Electromagnetic tunneling in a sandwich structure containing single negative media

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In this paper, the electromagnetic (EM) tunneling phenomenon in a sandwich structure consisting of an mu-negative (MNG) medium, air, and an epsilon-negative (ENG) medium is investigated by means of the transfer-matrix method and microwave experiments. Both results demonstrate that by properly choosing parameters, EM waves can efficiently tunnel through a long distance over several hundreds times the length of the device. Unlike in the ENG-MNG slabs, the electric and the magnetic field of the tunneling mode is interestingly separated and localized at the interface of MNG-air and ENG-air, respectively. Therefore, this structure may be important for potential applications in wireless information and energy transmission, for its high efficiency, security, and health.

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In the last decade, people's knowledge about electromagnetic waves expanded quickly as a new concept, metamaterial, was introduced [1–13]. Metamaterials include double negative (DNG) materials and single negative (SNG) materials. For DNG materials, both the permittivity and the permeability are negative; for SNG materials, only one, either the permittivity or the permeability is negative. In metamaterials, the propagation of electromagnetic (EM) waves exhibits lots of unique properties, leading to some extraordinary applications, for instance, subwavelength lensing, electromagnetic cloaking, and so on [5–10]. In particular, the phenomenon of light tunneling in opaque SNG metamaterials has attracted many people's interest recently [11–13]. Although an isolated SNG metamaterial is opaque, for the reason that the wave propagating in it is evanescent, a conjugate matched pair made of epsilon-negative (ENG) and mu-negative (MNG) metamaterials will be transparent.

Recently, nonradiative electromagnetic transfer has attracted many people's interest for its promising applications in wireless information and energy transfer [14,15]. Another scheme is described as follows: When two resonant objects work at the same frequency, they tend to efficiently exchange energy through evanescent wave coupling; if any one of them is turned off, the electromagnetic energy is just highly localized around one resonator, almost without power losses. These properties are found useful in the quickly developing wireless technologies—WIFI, Bluetooth, ID tags, and so on. As we know, a traditional wireless system should include two antennas at least, with EM energy propagating between them in the form of a plane wave. As the antenna emitting EM waves cannot tell whether any receivers exist in its functional area, it has to work endlessly, with massive unnecessary power losses. Moreover, as most of the antennas used in wireless communication are omnidirectional, only a small part of the EM energy is received by the receiver, with most energy spreading to the wide and empty space. This reveals another reason for the inefficient use of power in traditional antenna systems. In order to increase the received signal strength, a common method is to enlarge the emitting power. However, it could cause another unwanted security problem: your wireless signals may be received by your neighbors. In addition, the enlarged EM signals may do harm to people's health. In order to solve these problems, new concepts must be introduced.

In this paper, we investigate the EM tunneling phenomenon in a MNG-air-ENG structure, implied by the common property of evanescent wave coupling both in the nonradiative EM transfer system and in the SNG slabs. By means of the transfer-matrix method and microwave experiments, we investigate the transmission properties of this sandwich structure including an ENG slab, air, and a MNG slab. Both results demonstrate that by properly choosing parameters, EM waves can efficiently tunnel through a long distance in air that is over several hundreds of times the length of the SNG slabs. Unlike in the ENG-MNG slabs, the electric and the magnetic field of the tunneling mode are interestingly separated and localized at the interface of MNG-air and ENG-air, respectively. Therefore, this structure may be important for potential applications in wireless information and energy transfer, for its high efficiency, security, and health.

First we investigate the tunneling phenomenon in a MNG-air-ENG structure by means of the transfer-matrix method. Let a wave be normally incident from a vacuum onto the MNG-air-ENG structure, as shown in Fig. 1. The black, the light gray, and the gray regions denote the MNG material,

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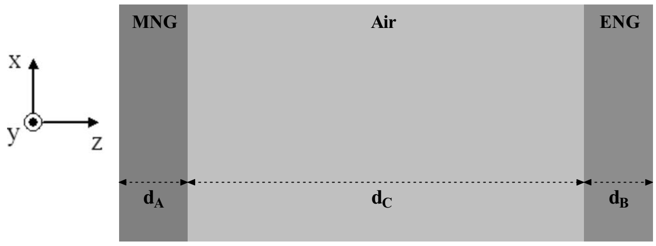

