MSSW and MSVW in a Multilayered Ferrimagnetic Structure with an Arbitrary Orientation Between Two Static Magnetizations

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Abstract—**This paper presents a study of both magnetostatic surface wave (MSSW) and magnetostatic volume wave (MSVW) propagation in multilayered magnetic thin films with noncollinear magnetizations. YIG/GGG/YIG structure is used, where YIG and GGG are the abbreviations for yttrium iron garnet and gadolinium gallium garnet, respectively. The layered film is in the (110) plane. Due to the existence of both cubic and induced in-plane uniaxial anisotropy fields in the two YIG films, the two magnetizations ($\vec{M}_1$ and $\vec{M}_2$) are not aligned with the applied dc field. Since there is an arbitrary angle between $\vec{M}_1$ and $\vec{M}_2$, there is a new configuration to study both MSSW and MSVW propagations. The interested MSVW propagation in the plane formed by $\vec{M}_1$ and $\vec{M}_2$ shows a different dispersion relationship from that in the direction perpendicular to the plane formed by $\vec{M}_1$ and $\vec{M}_2$. For a given applied dc field normal to the film plane, MSVW is excited in the $\vec{M}_2$ layer, while MSSW is excited in the $\vec{M}_1$ layer. We have found that the angle between the two static magnetizations strongly affects the dispersion relationship. In addition, the effect of the separation between the two magnetic layers on the dispersion and time delay has been studied.**

I. Introduction

The propagation of magnetostatic waves (MSW's) in layered planar magnetic structures has been studied by many investigators [1]–[12]. Much of this interest is geared to achieve technically desired delay characteristics, especially in conjunction with the microwave integrated circuits. It is known that delay properties of double layered structures are superior to those of single layer structures, since double layered structures can provide a wider range of nondispersive time delay characteristics for MSW propagation compared to those from single layer structures. For instance, the bandwidth of nondispersive delay of MSW excited in double layered slabs is twice [4] as much as that obtained from a single layer slab. In the above-mentioned investigations, the applied dc magnetic field is fixed in the direction either in the film plane or perpendicular to it. In practice, the direction of the biasing field may be neither in the film plane nor perpendicular to the film plane by either controlling the direction of the biasing field or a small deviation of the biasing field from the specified direction.

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Studies of such configurations for single layer magnetic structure were carried out in the past [13]–[16]. For the multilayered magnetic structure, it has been found [17] that when the applied magnetic field is small, the magnetizations in the layers of a single crystal double layered YIG structure are not collinear to each other because of the induced in-plane anisotropy field being different in each layer. This is caused by the strain arising from the substrate strain being different in each layer. The effect of the misalignment between the two static magnetizations on the propagation of MSSW in such a structure has been studied [18]. In this paper, we have purposely considered a biasing case in which misalignment between the static magnetizations is possible. Thus, we present a theoretical investigation of both MSVW and MSVW propagation in a double layered magnetic structure, in which we assume that there exists a certain angle between the two static magnetizations for a given value of the applied field. The importance of this study is that one may control the dispersion and time delay by changing the relative orientation of the static magnetizations.

In this study, a single crystal double layered YIG structure is considered. First, biasing conditions for misalignment of the two static magnetizations of the two YIG layers will be given according to the analysis of the free energy of the whole structure and equilibrium conditions. Then the dispersion relations for both MSSW and MSVW propagations will be derived. As shown in Fig. 1, two cases are of interest. One is the propagation along x-direction ($\vec{k}$ in the plane of $\vec{M}_1$ and $\vec{M}_2$), and the other is the propagation along y-direction ($\vec{k}$ perpendicular to the plane of $\vec{M}_1$ and $\vec{M}_2$). In the latter case, both MSVW and MSSW are excited, whereas only MSVW is excited in the former case when the applied dc field is normal to the film plane. Finally, we will discuss the effect of the misalignment and the separation between the two magnetic layers on the propagations of MSVW and MSSW, dispersion, and time delays.

