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To cite this version:

T. Wolfram, R. De Wames. DIPOLE-EXCHANGE SURFACE WAVE DISPERSION AND LOSS FOR A METALLIZED FERRITE FILM. Journal de Physique Colloques, 1971, 32 (C1), pp.C1-1171-C1-1173. <10.1051/jphyscol:19711419>. <jpa-00214461>

HAL Id: jpa-00214461
https://hal.archives-ouvertes.fr/jpa-00214461
Submitted on 1 Jan 1971

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DIPOLEx-EXCHANGE SURFACE WAVE DISPERSION
AND LOSS FOR A METALLIZED FERRITE FILM

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Résumé. — Les courbes de dispersion pour un conducteur sur un film ferromagnétique sont calculées, comprenant les effets de dipôle, échange et de conductivité. Les pertes de conductivité dominent pour \( f \sim 1 \) tandis que les pertes d'échange sont grandes pour \( \alpha^2 \gg 1 \), \( f \) est la constante de propagation de l'onde de surface, \( \delta \) la longueur de peau et \( \alpha \) la constante d'échange. La courbe de dispersion de l'onde de surface montre une variété de forme qui dépend des valeurs de \( \delta \), \( \alpha \) et la proportion \( \delta / \alpha \). Les caractéristiques de la dispersion de l'onde de surface et des pertes sont résumées.

Abstract. — The frequency versus wavenumber dispersion for a conductor on an insulating ferromagnetic film is calculated including dipolar, exchange and conductivity effects. Conductivity losses dominate for \( f \sim 1 \) while propagation losses are largest for \( \alpha^2 \gg 1 \) where \( f \) is the surface wave propagation constant, \( \delta \) the skin depth and \( \alpha \) is the exchange constant. The surface wave dispersion curve exhibits a variety of shapes depending upon the values of \( \delta \) and \( \alpha \) and ratio \( \delta / \alpha \). The general features of magnetic surface wave dispersion and loss are summarized.

Magnetostatic surface spin waves [1, 2] are important to magnetic device technology. Time delay, beam steering, filtering, and pulse compression devices have been designed utilizing the properties of the surface spin wave [3]. Layered magnetic on magnetic [4] and conductor on magnetic [5] film systems appear to offer desirable device characteristics. Recent studies have been made in order to determine the rather complex behavior of the surface wave spectrum when both dipolar and exchange interactions are considered [2].

We consider here some of the dispersive and loss characteristics of the conductor-on-magnetic system including both dipolar and exchange interactions.

Consider a metallized insulating ferromagnetic film which is infinite in the \( z \)-plane and extends from \( x = 0 \) to \( x = S \). The non-magnetic conducting film with skin depth \( S \) extends from \( x = 0 \) to \( x = -d \).

In order to simplify the theory presented here, we approximate the conductor-magnetic system by two semi-infinite films (i.e., \( S \to d \to \infty \)) and discuss only surface waves propagating in the \( +y \) direction with propagation constant \( f \). The theoretical results derived for this model apply to the finite thickness film system when \( f \gg 1/S \) and \( d \gg \delta \). The behavior of the surface waves for \( f \ll 1/S \) and \( d \ll \delta \) have been discussed elsewhere [5].

Propagation effects and displacement currents may be neglected for most film systems of practical interest.

When dipolar and exchange interactions are included for the ferromagnetic film the magnetic potential \( \Phi \) satisfies the dipole-exchange differential equation, [2],

\[
\left( \Omega^2 - \theta^2 - \theta \right) \nabla^2 + \theta \frac{\partial^2}{\partial z^2} \Phi = 0 ,
\]

where \( \theta = \Omega H - \alpha V^2 \), \( \Omega = c/(4 \pi \tau M_0) \), \( \Omega H = H/4 \pi M_0 \), \( H \) is the applied field, \( M_0 \) is the saturation magnetization and \( \alpha \) is the exchange constant. The solutions of eq. (1) are admixtures of three waves whose relative amplitudes are determined by the boundary conditions [2].

In the conducting medium \( \nabla \times h = 4 \pi r E/c \), and \( \nabla \times E = i \omega H/c \) where \( \sigma \) is the conductivity, \( c \) is the velocity and \( \omega \) is the angular frequency.

