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Characteristics of TM Surface Waves in a Nonlinear Antiferromagnet–Semiconductor–Superconductor Waveguide Structure

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The frequency characteristics of the transverse magnetic (TM) surface waves at mid-infrared frequencies in a layered system, consisting of $YBa_2Cu_3O_{7-x}$ superconductor film bounded by a nonlinear antiferromagnet (FeF_2) cover and a resonant semiconductor plasma ($In_{0.53}Ga_{0.47}As$) substrate, are fully described. The permeability tensor of the antiferromagnet crystal, for the absence of an applied Zeeman field, has a nonlinear response to the intense rf field. The complex wave number of TM wave is computed by solving the dispersion equation in order to determine the effects of the superconductor and resonant semiconductor on the dispersion characteristics for both the reduced phase and reduced attenuation constants as a function of the temperature and frequency. The power flow through the waveguide structure has also been investigated. We have found that superconductors have the ability to reduce the propagation losses. We have also found that the reduced attenuation constant is highly dependent on the temperature of the superconductor.

KEY WORDS: dispersion relation; phase constant; attenuation constant; nonlinear waves.

1. INTRODUCTION

The propagation of nonlinear electromagnetic waves in a structure containing a semiconductor or superconductor is of particular interest for both fundamental research and applications [1–13]. Specifically, the structures can be used in future developments of optoelectronic devices, such as isolators, switches, circulators, and signal-processing devices [1–3]. The combination of resonant semiconductor plasma ($In_{0.53}Ga_{0.47}As$) and high-temperature superconductor ($YBa_2Cu_3O_{7-x}$) make it possible to considerably improve the performance of optomicrowave devices. The study of nonlinear electromagnetic waves in antiferromagnetic films also has attracted a significant degree of attention [4,5]. Almieda and Mills derived the nonlinear susceptibility χ_{NL} for the first time [6] in the study of the nonlinear infrared responses of the antiferromagnetics, and employed χ_{NL} to explore the power-dependent transmission of electromagnetic fields through thin antiferromagnetic films. In this work, the frequency characteristics of transverse magnetic (TM) waves at mid-infrared frequencies in a layered structure consisting of $YBa_2Cu_3O_{7-x}$ superconductor film bounded by a nonlinear antiferromagnet (FeF_2) cover and a resonant semiconductor plasma ($In_{0.53}Ga_{0.47}As$) substrate are fully described. We are taking into account the effect of the temperature of the superconductor and the nonlinearity of the antiferromagnet. The complex effective wave number of the TM surface waves is computed by solving the dispersion equation in order to determine the effect of the temperature of superconductor and the frequency response on the reduced phase and attenuation constants. The power flow has also

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been studied against the reduced propagation and attenuation constants. We have found that the superconductor has the ability to reduce the propagation losses.

2. BASIC EQUATIONS

The structure geometry of the problem considered here is shown in Fig. 1. The z-axis is the direction of the light propagation. We consider a superconductor film (medium **2**) of finite thickness (t) characterized by a negative dielectric function $\varepsilon_2(\omega)$. The superconductor film is bounded by a semi-infinite resonant semiconductor plasma substrate $\varepsilon_1(\omega)$ (medium **1**) $x < 0$, and a two-sublattice uniaxial antiferromagnet cover (medium **3**) in the region $x > 0$, its permeability function being μ^{NL}. The permeability tensor in the absence of an applied Zeeman field, which describes the nonlinear response of the crystal to the intense rf field, is a diagonal one [4,6] as:

$$\mu_{yy}(\omega) = \mu^{\mathrm{NL}}(\omega) = \mu^{\mathrm{L}}(\omega) + \chi_{\mathrm{NL}}(\omega)|h|^2, \quad (1)$$

where $\mu^{\mathrm{L}}(\omega)$ is the linear permeability, which has the form

$$\mu^{\mathrm{L}}(\omega) = 1 + \frac{2\omega_{\mathrm{M}}\omega_{\mathrm{A}}}{\omega_{\mathrm{c}}^2 - \omega^2}, \quad (2)$$

where $\omega_{\mathrm{M}} = \gamma\mu_0 M_{\mathrm{s}}$, $\omega_{\mathrm{A}} = \gamma\mu_0 H_{\mathrm{A}}$, $\omega_{\mathrm{E}} = \gamma\mu_0 H_{\mathrm{E}}$, and $\omega_{\mathrm{C}}^2 = \omega_{\mathrm{A}}^2 + 2\omega_{\mathrm{A}}\omega_{\mathrm{E}}$ is the resonance frequency of the system. M_{s} is the saturation magnetization field. H_{A} is the anisotropy field, H_{E} is the exchange field of the crystal, and γ is the gyromagnetic ratio.

