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SLOW MICROWAVE WAVEGUIDE MADE OF NEGATIVE PERMEABILITY METAMATERIALS

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ABSTRACT: *The framework for designing a slow light waveguide structure which operates in the GHz and up to THz frequencies is outlined. The design for the structure consists of a dielectric core layer cladded with negative permeability metamaterials. The parameter space for the metamaterial has been identified for the waveguide to stop light and the negative permeability is achieved by split-ring resonator (SRR) metallic elements. A prototype structure operating at 8.5 GHz is proposed. Numerical simulations of electromagnetic waves interacting with SRRs have been performed to extract scattering parameters and a parameter retrieval method has been used to verify the designed window for negative permeability.* © 2009 Wiley Periodicals, Inc. Microwave Opt Technol Lett 51: 2705–2709, 2009; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.24727

Key words: *slow light; negative permeability metamaterials; guided modes; split-ring resonators; parallel plate waveguide*

1. INTRODUCTION

Recently there is a strong interest in slow light [1] for optical buffers [2] and memories. This is partly driven by the progress in optical integrated circuits where optical buffers are one of the most important components. Without slow light architectures, only an optical fiber with a length of a few kilometers can provide enough delay time for optical networking switching. However in microwaves, the use of coaxial cable for wave delay is impractical due to the much longer wavelength in the radio frequency (RF) and microwave wavelengths. A long pulse delay is normally achieved by electronic circuits. Nevertheless, it is still very desirable to have RF and microwave delay lines without electronic circuits.

Slow light has been demonstrated in many systems by using very different methods, such as the electromagnetic induced transparency [3] and the coupled resonator structures [4, 5]. Slow light in optical fibers has also been achieved [6]. Only very recently the idea of using double-negative metamaterial (DNM) [7] as waveguide core layer to slow down or stop light was proposed by Tsakmakidis et al. [8] and the trapped rainbow phenomenon was illustrated. The drawback with delay lines made of these types of structures [8, 9] is the narrowness of the bandwidth of DNM, which will yield a very small delay-bandwidth product [4]. The scheme to design broad bandwidth slow light waveguide [10] utilizing indefinite metamaterials [11] has been developed [12, 13]. It was also reported that other types of metamaterials such as metallic gratings in THz range [14] can reduce the group velocity by a factor of 10^3–10^4. Interestingly, the intrinsic loss in negative-index metamaterials will render stopping light impossible [15, 16]. To avoid the difficulty of realizing DNM with small loss, slow light waveguide with dielectric core layer and single-negative metamaterial cladding was subsequently proposed [17]. This design of slow light waveguide also opens the door of using gain media to compensate loss and bring light to a standstill possible.

The idea of electromagnetic metamaterials started in the field of RF and microwaves with the so-called artificial dielectrics [18]. Active research on negative refraction [19] was fueled by the realization of DNM by using split-ring resonators (SRR) [20] and wires [21] structure in microwaves [22]. Thus, single-negative metamaterials in microwaves is a natural platform to demonstrate the realization of stopping light.

Microwaves are often guided in hollow or dielectric filled waveguide cladded with metal. It is well known that near the cutoff thickness or diameter, the group velocity of microwaves can be very small. However, the problem is that at the cutoff thickness or wavelength, both group velocity and phase velocity are zero, leading to complete reflection.

In this article, we focus on trapping transverse electric (TE) waves by using negative permeability metamaterials. We show that zero group velocity can be realized at finite phase velocity. The article is organized as follows: In Section 2, we give exact solutions for guided TE modes in a planar waveguide and derive the condition on parameter space for stopping light. In Section 3, SRRs are designed to achieve negative permeability below 10 GHz. Numerical simulations on the SRRs were performed to extract the effective permittivity and permeability. A prototype slow-light microwave structure is theoretically proposed in Section 4. We conclude in Section 5.

2. TE MODES IN PLANAR WAVEGUIDE

We consider a two-dimensional (2D) structure which is formed by a parallel plate waveguide (PPW). The vertical direction or the normal to the PPW is along the y-direction. If the thickness of the PPW is h, then for frequency below $c/2h$, the waveguide can only support TE waves whose electric field is in the y-direction. For example for $h =$ 1 cm, microwaves below 15 GHz will be only TE waves.

