J. Plasma Physics (2001), *vol.* 65, *part* 4, *pp.* 291–303. © 2001 Cambridge University Press
DOI: 10.1017/S0022377801001052 Printed in the United Kingdom

The spectrum of electromagnetic waves in a magnetized gaseous plasma layer. Part 2. Anisotropic modes

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(Received 23 May 2000 and in revised form 27 October 2000)

Abstract. A numerical investigation of anisotropic waves propagating in a magnetized plasma layer is performed. In gyrotropic plasma layers, there are two regions in which electromagnetic waves exist owing to the anisotropic properties of the plasma. Mainly these are Rayleigh pseudosurface waves. In the upper anisotropic region, a wave exists only in a planar waveguide. In the lower anisotropic region, there are two waves. The dispersion and the origin of these waves are analysed. The distribution of the energy and the Poynting vector are unique, and they differ from those of other families of electromagnetic waves. At small wavenumbers, the energy is concentrated in one of the dielectrics and at large wavenumbers, it is concentrated in the plasma.

1. Introduction

In Part 1 of this work (Ivanov *et al.* 2001), the importance of the propagation of electromagnetic radiation in gyrotropic gaseous plasma layers was explained, and the dispersion equations and the propagation of the waves at the crossing points of the dispersion curves with the complex-zone boundary and with the boundaries of different propagation regions were considered. It was shown that four families of waves can propagate – plasma, cyclotron, anisotropic and waveguide modes – and the influence of the layer width and the magnetization of the plasma on wave propagation was analysed. We should mention here that the investigation of the waves in gaseous plasma layers is important because of the creation and application of such structures in very large volumes (the concept is due to Nonaka) for implantation and other advanced technologies (Nonaka 1990, 1994a,b). The presence of a magnetic field leads to the appearance of new and interesting properties in radio-frequency discharges in planar waveguides (Nonaka 1991). The electromagnetic waves that exist in plasma layers owing to the presence of a magnetic field are the subject of the present paper.

In this paper, we focus attention on the electromagnetic waves that exist owing to the anisotropy of the plasma – we have called them 'anisotropic waves' (Ivanov and Alexov 1990). This class of electromagnetic waves does not exist in isotropic gaseous plasma layers. Analysis of anisotropic waves in a plasma waveguide (Ivanov 1999) has shown that a number of questions concerning these waves have no clear

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answer – the origin of the waves, the movement of their dispersion curve, in the (ω, k_z) plane, the transverse distributions of the field components and the Poynting vector, etc. These waves have been investigated in a cylindrical waveguide (Ding and Ren 1997; Hu and Ruan 1998).

There is a difference between anisotropic waves and other families of waves – plasma, cyclotron and waveguide modes. The waveguide, cyclotron and plasma modes have analogues in plasma layers (and cylindrical waveguides) at $\mathbf{B}_0 \to 0$ or $\mathbf{B}_0 \to \infty$. Anisotropic waves exist only for a finite magnetic field, and propagate in the regions of Rayleigh pseudosurface waves (RPSW), generalized Rayleigh surface waves (GRSW) and Rayleigh surface waves (see Ivanov et al. 1998). In the region of RPSW, the wave is a superposition of oscillating and exponentially decaying partial waves; in the region of GRSW, the oscillations of all partial waves decay exponentially. Such regions and waves cannot exist in isotropic plasmas, where the wave is a superposition only of oscillating or of exponentially decaying partial waves. When the anisotropic modes propagate in RPSW regions, the wave can have surface or volume character depending on which partial waves dominate exponential decay or oscillation.

2. Dispersion curves of anisotropic waves in the upper anisotropic region

The main part of the dispersion curves of anisotropic waves lies in regions of RPSW where $\alpha_1^2 > 0$ and $\alpha_2^2 < 0$. But the beginning of these curves (except in these regions) may be in regions where the GRSW (the complex zone) or Rayleigh surface waves ($\alpha_1^2 > 0$ and $\alpha_2^2 > 0$) propagate. There are two regions of existence of anisotropic waves: upper ($\omega_n > \omega_{nh}$) and lower ($\omega_n < \omega_{nh}$). In general, the anisotropic waves are pseudosurface waves. But in all regions of their existence, the positive propagation constant predominates, and they as a rule have a character similar to the surface wave.

In the upper anisotropic region, the anisotropic wave exists only in a planar waveguide and it has HE character (see Figs 1(a) and Fig 2(a) in Part 1 and Fig. 1 here).

At small widths of a planar waveguide, the waveguide modes have volume character along the whole dispersion curve. The anisotropic HE_u^a mode in the upper anisotropic region has pseudosurface character. Some of the components of the fields have surface character, and their maximum is near the walls of the waveguide; the other components have volume character. With increasing width of the waveguide, the beginning of the waveguide modes enters the region of upper anisotropic modes (Fig. 1). Those parts of waveguide modes that are in the upper anisotropic region have surface character. At large wavenumbers, the dispersion curves of the above-mentioned modes go into the region of waveguide waves, and they became volume waves. The distributions of the modes here are the same as at small widths of the waveguide, when waveguide modes do not enter the region of the anisotropic modes.