The negative relative dielectric constant of (ε_2) for the superconductor can be approximated by the two-fluid model as [7]

$$\varepsilon_2(\omega) = \left[1 - \frac{1}{\omega^2\mu_0\lambda_{\mathrm{L}}^2\varepsilon_0}\right] - i\frac{\sigma}{\omega\varepsilon_0}, \quad (3)$$

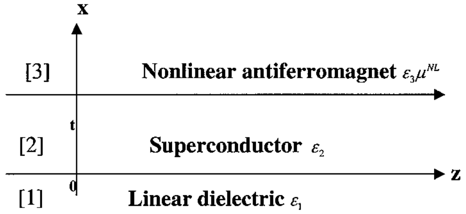

Fig. 1. Configuration of a three waveguide structure.

where

$$\lambda_{\mathrm{L}}^2 = \frac{\lambda_0^2}{[1 - (T/T_{\mathrm{c}})^4]},$$

λ_0 is the field penetration depth at temperature $T = 0K$, $\sigma = \sigma_0[T/T_{\mathrm{c}}]^4$ and T_{c} is the critical temperature of the superconductor.

For mid-infrared wavelengths, the dielectric refractive index $\varepsilon_1(\omega)$ of the resonant semiconductor plasma can be deduced from Drude's formula [8] as

$$\varepsilon_1(\omega) = \varepsilon_\infty\left\{1 - \frac{\omega_{\mathrm{P}}^2}{\omega^2}\frac{1}{1 + i\omega_{\mathrm{a}}/\omega}\right\}, \quad (4)$$

where ω_{P} is the plasma frequency and ω_{a} is the absorption frequency are

$$\omega_{\mathrm{P}}^2 = q^2 N/m^*\varepsilon_\infty\varepsilon_0 \quad (5)$$

and

$$\omega_{\mathrm{P}}^2 = m^*\mu/q. \quad (6)$$

Here N is the electron density, m^* is the optical effective mass, μ is the electron mobility, q is the absolute value of the electron charge, and $\varepsilon_\infty\varepsilon_0$ is the high-frequency permittivity of the bulk material. A resonant semiconductor plasma can be defined as a material with $\mathrm{Re}(\varepsilon_1) = 0$. However, if $\mathrm{Re}(\varepsilon_1) > 0$, the material is considered a dielectric, and if $\mathrm{Re}(\varepsilon_1) < 0$, the material is considered a metal.

The TM electromagnetic waves propagate along the z-axes in the xz-plane with a complex wave vector $\boldsymbol{k}$ and an angular frequency ω. The electric and magnetic vectors of the electromagnetic field take the form

$$E = (H_{\mathrm{x}}, 0, H_z)\exp[ik_0(\beta_{z-ct})] \quad (7\text{-a})$$

and

$$H = (0, H_{\mathrm{y}}, 0)\exp[ik_0(\beta z - ct)], \quad (7\text{-b})$$

where $\beta = k/k_0$ is the complex effective wave index constant, k_0 is the wave number of the free space, and c is the velocity of light in free space. The complex effective wave index constant can be written as

$$\beta = \frac{k}{k_0} = \mathrm{Re}(\beta) + i\,\mathrm{Im}(\beta), \quad (8)$$

where $Re(\beta)$ is the reduced phase constant, and $\mathrm{Im}(\beta)$ is the reduced attenuation constant. The wave equation in each layer is obtained from Maxwell's equations:

$$\nabla \times H = i\omega\varepsilon_0\varepsilon E \quad (9a)$$