Therefore, we only need to consider TE wave propagation in the xz-plane. We further consider a slab waveguide made of a dielectric with ε_D cladded by a negative permeability metamaterial with $\mu_M < 0$ and $\varepsilon_M > 0$ as shown in Figure 1. The dielectric core layer has a thickness d in the x-direction. The guided mode

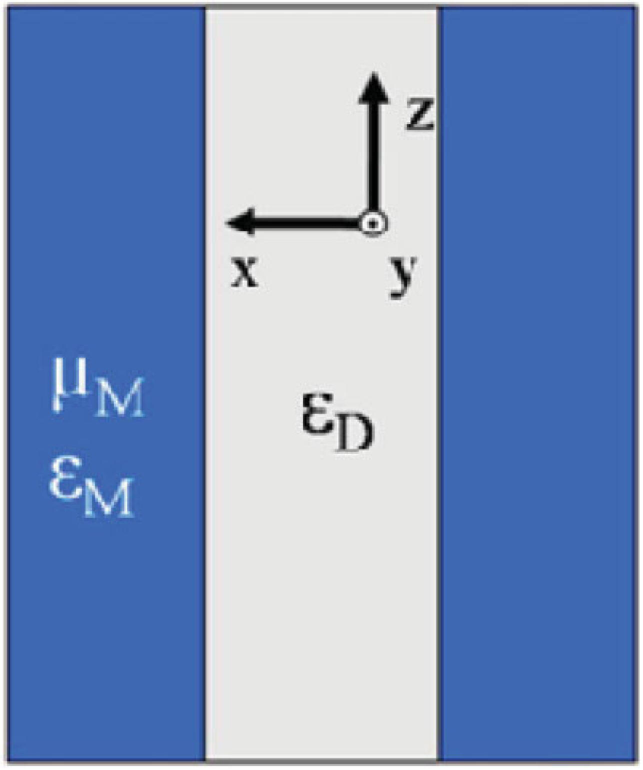

Figure 1 A sketch of a slab waveguide (top view) inside a parallel plate waveguide. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

travels along the z-direction with the phase $\exp[i(k_z z - \omega t)]$. The transverse direction of the waveguide is along the x-axis.

The transverse component of the TE modes inside the core layer and the decay constant in the cladding are $k_D = \sqrt{\varepsilon_D k_0^2 - k_z^2}$ and $\kappa_M = \sqrt{k_z^2 - \varepsilon_M \mu_M k_0^2}$, respectively. We introduce a free parameter ξ which gives $k_D = \sqrt{\varepsilon_D - \varepsilon_M \mu_M} k_0 / \sqrt{1 + \xi^2}$ and $\kappa_M = \sqrt{\varepsilon_D - \varepsilon_M \mu_M} k_0 \xi / \sqrt{1 + \xi^2}$. After matching the continuity condition for the tangential electric and magnetic field at the boundary, the eigenmodes equation is obtained as

$$\sqrt{\varepsilon_D} k_0 d = f_{TE}(\xi) \tag{1}$$

where

$$f_{TE}(\xi) = \sqrt{1 + \xi^2}[m\pi - 2\arctan(\xi/\rho)]/\sqrt{1 + \sigma} \tag{2}$$

with $\sigma = -\varepsilon_M \mu_M / \varepsilon_D$ and $\rho = -\mu_M$. Here the index m denotes the parity of the TE modes with $m \geq 1$. In terms of ξ, the phase index is given by

$$n_p = \frac{\sqrt{\varepsilon_D}\sqrt{\xi^2 - \sigma}}{\sqrt{1 + \xi^2}}. \tag{3}$$

To support guided TE modes which are our interest, one has $\xi \geq \xi_{min} = \sigma^{1/2}$ so that n_p is real.

For an ordinary waveguide such as a free-standing dielectric waveguide, the phase index n_p is a monotonically increasing function of the waveguide thickness d. Thus the waveguide will only support at most one forward-wave TE$_m$ mode for a fixed m. However if the following condition is satisfied [17],

$$\rho(1 + \sigma)/[\sqrt{\sigma}(\sigma + \rho^2)] + \arctan(\sqrt{\sigma}/\rho) \geq m\pi/2. \tag{4}$$

Equation (1) will give two solutions for a fixed m for certain d. One solution is a forward-wave mode and the other is a backward-wave mode. At a critical thickness d_c, these two modes will merge into a single mode, which has both zero total energy flow and zero group velocity. One can prove that the total energy flow P_z is indeed zero at the critical thickness [17],

$$P_z = -\int_{-\infty}^{\infty} E_y H_x^* dx = P_z^{in} + P_z^{out} \tag{5}$$

with

$$P_z^{in} = \frac{k_z d}{2k_0}\left[1 + (-1)^m \frac{\sin k_D d}{k_D d}\right].$$

$$P_z^{out} = \frac{k_z d}{2k_0}\left[\frac{1 + (-1)^m \cos k_D d}{\mu_M \kappa_M d}\right]. \tag{6}$$

One notes that $P_z^{in} > 0$ and $P_z^{out} < 0$. When dissipation is present, the physical energy flow is Re P_z.