In the other layers for a semiconductor plasma (Ivanov and Nikolaev 1999a,b), only the beginning of the waveguide modes penetrates this region and acquires an anisotropic character. In the case of free and grounded layers for a gaseous plasma, no waves can propagate for frequencies greater than ω_{nh} and hence in the upper anisotropic region.

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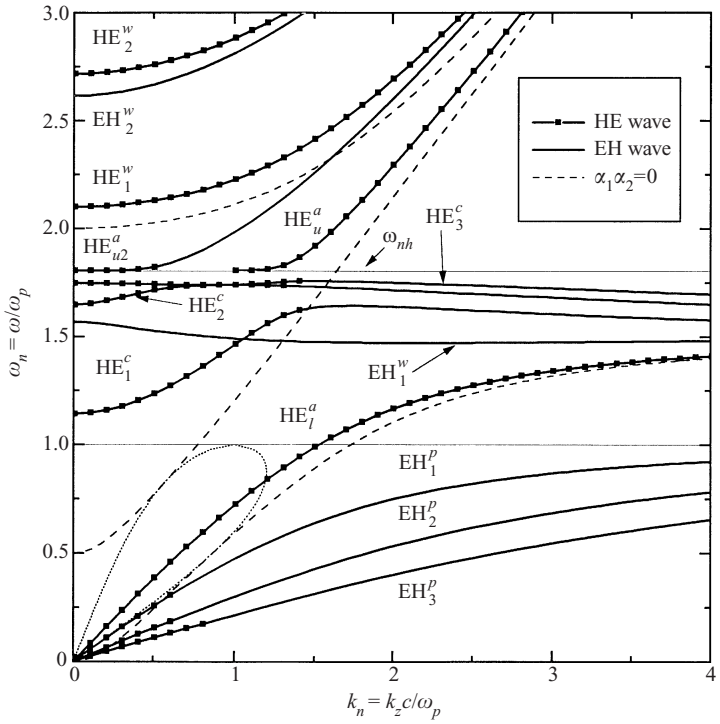


Figure 1. With increasing layer width and magnetic field, the waveguide modes go down into the upper anisotropic region, and HE_u^a starts at $k_n \neq 0$. $N = \omega_e/\omega_p = 1.5$, $d_n = 2.6$.

3. Dispersions and origin of anisotropic waves in the lower anisotropic region

In the lower anisotropic region, in every one of the considered structures, two anisotropic waves exist. In a free layer and in a layer on a substrate, they have EH character and are denoted as upper EH_u^a and lower EH_l^a modes. In a planar waveguide, the first anisotropic (upper) mode is HE_l^a and the second (lower) is the mode that is traditionally regarded as the plasma wave EH_1^p (Ivanov and Alexov 1990; Margot et al. 1992; Onischenko and Sotnikov 1992).

As mentioned in Part 1, the anisotropic modes in this region start at the origin of the (ω, k_z) plane (with exception of the EH_u^a mode in an asymmetric free layer).

In a strongly magnetized plasma, the asymptotic frequencies of the anisotropic modes are $\omega_{nas} = \omega_{np} = 1$ and $\omega_{nas} = \omega_{nc} = N$. In a weakly magnetized plasma, the asymptotic frequencies of the anisotropic modes are the same as the asymptotic frequencies of the surface modes SW_1 and SW_2 that propagate along the half-space interface between plasma and dielectric or metal screen (Wallis 1982; Halevi 1982; Ivanov et al. 1998).

As mentioned in Part 1, the discussed layers and the planar waveguide can be considered as being composed from two of the above-mentioned interfaces in which plasma does not occupy the half-space but only a layer of width d. In a plasma layer, the two anisotropic modes originate from the two surface modes SW_1 and SW_2 that propagate at two half-space interfaces. That is why, in the lower anisotropic region, there are always two modes: upper and lower.

