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Experimental research of the tunable magnetic plasmon polaritons waveguide filter in microwave band

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ABSTRACT

Based on theoretical analysis, this paper studied experimentally the tunable low-pass, band-stop and band-pass filter effects of the MNG-DPS-MNG (μ-negative materials/double positive materials/μ-negative materials) magnetic plasmon polaritons waveguide. The research results show that the MNG-DPS-MNG waveguide without defect possesses the tunable low-pass filter characteristic. The waveguide with defect in the MNG region possesses the band-stop filter characteristic where the defect is equivalent to a sub wavelength cavity. And the waveguide with cavity in the DPS region possesses the band-pass filter characteristic. So the filter characteristics of the magnetic plasmon polaritons waveguide can be tuned by drawing into the resonators and changing the position and parameters of resonators. The experimental results are in good agreement with the simulation results. These properties will have potential application value in the tunable single channel or multi-channel filters.

1. Introduction

Recently, the concept of surface plasmon polaritons (SPPs) have been produced, for which electromagnetic (EM) waves propagate along the interface between dielectric and metal with amplitudes decaying exponentially at the two sides perpendicular to the interface [1,2]. SPP waves appear at the positive–negative permittivity interface and/or positive–negative permeability interface, the SPPs on the dielectric-metal are an example of the former. While these two interfaces are close to each other enough, the SPP waves at the interfaces are so strongly coupled that the SPPs waveguide is formed [3,4]. This waveguide has the most promising applications for the optical signal transmission and processing in the future high density integrated platform because they can overcome diffraction limit and manipulate light on sub-wavelength scales [5,6], as cannot be achieved through the traditional dielectric waveguides. At the same time, these SPP waveguides support the propagation of the optical signal and electric signals, but the normal dielectric waveguides can only support optical signals. So the SPPs waveguide components have become a hot spot in the plasma study realm. There have been many researchers proposed different kinds of SPPs waveguide component by now, for example bends and splitters [7,8], Mach–Zehnder interferometers [9], Y-shaped combiners [10], de-multiplexer [11], high-sensitivity nano-sensor [12], high-channel-count band-pass filter [13], etc. Waveguide filters have such characteristics as low insert loss and good out-of-band rejection, and the SPPs waveguide filter is very important to form the SPPs integration platform. So many kinds of SPPs waveguide filter have been proposed, as include the Bragg grating filters [14], ring resonator filters [15], tooth shaped filters [16] and metal/insulator/metal (MIM) waveguide filter with sub-wavelength resonator [17–19]. In Refs. [17–19], tunable band-pass and band-stop SPPs waveguide filters was realized through changing the resonators' size and refractive index based on MIM structure with resonators.

The theoretical and experimental study about the SPPs waveguide filter is mainly focused on the optical frequencies [20–22]. With the concept of metamaterials being proposed, the study about SPPs waveguide filter can continuously extend to the infrared, microwave and the other frequencies. Metamaterials could be used to construct the SPPs waveguide because their permittivity and/or permeability can be negative at some frequencies [23–25]. Metamaterials comprise double negative materials (DNG, $\varepsilon<0, \quad \mu<0$) and single negative materials (ENG and MNG) [26]. A medium with permittivity less than zero and permeability greater than zero is called ENG ($\varepsilon<0, \quad \mu>0$) material. And a medium with the permittivity greater than zero and permeability less than zero is called MNG ($\varepsilon>0, \quad \mu<0$) material. Normal medium is also named as double positive material (DPS) because its permittivity and permeability are both positive ($\varepsilon>0, \quad \mu>0$). Metamaterials have metal-like (negative magnetic material) optical properties, so the metamaterials structure support TM (negative permittivity) and/or TE (negative permeability)—polarized surface plasmon mode in different frequencies [27]. The latter can also be named as magnetic

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plasmon polaritons (Mpps). At microwave frequencies, metamaterials can be realized by LC-loaded microstrip transmission line [28]. In this paper, several waveguide filters based on metamaterials are designed at the microwave frequencies. The adjustable low-pass, band-stop and band-pass filter effect of MNG–DPS–MNG Mpps waveguide is experimentally studied based upon two dimensional (2D) microstrip lines. The low-pass filter property can be tuned by changing the effective permeability (unit capacitor), which is regardless of the filter size. The pass-stop and pass-band filter peculiarity can be adjusted by changing the cavity′s parameter. These properties will have potential applications in the miniature and tunable microwave or optics filters.