FIG. 1. Schematic of the sandwich structure consisting of ENG material, air, and MNG material.

the air, and the ENG material, respectively. For each layer, we obtain a 2×2 transfer matrix, given as

$$M_i = \begin{bmatrix} \cos\delta_i & \dfrac{i}{\sigma}\sin\delta_i \\ i\sigma_i\sin\delta_i & \cos\delta_i \end{bmatrix},$$

where $\sigma=\varepsilon/n$ and $\delta=kd$. The transfer matrix that includes the entire three layers can also be given as

$$M = M_A M_C M_B = \begin{bmatrix} A & B \\ C & D \end{bmatrix},$$

where M_A, M_B, M_C are the transfer matrix for the MNG, ENG, and air layer, respectively. Therefore, the reflection coefficient r and the transmission coefficient t can be figured out as follows:

$$r = \frac{A\sigma_0 + B\sigma_0\sigma_0 - C - D\sigma_0}{A\sigma_0 + B\sigma_0\sigma_0 + C + D\sigma_0},$$

$$t = \frac{2\sigma_0}{A\sigma_0 + B\sigma_0\sigma_0 + C + D\sigma}.$$

If there is no absorption, we can obtain the perfect transmission condition ($T=|t^2|=1$) when the reflection coefficient satisfies $|r|=0$, given as

$$\sin\delta_A\sin\delta_C\cos\delta_B\left(\frac{\sigma_A}{\sigma_C}-\frac{\sigma_C}{\sigma_A}\right) + \cos\delta_A\sin\delta_C\sin\delta_B\left(\frac{\sigma_C}{\sigma_B}-\frac{\sigma_B}{\sigma_C}\right) + \sin\delta_A\cos\delta_C\sin\delta_B\left(\frac{\sigma_A}{\sigma_B}-\frac{\sigma_B}{\sigma_A}\right) = 0, \quad (1)$$

$$\cos\delta_A\cos\delta_C\sin\delta_B\left(\frac{1}{\sigma_B}-\sigma_B\right) + \sin\delta_A\cos\delta_C\cos\delta_B\left(\frac{1}{\sigma_A}-\sigma_A\right) = 0. \quad (2)$$

By utilizing the two equations above, we can exactly determine the tunneling frequency of the MNG-air-ENG structure. In particular, in the case of $d_C=0$, e.g., $\delta_C=k_C d_C=0$, the above equations can be written in a simple form as

$$\sigma_A = -\sigma_B, \quad \delta_A = \delta_B, \quad (3)$$

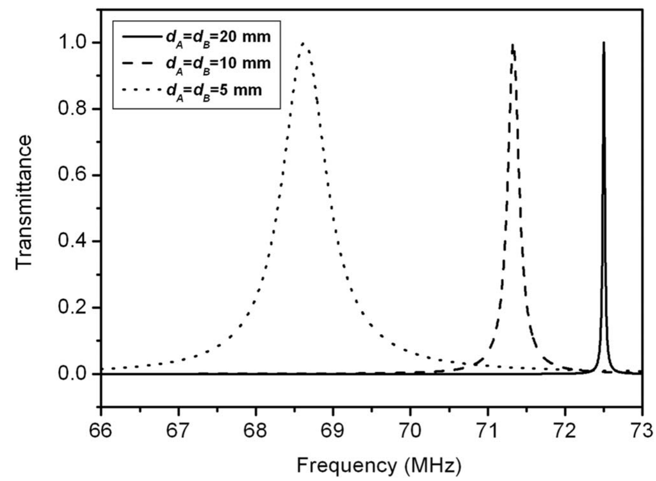

FIG. 2. The transmittance of the MNG-air-ENG structure with a different thickness of SNG materials (the length of the air is 1000 mm).

$$\eta_A = -\eta_B, \quad k_A d_A = k_B d_B, \quad (4)$$

which is a familiar result that determines the tunneling frequency of two pairing single negative slabs, for instance, the ENG-MNG pair. The above analysis also shows that, if any one layer of the composite structure is removed or its parameters are changed, the tunneling phenomenon will no longer exist, leading to flexible control of the wireless transfer devices. This property also implies that the inefficient energy loss in traditional wireless antenna systems may be avoided. In addition, at the tunneling frequency the distance in the air layer that the EM waves tunnel through can be determined exactly by the resonant condition. Therefore, it is optimistic to achieve a wireless information transfer system with high security.

