Insertion Loss of Magnetostatic Surface Wave Delay Lines

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Abstract —**This paper presents an experimental and theoretical study of the insertion loss of magnetostatic surface wave delay line. The magnetostatic surface waves are excited by single microstrip transducer and propagate in a delay line consisting of conductor–dielectric–YIG–GGG. The effect of nonuniformity in microstrip current and the effect of finite width of YIG film are included in the theory. It is seen that an undesired notch seen in the insertion loss response of the surface wave delay line in the low-frequency region of the band can be explained by the present theory, which includes the finite width of the YIG film. Magnetostatic wave delay lines have potential applications in microwave signal processing and phased array antennas in the 1–20 GHz frequency range.**

I. Introduction

In RECENT YEARS there has been considerable progress in magnetostatic wave technology because of its potential applications in several signal processing devices, such as delay lines, filters, resonators, and oscillators [1]–[4]. This technology is based on the low-loss propagation of magnetostatic waves in biased yttrium iron garnet (YIG) thin films. These films are grown epitaxially on gadolinium gallium garnet substrates. Propagation loss as low as 12 dB/μs at microwave frequencies has been observed [1]. The magnetostatic waves are efficiently excited by simple microstrip transducers. The initial theory and experiment on the excitation were presented by Ganguly and Webb [5]. Later, several more useful papers on the excitation of magnetostatic surface waves [6]–[9] were published. In the above publications, wave fields are assumed uniform along the width of the YIG film. However in a real delay line, YIG film has a finite width and thus the fields are no longer uniform. The effect of the finite width of YIG film on time delays has been investigated in detail previously [10]. Morgenthaler and Bhattacharjee [11] have also considered finite width in their rigorous dispersion analysis. Adam and Bajpai have studied excitation of magnetostatic forward volume waves in YIG stripes [12] and interesting results were obtained. Bajpai [13] studied the excitation of magnetostatic surface waves in finite YIG film using uniform microwave current in single microstrip transducer.

This paper presents a theoretical and experimental investigation of the insertion loss of magnetostatic surface wave delay line consisting of conductor–dielectric–YIG–GGG. Since in a decay line the YIG film has finite width, the theory includes this finite width of YIG film. A permanent feature of the insertion loss of this surface wave delay line is a undesired notch (or a dip) in the lower frequency region of the allowed frequency band. This has always been seen in the past, but has never been explained. This paper demonstrates that the undesired notch seen in the lower frequency region of the allowed frequency band can be explained on the basis of the inclusion of finite width of YIG film. The effect of nonuniformity in the microwave current in the transducers is also included. It appears that to achieve a smooth or notch-free insertion loss of surface wave delay line one should use wider YIG films. More study has to be conducted for achieving this.

II. Theory

Consider the propagation of magnetostatic (MS) surface waves in the y direction (Fig. 1). The dc magnetic field is applied in the z direction, so that MS surface waves are excited. The YIG film has thickness d and width W along the z axis and is separated from conductor by a distance t. The above configuration has been found potentially useful in MS devices, specifically delay lines [1]–[4] based on the propagation of MS waves in YIG thin films. The relative permeability tensor for the YIG region can be written as

$$\mu_r = \begin{bmatrix} \mu & jK & 0 \\ -jK & \mu & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1}$$

where

$$\mu = \frac{\omega_0(\omega_0+\omega_m)-\omega^2}{\omega_0^2-\omega^2} \qquad K = \frac{\omega\omega_m}{\omega_0^2-\omega^2} \tag{2a}$$

$$\omega_0 = \gamma H \qquad \omega_m = 4\pi\gamma M_0. \tag{2b}$$

In (2), H, $4\pi M_0$, γ, and ω are the internal dc magnetic field, saturation magnetization, gyromagnetic ratio, and wave frequency, respectively.

Under magnetostatic approximation, Maxwell's equations can be written as

$$\nabla \times \boldsymbol{h} = 0 \qquad \nabla \cdot \boldsymbol{b} = 0 \tag{3}$$

Manuscript received April 13, 1987; revised August 14, 1987.

