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Unique properties of microwave in interlayer exchange-coupled trilayer ferromagnetic films associated with negative imaginary part of permeability

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ABSTRACT

Based upon Landau–Lifshitz equation and Maxwell's equations, we theoretically investigated properties of normally incident microwave propagation in interlayer exchange-coupled trilayer ferromagnetic film. It is found that, near resonance frequency of optic mode, imaginary part of permeability of one ferromagnetic layer is smaller than zero unusually, i.e., the ferromagnetic layer may be taken as an active medium. Thus a number of unique electromagnetic properties are presented, such as, the ferromagnetic layer becomes a left-handed material near low side of the resonance frequency of optic mode, and both phase velocity and time-averaged Poynting flow of the usually defined forward wave are negative simultaneously near high side of the resonance frequency. This work provides a feasible active medium to demonstrate the unique microwave properties.

1. Introduction

Left-handed material (LHM) has been received much attention due to its highly unusual electromagnetic properties and promise for new applications [1–15]. In a paper published in 1968 [1], Veselago predicted that, in the medium having simultaneously negative (real parts of) permeability and permittivity, triple of vectors of electric field E, magnetic field H, and wave vector Re(k) of electromagnetic wave (EMW) form a left-handed orthogonal set. The first experimental demonstration of a LHM is implemented by Shelby et al. [2] following the pioneering works of Pendry et al. [3,4]. These revolutionary works aroused great interest in the unusual electromagnetic properties of LHMs. Previous studies mainly focused on the electromagnetic properties of passive media with positive imaginary parts of both permeability and permittivity [5–10]. On the other hand, it is found that metamaterials may hold negative imaginary part of either effective permeability or effective permittivity [11,12]. In addition, the active media are proposed as a new type of LHM, and a lot of unique electromagnetic properties of LHM made of active media have been theoretically predicted [13–15]. However, the feasible active LHMs are still scarce.

On the other hand, metallic ferromagnetic structures generally exhibit abundant magnetic properties in gigahertz frequency range [16–21]. It is proposed that, in the low side of resonance frequency, metallic ferromagnetic films are promising for potential applications in magnetic storage media and microwave devices [16–18], and near high side of resonance frequency, the metallic ferromagnetic structures may be deemed to be the naturally occurring left-handed materials [19–21]. 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 [22–27]. It is also found that the permeability of trilayer (or multilayer) film may be remarkably influenced by IEC [24–27]. For instance, in trilayer ferromagnetic film, the imaginary part of permeability of one ferromagnetic layer is unusually smaller than zero near resonance frequency of optic mode [27], i.e., the ferromagnetic layer may be taken as an active medium, and used to demonstrate unique electromagnetic properties predicted previously [13–15].

In this work, we shall demonstrate microwave properties associated with negative imaginary part of permeability by investigating properties of normally incident microwave propagation in the trilayer ferromagnetic films. The remaining of this paper is organized as follows: in Section. 2, we introduce theories employed in this paper. In Section 3, properties of normally incident microwave propagation in the trilayer ferromagnetic

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films are calculated and addressed. Finally, some conclusions are presented in Section. 4.

2. Theory for normally incident microwave in exchange-coupled trilayer ferromagnetic films

Theoretical treatments on properties of microwave in the exchange-coupled trilayer ferromagnetic film are based on solving Maxwell's equations for electromagnetic fields coupled with Landau–Lifshitz equation for the magnetizations [27–30].

The film to be considered in this work is shown in Fig. 1, which consists of two ferromagnetic layers separated by a nonmagnetic spacer. Conventionally, the single magnetization vector M_1 (or M_2) is used to represent behavior of magnetic moment in the first (or second) ferromagnetic layer, and the energies involved in the exchange-coupled trilayer film are taken as [25–27]

$$E=\sum_i -(d_i\vec{H}_0\cdot\vec{M}_i)-\sum_i\left[\frac{1}{2}d_iH^{eff}_{u2,i}\frac{M^2_{i,\perp}}{M_i}\right]J\vec{M}_1\cdot\vec{M}_2, \tag{1}$$

where $i=1$ (or 2) refers to the first (or second) ferromagnetic layer having thickness of d_1 (or d_2), H_0 external magnetic field along the positive direction of z-axis, $M_{i,\perp}$ the normal component of magnetization of the ith ferromagnetic layer, $H^{eff}_{u2,i}$ the effective field due to shape, surface, stress, or other anisotropy, its direction is assumed parallel to the z-axis. Negative J is the bilinear exchange energy constant per unit surface area for the parallel coupled system. Apparently, M_1 and M_2 stay parallel to z-axis in their equilibrium state as shown in Fig. 1.

