

Metasurface-Epsilon Near Zero-based Electromagnetic Wave Absorber

L. La Spada

Department of Engineering, University of Roma Tre, Via Vito Volterra 62, Rome 00146, Italy

School of Electronic Engineering and Computer Science, Queen Mary University of London, London, E1 4NS, United Kingdom

luigi.laspada@uniroma3.it

l.laspada@qmul.ac.uk

ABSTRACT

The purpose of this paper is to design a new electromagnetic wave absorber. It consists of a planar layered structure with an isotropic Epsilon-Near-Zero (ENZ) material and a gold metal inclusion, both placed over a perfect conductor (PEC) plate. Absorption is obtained by exploiting the combination of both ENZ and metasurface materials. The electromagnetic properties of the structure, in terms of reflection coefficient, are analytically described by the use of the transmission line theory. The proposed analytical closed-form formula provides us the possibility to correlate the electromagnetic absorption properties of the structure (magnitude, bandwidth and resonant frequency) with its geometrical characteristics. Such a formula represents a useful tool in order to design the absorber for specific required applications. The main issue is to absorb the incident electromagnetic wave in the broadest angle range possible. In particular, an absorption in a wide angle range (0° - 80°), for different frequencies (multi-resonant), with a large frequency bandwidth (wide-band) for small structure thicknesses ($d < \lambda_r/4$) is demonstrated, compared to the conventional absorbers existing in literature.

Keywords

Epsilon-Near-Zero Materials, Metasurfaces, Electromagnetic Wave Absorbers, Sensing, Telecommunications Applications.

1. INTRODUCTION

A near unity absorber is a device in which all the incident radiation is absorbed, meanwhile transmission, reflection and scattering are zero. Electromagnetic wave absorbers can be categorized into two types: resonant absorbers and broadband absorbers [1]. Initial interests in electromagnetic wave resonant absorbers were largely in the microwave range. Salisbury and Jaumann, independently, created similar devices: one or more resistive sheets are placed $\lambda_0/4$ in front of a metal ground plane, usually separated by some lossless dielectric [2, 3].

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. To copy otherwise, to republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee.

BODYNETS 2014, September 29-October 01, London, Great Britain

Copyright © 2014 ICST 978-1-63190-047-1

DOI 10.4108/icst.bodynets.2014.257016

The Dällenbach layer employs a different mechanism compared to the Salisbury screen; its design consists of a homogeneous layer in front of a ground plane [1]. Another type of resonant electromagnetic wave absorber, the crossed grating absorber, uses a reflective metal plane with a periodic grid for the unpolarized incident light [4]. Circuit Analog (CA) absorbers (an extension of the Salisbury screen), consist of one or more sheets composed of both resistive and reactive components arranged in a periodic array in front of a single ground plane [5].

First examples of broadband absorbers are geometric transition absorbers: the idea is to create a slowly varying transition from free space into lossy material using shapes such as pyramids or wedges [1]. Another type is the low-density absorber which utilizes a porous or sparse material so that its parameters can generally be taken to be approximately those of free space [1].

Recently, the advent of metasurfaces permitted to enhance all aforementioned devices performances. Metamaterial-based absorber were proposed in several frequency ranges: microwave [6], millimeter waves [7], THz [8], infrared [9], and optical wavelengths [10]. The general idea is to minimize reflection on the metamaterial surface and then, by utilizing geometrical and material properties, create losses to give high absorptivity. From what we have seen so far, the major issues in the electromagnetic wave absorber design concern satisfying the following requirements:

- Small thickness: most of the presented absorbers require a thickness at least around $\lambda/4$
- Broad angle range: the absorption is required at all angle of incidence
- Broad bandwidth and multi-resonant behavior: wide the bandwidth of the single resonant frequency and/or create multiple resonant bands with the wider bandwidth possible
- Scaling the structure: the possibility to replicate the same behavior and performances in all the electromagnetic spectrum frequency ranges.

The main goal, not easily achievable, is to satisfy all the features listed above at the same time. Such an aim is really complicated, due to the fact that all the aforementioned requirements are related each other. Optimizing one of them, it can lead to not satisfy the others.