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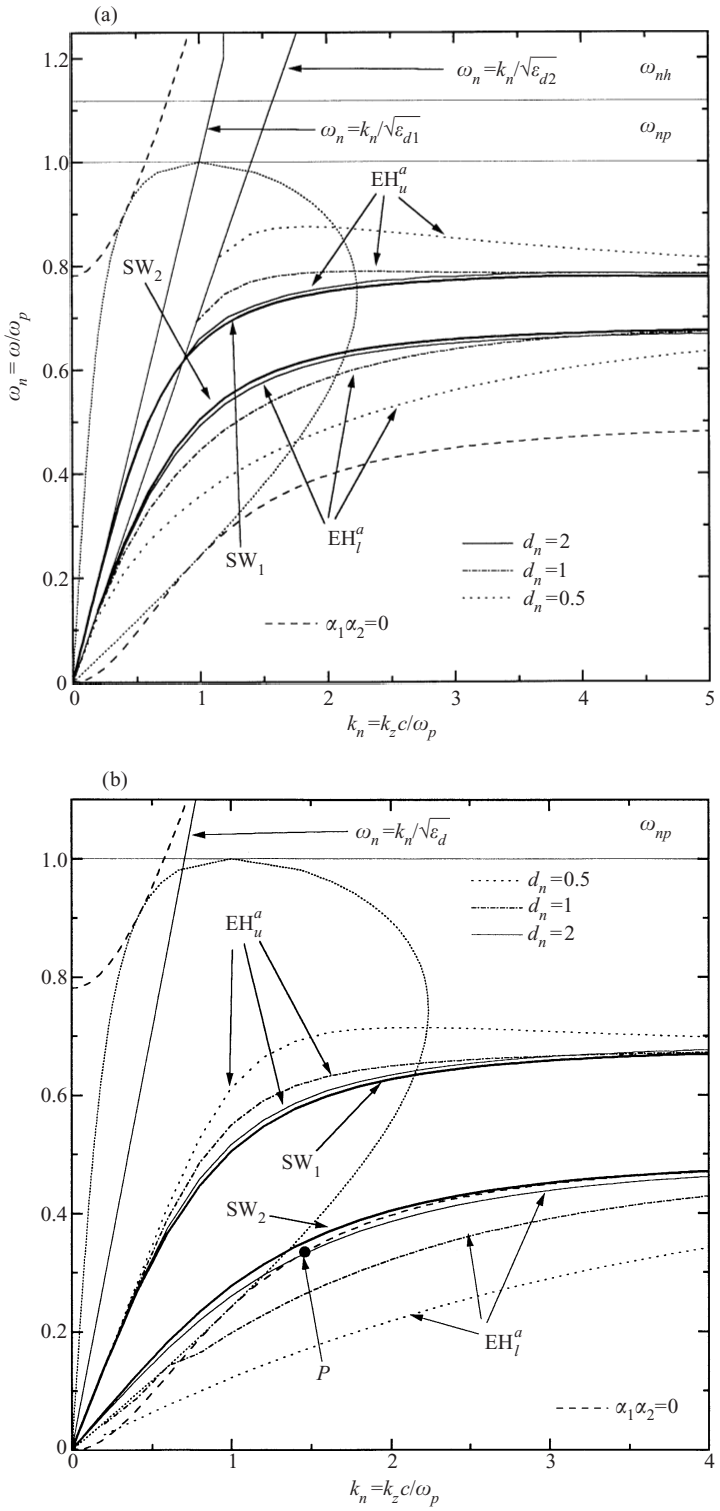


Figure 2. For caption see facing page.

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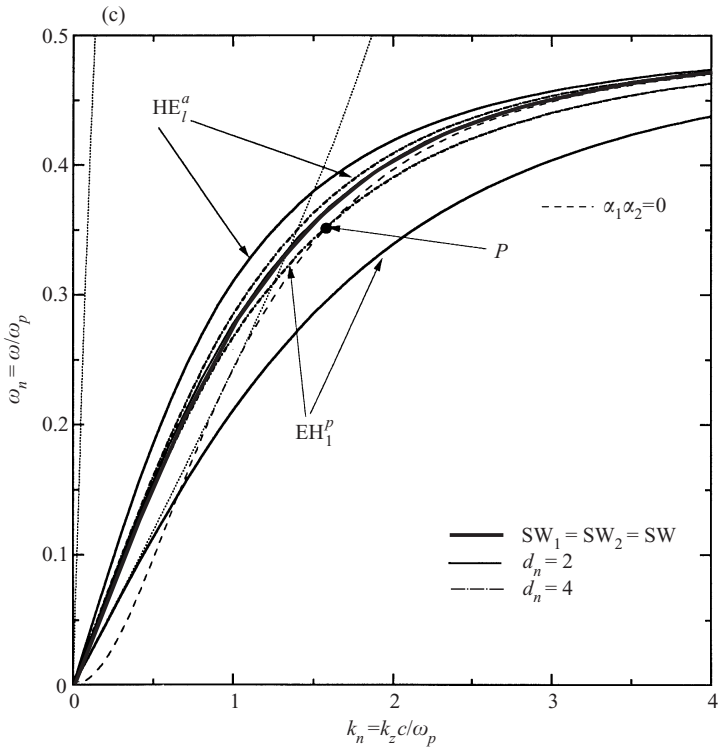


Figure 2. Anisotropic modes in a weakly magnetized plasma: with increasing width and wavenumber, the dispersion curves of anisotropic modes tend to those of the surface waves SW_1 and SW_2: (a) EH_l^a and EH_u^a in a free layer ($\varepsilon_{d1} = 1, \varepsilon_d = \varepsilon_{d2} = 2$); (b) EH_l^a and EH_u^a in a layer on a substrate ($\varepsilon_d = 2$); (c) EH_1^p mode and HE_l^a planar waveguide. $N = \omega_c/\omega_p = 0.5$.