II. Theory

The geometry of the two-layered structure is shown in Fig. 1, where a paramagnetic GGG film of thickness d_2 is placed between two YIG films. The film planes were chosen to be (110) planes so that the easy axis of magnetization in each layer was in the film plane. The applied dc field ($\vec{H}_a$) is normal to the film plane. The two magnetizations of the

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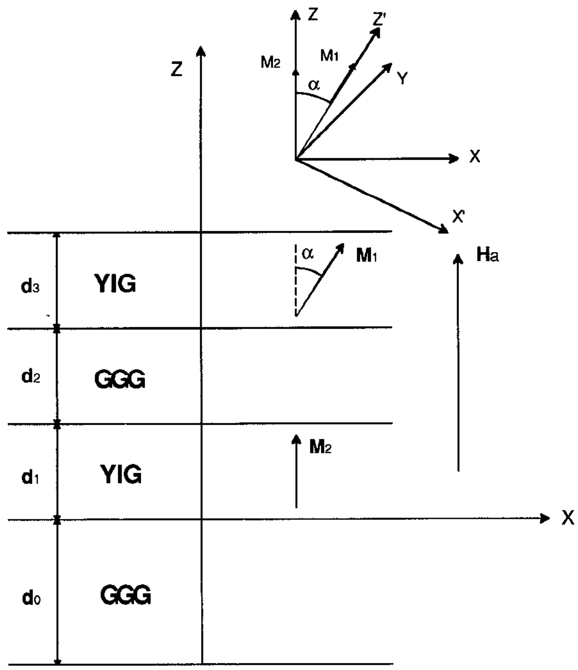

Fig. 1. A cross view of the geometrical configuration of the double layered YIG film. The two YIG layers were grown in $(1\bar{1}0)$ plane. The applied field is perpendicular to the film plane. The angle between the two static magnetizations is equal to α.

two YIG layers are represented by $\vec{M}_1$ and $\vec{M}_2$, respectively. As shown in Fig. 1, it is assumed that $\vec{M}_2$ is aligned with the applied dc field, while $\vec{M}_1$ has an arbitrary angle α with respect to $\vec{M}_2$. It will be explained later that this α is dependent upon the applied field. The bulk parameters for this structure are adopted from previous work [17]. The assumed parameters for one layer are $4\pi M_1 = 1750$ Gauss, $2K_1^{(1)}/M_1 = -82$ Oe, $2K_u^{(1)}/M_1 = 0$, $d_1 = 1$ μm; for the other layer, $4\pi M_2 = 4\pi M_1 - H_A^{\perp} = 1256$ Gauss, $H_A^{\perp} = 494$ Oe, $2K_1^{(2)}/M_2 = -82$ Oe, $2K_u^{(2)}/M_2 = 50$ Oe, $d_3 = 1$ μm, where $H_A^{\perp}$ is the uniaxial anisotropy field normal to the film plane, and $K_1^{(i)}$ and $K_u^{(i)}$ $(i = 1, 2)$ are the cubic anisotropy and induced in-plane anisotropy energies, respectively. d_0 is the thickness of substrate GGG, and is far greater than the sum of d_1, d_2, and d_3. The separation between the two magnetic layers d_2 is a variable in this study.

Equilibrium positions of the static magnetizations in the layered structure can be found by the analysis of free energy and equilibrium conditions. The total free energy (F) of the structure includes the magnetizing energy, demagnetizing energy, cubic anisotropy energy, and induced in-plane anisotropy energy. It is know that F is a function of angular orientations (θ_1, ϕ_1), (θ_2, ϕ_2), and (β_a, ϕ_a) of the static magnetizations $\vec{M}_1$ and $\vec{M}_2$, and the applied field $\vec{H}_a$. In this study, the applied dc field is fixed in the direction which is normal to the film plane. The equilibrium conditions require

$$\frac{\partial F}{\partial \theta_1} = \frac{\partial F}{\partial \phi_1} = \frac{\partial F}{\partial \theta_2} = \frac{\partial F}{\partial \phi_2} = 0 .$$