Recently, several studies focused their attention on a particular kind of metamaterials entitled Epsilon-Near-Zero and on their particular electromagnetic properties. Such materials,

characterized by low (mostly near zero) values of the real part of the relative permittivity, have several interesting applications such as tailoring the phase-front of an electromagnetic wave and designing filters [11], obtaining directive antennas [12], implementing optical nano-circuits [13], confining electromagnetic fields [14], enhancing transmission [15], obtaining anomalous tunneling effects [16], focusing the electromagnetic field [17], cloaking objects [18] improving sensing systems [19].

Recent evidence suggests that good absorption could be obtained by thin ENZ and Mu-Near-Zero (MNZ) with low losses [20] in thin anisotropic ENZ [21] and with high losses MNZ materials [22].

Considering all these issues, in this paper, by combining the particular properties of ENZ and metasurfaces, we propose the design of an electromagnetic absorber, in order to satisfy all the mentioned requirements at the same time.

Because such absorbers are tunable with respect to their operational wavelength, they can be used as spectrally sensitive detectors, sensors, for imaging and telecommunications applications.

The article is structured as follows: first of all, the general operation pattern is presented and analytically described by the use of the Transmission Line Theory. To do this, the impedance of the resonator is analytically evaluated, by using the equivalent circuit model theory. Then, the closed-form formula for the reflection coefficient of the structure is obtained. This provides us the possibility to correlate the electromagnetic properties of the absorber (in terms of absorption magnitude and resonant frequency) with its geometrical characteristics. Finally, the electromagnetic absorber properties are evaluated by using full-wave simulations.

2. THE METAMATERIAL-BASED ELECTROMAGNETIC WAVE ABSORBER

2.1 The operation pattern

The structure under study is shown in Figure 1. An isotropic ENZ material slab with a thickness d is placed on top of a perfect electric conductor (PEC) sheet. On the ENZ slab the considered metasurface (gold cross) is deposited. Let's assume the top layer as free space with electric permittivity ϵ_0 and magnetic permeability μ_0 . The ENZ material is described by the electric permittivity $\epsilon_{ENZ}(\omega) = \epsilon_0(\epsilon_r(\omega) - j\epsilon_i(\omega))$ and magnetic permeability $\mu_{ENZ} = \mu_0\mu_r$ with $\mu_r = 1$ the relative magnetic permeability of the free space and $\omega = 2\pi f$ is the angular frequency (rad/s). The structure is excited by an electromagnetic plane wave, having the electric field and the propagation vector \mathbf{k} inclined to the ground plane with a generic Angle Of Incidence (AOI) α , as depicted in Fig. 1(a). In this way, there is always an electric field component that can excite the structure. A wave may be reflected (r), transmitted (t), or absorbed (a), with their relationship given as $a = 1 - t - r$. In our case, due to the presence of the PEC, the transmission coefficient is zero, so the corresponding absorption a , is related to the reflection coefficient as $a = 1 - |r|^2$. As a consequence the absorption is obtained when the coefficient r approaches to 0.

2.2 Reflection Coefficient Evaluation

By using the Transmission Line Theory we developed an analytical approach to find the reflection coefficient r . The formula provides a powerful tool in order to link the absorption properties to the electromagnetic ENZ material ones (ϵ_r and ϵ_i), the angle of incidence (α) and the thickness d of the ENZ layer. We consider each layer as a section of the transmission line, each of one characterized by their parameters, as depicted in Figure 1 (b). In particular, $Z_0 = \eta \cdot \cos(\alpha)$ is dependent on the angle of incidence α with η the free space characteristic impedance ($\eta = 120\pi$). Z_{ENZ} is the impedance of the ENZ material, the PEC layer is represented by a short circuit.

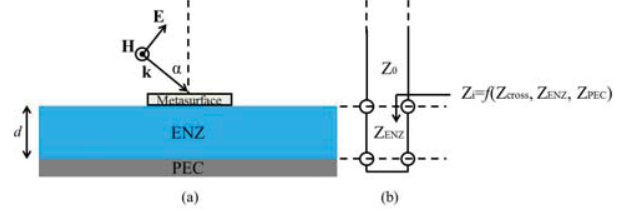


Figure 1. (a) A plane wave impinges (with an angle α) on the structure; (b) equivalent transmission line model.

