MAGNETOSTATIC FORWARD VOLUME WAVE REFLECTION CHARACTERISTICS OF A SHALLOW GROOVED GRATING ON A YIG FILM*

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ABSTRACT

The magnetostatic forward volume wave (MSFVW) reflection characteristics of a uniform grating of shallow grooves etched on the planar surface of an epitaxial YIG film are treated using an approach which integrates field theory with the coupled mode approach. The MSFVW reflection per groove is found to be significantly large considering that the volume waves are reflected by surface-localized and shallow grooves.

I. Introduction

A class of high-performance surface-acoustic-wave (SAW) devices employing shallow grooved reflector arrays, e.g., resonators and bandpass and chirp filters, has recently emerged.[1] A potential exists for the realization of similar devices operating at higher frequencies based on the use of magnetostatic waves in epitaxial YIG films. Recent experimental[2] and theoretical[3-5] studies have shown that magnetostatic surface waves (MSSWs) on a YIG film are reflected significantly more strongly by a groove than are SAWs by an equivalent groove on a $LiNbO_3$ substrate. While the MSSW reflectors have potential for application to resonator and filter structures, these structures must employ normal or near-normal incidence of MSSW at the grooves because of the limited range of angle over which MSSW propagation can exist. In contrast, magnetostatic forward volume waves (MSFVWs)[6-8] obtaining in a YIG film magnetized normal to its surface are isotropic and thus amenable for application to oblique-incidence grooved reflector configurations, e.g., ring resonators and filters, chirp filters, and contiguous filter banks. The present paper represents the first theoretical treatment of MSFVW shallow grooved reflector gratings which employs field theory in conjunction with the theory of two-mode coupling. The approach used here parallels our previously reported studies of SAW[9] and MSSW[4] grooved reflector gratings. It is found that the MSFVW reflectivity per groove is significantly large considering that the volume-wave reflector, viz. the grooved grating, is surface localized and shallow.

II. Theory

The geometry of the problem treated in this paper is shown in Fig. 1. The grating is comprised of N identical grooves of constant cross-sectional profile in the y direction which are spaced with a period p along the x direction. The YIG film has thickness d, the grooves have height h, and the groove width is 2a corresponding to the separation between two points on a groove which are half-way down the groove. Only the normal-incidence problem is treated in this paper, i.e., the incident MSFVW travelling in the +x direction impinges on the grating from the left. A boundary perturbation analysis is performed which requires the grooves to be shallow, hence it is assumed that $h \ll \lambda$ where λ is the wavelength of MSFVW. The grooves are considered to be almost rectangular so that the external saturating bias field $H_o \underline{i}_z$, applied normal to the film, may be assumed to produce an internal field $\underline{H}_i$ and saturation magnetization $\underline{M}_o$ which are uniform within the film and z-directed, i.e., $\underline{H}_i = H_i\, \underline{i}_z$ and $\underline{M}_o = M_o\, \underline{i}_z$.

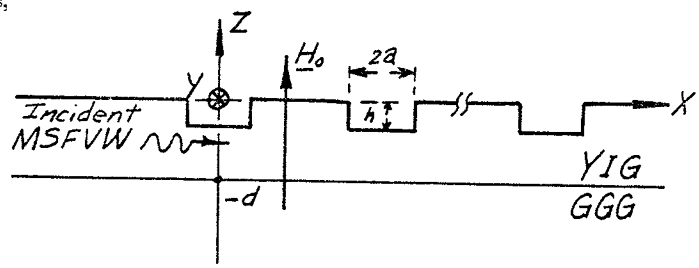

Fig. 1. Geometry of the MSFVW grooved reflector grating

The solution technique for determining the reflection characteristics of a grating of shallow grooves employing an integration of field theory and the coupled-mode approach has previously been described in detail in the context of SAW[9] and MSSW[4] reflectors. As with MSSW grooved reflectors,[4] the absence of bulk-wave loss in the present problem simplifies the solution technique significantly over that of SAW reflectors. In light of the fact that the solution technique for a MSFVW reflector is identical to that for a MSSW reflector, only the final analytical results for MSFVW reflector are presented here. The expression for MSFVW amplitude reflection coefficient R is found to be

$$R = -\, j(h/\lambda)\zeta k H(-k) \tag{2}$$

where k is the wave number of the incident or reflected MSFVW satisfying the dispersion relation

$$|k| = \frac{1}{\beta d} \tan^{-1}\left(\frac{2\beta}{1-\beta^2}\right). \tag{3}$$

