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Inhomogeneous exciting field dependence of permeability and microwave properties of trilayer ferromagnetic films with in-plane uniaxial anisotropy

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Abstract
Based upon the Landau–Lifshitz equation and Maxwell's equations, the permeability and microwave properties of trilayer ferromagnetic films with in-plane uniaxial anisotropy are investigated simultaneously. It is found that, due to coexistence of interlayer exchange coupling and the gyrotropic permeability tensor in the film, the permeability, especially the magnetic parameter $1/\nu = \mu_{yy} - \mu_{xy}^2/\mu_{xx}$, related directly to properties of the normally incident microwave propagation in the film, may be influenced significantly by inhomogeneous exciting fields applied in the layer magnetic moments. In turn, properties of normally incident microwave propagation in the film may be modified strongly; e.g., giant modification of absorption peaks, such as the number, frequency position, shape, and so on, are predicated.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Recently, there has been a growing interest in applications of metallic ferromagnetic films in the microwave region [1–5]. For layered metallic ferromagnetic structures, interlayer exchange coupling (IEC) between the magnetic layers mediated by nonmagnetic spacers is believed to be one of the key factors for many properties observed in magnetic/nonmagnetic artificial structures [6, 7]. It is also found that the permeability of a trilayer (or multilayer) film may be remarkably influenced by IEC [8–10]. Thus its use is promising for modification of microwave properties of the layered film.

Previous studies [8–10] mainly focused only on the permeability of the ferromagnetic films. Generally, the exciting magnetic field applied in the magnetic moments of the film is the magnetic field component of a standing microwave with wavevector parallel to the film plane, and is assumed to be homogeneous. However, Youssef *et al* have recently demonstrated

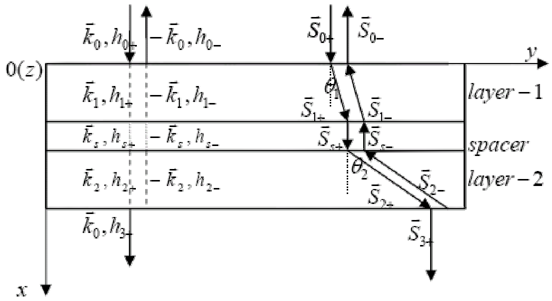

Figure 1. The trilayer ferromagnetic film with two magnetization vectors parallel to the z axis, and a schematic view of a normally incident E-polarized microwave passing from the free space through the film, in which $\vec{k}_i$ refers the wavevector of microwave propagation in the ith layer (or space), h_{i+} (or h_{i-}) the magnetic field component of the forward (or backward) microwave, $\vec{S}_{i+}$ (or $\vec{S}_{i-}$) the Poynting flow of the forward (or backward) microwave, and θ_i the angle between the Poynting flow and the x axis in the ith ferromagnetic layer.

that the permeability of the monolayer ferromagnetic film may be significantly influenced by the heterogeneity of the exciting magnetic field in the film [11]. For multilayer ferromagnetic films, to the best of our knowledge, effects of heterogeneity of the exciting magnetic field on permeability are still open questions. In turn, the properties of microwaves existing in the film may be altered by the modified permeability simultaneously. Therefore, for a full understanding of the permeability of the film, theoretical treatments must include all the permeability and microwave properties of the film.

In this work, based upon the Landau–Lifshitz equation and Maxwell's equations, we shall theoretically investigate both permeability and microwave properties of trilayer ferromagnetic films. To give prominence to effects of inhomogeneity of the exciting magnetic field, here, the exciting magnetic field is unusually adopted as the magnetic field component of a normally incident traveling microwave as shown in figure 1. In addition, it is emphasized that the permeability and permittivity of the ferromagnetic film are gyrotropic tensors generally. Thus our study has to take into account influences of the gyrotropy of the permeability and permittivity. Furthermore, it is pointed out that, usually, only one element of the permeability tensor is measured experimentally. However, due to gyrotropy of the permeability tensor, the magnetic parameter related directly to the properties of the microwave propagation in the ferromagnetic film may be a combination of some elements of the tensor instead of a single one (see below). On the other hand, in some cases, properties of normally incident microwaves in the film are involved [3, 4]. Therefore, studies on properties of normally incident traveling microwave propagation in the film and its effects on the permeability are interesting both theoretically and experimentally.

The paper is organized as follows: in section 2, we give the model and theories employed in this work. In section 3, numerical simulations and discussions are presented. Finally, some conclusions are demonstrated in section 4.