Next, a Drude model is used to describe the isotropic single-negative materials, given as

$$\varepsilon_A = \varepsilon_a - \frac{\alpha}{\omega^2}, \quad \mu_A = \mu_a \quad (5)$$

in ENG materials and

$$\varepsilon_B = \varepsilon_b, \quad \mu_B = \mu_b - \frac{\beta}{\omega^2} \quad (6)$$

in MNG materials. These kinds of dispersion for ε_A and μ_B may be realized in special metamaterials [16]. The angular frequency $\omega/2\pi$ is in units of GHz. In the following calculation, we choose a set of parameters of $\varepsilon_a=\mu_b=1$, $\mu_a=\varepsilon_b=1$, and $\alpha=\beta=400$. The thicknesses of the ENG slab, the MNG slab, and air are assumed to be $d_A=20$ mm, $d_B=20$ mm, respectively; $d_C=1000$ mm, corresponding to a considerable distance between two wireless devices. We consider the transverse electric wave case, e.g., the electric field $\vec{E}$ lies in the y direction. The treatment for the transverse magnetic wave is similar. After we depict the calculated transmittance of the MNG-air-ENG structure in Fig. 2, it is clear that the EM energy completely tunnels through the composite structure at $f_0=72.5$ MHz, shown as the solid

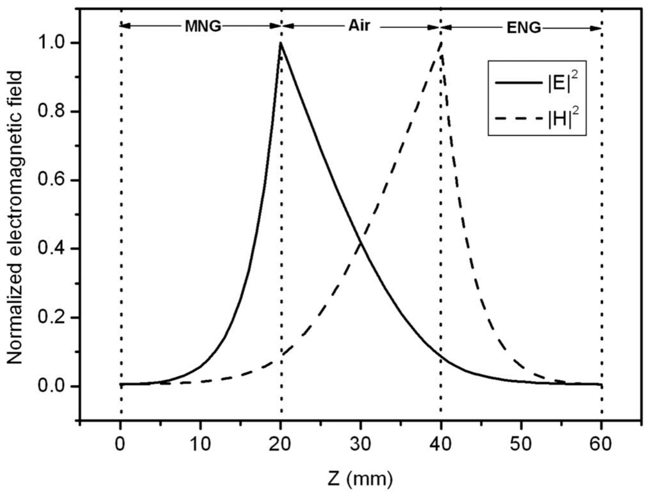

FIG. 3. The electromagnetic field distribution corresponding to the tunneling mode in the MNG-air-ENG structure (the origin is at the starting side of the MNG material) d_A=20 mm, d_B=20 mm, d_C=20 mm.

line. In this case, the sizes of the SNG slabs (regarded as emitting or receiving devices) that participate in the wireless transfer are smaller than the distance between devices by a factor of $R=L_{trans}/L_{dev}=d_C/d_A=1000/20=50$. According to Ref. [15], if the ratio R of a wireless transfer system is larger than 2–3, the wireless transfer can be regarded as midrange. Compared to the results with ∼40% efficiency at the ratio $R=8$ in Ref. [15], our structure shows the possibility to obtain a highly efficient wireless device with a functional region beyond midrange. Furthermore, the results in the cases of $d_A=d_B=10$ mm and $d_A=d_B=5$ mm are also given in Fig. 2, shown as the dotted line and the dashed line, respectively. It is found that when the length of the SNG slabs is shortened by 4 times, the frequency shift of the tunneling mode is only 5%. In the meantime, $R=L_{trans}/L_{dev}=d_C/d_A=1000/5=200$. The ratio R is increased greatly due to the deep subwavelength size of the SNG slabs. This means the tunneling phenomena still occur through a long distance over several hundreds of times the length of the device, which is far beyond midrange. Of course, in our case the air gap width constitutes about a quarter of a wavelength, which is not a long distance in electrical units. However, this distance between devices is long enough for the subwavelength SNG wireless devices working at a low frequency below 100 MHz.