The reflection coefficient is calculated by using the relation:

$$r = \left| \frac{Z_i - Z_0}{Z_i + Z_0} \right|^2 \quad (1)$$

where Z_i is a function of the metasurface (Z_{cross}), Epsilon-Near-Zero (Z_{ENZ}) and PEC (Z_{PEC}) impedance. In particular, from the transmission line theory:

- the ENZ layer is characterized by the following impedance:

$$Z_{ENZ} = \eta_{ENZ} \cos \left[\text{ArcSin} \left[\frac{\sin(\alpha)}{\sqrt{\epsilon_{ENZ}}} \right] \right] \quad (2)$$

where η_{ENZ} is the characteristic impedance of the ENZ layer.

- the PEC layer impedance reads $Z_{PEC} = 0$.
- the inclusion impedance Z_{cross} reads:

$$Z_{cross} = 2 \sqrt{\frac{L_{tot}}{C_{tot}}} \quad (3)$$

2.3 Metasurface Lumped Elements Evaluation by equivalent circuit model

The metasurface structure consists of planar array of resonant metallic cross-shape structure. In order to evaluate the Metasurface impedance Z_{cross} we can refer to the quasi-static approximation approach. Due to the fact that the inclusion size and their spatial periodicity are much smaller than the operative wavelength, the structure can be treated as a homogeneous medium described by effective parameters such as ϵ_{eff} and μ_{eff} ; electric permittivity and magnetic permeability, respectively. In other words its electromagnetic behavior can be studied through an equivalent LC resonant circuit model representation. Therefore, it can be possible to describe the reactive electric and magnetic phenomena, with lumped circuit elements such as

capacitance and inductance, respectively. The resonant frequency of the LC circuit is mainly determined by the geometry of the metallic structures and it reads:

$$\omega_0 = \frac{1}{\sqrt{L_{\text{tot}} \cdot C_{\text{tot}}}} \quad (4)$$

We assume, for simplicity, that the structure is excited by an impinging plane-wave having the electric and magnetic fields parallel and the propagation vector \mathbf{k} perpendicular to the plane containing the metal inclusion, as depicted in Figure 2(a), where only the unit-cell of the array structure is depicted. In this way, the resonator is excited by both the electric and magnetic field. The electric field, in fact, oscillates parallel to the metallic strip, exciting conduction currents on the resonator; instead the magnetic field oscillates transversally, generating a magnetic loop around the structure. The evaluation of the capacitive and inductive terms in the resonant circuit is related to the frequency range in which the structure works. Typically in the microwave region such terms depend exclusively on the size and geometry of the resonator. Consequently they are labeled as “geometric capacitance” and “geometric inductance”.

The geometrical terms can be written as the three-dimensional loop inductance and strip capacitance (in absence of the ground plane, in other words for the cross metal in air) as follows [23]:

$$L_{\text{geom}} = \mu_0 \mu_r \frac{1}{5} l \left(\text{Log} \left(\frac{2l}{w+t} \right) + \frac{1}{2} + \frac{w+t}{3l} \right) \quad (5)$$

$$C_{\text{geom}} = \varepsilon_0 \varepsilon_r \frac{w \cdot l}{t} \quad (6)$$

where l is the strip length, w the width and t the thickness. In presence of the ground plane the inductance of a strip inductor is decreased and for the capacitance the core and fringing effects arise. Therefore, the aforementioned formulas reads:

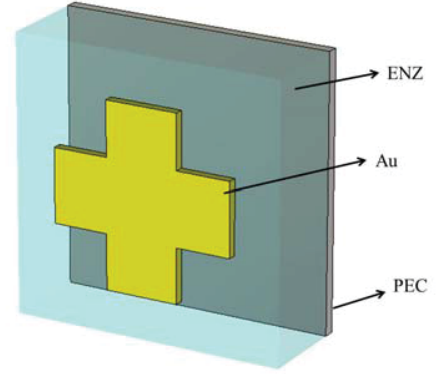
$$L_{\text{geom}} = \mu_0 \mu_r l \left(\frac{1}{2} - \frac{1}{5} \text{Log} \left(\frac{w}{t} \right) \right) \quad (7)$$

$$C_{\text{geom}} = \varepsilon_0 \varepsilon_r \left(\frac{(w-d)(l-d)}{d} \right) + 26(\varepsilon_r + \sqrt{2}) \frac{(w+l)}{\text{Log} \left(\frac{6d}{(d+t)} \right)} \quad (8)$$