The tangential component of \( h \) and the normal component of \( h \) + 4 \( \pi m \) are continuous across the interface and in addition the normal derivative of \( m, \partial m/\partial n \), is assumed to vanish. These conditions lead to the eigenvalue equation:

\[
-2i[(1+\epsilon)(\Omega_H - \Omega) + 1] + \left[ \frac{1}{\kappa_1 \kappa_3} \right] \left( \frac{1}{\kappa_1} \frac{1}{\kappa_3} \frac{1}{\kappa_2} \right) = 0 ,
\]

where \( \epsilon = f^2/g^2 \), \( g^2 = f^2 - 2i \delta^2 \), \( \delta^2 = c^2/(2 \pi \omega) \), \( \kappa^2 = \alpha^2 - \kappa_1 \kappa_3 \), \( \kappa_1 = \alpha(r - r') \), \( \kappa_3 = \alpha(r + r') \), \( r = (\Omega^2 + 1)^2 \), \( r' = \Omega_H + \alpha^2 + 1/2 \) and

\[
\Omega_{1,3} = \Omega_H + \alpha^2 \kappa_1 \kappa_3 .
\]

The imaginary part of \( \Omega \), determined from eq. (2), gives the surface wave losses. These losses stem from two quite different sources. The first is a conduction loss which arises from the penetration of the electric field \( E \) into the conductor. The second type, exchange loss, arises from the decay of the surface wave into the bulk continuum of spin waves.

For yttrium iron garnet \( \alpha \approx 2.6 \times 10^{-12} \text{ cm}^2 \) so that \( \kappa \) is small for values of \( f \ll 10^6 \text{ cm}^{-1} \). If \( \alpha \equiv 0 \) (no exchange interaction), then the solution of eq. (8) is \( \Omega = \Omega_H + (1 + \epsilon)^{-1} \). We note from the definition \( \epsilon = f^2/(2 (\Omega^2)^2 / \delta^2) + 1 \) as \( f \to 0 \) and \( \Omega \to \Omega_H + 1/2 \) when \( f \to \infty \). The latter result is identical to the surface wave frequency of an unmetallized magnetic film discussed by Damon and Eshbach [1], while the former result was obtained by Seshadri [6] for the case in which the conductor has infinite conductivity. The same limiting frequencies are approached.
if \( f \neq 0 \) is fixed and \( \delta \to 0 \) (infinite conductivity) or \( \delta \to \infty \) (vanishing conductivity). For finite and nonzero values of \( f \) and \( \delta \), \( \varepsilon \) is a complex number and conduction losses exist. For a given value of \( \delta \) the magnitude of the imaginary part of \( \varepsilon \), \( |\text{Im} \varepsilon| \), increases linearly with \( x = f \delta \) for small \( x \). For large values of \( x \), \( |\text{Im} \varepsilon| \) decreases as \( 1/x^2 \). Thus the maximum conduction losses occur for \( x \sim 1 \). The maximum value of \( |\text{Im} \varepsilon| \) occurs for \( x = (4/3)^{1/4} = 1.07 \). The reason for the decrease in the conduction loss with increasing \( f \) is that the penetration of the surface wave electric field into the conductor decreases. For metals such as gold, silver, copper, and aluminium \( \delta \sim 10^{-4} \) cm for \( \omega \sim 10^9 - 10^{10} \) rad/s so that the maximum conduction losses occur for \( f \sim 10^5 \) cm\(^{-1} \). Semiconductors may have much larger values of \( \delta \) and the maximum losses occur at smaller values of \( f \). The behavior of the surface wave dispersion is indicated schematically in figure 1 by the curve segments \( \text{AB}' \), \( \text{AC}' \), \( \text{AD}' \) and \( \text{FE} \). The solid curves are \( \Omega R \), the real part of \( \Omega \). The shading of the curves represents \( \Omega i \), the imaginary part of \( \Omega \). The solutions derived here do not apply to films of finite thicknesses when \( f \lesssim 1/S \). The behavior of the solutions for \( f \lesssim 10^5 \) cm\(^{-1} \) we can obtain approximate solutions of eq. (2) by power series expansion in \( \kappa \). We find that

\[
\Omega = \Omega H + (1 + \varepsilon)^{-1} + \omega_2 \kappa^2 + \omega_3 \kappa^3, \tag{3}
\]

where

\[
\omega_2 = \left\{ \left[ 2\Omega_H (1 + \varepsilon) + 1 - \Omega_H (1 + \varepsilon)^2 \right] \right\}^{-1/2}
\]

\[
(1 + \varepsilon) \left\{ 2\Omega_H (1 + \varepsilon) + 1 - \Omega_H (1 + \varepsilon)^2 \right\}^{-1/2}
\]

