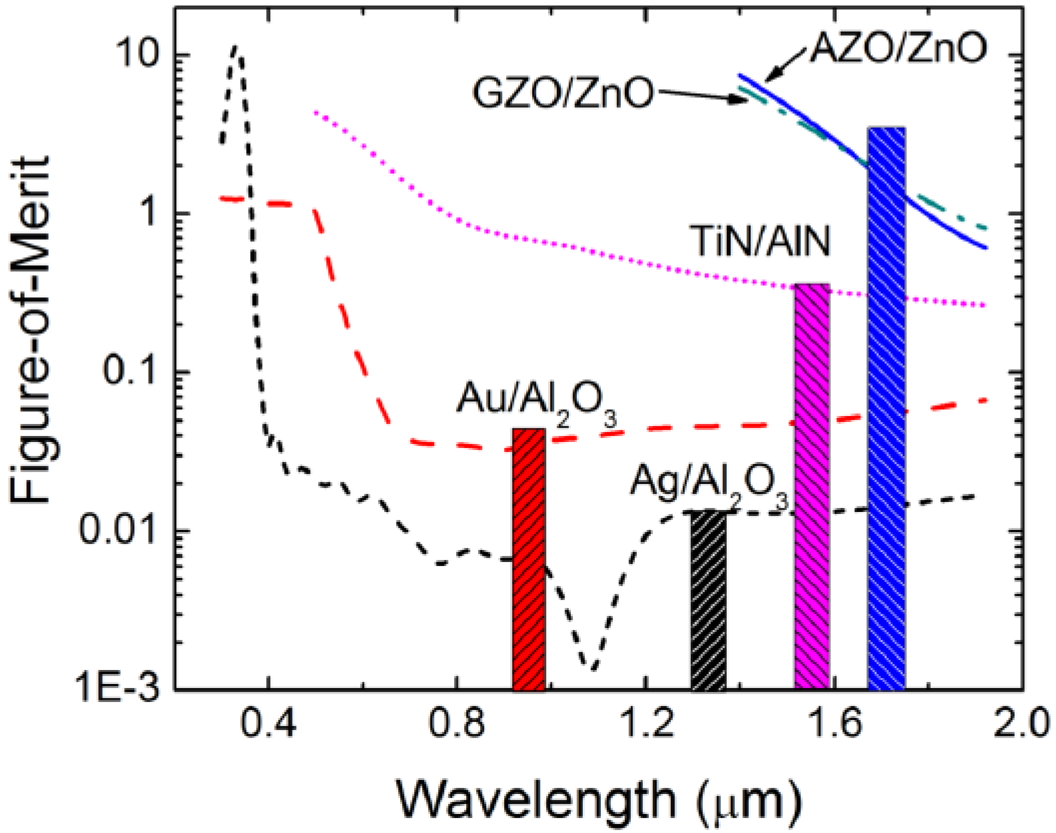
Integrated Lidars using Nano-Photonic Devices and Circuits



C. Poulton, Physics, 2016.

New Plasmonic Materials

FOM=Re{$k_\perp$}/Im{$k_\perp$}



*G.V. Naik and A. Boltasseva, Metamaterials 5, 2011.

Summary

- Light can be shaped and manipulated at Nano-Scale using Nano-Structures and Metamatrials.
- This manipulation can be used for developing:
  - Next Generation Integrated Optical Devices
  - Efficiency Enhanced Ultra-Thin Solar Cells
  - High Resolution Imaging Systems
  - Invisibility Cloaks and Illusion