For a given applied field, solving the four equations from the equilibrium conditions gives rise to the orientations (θ_{10}, ϕ_{10}) and (θ_{20}, ϕ_{20}) of the two static magnetizations. The angle α between the two static magnetizations thus can be determined by

$$\cos\alpha = \sin\theta_{10}\sin\theta_{20}\cos(\phi_{20} - \phi_{10}) + \cos\theta_{10}\cos\theta_{20}$$

where the angle is applied field dependent. Fig. 2 shows the relationship between the angle α and the applied dc field, which is perpendicular to the film plane. It is obvious that the two static magnetizations are not parallel to each other until the applied field is equal to 1780 Gauss. When the applied field is low or near zero, the two magnetizations lie in the film plane. As the applied dc field increases, the static magnetizations come out of the film plane. The analysis indicates that when the applied field is approximately greater than the sum of $4\pi M_2$, the cubic anisotropy field and the induced in-plane field, $\vec{M}_2$ is aligned with the applied field, that is, perpendicular to the film plane, whereas $\vec{M}_1$ is neither normal to the film plane nor in the film plane. Our interest is focused on the region of the applied filed greater than the sum since both MSVW and MSSW can be excited in the layered structure.

In order to obtain the magnetostatic dispersion relations, one has to find the permeability tensor elements for each layer. In the configuration, where $\vec{M}_2$ is normal to the film plane and $\vec{M}_1$ has an arbitrary angle α with $\vec{M}_2$, we introduce two coordinate systems. One is the primed system (x', y', z') corresponding to layer 1 $(\vec{M}_1)$, and the other is the unprimed (x, y, z) system corresponding to layer 2 $(\vec{M}_2)$. The z'- and z-axes are chosen to be parallel to the static magnetization directions of $\vec{M}_1$ and $\vec{M}_2$, respectively (see Fig. 1). $\vec{M}_1$ and $\vec{M}_2$ lie in the xz or $x'z'$ plane.

The angle between z' and z is equal to α and is a measure of misalignment between the two magnetization directions. The permeability tensors ($\bar{\mu}_1$ and $\bar{\mu}_2$) of $\vec{M}_1$ and $\vec{M}_2$ in the (x, y, z) system can be written as 1(a) and 1(b) shown at the bottom of the next page.
where μ'_{11}, μ'_{12}, and μ'_{22} are calculated in the primed system, while μ_{11}, μ_{12}, and μ_{22} are calculated in the unprimed system. The determinations of these permeability elements can found in [18] and [19].

Under the magnetostatic approximation $\vec{h}_m = -\nabla\psi$, where ψ is a magnetic scalar potential, combined with $\vec{B} = \mu_0\bar{\mu}\cdot\vec{h}_m$,

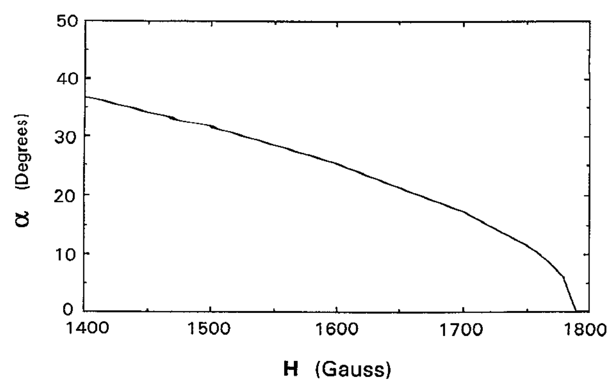

Fig. 2. The angle between the two static magnetizations with the applied field perpendicular to the film plane. The parameters used in this calculation are $4\pi M_1 = 1750$ Gauss, $2K_1^{(1)}/M_1 = -82$ Oe, $2K_u^{(1)}/M_1 = 0$; and $4\pi M_2 = 1256$ Gauss, $2K_1^{(2)}/M_2 = -82$ Oe, $2K_u^{(2)}/M_2 = 50$ Oe.