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where $\boldsymbol{b}=\mu_0\mu_r\cdot\boldsymbol{h}$, μ_0 is the permeability of free space, and $\boldsymbol{h}=\nabla\psi$, ψ being the magnetic potential. Assuming that the magnetic potential vanishes [10] at the surface $Z=\pm W/2$, the Z dependence of the ψ's can be expressed as $[e_n\sin(K_zz)+(1-e_n)\cos K_zz]$, where $K_z=n\pi/W$. Here $n=1,3,5,\cdots$, $e_n=1$ or 0 depending on whether n is even or odd, respectively. Thus the wave magnetostatic potential ψ varies as $[e_n\sin(K_zz)+(1-e_n)\cos K_zz]e^{j(\omega t-\beta sy)}$, where β is the wavenumber and $s=\pm1$ is for propagation along the $\pm y$ direction.

Following Ganguly and Webb [5] and Sethares [8], the magnetostatic potential (ignoring time dependence) in different regions can be expressed as

$$\psi^{(1)}=\sum_{n=1}^{+\infty}\int_{-\infty}^{+\infty}A_ne^{K_dx}\cdot[e_n\sin(K_zz)+(1-e_n)\cos(K_zz)]e^{-j\beta sy}\,d\beta$$

$$\psi^{(f)}=\sum_{n=1}^{+\infty}\int_{-\infty}^{+\infty}[C_ne^{K_fx}+D_ne^{-K_fx}]\cdot[e_n\sin(K_zz)+(1-e_n)\cos(K_zz)]^{-j\beta sy}\,d\beta$$

$$\psi^{(2)}=\sum_{n=1}^{+\infty}\int_{-\infty}^{+\infty}[E_ne^{K_dx}+F_ne^{-K_dx}]\cdot[e_n\sin(K_zz)+(1-e_n)\cos(K_zz)]e^{-j\beta sy}\,d\beta. \quad (4)$$

In (4),

$$K_f=\left(\beta^2+\frac{K_z^2}{\mu}\right)^{\frac{1}{2}} \quad (5)$$

$$K_d=(\beta^2+K_z^2)^{\frac{1}{2}}. \quad (6)$$

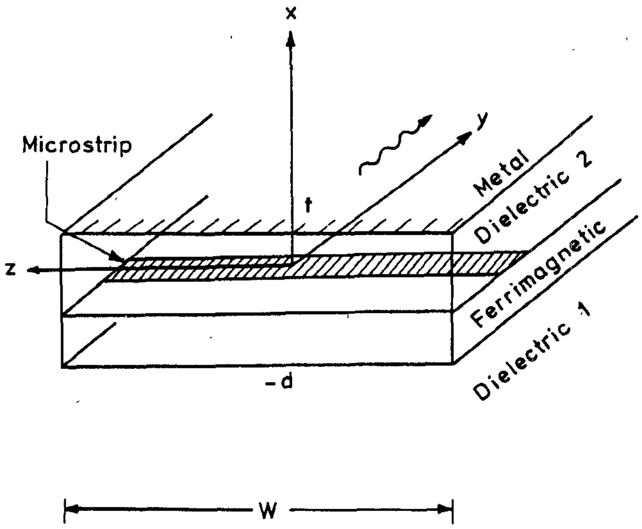

Fig. 1. Schematic of magnetostatic surface wave delay line.

The normal components of wave magnetic induction (b_x's) and the tangential component of magnetic fields (h_y's) in different regions can be obtained from (4) as

$$b_x^{(1)}=\mu_0\sum_{n=1}^{\infty}\int_{-\infty}^{+\infty}K_dA_ne^{K_dx}[e_n\sin(K_zz)+(1-e_n)\cos(K_zz)]e^{-j\beta sy}\,d\beta$$

$$b_x^{(f)}=\mu_0\sum_{n=1}^{\infty}\int_{-\infty}^{+\infty}[(\mu K_f+sK\beta)C_ne^{K_fx}-(\mu K_f-sK\beta)D_ne^{-K_fx}][e_n\sin(K_zz)+(1-e_n)\cos(K_zz)]e^{-j\beta sy}\,d\beta$$

$$b_x^{(2)}=\mu_0\sum_{n=1}^{\infty}\int_{-\infty}^{+\infty}K_d[E_ne^{K_dx}-F_ne^{-K_dx}][e_n\sin(K_zz)+(1-e_n)\cos(K_zz)]e^{-j\beta sy}\,d\beta \quad (7)$$

