# Diffractive , refractive and absorptivei optical elements based on periodic sub - wavelength metallic structures

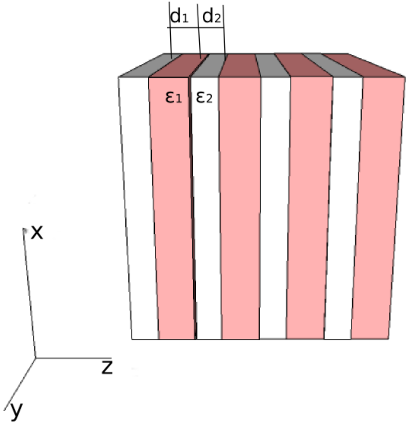
## Summary of PhD studies

Marcin Stolarek

Information Optics Division, Faculty of Physics

March 23, 2017

1. Metal-dielectric multilayers
   - Superresolving prism
   - Pseudo ray-tracing design
   - The effect of surface roughness
2. Subwavelength metallic gratings for THz radiation
   - Antenna for THz detection
   - Double metallic gratings
3. PML based on multilayers




$$\varepsilon = \begin{bmatrix} \varepsilon_{\|} & 0 & 0 \\ 0 & \varepsilon_{\|} & 0 \\ 0 & 0 & \varepsilon_{\perp} \end{bmatrix}$$

$$\mu = \begin{bmatrix} \mu_{\|} & 0 & 0 \\ 0 & \mu_{\|} & 0 \\ 0 & 0 & \mu_{\perp} \end{bmatrix}$$

$$\varepsilon_{\|} = f \cdot \varepsilon_1 + (1 - f) \cdot \varepsilon_2$$

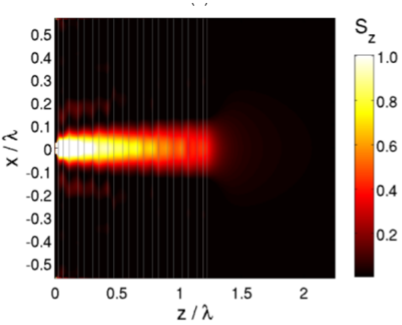
$$\varepsilon_{\perp} = \left(f \cdot \varepsilon_1^{-1} + (1 - f) \cdot \varepsilon_2^{-1}\right)^{-1}$$

$$\mu_{\|} = f \cdot \mu_1 + 1 - f \cdot \mu_2$$

$$\mu_{\perp} = \left(f \cdot \mu_1^{-1} + (1 - f) \cdot \mu_2^{-1}\right)^{-1}$$

Initial design of metamaterial is based on effective medium theory and is further refined with numerical simulations ( TMM/SMM, FDTD).

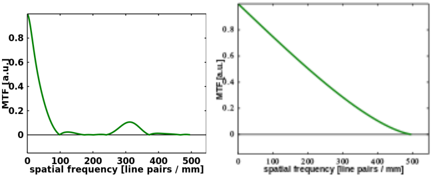
J. B. Pendry. "Negative Refraction Makes a Perfect Lens". In: *Phys. Rev. Lett.* 85 (18 2000)

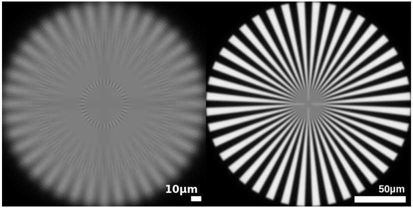



Initial design of metamaterial is based on effective medium theory and is further refined with numerical simulations ( TMM/SMM, FDTD).