2. Model and theories

The film to be considered in this paper consists of two ferromagnetic layers separated by a nonmagnetic spacer as shown in figure 1. It has been demonstrated that the monolayer ferromagnetic films with thickness below critical thickness t_c may exhibit a well defined uniform ferromagnetic resonance model [11, 12]. The critical thickness t_c is partly related to the components of the film, e.g., $t_c \approx 300$ nm for $Ni_{82}Fe_{18}$ thin films [11], and $t_c \approx 85$ nm for $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ thin films [12], respectively. Here, we assumed that the ferromagnetic layers of the film are thinner than the critical thickness, and the magnetic moments of every layer exhibit a uniform ferromagnetic resonance model [8–10]. Thus the single magnetization vector $\vec{M}_1$ (or $\vec{M}_2$) may be used to represent the behavior of the magnetic moment in the first (or second) ferromagnetic layer. The energies involved in the exchange-coupled trilayer film are conventionally taken as [8]

$$E = \sum_i -(t_i \vec{H}_0 \cdot \vec{M}_i) - \sum_i \left[\frac{1}{2} t_i H_{u2,i}^{\text{eff}} \frac{M_{i,\parallel}^2}{M_i}\right] + J\vec{M}_1 \cdot \vec{M}_2, \tag{1}$$

where $\vec{H}_0$ is the external magnetic field and is assumed to be along the positive direction of the z axis and $i = 1$ (or 2) refers to the first (or second) ferromagnetic layer having thickness of t_1 (or t_2). $M_{i,\parallel}$ indicates the in-plane component of magnetization of the ith ferromagnetic layer; $H_{u2,i}^{\text{eff}}$ is the effective field due to the shape, surface, magnetocrystalline, stress, or other anisotropy: its direction is assumed to be parallel to the z axis. Negative J is the bilinear exchange energy constant per unit surface area for the parallel coupled system. Apparently, $\vec{M}_1$ and $\vec{M}_2$ stay parallel to the z axis in their equilibrium state.

The magnetic moment in each layer, if perturbed by magnetic field $\vec{h}_i$ from its equilibrium orientation, will precess around its equilibrium direction. Assuming a small deviation of the magnetization $\vec{M}_i = \vec{M}_{i0} + \vec{m}_i$ from its equilibrium position $\vec{M}_{i0}$, according to the Landau–Lifshitz equation,

$$\frac{\mathrm{d}M_i}{\mathrm{d}t} = -\gamma \vec{M}_i \times (\vec{H}_{\text{effi}} - \ddot{N}\vec{M}_i + \vec{h}_i) + \alpha_i \frac{\vec{M}_i}{\vec{M}_i} \times \frac{\mathrm{d}\vec{M}_i}{\mathrm{d}t}, \tag{2}$$

the linearized magnetization motion equations may be obtained:

$$\begin{pmatrix} \mathrm{j}\omega & \gamma_1 H_{\text{eff1}} + \mathrm{j}\omega\alpha_1 & 0 & \gamma_1 J M_{01}/t_1 \\ -\gamma_1(M_{01} + H_{\text{eff1}}) - \mathrm{j}\omega\alpha_1 & \mathrm{j}\omega & -\gamma_1 J M_{01}/t_1 & 0 \\ 0 & \gamma_2 J M_{02}/t_2 & \mathrm{j}\omega & \gamma H_{\text{eff2}} + \mathrm{j}\omega\alpha_2 \\ -\gamma_2 J M_{02}/t_2 & 0 & -\gamma_2(M_{02} + H_{\text{eff2}}) - \mathrm{j}\omega\alpha_2 & \mathrm{j}\omega \end{pmatrix}$$

$$\times \begin{pmatrix} m_{1x} \\ m_{1y} \\ m_{2x} \\ m_{2y} \end{pmatrix} = \begin{pmatrix} \gamma_1 M_{01} h_{1y} \\ -\gamma_1 M_{01} h_{1x} \\ \gamma_2 M_{02} h_{2y} \\ -\gamma_2 M_{02} h_{2x} \end{pmatrix} \tag{3}$$

where γ_i is the gyromagnetic ratio, $\ddot{N}$ the demagnetization coefficient with $N_{xx} = 1$ and the other elements approximately zero, α_i the Gillbert damping coefficient, $H_{\text{eff1}} = H_0 + H_{u2,1}^{\text{eff}} - JM_{02}/t_1$, and $H_{\text{eff2}} = H_0 + H_{u2,2}^{\text{eff}} - JM_{01}/t_2$, respectively. Solving equation (3) yields the dynamic magnetizations $\vec{m}_1$ and $\vec{m}_2$, then the magnetic susceptibility χ_i and permeability μ_i of the ith ferromagnetic layer are defined by

$$\chi_i = \chi_i' - \mathrm{j}\chi_i'' = \mu_i - 1 \equiv \frac{\vec{m}_i \cdot \vec{h}_i}{|\vec{h}_i|^2}. \tag{4}$$