The parameter space for stopping TE$_2$ modes is shown in Figure 2(a). From this plot, one finds that there exists a maximum $\sigma_{max} = 0.2775$. For $\sigma < \sigma_{max}$, there is a finite range of μ_M such that the waveguide can stop light. For example, if $\mu_M = -1$, and $\sigma < 0.1277$, the waveguide can trap TE mode waves.

We note that the above condition is also valid for cladding with anisotropic permeability, such that one has $\mu_{Mx}, \mu_{Mz} < 0$ and $\mu_{Mx} \neq \mu_{Mz}$. For this cladding, one has $\sigma = -\mu_{Mx}\varepsilon_{My}/\varepsilon_D$ and $\rho = \sqrt{\mu_{Mx}\mu_{Mz}}$. This can be used to model the TE modes in line defect waveguide in photonic band gap materials [4].

For wave propagating in waveguide structure, one has $n_p = n_p(k_0, d)$ with k_0 the free space wave number and d the waveguide dimension. For planar waveguide, d is the thickness while for cylindrical waveguide, d is the diameter. The group refractive index is $n_g = n_p + k_0 \partial_{k_0} n_p$. Thus the divergence of $\partial_{k_0} n_p$ will lead to stopping light, which can be realized by engineering the dispersion of a bulk medium. However, for waves in a waveguide, $\partial_{k_0} n_p$ and $\partial_d n_p$ can share the same divergence. Thus, in certain waveguide structure, the divergence of $\partial_d n_p$ will also lead to stopping light. In this case, the light with certain wavelength will be stopped at certain waveguide dimension d. Thus, one is able to stop light by controlling the geometrical parameters.

For comparison, we consider the TE modes in a planar dielectric waveguide cladded with a perfect electric conductor (PEC). Only with PEC cladding, one can have $P_z = 0$ at the band cutoff thickness $d_c = \pi/\sqrt{\varepsilon_D} k_0$. One has $n_p = \sqrt{\varepsilon_D - (\pi/k_0 d)^2}$ and $n_g = n_p + (\pi/k_0 d)^2/n_p$. When $d = d_c$, one has, $n_p = 0$ and $n_g = \infty$. Due to the vanishing of $n_p = 0$, one has $P_z = 0$ and complete reflection at $d = d_c$. This waveguide does not support degenerate modes. For dielectric waveguide cladded by metal with finite conductivity such as copper in the microwave range, the group velocity of the TE modes is always positive. However, for our waveguide, the negative permeability of the cladding material will give rise to zero group velocity mode. The presence of loss will impart a small imaginary part to the energy flow. Thus, with moderate material loss, our waveguide will be able to trap light.

