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NONLINEAR ELECTROMAGNETIC SURFACE WAVES IN A SINGLE HEXAGONAL PLANAR FERRITE

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الموجات السطحية الكهرومغناطيسية غير الخطية في مادة أحادية من الحديد السداسي

Abstract This paper describes the theoretical investigation of TE surface waves propagation along the single interface of a nonlinear dielectric cover and a hexagonal planar ferrite with anisotropy. Numerical results show the possibility of the control of the dispersion characteristics and the non-reciporacal behavior of the waves by varying the external magnetic field, magnetization, and the carried wave power.

ملخص يصف هذا البحث تحريات نظرية لإنتشار الموجات السطحية (TE) خلال تداخل أحادي الغطاء عازلي غير خطي ومادة الحديد السداسية التي لها خاصية عدم التماثل .
لقد عرضت النتائج العددية إحتمالية التحكم في الخصائص التشتتية وظاهرة عدم التماثل للموجات وذلك بتغير المجال المغناطيسي الخارجي وكذلك التمغنط وقدرة الموجة المنتشرة .

1. Introduction

Recently, several theoretical investigations of the dispersion characteristics have been reported in the area of nonlinear electromagnetic waves propagating in gyromagnetic media[1-7] as ferrite (YIG) [2-4], or ferroelectric [5,6], or hexagonal ferrite [7]. The interest in nonlinear electromagnetic waves is due to their potential use

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in the design of some microwave or optical telecommunication components. Similarly, the interest in a hexagonal planar ferrite with anisotropy is due to its high anisotropy of the permeablility compared with the usual ferrite [2-4], and its high sensitivity to external magnetic fields or magnetization. The object of the present work is to examine theoretically the dispersion characteristics of TE nonlinear surface waves propagating along the single interface of a nonlinear dielctric cover and a hexagonal planar ferrite with anisotropy. This problem [7] may have potential applications because the dispersion characteristics can be controlled by tuning external physical parameters such as the applied magnetic field and magnetization or the power carried by the waves, especially that non-reciprocity has been observed significantly, in the structure. The non-reciprocity property is very important in the function of many microwave or optical devices such as switches, circulators, isolators, phase shifters and directional couplers [10,11].

2. Formulation and dispersion equation

We consider, as shown in figure 1, a single interface of a linear hexagonal ferrite substrate and a nonlinear dielectric cover with the coordinate system being chosen so that the wave vector k(the propagation constant) is along the x direction. The external magnetic field and magnetization are in the y direction, and the structure is normally along the z direction. The structure is assumed unbounded in the x direction. We are dealing here with TE waves only. The permeability tensor of the hexagonal ferrite medium is considered as a frequency dependent tensor, while the nonlinear dielectric permittivity of a nonlinear medium is considered as a frequency independent function. The magnetic permeabililty tensor of the hexagonal ferrite substrate with anisotropy in the basal plane (ZY case) is written as [7-10]

$$\mu(\omega) = \begin{pmatrix} \mu_{xx} & 0 & \mu_{xz} \\ 0 & \mu_{yy} & 0 \\ -\mu_{xz} & 0 & \mu_{zz} \end{pmatrix}$$

where

$$\mu_{xx} = \mu_B \frac{\omega_1^2 - \omega^2}{\omega_2^2 - \omega^2}, \ \mu_{xz} = \mu_B \frac{\omega \omega_m}{\omega_2^2 - \omega^2}, \ \mu_{zz} = \mu_B \frac{\omega_4^2 - \omega^2}{\omega_2^2 - \omega^2},$$

$\omega_2^2 = \omega_0 (\omega_0 + wa)$, $\omega_1^2 = (\omega_0 + \omega_a)(\omega_0 + \omega_m)$, $\omega_4^2 = \omega_0 (\omega_0 + \omega_a + \omega_m)$, $\omega_0 = \gamma\mu_0 H_0$, $\omega_a = \gamma\mu_0 H_a$, $\omega_m = \gamma\mu_0 M_0$, $\mu_0 H_0$ is the applied magnetic field, $\mu_0 M_0$ is the dc saturation magnetization, $\mu_0 H_a$ is the anisotropy field, μ_B is the background permeability, and γ is the gyromagnetic ratio and $\omega = 2\pi f$, where f is operating frequency. The nonlinear cover is assumed to b kerr-like, isotropic. Its dielectric function may be written as [2]

$\epsilon^{(NL)} = \epsilon_2 + \alpha E^2{}_y$, where ϵ_2 is a frequency-dependent linear part, and α is a nonlinear coefficient. From Maxwell's equations with the help of the boundary conditions it is easy to obtain the dispersion relation [2,7] in terms of the interface non-linearity,($\alpha/2$) $E^2{}_{,(0)}$ as

$$(\alpha/2)\, E^2_y = 1 - u^2$$

where

$$u = -\frac{\left[k\mu_{xz} + \mu_{zz}k_1\right]}{k_2\mu_v\mu_{xx}}, \mu_v = \frac{\mu_{xx}\mu_{zz} - \mu_{xz}^2}{\mu_{xx}},$$

$$k_1 = \left[\frac{\mu_{xx}}{\mu_{zz}}\left(k^2 - \frac{\omega^2}{c^2}\mu_v\right)\right]^{1/2}, k_2 = \left[k^2 \frac{\omega^2}{c^2}\varepsilon_2\right]^{1/2}$$

The dispersion relation is then numerically evaluated for various values of the interface non-linearity, the applied magnetic field and magnetization. Numerical calculations and predictions for various values of the structure are investigated, and the potential applications are also discussed. The region of the existence of nonlinear surface waves can be deduced from the condition that both k_1 and k_2 are real. It also requires that μ_{xx}/μ_{zz} should be real. So it is easy to find, from the previous condition, that the range of the linear waves lies in the region $\omega_2 < \omega < \omega_4$ [7].