On the other hand, according to Maxwell's equations, the wave eigenmodes of the normally incident microwave propagation in the ferromagnetic layer with in-plane uniaxial anisotropy are expressed as [4, 13]

$$\text{(i)}\ k = \frac{\omega}{c_0}\sqrt{\frac{\varepsilon_{zz}}{\nu}}, \qquad \vec{e} = -\frac{k}{\omega\varepsilon_0\varepsilon_{zz}} h_0 \vec{e}_z, \qquad \vec{h} = -\mathrm{i}\frac{\nu'}{\nu} h_0 \vec{e}_x + h_0 \vec{e}_y$$

$$\text{(ii)}\ k = \frac{\omega}{c_0}\sqrt{\frac{1}{\kappa}}, \qquad \vec{e} = -\mathrm{i}\frac{k\kappa'}{\omega\varepsilon_0} h_0 \vec{e}_x + \frac{k\kappa}{\omega\varepsilon_0} h_0 \vec{e}_y, \qquad \vec{h} = h_0 \vec{e}_z$$

where

$$\nu = \frac{\mu_{xx}}{\mu_{xx}\mu_{yy} - \mu_{xy}^2}, \qquad \nu' = \frac{-\mu_{xy}}{\mu_{xx}\mu_{yy} - \mu_{xy}^2},$$
$$\kappa = \frac{\varepsilon_{xx}}{\varepsilon_{xx}\varepsilon_{yy} - \varepsilon_{xy}^2}, \qquad \kappa' = \frac{-\varepsilon_{xy}}{\varepsilon_{xx}\varepsilon_{yy} - \varepsilon_{xy}^2},$$

c_0 is the light velocity in free space and $\vec{e}_x$, $\vec{e}_y$, and $\vec{e}_z$ unit vectors along the x, y, and z axes, respectively. It can be easily seen that wave eigenmode (i) is an E-polarized plane microwave satisfying $\vec{k} \cdot \vec{e} = 0$, and wave eigenmode (ii) is an H-polarized plane microwave satisfying $\vec{k} \cdot \vec{h} = 0$. To take into account the effects of gyrotropy of the permeability tensor, we consider the microwave with its electric field parallel to the z-axis passing from free space through the film as shown in figure 1, i.e., the microwave eigenmode in the film is E-polarized as described by solution (i). It is noted that, here, only the element ε_{zz} of the permittivity tensor needs to be considered. In addition, previous studies [14] have demonstrated that Drude's free-electron theory is valid for the permittivity of metallic films below the visible frequency regions. Thus, for simplicity, ε_{zz} ($\equiv\varepsilon$) of the film is assumed to be homogeneous and given by the Drude model [3, 4, 14]

$$\varepsilon = \varepsilon' - \mathrm{j}\varepsilon'' = 1 - \frac{\omega_\mathrm{p}^2}{\omega^2 - \mathrm{j}\omega/\tau}, \tag{5}$$

where ω_p is the plasma frequency and τ the relaxation time, taken as $\tau = 100/\omega_\mathrm{p}$.

Adopting permeability and permittivity obtained above, magnetic fields of the microwave in free spaces and film layers may be gained by using the following transfer matrix relations [4, 13]:

$$\eta_i h_{i+} \frac{1 \pm \eta_{ij}}{2} \exp(-\mathrm{i}k_i t_i) - \eta_i h_{i-} \frac{1 \mp \eta_{ij}}{2} \exp(\mathrm{i}k_i t_i) = \pm\eta_j h_{j\pm}, \tag{6}$$

where $\eta_{ij} = \eta_j/\eta_i$ (i (j) is taken as 0 (1), 1 (s), s (2), and 2 (3), respectively. $i = 1$ (or 2) refers to the first (or second) ferromagnetic layer, $i = 0$ and 3 indicate free space, and $i = \mathrm{s}$ the nonmagnetic spacer), $\eta_{0(3)} = 1$, $\eta_\mathrm{s} = \sqrt{1/\varepsilon}$, $\eta_{1(2)} = \sqrt{1/(\nu_{1(2)}\varepsilon)}$, $\nu_{1(2)} = \frac{\mu_{1(2)xx}}{\mu_{1(2)xx}\mu_{1(2)yy} - \mu_{1(2)xy}^2}$ [4]. h_{i+} (or h_{i-}) is the magnetic field of the forward (or backward) microwave. In the calculations, we take $h_{0+} = 1.0$, $t_0 = 0$, and $h_{3-} = 0$, respectively. Since, for the ultra-thin films considered in this work, the inhomogeneity of the exciting magnetic field along the film thickness is mainly attributed to the reflection at the interface between either the layers or the free space and the layer of the film, and the exciting magnetic field in every ferromagnetic layer is nearly constant, the exciting magnetic field applied in magnetization of the ith ferromagnetic layer is approximately adopted as

