TERAHERTZ AND SOFT X RAYS RADIATION FROM SUDDENLY CREATED PLASMA LAYER

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We study in this paper the effect of shock excitation of leaky and surface modes by the *p*-polarized electromagnetic wave incident on the rapidly ionized gaseous or solid layer. The amplitudes of these modes are calculated through the use of Laplace transforms. The results obtained show the potentialities for applying of the phenomenon of leaky modes excitation for generation (at corresponding density of ionized medium) of terahertz and soft x rays radiation.
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1. INTRODUCTION

The phenomena of ionization-induced spectrum conversion of electromagnetic wave attracts the researchers attention in connection with the problems of transformation and generation of radiation in some hardly accessible frequency bands (THz, UV, X-ray). The most theoretical works concerned these problems dealt with the wave propagation in quasi-homogeneous time-varying plasma (created by an external ionization source or by the wave itself) or with the reflection of the normal-incident wave by moving ionization front or suddenly created plasma [1]. It was considered also the effects of "bulk-to-surface" mode conversion (with frequency downshifting) at sudden [2] or slow (adiabatic) [3] creation of plasma layers. Frequency upshifting of re-radiated waves caused by excitation (and following adiabatic conversion) of Langmuir oscillations in plasma layers was analyzed only for the case of slow ionization [4], when this effect occurs to be depressed strongly due to collision or radiation damping of this oscillations.

We study in this paper the effect of shock excitation of natural (leaky and surface) electromagnetic modes by the *p*-polarized electromagnetic wave incident on the rapidly ionized gaseous or solid layer. The model considered is based on the following assumptions: (i) the ionization leads to the formation of homogeneous plasma layer with Langmuir frequency which is much greater than the incident wave frequency, (ii) the time of ionization (unlike the cases considered in [4, 5]) is much smaller than the period of plasma oscillations, (iii) the layer thickness is much smaller than the space scale of the incident wave in plasma. It has been found that besides the known phenomenon of the symmetric surface waves excitation [2], the rapid ionization leads to effective generation of low-frequency antisymmetric surface waves and symmetric leaky waves with strongly upshifted (Langmuir) frequency.

2. FORMULATION OF THE PROBLEM AND BASIC EQUATIONS

Let the electromagnetic field before plasma creation ($t<0$) is given in Cartesian coordinates as a plane p -polarized wave of frequency ω_0

$$B_0=z_0 B_0 \exp(-i\omega_0 t+ik_0\cos\theta\ x+ik_0\sin\theta\ y)\ ,$$

$$E_0=B_0(-x_0\sin\theta+y_0\cos\theta)\times \exp(-i\omega_0 t+ik_0\cos\theta\ x+ik_0\sin\theta\ y)\ ,$$

incident at the angle θ on the infinite layer of transparent (unionized at $t<0$) medium, occupying the space between the planes $x=\pm d$. Here $k_0=\omega_0/c$ is the free-space wave number.

At the time instant $t=0$ the layer is ionized suddenly by some external source (for example, high intensity laser pulse), so that the plasma density within the layer grows instantly from 0 to N =const. The approximation of instant plasma creation, supported by a number of theoretical and experimental studies [1] is valid if the electron density rise time is much shorter then the period of plasma oscillation. The spatiotemporal evolution of the electromagnetic field after the plasma creation (at $t>0$) is governed by Maxwell's equations

$$\frac{\partial E_y}{\partial x}-ik_0\sin\theta\ E_x=-\frac{1}{c}\frac{\partial B_z}{\partial t}\ , \qquad (1)$$

$$ik_0\sin\theta\ B_z=\frac{4\pi}{c}j_x+\frac{1}{c}\frac{\partial E_x}{\partial t}\ , \qquad (2)$$

$$-\frac{\partial B_z}{\partial x}=\frac{4\pi}{c}j_y+\frac{1}{c}\frac{\partial E_y}{\partial t}\ , \qquad (3)$$

with current density equations for the cold collisionless plasma

$$\frac{\partial j_x}{\partial t}=\frac{\omega_p^2}{4\pi}E_x\ ,\ \frac{\partial j_y}{\partial t}=\frac{\omega_p^2}{4\pi}E_y\ . \qquad (4)$$

Here $\omega_p=\sqrt{4\pi e^2 N/m}$ is the electron plasma (Langmuir) frequency, j_x and j_y are the x and y components of the electron current density.

Initial conditions (at $t=0$) for the field and electron current are the temporal continuity of the fields E_x , E_y , B_z and zero value of the current density $j_x(0)=j_y(0)=0$ (newly created electrons have zero velocity at $t=0$). Boundary conditions (at $x=\pm d$) are spatial continuity of E_y and B_z .

Method of the solution is Laplace transform of Maxwell's and current density equations:

$$L[f(x,y,t)]=\int_0^\infty f(x,y,t)\exp(-st)\,dt\ ,$$

where s is Laplace variable, f is a component of the fields or current density.