In the regions $\mathrm{Re}\,\alpha_{1,2} > 0$ where the condition

$$1 \ll \alpha_{1,2} d \tag{1}$$

is satisfied with the increasing layer width d_n or wavenumber k_n, the term proportional to $\exp[(\alpha_1 + \alpha_2)d]$ in the dispersion equation become very large compared with the other terms, and only it determines the dispersion. It is the product of two factors. The first factor describes the propagation of the surface wave SW_1 (Fig. 2) that would propagate if only the first interface existed and was a half-space interface between plasma and dielectric or metal screen. The second factor describes the propagation of the surface wave SW_2 (Fig. 2) that would propagate if only the second interface existed and was a half-space interface between plasma and dielectric or metal screen. So, in the regions with $\mathrm{Re}\,\alpha_{1,2} > 0$, with increasing layer width and wavenumber, the dispersion curve of the anisotropic modes tends to the dispersion curve of the surface modes. That is why the anisotropic modes that propagate in the regions of surface waves in a weakly magnetized plasma have a surface character and the same asymptotic frequencies as the surface modes SW_1 and SW_2 from which they originate.

Note that this does not occur in the cases when the dispersion curves of the anisotropic modes leaves the regions with $\mathrm{Re}\,\alpha_{1,2} > 0$. For a weakly magnetized plasma, this happens with dispersion curves of the EH_1^p mode in a planar waveguide

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and of the EH_l^a mode in a layer on a substrate (see Fig. 2). Although the dispersion curves of these modes have the same asymptotic frequencies as the surface wave SW_2, these modes propagate in the region of pseudosurface waves. Here they do not remain surface waves and acquire a volume character. For a strongly magnetized plasma, with increasing wavenumber, both anisotropic modes go into the region of pseudosurface waves, where the condition $\mathrm{Re}\,\alpha_{1,2} > 0$ is not fulfilled. In this case, the dispersion curve of the surface modes SW_1 and SW_2 is bounded. So, in a strongly magnetized plasma at large wavenumbers k_n, there are no surface waves (Ivanov et al. 1998), and consequently at such wavenumbers, comparison of the dispersion curves of the anisotropic modes with those of the surface waves is impossible.

It is clear from Fig. 2 that with increasing layer width d_n, the dispersion curves of anisotropic modes tend to the dispersion curves of surface waves, where this is possible.

An increase in the dielectric constant ε_d of the bounding dielectric causes a decrease in the asymptotic frequency of the anisotropic modes in a weakly magnetized plasma. We have found that for large values of $\varepsilon_d \geqslant \varepsilon_d \approx 1 + 4/N^2$, a gap occurs in the dispersion curves of anisotropic modes in a free layer and a layer on a substrate.

4. Distributions of energy and the Poynting vector of the waves

The energy and the power flow are given by the classic formula for the time-averaged energy density and the Poynting vector (Landau and Lifshitz 1960):

$$U = \frac{1}{16\pi}\left[\frac{d(\omega\varepsilon)}{d\omega}\mathbf{E}\cdot\mathbf{E}^* + \frac{d(\omega\mu)}{d\omega}\mathbf{H}\cdot\mathbf{H}^*\right], \tag{2a}$$

$$\mathbf{S} = \frac{c}{8\pi}\,\mathrm{Re}(\mathbf{E}\times\mathbf{B}^*). \tag{2b}$$

It is interesting to analyse the distributions of the energy along the dispersion curves for different anisotropic modes.

For the free layer, two anisotropic waves have particular distributions. Therefore we shall study them in detail. We begin with a weakly magnetized plasma. In an asymmetric layer, the distributions for the EH_u^a and EH_l^a modes show their origin from surface waves. The energy density and the Poynting vector distributions of the EH_u^a mode, the asymptotic frequency of which is determined by ε_{d1} ($\varepsilon_{d1} < \varepsilon_{d2}$), are concentrated on the boundary with ε_{d1} (the right-hand side of Fig. 3a). The energy density and the Poynting vector distributions of the EH_l^a mode are concentrated on the boundary with ε_{d2} (the left-hand side of Fig. 3a); here and further on, $U_n = U/U_{\max}$. The distributions of energy and the Poynting vector have different signs.

Both distributions of the anisotropic modes in a symmetric layer (Fig. 3b) have clearly expressed surface character, and their pictures are similar to the superposition of pictures in an asymmetric slab, i.e. of EH_u^a and EH_l^a in Fig. 3(a).

When the anisotropic modes tend to their anisotropic frequencies, the main part of the energy remains in the plasma. This part is a function only of the normalized dielectric constant ε_{DL} (Fig. 4a).