$$\vec{h}_i = \vec{h}_{i+} + \vec{h}_{i-}.$$

It is noted that determination of permeability μ_i requires a knowledge of $\vec{h}_i$, which in turn requires a knowledge of the permeability μ_i. Thus equations (3), (4), and (6) may be solved self-consistently. Once the self-consistent solution is determined, the absorption can be obtained by

$$A = 10\,\mathrm{lg}(1 - |h_{0-}/h_{0+}|^2 - |h_{3+}/h_{0+}|^2). \tag{7}$$

3. Numerical simulations and discussions

Below, we numerically investigate permeability and microwave properties of the exchange-coupled trilayer ferromagnetic films. Assuming the exciting magnetic field sweep in a certain frequency range, some typical results are shown in figures 2–4, respectively.

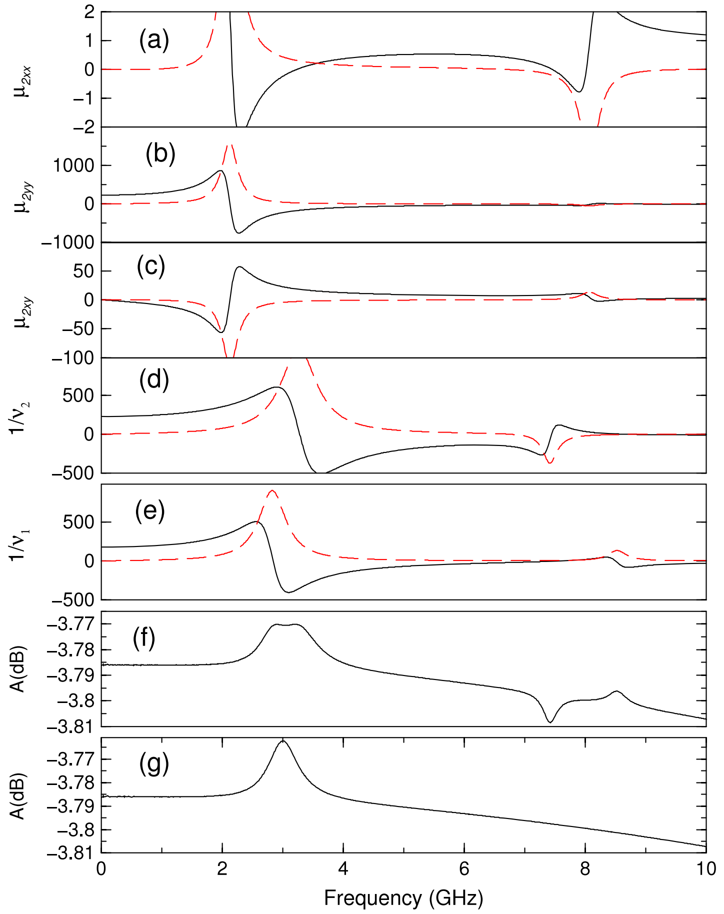

Figure 2. The calculated elements of permeability tensor (a) μ_{2xx}, (b) μ_{2yy}, and (c) μ_{2xy}. (d) $1/\nu_2$ of the second ferromagnetic layer; (e) $1/\nu_1$ of the first ferromagnetic layer. Solid lines refer to the real parts of the parameters, and dashed lines to the imaginary parts. (f) Absorption; (g) absorption for the same film perturbed by the assumed uniform exciting magnetic field.

We first present the basic characteristics of the permeability and microwave properties of the films associated with the inhomogeneity of the exciting magnetic field. The parameters of the considered film are arbitrarily chosen as follows [15]: $\gamma_1(H_0 + H^{\text{eff}}_{u2,1}) = \gamma_2(H_0 + H^{\text{eff}}_{u2,2}) = 0.3\pi$ GHz, $\gamma_1 M_{01} = \gamma_2 M_{20} = 60\pi$ GHz, $\omega_{\text{p}} = 2\pi \times 10^4$ GHz, the thickness of the layers $t_1 = t_2 = 20$ nm and $t_{\text{s}} = 0.5$ nm, the coupling parameter J is adopted as $-\gamma_1 J M_{02}/t_1 = -\gamma_2 J M_{01}/t_2 = 0.01\pi$ GHz, and the two Gilbert damping coefficients are conventionally taken as $\alpha_1 = \alpha_2 = 0.01$, respectively. It is noted that, for an ultra-thin layer, the effects of surface and interface may become dominant for the magnetic properties. For simplicity, we artificially assume that, here, these effects may be neglected, and magnetization in each layer can still be represented by a single magnetization. According to equation (3), the symmetric system has two resonance frequencies of 2.1 GHz for the acoustic mode and 8.0 GHz for the optic mode, respectively. However, the optic mode disappears in the dispersion relation curves when the exciting magnetic field is homogeneous, since the precessions of the two moments are identical, thus interlayer exchange coupling does not influence the motion of the two moments [8]. In fact, here, the microwave propagating in the film may be reflected