3. LAPLACE TRANSFORMS

Applying Laplace transform to equations (1)-(4) gives the following equations for the electromagnetic field and current density transforms ($b=L[B_z]$, $e_y=L[E_y]$, $e_x=L[E_x]$, $J_x=L[j_x]$, $J_y=L[j_y]$):

$$\frac{\partial^2 b}{\partial x^2}-\frac{\omega_p^2+\omega_0^2\sin^2\theta+s^2}{c^2}b=$$
$$¿\frac{i\omega_0 s-s^2-\omega_p^2}{sc^2}B_0\exp\left(ik_0\cos\theta\ x+ik_0\sin\theta\ y\right.$$

$$e_x=$$
$$¿\frac{s}{\omega_p^2+s^2}\sin\theta\left(i\omega_0 b-B_0\exp(ik_0\cos\theta\ x+ik_0\sin\theta\right.$$

$$e_y=$$
$$¿\frac{s}{\omega_p^2+s^2}\left(\cos\theta B_0\exp(ik_0\cos\theta\ x+ik_0\cos\theta\ y)-\right.$$

$$J_x=\frac{\omega_p^2}{4\pi s}e_x\ ,\ J_y=\frac{\omega_p^2}{4\pi s}e_y\ .$$

Boundary conditions for the Laplace transforms are spatial continuitiy of b and e_y at $x=\pm d$.

The solution for the transform of the magnetic field inside the plasma ($|x|<d$) has the form

$$\frac{\omega_p^2+s^2-i\omega_0 s}{s\,(\omega_p^2+\omega_0^2+s^2)}\exp(ik_0\cos\theta\ x)+$$
$$¿$$
$$b=B_0\{¿+D_1\cosh(\lambda_2 x)+D_2\sinh(\lambda_2 x)\}\exp(i$$
$$¿$$

where

$$D_1=-i\frac{\omega_p^2(\omega_p^2+s^2)}{s(s+i\omega_0)(\omega_p^2+\omega_0^2+s^2)}\times¿$$
$$¿\times\frac{\left(\omega_0 c\lambda_1\cos(k_0\cos\theta\ d)+s^2\cos\theta\ \sin(k_0\cos\theta\right.}{\left((\omega_p^2+s^2)c\lambda_1\cosh(\lambda_2 d)+s^2 c\lambda_2\sinh(\lambda_2 d)\right)}$$

$$D_2=-\frac{\omega_p^2(\omega_p^2+s^2)}{s(s+i\omega_0)(\omega_p^2+\omega_0^2+s^2)}\times¿$$
$$¿\times\frac{\left(s^2\cos\theta\ \cos(k_0\cos\theta\ d)-\omega_0 c\lambda_1\sin(k_0\cos\theta\right.}{\left((\omega_p^2+s^2)c\lambda_1\sinh(\lambda_2 d)+s^2 c\lambda_2\cosh(\lambda_2 d)\right)}$$

$$\lambda_1=\sqrt{\frac{\omega_0^2\sin^2\theta+s^2}{c^2}}\ ,\ \lambda_2=\sqrt{\frac{\omega_p^2+\omega_0^2\sin^2\theta+s^2}{c^2}}\ .$$

4. MAGNETIC FIELD IN THIN LAYER

If the following inequalities are fulfilled

$$k_0 d<<1\ ,\ \frac{\omega_p}{c}d<<1\ ,\ \omega_p>>\omega_0\sin\theta\ ,$$

the magnetic field inside the layer can be written in the form $B_z=(B_{sym}+B_{asym})\exp(ik_0\sin\theta\ y)$,

where symmetric term B_{sym} does not depend on *x*, antisymmetric term $B_{asym}\sim x$ and

$$B_{sym}=A_1\exp(-i\omega_0 t)+A_2\exp(i\omega_{s1}t)+$$
$$+A_3\exp(-i\omega_{s1}t)+A_4\exp(i\omega_{l1}t)+A_5\exp(i\omega_{l2}t),$$

$$B_{asym}=k_0\cos\theta\ x\times¿$$
$$¿\times\left(B_1\exp(-i\omega_0 t)+B_2\exp(i\omega_{s2}t)+B_3\exp(-i\omega_{s2}t)\right)\ .$$

The waves with the frequencies $\pm\omega_{s1,2}$ are the surface waves propagating in the forward ($+y$) and backward ($-y$) directions, respectively. The waves with the frequencies $\omega_{l1,2}$ are the leaky waves emitted into vacuum ($\mathrm{Im}(\omega_{l1,2})>0$). The amplitudes of the these waves are determined by the reduces of D_1 and D_2 at the corresponding poles ($s=i\omega$).