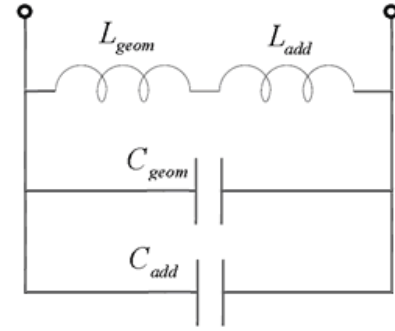
However, at higher frequencies (e.g., THz, infrared, and visible), the thickness of the metal can no longer be neglected and metals are not ideal conductors any more. At such frequencies, metals exhibit quite high losses and a dispersive behavior which can be represented in a given frequency range by the Drude model:

$$\varepsilon_{\text{metal}} = 1 - \frac{\omega_p^2}{\omega^2 - j\omega\gamma} \quad (9)$$

where $\omega_p = 2\pi f_p$ is the plasma frequency, $\omega = 2\pi f$ is the angular frequency and γ is the damping frequency.



(a)



(b)

Figure 2. (a) Metasurface-based Electromagnetic Wave Absorber unit cell; (b) equivalent circuit model of the metallic inclusion.

Considering such additional effects, the equivalent circuit model of the individual inclusion is the one reported in Figure 2(b), and the additional capacitance and inductance terms can be expressed as [24]:

$$C_{\text{add}} = \varepsilon_0 \varepsilon_r \frac{wt}{l} \quad (10)$$

$$L_{\text{add}} = \varepsilon_0 \frac{1}{wt} \frac{\omega^2 + \gamma^2}{\omega^2 \omega_p^2} \quad (11)$$

L_{add} and C_{add} represent the additional energy stored within the metal. The expression of L_{add} is strictly related to the inductive inertia of the electrons oscillating in the metal. Instead, the additional capacitance takes into account the stored electron potential energy (energy of electric field created by separate charges within the metal). Consequently, the resulting resonant frequency of the inclusion becomes:

$$\omega_0 = \frac{1}{\sqrt{(L_{\text{geom}} + L_{\text{add}}) \cdot (C_{\text{geom}} + C_{\text{add}})}} \quad (12)$$

and Z_{cross} reads:

$$Z_{\text{cross}} = 2 \sqrt{\frac{(L_{\text{geom}} + L_{\text{add}})}{(C_{\text{geom}} + C_{\text{add}})}} \quad (13)$$

2.4 The Metasurface-ENZ electromagnetic wave absorber

Starting from (1) and by using the formulas found in the previous paragraphs, in the following an analytical approach is developed to find the reflection coefficient r . It links the structure absorption properties to the electromagnetic material characteristics (ENZ and metasurface), the angle of incidence (α) and the geometrical parameters of ENZ and metallic inclusion (the ENZ layer thickness d , the strip layer thickness t , its width w and its length l). The corresponding reflection coefficient formula reads [25]:

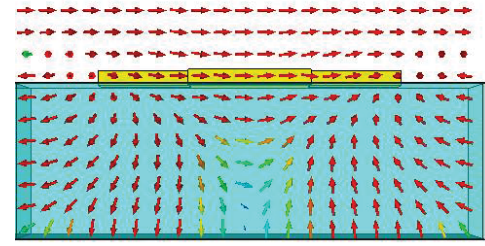
$$r = \frac{a_3 \rho^3 + a_2 \rho^2 + a_1 \rho + a_0}{b_3 \rho^3 + b_2 \rho^2 + b_1 \rho + b_0} \quad (14)$$

being $\rho = d_{\text{tot}}/\lambda_r$ (where d_{tot} is the sum of the ENZ and Metasurface thicknesses, λ_r is the resonant wavelength) and the coefficients are a function (not simple) of all the geometrical and electromagnetic parameters listed above of the ENZ and metasurface.