Moreover, the electromagnetic field distribution of the tunneling modes with its frequency at 1.389 GHz corresponding to the parameters of d_A=20 mm, d_B=20 mm is shown in Fig. 3. In contrast to the traditional resonance or tunneling phenomena, amazing results are obtained that the electric field and the magnetic field are localized at a different location: The electric field is localized at the interface of the MNG layer and air but the magnetic field is localized at the interface between air and the ENG slab. By utilizing the ENG medium as a wireless receiving device, it will benefit the people that carry it for the reason that the magnetic field localizing at the interface between air and the ENG slab will not interact with common environmental objects.

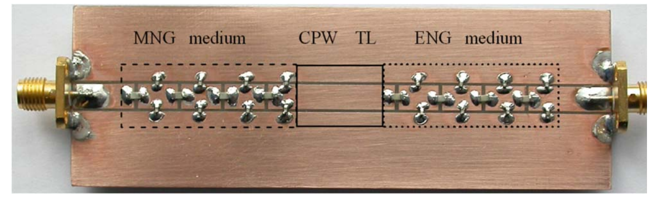

FIG. 4. (Color online) The photograph of the sandwich structure fabricated using CPW with lumped element capacitors (C) and inductors (L) loading.

Finally, microwave experiments are carried out to verify the properties of the ENG-air-MNG structure mentioned above. The ENG and MNG media are implemented by periodically loading lumped-element series capacitors (C) and shunt inductors (L) on a coplanar waveguide (CPW). The CPW transmission line is designed with a center conductor width of 4.5 mm and a slot width of 0.52 mm. The substrate is FR4 with a thickness h=1.6 mm and relative permittivity ε_r=4.75. For these parameters, the effective relative permittivity of the CPW transmission line is ε_{re}=2.446 and the characteristic impedance is Z_0=50 Ω. In addition, the length of the unit cell is d=8 mm. In this case, when we choose the parameters of L=5.6 nH and C=3.0 pF, we will obtain ENG media in the frequency range from f_{c1}=1.75 GHz to f_{c2}=3.15 GHz for experiment value and the MNG media can be acquired in the same frequency range as for the parameters of L=15 nH and C=1.0 pF. Utilizing the ENG and MNG media implemented by loading lumped-element series capacitors and shunt inductors on CPW, we can fabricate a structure shown in Fig. 4 to verify the properties of the ENG-air-MNG structure. Here, the CPW transmission line (TL) between the ENG medium and the MNG medium could be considered as a normal medium, taking the role of air. The simulated (by CST Microwave Studio) and measured (by the Angilent 8722ES network analyzer) S_{21} parameters are shown in Fig. 5. The simulated results show clearly that there exists a tunneling mode at f_0=1.95 GHz, which agrees well with the experimental observation of the tunneling mode at

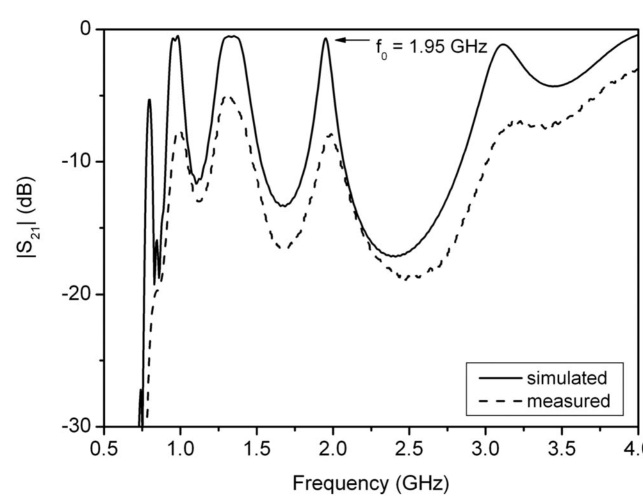

FIG. 5. The simulated and measured S_{21} parameters of the sandwich structure shown in Fig. 5.