The amplitudes of symmetric and antisymmetric parts of the basic wave with the frequency ω_0 are

$$A_1=B_0\frac{(\omega_p^2-\omega_0^2)\cos\theta\ (1+ik_0 d\cos\theta)}{(\omega_p^2-\omega_0^2)\cos\theta+ik_0 d\,(\omega_p^2-\omega_0^2\cos^2\theta)}\ ,$$

$$B_1=-iB_0\frac{\omega_p^2-\omega_0^2}{\omega_0^2}\ .$$

The frequencies and amplitudes of symmetric surface waves are

$$\omega_{s1}=\omega_0\sin\theta\left(1-\sin^2\theta\ k_0^2 d^2/2\right),$$

$$A_2=B_0\frac{\omega_p^2 k_0^2 d^2\sin^4\theta}{2\,(\omega_p^2+\omega_0^2\cos^2\theta)\,(1+\sin\theta)}\ ,$$

$$A_3=B_0\frac{\omega_p^2 k_0^2 d^2\sin^4\theta}{2\,(\omega_p^2+\omega_0^2\cos^2\theta)\left(1-\sin\theta+\sin^3\theta\ k_0^2 d^2/2\right)}$$
.

The frequencies and amplitudes of antisymmetric surface waves are

$$\omega_{s2}\ =\ \omega_p\sqrt{k_0 d\sin\theta}\ <<\ \omega_0\sin\theta\ ,$$

$$B_2=B_3=iB_0\frac{\omega_p^2}{2\omega_0^2}\ .$$

The frequencies and amplitudes of symmetric leaky waves are

$$\omega_{l1}=\omega_p+i\omega_0\sin^2\theta\ k_0 d/2\ ,$$

$$A_4=-iB_0\frac{\omega_p\ k_0 d\ \sin^2\theta}{2\left(\omega_p+\omega_0\right)}\ ,$$

$$\omega_{l2}=-\omega_p+i\omega_0\sin^2\theta\ k_0 d/2\ ,$$

$$A_5=-iB_0\frac{\omega_p k_0 d\sin^2\theta}{2\left(\omega_p-\omega_0-i\omega_0\sin^2\theta\ k_0 d/2\right)}\ .$$

The leaky waves are emitted into vacuum under the angles

$$\theta_{l1,2}=\pm\arcsin\left(\frac{\omega_0}{\omega_p}\sin\theta\right)\ .$$

5. DISCUSSION

The phenomenon of leaky wave excitation may have important applications for development of X-ray and THz lasers.

For example, if $N\sim10^{23}\ cm^{-3}$ (solid density, multiple ionized plasma), the basic frequency $\omega_0\sim2\times10^{15}\ s^{-1}$, $d\sim10$ nm , $\sin\theta\sim1$ we find, that the wavelength of leaky wave $\lambda\sim100$ nm is in soft x rays band. The intensity of x rays radiation in this case is $I\sim10^{-3}I_0$, where I_0 is the intensity of incident (basic) radiation.

If $N\sim10^{16}\ \mathrm{sm}^{-3}$ (low density gaseous plasma), the basic frequency $\omega_0\sim2\times10^{11}\ s^{-1}$, $d\sim30\ \mu m$, $\sin\theta\sim1$ we find, that the wavelength of leaky wave $\lambda\sim300\ \mu m$ is in THz band. The intensity of THz radiation in this case is $I\sim10^{-4}I_0$.

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ТЕРАГЕРЦОВОЕ И МЯГКОЕ РЕНТГЕНОВСКОЕ ИЗЛУЧЕНИЕ, СОЗДАВАЕМОЕ БЫСТРО ИОНИЗОВАННЫМ СЛОЕМ

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В настоящей работе исследуется эффект ударного возбуждения поверхностных и вытекающих волн *p*-поляризованной электромагнитной волной, падающей на быстро ионизируемый газообразный или твердотельный слой. С помощью преобразования Лапласа рассчитаны амплитуды этих волн. Полученные результаты указывают на возможность использования эффекта возбуждения вытекающих волн для генерации (при соответствующих плотностях ионизируемой среды) терагерцового и мягкого рентгеновского излучения.

ТЕРАГЕРЦОВЕ І М'ЯКЕ РЕНТГЕНІВСЬКЕ ВИПРОМІНЮВАННЯ, СТВОРЮВАНЕ ШВИДКО ІОНІЗОВАНИМ ШАРОМ

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У даній роботі досліджується ефект ударного збурення поверхневих і хвиль, що витікають, *p*-поляризованою електромагнітною хвилею, що падає на швидко іонізуємий газоподібний або твердотільний шар. За допомогою перетворення Лапласа розраховані амплітуди цих хвиль. Отримані результати вказують на можливість використання ефекту збудження хвиль, що витікають, для генерації (при відповідній густині середовища, що іонізується) терагерцового і м'якого рентгенівського випромінювання.