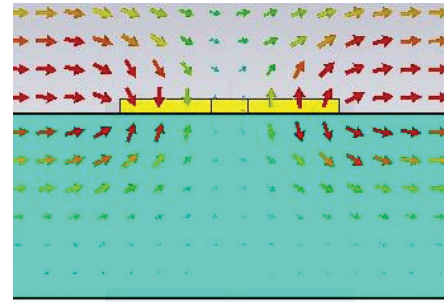
To describe the behavior of the structure under study with real materials, the dispersive permittivity models for Aluminum Zinc Oxide (AZO, $f_p=193\text{THz}$), Gallium Zinc Oxide (GZO, $f_p=217\text{THz}$) and Indium Tin Oxide (ITO, $f_p=210\text{THz}$) [26] were used. Simulations are performed by using a frequency domain solver, implemented by the finite integration commercial code CST Microwave Studio [27].

In absence of the metasurface on top, for normal incidence the reflection coefficient is reduced only when the thickness is large. Due to the fact that the only component of the electric field is purely longitudinal and it doesn't affect the absorption, at normal incidence ($\alpha=0$) the absorption can be exclusively attributed to the presence of both high losses and large thicknesses of the ENZ material. Instead, for all the other angle of incidence ($\alpha>0$) the electric field is magnified by the ENZ layer. As a consequence to obtain a good absorption, thin thicknesses can be used.

In order to avoid large thicknesses and to obtain a good absorption, on the top of the ENZ layer the metal cross was deposited. The metal inclusion, resonating in the ENZ region of the substrate material, permits to create additional electric field, not present before, between the strip and the ground plane (Figure 3a). In addition to this, to achieve polarization independent absorptivity the "cross" structure was used. In this way the structure can absorb for both polarization conditions (TE and TM waves) in a similar way.



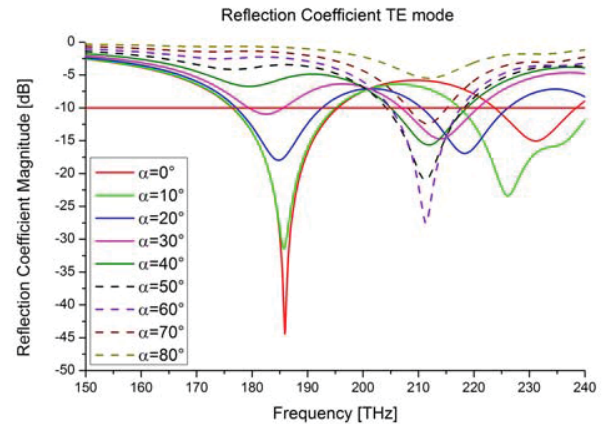
(a)



(b)

Figure 3. Electric field enhancement by combining the ENZ and Metasurfaces electromagnetic properties (a). Metasurface and standard dielectric substrate (b).

In Figure 4 the reflection coefficient spectra for the proposed structure in the TE case and TM case is presented for the AZO material. Similar results can be obtained with the other two materials (GZO and ITO). Let us fix the good absorption criteria when the resonant dip reaches the value of -10dB . From Figure 4 it is possible to note how absorption is achieved at all angles, from 0° to 80° ; in particular at the same frequency in the angle range $0^\circ - 30^\circ$ and for $\alpha>30^\circ$ the central resonant frequency blue shifts and the bandwidth enlarges ($40^\circ - 70^\circ$). It is interesting to note that for $\alpha>30^\circ$ new absorption resonant frequencies (in the ENZ region and outside) arise. It confirms the possibility to use the structure as a multi-band electromagnetic wave absorber.