There is a difference between the evolution of the distributions of the energy of the EH_u^a and EH_l^a anisotropic modes in a free asymmetric layer (see Figs 4b,c). The EH_u^a mode originates from the surface wave SW_1 that propagates on the interface with a dielectric with ε_{d1}. This surface wave determines the asymptotic frequency of the EH_u^a wave. It can be seen from Fig. 4(b) that at small k_n (small ω_n), the energy of

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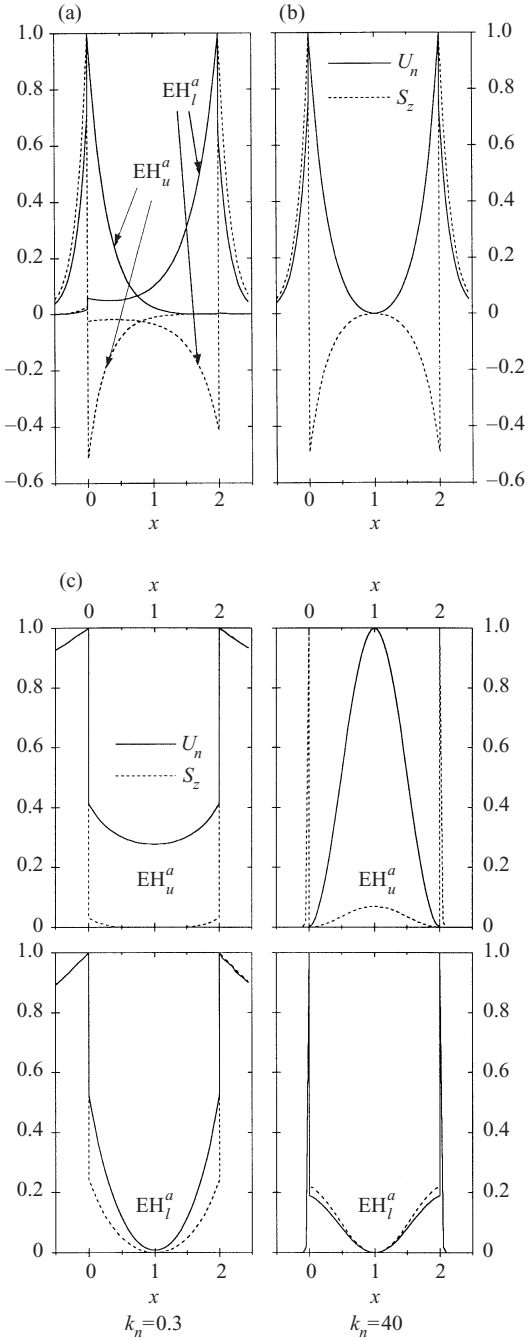


Figure 3. The distribution of the energy (solid lines) and the Poynting vector (dashed lines) of the anisotropic waves (EH_u^a and EH_l^a modes) in a free layer. (a,b) Weakly magnetized plasma ($N = 0.5$, $k_n \approx 5$): (a) an asymmetric layer; (b) a symmetric layer (only the distribution of EH_l^a is plotted, because the distribution of EH_u^a is very similar). (c) Strongly magnetized plasma ($N = 1.5$): evolution of distributions of energy density and the Poynting vector for the EH_l^a and EH_u^a modes.

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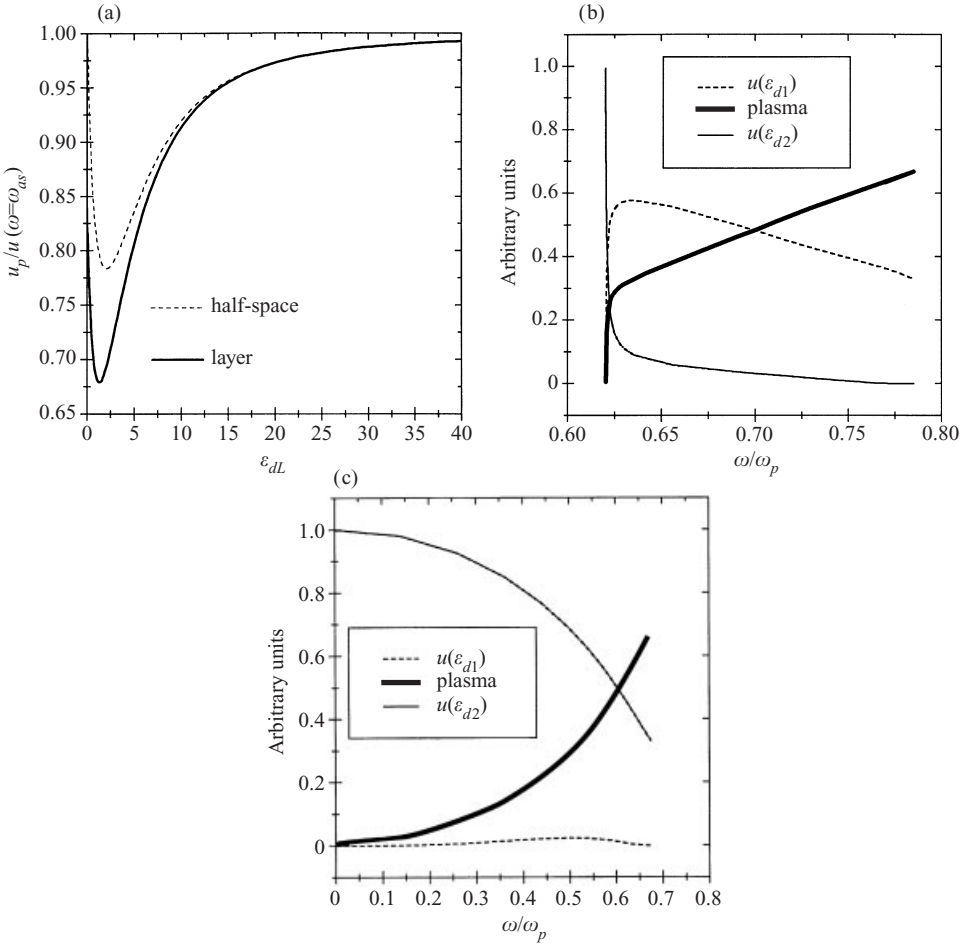


