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TUNABLE SINGLE-NEGATIVE METAMATERIALS BASED ON MICROSTRIP TRANSMISSION LINE WITH VARACTOR DIODES LOADING

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Abstract—In this paper, tunable single-negative (TSNG) metamaterials based on microstrip with varactor diodes loading are investigated. By tuning the external voltage, our structure can provide either an epsilon-negative or a mu-negative band gap, with varying gap width (the ratio of bandwidth to center frequency can be from 0 to over 100%) and depth (from 0 dB to about −30 dB). Moreover, the tunneling mode in a heterostructure constructed by epsilon-negative and TSNG metamaterials is also studied. The results show that its transmission, Q-factor, and electromagnetic localization can also be controlled conveniently. All these properties make our structure promising to be utilized as a practical switching device, or a suitable platform for the study of nonlinear effect in metamaterials.

1. INTRODUCTION

Metamaterials, including double-negative (DNG) metamaterials and single-negative (SNG) metamaterials, have attracted intensive studies in the past few years, due to their unique electromagnetic properties and potential applications [1–59]. For DNG metamaterials (also called left-handed materials), the electromagnetic parameters, permittivity

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and permeability, are simultaneously negative. There are two kinds of SNG metamaterials: one is the epsilon-negative (ENG) metamaterial, in which the permittivity is negative but the permeability is positive; the other is the mu-negative (MNG) metamaterial, whose permeability is negative but permittivity is positive. In order to implement DNG or SNG metamaterials, a number of structures have been presented [32–41], such as the array of split ring resonators and (or) thin metal wires [32–34], Ω-like or S-like ring array [35, 36], transmission lines with series capacitors and shunt inductors loading [3, 37, 38], as well as those with split ring resonators or complementary split ring resonators loading [39–41], Nevertheless, all these metamaterials have fixed operating frequencies and their working band can't be tuned, which limits their practical applications a lot.

In recent years, tunable metamaterials have attracted intensive attentions due to their particular applications in optical switching, nonlinear modulation, and so on [42–59]. The common mechanism is to introduce certain controllable materials or lumped elements into the metamaterial units. For example, in [42–48] ferroelectric materials, ferromagnetic materials and liquid crystals are hired. In [49] and [50], the authors also show employing photosensitive semiconductor in the split ring resonators or electric-field-coupled inductor-capacitor resonators can make them become tunable. In short, by controlling the external factors, like magnetic fields, temperature, or light intensity, many electromagnetic properties of these metamaterials can be tuned conveniently. People also find in the transmission line metamaterials, varactor diodes can give rise to the tunability as they are very sensitive to a low direct current voltage, for instance, leaky-wave antenna with tunable radiation angle and beamwidth, tuneable directional coupler, and so on [51–55]. Specifically, transmission line metamaterials with varactor diodes can even serve as model systems for investigating several nonlinear phenomena in negative-index metamaterials, like asymmetric parametric amplification, abnormal pulse formation, dark schrodinger solitons and harmonic generation [56–59].

In this paper, tunable single-negative (TSNG) metamaterials based on microstrip with varactor diodes loadings are investigated by microwave experiments. The results show that by tuning the external voltage, our structure can provide either an epsilon-negative or a mu-negative bandgap, with varying gap width (the ratio of bandwidth to center frequency can be from 0 to over 100%) and depth (from 0 dB to about −30 dB). Moreover, the tunneling mode in a heterostructure constructed by epsilon-negative metamaterials and TSNG ones are also studied. It is found that the tunneling mode localized at the interface of ENG and TSNG metamaterials will conditionally emerge along with the various external voltages. The Q-factor and electromagnetic (EM) field density of the tunneling mode are also greatly influenced by the external voltages. Therefore, we demonstrate that the microstrip-based TSNG metamaterials are quite promising to be utilized in the practical switching device, and may be hopeful to provide a suitable platform for the study of nonlinear effect in metamaterials.