and

$$h_y^{(1)}=-js\sum_{n=1}^{\infty}\int_{-\infty}^{+\infty}\beta A_ne^{K_dx}[e_n\sin(K_zz)+(1-e_n)\cos(K_zz)]e^{-j\beta sy}\,d\beta$$

$$h_y^{(f)}=-js\sum_{n=1}^{\infty}\int_{-\infty}^{\infty}\beta[C_ne^{K_fx}+D_ne^{-K_fx}][e_n\sin(K_zz)+(1-e_n)\cos(K_zz)]e^{-j\beta sy}\,d\beta$$

$$h_y^{(2)}=-js\sum_{n=1}^{\infty}\int_{-\infty}^{+\infty}\beta[E_ne^{K_dx}+F_ne^{-K_dx}][e_n\sin(K_zz)+(1-e_n)\cos(K_zz)]e^{-j\beta sy}\,d\beta. \quad (8)$$

The arbitrary constants are evaluated in terms of D_n. Usual boundary conditions are applied; i.e., b_x's and h_y's should be continuous at the interfaces except that

$$h_y^{(2)}-h_y^{(f)}=J_z(y) \qquad \text{at } x=0 \quad (9)$$

where $J_z(y)$ is the current distribution in microstrip and is given as

$$J_z(y)=\begin{cases}1+\left|2\dfrac{y}{b}\right|^3 & -\dfrac{b}{2}\le y\le\dfrac{b}{2}\\ 0 & \text{otherwise}\end{cases}.$$

Here b is the width of the microstrip, and nonuniform microwave current in microstrip has been assumed [14] as

$$I_0=\int_{-\infty}^{+\infty}J_z(y)\,dy.$$

At $x=0$, (9) yields

$$-js\sum_{n=1}^{\infty}\int_{-\infty}^{+\infty}\beta F_n^d(\omega,\beta)D_ne^{-j\beta sy}\cdot[e_n\sin(K_zz)+(1-e_n)\cos(K_zz)]\,d\beta=J_z(y) \quad (10)$$

where

$$F_n^d(\omega,\beta)D_n = E_n + F_n - C_n - D_n.$$

Equation [10] is now multiplied by $[e_m \sin(m\pi z/W)+(1-e_m)\cos(m\pi z/W)]$ and $e^{j\beta' sy}$ and integrated over z and y. Using the condition that

$$\int_{-W/2}^{+W/2}\left[e_n \sin\left(n\pi\frac{z}{W}\right)+(1-e_n)\cos\left(n\pi\frac{z}{W}\right)\right] \cdot\left[e_m \sin\left(m\pi\frac{z}{W}\right)+(1-e_m)\cos\left(m\pi\frac{z}{W}\right)\right]dz = \frac{W}{2}\delta m,n \tag{11}$$

we obtain

$$D_n = \frac{j\tilde{J}_n(\beta)e^{-2K_f d}}{2\pi s\beta F_T(\omega,\beta)} \tag{12}$$

where

$$F_T(\omega,\beta) = F_n^d(\omega,\beta)e^{-2K_f d}$$

$$\tilde{J}_n(\beta) = \frac{2}{W}\int_{-W/2}^{+W/2}\tilde{J}(\beta) \cdot\left[e_n \sin\left(n\pi\frac{z}{W}\right)+(1-e_n)\cos\left(n\pi\frac{z}{W}\right)\right]dz$$

$$\tilde{J}(\beta) = \int_{-\infty}^{+\infty}J_z(y)e^{j\beta sy}\,dy. \tag{13}$$

The dispersion relation is obtained by equating $F_T(\omega,\beta)$ to zero; thus

$$e^{-2K_f d} = \frac{T\left[(\mu K_f + s\beta K)+K_d\tanh(K_d t)\right]}{(\mu K_f - s\beta K)-K_d\tanh(K_d t)} \tag{14}$$

where

$$T = \frac{(\mu K_f - s\beta K)+K_d}{(\mu K_f + s\beta K)-K_d}. \tag{15}$$

After following [8] the magnetic potentials in different regions are obtained by substituting arbitrary constants into (4).

