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Experimental research of magnetic plasmon polaritons in two-dimensional metamaterials based on microstrip lines

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ABSTRACT

The magnetic plasmon polaritons (MPPs) and their slow wave effect are experimentally studied in the two-dimensional (2D) ENG/MNG (ε-negative materials/μ-negative materials) metamaterials based on microstrip lines' structure. Electric field mainly locates at the ENG/MNG interface and decays in the ENG materials and MNG ones, as reveals evident MPPs characteristics. MPP waves propagate slowly along the ENG/MNG metamaterials with opposite group and phase velocities, as is studied through the time-domain analysis. Theoretical analysis agrees well with CST simulation and microwave measurement.

1. Introduction

Surface plasmon polaritons (SPPs) are electromagnetic waves propagating at the dielectric–metal interface and the amplitude decays exponentially at both sides perpendicular to the interface [1–3]. In fact, SPP waves appear at the positive–negative permittivity interface (TM-polarized) and/or positive–negative permeability interface (TE-polarized, as can be also named as magnetic plasmon polaritons (MPPs)) [4]. They have shown a widespread range of interesting and useful properties, for example, sub-wavelength confinement, resonances, field enhancement and localization, high surface and bulk sensitivities, and energy asymptotes in dispersion curves. Because of these characteristics, SPPs have potential applications in fields such as spectroscopy [5], nanophotonics [6,7], imaging [8], biosensing [9,10] and circuitry [11].

TM-polarized SPPs can be generally excited at optical frequencies through the attenuated total internal reflection (ATR) based on metal–dielectric interface. However, the research about SPPs-excitation can also be extended to other frequency bands (i.e., microwave frequencies) [12–14]. Research about SPPs being carried out in microwave band, we could not only explore their application in this band but also provide reference for the uses of SPPs in the optical band. Therefore, how to construct these materials whose relative permittivity/permeability is negative is a key problem in this regime. The effective permittivity and/or permeability of metamaterials can be negative in some frequencies, so metamaterials can be used to support various kinds of SPPs.

Metamaterials include double negative materials (DNG, $\varepsilon<0$, $\mu<0$) and single negative materials (ENG and MNG) [15–23]. A medium with permittivity less than zero and permeability greater than zero is called ENG ($\varepsilon<0$, $\mu>0$) material. And a medium with the permittivity greater than zero and permeability less than zero is called MNG ($\varepsilon>0$, $\mu<0$) material. Normal medium is also named as double positive material (DPS) because its permittivity and permeability are both positive ($\varepsilon>0$, $\mu>0$). Among these metamaterials only DNG medium supports EM waves' propagating, either ENG medium or MNG medium does not support EM waves propagating. At microwave frequencies metamaterials can be realized by LC-loaded microstrip transmission line [24]. In this paper, MPPs and their abnormally slow wave effect are experimentally studied based on ENG/MNG metamaterials in microwave band. The EM waves propagate along the ENG–MNG interface and they possess the characteristic of abnormal dispersion. The slowest group velocity is about equal to $c/38$ (c is the light velocity in vacuum). And the slowest phase velocity is about equal to $-c/6$, here the sign "$-$" indicates that the group velocity is opposite with the phase one. These properties will have potential applications in the miniature microwave/optical devices and storing signals.

2. Theoretical analysis

Fig. 1(a) displays the metamaterials composed structure which is made up of the semi-infinite ENG plane and the MNG one, where the effective permittivity and permeability are respectively $\varepsilon_1, \mu_1, \varepsilon_2, \mu_2$ ($\varepsilon_1<0,\ \mu_1>0;\ \ \varepsilon_2>0,\ \mu_2<0$). k is the MPPs' wave number. k_1 is the decaying wave number separately in ENG region and k_2 is the

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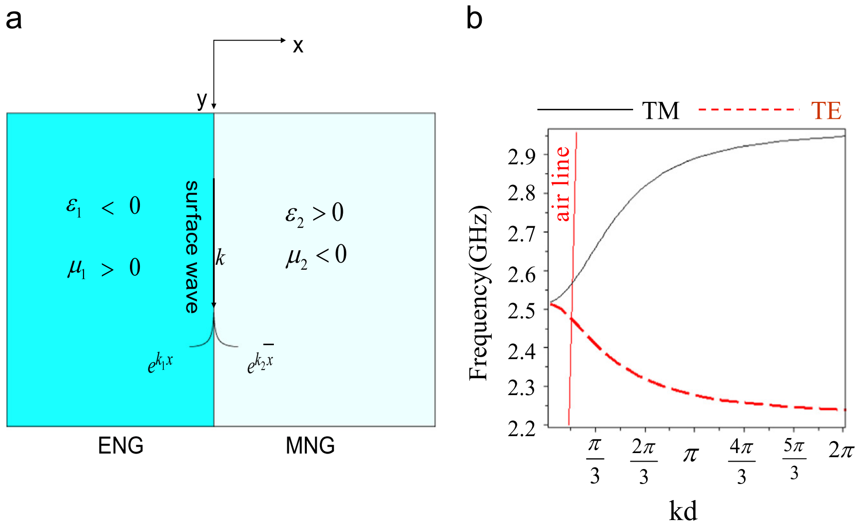

Fig. 1. The model of ENG–MNG metamaterials composed structure (a) and the dispersion relations of SPPs in this structure (b).