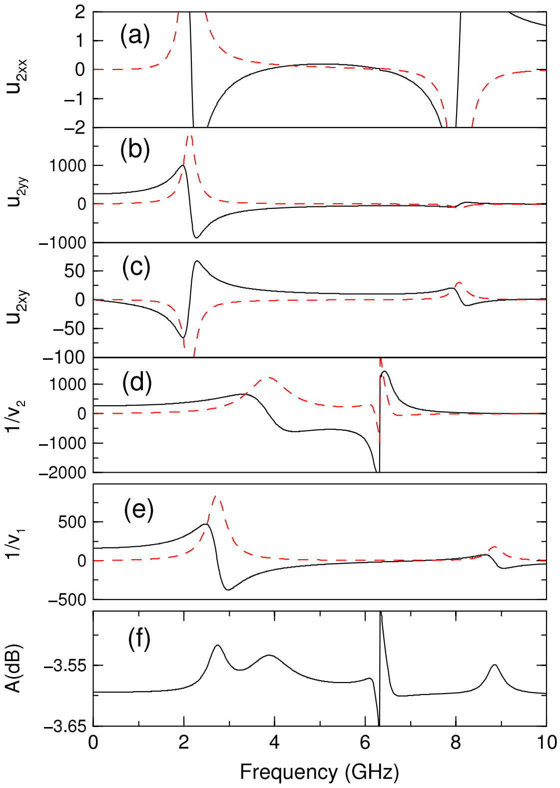

Figure 3. The calculated elements of permeability tensor for a thicker film: (a) μ_{2xx}, (b) μ_{2yy}, and (c) μ_{2xy}. (d) $1/\nu_2$ of the second ferromagnetic layer; (e) $1/\nu_1$ of the first ferromagnetic layer. (f) Absorption.

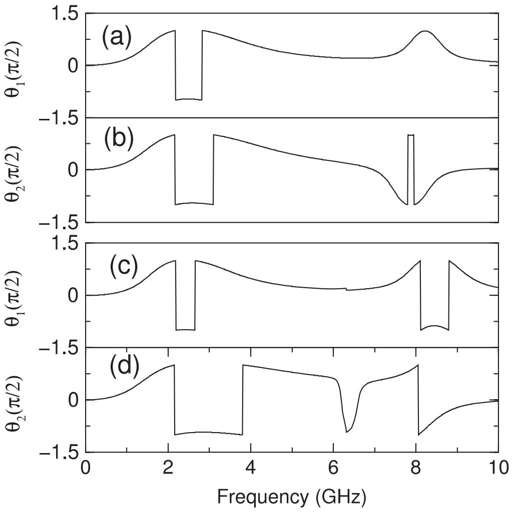

Figure 4. Angle between the Poynting flow and the x axis in (a) the first ferromagnetic layer and (b) the second ferromagnetic layer for the case shown in figure 2; (c) the first ferromagnetic layer, and (d) the second ferromagnetic layer for the case shown in figure 3.

