Miniaturizing Electromagnetic Invisibility Cloaks Using Double Near Zero Slabs

Reza Dehbashi, Konstanty S. Bialkowski, and Amin M. Abbosh
The School of ITEE, University of Queensland, St. Lucia, Brisbane, QLD 4067, Australia
(e-mail: r.dehbashi@uq.edu.au).

***Abstract*— A novel method to miniaturize electromagnetic invisibility cloaks is introduced using Double Near Zero (DNZ) slabs, in which both the permittivity and permeability are close to zero. Based on the proposed technique, the phase pattern tailoring property of DNZ materials is utilized to miniaturize electromagnetic devices. The concept is applied to both types of internal and external cloaks, where their sizes are reduced by 50% by changing their structure from a cylindrical shape to a half cylinder shell. The half-sized internal and half-sized external cloaks can still conceal any object with any shape and material, inside and outside the cloaks, respectively. To illustrate that, the results show that an arbitrary shape of dielectric with arbitrary high value of relative permittivity of 20 is concealed by the half-sized internal cloak. For the half-sized external cloak, the presented results show that it can conceal an external half ring dielectric with high relative permittivity of 20 using anti-object in the structure of the cloak. For the analysis, the transverse electric (TE) Z-polarization is used. For the transverse magnetic (TM) Z-polarization, the duality principal can be applied.**

Keywords*— *Double near zero materials (DNZ), permittivity near zero (MNZ) materials, permeability near zero (ENZ) materials, miniaturization, cloaking.

I. INTRODUCTION

Considering the recent developments in near-zero-parameter materials [1-8], a new method of miniaturizing electromagnetic devices is introduced using Double Near Zero (DNZ) slabs. The outgoing waves' phase front get the exterior shape of the DNZ materials. This property of the DNZ materials is used to miniaturize electromagnetic devices. Thickness of the slab compared to the wavelength of the field for very imperfect DNZ materials could be concerning for phase-delay-sensitive applications. However, due to the high velocity of waves inside the near perfect DNZ materials, the phase delay is not of a concern. Another solution could be using thin slabs compared to the wavelength for phase-delay-sensitive applications.

In this paper, the phase pattern tailoring property of DNZ is applied to both the internal and external cloaks which have the structures explained in [9]. Using our proposed technique, the sizes of both types of cloaks are reduced by 50%. For the half-sized internal cloak, it is shown that the cloak can still hide any objects with any shape and material. It has been illustrated with a cloaked object with arbitrary shape and a high dielectric value of 20. For the half-sized external cloak, it is shown that it can hide external objects using anti-object in the cloak structure. In the simulations a ring with high dielectric value of 20 has been concealed. For the numerical and analytical analysis, the TE_z polarization is used. For the TM_z polarization, the duality principal can be applied.

II. MINIATURIZING ELECTROMAGNETIC DEVICES CONCEPT USING DOUBLE NEAR ZERO SLABS

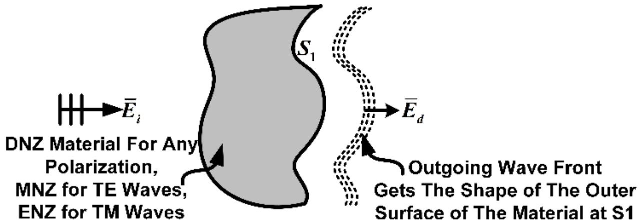

Fig. 1. Phase pattern tailoring of waves using near-zero-materials.

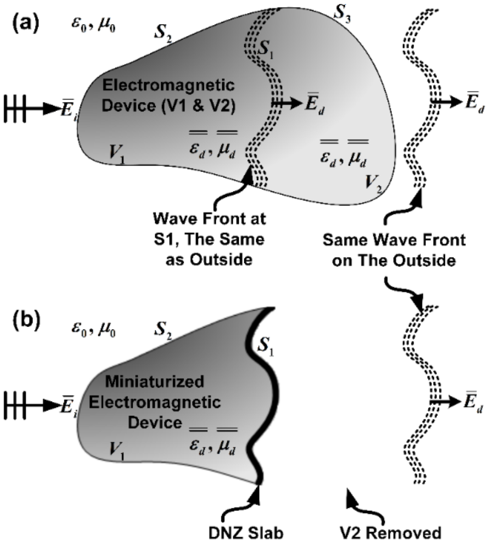

Fig. 2. The idea of miniaturization of electromagnetic devices using DNZ slabs: (a) The whole electromagnetic device where at a certain surface of S_1 has the same phase front as the outgoing wave $\bar{E}_d$ does. (b) Miniaturized electromagnetic device using DNZ slab at S_1.