Consider YIG (yttrium iron garnet) with \( \delta \sim 10^{-4} \) cm in contact with a conducting film have \( \delta \sim 10^{-4} \) cm. Since \( \delta > \alpha \), the effects of exchange will be important only for large values of \( \alpha \). Therefore, we may obtain a simple result for \( \omega_2 \) and \( \omega_3 \), by evaluating these terms for \( \varepsilon \sim 1 \) and \( \Omega \sim \Omega H + \frac{1}{2} \). This procedure leads to the result that

\[
\Omega_R = \Omega_H + \text{Re}(1 + \varepsilon)^{-1} + \frac{2\kappa^2}{1} \left[ \kappa_1 (1 - 8 \kappa_1^2 (\Omega_H + \frac{1}{2})) \right] \left[ (\Omega_H + \frac{1}{2})^2 + 4 \right]^{-1/2} \kappa^3, \tag{5}
\]

\[
\Omega_i = \text{Im}(1 + \varepsilon)^{-1} - \kappa_1 [1 + 8 \kappa_1^2 (\Omega_H + \frac{1}{2})] \times \left[ (\Omega_H + \frac{1}{2})^2 + 4 \right]^{-1/2} \kappa^3.
\]

The imaginary part of \( \Omega \) must be negative since the fields vary as \( \exp(-i \omega t) \). The results of eq. (5) apply for values of \( f \lesssim 10^5 \) cm\(^{-1} \). This type of behavior is shown schematically in figure 1 by the curve \( \text{AD}' \). For small \( x \),

\[
\text{Re}(1 + \varepsilon)^{-1} = 1 - x
\]

and

\[
\text{Im}(1 + \varepsilon)^{-1} = -i x.
\]

When \( x > \kappa \) the conductive losses dominate the exchange losses. For \( \delta = 10^{-4} \) cm and YIG with \( 4 \pi M_0 = 1.750 \) Oe and an applied field of \( 10^3 \) Oe, eq. (8) yields

\[
\Omega_R \approx 0.571 4 + 0.975 8 + 0.000 5 + 0.000 0 = 1.547 7
\]

\[
\Omega_i = -0.218 7 - 0.000 0 = -0.218 7 \quad \text{for} \quad f = 10^4 \text{ cm}^{-1}. \]

When \( \delta \) is large, the \( \text{Re}(1 + \varepsilon)^{-1} = \frac{1}{2} \) and \( \text{Im}(1 + \varepsilon)^{-1} = -i(4 x^2) \). For \( f \sim 10^5 \) cm\(^{-1} \)

\[
\Omega_R = 1.071 4 + 0.052 0 + 0.000 3 = 1.123 7
\]

and

\[
\text{Im}(\Omega) = -0.002 5 - 0.024 5 = -0.027 05
\]

where the first contribution to \( \text{Im}(\Omega) \) is conductive loss and the second is exchange loss. For

\[
f \approx 3.5 \times 10^5 \text{ cm}^{-1}
\]

the exchange loss is very large. Im \( \Omega \sim \text{Re} \Omega \) and a well-defined surface state does not exist. The above results may be expressed in Oe by multiplying by \( 4 \pi M_0 = 1.750 \) or in frequencies by multiplying by \( 2 \gamma M_0 = 4.90 \times 10^9 \) Hz.

When \( x \approx \delta \), then \( \omega_2 \) and \( \omega_3 \) must be evaluated for \( \Omega = \Omega_H + (1 + \varepsilon)^{-1} \) and the regions of conductive and exchange loss overlap. In such a case \( \Omega_R \) does not

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**Figure 1.** Schematic summary of behavior of the dispersion and linewidth of magnetic surface waves for a magnetic insulating film in contact with a conducting film. \( \Omega \) is the surface wave angular frequency in units of \( 4 \pi M_0 \), and \( f \) is the surface wave propagation constant. The bulk spin wave continuum which extends upward in \( \Omega \) from the line \( (\Omega_H^2 + \Omega_i^2)^{1/2} \) is indicated by the crosshatching region. The solid lines are the real part of the surface wave frequency \( \Omega_R \) and the imaginary part is represented by the shaded regions. The solid lines which end at the points A and F are the results for infinite film thickness.

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reach $\Omega_f + \frac{1}{2}$ before the exchange effects become large. This type of situation is illustrated by the curve segment $AC'C$. For the other extreme $\delta \sim S \gg \alpha^{\frac{1}{2}}$ effects of the conductor occur for $f \leq 1/S$. The behavior of this type of system is illustrated by the curve $GF'E$.

References