The microwave power flowing in different regions has been obtained as [15]

$$\boldsymbol{P} = \text{Real part of}\left(\frac{-j\omega\psi^{*}\cdot\boldsymbol{b}}{2}\right) \tag{16}$$

where ψ^* is complex conjugate of ψ, the wave magnetic potential. The total power (per unit width of the YIG sample) is obtained by integrating (16) in different regions and is obtained as

$$\boldsymbol{P} = \sum_{n=1}^{\infty}\boldsymbol{P}_n \tag{17}$$

where

$$\boldsymbol{P}_n = \frac{-\omega s\mu_0|G_n|^2}{4\beta K_d}M_n$$

$$M_n = M_n^{(1)} + M_n^{(2)} + M_n^{(f)}. \tag{18}$$

Here $\boldsymbol{P}_n$ represents the total power (per unit width) flowing in the nth mode in the delay line structure (Fig. 1):

$$M_n^{(1)} = \frac{(T+1)^2}{2} \tag{19}$$

$$M_n^{(2)} = \left[\frac{(\mu K_f + s\beta K)Te^{(K_f d)} - (\mu K_f - s\beta K)e^{(-K_f d)}}{K_d\sinh(K_d t)}\right]^2 \cdot\left[\frac{\sinh(2K_d t)}{4}+\frac{K_d t}{2}\right] \tag{20}$$

$$M_n^{(f)} = \frac{K_d}{K_f}\left[\frac{T^2}{2}\left(\mu+\frac{KsK_f}{\beta}\right)(e^{(2K_f d)}-1) - \frac{1}{2}\left(\mu-\frac{sKK_f}{\beta}\right)(e^{(-2K_f d)}-1)+2K_f\mu Td\right] \tag{21}$$

where

$$G_n = \frac{\tilde{J}_n(\beta)e^{(-K_f d)}}{\dfrac{\partial F_T}{\partial\beta}}$$

$$\frac{\partial F_T}{\partial\beta} = Q_1 + Q_2 + Q_3 + Q_4 \tag{22}$$

$$Q_1 = \left[\frac{(\mu K_f + s\beta K)T - (\mu K_f - s\beta K)e^{(-2K_f d)}}{K_d^2}\right] \cdot\beta t\,\mathrm{cosech}^2(K_d t) \tag{23}$$

$$Q_2 = \frac{2\beta de^{(-2K_f d)}}{K_f}\left[1-\frac{(\mu K_f - s\beta K)\coth(K_d t)}{K_d}\right] \tag{24}$$

$$Q_3 = \left(\left[\frac{\left(\dfrac{\mu\beta}{K_f}-sK\right)e^{(-2K_f d)} - \left(\dfrac{\mu\beta}{K_f}+sK\right)T}{K_d}\right] - \frac{\beta}{K_d^3}\left[(\mu K_f - sK\beta)e^{(-2K_f d)} - (\mu K_f + s\beta K)T\right]\right) \cdot\coth(K_d t) \tag{25}$$

$$Q_4 = -\left[1+\frac{(\mu K_f + s\beta K)\coth(K_d t)}{K_d}\right]\frac{\partial T}{\partial\beta} \tag{26}$$

$$\frac{\partial T}{\partial\beta} = \frac{\dfrac{2K_z^2}{K_f}\left[\dfrac{\beta(1-\mu)}{K_d}-sK\right]}{\left[(\mu K_f + s\beta K)-K_d\right]^2}. \tag{27}$$

The radiation resistance R_n (per unit width of YIG) for the nth mode is defined as

$$P_n = \tfrac{1}{2}R_n I_0^2.$$

Also,

$$R_{nt} = [|R_{n+}| + |R_{n-}|]W \tag{28}$$

where the + and − signs indicate the $+y$ and $-y$ propagating wave, respectively, and R_{nt} is the total radiation resistance. Finally the radiation resistance for the nth mode can be expressed as

$$R_n = \frac{-\omega s \mu_0 e^{-K_l d} M_n}{2\beta K_d \left| \frac{\partial F_T}{\partial \beta} \right|^2} \left[\frac{\tilde{J}_n(\beta)}{I_0} \right]^2. \tag{29}$$

In the above equation

$$\left| \frac{\tilde{J}_n(\beta)}{I_0} \right|^2 = \left(\frac{4}{n\pi} \right)^2 \left| \frac{\tilde{J}(\beta)}{I_0} \right|^2$$

where n is odd and

$$\frac{\tilde{J}(\beta)}{I_0} = \frac{8}{5} \frac{\sin\left(\frac{\beta b}{2}\right)}{\frac{\beta b}{2}} + \frac{12}{5\left(\beta \frac{b}{2}\right)^2} \cdot \left[\cos\left(\frac{\beta b}{2}\right) - \frac{2\sin\left(\frac{\beta b}{2}\right)}{\beta \frac{b}{2}} + \frac{\sin^2\left(\beta \frac{b}{4}\right)}{\left(\beta \frac{b}{4}\right)^2} \right]. \tag{30}$$