3. Numerical Calculations and discussion

The characteristic dispersion equation is solved numerically by the usual newton's routine[2]. Investigating the influence of the interface non-linearity, or the power carried by the waves as a function of the interface non-linearity described in [2] is of primary interest. For numerical calculations, we assumed that the ferrite material is a lossless single Hexagonal crystal with $\mu_0 H_0$ = 0.05 T, $\mu_0 H_a$ = 0.9T , $\mu_0 M_s$ =0.23 T, γ= $1.76\text{x}10^{11}$ s^{-1} T^{-1} , and ϵ_f =1. The nonlinear dielectric cover is chosen as the same material used in [3] with ϵ_2 = 2.25.

Figure (2) shows the dependence of the propagation characteristics on the interface non-linearity $\alpha E^2_y(0)$. The three top curves (f1,f2,f3) correspond to the nonlinear electromagnetic waves propagating in the forward direction, while the three bottom curves(b1,b2,b3) correspond to waves propagating in the reverse direction (or the reverse direction of magnetization).This figure shows the non-reciprocal behavior of the nonlinear electromagnetic waves, i.e., waves propagating with the wave vector + k (forward direction of wave propagation) are significantly different from those propagating with the wave vector-k (reverse or backward direction of wave propagation). The same feature can also be obtained if the direction of the applied magnetization is reversed. Figure (3) illustrates the dependence of the wave number k on the applied magnetic field for three different values of the operating frequency in both directions of the wave propagation (forward and backward). The figure shows remarkable non-reciprocity resulting from the fact that, this μ_0H_0 (+k) #μ_0H_0 (-k) non-reciprocity is very sensitive to the tuning of the operating frequency especially at high operating frequencies. Figure (4) Shows the variation of the wave number with the applied magnetization for both directions of propagation and for different values of the interface nonlinearely $\alpha/2\ E^2_y(0)$. It has been found that, the waves cover the frequency range $\omega_2 < \omega < \omega_4$. This means that if we increase the value of the interface non-linearity $\alpha/2\ E^2_y(0)$, i.e the power carried by the waves, the initial value of the physical solution of the dispersion equation shifts to higher values, and the dispersion characteristics can be controlled by the small value of the operating power (interface nonlinearely $\alpha/2\ E^2_y(0)$). The obtained non-reciprocity could be used in designing some future microwave devices such as switches, isolators and all signal processing when the propagation characteristics can be tuned and varied by changing the direction of propagation as well as the value of the external magnetic fields and other physical parameters.

4. Conclusion

The present paper has shown that the dispersion characteristics of TE nonlinear surface waves in a hexagonal planar ferrite has strong non-reciprocal behavior, and can be tuned by various external physical parameters such as the applied magnetic filed and magnetization or the power carried by the waves. Certain aspects related to the propagation of nonlinear electromagnetic waves in multi-layered structures are under consideration as their features will be of special interest to the microwave electronic industry. These calculations may be considered as the basis for future investigation.

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Figure Captions:

Fig. 1 Geometry structure of a single interface of a linear hexagonal ferrite and a nonlinear dielectric cover.

Fig. 2 Computed dispersion curves in both directions for different values of the interface non-linearity $\alpha E^2{}_y(0)$. The three top curves (f1,f2,f3) are labeled respectively for $\alpha\ E^2{}_y(0) = 0.0$, $\alpha\ E^2{}_y(0) = 0.08$, $\alpha\ E^2{}_y(0) = 0.16$, while the three bottom curves (b1,b2,b3) correspond to the backward waves with the same values of the interface nonlinearity.

Fig. 3 computed variation of the wave number versus the applied magnetic field in both directions of propagation for different values of the operating frequency f. Curves are labeled as follows, 1), f =6.5GHz ;2), f = 7.5 ;3), f =8.5GHz. f and b correspond to the forward and backward wave propagation directions respectively.

Fig4. Computed variation of the propagation constant versus the applied magnetic field in both directions for different values of the interface non-linearity $\alpha\ E^2_y(0)$ at f = 6.5GHz. The first top three curves (f1,f2,f3) are labeled respectively for $\alpha\ /2\ E^2_y(0) = 0.0$, $\alpha\ /2\ E^2_y(0) = 0.05$, $\alpha\ /2\ E^2_y(0) = 0.10$ for the forward waves, followed by the three bottom curves (b1,b2,b3) for the backward waves with the same quoted nonlinearties.