we have

$$\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}+\frac{\partial^2\psi}{\partial z^2}=0, \qquad -\infty<z\le 0 \tag{2}$$

$$\mu_{11}\frac{\partial^2\psi}{\partial x^2}+\mu_{22}\frac{\partial^2\psi}{\partial y^2}+\frac{\partial^2\psi}{\partial z^2}=0, \qquad 0<z\le d_1 \tag{3}$$

$$\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}+\frac{\partial^2\psi}{\partial z^2}=0, \qquad d_1<z\le d_1+d_2 \tag{4}$$

$$\left(\mu'_{11}\cos^2\alpha+\sin^2\alpha\right)\frac{\partial^2\psi}{\partial x^2}+\mu'_{22}\frac{\partial^2\psi}{\partial y^2}+\left(\mu'_{11}\sin^2\alpha+\cos^2\alpha\right)\cdot\frac{\partial^2\psi}{\partial z^2}+(1-\mu'_{11})\sin 2\alpha\frac{\partial^2\psi}{\partial x\partial z}=0, \quad d_1+d_2<z\le d_1+d_2+d_3 \tag{5}$$

$$\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}+\frac{\partial^2\psi}{\partial z^2}=0, \qquad d_1+d_2+d_3<z<\infty. \tag{6}$$

There are two cases of interest. One is the propagation along the x-axis, and has a uniform field in the transverse direction ($\frac{\partial}{\partial y}=0$). In this case, the wave vector $\vec{k}$ is in the plane of $\vec{M}_1$ and $\vec{M}_2$. The corresponding magnetostatic potential in each region as shown in Fig. 1 can be expressed as

$$\Psi_I=C_1e^{kz-jkx}, \qquad -\infty<z\le 0 \tag{7}$$

$$\Psi_{II}=\left(C_2e^{j\kappa z}+C_3e^{-j\kappa z}\right)e^{-j\kappa x}, \qquad 0<z\le d_1 \tag{8}$$

$$\Psi_{III}=\left(C_4e^{kz}+C_5e^{-kz}\right)e^{-jkx}, \quad d_1<z\le d_1+d_2 \tag{9}$$

$$\Psi_{IV}=\left(C_6e^{j\kappa'_+z}+C_7e^{-j\kappa'_-z}\right)e^{-jkx}, \quad d_1+d_2<z\le d_1+d_2+d_3 \tag{10}$$

$$\Psi_V=C_8e^{-kz-jkx}, \qquad d_1+d_2+d_3<z<\infty \tag{11}$$

where

$$\kappa^2=-\mu_{11}k^2,$$
$$\kappa'_+=\sqrt{p^2-q^2}+p; \qquad \kappa'_-=\sqrt{p^2-q^2}-p,$$
$$p=k\frac{(1-\mu'_{11})\sin\alpha\cos\alpha}{\mu'_{11}\sin^2\alpha+\cos^2\alpha}$$
$$q=k\sqrt{\frac{\mu'_{11}\cos^2\alpha+\sin^2\alpha}{\mu'_{11}\sin^2\alpha+\cos^2\alpha}}.$$

By imposing the boundary conditions, that the tangential components of $\vec{h}_m$ and normal components of $\vec{B}$ are continuous at each interface, a set of homogeneous equations is generated. The condition for the existence of a nontrivial solution to this set yields the following dispersion equation:

$$\left[2\alpha_v+\left(1-\alpha_v^2\right)\tan\kappa d_1\right]\cdot\left\{2\alpha'_v\overline{\mu}_{33}+\left[1-\left(\alpha'_v\overline{\mu}_{33}\right)^2\right]\tan\alpha'_vkd_3\right\}+\left(1+\alpha_v^2\right)\left[1+\left(\alpha'_v\overline{\mu}_{33}\right)^2\right]\tan\kappa d_1\tan\alpha'_vkd_3e^{-2kd_2}=0 \tag{12}$$

where $\alpha_v=\kappa/k$, $\alpha'_v=\sqrt{p^2-q^2}/k$, and $\overline{\mu}_{33}=\mu'_{11}\sin^2\alpha+\cos^2\alpha$.