2. REALIZATION OF SNG METAMATERIALS

The SNG metamaterials can be realized by periodically loading lumped-element series capacitors and shunt inductors on microstrip transmission line as shown in Fig. 1(a). Each unit cell has the same length of d, consisting of a series capacitor and a shunt inductor. The microstrip transmission line is designed with strip width 2.73 mm to match the characteristic impedances 50Ω. The substrate is F4B with thickness $h = 1$ mm and relative permittivity $\varepsilon_r = 2.65$. For these parameters, the distributed parameters are $L_0 = 248$ nH/m and $C_0 = 99$ pF/m, respectively. According to the periodical analysis of the structure shown in Fig. 1(a), the effective permittivity and permeability can be determined by the following approximate expressions [3]:

$$\varepsilon_{eff} \approx \left(C_0 - 1/\omega^2 Ld\right)/p, \tag{1a}$$

$$\mu_{eff} \approx p\left(L_0 - 1/\omega^2 Cd\right), \tag{1b}$$

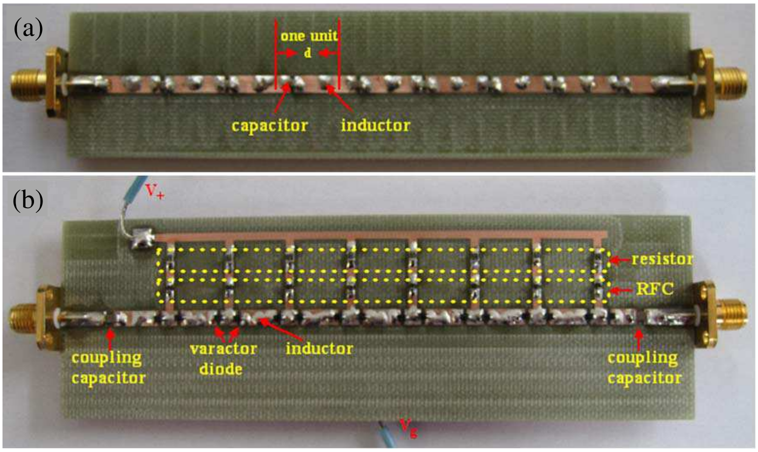

Figure 1. The photograph of (a) the SNG metamaterial and (b) the tunable SNG metamaterial based on microstrip.

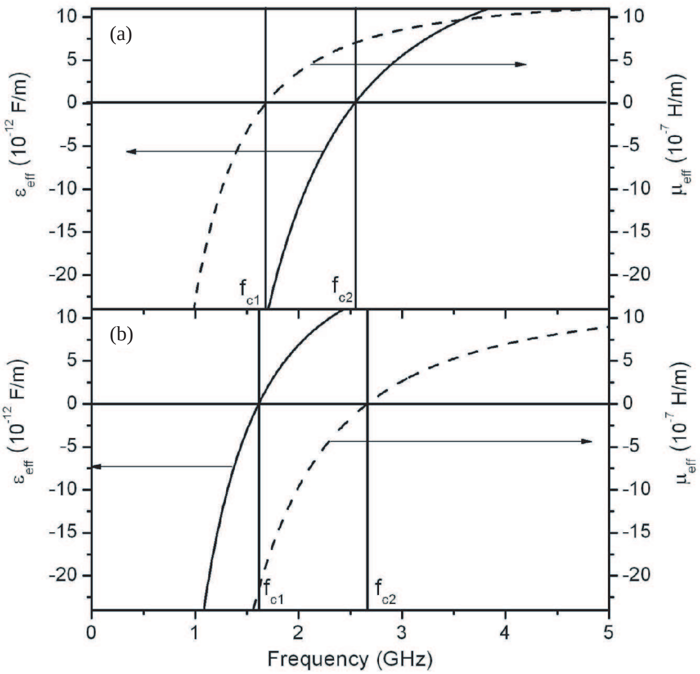

Figure 2. The calculated effective permittivity and permeability of the microstrip metamaterials (a) with shunt inductor $L = 3.3\,\text{nH}$, series capacitor $C = 3.0\,\text{pF}$ and unit length $d = 12\,\text{mm}$ and (b) with shunt inductor $L = 8.2\,\text{nH}$, series capacitor $C = 1.2\,\text{pF}$ and unit length $d = 12\,\text{mm}$.

