Tunable microwave multiband filters based on a waveguide with antiferromagnetic and dielectric sandwiches

J. S. Zhang, R. L. Zhang,[a] Qing Hu, R. H. Fan, and R. W. Peng[a]
National Laboratory of Solid State Microstructures and Department of Physics, Nanjing University, Nanjing 210093, China

(Presented 16 November 2010; received 23 September 2010; accepted 15 October 2010; published online 18 March 2011)

We theoretically study the propagation of hybrid electromagnetic-spin waves in a multiple-band-stop microwave waveguide, which is constructed as an antiferromagnetic (AFM1)/dielectric/antiferromagnetic (AFM2) sandwiched structure. Band stops, which are characterized by multiple attenuation peaks, have been found in the system. The frequencies of multiple band stops and the intensities of attenuation peaks can be manipulated by external magnetic field. However, by tuning the thickness of the dielectric layer or the thickness of AFM layers, the frequencies of the band stop are almost invariable, while the intensities of the attenuation peaks change significantly. This feature originates from the coupling between the microwave and spin wave associated with the collective excitations of spin motions. Our investigation may potentially be applied to the design of high-frequency microwave band-stop filters. © *2011 American Institute of Physics*. [doi:10.1063/1.3535440]

High-frequency electromagnetic devices are currently attracting much attention with the development of the fabrication technique of multilayer structures.[1–8] Microwave bandpass filters and phase shifters can be applied to satellite and mobile communication, security, and military applications in particular. Recently, microstrip notch filters have been realized by using metallic magnetic materials. It is found that the input signal is strongly absorbed at the resonant frequency of the ferromagnet by varying the external magnetic in the microstrip notch filters.[8–10] However, ferromagnetic metals have the intrinsic restriction that they cannot be operated in the frequency region above 100 GHz. They also have the disadvantage that they induce electromagnetic damping, which can result in energy loss.

Recently a wide variety of applications for antiferromagnetic (AFM) materials has been found in some areas of engineering and technology.[11] One of the important aspects is the application in electromagnetic wave devices. Generally speaking, antiferromagnetic materials have extremely high exchange and effective anisotropy fields.[12] By using the former property, there is a possibility of fabricating notch filters by using AFM materials, in which the operating frequency can be high, even approaching the infrared region.[13,14] Here, we investigate the propagation of hybrid electromagnetic-spin waves in a multiple-band-stop microwave filter based on AFM1/dielectric/AFM2 sandwiched structure. Band stops, which are characterized by multiple attenuation peaks, have been found in the system. The frequencies of multiple band stops and the intensities of attenuation peaks can be manipulated by an external magnetic field. However, by tuning the thickness of the dielectric layer or the thickness of AFM layers, the frequencies of the band stop are almost invariable, while the intensities of the attenuation peaks change significantly. This feature originates from the coupling between the microwave and spin wave associated with the collective excitations of spin motions. Our investigation may potentially be applied to the design of high-frequency microwave band-stop filters.

Consider the propagation of electromagnetic waves in the AFM1/dielectric/AFM2 sandwiched waveguide. The inset of Fig. 1(a) schematically shows a sandwiched planar waveguide, where the top and bottom are covered with thick silver layers. It is shown that the interfaces are parallel to the *x-z* plane. The top of the first AFM layer is defined as $y=0$ and the thickness of the top AFM layer and bottom AFM layer are set as d_1 and d_2, respectively, while the thickness of the dielectric layer is set as D. The waveguide extends from $x=-\infty$ to $+\infty$. Then the edge effect can be ignored in the x direction, and $k_x=0$ due to the symmetry in the waveguide. We assume that the microwaves propagate along the z-axis, which is the direction of the external magnetic field H_{ext}. The Maxwell equation has the form

$$\nabla \times (\nabla \times \mathbf{H}) = -\frac{1}{c^2}\frac{\partial^2}{\partial t^2}(\boldsymbol{\varepsilon\mu}\mathbf{H}), \quad (1)$$