at the interface and absorbed by layers of the film. Thus the magnetic field component of the microwave in the ferromagnetic layers, i.e. the exciting magnetic field applied in the two magnetizations, is depressed along the film thickness. Excited by the inhomogeneous magnetic field, the precession of one moment differs from that of the other one. Thus the interlayer exchange energy of $J\vec{M}_1 \cdot \vec{M}_2$ is altered, i.e. the effects of the effective field corresponding to interlayer exchange coupling on the motion of the two moments emerge. It is seen from figures 2(a)–(c) that, excited by the inhomogeneous magnetic field, the optic mode is exhibited in dispersion relation curves near the frequency of 8.0 GHz. In particular, there are $\mu''_{2xx} < 0$ and $\mu''_{2yy} < 0$ near the resonance frequency of 8.0 GHz for the optic mode abnormally, which indicates the damping angle $\pi < \alpha_{2\mu} < 2\pi$ corresponding to the out of phase oscillation of the two magnetizations for the optic mode. The unusual sign of $\mu''_{2xx} < 0$ and $\mu''_{2yy} < 0$ may induce some unique behaviors of the microwave propagation in the film (see below). It is stressed that, due to gyrotropy of the permeability tensor, the magnetic parameter related directly to properties of the normally incident E-polarized plane microwave propagation in the ith ferromagnetic layer is $1/\nu_i = \mu_{iyy} - \frac{\mu_{ixy}^2}{\mu_{ixx}}$ instead of the single element of the permeability tensor [4, 13]. For convenience, we still term the frequency of peaks (or dip) of $\mathrm{Im}(1/\nu_i)$ as the resonance frequency. From figure 2(d), we can see that $1/\nu_2$ has two resonance frequencies of 3.2 GHz and 7.4 GHz, respectively, which are not equal to those of elements μ_{2xx}, μ_{2yy}, and μ_{2xy} of the corresponding permeability tensor μ_2. Similarly, $1/\nu_1$ shown in figure 2(e) has two resonance frequencies of 2.8 GHz and 8.5 GHz, respectively, which also differ from those of elements of the corresponding permeability tensor μ_1. Abnormally, the resonance frequency 7.4 GHz of $\mathrm{Im}(1/\nu_2)$ dip is lower than the resonance frequency 8.0 GHz of the corresponding elements of the permeability, which is opposite to the case of $\mathrm{Im}(1/\nu_i)$ peaks and attributed to the unusual sign of $\mu''_{2xx} < 0$ and $\mu''_{2yy} < 0$. Further, the absorption is presented in figure 2(f). There are two peaks at frequencies of 3.0 GHz and 8.5 GHz, and one dip at a frequency of 7.4 GHz, respectively. The absorption peak at 3.0 GHz is in correspondence with the peaks of both $\mathrm{Im}(1/\nu_1)$ at the frequency of 2.8 GHz and $\mathrm{Im}(1/\nu_2)$ at the frequency of 3.2 GHz, respectively. The absorption dip near the frequency of 7.4 GHz may be attributed to the small transmission losses induced by the opposite signs of $\mathrm{Im}(1/\nu_2)$ and ε'' in the second ferromagnetic layer [16]. For comparison, the absorption of the same film perturbed by the assumed uniform exciting magnetic field is shown in figure 2(g); here, only an absorption peak is exhibited near a frequency of 3.0 GHz. Therefore, it is apparent that the number, frequency position, and shape of absorption peaks are strongly modified by the heterogeneity of the exciting magnetic field along the film thickness.

Second, we demonstrate further effects of depressed exciting magnetic field on both the permeability and properties of microwave propagation in the film. We increase the thickness of the two ferromagnetic layers to be $t_1 = t_2 = 100$ nm, and the other film parameters remain the same as the previous case. The calculated results are shown in figure 3. From figures 3(a)–(c), we see that the system keeps two resonance frequencies of 2.1 GHz for the acoustic mode and 8.0 GHz for the optic mode, respectively. Comparing with figures 2(a)–(c), it is found that the diagonal element μ_{2xx} in the frequency range from 3.9 to 6.3 GHz decreases; however, μ_{2yy} and μ_{2xy} increase slightly. Since the magnetic parameter related directly to properties of normally incident E-polarized plane microwave propagation in the film is $1/\nu_i = \mu_{iyy} - \frac{\mu_{ixy}^2}{\mu_{ixx}}$, the alteration of μ_{2xx} and μ_{2xy} mentioned above may modify the ratio of $\frac{\mu_{2xy}^2}{\mu_{2xx}}$, and thus influence microwave properties of the film. From $1/\nu_2$ shown in figure 3(d), we see that resonance frequencies of $1/\nu_2$ become 3.9 and 6.3 GHz. In particular, the shape of $1/\nu_2$ near the frequency of 6.3 GHz differs significantly from that of $1/\nu_2$ near the resonance frequency of 3.9 GHz and $1/\nu_1$ near its two resonance frequencies. But, the change of $1/\nu_1$ is trivial. The significant alterations of $1/\nu_2$ modify the absorption strongly, which can be seen from figure 3(f). Corresponding to the resonance frequencies of $1/\nu_2$, there is an absorption peak (dip) near frequencies of 3.9 GHz (6.3 GHz), respectively.