Figure 4. The variation of the energy in a free layer in a weakly magnetized plasma ($N = 0.5$): (a) the part of energy in the plasma layer u_p/u for anisotropic modes; (b) variation of the distribution of the energy along the dispersion curve and (c) the distribution of the energy along the dispersion curve for EH_l^a mode in an asymmetric free layer ($\varepsilon_{d1} = 1, \varepsilon_{d2} = 2, d_n = 2$) (see Fig. 2a). Here $u(\varepsilon_{d1}) = u^{-1}\int_{-\infty}^{0} U\,dx$, $u(\varepsilon_{d2}) = u^{-1}\int_{d}^{\infty} U\,dx$ and $u_p = u^{-1}\int_{0}^{d} U\,dx$, with $u = \int_{-\infty}^{\infty} U\,dx$.

this mode is concentrated in the dielectrics – first in the dielectric with ε_{d2} and then in the dielectric with ε_{d1} ($\varepsilon_{d2} > \varepsilon_{d1}$). With increasing frequency, the energy rapidly leaves these dielectrics and concentrates in the plasma. Taking into consideration the distributions at small k_n (small ω_n), from Fig. 3(a), we can conclude that the energy goes from the boundary with the dielectric ε_{d2} (it is concentrated to the right of this boundary, i.e. in the dielectric ε_{d2}) to the boundary with the dielectric ε_{d1} (it is concentrated to the left of this boundary, i.e. the plasma). So, along the dispersion curve, the energy goes from one boundary to another. As can be seen from Fig. 4(c), this does not happen with the lower anisotropic mode EH_l^a, for which the energy remains in the boundary with the dielectric ε_{d2} and passes from dielectric to plasma.

We should like to mention here that at large k_n, the phase velocity of the elec-

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tromagnetic wave becomes very small and the wave is almost a potential one. The wave cannot be radiated from the plasma, and remains within it.

In a strongly magnetized plasma, the behaviour of both anisotropic modes is different compared with a weakly magnetized plasma. At small values of the wave vector, they have surface character – Fig. 3(c) ($k_n = 0.3$). The energy and the Poynting vector are concentrated predominantly in the dielectric, where they decay very slowly. With increasing wavenumber, both modes enter the region of pseudosurface waves, and consequently acquire a volume character – Fig. 3(c) ($k_n = 40$). In the plasma, the volume character of the EH_u^a mode is more clearly expressed. Note that the signs of the distribution of the energy density and the Poynting vector are opposite in a weakly magnetized plasma, but the same in a strongly magnetized plasma. An exception is the EH_u^a mode, which at large wavenumber becomes a backward wave.

For a strongly magnetized plasma, the energy remains entirely in the plasma when the anisotropic modes go to the asymptotic frequencies. For a weakly magnetized plasma, a small part of the energy remains in the dielectric.

For a grounded layer with a weakly magnetized plasma, at the beginning of the dispersion curve of the EH_u^a mode, the energy is entirely in the dielectric, and with increasing frequency it goes into the plasma. The distribution of the energy in the plasma and in the dielectric along the dispersion curve is almost the same as that for the EH_l^a mode in a free layer shown in Fig. 4(c). When the mode tends to its asymptotic frequency, the main part of the energy remains in the plasma. (Compare in Fig. 5(a) the transverse distributions of energy density and the Poynting vector for the EH_u^a mode for small wavenumber $k_n = 0.3$ and large wavenumber $k_n = 40$.) This part is only a function of the normalized dielectric constant ε_d, and is the same as plotted in Fig. 3(c) for modes in a free layer. Along the whole dispersion curve, the energy for the EH_l^a mode lies entirely in the plasma – it can be seen from the dispersion curve (Fig. 2b) that the phase velocity of the wave is very small compared with the velocity of light in the dielectric. From the transverse distributions in Fig. 5(a), it is easy to see the volume character that the EH_l^a mode acquires where at large values of the wavenumber it propagates in the region of pseudosurface waves.

In a strongly magnetized plasma, the distribution for the EH_l^a mode is the same. The EH_u^a mode is similar to EH_u^a in a weakly magnetized plasma, with the difference that the whole of the energy goes into the plasma when the mode tends to its asymptotic frequency. Both modes at small wavenumber have a surface character, and with increasing wavenumber, they enter the region of pseudosurface waves and become volume waves (see the transverse distributions in Fig. 5(b) at $k_n = 40$).