where $\mathbf{H}$ is the magnetic field and has the form $\mathbf{H(t)} = \mathbf{H}e^{i(\mathbf{kx}-\omega t)}$. Here, $\mathbf{k}$ is the wave vector and ω is angular frequency. Then Eq. (1) can be written in the matrix form $\mathbf{QH}=0$, which has a nontrivial solution only if $|\mathbf{Q}|=0$. Moreover, the magnetic filed in the waveguide can be written as

$$\begin{cases} H_x = \sum_{j=1}^{4} A(j)e^{ik_y(j)y}e^{ik_z z} \\ H_y = \sum_{j=1}^{4} \alpha(j)A(j)e^{ik_y(j)y}e^{ik_z z} \\ H_z = \sum_{j=1}^{4} \beta(j)A(j)e^{ik_y(j)y}e^{ik_z z} \end{cases}, \quad (2)$$

[a]Electronic addresses: rlzhang@nju.edu.cn and rwpeng@nju.edu.cn.

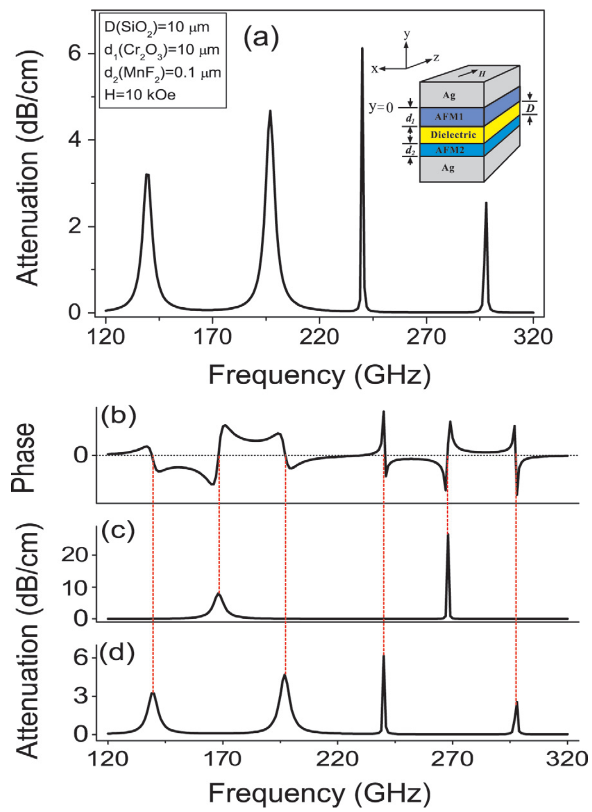

FIG. 1. (Color online) (a) Microwave attenuation as a function of frequency in the $Cr_2O_3/SiO_2/MnF_2$ sandwiched waveguide with the applied magnetic field $\mathbf{H} = 10$ kOe. Here, the thickness of the dielectric layer SiO_2 is set as $D = 10$ μm, and the thickness of the Cr_2O_3 (AFM1) and MnF_2 (AFM2) layer is set as $d_1 = 10$ μm and $d_2 = 0.1$ μm, respectively. The inset of (a) shows the geometry of the filter structure. (b) Microwave phase difference. (c) and (d) illustrate the microwave attenuation when the external magnetic field is 0 and 10 kOe, respectively. The other parameters are the same as those in (a).

where *A(j)* are the independent variables, and the parameters α and β are determined by the matrix **Q**. If we have the magnetic field, the electric field in the AFM layers and the dielectric layer can be obtained. On the other hand, the boundary condition at the interface between the AFM layer and the dielectric layer is that the tangential components of **E** and **H** are continuous, and it requires that the tangential component of the electric field ($E_{//}$) be zero for silver.[15] Then it is possible to find the numerical solutions of k_z for a given ω and give the dispersion curves in the waveguide.