Third, we investigate the physics mechanics of the strong modifications of absorption mentioned above. On one hand, according to equation (3), it is found that the magnitudes

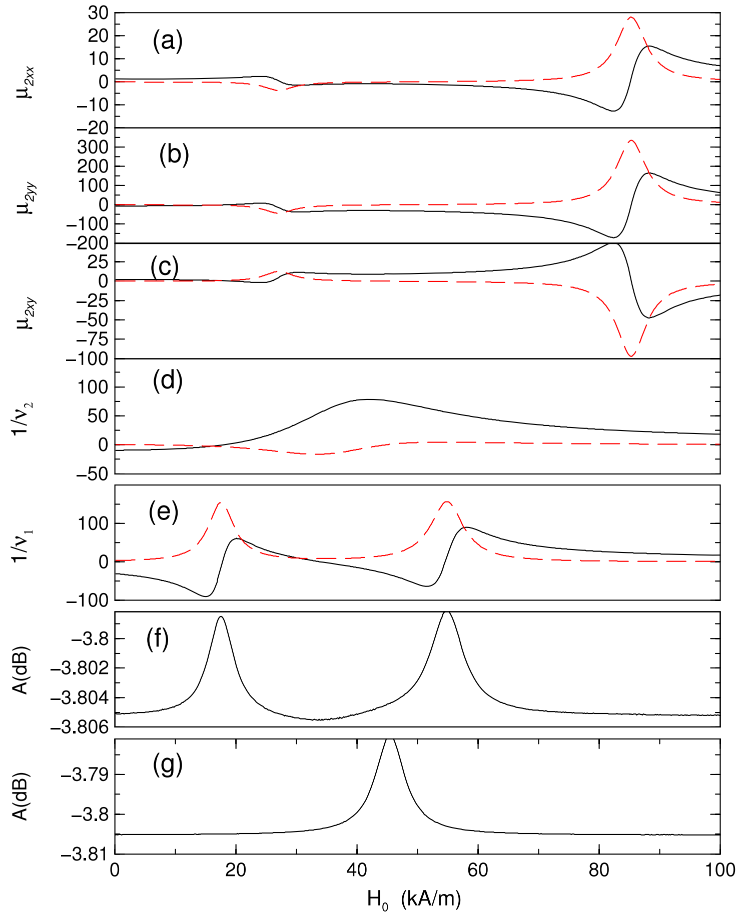

Figure 5. The calculated magnetic parameters and absorption as a function of the applied in plane DC magnetic field at constant microwave frequency of 9.5 GHz (X-band) for the same film as considered in figure 2. (a) μ_{2xx}, (b) μ_{2yy}, and (c) μ_{2xy}. (d) $1/\nu_2$ of the second ferromagnetic layer; (e) $1/\nu_1$ of the first ferromagnetic layer. (f) Absorption. (g) Absorption for the same film perturbed by the assumed uniform exciting magnetic field.

of elements of the permeability tensor of the ferromagnetic layers are unusually related to the ratio of h_1/h_2. The alteration of the elements of the permeability tensor shown in figures 3(a)–(d) compared with that shown in figures 2(a)–(d) is attributed to the enhancement of the ratio of h_1/h_2. Since increasing the plasma frequency of ω_p may also enhance the ratio of h_1/h_2, similar results to those shown in figure 3 may also be obtained by only increasing the plasma frequency (for example, chosen as $\omega_\mathrm{p} = 2\pi \times 10^5$ GHz, not shown). On the other hand, based on Maxwell's equations, the wavevector of the normally incident microwave in the film is always parallel to the x axis as shown on the left side of figure 1. However, the Poynting flow is not so (see the right side of figure 1). The angle θ_i between the Poynting flow and the x axis is given by [4, 13]

$$\theta_i = \arctan\left(\mathrm{Re}\,\frac{\mathrm{i}\mu^*_{ixy}}{\mu^*_{ixx}}\right). \tag{8}$$