The two magnetizations, if perturbed by the exciting magnetic field $\vec{h}_i(t)=\vec{h}_{i0}\exp(j\omega t)$ from their equilibrium orientation, will precess around its equilibrium direction. Assuming a small deviation $\vec{m}_i(t)$ of the magnetization $\vec{M}_i(t)=\vec{M}_{i0}+\vec{m}_i(t)$ from its equilibrium position $\vec{M}_{i0}$, according to Landau–Lifshitz equation, the linearized magnetizations dynamic equations may be expressed as [14,27]

$$\begin{aligned}\frac{dm_{ix}(t)}{dt}=\frac{\gamma_i}{1+\alpha_i^2}[&-\alpha_iH_{effi}m_{ix}(t)-H_{effi}m_{iy}(t)\\&-\alpha_iJM_{0i}m_{jx}(t)/d_i-JM_{0i}m_{jy}(t)/d_i+\alpha_iM_{0i}h_{ix}(t)+M_{0i}h_{iy}(t)],\end{aligned} \tag{2a}$$

and

$$\begin{aligned}\frac{dm_{iy}(t)}{dt}=\frac{\gamma_i}{1+\alpha_i^2}[&H_{effi}m_{ix}(t)-\alpha_iH_{effi}m_{iy}(t)\\&+JM_{0i}m_{jx}(t)/d_i-\alpha_iJM_{0i}m_{jy}(t)/d_i-M_{0i}h_{ix}(t)+\alpha_iM_{0i}h_{iy}(t)],\end{aligned} \tag{2b}$$

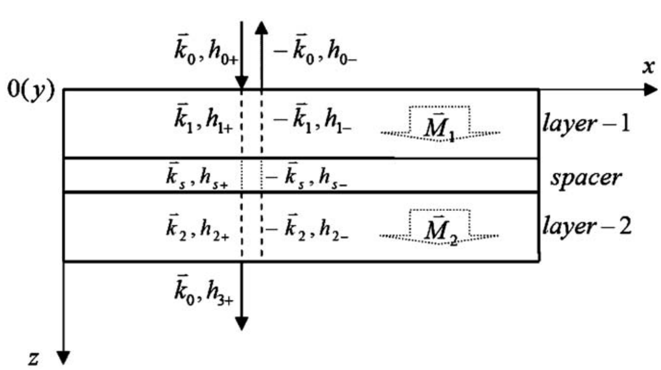

Fig. 1. The parallel-coupled trilayer ferromagnetic film, and schematic diagram of normally incident RCP microwave passing from the free space through the film. In which, k_i refers the propagation constant of microwave in the ith layer (or space), h_{i+} (or h_{i-}) the magnetic field component of the forward (or backward) microwave.

where right low label $i=1$, 2 ($j=2$, 1), γ_i is the gyromagnetic ratio, α_i the Gilbert damping coefficient. $H_{eff1(2)}=H_0$+-$H^{eff}_{u2,1(2)}$–$JM_{02(1)}/d_{1(2)}$. The permeability tensors computations were performed for every elements of $\mu_{i\xi\xi}$ ($\xi(\zeta)=x$ or y) at each frequency $f(=\omega/2\pi)$, respectively. Assuming the initiation state to be $\vec{m}_{1(2)}(0)=0$, for a given frequency $f(=\omega/2\pi)$, the exciting magnetic field is taken as $h_{i\xi}(t)=h_0\exp(j\omega t)$, the dynamic magnetizations $\vec{m}_{ix}(t)$ and $\vec{m}_{iy}(t)$ are obtained by integrating Eqs. (2a) and (2b) based on the simple forward difference method with a time step of 10^{-3} ns, which is sufficiently small to avoid numerical instability. Finally, the elements $\mu_{i\xi\xi}$ of permeability tensor of the ith ferromagnetic layer are defined by [14,27]

$$\begin{aligned}\mu_{i\xi\zeta}&=\mu'_{i\xi\zeta}-j\mu''_{i\xi\zeta}=|\mu_{i\xi\zeta}|\exp(-j\alpha_\mu)\\&=\mu_0(1+\chi_{i\xi\zeta})\equiv\mu_0\left(1+\frac{\vec{m}_{i\xi}(t)\cdot\vec{h}_{i\zeta}(t)}{|\vec{h}_{i\zeta}(t)|^2}\right).\end{aligned} \tag{3}$$

To test reliability of this approach, we have also performed the calculations of permeability tensor based on the Gauss factorization in frequency space employed in Ref. [27], and found that the results obtained by using the two ways are well consistent with each other.

