;urface polaritons due to allowance for spatial lispersion

V. M. Agranovich and O. A. Dubovskiĭ

Spectroscopy Institute, USSR Academy of Sciences

(Submitted 26 September 1977)
Pis'ma Zh. Eksp. Teor. Fiz. **26**, No. 9, 641–644 (5 November 1977)

Attention is called to a new class of surface electromagnetic waves, the very existence of which is due to allowance for spatial dispersion. The dispersion law of such surface solutions is obtained for the contact region of the "right" and "left" modifications of crystals of symmetry C_{2v} and D_{2d}.

PACS numbers: 71.36.+c, 77.90.+k

The presently investigated surface polaritons are realized on interfaces of media whose dielec-:ic constants differ in sign (in some frequency interval or another) (see, e.g.,[1] where the onditions for the existence of waves in anisotropic crystals are also discussed). Although the patial dispersion for the aforementioned waves can lead in some cases to the appearance of dditional solutions,[1] on the whole its role is of little importance in this case.

It is of interest, however, to search for such media in situations wherein the very appearance f natural surface electromagnetic waves is due only to spatial dispersion of the dielectric tensor. It ppears that greatest interest can attach here to a discussion of the conditions for the existence of urface polaritons on the interface between media whose dielectric tensor differ only when spatial ispersion is taken into account. This can be, in particular, the boundary separating the "right" nd "left" modifications of a gyrotropic crystal (e.g., quartz) or of a gyrotropic liquid crystal that as under certain conditions coexisting "right" and "left" phases.[2] We confine ourselves here recisely to the case of gyrotropic media with account taken of only the terms linear in the wave ector **k** in the expansion of the dielectric tensor.

To find the surface waves we shall use for the fields the interface conditions obtained in[3]. We ssume that the "right" ($\alpha=\mathrm{I}$, $Z<0$) and the "left" ($\alpha=\mathrm{II}$, $Z>0$) nonmagnetic media are :parated by the plane $z=0$. Following[3] we represent the equation connecting the electric induc-on **D** and the intensity **E** of a field of frequency ω in each of the media ($\alpha=\mathrm{I,II}$) in the form

$$D_i^\alpha=\epsilon_{ij}E_j^\alpha-\tfrac{1}{2}e_{ijm}g_{ml}^\alpha(\mathbf{r})\frac{\partial}{\partial x_l}E_j^\alpha(\mathbf{r})-\tfrac{1}{2}e_{ijm}\frac{\partial}{\partial x_l}[g_{ml}^\alpha(\mathbf{r})E_j^\alpha(\mathbf{r})], \tag{1}$$

here $\epsilon_{ij}(\omega)$ is the dielectric tensor without allowance for spatial dispersion, $g_{ij}(\mathbf{r})$ is the gyration seudotensor, $g_{ij}^I=-g_{ij}^{\mathrm{II}}$, and e_{ijl} is the fully antisymmetrical unit pseudotensor. The surface solu-ons for fields that decrease as $z\to\pm\infty$ and propagate along the x axis will be sought, as usual, in ıe form

$$\mathbf{E}^\alpha(\mathbf{r})=\mathbf{E}^\alpha\exp(i\vec{\mathscr{K}}^\alpha\mathbf{r}),\quad \mathbf{H}^\alpha(\mathbf{r})=\mathbf{H}^\alpha\exp(i\vec{\mathscr{K}}^\alpha\mathbf{r}),$$
$$\vec{\mathscr{K}}^\alpha\equiv(k,0,k_3^\alpha),\quad \mathrm{Im}k_3^{\mathrm{I}}<0,\quad \mathrm{Im}k_3^{\mathrm{II}}>0. \tag{2}$$

'or from the boundary, the dielectric tensor is

$$\epsilon_{ij}^\alpha=\epsilon_{ij}^\alpha(\omega)-ie_{ijm}g_{ml}^\alpha\mathscr{K}_l^\alpha,\quad D_i^\alpha=\epsilon_{ij}^\alpha(\omega,\vec{\mathscr{K}}^\alpha)E_j^\alpha \tag{3}$$

nd for fields (2) satisfying Maxwell's equations

$$\mathrm{rot}\mathbf{E}^\alpha(\mathbf{r})=i\frac{\omega}{c}\mathbf{H}^\alpha(\mathbf{r}),\quad \mathrm{rot}\mathbf{H}^\alpha(\mathbf{r})=-i\frac{\omega}{c}\mathbf{D}^\alpha(\mathbf{r}) \tag{4}$$

we can obtain the boundary conditions in the same manner as used in[3] for volume waves.

By way of example we consider here crystals of class C_{2v} of the rhombic system and uniaxial crystals of class D_{2d} of the trigonal system, where (the crystallographic axes are oriented in the same way as in[4] and the twofold axes are normal to the interface) the gyration tensors are determined by a single parameter only (see[4,5]).

$$g_{ij}^{\alpha}=g^{\alpha}(e_{ij3})^2, \quad g^{\mathrm{II}}=-g^{\mathrm{I}}\equiv g>0 \tag{5}$$

and, in addition, for uniaxial crystals we have

$$\epsilon_{ij}(\omega)=\epsilon_i(\omega)\delta_{ij}, \quad \epsilon_1=\epsilon_2\equiv\epsilon_\perp, \quad \epsilon_3\equiv\epsilon_\parallel.$$