Now, we choose Cr_2O_3 and MnF_2 as the AFM1 layer and AFM2 layer, respectively, and SiO_2 as the dielectric layer. The permeability tensor $\boldsymbol{\mu}$ in AFM is of the form

$$\boldsymbol{\mu} = \begin{bmatrix} \mu_1 & i\mu_t & 0 \\ -i\mu_t & \mu_1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

with[16,17] $\mu_1 = 1 - 4\pi\gamma^2 MH_a(X+Y)$, and $\mu_t = -4\pi\gamma^2 MH_a(X-Y)$. Here X and Y are defined as such:

$$X = \{[\omega + \gamma(H_0 + i\Delta H)]^2 - \Omega^2\}^{-1}, \tag{4}$$

$$Y = \{[\omega + \gamma(-H_0 + i\Delta H)]^2 - \Omega^2\}^{-1}, \tag{5}$$

and the resonance frequency $\Omega = \gamma\,[H_a(2H_e + H_a)]^{1/2}$. Here γ is the gyromagnetic ratio, M is the saturation magnetization, and ΔH is the linewidth. H_e and H_a represent the magnitude of the exchange field and anisotropy field, respectively.

We have calculated the microwave attenuation and the phase difference in the multiple-band-stop microwave waveguide based on AFM1/dielectric/AFM2 sandwiched structure (as shown in Fig. 1). It is shown in Fig. 1(a) that the band stops, which are characterized by multiple attenuation peaks, appear in the waveguide system. The attenuation peaks associated with microwave resonant absorption are located at four different frequencies and they have distinct widths. This means that the four resonant modes correspond to the four stop bands. Then the multiple band stops are realized in the AFM1/dielectric/AFM2 sandwiched waveguide. On the other hand, the phase difference of the microwave signal in the sandwiched waveguide is also illustrated as a function of frequency [Fig. 1(b)]. Here, the phase difference is calculated for a zero external field [as shown in Fig. 1(c)] subtracted from an external field of 10 KOe [as shown in Fig. 1(d)]. Obviously, the phase difference can be changed alternatively from positive to negative against the frequency. Around resonant frequencies, a large phase difference is observed and the phase difference is reversed dramatically. However, the phase difference is blocked at resonant frequencies according to the attenuation curves of Figs. 1(c) and 1(d). This feature makes it possible to use the waveguide as an effective phase shifter.

It is worthwhile to study the influence of applied magnetic field on the microwave attenuation in the multiple-band-stop microwave waveguide of AFM1/dielectric/AFM2. Figure 2 presents the attenuation curves with different magnetic fields **H**. Obviously, the band-stop frequencies are shifted dramatically by varying the magnetic field and the intensity of attenuation peaks is changed when the magnetic field is varied. On the other hand, we can also consider the waveguide as a local bandpass filter. For example, the bandpass property can be realized around 170 GHz and around 220 GHz at a high field of $\mathbf{H} = 15$ kOe. These local bandpass regions are of low attenuation and are protected from high attenuation peaks on both sides. It should be noted that the width of the bandpass

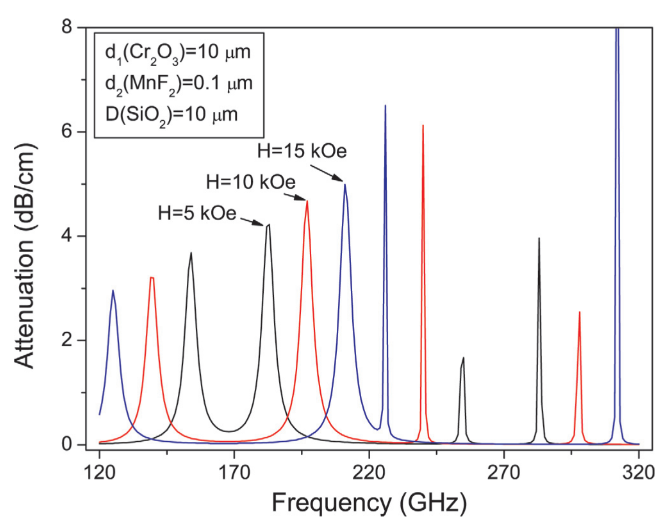

FIG. 2. (Color online) The microwave attenuation versus frequency in the $Cr_2O_3/SiO_2/MnF_2$ waveguide with different external magnetic fields (**H**).

