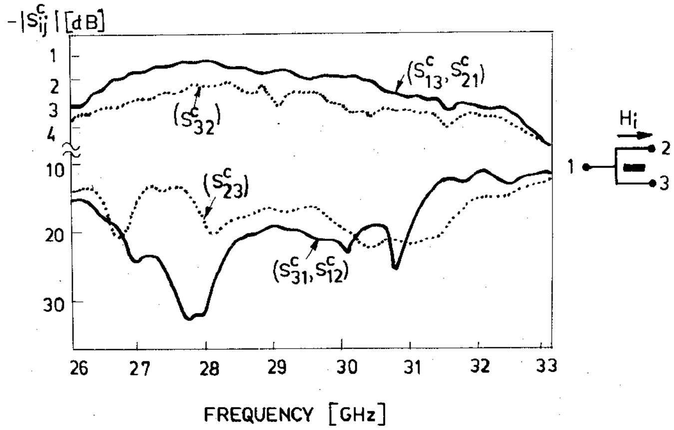

Fig. 7. Experimental transmission characteristics for the three-port circulator prototype shown in Fig. 2 (cf. Figs. 5 and 6).

line structure magnetized longitudinally has been presented. As expected, the proposed method allows us to design only approximately the circulater structure. This is because the operational principle of the device was derived under a few simplifying assumptions. For instance, only two basis modes were considered, and the interaction between the traveling and reflected waves in the structure of CFL has been neglected. Nevertheless, the comparison of the theoretical and experimental characteristics proves that the procedure can be applicable for approximate design of the nonreciprocal CFL components. The finline circulator proposed in this paper, as well as nonreciprocal CFL devices presented earlier [2], can be competitive with the traditional nonreciprocal structures operating at millimeter-wave band. Therefore, further theoretical and experimental investigations are needed to allow us to design optimal structures.

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The Magnetostatic Waves in Ferrite Film with Losses

S. A. Vyzulin, A. E. Rosenson, and S. A. Shekh

***Abstract*—The influence of relaxation processes on dispersion equation solutions for surface and volume magnetostatic waves (MSW) propagating in ferrite film has been theoretically investigated. It has been shown that dissipation is the reason for the appearance of complementary MSW branches in frequency intervals which adjoin to "standard" branches in spectra. The existence of the threshold MSW wave numbers which are restricted above the spectra of possible wave numbers is established. Asymptotic frequencies and frequencies corresponding to the threshold values of wave numbers have been calculated. The features of dissipation effects on boundary locations of MSW existence ranges were calculated. The frequental dispersion of the losses spectra was also calculated.**

I. Theory

One of the main problems with using ferrite films for designing a magnetostatic wave (MSW) device [1]–[3] is the necessity of carrying out the additional analysis of MSW spectrum, taking into account the MSW attenuation. These analyses are being carried out actively, both theoretically and experimentally, by several authors [4]–[10]. The new results of a theoretical analysis of a feature MSW spectrum in ferrite film with losses are presented in this paper.

Let the thin ferrite film with thickness d and magnetized at saturation be in the constant internal magnetic bias field $\vec{H}$ ($\vec{H}_e$ is the corresponding external field). There are three pure kinds of modes of MSW which can propagate in the ferrite film:

- magnetostatic surface waves (MSSW) (at $\vec{H} \perp \vec{n}, [\vec{H}, \vec{n}] \parallel \vec{k}$),
- magnetostatic forward volume waves (MSFVW) (at $\vec{H} \parallel \vec{k} \perp \vec{n}$), and
- magnetostatic backward volume waves (MSBVW) ($\vec{H} \parallel \vec{n}$).

$\vec{n}$ is a unit vector normal to the film plane.

The dispersion equations for these modes, without taking into account finite film width depending on mutual orientation of the vector $\vec{H}$, the wave propagation direction, and surface of film, are as follows:

$$k = -\frac{1}{2d}\ln\frac{\omega_0^2 - \omega^2}{(\omega_M/2)^2}, \tag{1}$$

for MSSW;

$$k = \frac{\sqrt{-\mu}}{d}\left[\operatorname{arctg}\left(\frac{2\sqrt{-\mu}}{1+\mu}\right) + \pi l\right], \quad l = 0, 1, 2, \cdots, \tag{2}$$

for MSBVW;

$$k = \frac{1}{\sqrt{-\mu}d}\left[\operatorname{arctg}\left(\frac{-2\sqrt{-\mu}}{1+\mu}\right) + \pi l\right], \quad l = 0, 1, 2, \cdots, \tag{3}$$

for MSFVW; where

$$\mu' = 1 + \frac{\omega_M[\omega_H(\omega_H^2 - \omega^2(1+\alpha^2)) + 2\cdot\alpha^2\omega\cdot\omega_H]}{[\omega_H^2 - \omega^2(1+\alpha^2)]^2 + 4\alpha^2\omega_H^2\cdot\omega^2},$$