For simplicity, the permittivity of the film is assumed homogeneous and given by the Drude model $\varepsilon=\varepsilon'-j\varepsilon''=|\varepsilon|\exp(-j\alpha_\varepsilon)=\varepsilon_0(1-(\omega_p{}^2/(\omega^2-j\omega/\tau)))$ [27,31], where ω_p is the plasma frequency, and τ is the relaxation time.

On the other hand, according to Maxwell's equations, the normally incident microwave propagation in the film mentioned above is either right circularly polarized (RCP) or left circularly polarized (LCP) [14,31]. Below, to demonstrate unique microwave properties associated with negative imaginary part of permeability, we shall consider the case of RCP microwave passing from free space through the film as shown in Fig. 1. Adopting permeability and permittivity obtained above, magnetic fields of the microwave in free spaces and ferromagnetic layers may be gained by using the following transfer matrix relations [27,31]:

$$\eta_ih_{i+}(t)\frac{1\pm\xi_{ij}}{2}\exp(-jk_id_i)-\eta_ih_{i-}(t)\frac{1\mp\xi_{ij}}{2}\exp(jk_id_i)=\pm\eta_jh_{j\pm}(t), \tag{4}$$

where $k_i\equiv\omega\sqrt{\mu_{iR}\varepsilon_i}=\omega\sqrt{|\mu_{iR}\varepsilon_i|}\exp(-j(\alpha_{i\mu}+\alpha_{i\varepsilon}/2))=\omega\sqrt{|\mu_{iR}\varepsilon_i|}\exp(-j\alpha_{ik})$ [5–8] is propagation constant, $\eta_i\equiv\sqrt{\mu_{iR}/\varepsilon_i}=\sqrt{|\mu_{iR}/\varepsilon_i|}\exp(-j(\alpha_{i\mu}-\alpha_{i\varepsilon}/2))=\sqrt{|\mu_{iR}/\varepsilon_i|}\exp(-j\alpha_{i\eta})$[5–8] the wave impedance, $\xi_{ij}=\eta_j/\eta_i$, $\mu_{iR}=\mu_{ixx}-\mu_{ixy}$, $h_{i+}(t)$ (or $h_{i-}(t)$) the magnetic field of the forward (or backward) microwave, (right low label $i(j)$ is taken as 0(1), 1(s), s(2), and 2(3), respectively. $i=1$ (or 2) refers the first (or second) ferromagnetic layer, i = 0 and 3 indicate the free space, and $i=s$ the nonmagnetic spacer). In the calculations, we take into account of $h_{0+}(t)=1.0\times\exp(j\omega t)$, $d_0=0$, and $h_{3-}=0$, respectively.

It is noted that determination of permeability μ_i require a knowledge of h_i, which in turn require the knowledge of permeability μ_i. Thus Eqs. (2a)–(4) are solved in turn. In addition, it is pointed out that the inhomogeneity of the exciting magnetic field along the ultra-thin film thickness is mainly attributed to the reflection at the interfaces, and the magnetic field in every thin ferromagnetic layer is nearly constant. Thus exciting magnetic field applied in the magnetization of the ith ferromagnetic layer is approximately taken as $h_i(t)=h_{i+}(t)+h_{i-}(t)$. Once $h_{i\pm}$ is determined, time-averaged Poynting flow $\langle S_i\rangle$ and the transmission T are given as

$$\begin{aligned}\langle\vec{S}_i\rangle&=\tfrac{1}{2}\mathrm{Re}(\eta_ih_{i+}(t)h^*_{i+}(t))\vec{e}_z+\tfrac{1}{2}\mathrm{Re}(-\eta_ih_{i-}(t)h^*_{i-}(t))\vec{e}_z\\&\quad+\tfrac{1}{2}\mathrm{Re}[\eta_i2j\mathrm{Im}(h_{i+}(t)h^*_{i-}(t))]\vec{e}_z\equiv\langle\vec{S}_{i+}\rangle+\langle\vec{S}_{i-}\rangle+\langle\vec{S}_{i\mathrm{int}}\rangle,\end{aligned} \tag{5}$$