where p is a structure constant (in our experiment, its value is 5.04), L and C are the values of the loaded inductors and capacitors respectively. By choosing a set of parameters as $L = 3.3\,\text{nH}$, $C = 3.0\,\text{pF}$ and $d = 12\,\text{mm}$, the effective permittivity and permeability of the microstrip metamaterial are calculated and shown in Fig. 2(a). In this case, it is obvious that the microstrip metamaterial has $\mu_{eff} > 0$ and $\varepsilon_{eff} < 0$ in the frequency range from $f_{c1} = 1.68\,\text{GHz}$ to $f_{c2} = 2.55\,\text{GHz}$. Similarly, Fig. 2(b) depicts the calculated results under another set of parameters as $L = 8.2\,\text{nH}$, $C = 1.2\,\text{pF}$ and $d = 12\,\text{mm}$. The results show that the microstrip metamaterial has $\mu_{eff} < 0$ and $\varepsilon_{eff} > 0$ in the frequency range between $f_{c1} = 1.61\,\text{GHz}$ and $f_{c2} = 2.60\,\text{GHz}$. A transmission gap should be observed in the frequency range between f_{c1} and f_{c2} since SNG metamaterials are opaque for electromagnetic waves. To illustrate SNG (ENG or MNG) gaps directly, the simulated (by CST Microwave Studio) and measured

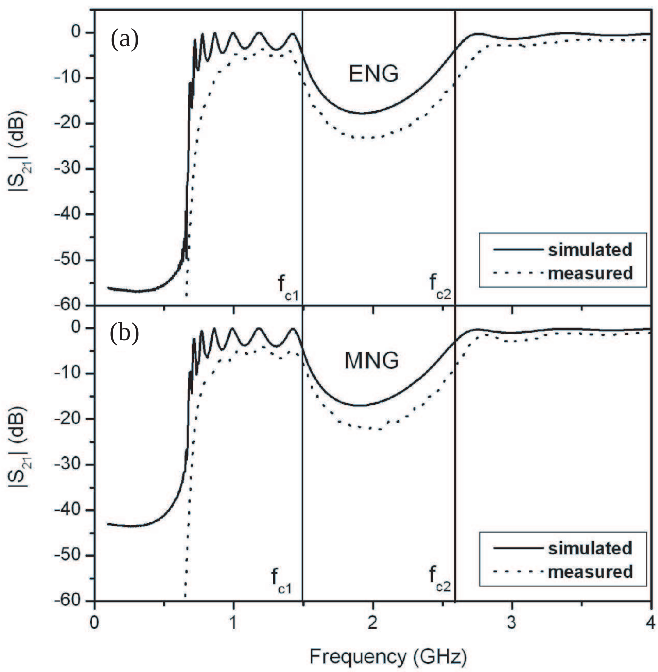

Figure 3. The simulated and measured S_{21} parameters of the microstrip metamaterials (a) with shunt inductor $L = 3.3\,\mathrm{nH}$, series capacitor $C = 3.0\,\mathrm{pF}$ and unit length $d = 12\,\mathrm{mm}$ and (b) with shunt inductor $L = 8.2\,\mathrm{nH}$, series capacitor $C = 1.2\,\mathrm{pF}$ and unit length $d = 12\,\mathrm{mm}$.

(by Angilent 8722ES vector network analyzer) S_{21} parameters for these two kinds of metamaterials are shown in Figs. 3(a) and (b). The two stop bands between f_{c1} and f_{c2} in Figs. 3(a) and (b) are ENG and MNG gaps respectively, corresponding to Figs. 2(a) and (b). Comparing the values of f_{c1} and f_{c2} in Figs. 3(a) and (b) with the calculated values shown in Figs. 2(a) and (b), they are slightly different due to the discrepancy between ideal and real lumped elements (the real lumped elements have dispersive characteristic). Therefore, through properly choosing the values of the loaded lumped elements we can obtain both ENG and MNG metamaterials using the structure shown in Fig. 1(a). In this case, the unit length d of our metamaterials is about 0.15λ, a little longer comparing with the condition $d << \lambda$ under which an artificial material is defined as a metamaterial. Several works have show that the effective medium approximation is still valid in such microstrip transmission line metematerials. Direct evidence is given that the SNG gap is not shifted along with the changed geometric scales and insensitive to the breakdown of periodicity [26]. This makes us believe that for our structure the effective medium approximation is valid and microstrip transmission line metamaterials can be achieved.