In the other case of interest, the propagation is along the y-axis, and has a uniform field in x direction ($\frac{\partial}{\partial x}=0$). Therefore, the wave vector $\vec{k}$ is perpendicular to the plane of $\vec{M}_1$ and $\vec{M}_2$. The magnetostatic potential in the regions other than layer 1 ($\vec{M}_1$) has similar forms to those in the former case, except that y is replaced by x. The potential in layer 1 can be easily given as follows:

$$\Psi_{IV}=\left(C_6e^{j\kappa'z}+C_7e^{-j\kappa'z}\right)e^{-jky}, \quad d_1+d_2<z\le d_1+d_2+d_3 \tag{13}$$

where $\kappa'^2=-k^2\mu'_{22}/\overline{\mu}_{33}$. Similarly, the dispersion relation can be expressed as

$$\left[2\alpha_v+\left(1-\alpha_v^2\right)\tan\kappa d_1\right]\cdot\left\{2\alpha'_v\overline{\mu}_{33}+\left[1-\left(\mu'_{12}\sin\alpha\right)^2-\left(\alpha'_v\overline{\mu}_{33}\right)^2\right]\tan\alpha'_vkd_3\right\}+\left(1+\alpha_v^2\right)\left[\left(1+\mu'_{12}\sin\alpha\right)^2+\left(\alpha'_v\overline{\mu}_{33}\right)^2\right]\cdot\tan\kappa d_1\tan\alpha'_vkd_3e^{-2kd_2}=0 \tag{14}$$

where $\kappa^2=-\mu_{22}k^2$ and $\alpha'_v=\kappa'/k$.

III. Results and Discussions

The dispersion relation itself will be discussed first. The dispersion includes two parts. One is the product of the individual dispersion of each layer. The other is the coupling term due to the interaction between the two magnetic layers. As the separation between the two magnetic layers goes to infinity, the coupling term disappears from the dispersion, then one can obtain the individual dispersion for each layer. When $\alpha=0$, the dispersion equations (12) and (14) reduce to the form obtained in [7] and [11]. This implies that our dispersion relation is more general, and can be easily reduced to the normal magnetization case.

In accordance with (8), (10), and (12), the MSVW propagation only exists when $\alpha_v>0$ and $\alpha'_v>0$. This implies that $\mu_{11}<0$ and $p^2-q^2>0$. The consequent MSVW

$$\overline{\mu}_1=\begin{pmatrix}\mu'_{11}\cos^2\alpha+\sin^2\alpha & -j\mu'_{12}\cos\alpha & (1-\mu'_{11})\cos\alpha\sin\alpha\\ j\mu'_{12}\cos\alpha & \mu'_{22} & j\mu'_{12}\sin\alpha\\ (1-\mu'_{11})\cos\alpha\sin\alpha & j\mu'_{12}\sin\alpha & \mu'_{11}\sin^2\alpha+\cos^2\alpha\end{pmatrix} \tag{1a}$$

$$\overline{\mu}_2=\begin{pmatrix}\mu_{11} & -j\mu_{12} & 0\\ j\mu_{12} & \mu_{22} & 0\\ 0 & 0 & 1\end{pmatrix} \tag{1b}$$