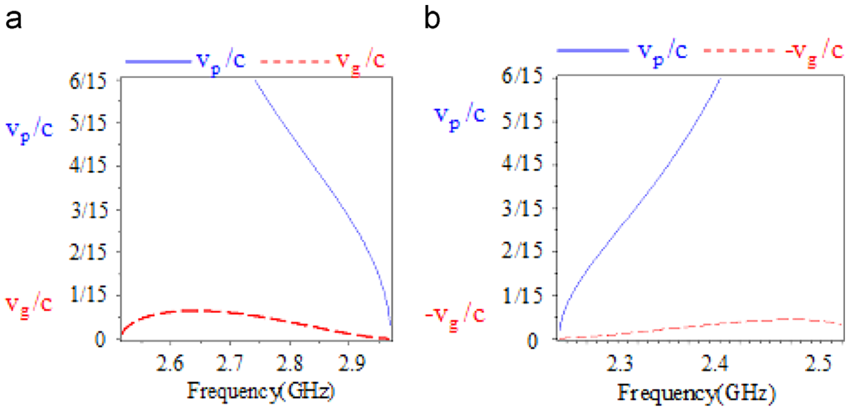

Fig. 2. The phase velocity and the group velocity of SPPs in the ENG/MNG metamaterials, TM mode (a) and TE mode (b).

decaying wave number in the MNG one. Theoretical research indicates that TE-polarized and TM-polarized surface plasmon polaritons arise in the ENG/MNG metamaterials composed structure [14,25]. The dispersion relations can be written as [4]

$$k=\frac{\omega}{c}\sqrt{\frac{\varepsilon_1\varepsilon_2(\varepsilon_2\mu_1-\varepsilon_1\mu_2)}{\varepsilon_2^2-\varepsilon_1^2}} \tag{1}$$

$$k=\frac{\omega}{c}\sqrt{\frac{\mu_1\mu_2(\varepsilon_2\mu_1-\varepsilon_1\mu_2)}{\mu_1^2-\mu_2^2}} \tag{2}$$

where $k_1=(k^2-\varepsilon_1\mu_1(\omega^2/c^2))^{1/2}$, $k_2=(k^2-\varepsilon_2\mu_2(\omega^2/c^2))^{1/2}$, $\omega=2\pi f$, here f is the frequency of SPPs. Eq. (1) is corresponding to TM mode of SPPs in ENG/MNG structure, and Eq. (2) is corresponding to TE mode. The solid line and the dashed one in Fig. 1(b) separately show the dispersion relation of TM and TE mode, d is the unit length of ENG/MNG structure. The solid line which is approximately vertical is the light line in vacuum. Here the effective permittivity and permeability in this ENG/MNG metamaterials combined structure can be respectively written as

$$\varepsilon_1\approx 6.6-\frac{116.5}{f^2},\quad \mu_1\approx 1,\quad \varepsilon_2\approx 6.6,\quad \mu_2\approx 1-\frac{9.88}{f^2} \tag{3}$$

where f is measured in GHz. And these parameters can be realized by 2D LC-loaded transmission line grids in some frequencies [26]. It can be seen from Fig. 1(b) that the slope of TM mode decreases along with the wave number increasing in the frequency regime 2.52–2.95 GHz, as reveals that the group velocity $v_g=(d\omega/dk)$ decreases when the frequency increases and $v_g=0$ at the frequency 2.95 GHz. The phase velocity ($v_p=(\omega/k)$) is in the same direction with the group one. As for TE mode, v_g decreases while the wave number increases in the frequency regime 2.25–2.52 GHz and $v_g=0$ at the frequency 2.25 GHz. But the phase velocity is at the opposite direction with the group one ($v_p\cdot v_g<0$).

The SPPs phase velocity and group velocity of TM mode and TE mode are respectively shown in Fig. 2(a) and (b), which are obtained from Eqs. (1) and (2). From Fig. 2(a) we can see that the phase velocity of SPPs TM mode decreases while the frequency increases in the band 2.52–2.95 GHz. The group velocity of TM mode is lower than $c/15$ and it can be theoretically equal to zero at the frequencies 2.52 GHz and 2.95 GHz. However the phase velocity of SPPs TE mode (Fig. 2(b)) increases while the frequency increases in the band 2.25–2.52 GHz. The group velocity of TE mode is also lower than $c/30$ and it can be theoretically equal to zero at the frequencies 2.25 GHz and 2.52 GHz. And the phase velocity and group velocity of SPPs TE mode propagate in the opposite direction.

3. Simulations and experiments

3.1. Transmission property and the electric field distribution of MPP waves

The practical sample of the ENG/MNG metamaterials is shown in Fig. 3(a). The ENG media and the MNG one are designed on a dielectric substrate (relative permittivity of 4.75) of height