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REFLECTION OF SURFACE WAVES AND THEIR COUPLING WITH WAVE BEAMS AT ANISOTROPICALLY PERTURBED IMPEDANCE PLANE

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ABSTRACT

Effects of coupling of waves at plane with spatially oscillating surface impedance (anisotropic and/or gyrotropic) are theoretically considered. A combination of the two processes is investigated. The first process is reflection of surface waves propagating along impedance surface. The second process is input-output coupling of falling paraxial wave electromagnetic beams (both TM and TE type) with both surface TM waves. This electromagnetics problem is important for consideration of devices combining functions of nonreciprocal antenna and microwave generator.

INTRODUCTION

In open periodic waveguiding structures Bragg scattering can be observed in different forms [1]. Type of the wave transformation depends on from a value of perturbation period. If a perturbation wavenumber is twice as large as longitudinal wavenumber of surface wave, then coupling of two surface waves with opposite propagation directions occurs, that is reflection of surface waves is observed. If wavenumber of perturbation is equal to difference of longitudinal wavenumbers of surface and volume waves then a coupling of these waves secures, that is why we can obtain output of radiation from structure. Anisotropy of parameters causes coupling of waves with different polarization. If incident wave can excite surface wave reflected wave would be very differed from mirror one even if surface perturbation amplitude were small [2]. Open structures become more interesting when parameter perturbation is not periodic [3].

METHOD OF ANALYSIS

In the paper physical effects of coupling of paraxial wave electromagnetic TM and TE beams falling on surface with spatially oscillating surface anisotropic impedance and two TM surface waves are theoretically considered. Moreover we suppose Bragg coupling (reflection) of surface waves. Asymptotic method [3] based on ideas of KBM method [4] is used. Perturbations are expressed as sum of sinusoidal components with small amplitudes smoothly varying along longitudinal coordinate. Amplitudes of incident TM and TE wave beams are smoothly varied across beam. The same small parameter β is used for all small values and as smoothness parameter [4]. For case $\partial/\partial x \equiv 0$ all components of electromagnetic field are expressed in terms of x component of fields H_x and E_x. The potential functions $H(y,z) \equiv H_x$ and $E(y,z) \equiv E_x$ are determined by the solution of the following boundary-value problem:

$$\frac{\partial^2 H}{\partial z^2} + \frac{\partial^2 H}{\partial y^2} + k^2 H = 0, \quad \frac{\partial^2 E}{\partial z^2} + \frac{\partial^2 E}{\partial y^2} + k^2 E = 0, \tag{1}$$

$$\left(\frac{\partial H}{\partial y}+w_H H+w_{HE}\frac{\partial E}{\partial y}\right)\Bigg|_{y=0}=0,\quad \left(E+w_E\frac{\partial E}{\partial y}-Z_{xx}H\right)\Bigg|_{y=0}=0, \qquad (2)$$

Impedance parameters w_H, w_{HE} and w_E as functions of z are expressed through components of surface impedance tensor **Z** in a form of sums of spatial harmonics

$$w_H=i\omega\varepsilon Z_{zx}=w_{H,0}+\beta\sum_j w_{H,j}(\beta z)\exp(i\chi_j z)+\beta^2\sum_{j,l} w_{H,j,l}(\beta z)\exp(i\chi_j z+i\chi_l z)$$
$$w_E=iZ_{xz}/(\omega\mu)=w_{E,0}+\beta\sum_j w_{E,j}(\beta z)\exp(i\chi_j z),$$
$$w_{HE}=\varepsilon Z_{zz}/\mu=\beta\sum_j w_{HE,j}(\beta z)\exp(i\chi_j z),\quad Z_{xx}=-\beta\sum_j w_{EH,j}(\beta z)\exp(i\chi_j z),$$

where χ_j is wavenumber of the jth spatial harmonics of the perturbation; $w_{H,j}$, $w_{E,j}$, $w_{HE,j}$ and $w_{EH,j}$ are amplitudes of these harmonics, $w_{H,j,l}$ are amplitudes of the second order perturbation. Alongside with coordinate z we introduce a "smooth" variable $\zeta=\beta z$ [4]. The Bragg coupling of surface waves and TM and TE beams occurs, when the wavenumber mismatches $\eta_{V,s}=k_z+\chi_{\mathrm{pv}(s)}-h_s$ ($s=1,2$) become small. Here k_z is longitudinal wavenumber of the beams, h_s is longitudinal wavenumber of the surface wave, and pv(s) is integer-value function that coincide with the number of a spatial harmonic of the perturbation ensuring Bragg coupling. The Bragg reflection of a surface wave is observed if wavenumber mismatches $\eta_{S,s,l}=-2h_s-\chi_l-\chi_{\mathrm{ps}(s,l)}$ are close to zero. The solution of the boundary-value problem (1), (2) are searched as an asymptotic series on orders of small parameter β [3, 4].