The boundary conditions at $z=0$ for the fields (2) take in this case the form:

$$\epsilon_3 E_3^{\mathrm{I}}-igkE_1^{\mathrm{I}}=\epsilon_3 E_3^{\mathrm{II}}+igkE_1^{\mathrm{II}}, \quad H^{\mathrm{I}}=H^{\mathrm{II}}, \quad E_{x,y}^{\mathrm{I}}=E_{x,y}^{\mathrm{II}}. \tag{6}$$

On the other hand, the use of Maxwell's equations (4) leads for each of the media I and II to linear relations between the amplitudes of the fields (2). An elementary analysis of these relations shows that they, as well as conditions (6) are satisfied by solutions of the type (2), for which only E_z and H_y differ from zero in both media, with

$$\begin{aligned} &E_3^{\mathrm{I}}=E_3^{\mathrm{II}}\equiv E_3\neq 0, && H_2^{\mathrm{I}}=H_2^{\mathrm{II}}=-\frac{kc}{\omega}E_3,\\ &D_1^{\mathrm{I}}=-D_1^{\mathrm{II}}=igkE_3, && D_2^{\mathrm{I}}=D_2^{\mathrm{II}}=0,\\ &D_3^{\mathrm{I}}=D_3^{\mathrm{II}}=\epsilon_3 E_3, && k_3^{\mathrm{II}}=-k_3^{\mathrm{I}}=ig\left(\frac{\omega}{c}\right)^2. \end{aligned} \tag{7}$$

The dispersion law for the obtained surface waves is

$$k^2=(\omega^2/c^2)\epsilon_3(\omega), \tag{8}$$

and consequently corresponds to the frequency region where $\epsilon_3(\omega)>0$.

Thus, the obtained surface wave is transverse, and its dispersion law (8) does not depend on the parameter of the spatial dispersion. At the same time, this parameter enters in the relation between the field amplitudes, and also determines the rate at which they decrease with increasing z (see the expressions for k_3). It is interesting that as $c\to\infty$ we have $k_3^{\mathrm{I,II}}\to 0$. This means that the *obtained solution exists only when retardation is taken into account. Their penetration depth* $L=|k_3|^{-1}=c^2/\omega^2 g$ is much larger than the lattice constant. In the frequency region where $\epsilon_3(\omega)>0$ generally speaking, there exist also volume electromagnetic waves. However, the conversion of the discussed surface waves into volume waves may turn out to be possible only if scattering is taken into account, i.e., outside the scope of linear electrodynamics. Comparing the spectra of the surface and volume waves, we confine ourselves, for simplicity, to the case of uniaxial crystals. In addition inasmuch as in these wave-transformation processes only the tangential component of the wave vector is conserved, we consider the dispersion of volume waves with wave vector $\vec{\mathscr{K}}=(k,0,k_3)$ where k_3 is a real quantity. For "ordinary" waves ($E_1=E_3=0$, $E_2\neq 0$) the gyrotropy does not enter in (3). In this case the dispersion law takes the usual form $k^2+k_3^2=(\omega^2/c^2)\epsilon_\perp(\omega)$. The spectrum of these waves overlaps the spectrum of the surface waves only at $\epsilon_\perp(\omega)>\epsilon_\parallel(\omega)$, but the decay of the surface polariton is forbidden because the fields are orthogonal.

The spectrum of the "extraordinary" waves ($E_2=0, E_1\neq 0, E_3=0$) is defined by the relation

$$(\omega^2/c^2)\epsilon_\perp(\omega)\epsilon_\parallel(\omega)-\epsilon_\parallel(\omega)k_3^2-\epsilon_\perp(\omega)k^2=(\omega^2/c^2)g^2k^2.$$

It is easy to verify that the function $\omega=\omega(k)$ obtained from this ratio does not cross the dispersion law of the surface waves $\omega_s=\omega_s(k)$ [obtained from (8)] at any real value of k_3.

The obtained surface waves can be investigated by the usual methods of surface-polariton spectroscopy (ATIR, Raman scattering of light, and others, see[1]). Since these waves can appear also far from absorption bands (i.e., at $\epsilon_{\parallel}(\omega) > 0, \epsilon_{\perp}(\omega) > 0$) they cannot be confused with heretofore known waves.

[1]V.M. Agranovich, Usp. Fiz. Nauk **115**, 199 (1975) [Sov. Phys. Usp. **18**, 99 (1975)].

[2]Ya.B. Zel'dovich, Zh. Eksp. Teor. Fiz. **67**, 2357 (1974) [Sov. Phys. JETP **40**, 1170 (1975)].

[3]B.V. Bokut' and A.N. Serdyukov, Zh. Eksp. Teor. Fiz. **61**, 1808 (1971) [Sov. Phys. JETP **34**, 962 (1972)]; V.M. Agranovich and V.L. Ginzburg, Zh. Eksp. Teor. Fiz. **63**, 838 (1972) [Sov. Phys. JETP **36**, 440 (1973)]; V.M. Agranovich and V.I. Yudson, Opt. Commun. **9**, 58 (1973); V.B. Bokut' and A.N. Serdyukov, Zh. Prikl. Spektrosk. **20**, 677 (1974); U. Schlagheck, Z. Phys. **266**, 313 (1974).

[4]V.M. Agranovich and V.L. Ginzburg, Kristallooptika s uchetom prostranstvennoĭ dispersii i teoriya eksitonov (Spatial Dispersion in Crystal Optics and the Theory of Excitons), Nauka, 1965 [Wiley, 1966].

[5]Yu.V. Denisov, V.A. Kizel', and E.P. Sukhenko, Zh. Eksp. Teor. Fiz. **71**, 679 (1976) [Sov. Phys. JETP **44**, 357 (1976)].