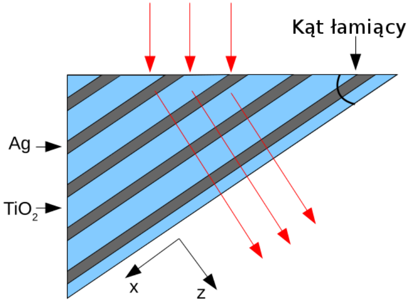
- for instance $\varepsilon_{\|} = 0$, $\varepsilon_{\perp} = \infty$
- with real metamaterials we can achieve point spread function with FWHM of 10nm
- two modes of operation: canalization and resonant tunneling
- transmission enhancement with coupling/decoupling layers, impledance matching, up to 70%

Fourier Optics provides us nice framework to deal with linear shift-invariant (LSI) systems. We can describe such a system with point spread function (PSF) and it's Fourier transform modulation transfer function (MTF).



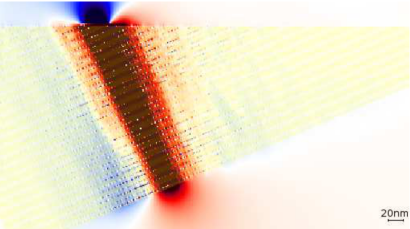



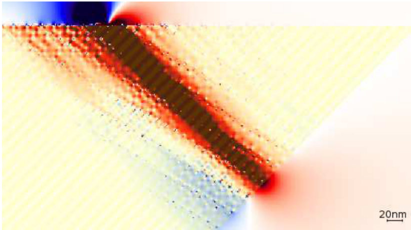
The aim - to couple near-field subwavelength sized field distribution and far-field images (applications in microscopy, lithography, etc)

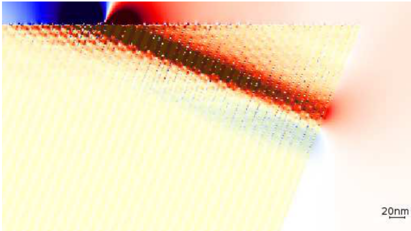



High transmision coefficent can be achieved with impedance matching with surrounding media or using the resonant tunneling.

M. Scalora, M. J. Bloemer, A. S. Pethel, J. P. Dowling, C. M. Bowden, and A. S. Manka. "Transparent, metallo-dielectric, one-dimensional, photonic band-gap structures". In: *J. Appl. Phys.* 83 (1998)



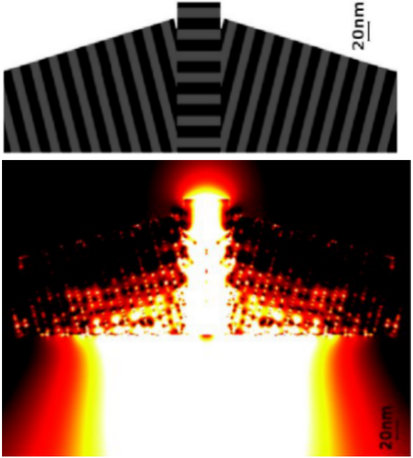




Transmision efficiency and FWHM of the outgoing beam depends not only on the appex angle, but also on shift of illuminating beam. (Not an LSI system)

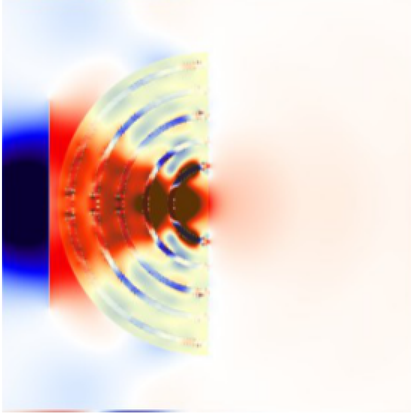
M. Stolarek, A. Pastuszczak, J. Pniewski, and R. Kotyński. "Sub-wavelength imaging using silver-dielectric metamaterial layered prism". In: *Proc. SPIE* 7746 (2010)