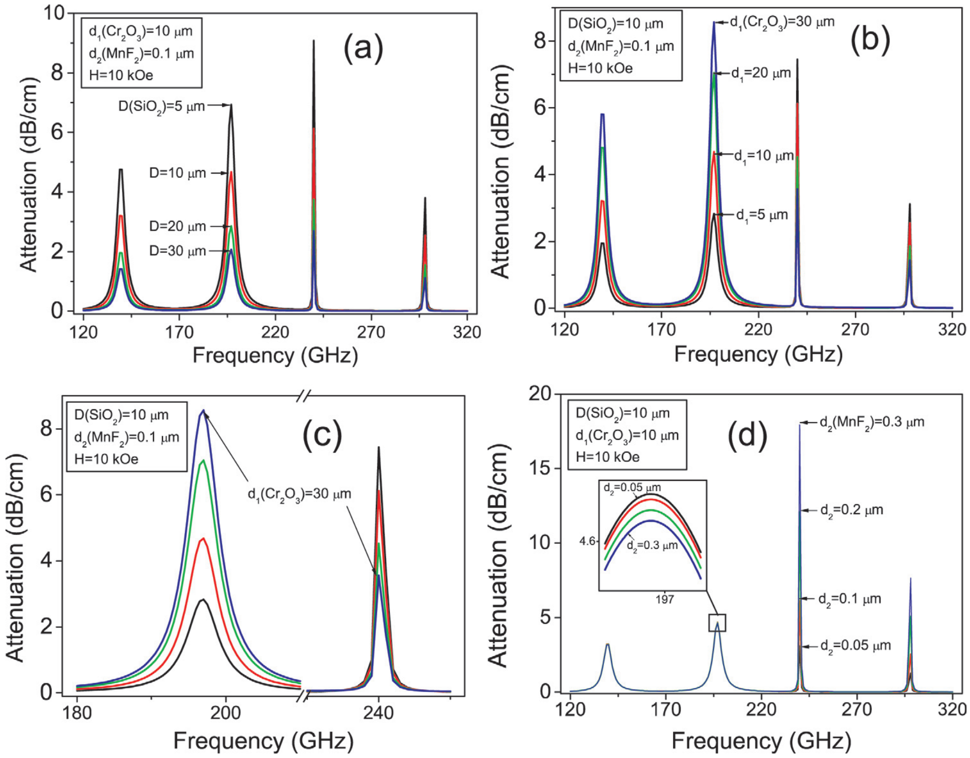

FIG. 3. (Color online) Microwave attenuation against frequency in the $Cr_2O_3/SiO_2/MnF_2$ waveguides with the applied magnetic field $\mathbf{H} = 10$ kOe. (a) $d_1 = 10$ μm, $d_2 = 0.1$ μm, but $D = 5$, 10, 20, and 30 μm, respectively. (b) $D = 10$ μm, $d_2 = 0.1$ μm, but $d_1 = 5$, 10, 20, and 30 μm, respectively. (c) The enlargement of the resonant modes around 195 and 240 GHz in (b). (d) $D = 10$ μm, $d_1 = 10$ μm, but $d_2 = 0.05$, 0.1, 0.2, and 0.3 μm, respectively.

can be tuned by the external magnetic field. Therefore, by manipulating the external magnetic field, the bandpass frequencies and the band-stop modes can be tuned efficiently.