The insertion loss is obtained as

$$I.L. = 20 \log \frac{(R_g + R_{\text{total}})^2 + (X_{\text{total}} + X_l)^2}{4 R_g R^+} + \text{Propagation Loss.} \tag{31}$$

In (31), R_g is the source resistance (50 Ω); R_{total} and X_{total} are the total radiation resistance and total radiation reactance summed over all the modes; $X_l = 97 \sin(\beta_0 W)$; $\beta_0 = 2\pi/\gamma$, where γ is the guide wavelength; and R^+ is the radiation resistance of the plus propagating wave in the lowest order wave. Propagation loss was obtained as $76.4 \times \Delta h \times \tau_g$; where Δh is the line width of YIG and τ_g is the group delay time in microseconds.

III. Results

Experimental and theoretical results were obtained and compared using 3-mm-wide and 27.4-μm-thick YIG film. The transducers were 3 mm long and 50 μm wide and were short-circuited at one end defined in gold on 250-μm-thick alumina substrate. The separation between the transducers was 1 cm.

Fig. 2 shows the comparison between the insertion loss obtained from theory and experimental measurements. The measurements were made on an HP automatic network analyzer. The curve × × × × has been obtained considering that the width is infinite; hence fields are uniform. The difference between the results of insertion loss obtained from theory when the YIG film width (W) is finite (curve ----) and when the YIG film width is infinite (× × × × curve) can be seen clearly in the low-frequency region of the band. As is obvious from the figure, the theoretical results for finite width show a dip or an undesired notch in the low-frequency region of the band of the surface wave delay line. This gives qualitatively and quantitatively closer agreement with experimental results; whereas the model which assumes infinite width of the YIG film has a very large insertion loss and shows no notch in the low-frequency region, as seen in the experiment. Below the surface wave region, a very small frequency band also exists, where volume waves propagate. In this region also the theoretical results are in good agreement with the measurements.

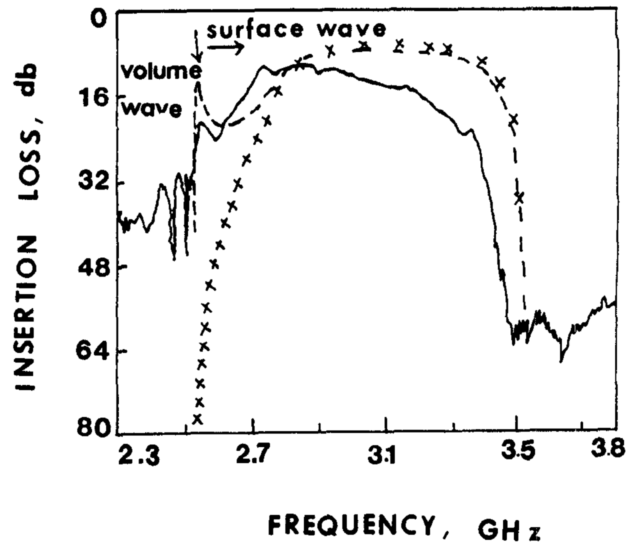

Fig. 2. Variation of measured and calculated insertion loss (S_{21} in dB) with frequency using different models: ——— experiment; ---- theory (W finite); × × × × theory (W infinite). The frequency which separates surface wave and volume wave frequency bands is also shown by arrow.

IV. Conclusions

A study of the insertion loss of magnetostatic surface wave delay line has been presented. An insertion loss expression including the finite width of YIG was derived. Insertion loss of magnetostatic surface wave delay line utilizing a conductor–dielectric–YIG–GGG structure was also measured. It was seen that the effect of finite width is quite obvious in the low-frequency region of the band. The theoretical results in terms of insertion loss are in good agreement, specifically in the low-frequency region of the allowed frequency band. An undesired notch observed in the low-frequency region of the insertion loss response of magnetostatic surface wave delay lines has been found to be due to the finite width of YIG film.

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