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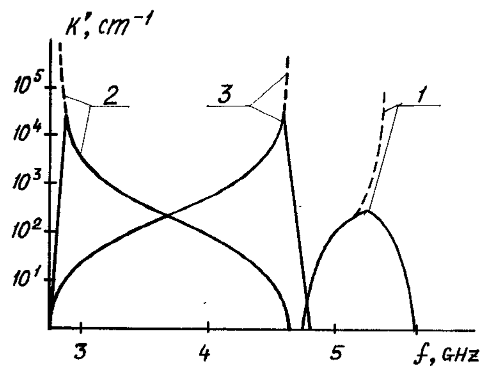

Fig. 1. Spectra of magnetostatic waves. 1—MSSW; 2—MSBVW; 3—MSFVW; 4—DMSSW; 5—DMSBVW; 6—DMSFVW; 7—MSSW-DE; 8—MSBVW-DE; 9—MSFVW-DVV.

$$\mu = \frac{\alpha\omega_H\omega\cdot(\omega_H^2+\omega^2(1+\alpha^2))}{[\omega_H^2-\omega^2(1+\alpha^2)]^2+4\alpha^2\omega_H^2\cdot\omega^2} \tag{4}$$

are the real and imaginary parts of the diagonal component of the permeability tensor $\hat{\mu} = \hat{\mu}' - i\hat{\mu}$, respectively,

$$\omega_H = \gamma\cdot H,\quad \omega_M = \gamma\cdot 4\pi\cdot M,\quad \omega_0 = \omega_H + \omega_M/2.$$

γ is the gyromagnetic ratio, $4\pi\cdot M$ is saturation magnetization, $H = H_e$ for $\vec{H}_e$ as tangential to the film plane, and $H = H_e - 4\pi M$ for H_e as normal to the film plane. It is well known [11] that the dependence of the permeability tensor components on damping of the magnetostatic waves may be taken into account by means of replacements

$$\omega_H \to \omega_H + i\cdot\alpha\cdot\omega,\qquad k\to k' - i\cdot k, \tag{5}$$

where α is a dimensionless damping parameter. The relationship between α and the full ferromagnetic resonance (FMR) line width $2\Delta H$ is $\alpha = \gamma\cdot\Delta H/\omega_H$; k' and k are the real and imaginary parts of the MSW wave number, respectively.

Let us consider the solutions of the dispersion equations for MSSW, MSFVW, MSBVW separately.

II. The Surface Waves (at $\vec{H}\perp\vec{n}, [\vec{H},\vec{n}]\parallel\vec{k}$)

Equation (1) by means of (5) may be transformed into

$$k' = -\frac{1}{4d}\cdot\ln\frac{[\omega_0^2-\omega^2(1+\alpha^2)]^2+4\alpha^2\omega^2\omega_0^2}{(\omega_M/2)^4} \tag{6}$$

and

$$\mathrm{tg}(2\cdot kd) = 2\cdot\alpha\cdot\frac{\omega\cdot\omega_0}{\omega_0^2-\omega^2(1+\alpha^2)}. \tag{7}$$

The frequental dispersion $k'(\omega)$ from (6) in Fig. 1 (curve 1) is presented. The calculation was carried out for $\alpha = 3\cdot10^{-4}$ ($2\Delta H = 0.5$ Oe at 3 GHz), $4\pi\cdot M = 1750\,\mathrm{G}, d = 10\,\mu$, and $H = 1000$ Oe. The dashed line in Fig. 1 represents the classic dispersion curve for MSSW Damon–Eschbach (DE) at $\alpha = 0$ [12]. When $\alpha\neq 0$, the spectrum of the MSSW has both low-frequental (the standard MSSW situation) and high-frequental (backward MSSW = the new "damped" MSSW = the new MSSW situation = DMSSW) branches. There is the maximum value of $k' = k'_m$ so that if $k' > k'_m$, MSSW in the ferrite film does not propagate for the fixed α, H, d.