For a planar waveguide in the lower anisotropic region, there are, as we have said, two anisotropic modes: HE_l^a and EH_1^p. We should like to mention that the EH_1^p mode is only traditionally mentioned as a plasma mode. Its origin and behaviour are different from the other plasma modes. This mode propagates in the complex zone, and has surface character there (with increasing width of the waveguide, its dispersion curve tends to that of SW_2). In comparison, the next plasma mode EH_2^p has quite different behaviour – it does not enter the complex zone, and along the whole dispersion curve, it has a volume character.

So, one can say that the anisotropic mode EH_1^p sometimes (for given parameters of the system) may leave the complex zone (not that the first plasma mode enters the complex zone), and then plays the role of the first plasma mode.

At small wavenumber in the complex zone, the HE_l^a and EH_1^p modes have a

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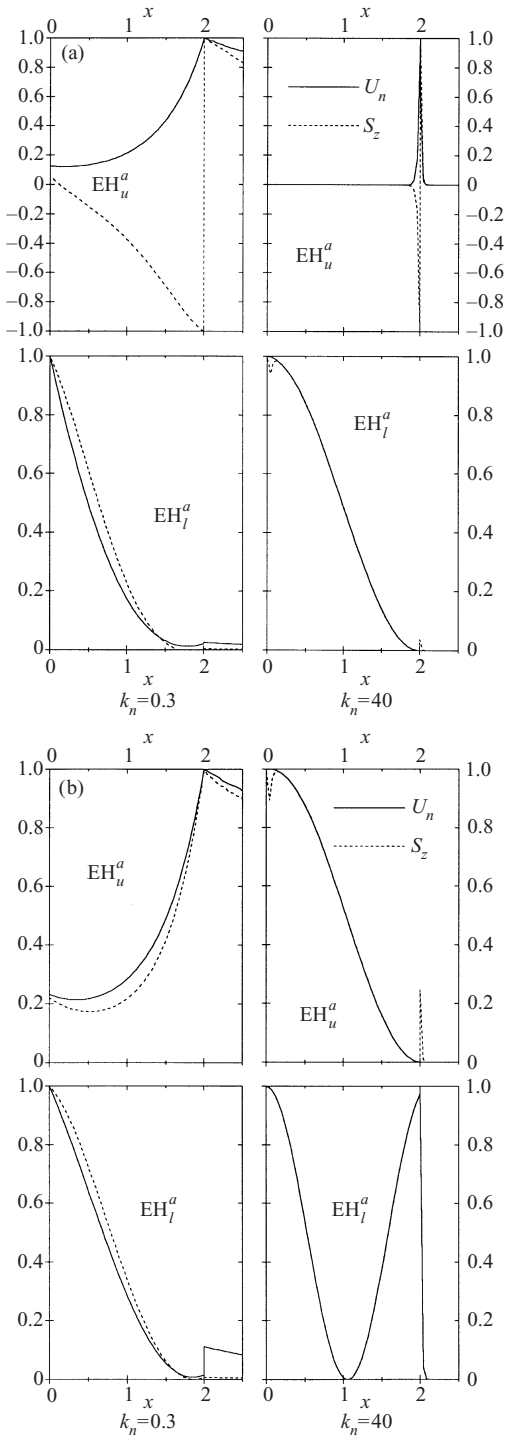


Figure 5. (a) The transverse distributions of energy density (solid lines) and the Poynting vector (dashed lines) in a weakly magnetized plasma in a grounded plasma layer for the EH_l^a and EH_u^a modes. (b) The transverse distributions of energy density (solid lines) and the Poynting vector (dashed lines) in a strongly magnetized plasma in a free plasma slab for the HE_l^a and HE_u^a modes.

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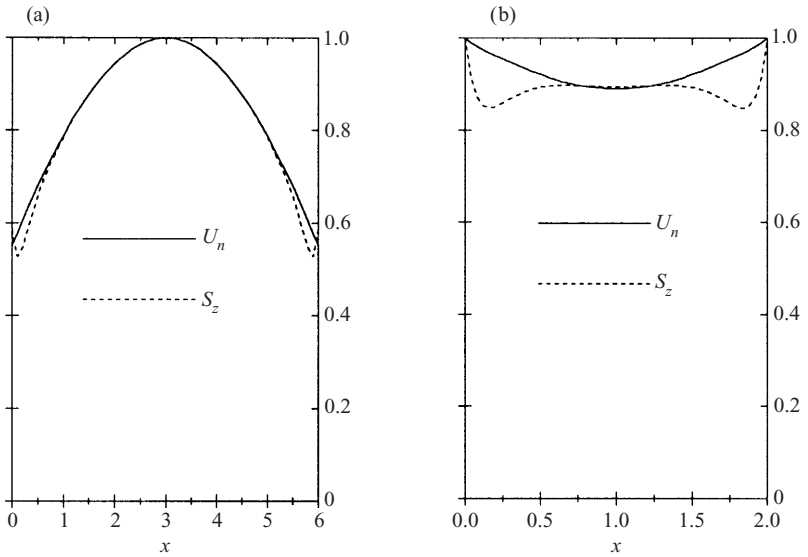


Figure 6. The transverse distributions of energy density (solid lines) and the Poynting vector (dashed lines) in a planar waveguide for the HE_l^a mode at $k_n = 5$ for (a) a strongly magnetized plasma ($N = 1.5$) and (b) a weakly magnetized plasma ($N = 0.5$).