(a)

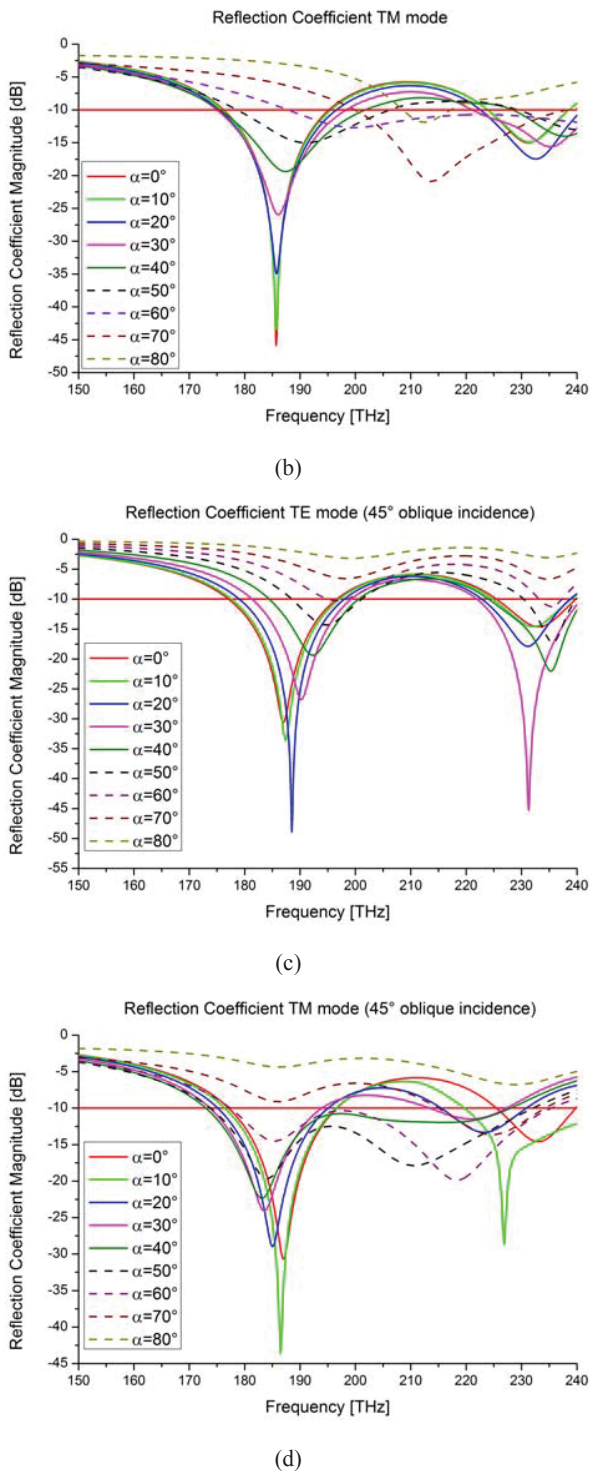


Figure 4. Absorption of the proposed structure for: (a) the TE case, (b) TM case, (c) TE 45° oblique and (d) TM 45° oblique incidence.

3. CONCLUSIONS

The study has shown that it is possible to combine the peculiar properties of ENZ and metasurface materials to design a new electromagnetic absorber, satisfying specific requirements. In this regard, first of all a new analytical model, describing the electromagnetic absorption characteristics of the structure (in terms of magnitude, bandwidth and frequency position) was presented. The proposed model is compared to the results obtained by full-wave simulations. Full-wave simulations have confirmed the ability of the proposed configuration to absorb in a larger incidence angles range (compared to absorbers existing in literature) for small thicknesses ($d_{\text{tot}} < \lambda_r/4$). The proposed structure offers great potential in a wide variety of practical application fields such as to build-up selective thermal emitters, for detection and sensing, for imaging and defense applications.