spectra are found to be $\omega_{01} < \omega < \sqrt{\omega_{02}(\omega_{02} + \omega_{m2})}$. ω_{01} is the lower bound of the MSVW spectrum for layer 1, and $\sqrt{\omega_{02}(\omega_{02} + \omega_{m2})}$ is the upper bound for layer 2, where $\omega_{mi} = \gamma 4\pi M_i$ and $\omega_{0i} = \gamma\sqrt{(H_{0i} - a_i M_i)(H_{0i} - b_i M_i)}$ $(i = 1, 2)$, in which H_{0i} are the internal fields including the applied dc field, demagnetizing field, cubic anisotropy field, and induced in-plane anisotropy field, γ is the gyromagnetic ratio, and a_i and b_i can be found in [18]. Apparently, both lower and upper bounds of the MSVW spectrum are independent of angle α. However, in the case of propagation along the y-axis, which is dominated by (14), the lower bound of the MSVW spectrum depends upon the angle α. The lower bound can be determined from α_v and α'_v in (14). The spectrum of the MSVW propagation along the y-axis is found to be in the region

$$\sqrt{\omega_{01}(\omega_{01} + \omega_{m1} \sin^2 \alpha)} < \omega < \sqrt{\omega_{02}(\omega_{02} + \omega_{m2})}.$$

As the applied field increases, the angle α decreases. Thus, the frequency range of the MSVW propagation becomes wider. If the applied field is greater than the sum of $4\pi M_1$ and $2K_1/M_1$, both $\vec{M}_1$ and $\vec{M}_2$ are normal to the film plane and $\alpha = 0$. This leads to the lower bound of the MSVW propagation being the same as that in the case of $\vec{k} \parallel \hat{a}_x$.

Since $\vec{M}_1$ has an arbitrary angle with respect to the film plane, $\vec{M}_1$ has a nonzero projection in the film plane. It is assumed that the interesting propagation is along the y-axis, that is, normal to the plane formed by $\vec{M}_1$ and $\vec{M}_2$. As a result of existence of the nonzero projection of $\vec{M}_1$ in the film plane, MSSW mode may be excited in the $\vec{M}_1$ layer if $j\kappa'$ is replaced by κ' in (14), whereas MSVW mode may be excited in the $\vec{M}_2$ layer.

Dispersion curves of MSVW fundamental mode are illustrated in Fig. 3, where $H_a = 1400$ Gauss, $\alpha = 36.72°$, and $\vec{k} \parallel \hat{a}_x$. Unless noted otherwise, the parameters used in this section are the same as those in Section II. There exist two branches of dispersion curves. Each branch corresponds to the individual magnetic layer. The difference between the two branches is caused by the static magnetization and anisotropy fields in each layer. As the separation between the two magnetic layers varies with $d_2 = 1$ μm, 10 μm, and 100 μm, the splitting between the two branches decreases as d_2 increases. This results from the coupling between the two magnetic layers. The smaller the separation, the stronger the coupling.

In Fig. 4, we illustrate the spectra of the MSVW with the propagation vector $\vec{k}$ in the xy plane. The separation between the two magnetic layers chosen was 1 μm, and other parameters were $H_a = 1400$ Gauss, and $\alpha = 36.72°$. The resultant spectrum for $\vec{k}$ normal to the plane formed by $\vec{M}_1$ and $\vec{M}_2$ is shifted up relative to that for $\vec{k}$ in the plane formed by $\vec{M}_1$ and $\vec{M}_2$. The shadow which appears in the spectra is the region of the MSVW propagation when $\vec{k}$ rotates from $\hat{a}_x$ to $\hat{a}_y$ direction or vice versa. For a different propagation direction, the dispersion curve or time delay is different. It is noted that if the propagation direction is reversed, for example, $\hat{a}_x \to -\hat{a}_x$ or $\hat{a}_y \to -\hat{a}_y$, the resulting dispersion curve would be different due to the asymmetry of the system.

As the applied dc field is increased to 1750 Gauss, the angle α is reduced to 11.4°. The corresponding dispersion is shown in Fig. 5, where the propagation direction $\vec{k}$ is normal to the plane formed by $\vec{M}_1$ and $\vec{M}_2$, that is, along the y-axis. It is seen that magnetostatic surface mode is excited in the $\vec{M}_1$ layer, while magnetostatic volume mode is excited in the $\vec{M}_2$ layer. The time delay characteristics is illustrated in Fig. 6.