In Eq. (3), $\beta=(-\mu)^{1/2}$ where $\mu=(f^2-f_3^{\,2})/(f^2-f_o^{\,2})$ is the xx or yy component of the permeability tensor characterizing the YIG medium. The frequency $f_3=[f_o(f_o+f_m)]^{1/2}$ is the top bound of the MSFVW spectrum, with the frequencies $f_o = \gamma\mu_o H_i$ and $f_m = \gamma\mu_o M_o$ (γ=2.8 MHz/G) being the gyrofrequency and magnetization frequency, respectively. In Eq. (2), ζ is an array factor while $H(-k) = \lim_{\xi \to -k} H(\xi)$, with $H(\xi)$ being the Fourier transform of the function $f(x) \exp(-jkx)$ where $f(x)$ is a function defining the profile of a single groove centered at the origin. The expressions for ζ and $H(-k)$ are

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$$\zeta = \frac{1}{2\cosh KL}\left\{\frac{(1-g^{N}e^{-N\nu})}{(1-ge^{-\nu})}e^{KL} + \frac{(1-g^{N}e^{N\nu})}{(1-ge^{\nu})}e^{-KL}\right\} \quad (4)$$

and

$$H(-k) \simeq -k^{-1}\sin 2ka. \quad (5)$$

In Eq. (4) $L = (N-1)p$ is the total length of the grating, $\nu = Kp$, $g = \exp(-j2kp)$, and K is a phenomenological coupling constant characterizing the coupling of the incident and reflected waves within the grating. The expression for $H(-k)$ in Eq. (5) is for a groove profile that is almost rectangular.

Equation (2) reduces to the reflection coefficient for a single groove by making the array factor ζ unity. For a grating, since ζ contains an unknown K, a determination of R requires a second equation connecting R and K, which is provided by the coupled-mode theory and assumes the expression

$$|R| = \tanh KL. \quad (6)$$

An iterative procedure must be used to solve Eqs. (2) and (6) simultaneously for the unknowns K and R. The reflection coefficient depends on the groove width 2a through the function $H(-k)$ in Eq. (2) and on the groove periodicity p through the function g in Eq. (4). The optimum values of 2a and p which maximize $|R|$ are $2a=\lambda/4$ and $p=\lambda/2$. In order to design a MSFVW reflector with known YIG film parameters and for operation at a prescribed frequency and bias field one would simply need to solve Eq. (3) for λ pertinent to these parameters and then use the foregoing optimum values of groove width and periodicity.

III. Numerical Results and Discussion

Equation (1) shows that the frequency variation of $|R|/(h/\lambda)$ for a single groove exhibits maxima at frequencies corresponding to $2ka = (2n+1)\pi/2$, $n=0,1,2...$ and zeroes at frequencies corresponding to $2ka = m\pi$, $m=1,2,3,...$ The reflection coefficient at all of these maxima has the same value $|R|_{max} \simeq h/\lambda$. For $h/\lambda=0.015$ this yields a value $|R|_{max} = 1.5\%$ which is approximately 150% of the SAW amplitude reflection coefficient $|R| = 0.9\%$ obtaining for a groove of the same geometry and normalized depth on a y-cut z-propagating $LiNbO_3$ substrate.[9] The value $|R|_{max}$ obtained here is somewhat comparable to the peak value of $|R|$ obtaining for the MSSW reflectivity of the same geometry and normalized depth on a YIG film.[5] In light of the fact that in the present work it is volume waves that are reflected by grooves that are surface-localized as well as shallow, it is concluded that the MSFVW reflectivity of a groove is significantly large.