In addition, from Eqs. (1a) and (1b) we can derive the expressions of the cut-off frequencies f_{c1} and f_{c2} as follows [3, 37, 38],

$$f_{c1} = \frac{1}{2\pi\sqrt{LC_0d}}, \quad f_{c2} = \frac{1}{2\pi\sqrt{CL_0d}}, \tag{2a}$$

for $LC_0 > CL_0$; or

$$f_{c1} = \frac{1}{2\pi\sqrt{CL_0d}}, \quad f_{c2} = \frac{1}{2\pi\sqrt{LC_0d}}, \tag{2b}$$

for $LC_0 < CL_0$. When $LC_0 > CL_0$, the gap of the microstrip metamaterials is MNG in nature and while it is ENG for $LC_0 < CL_0$. Eqs. (2a) and (2b) imply that, by varying the values of lumped elements one can control conveniently the frequency range in which microstrip metamaterials can provide different kind of SNG gaps.

3. TUNABLE SNG METAMATERIALS

In stead of series capacitors mentioned above, varactor diodes are periodically loaded to construct the TSNG metamaterials, as shown in Fig. 1(b). Each unit cell consists of one inductor and two varactor diodes with its unit length of $d = 12$ mm. Direct current (DC) power is applied on the varactor diodes through restricting circuit resistors and series radio frequency chokes (RFC) used to separate the alternating current (AC) signal network from the DC power supply. All varactor dioded are connected end to end or head to head, which makes them all parallel. In the circuit, two coupling capacitors are used to avoid the diode reverse saturation current flowing into the measurement equipment of network analyzer. The wire denoted by V_+ is connected to the positive electrode of DC power supply, as well as the cathode of DC power supply is connected to the ground plane of microstrip through wire V_g. In this case, the microstrip is also designed with strip width 2.73 mm and the substrate is also F4B with thickness $h = 1$ mm and relative permittivity $\varepsilon_r = 2.65$. The value of the loaded inductors is 8.2 nH.

Then, we investigate the transmission property of TSNG metamaterial. The measured S_{21} parameters of the TSNG metamaterial with different bias voltages are shown in Figs. 4(a) and (b). In Fig. 4(a), the stopband is ENG in nature according to the calculation results by Eqs. (1a) and (1b). Its lower gap edge frequency is sensitive to the external bias, while the higher one is not, resulting in the change of