Further increasing the applied field leads to $\alpha = 0$. The resultant dispersions for $\vec{k}$ along both $\hat{a}_x$ and $\hat{a}_y$ directions are equivalent, that is, the shaded region is diminished. Fig. 7 displays the MSVW dispersion curves of relative orientation $\alpha = 0°$ with the separation d_2 equal to 1 μm. The corresponding time delays are shown in Fig. 8. It is found that the time delay for layer 1 has a wide nondispersive range compared to that for layer 2. The difference is caused by the existence of the induced in-plane anisotropy field in layer 2.

In summary, we have studied the MSWs propagation in multilayered magnetic structures with misalignment between the static magnetizations. For a given applied dc field normal to the film plane, there exists an angle between the magnetizations. It is the angle that leads to the excitation of MSSW in

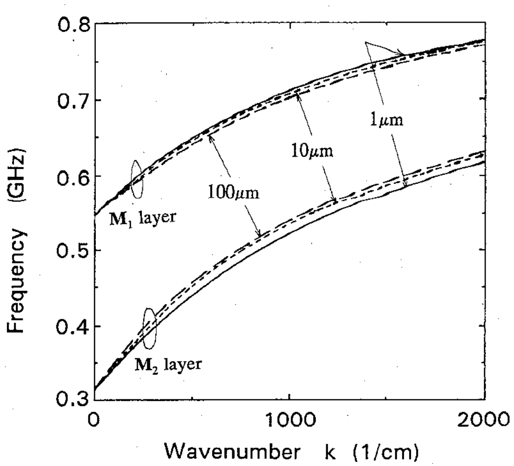

Fig. 3. The dispersion curves for $\vec{k} \parallel \hat{a}_x$. $H_a = 1400$ Gauss, $\alpha = 36.72°$. The other parameters are the same as those used in Fig. 2. The thickness of the separation is a parameter. The value of d_2 was chosen to be 1, 10, and 100 μm, respectively.

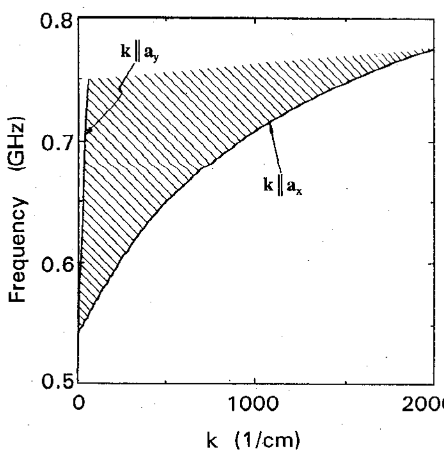

Fig. 4. The spectra of the MSVW for $\vec{k}$ swept in the xy plane for $H_a = 1400$ Gauss, $\alpha = 36.72°$. The thickness of the separation is 1 μm. The other parameters are the same as those used in Fig. 2.

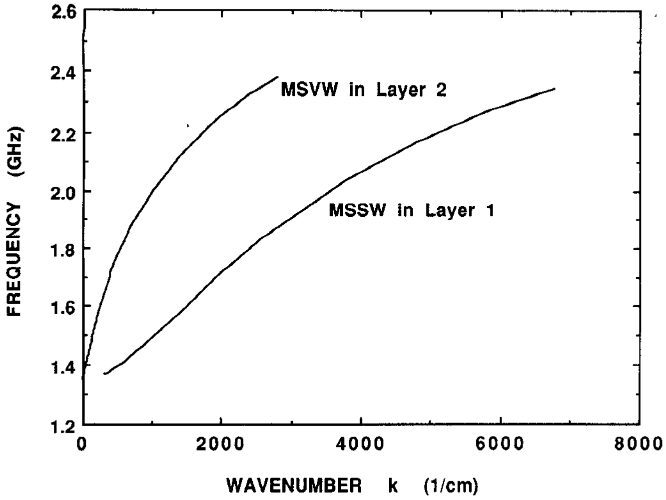

Fig. 5. The dispersion for $H_a = 1750$ Gauss, $\alpha = 11.4°$, and the separation $d_2 = 1$ μm. The propagation direction is normal to the plane formed by $\vec{M}_1$ and $\vec{M}_2$, that is, along the y-axis. MSSW is excited in the $\vec{M}_1$ layer, while MSVW is excited in the $\vec{M}_2$ layer.