The intensity of the attenuation peaks can also be tuned by changing the thickness of the dielectric layer (i.e., D). Figure 3(a) illustrates the microwave attenuation versus frequency with dielectric layers of different thicknesses. Obviously, the thickness of the dielectric layer has little effect on the frequencies and widths of the band stop. However, the intensity of the attenuation peaks is suppressed simultaneously with the increase of the thickness of the dielectric layer. We suggest that at the band-stop frequencies, more and more electromagnetic energy is concentrated in the dielectric layer when it becomes thicker. From this point of view, an enhancement of microwave attenuation is obtained by decreasing the thickness of the dielectric layer.

It is interesting to study microwave attenuation by varying the thickness of the AFM layers. In Fig. 3(b), we have plotted the attenuation curves with different thicknesses of Cr_2O_3 (AFM1) layer d_1. It is found that the frequencies of the band stop are not change by varying d_1. The intensity of the attenuation peaks in the lower frequency region (centered at 140 and 195 GHz) is enhanced, while the magnitude of the attenuation peaks is weakened in the higher frequency region (centered at 240 and 300 GHz) by increasing the thickness of the Cr_2O_3 (AFM1) layer. This feature becomes much clearer in Fig. 3(c), which plots the enlargement of the resonant modes around 195 and 240 GHz in Fig. 3(b). On the contrary, here the intensity of attenuation peaks is weakened in the lower frequency region and enhanced in the higher frequency region by increasing the thickness of MnF_2 (AFM2) layer d_2 [as shown in Fig. 3(d) and its inset]. The reason for this contrast is that the Cr_2O_3 (AFM1) layer contributes to the lower frequency resonant modes (centered at 140 and 195 GHz) and the MnF_2 (AFM2) layer contributes to the higher frequency modes (centered at 240 and 300 GHz), respectively, because of the geometry of the structure. In other words, the increase of the thickness of the AFM1 layer will suppress the contribution by the AFM2 layer and vice versa. This indicates that the motions of the spin wave in the two AFM layers interact with each other near the tail of the evanescent field. The collective excitation of the spin waves is coupled with the microwave and affected the microwave propagation. Therefore, we can intentionally manipulate the intensity of attenuation peaks by tuning the thickness of the dielectric layer or the AFM layers.

This work was supported by grants from the National Natural Science Foundation of China (Grant Nos. 10904061, 10625417, 11034005, 11021403, and 61077023, the State Key Program for Basic Research from the Ministry of Science and Technology of China (Grant No. 2010CB630705).

[1]E. Schloemann *et al.*, J. Appl. Phys. **63**, 3140 (1988).
[2]V. S. Liau *et al.*, IEEE MTT-S. Dig. **3**, 957 (1991).
[3]R. E. Camley and D. L. Mills, J. Appl. Phys. **82**, 3058 (1997).
[4]R. J. Astalos and R. E. Camley, J. Appl. Phys. **83**, 3744 (1998).
[5]C. S. Tsai, J. Su, and C. C. Lee, IEEE Trans. Magn. **35**, 3178 (1999).
[6]N. Cramer *et al.*, J. Appl. Phys. **87**, 6911 (2000).
[7]B. Kuanr *et al.*, J. Appl. Phys. **93**, 8591 (2003).
[8]A. Maeda and M. Kume, Mater. Sci. Eng., A **217–218**, 207 (1996).
[9]B. Kuanr *et al.*, Appl. Phys. Lett. **83**, 3969 (2003).
[10]B. Kuanr *et al.*, Appl. Phys. Lett. **87**, 222506 (2005).
[11]K. Abraha and D. R. Tilley, Surf. Sci. Rep. **24**, 125 (1996).
[12]F. Keffer and C. Kittel, Phys. Rev. **85**, 329 (1952).
[13]R. E. Camley *et al.*, J. Appl. Phys. **83**, 6280 (1998).
[14]V. Veerakumar and R. E. Camley, J. Appl. Phys. **101**, 093906 (2007).
[15]J. D. Jackson, *Classical Electrodynamics* (Wiley, New York, 1975).
[16]S. Foner, Phys. Rev. **130**, 183 (1963).
[17]J. S. Zhang *et al.*, Jpn. J. Appl. Phys. **49**, 033004 (2010).