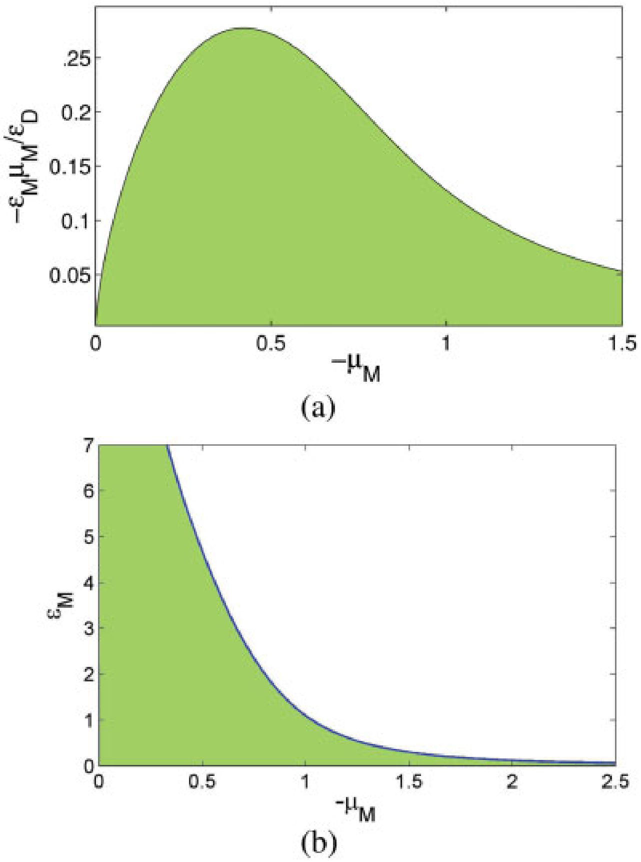

Figure 2 Parameter space (shaded area) for stopping light in a waveguide with (a) dielectric core (ε_D) and cladded with a negative permeability metamaterial ($\mu_M < 0$ and $\varepsilon_M > 0$) and (b) dielectric core with and cladded with a negative permeability metamaterial. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

3. NEGATIVE PERMEABILITY METAMATERIALS

The booming growth of the field of negative-index metamaterials is largely due to the possibility of designing and artificially engineering micro-/nano metamaterials with tailor-made negative permeability. The obstacle to realizing negative-index metamaterials in the visible is also due to the difficulty of creating magnetic resonance in the region above the infrared.

Since there is no need for DNMs, the relative easiness of design and fabricating single-negative metamaterials will enable our proposed scheme to trap and stop light be realized for all frequencies in principle. Of course, different designs of the single-negative metamaterials will be needed for different frequency bands. Negative permeability materials in microwave are readily available, e.g. ferrite in the GHz range. Furthermore negative permeability has also been realized in high dielectric systems [23, 24] and other metamaterial architectures [25].

Metamaterials with negative permeability can also be realized by using SRRs [20]. Here, we will focus on using SRR as negative-μ metamaterial. To meet the required parameters as shown in Figure 2(a), core layer with high relative permittivity is required, e.g. alumina ($\varepsilon_D = 8.6$). The requirement on μ_M and ε_M is shown in Figure 2(b).

A more detailed schematic of a single SRR is shown in Figure 3. For our design, we consider a simple cubic lattice of SRR with a periodicity $a = 5$ mm. The lateral size of the SRR is $w = 3$ mm, whereas the other parameters are $d = c = g = 0.33$ mm. The 0.25 mm thick copper SRRs are deposited on a 0.45 mm thick epoxy dielectric substrate ($= 4.4$).

The effective parameters are retrieved from the inversion of the transmission and reflection coefficients by using the approach described in Refs [26, 27]. The numerical computation is performed on a single unit cell with periodic boundary condition by using the commercially available software HFSS [28]. Figure 4(a) shows the simulated transmission and reflection coefficient for normal incidence. For this design the resonance at which the transmission reaches a minimum is at 8.2 GHz. The retrieved effective parameters [Figs. 4(b) and 4(c)] show, as theoretically predicted, a positive imaginary part for the permeability and a negative imaginary part for the permittivity. The reason that the imaginary part of the permittivity can be negative is due to the finite lattice period a associated with the metamaterial structure, as discussed in [27]. This effect is called antiresonance, in contrast to the resonance shown by the positive imaginary part of μ_M.

The next step for the slow light waveguide design is to find the more appropriate values of ε_M and μ_M to meet the condition in Eq. (4) for TE$_2$. This requires that the magnitudes of both ε_M and μ_M be small. From our simulations we fixed our choice at $f = 8.57$ GHz, where $\mu_M = -0.22 + i0.27$ and $\varepsilon_M = 4.4 - i0.14$.