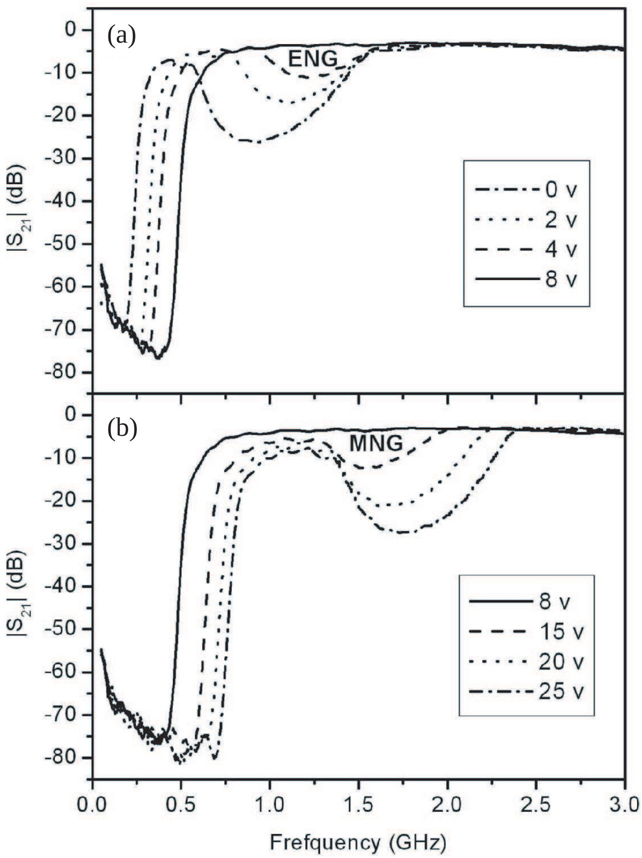

Figure 4. The measured S_{21} parameters of the tunable SNG metamaterial with different bias voltages.

gap width and depth. Especially, when the external voltage reaches 8 V, the two band edge frequencies become equal, with the result that the ENG gap is closed. For MNG gap, the situation is similar, except that its higher edge frequency is sensitive to the external bias, while the lower one is not, as shown in Fig. 4(b). Therefore, we demonstrate that, for TSNG metamaterial shown in Fig. 1(b), the EM property of bandgap can be alternated by tuning the external voltage applied on the varactor diodes. In addition, as the bandgap can be either closed or as deep as -30 dB, this kind of TSNG metamaterial is hopeful to be used as an efficient switching device in microwave communication systems.

4. TSNG-ENG METAMATERIAL HETEROSTRUCTURE

In order to explore the application of the TSNG metamaterial, a heterostructure constructed by the TSNG metamaterial and the ENG metamaterial is designed, shown in Fig. 5. The left part denotes a TSNG metamaterial, while the right part is a nontunable ENG metamaterial fabricated by loading lumped-element series capacitors (3.0 pF) and shunt inductors (3.9 nH) on microstrip. The simulated and measured S_{21} parameters of nontunable ENG metamaterial and the heterostructure with different bias voltages are depicted in Figs. 6(a) and (b). It is obvious that the bias voltage also has a great effect on the transmission properties of the hetorostructure. As we know, EM tunneling only occurs in the MNG-ENG heterostructure when the average permittivity and average permeability is simultaneously zero [24, 27].

When the used bias voltage is small, e.g., 6 V, there is no EM tunneling as the TSNG metamaterial is ENG here and the tunneling condition isn't met. However, when the bias voltage is increased, making the TSNG metamaterial act as a MNG one, EM tunneling begins to emerge in the heterostructure. When the bias is increased to a certain value (for our sample, about 18 V), the tunneling condition is best satisfied, with a highest transmittance obtained. With these features, the tunable heterostructure may also be important for some practical microwave switching devices. It is necessary to point out that in Figs. 6(a) and (b), the first pass band is the left handed passband and it is insensitive to the bias voltage.

Moreover, we find that the external voltages also have a great impact on the Q-factor and EM localization of the tunneling mode. We calculate the Q-factors of the tunneling modes, which are 3.46, 5.15, and 6.50, corresponding to the increasing bias voltages of 13, 16, and 18 V, respectively. It implies that the EM localization of the tunneling mode is also enhanced during this procedure. To show more clearly the gradually strengthened EM localization, in Fig. 7 we depict the

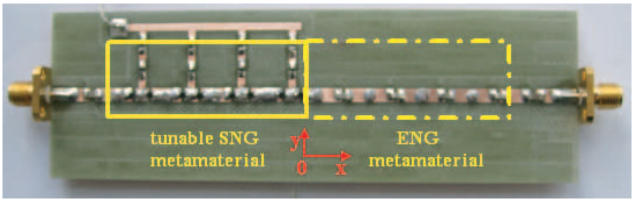

Figure 5. The photograph of the heterostructure constructed by ENG metamaterials and tunable SNG metamaterials.