## Subwavelength beam concentrator based on metal-dielectric multilayers

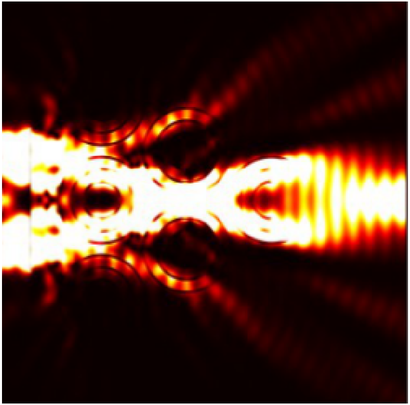


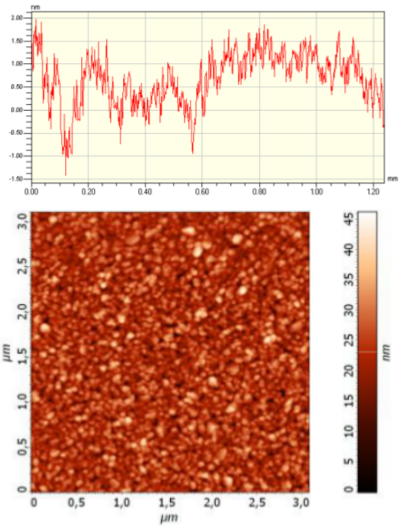

- Simple model based on EMT and ray-tracing (good for engineeing)
- Limited by strong diffraction outside the structure
- Rigorous modeling is needed to explain the appearance of resonanses, reflections and losses

Cylindrical concentrator



Simillar concentrator based on core-shell's






- Statistical model of surface roughness based on AFM measurements
- Rigorous FDTD simulations of rough surfaces

Marcin Stolarek, Piotr Wróbel, Tomasz Stefaniuk, Mateusz Wlazło, Anna Pastuszczak, and Rafał Kotyński. "Spatial filtering with rough metal-dielectric layered metamaterials". In: *Photonics Lett. Pol.* 5 (2013)

The surface mode is no longer excited in the presence of arbitrary surface roughness. Additionally roughness (sinusoidal) can improve the PSF.

Shaowu Huang, Haogang Wang, Kung-Hau Ding, and Leung Tsang. "Subwavelength imaging enhancement through a three-dimensional plasmon superlens with rough surface". In: *Opt. Lett.* 37 (2012)

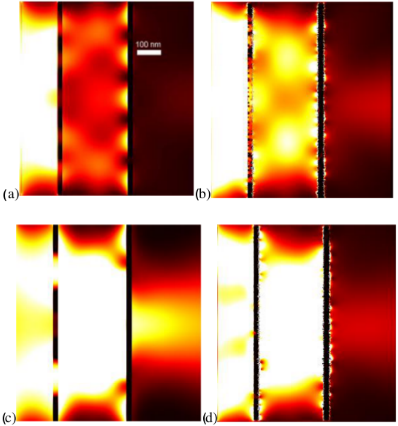
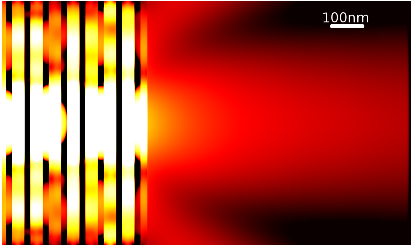
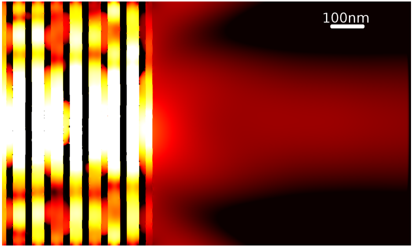
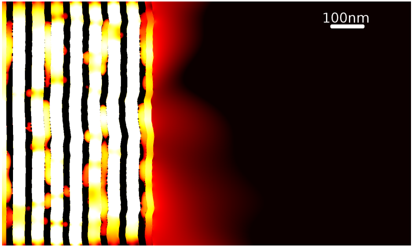



Figure : a,b - 430nm , c,d -490 nm



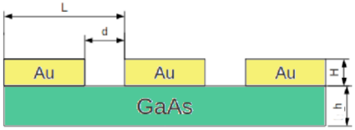



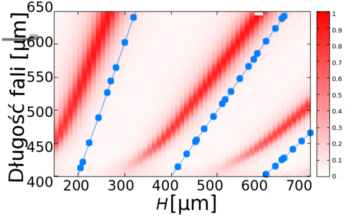

Surface roughness of $RMS = 1$ nm can significantly decrease transmission through mulitlayer structure. Especially when the number of layers is large. RMS on the pictures equal to 0, 1 and 5 nm.