As follows from (6), at the long-wavelength approach when $k'\to 0$,

$$\omega_\pm \to \frac{1}{1+\alpha^2}\left\{(1-\alpha^2)\omega_0^2 \pm \left[\left(\frac{\omega_M}{2}\right)^4(1+\alpha^2)^2 - (2\alpha\cdot\omega_0^2)^2\right]^{1/2}\right\}^{1/2} \tag{8}$$

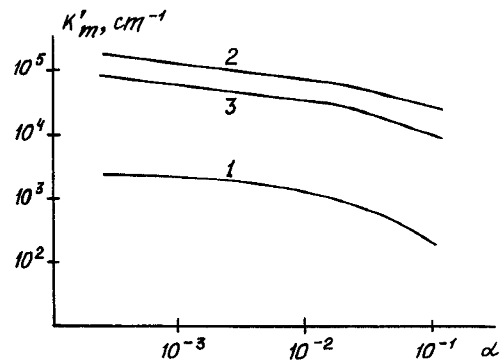

Fig. 2. Threshold wave numbers. 1—MSSW; 2—MSBVW; 3—MSFVW.

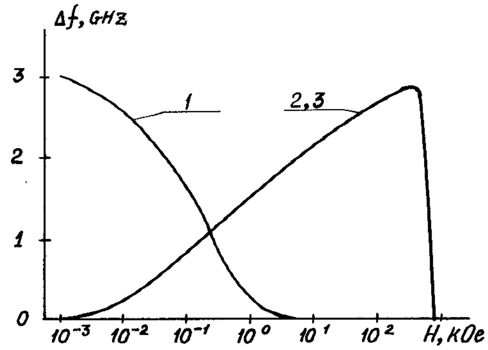

Fig. 3. Imaginary part of the wave number. 1—MSSW; 2—MSBVW; 3—MSFVW.

where ω_+ and ω_- are the upper and lower boundary frequencies, respectively.

The calculations performed for $\alpha\neq 0$ proved that the value of ω_- increases and ω_+ decreases with the increases of α. If $k'\to\infty$ and $\alpha\neq 0$, the condition from (6) assumes the form

$$\omega_0^2-\omega^2(1+\alpha^2) = 0,\qquad 2\alpha\cdot\omega\cdot\omega_0 = 0, \tag{9}$$

which cannot be satisfied with any value of ω. The maximum possible wave number k'_m for that α is

$$k'_m = -\frac{1}{2d}\cdot\ln\left[\frac{8\cdot\alpha\omega_0^2}{\omega_M^2(1+\alpha^2)}\right]. \tag{10}$$

The dependence $k'_m(\alpha)$ is presented in Fig. 2 (curve 1). The maximum value of the wave number k'_m is achieved at frequency

$$\omega_m = \omega_0\cdot\frac{\sqrt{1-\alpha^2}}{1+\alpha^2}. \tag{11}$$

Let us analyze the influence of the bias magnetic field itensity on the value of the MSSW excitation bandwidth $\Delta\omega = \omega_+ - \omega_-$. This dependence is presented in Fig. 3 (curve 1). There is maximum value of $H = H_c$ so that MSSW is not excited, when $H > H_c$ (for $\alpha\neq 0$). This follows from dependence ω_+ and ω_- on H. Hence, from (8),

$$H_c = 2\pi\cdot M[\sqrt{(1+\alpha^2)/2\alpha} - 1] \tag{12}$$

and

$$\omega_c = \omega(H_c) = \frac{\omega_m}{2}\sqrt{\frac{1-\alpha^2}{2\alpha(1+\alpha^2)}}. \tag{13}$$

For yttrium iron garnet (YIG) film with damping parameter $\alpha = 3\cdot10^{-4}$, we can obtain: $f_c = \omega_c/2\pi = 98$ GHz and $H_c = 34.8$ kOe.

Let us consider the frequental dispersion MSSW propagation losses $k(\omega)$ (Fig. 4, curve 1). We can obtain the following expressions for real and imaginary parts of the MSSW wave number:

$$k' = -\frac{1}{2d}\ln\frac{\omega_0^2 - \omega^2(1+\alpha^2)}{(\omega_m/2)^2\cos(2kd)}$$

and

$$k = -\frac{1}{2d}\ln\frac{2\alpha\cdot\omega\cdot\omega_0}{(\omega_m/2)^2\,\sin(2kd)}. \tag{14}$$

The expression for interval of change of the imaginary part follows from here $0 < k < \pi/4d$ for forward MSSW and $\pi/4d < k < \pi/2d$ for backward MSSW. Let us take a note of $0 < k < \pi/4d$ when

$$\omega_m < \omega < \frac{\omega_0}{\sqrt{1+\alpha^2}}.$$

Therefore, the damping MSSW can propagate and may be detected in ferrite film at these frequencies.