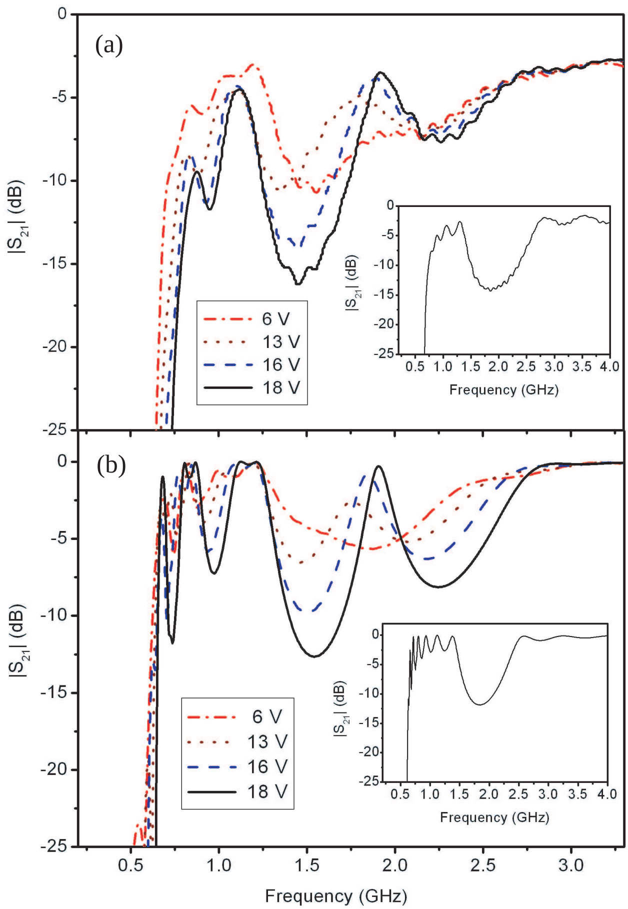

Figure 6. The (a) measured and (b) simulated S_{21} parameters of the heterostructre shown in Figure 5 with different bias voltages. The insets show the (a) measured and (b) simulated S_{21} parameters of the ENG metamaterial.

electric energy density along the propagating direction X at 1.91 GHz (At this frequency best EM tunneling will occur when the bias voltage is 18 V) under different bias voltages. It is clear that, the EM field located at the interface of ENG and TSNG metamaterials is slowly amplified along with the increasing external voltages. As is known, the strength of nonlinear effect is directly related with the Q-factor and EM localization of a resonator. Thus, the properties mentioned above make our structure a promising candidate for the study of nonlinear effect in metamaterials.

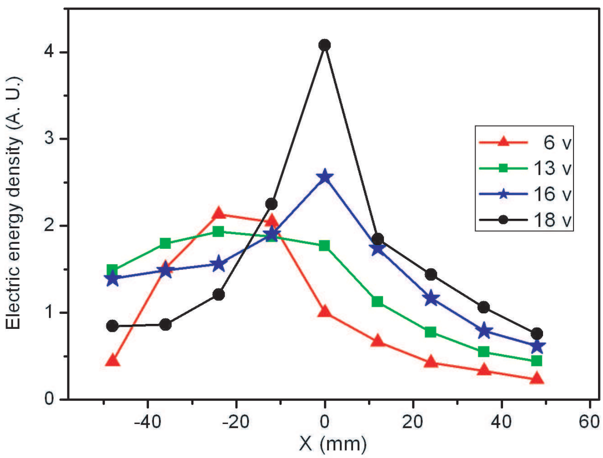

Figure 7. The measured electric energy density in the heterostructre shown in Figure 5 along the propagating direction X at 1.91 GHz under different bias voltages.

5. CONCLUSION

In summary, by numerical simulation and microwave experiment we investigate the TSNG metamaterials based on microstrip with varactor diodes loading. We find that by tuning the external voltage, our structure can provide either a complete pass band or a SNG (ENG or MNG) stop band, with varying gap depth up to -30 dB simultaneously. Moreover, a heterostructure constructed by an ENG metamaterial and a TSNG metamaterial is also studied. It is found that a tunneling mode localized at the interface of ENG and TSNG metamaterials will conditionally emerge along with the various external voltages. Its transmission, Q-factor, and electromagnetic localization can also be controlled conveniently. Therefore, the TSNG metamaterials is quite promising to be utilized in the practical switching devices, and hopeful to provide a suitable platform for the study of nonlinear effect in metamaterials.

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