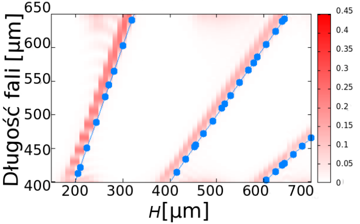
A. Pastuszczak, M. Stolarek, and R. Kotyński. "Engineering the point spread function of layered metamaterials". In: *Opto-Electron. Rev.* 21 (2013)

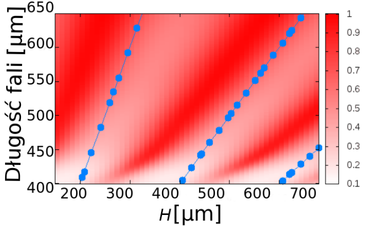
Theoretical maximum of transmission:

$$\frac{\lambda}{n_{eff}} = 2\frac{h}{m}$$

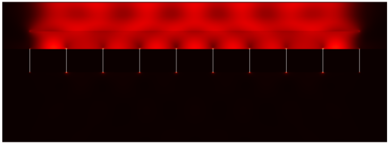


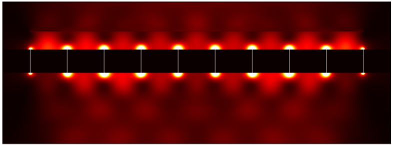



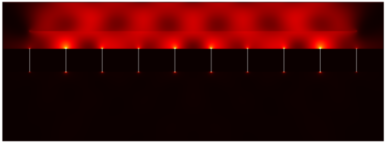

L Martin-Moreno, FJ Garcia-Vidal, HJ Lezec, KM Pellerin, T Thio, JB Pendry, and TW Ebbesen. "Theory of extraordinary optical transmission through subwavelength hole arrays". In: *Phys. Rev. Lett.* 86 (2001)



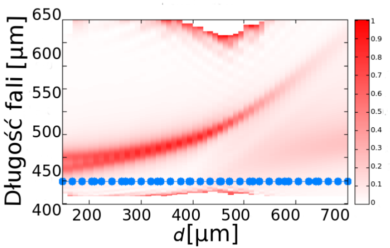
Rysunek 12: Energia pola E-M, dla h=250$\mu m$; $\lambda = 500\mu m$



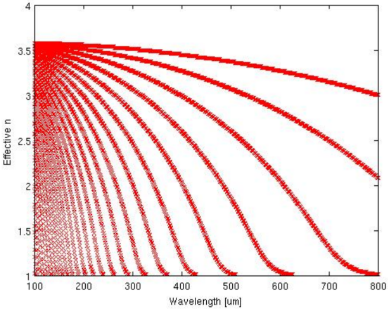
Rysunek 13: Energia pola E-M, dla h=250$\mu m$; $\lambda = 525\mu m$



Rysunek 14: Energia pola E-M, dla h=250$\mu m$ $\lambda = 550\mu m$




- Material properties for THz and visible light are different
- Frequency selective transmission due to mode coupling in a thick metallic grating




## Excitation of guided modes in GaAs with thin metallic grating

M. Stolarek, A. Pastuszczak, and R. Kotyński. "Numerical analysis of transmission through a sub-wavelength metallic aperture or grating at visible and Terahertz wavelengths". In: *Proc. of ICTON* (2011)

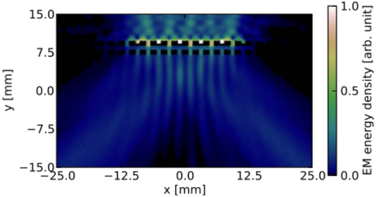
J. Szczytko, M. Stolarek, B. Pietka, and J. Łusakowski. "Terahertz properties of metallic layers and grids". In: *Proc. of MIKON* 1 (2012)

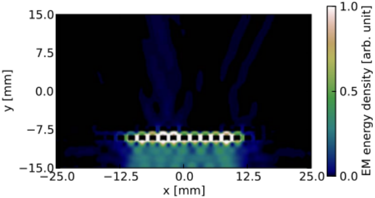
Asymmetric transmission doesn't mean the device is an optical isolator.