In Fig. 2, computed frequency variation of $|R|$ for a single groove is presented for the lowest MSFVW mode. (Note that the theoretical results of Sect. II apply to any of the even or odd MSFVW modes supported by the YIG film.) The computations are for internal bias field $\mu_o H_i=500G$, saturation magnetization $\mu_o M_o=1750G$, YIG film thickness $d=10\mu m$, and two values of groove width, namely, $2a=10\mu m$ (dashed curve) and $2a=20\mu m$ (solid curve). Only the lowest two or three peaks are shown in Fig. 2 because the increasingly smaller frequency spacing of the higher peaks makes them difficult to show on the frequency scale of the figure. The monotonic and rapid decrease in the frequency spacing of the peaks is consistent with the MSFVW dispersion characteristics, viz., the MSFVW dispersion curve for a given d and mode corresponds to a monotonically increasing k with f.

In Fig. 3, the variation with N of the grating

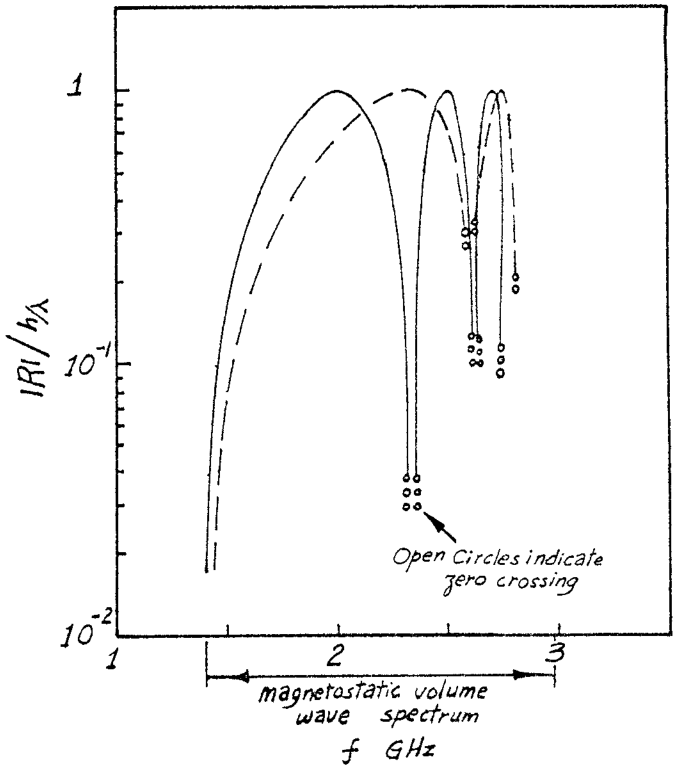

Fig. 2. Frequency variation of the MSFVW reflection coefficient for a single shallow groove

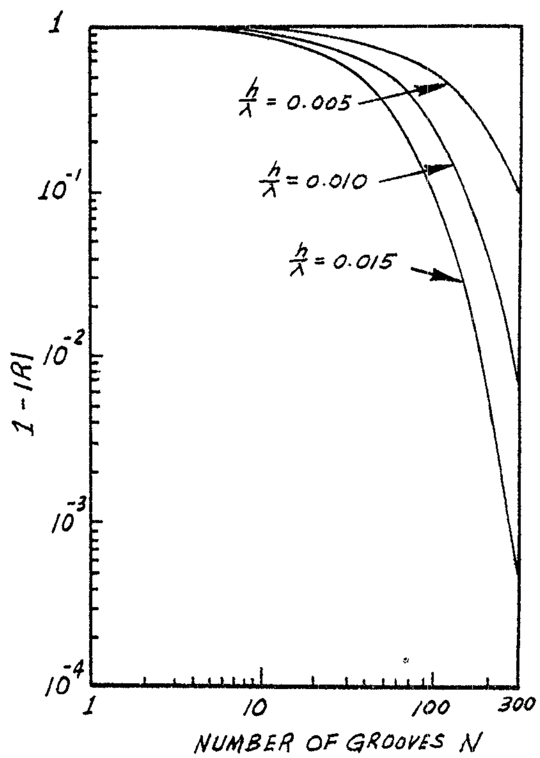

Fig. 3. Variation with N of $1-|R|$ for a MSFVW grooved grating

reflectivity is presented (for the lowest MSFVW mode) for a fixed frequency f=2.02 GHz, groove width 2a=20μm, grating period p=40μm, and three values of groove height, i.e., h/λ=0.005, 0.01 and 0.015. All the other parameter values pertinent to Fig. 3 are the same as those of Fig. 2. The computations of Fig. 3 correspond to the lowest peak reflectivity point on the solid curve of Fig. 2 which occurs at f≈2.02 GHz and λ=80μm. In order to highlight the small deviation from 1 of |R| for large values of N, a plot of 1-|R| vs. N is presented and a logarithmic scale is used. As h/λ is increased, |R| for a given N is seen to go up in agreement with expectation.