$$H=\sum_{s=1}^{2}a_s\exp(-ih_s z-wy)+\beta a_H(\zeta+\beta yk_z/k_y)\exp(-ik_z z+ik_y y)+\Gamma_H\beta a_H(\zeta-\beta yk_z/k_y)\times$$
$$\times\exp(-ik_z z+k_y y)+\beta u_1(a_1,a_2,k_z z,hz,\chi z,\zeta,y)+\beta^2u_2(a_1,a_2,k_z z,hz,\chi z,\zeta,y)+\ldots,$$
$$E=\beta a_E(\zeta+\beta yk_z/k_y)\exp(-ik_z z+k_y y)+\Gamma_E\beta a_E(\zeta-\beta yk_z/k_y)\exp(-ik_z z-k_y y)+$$
$$+\beta v_1(a_1,a_2,k_z z,hz,\chi z,\zeta,y)+\beta^2v_2(a_1,a_2,k_z z,hz,\chi z,\zeta,y)+\ldots, \qquad (3)$$

where Γ_E and Γ_H are the reflection coefficients of plane waves from an undisturbed plane, $k_y=\sqrt{k^2-k_z^2}$, a_H and a_E are distributions of amplitudes of wave beams, u_n and v_n ($n=1,2,\ldots$) are 2π-periodic versus $k_z z$, $h_s z$ and $\chi_j z$ functions. First derivatives of complex amplitudes a_s are expressed in form of asymptotic expansions too [3, 4].

In a second approximation on small parameter value da_s/dz can be obtained as

$$\frac{da_s}{dz}=\beta^2\left[a_sA_{s,2}+\exp(-i\eta_{V,s}z)(a_HG_{s,2,V,H}+a_EG_{s,2,V,E})+a_{3-s}\sum_l\exp(-i\eta_{S,s,l}z)G_{s,2,S,l}\right] \qquad (4)$$

where $A_{s,2}=-iw_{H,0}\left\{\sum_j\left[\frac{w_{HE,j}w_{EH,-j}ik_{-j}}{ik_{-j}w_{E,0}-1}-\frac{w_{H,j}w_{H,-j}}{ik_{-j}-w_{H,0}}\right]-w_{H,0,0}\right\}/h_s$,

$$G_{s,2,V,H} = 4w_{H,-\mathrm{pv}(s)}\, k_y\, w_{H,0}/[(2h_s + \eta_{V,s})(ik_y - w_{H,0})], \quad G_{s,2,V,E} = 4w_{HE,-\mathrm{pv}(s)}\, k_y\, w_{H,0}/ /[(2h_s + \eta_{V,s})(ik_y\, w_{E,0} - 1)], \quad G_{s,2,S,l} = -\imath 2\, w_{H,0}[w_{H,\mathrm{ps}(s,l)}\, w_{H,l}/(ik_{3-s,l} - w_{H,0}) - - ik_{3-s,l}\, w_{HE,\mathrm{ps}(s,l)}\, w_{EH,l}/(ik_y\, w_{E,0} - 1)]/(2h_s + \eta_{S,s,l}),$$

Deciding the equation (4) we find variation of amplitude of the surface waves along longitudinal coordinate z. Then we can define the field, radiated from the surface.

THE PHYSICAL EFFECTS

Total physical effect observed in the considered structure is result of combination of five phenomena – "unperturbed" specular reflections of volume TE and TM waves (they are characterized by parameters Γ_E and Γ_H), transformation of these waves into two surface TM waves propagating in opposite directions along impedance surface (characterized by parameters $G_{s,2,V,E}$ and $G_{s,2,V,H}$), leaking and heat dissipation of energy of surface waves (characterized by parameters $A_{s,2}$), mutual transformation (reflection) of surface waves (parameters $G_{s,2,S,l}$). If rigorous exponentiality of perturbations and incident wave is disturbed physical pattern changes fundamentally – structure can be exited by a surface wave going from " a minus of infinity " or energy of falling volume waves can be transformed into energy to a surface wave going to " a plus of infinity " Structures considered in the paper have high frequency and angular selectivity. They can be used as nonreciprocal reflector, transmitting or receiving antenna. Gyrotropy of impedance causes that antenna patterns for reception and transmission are essentially different. Combination of impedance gyrotropy and corrugation tilt allows using these structures as circulators concerning surface waves and TE wave beams.

CONCLUSIONS

Asymptotic method based on method of Krylov, Bogoliubov and Mitropolsky have allowed us to consider phenomena of Bragg reflection and volume-surface coupling of surface waves and TM and TE waves in open anisotropic quasiperiodic waveguiding structure. Found solution is valid for small and not small values of mismatch; so we have no need to splice resonant and not resonant asymptotics. Obtained results will be useful for analysis of wave scattering by structures with small surface nonperiodically oscillating gyrotropic perturbations of parameters and for designing resonators, leaky-wave antennas or nonreciprocal devices with untraditional properties.

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