$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

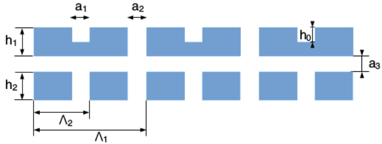
- Every system can be described in terms of scattering matrix.
- Backward transmission have to be blocked for ensembles of modes.
- If we consider only linear, time-independent and reciprocal the scattering matrix is symmetric.

Dirk Jalas, A Petrov, M Eich, W Freude, SH Fan, ZF Yu, Roel Baets, M Popovic, A Melloni, JD Joannopoulos, M Vanwolleghem, CR Doerr, and H Renner. "What is and what is not an optical isolator". eng. In: NATURE PHOTONICS 7 (2013). ISSN: 1749-4885



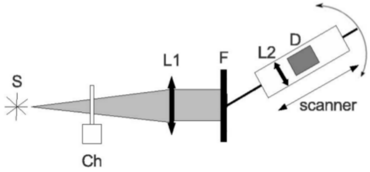



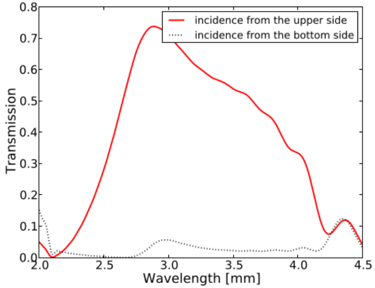

$$\Lambda_1 < \lambda,\ \Lambda_2 = 2 \cdot \Lambda_1 > \lambda$$

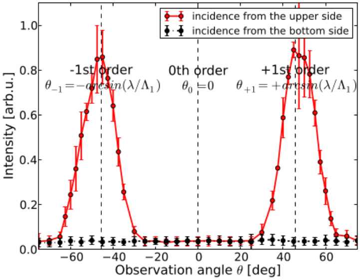



The transmission assymetry is not possible in 0th diffraction order, this is reciprocal setup.

Marcin Stolarek, Dmitryj Yavorskiy, Rafał Kotyński, Carlos Zapata-Rodríguez, J. Łusakowski, and Tomasz Szoplik. "Asymmetric transmission of terahertz radiation through a double grating". In: *Opt. Lett.* 38 (2013)

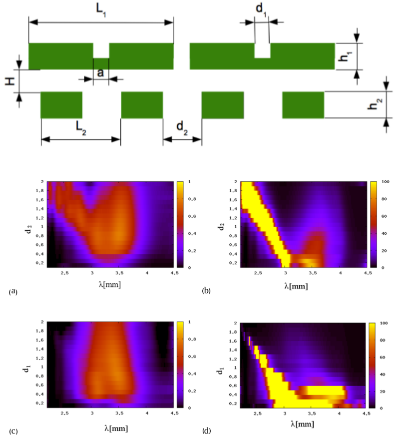


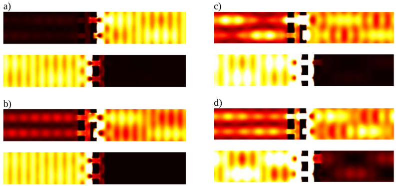




- Optimized for a broadband operation
- The grating exhibits assymetric transmission in $\pm$1st order
- The 0th diffraction order is blocked