4. REFERENCES

- [1] Ruck G.T., Barrick D.E., and Stuart W.D. 1970. *Radar Cross Section Handbook*. Plenum, New York.
- [2] Munk B.A. 2000. *Frequency Selective Surfaces*. John Wiley & Sons, New York.
- [3] Salisbury W.W. 1952 US Patent 2599944.
- [4] Popov E., Maestre D., McPhedran R. C., Nevière M., Hutley M. C., and Derrick G. H. 2008. Total absorption of unpolarized light by crossed gratings. *Opt. Exp.* 16, 6146-6155.
- [5] Knott E., Shaeffer J.F., and Tuley M.T. 2004. *Radar Cross Section*. 2 nd ed., Scitech, Raleigh.
- [6] Landy N. I., Sajuyigbe S., Mock J. J., Smith D. R., and Padilla W. J. 2008. Perfect Metamaterial Absorber. *Phys. Rev. Lett.* 100, 207402.
- [7] Ayala A. I. M., Master of Science Thesis, Tufts University, USA, 2009.
- [8] Bingham C. M., Tao H., Liu X., Averitt R. D., Zhang X., and Padilla W. J. 2008. Planar wallpaper group metamaterials for novel terahertz applications. *Optics Express*. 16, 23, 18565-18575.
- [9] Liu X., Starr T., Starr A. F., and Padilla W. J. 2010. Infrared spatial and frequency selective metamaterial with near-unity absorbance. *Phys. Rev. Lett.* 104, 20, 207403.
- [10] Aydin K., Ferry V. E., Briggs R. M., and Atwater H. A. 2011. Broadband, polarization-independent resonant light absorption using ultrathin, plasmonic super absorbers. *Nature Communications*. 2, 517.
- [11] Alù A., Silveirinha M.G., Salandrino A., and Engheta N. 2007. Epsilon-near-zero metamaterials and electromagnetic sources: Tailoring the radiation phase pattern. *Phys. Rev. B*. 75, 155410-1-12.
- [12] Ziolkowski R.W. 2004. Propagation in and scattering from a matched metamaterial having a zero index of refraction. *Phys. Rev. E*. 70, 046608-1-12.
- [13] Engheta N. 2007. Circuits with Light at Nanoscales: Optical Nanocircuits Inspired by Metamaterials. *Science*. 317, 1698-1702.

- [14] Silveirinha M.G., and Engheta N. 2007. Theory of supercoupling, squeezing wave energy, and field confinement in narrow channels and tight bends using ϵ near-zero metamaterials. *Phys. Rev. B.* 76, 245109-1-17.
- [15] Alù A., Bilotti F., Engheta N., and Vegni L. 2007. Sub-wavelength Planar Leaky-Wave Components with Metamaterial Bilayers. *IEEE Trans. on Ant. and Prop.*, 55, 882-891.
- [16] Edwards B., Alù A., Young M., Silveirinha M., and Engheta N. 2008. Experimental Verification of Epsilon-Near-Zero Metamaterial Coupling and Energy Squeezing Using a Microwave Waveguide. *Phys. Rev. Letters*, 100, 033903-1-4.
- [17] Vakil A. and Engheta N. 2012. One-Atom-Thick Reflectors for Surface Plasmon Polariton Surface Waves on Graphene. *Opt. Communications*. 285, 3428-3430.
- [18] Silveirinha M. G., Alù A., and Engheta N. 2007. Parallel-Plate Metamaterials for Cloaking Structures. *Phys. Rev. E.* 75, 036603-1-16.
- [19] Alù A. and Engheta N. 2010. Cloaked Near-Field Scanning Optical Microscope Tip for Non-Invasive Near-Field Imaging. *Phys. Rev. Letters*. 105, 263906-1-4.
- [20] Jin Y., Xiao S., Mortensen N. A., and He S. 2011. Arbitrarily thin metamaterial structure for perfect absorption and giant magnification. *Opt. Express*. 19, 12, 11114-11119.
- [21] Feng S. and Halterman K. 2012. Coherent perfect absorption in epsilon-near-zero metamaterials. *Phys. Rev. B.* 86, 16, 165103-1-6.
- [22] Zhong S. and He S. 2013. Ultrathin and lightweight microwave absorbers made of mu-near-zero metamaterials. *Nature Scientific Reports*. 3, 2083, 1-4.
- [23] Saad T. 2009. *The Microwave Engineers Handbook*. Artech House.
- [24] Zhou J., Koschny T., Kafesaki M., Economou E. N., Pendry J. B., and Soukoulis C. M. 2005. Saturation of Magnetic response of split ring resonator at optical frequencies. *Phys. Rev. Lett.* 95, 223902- 223905.
- [25] La Spada L. 2014. *Electromagnetic sensors for biomedical and telecommunications applications*. Doctoral Thesis. RomaTre University.
- [26] Caglayan H., Hong S.-H., Edwards B., Kagan C. R., and Engheta N. 2013. Near-IR Metatronic Nanocircuits by Design. *Phys. Rev. Lett.* 111, 073904.
- [27] CST STUDIO SUITE™ 2013, CST of America, Inc., www.cst.com.