In this way:

a) the propagation losses of the damping MSSW are larger than losses of the forward MSSW—the analog of the DE wave;

b) the MSSW excitation bandwidth is larger than the Damon–Eschbach at one;

c) the larger the thickness of the ferrite film, the smaller the MSSW propagation losses;

d) if α and/or H increases, then k'_m decreases (Fig. 2) (for every α (or H), there is the maximum value of H (or α) at $k'_m \to 0$);

e) the imaginary part of the wave number $k(\omega)$ as a function of frequency has a step increase of value k when frequency passes through ω_m, i.e., from the low branch of the spectrum to the high branch (Fig. 4); and

f) the propagation losses for forward MSSW are increased (and are decreased for backward MSSW) when damping parameter α is increased [10, Fig. 2], that is, value of step is decreased. The maximum of propagation losses is located near ω_m, which is the lowest frequency limit of damped mode exciting range.

III. The Volume Waves (at $\vec{H} \parallel \vec{k} \perp \vec{n}$)

This kind of MSW is propagated along the tangent to the bias magnetic field direction. Equation (2), taken into account with the transform (5), can be written as

$$k' = [B\,\mathrm{arcctg}(C) + \pi\cdot l) - A\cdot\ln(D)]/d,\quad l = 0, 1, 2\cdots \tag{15}$$

$$k = [A\,\mathrm{arcctg}(C) + \pi\cdot l) - B\cdot\ln(D)]/d,\quad l = 0, 1, 2\cdots \tag{16}$$

where

$$A = \sqrt{(\mu' + \sqrt{(\mu'^2 + \mu^2)}/2},$$
$$B = \sqrt{(-\mu' + \sqrt{(\mu'^2 + \mu^2)}/2},$$
$$C = \frac{1 - A^2 - B^2}{2B}, \qquad D = 1 + \frac{4A}{(1-A)^2 + B^2}. \tag{17}$$

The MSBVW spectrum includes the infinite numbers of modes, which are labeled by the integer $l\,(l = 0, 1, 2, \cdots)$. The frequental dispersion $k'(\omega)$ for main mode ($l = 0$) from (15) is presented in Fig. 1 (curve 2). The dispersion law for Damon–Eschbach MSBVW is shown in Fig. 1 (dashed line) ($l = 0, \alpha = 0$). The character of the frequental dispersion $k'(\omega)$ for MSBVW with $l > 0$ is analogous to the $l = 0$ spectrum.

The low-frequental branch of the damped magnetostatic formard volume waves (DMSFVW) appears in the MSW spectrum at the same time with the MSBVW (the high-frequental branch DE waves). There is a certain point $k'_1 = k'_{ml}$ of transition from the first kind of wave to the other (damped) for fixed l. If $k'_1 > k'_{ml}$, then MSW with indices smaller than l is not excited in this ferrite film.

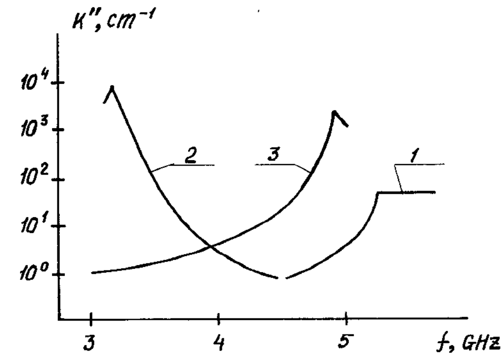

Fig. 4. Imaginary part of the wave number. 1—MSSW; 2—MSBVW; 3—MSFVW.

The equation for defining the boundary frequencies of spectrum may be obtained from (15) at the long-wavelength approximation ($k' \to 0$):

$$B(\mathrm{arcctg}(C) + \pi\cdot l) - A\cdot\ln(D) = 0. \tag{18}$$

We can see from (18) that MSW with different l has different boundary frequencies ω_-^l and ω_+^l. The low and upper frequental boundaries ω_-^l and ω_+^l are shifted down and up, respectively, on frequency when l is increased. It has been shown by (15) that values ω_-^l and ω_+^l are shifted to the low-frequental range when α is increased. The boundary frequencies ω_-^l and ω_+^l depend on l when $\alpha \neq 0$ and are independent of l for $\alpha = 0$.

The frequency ω_m^l is defined from condition of maximum k'_l. This kind of MSW is changed when $\omega = \omega_m^l$. The value ω_m^l depends on both the number l and damping parameter α. The point of change of wave kind is shifted to the low-frequental range when l is increased and when α is decreased. The corresponding value of wave number k'_{ml} may be obtained from (15) for given α and l when $\omega = \omega_m^l$. The value k'_{ml} is decreased when α is increased. This dependence is shown for main mode in Fig. 2 (curve 2).