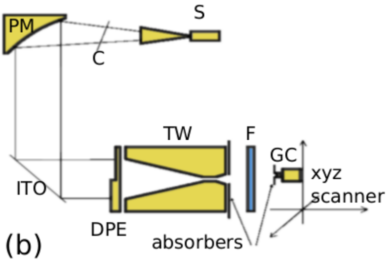
# Contrast tuning

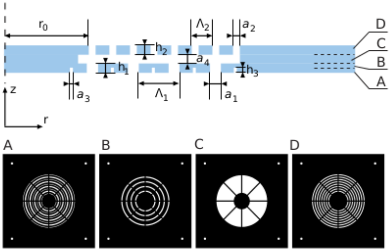



The dimensions of holes and grooves is further optimized to increase the contrast between transmission in opposite directions.

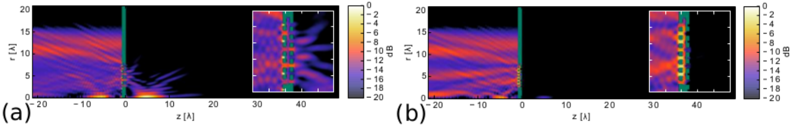
# Radial polarization



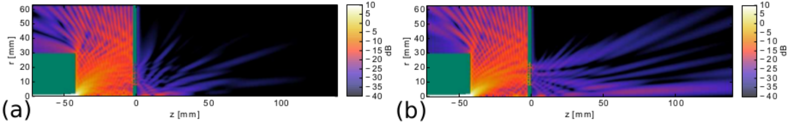



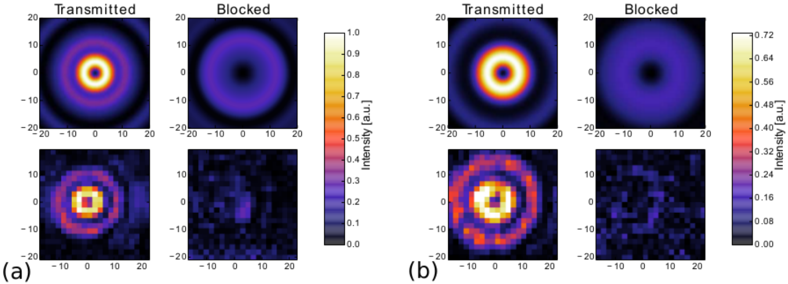

D. Yavorskiy, M. Stolarek, J. Łusakowski, and R. Kotyński. "Asymmetric transmission of radially polarized THz radiation through a double circular grating". In: *Opt. Express* 22 (2014)

The cylindrical double metallic grating was desinged to optimize the transmission asymmetry of a supergaussian radially polarized incident beem:

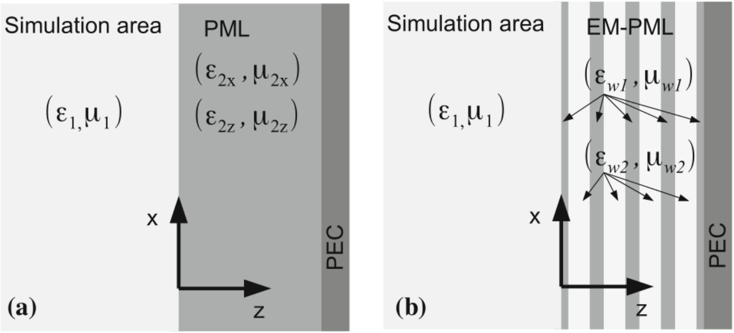


The experimental conditions differed from the previous assumptions:

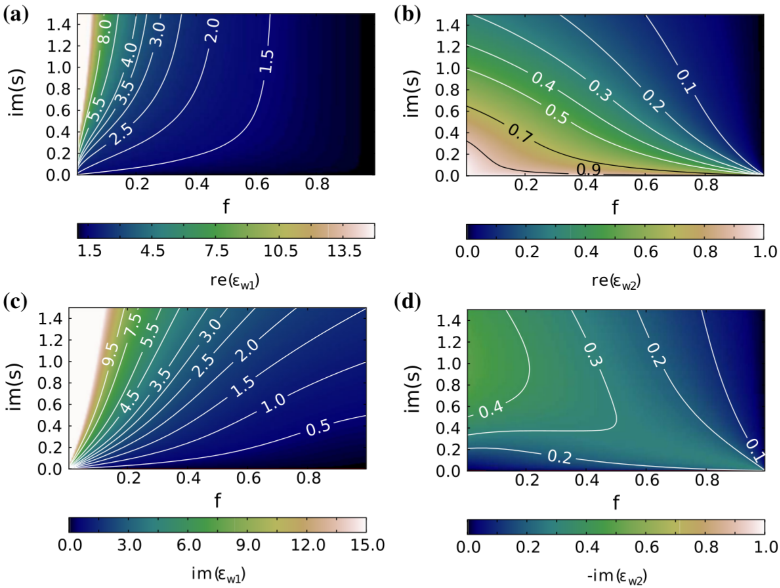


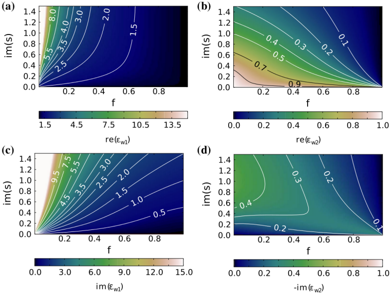


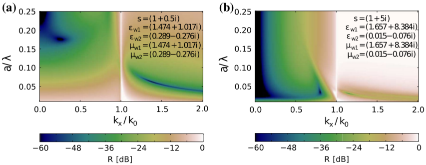

Experimental measurements are in very good agreement with numerical modeling.




A. Pastuszczak, M. Stolarek, T.J. Antosiewicz, and R. Kotyński. "Multilayer metamaterial absorbers inspired by perfectly matched layers". In: *Opt. Quant. Electron.* 47 (2015). ISSN: 0306-8919

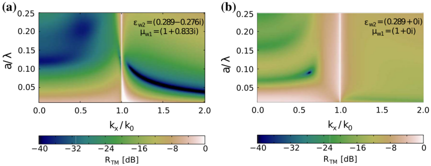

(a)
im(s)
f
re(εw1)
(b)
im(s)
f
re(εw2)
(c)
im(s)
f
im(εw1)
(d)
im(s)
f
-im(εw2)

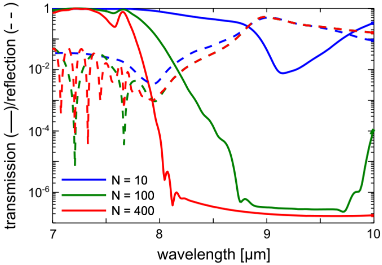


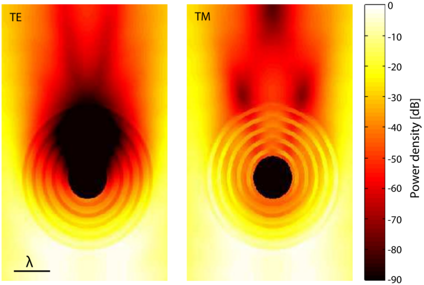




Thaks to equation seperations for for two polarizations we can exclude the dependence from a few of material parameters, but the complex character of $\mu$ is still difficult to deal with

"Natural" materials with $\mu \neq 1$ or with gain do not exist.




1
$10^{-2}$
$10^{-4}$
$10^{-6}$
7
8
9
10
transmission (——)/reflection (- - )
wavelength [μm]
N = 10
N = 100
N = 400


TE
TM
λ
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
Power density [dB]
(a) (b)

# Conclusions

- Metal-dielectric multilayers with subwavelength resolutions can be used to construct different optical elements hence to the geometry modifications.
- It is possible to achevie asymmetric, reciprocal transmission through double mettalic grating structures in THz regime.
- MDMs can also be used as electromagnetic absorbers.