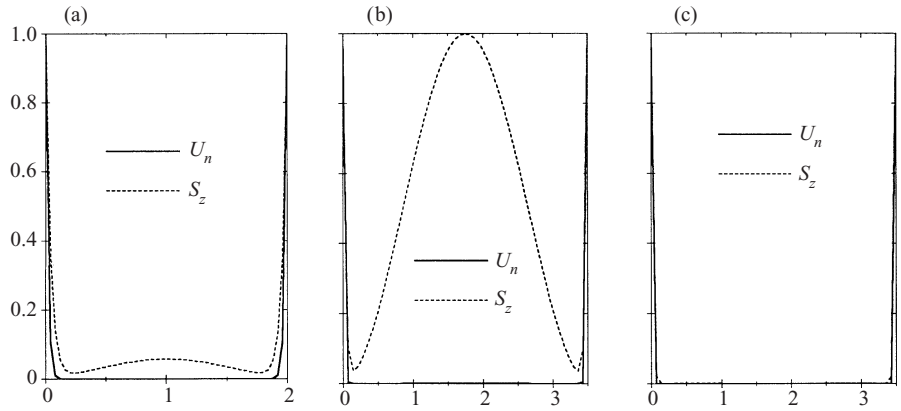


Figure 7. The transverse distributions of energy density (solid lines) and the Poynting vector (dashed lines) in a planar waveguide for (a) the HE_u^a mode at $d_n = 2$, (b) the HE_u^a mode at $d_n = 3.5$ and (c) the EH_1^w mode at $d_n = 3.5$ (the line of S_z is so close to the metal wall that it is not seen on the graph).

surface character. In a strongly magnetized plasma, with increasing wavenumber, they enter the region of pseudosurface waves and acquire a volume character (see Fig. 6(a) at $k_n = 5$ for HE_l^a). The same happens with the EH_1^p mode in a weakly magnetized plasma, which at the point P (see Fig. 2c) enters the region of pseudosurface waves. In this region, the EH_1^p mode has a volume character. The HE_l^a mode remains in the region of surface waves, but its transverse constant α_2 is small, and since this constant defines the exponential decrease, the distributions are almost constant over the cross-section (again see Fig. 6(b) at $k_n = 5$). This is an important

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fact with regard to creating and sustaining a plasma by travelling electromagnetic waves.

At relatively small widths of the waveguide (all waveguide modes propagate entirely in the region of waveguide modes), the distribution of the energy and the Poynting vector at the beginning of the dispersion curve of the HE_u^a mode have a surface character (Fig. 7a), and with increasing wavenumber, these distributions becomes similar to a volume one. With increasing width of the waveguide, the EH_1^w mode enters the region of anisotropic waves (for details, see Ivanov and Nikolaev 1998). Now the HE_u^a mode starts at $k_n \neq 0$, and only the energy density has a surface distribution (Fig. 7b).

At the same time, the EH_1^w mode at small wavenumbers in the region of anisotropic modes has a surface character for both distributions. Its distribution takes the form of the anisotropic HE_u^a mode (compare Figs 7(a) and (c)). With increasing wavenumber, this mode enters the region of waveguide modes and acquires a volume distribution typical of the waveguide modes.

5. Conclusions

There are two regions of existence of anisotropic waves: upper ($\omega_n > \omega_{nh}$) and lower ($\omega_n < \omega_{nh}$). In the upper anisotropic region, anisotropic waves exist only in a planar waveguide and have HE character. In the lower anisotropic region, in each of the considered structures, two anisotropic waves exist. They originate from the two surface modes SW_1 and SW_2 that propagate at two half-space interfaces between plasma and dielectric or metal screen. In a free layer and in a layer on a substrate, they have EH character and are denoted as upper EH_u^a and lower EH_l^a modes. In a planar waveguide, the first anisotropic mode is HE_l^a and the second is the mode that is traditionally regarded as the plasma wave EH.

Anisotropic modes start at the origin of the (ω, k_z) plane (with the exception of the EH_u^a mode in an asymmetric free layer and the HE_u^a mode in a planar waveguide).

The distributions of the energy and the Poynting vector usually change along the dispersion curves. At the beginning, energy is in the dielectric, and along the dispersion curve it goes into the plasma. For a strongly magnetized plasma, it goes entirely into the plasma, while for a weakly magnetized plasma, part of it remains in the dielectric.

Acknowledgement

This work was supported by the National Fund for Scientific Research under Grant F-826.

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