When a wave with any polarization passes through a DNZ material, the wave front of the outgoing wave gets the shape of the outer surface of the DNZ material. This phenomenon is used to miniaturize some electromagnetic devices. For TE and TM polarized waves, the same happens if the material is permeability-near-zero (MNZ) and permittivity-near-zero (ENZ), respectively (Fig. 1). However, for MNZ and ENZ materials, the amplitude of the outgoing waves can change. Therefore, they might not be good candidates for our application. Phase pattern tailoring of ENZ materials for TM polarized waves has been explained in [1]. The idea of miniaturization of electromagnetic devices using DNZ slabs is as follows: Assume an electromagnetic device is enclosed by surfaces S_2 and S_3, composed of volumes $V_1$and V_2, filled by a medium with tensors of $\overline{\overline{\varepsilon_d}}, \overline{\overline{\mu_d}}$. The device is illuminated by $\bar{E}_i$ field and the field at the other side of the device is $\bar{E}_d$. It is assumed the surrounding medium is free space, however it could be any material. Assume, at surface S_1 inside the device, the phase front of the field is the same as the phase front, outside of the device (or the same as the phase front at output of the electromagnetic device) (Fig. 2b). In this case, by removing the volume V_2 and adding a DNZ slab on the surface S_1, the same field front as in case (a) is obtained. In the following examples of miniaturizing of the cloaks, the amplitude would be not change, as well. Depends on the thickness of the slab, there would be a phase delay for the output field without changing the phase front, however due to the high speed of wave inside the slab that should not be concerning for most applications. For phase-shift sensitive applications, either the slab should be as thin as possible compared to the wavelength of the field or the material parameters be as close as possible to zero.

III. 50% REDUCTION OF SIZE OF CLOAKS USING THE INTRODUCED NOVEL MINIATURIZATION TECHNIQUE

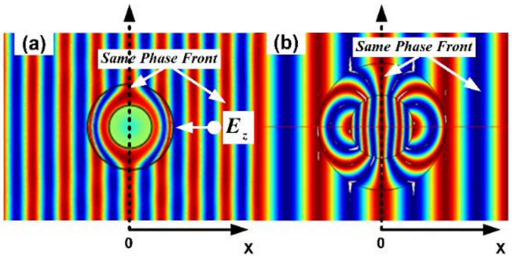

Fig. 3. The cloaks before miniaturization. Same phase fronts at the center line (dotted line at X=0) of the cloaks and outside. The simulation results for E_z field component due to a z-polarized plane wave incidence from right onto (a) an internal cloak with a=0.075λ_0, b=0.22λ_0. (b) an external cloak with a=0.5λ_0, b=λ_0 (λ_0 denotes the wavelength in free space). The parameters a and b are inner and outer radii of the cylinders, respectively.

Fig. 4 shows half-sized cloaks using DNZ material. A DNZ slab is replaced with the other half of the cloaks where the phase front of the field is the same as the phase front at outside of the cloak. The shape of the DNZ slab has the same shape of the phase front in that place (straight shape). The considered slab is thick, so the phase delay can be illustrated. However, that phase delay could be ignored, because according to the definition the speed of the wave inside the DNZ is almost infinite. As a result of that, it can be seen that at any time, the field across the slab is uniform. The field inside the DNZ slab is always a constant value. It is proven, analytically. For non-perfect DNZ slabs which the constitutive parameters have values not so close to zero, phase delay can be noticed, depends on the values of $\varepsilon_{slab}, \mu_{slab}$. For phase sensitive applications, either a perfect thick DNZ or a thin non-perfect DNZ slab proportional to the wavelength of the illuminated field should be used. The constitutive parameters of the DNZ slab in these simulations are: $\varepsilon_{slab} = 10^{-6}$, $\mu_{slab} = 10^{-6}$. Fig. 4(a) shows a half-sized internal cloak. The dielectric inside the cloak (ε_d) for the internal cloak could be in any shape and value. For the simulation, the dielectric value of 20 with arbitrary shape has been chosen. Fig. 4(b) shows half-sized external cloak. Unlike internal cloak, the dielectric value inside the external cloak (ε_d) cannot be in any arbitrary shape and value and it depends on the shape and size of the cloak. For the external cloak, $\varepsilon_d = (c/a)^2 = 16$ where c=2λ_0, a=0.5λ_0, b=λ_0. The parameters a and b are internal and external radii of the cylindrical cloak, respectively, and c is the radius where the external object must be placed within there to get invisible (within b<r<c). In this figure, the arbitrary value of ε_d=20 has been used.

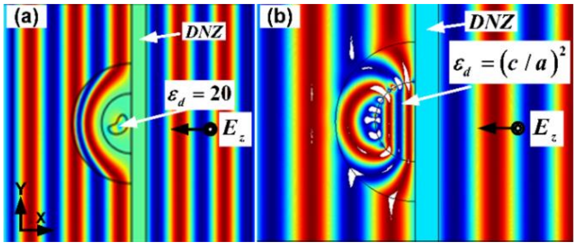

Fig. 4. (a) Half-sized internal cloak. (b) Half-sized external cloak.

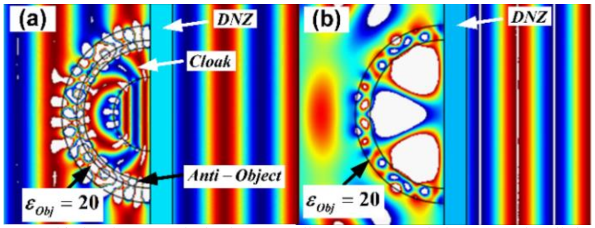

Fig. 5. Half-sized external cloak concealing an external ring: (a) The dielectric ring of ε_r =20 (1<r<1.2) is cloaked by an anti-object half-ring as the complementary medium for the half-sized external cloak can still function well even to cloak a high dielectric material. (b) The dielectric ring of ε_r =20 (1<r<1.2) without the cloak and anti-object. It can be seen how it strongly perturbed the field around.

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