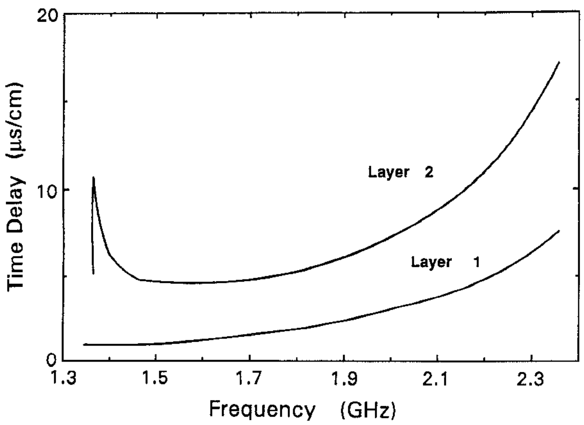

Fig. 6. Characteristics of time delay for dispersion curves shown in Fig. 6.

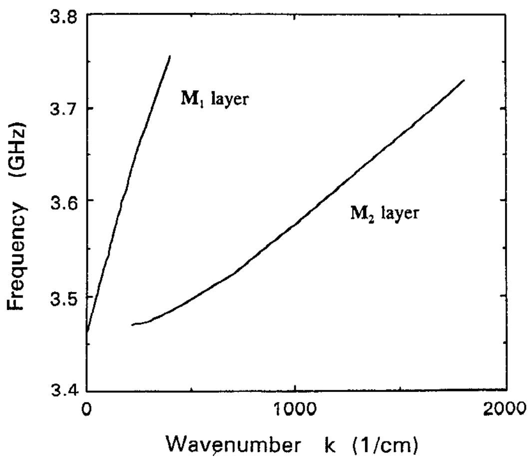

Fig. 7. The dispersion for $H_a = 2500$ Gauss, $\alpha = 0$. The separation between the two YIG layers is 1 μm. The bulk parameters used are the same as those in Fig. 2.

one layer and MSVW in the other layer. As the applied field is greater than the sum of the magnetization and anisotropy fields, the magnetization is forced to align with the applied field. The excited MSVW propagation along $\hat{a}_x$ direction shows a

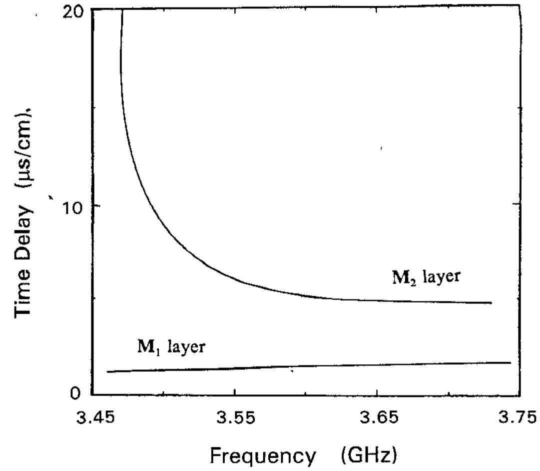

Fig. 8. The time delays corresponding to the dispersion curves illustrated in Fig. 7.

different dispersion from that along $\hat{a}_y$ direction as $\alpha \neq 0$. This angle affects the dispersion and the time delay. Also, the separation between the magnetic layers has a strong effect on time delay characteristics.

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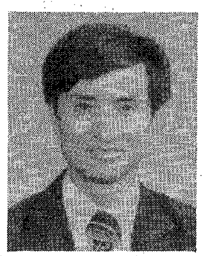

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