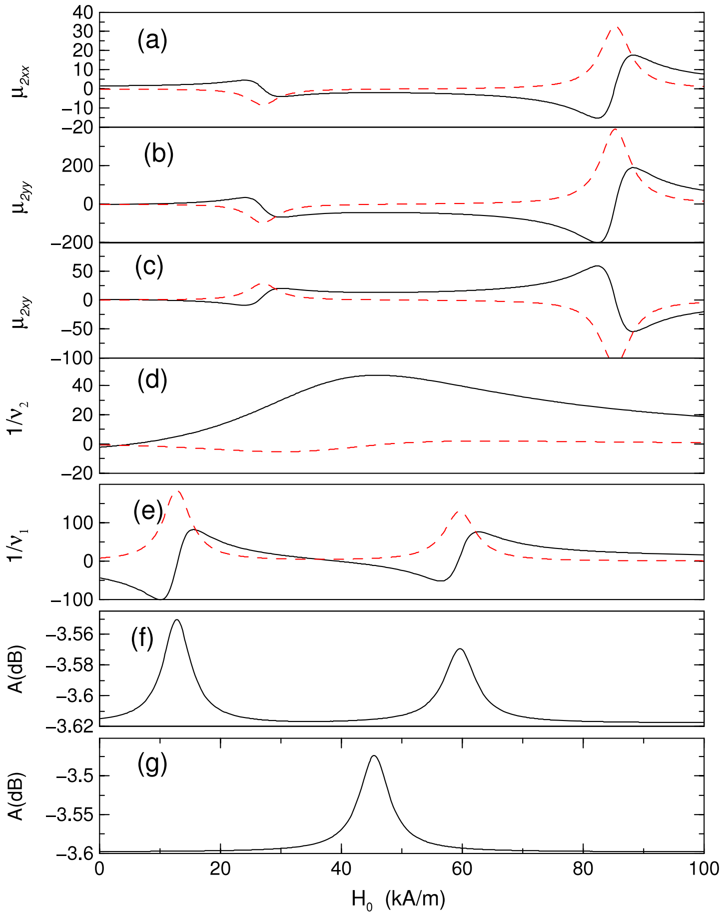

Figure 6. The calculated magnetic parameters and absorption as a function of the applied in plane DC magnetic field at constant microwave frequency of 9.5 GHz (X-band) for the same film as considered in figure 3. (a) μ_{2xx}, (b) μ_{2yy}, and (c) μ_{2xy}. (d) $1/\nu_2$ of the second ferromagnetic layer; (e) $1/\nu_1$ of the first ferromagnetic layer. (f) Absorption. (g) Absorption for the same film perturbed by the assumed uniform exciting magnetic field.

The angle θ_i versus frequency lines for the cases shown in figures 2 and 3 are demonstrated in figure 4. We note that angle θ_i near the frequency of the corresponding absorption peaks tends to be nearly $\pi/2$; i.e., $|\mathrm{Re}(\frac{\mathrm{i}\mu^*_{ixy}}{\mu^*_{ixx}})|$ is sufficiently large. The angle $\theta_i \approx \frac{\pi}{2}$ indicates that the Poynting flow in the ferromagnetic layer is nearly parallel to the film surface, thus the propagation distance of the Poynting flow in the ferromagnetic layer is significantly larger than the layer thickness, hence enhancing the absorption. In a few words, here, the effects of the depressed exciting magnetic field along the film thickness on different elements of the permeability tensor are different, thus altering the direction of the Poynting flow in the ferromagnetic layer and then the properties of the microwave propagation in the film.

Finally, we give the permeability tensors and absorption of the film as a function of the applied in-plane DC magnetic field at a constant microwave frequency of 9.5 GHz (X-band), which may be useful for most experiments carried out at constant frequency by varying external DC magnetic field. In the calculations, the same films as mentioned above associated with the cases shown in figures 2 and 3 are adopted. In addition, for simplicity, we assume $H_{u2,1}^{\rm eff} = H_{u2,2}^{\rm eff} = 0$. The obtained results are demonstrated in figures 5 and 6, respectively. It is noted that the obtained magnetic parameters and absorption differ significantly from the corresponding cases shown in figures 2 and 3, respectively, which is attributed to the fact that the effects of external DC magnetic field H_0 on the permeability tensor differ from those of the frequency of the exciting magnetic field. However, the remarkable alteration of the magnetic parameters of $1/\nu_1$, $1/\nu_2$, and absorption induced by the inhomogeneity of the exciting magnetic field is exhibited similarly. Since the magnetic parameters of $1/\nu_1$, $1/\nu_2$, and absorption are sensitive to the film parameters, the detailed discussions are not presented in this paper.

4. Conclusion

In summary, based upon the Landau–Lifshitz equation and Maxwell's equations, the permeability and properties of normally incident microwave propagation in exchange-coupled trilayer ferromagnetic films with in-plane uniaxial anisotropy are investigated. The obtained results show that, due to the coexistence of IEC and the gyrotropic permeability tensor in the film, the element value of permeability tensor of the ferromagnetic layers is related to the ratio of the exciting magnetic field h_1/h_2 unusually, and the effects of depressed exciting magnetic fields along the film thickness on different elements of the permeability tensor are different. Thus the magnetic parameter of $1/\nu = \mu_{yy} - \mu_{xy}^2/\mu_{xx}$ and then the microwave properties of the film may be strongly modified. This study offers new ways to tailor properties of microwave propagation in the layered ferromagnetic structures by using IEC and the gyrotropic permeability tensor. Experimental quantifications of the predictions of this paper should also motivate further theoretical progress.

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