2. Theoretical analysis

Fig. 1(a) displays the Mpps waveguide structure which is made up of two semi-infinite MNG claddings and the DPS material with thickness d in the middle of this MNG–DPS–MNG waveguide, where the effective permittivity and permeability is $\varepsilon_1, \mu_1, \varepsilon_2, \mu_2$, respectively. Magnetic plasmon polaritons exist in this MNG-DPS-MNG sandwich structure and the dispersion relations for TE waves can be written as [28]

$$\frac{\mu_2}{\mu_1} = -\frac{k_2}{k_1}\tanh\left(\frac{k_2 \times d}{2}\right) \tag{1}$$

$$\frac{\mu_2}{\mu_1} = -\frac{k_2}{k_1}\coth\left(\frac{k_2 \times d}{2}\right) \tag{2}$$

where $k_1^2 = k^2 - \mu_1\varepsilon_1\omega^2/c^2$, $k_2^2 = k^2 - \mu_2\varepsilon_2\omega^2/c^2$, $\omega = 2\pi f$ and c is the speed of light in vacuum, k is the propagation constant of the magnetic plasmon polaritons, f is the frequency of MPP waves. In this waveguide, the dispersion curve of a single interface is split into high-(plasmon anti-symmetric) and low-energy (plasmon symmetric) modes because of the coupling effect between the SPP waves on the two MNG-DPS interfaces. The two solid red lines in Fig. 1(b) show the dispersion relations of the MNG-DPS-MNG waveguide. Here the effective permittivity and permeability in this waveguide can be respectively written as $\mu_1 \approx 1 - (9.88 \times 10^{18})/f^2$, $\varepsilon_1 \approx 6.6, \mu_2 \approx 1, \varepsilon_2 \approx 6.6$, and these parameters can be realized by 2D LC-loaded transmission line grids in some frequencies [27]. The above red curve in Fig. 1(b) corresponds to the unsymmetrical mode while the below red curve corresponds to the symmetrical mode. And the SPPs symmetrical mode possesses low-pass filter which can be excited from a free space without momentum matching simply by perpendicular incidence to the end face of a waveguide structure [29]. However, according to the law of momentum conservation, the cutoff frequency of MPPs symmetrical mode is decided by the effective permeability in the MNG–DPS–MNG waveguide.

The effective permittivity and the effective permeability in MNG region of the SPPs waveguide can be shown as [30]

$$\mu \approx 1 - \frac{1}{C \times (2\pi f)^2 \times g' \times d}, \quad \varepsilon \approx 6.6 \tag{3}$$

where C refers to the loaded unit capacitor in series for constituting MNG materials, g' and d are both constants. It can be seen that the effective permeability in MNG region of the SPPs waveguide is decided by the loaded unit capacitor. Combined with Eqs. (1)–(3) we can believe that the dispersion relations can be decided by the effective permeability (which can decided by the loaded unit capacitor) in the MNG-DPS-MNG microstrip waveguide. If the effective permeability (unit capacitor) in MNG regions is changed, the cutoff frequency at the dispersion relations of the MNG-DPS-MNG waveguide would vary [31].

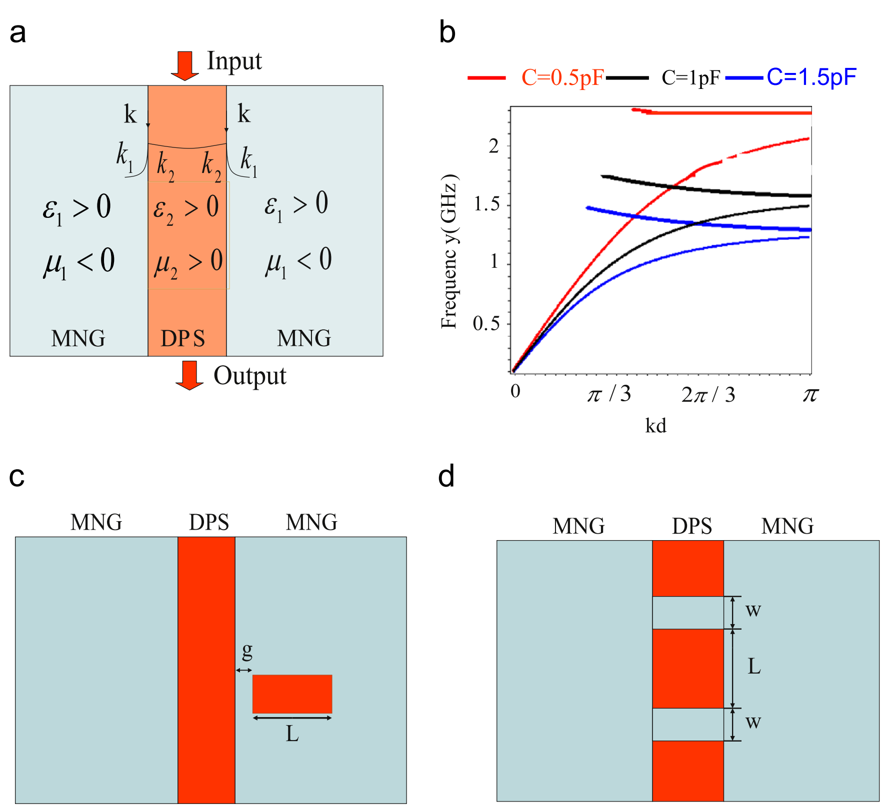

Fig. 1. The model of MNG-DPS-MNG waveguide (a), the dispersion relations of the waveguide (b), the waveguide with defect in the MNG region (c), the waveguide with defect in the DPS region (d). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)