The bandwidth $\Delta\omega^l = \omega_+^l - \omega_-^l$ depends on the value of magnetic bias field intensity (Fig. 3, curve 2). The character of function $\Delta\omega^l(H)$ at $\alpha \neq 0$ and at small values of H is similar to MSBVW-DE: at first ($H \leq (3\div 4)\cdot 4\pi\cdot M$), the sharp extending of the exciting range occurs, and then ($H > (3\div 4)\cdot 4\pi\cdot M$) is not changed practically. If $\alpha \neq 0$, then $\Delta\omega^l$ is increased when H is increased and $\Delta\omega^l$ is a constant practically for the DE wave (at $\alpha = 0$). The critical value of the magnetic field intensity H_c^l exists such that MSW with index l at $H > H_c^l$ does not exist in ferrite film. It is established that the H_c^l increases when l is increased and when α is decreased. It is necessary to note that the features of the bandwidth described above may be considered formally only because, in this case, $H_c = 3000$ kOe, and the corresponding frequency $f_c = \omega_c/2\pi = 300$ GHz for YIG film at $\alpha = 3\cdot 10^{-4}$, and the magnetostatic approach, is infringed. It can be seen from (16) that the value k is decreased when d is increased and/or l is decreased. The dependence $k(\omega)$ (Fig. 4, curve 2) is such that:

a) the propagation losses of MSBVW-"damped" modes are greater than MSBVW-DE-standard at one; and

b) the imaginary part of the wave number has a value of step increase that depends on the kind of wave from MSBVW to "damped"-MSFVW. Let us note that a value of step decreases when the damping parameter is increased and index l is decreased.

IV. The Volume Waves ($\vec{H} \parallel \vec{n}$)

The dispersion equation for MSFVW (3) in ferrite film, taking into account the replacement of (5), may be written as

$$k' = [B\,\mathrm{arcctg}(-C) + \pi \cdot l) - A \cdot \ln(D)]/(d(A^2 + B^2)) \quad (19)$$

and

$$k = [A\,\mathrm{arcctg}(-C) + \pi \cdot l) - B \cdot \ln(D)]/(d(A^2 + B^2)) \quad (20)$$

where A, B, C, D are defined by (17). The DMSBVW—"upper branch"—"damping" modes appear in the MSFVW spectrum (Fig. 1, curve 3) at $\alpha \neq 0$ side by side with MSFVW—"low" frequency branch—the analogs of the forward volume waves by Damon–Van der Vaart (DVV) [13].

The dissipation leads to a change of the MSFVW exciting range frequency boundaries. The expression for boundary frequencies of the MSFVW spectrum is obtained from (26) at long-wavelength approach ($k' \to 0$) and takes the form

$$B(\mathrm{arcctg}(-C) + \pi \cdot l) - A \ln D = 0. \quad (21)$$

The boundary frequencies ω_-^l and ω_+^l are shifted to high-frequency range when damping parameter α is increased.

Then, all other properties of the MSFVW spectrum at $\alpha \neq 0$ are similar according to the volume magnetostatic wave properties, which are discussed in the previous cases. Its characteristics are presented in Figs. 1–4, curves 3, without discussion.

The phenomenological theory of magnetostatic wave propagation losses has been reexamined. The results can be summarized as follows.

1) The propagation losses lead to the appearance of new kinds of magnetostatic waves: the magnetostatic backward surface wave (at $\vec{H} \perp \vec{n}, [\vec{H}, \vec{n}] \parallel \vec{k}$); the magnetostatic forward (at $\vec{H} \parallel \vec{k} \perp \vec{n}$); and backward ($\vec{H} \parallel \vec{n}$) volume waves; and to the corresponding broadening of the MSW exciting ranges.

2) The MSW with wave numbers, which are larger than corresponding threshold values, cannot be excited and cannot propagate in ferrite film. The values of the threshold wave numbers depend on mutual orientation of the bias magnetic field intensity, plane of the ferrite film, and the propagation direction of MSW. The values k'_m are defined by thickness of the ferrite film, by magnetization at saturation, by the value of the bias magnetic field intensity, damping parameter, and (for magnetostatic volume waves) by modes indices.

3) It is shown that there is a critical bias magnetic field (H_c) so that if $H > H_c$, then MSW is not excited in ferrite film. The value H_c depends on mutual orientation of the bias magnetic field intensity, plane of the ferrite film, and the propagation direction of MSW; and it is defined by values of magnetization at saturation, the damping parameter, and (for magnetic volume wave) mode index.

4) The imaginary part of the wave number for "damped" MSW is always greater than the analogs for DE and DVV waves.

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