Finally, in Fig. 4, the effect of moving off the synchronous frequency of a grating is shown for a grating comprised of N=25 grooves, and of parameters p=40μm and h/λ=0.005, i.e., the frequency variation of the magnitude and angle of R is presented in the vicinity of the synchronous frequency f=2.02 GHz. All other parameter values used in the computations are the same as those of Fig. 2, and only a small frequency interval is taken so as to indicate details of variation of the magnitude and angle of R.

In conclusion, the MSFVW reflection characteristics of a shallow grooved grating etched on top of a YIG film are treated for the case of normal incidence. The reflection is found to be significantly large considering that the volume waves are scattered by grooves that are shallow and surface-localized. The absence of MSVW generation outside of the YIG film region suggests that by deepening the grooves so that they are no more shallow, the MSFVW reflectivity of a grating might be enhanced significantly, thereby further reducing the number of grooves in a grating which would be required to produce a prescribed reflectivity.

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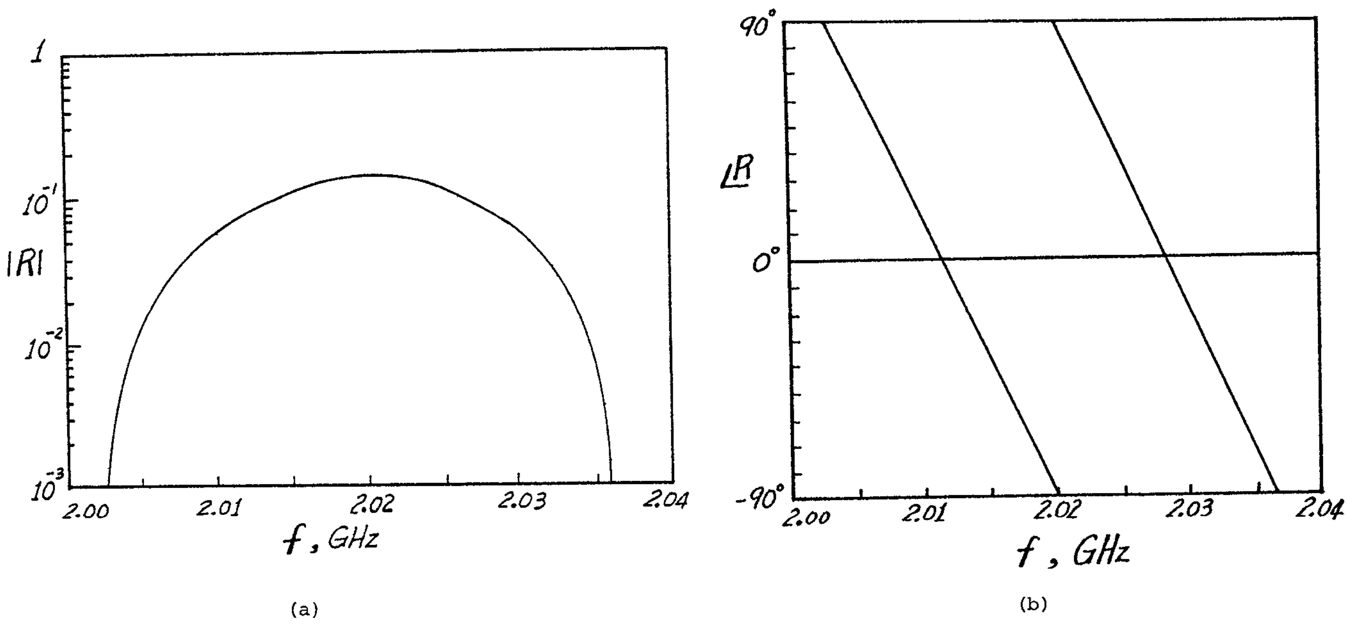

Fig. 4. Frequency variation of the (a) amplitude and (b) phase of the MSFVW reflection coefficient of a grooved grating