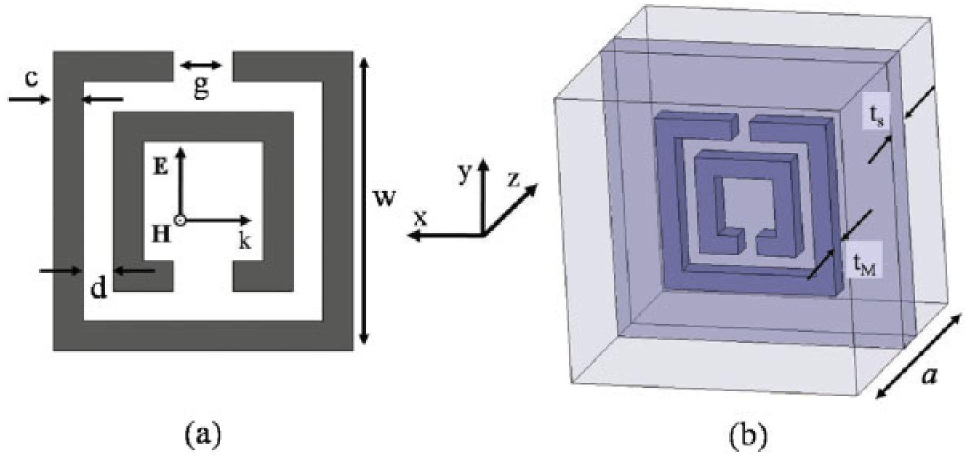

Figure 3 (a) SRR layout. (b) SRR unit cell. The dimensions are $w = 3$ mm and $d = c = g = 0.33$ mm. The unit cell size is $a = 5$ mm. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

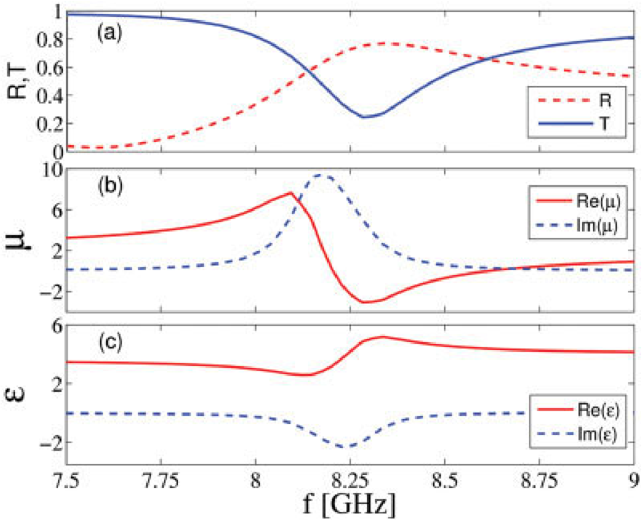

Figure 4 (a) Computed transmission and reflection coefficients. (b,c) The retrieved effective parameters μ and ε for SRR shown in Figure 3. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

The above SRR structure is not optimized yet. The loss in SRRs needs to be trimmed down. Recent designed SRRs for cloaking [29] have very small loss and can be used for our purpose at frequencies below that for cloaking. To have a broad bandwidth, ε_M should be reduced so that one can have larger window of μ_M to satisfy the stopping light condition Eq. (4).

4. SLOW LIGHT CONDITION AND EXPERIMENTAL SETUPS

The phase indices of TE_m modes are calculated and plotted in Figure 5 for a waveguide with core layer $\varepsilon_D = 8.6$ and cladded with $\varepsilon_M = 4.4$ and $\mu_M = -0.22$ at 8.57 GHz. The critical thickness is $d_c = 0.953$ cm. For simplicity of calculation, we have ignored the imaginary parts of the permittivity and permeability. By taking into account the dispersion relation of the SRRs, the group velocity of the guided TE modes can be calculated exactly [17]. Around the critical thickness, the group velocity has the behavior $v_g \propto \sqrt{d - d_c}$. The group velocity for different $d > d_c$ will be measured and compared with theoretical prediction.

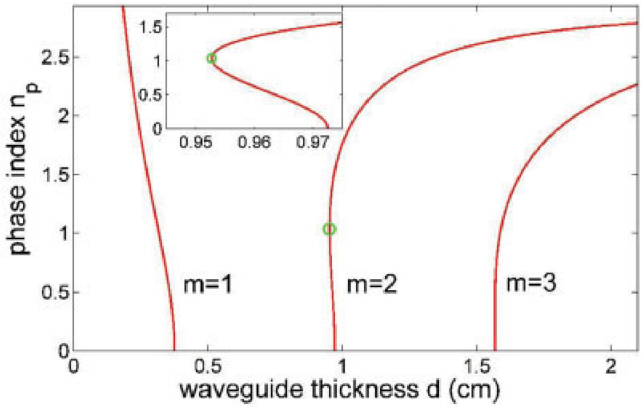

Figure 5 Phase index as a function of thickness d for waveguide with core layer $\varepsilon_D = 8.6$ and cladded with $\varepsilon_M = 4.4$ and $\mu_M = -0.22$ at 8.57 GHz. The circle marks the location of zero group velocity. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