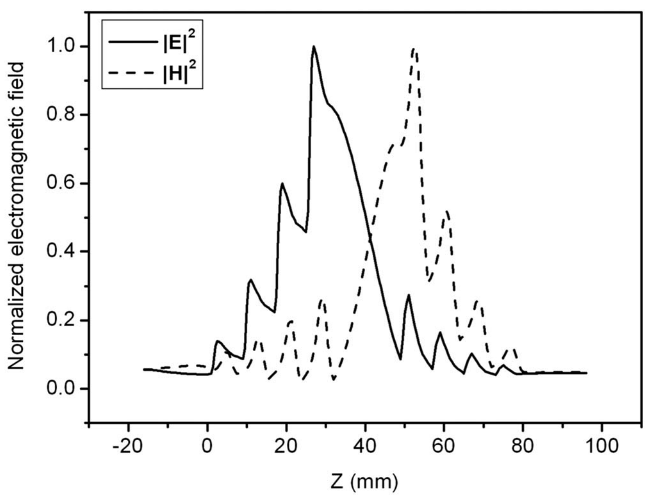

FIG. 6. The simulated (CST) electromagnetic field distribution at the middle slot of the CPW along the structure shown in Fig. 5 corresponding to the tunneling mode in Fig. 6.

1.98 GHz. Figure 6 shows the simulated electromagnetic field distribution at the middle slot of the CPW along the structure shown in Fig. 4 corresponding to the tunneling mode. It can be seen that, similar to Fig. 3, the electric field and magnetic field are localized at different interfaces, respectively.

In conclusion, we illustrate that there does exist an efficient tunneling mode in the MNG-air-ENG structure by means of the transfer-matrix method and microwave experiments. The results show that the tunneling phenomena can occur through a long distance over several hundreds times of the length of the device, which is far beyond midrange. The distribution of the EM fields demonstrated that, unlike in the ENG-MNG slabs, the electric and the magnetic fields of the tunneling mode are interestingly separated and localized at the interface of MNG air and ENG air, respectively. Finally, the resonant condition of the MNG-air-ENG structure is also discussed to determine the exact tunneling frequency. Therefore, the MNG-air-ENG structure may be important for potential applications in wireless information and energy transfer, for its high efficiency, security and health.

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[1] R. Liu, B. Zhao, X. Q. Lin, and T. J. Cui, Appl. Phys. Lett. **89**, 221919 (2006).
[2] J. D. Baena, L. Jelinek, R. Marques, and F. Medina, Phys. Rev. B **72**, 075116 (2005).
[3] K. Y. Kim and B. Lee, Phys. Rev. A **77**, 023822 (2008).
[4] A. Ahmadi and H. Mosallaei, Phys. Rev. B **77**, 045104 (2008).
[5] J. B. Pendry, Phys. Rev. Lett. **85**, 3966 (2000).
[6] A. Grbic and G. V. Eleftheriades, Phys. Rev. Lett. **92**, 117403 (2004).
[7] F. J. Garcia de Abajo, G. Gomez-Santos, L. A. Blanco, A. G. Borisov, and S. V. Shabanov, Phys. Rev. Lett. **95**, 067403 (2005).
[8] W. Cai, U. K. Chettiar, A. V. Kildishev, and V. M. Shalaev, Nat. Photonics **1**, 224 (2007).
[9] R. Liu, T. J. Cui, D. Huang, B. Zhao, and D. R. Smith, Phys. Rev. E **76**, 026606 (2007).
[10] J. Y. Xu, Y. X. Dong, and X. D. Zhang, Phys. Rev. E **78**, 046601 (2008).
[11] A. Alù and N. Engheta, IEEE Trans. Antennas Propag. **51**, 2558 (2003).
[12] G. S. Guan, H. T. Jiang, H. Q. Li, Y. W. Zhang, H. Chen, and S. Y. Zhu, Appl. Phys. Lett. **88**, 211112 (2006).
[13] L. Zhou, W. J. Wen, C. T. Chan, and P. Sheng, Phys. Rev. Lett. **94**, 243905 (2005).
[14] A. Karalis, J. D. Joannopoulos, and M. Soljacic, Ann. Phys. **323**, 34 (2008).
[15] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljacic, Science **317**, 83 (2007).
[16] G. V. Eleftheriades, A. K. Iyer, and P. C. Kremer, IEEE Trans. Microwave Theory Tech. **50**, 2702 (2002).