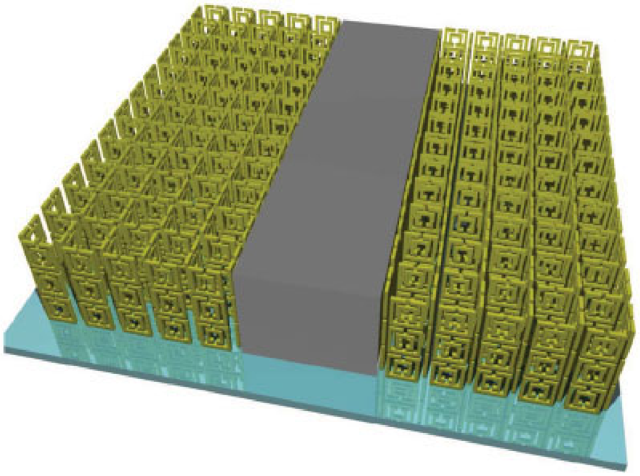

Figure 6 3D illustration of the slow-light structure. The SRRs and alumina rod (grey) are placed between two parallel metal plates. The top plate is not shown here. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

A 3D illustration of the designed structure is shown in Figure 6. To have isotropic permeability in the xz-plane, different orientations of SRRs will be used in our undergoing experiments.

5. CONCLUSIONS

In this article, we have considered the wave propagation in a planar dielectric waveguide cladded by negative permeability metamaterials. We have found that under certain conditions, the waveguide with a fixed thickness can support forward-wave and backward-wave modes. At critical thickness it can support degenerate TE modes with zero group velocity. Slow light can thus be achieved at the critical waveguide thickness without the use of DNMs.

The relaxation of the requirement of DNMs will greatly enhance the feasibility of realization and improve the performance of trapping light for applications. Cladding by single-negative metamaterials allows the realization of trapping light in wider range of frequencies with less dispersion. Our waveguide structure will have much lower loss than that made of DNMs. With the advance of magnetic metamaterials in the deep THz [30–32], our waveguide can be realized to slow down and trap from GHz to THz waves.

We have limited our discussion to only planar waveguides. Cylindrical waveguides can also be considered and similar results can be obtained. Our results can be readily tested in experiments. Work toward this end is underway.

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TRANSFORMATION OPTICS-INSPIRED METAMATERIAL COATINGS FOR CONTROLLING THE SCATTERING RESPONSE OF WEDGE/CORNER-TYPE STRUCTURES

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ABSTRACT: *Transformation optics has recently emerged as a powerful and systematic approach to design application-oriented metamaterials. In this letter, following up on our previous studies on thin planar retroreflectors, we show how it is possible, in principle, to design "transformation medium" coatings capable of controlling the scattering response of metallic corner- and wedge-type structures so as, e.g., to strongly enhance the specularly reflected component. We validate our results via a full-wave study of the near- and far-field responses, and envisage possible applications.* © 2009 Wiley Periodicals, Inc. Microwave Opt Technol Lett 51: 2709–2712, 2009; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.24720

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1. INTRODUCTION

The rapid advances in the engineering of metamaterials with controllable anisotropy and spatial inhomogeneity have recently led to the development of a novel framework, typically referred to as "transformation optics" [1, 2], for the design of metamaterial-based devices that allow unprecedented control in the electromagnetic (EM) response. Besides the celebrated "invisibility cloaking" (experimentally verified at microwave frequencies [3] and within the visible range [4]), many other exciting developments are foreseen in a wide range of applications (see, e.g., [5–13] for a sparse sampling).

In a series of ongoing investigations, we have been concerned with the application of transformation optics to the design of coatings for controlling the scattering response of flat metallic structures. For instance, in [14], we addressed the design of thin planar retroreflectors inspired by the dihedral corner-reflector geometry. In this framework, we showed that it was possible to design a metamaterial layer (with anisotropic and inhomogeneous distribution, and with constitutive parameters values that were positive, everywhere limited, and not particularly high), which laid on a metallic plate, would lead to a strong enhancement of the monostatic radar cross-section (RCS) response.

Following up on the earlier study, in this letter, we deal with more complicate geometries featuring wedge- or corner-type metallic scatterers. To illustrate the potentials of the transformation-optics approach in controlling the scattering response, we focus on a rather challenging example, namely, the design of metamaterial coatings capable of inducing an overall behavior similar to that exhibited by a planar metallic sheet (i.e., with a predominant specular response). Such response may be very useful in radar countermeasure applications, where dealing with wedge/corner-type structures represents a critical issue for the reduction of the overall visibility.

Following the standard transformation-optics approach, we first design the desired field behavior, for both the wedge- and corner-