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Terahertz radiation from interaction between an electron beam and a planar surface plasmon structure*

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The possibility of an electron beam exciting surface plasmons in conducting metal is discussed in this paper. A planar perfect-structure with subwavelength holes is proposed. The phenomenon that mimicking surface plasmon waves can be excited and amplified by an electron beam is proved theoretically and numerically. The mechanism of transmission through a subwavelength hole array is exploited to enhance the interaction between the electron beam and the mimicking surface plasmons.

Keywords: surface plasmon, electron beam
PACC: 4180D, 7320J

1. Introduction

A surface plasmon (SP) is the coherent fluctuation of the electronic charges on a metal boundary and can be excited by electrons and light,[1] at infrared and light frequencies. Metals can support SP modes, but a perfect conductor is an exception. However, Pendry *et al*[2] proposed that the formation of a perfect conductor also supported SP modes with an array of holes on the surface, called a mimicking surface plasmon (MSP) which has been verified experimentally in the microwave region.[3] The SP mode in a perfect-conducting metal or semiconductor has become one of the most attractive topics and has been investigated intensively both in theory and in experiment by using electromagnetic waves ranging from near-infrared to visible light.[4−10] It has been established that the resonant excitation of an SP creates a huge electric field at the surface which forces the light to pass through the holes, giving rise to a very high transmission coefficient.[5] Utilizing the MSP, some active electronic devices including a THz modulator, a switching device, etc have been developed.[11,12] Both the SP and MSP may have significant applications in areas including physics, optics, electronics, etc, and they even can open a new area for terahertz science and technology. However, till recently both of them have been applied mainly to positive component devices rather than radiation sources. In the present paper we research the possibility of the SP or the MSP being used to generate and amplify radiation. This is significant, especially for the terahertz frequency regime, for in this frequency regime the problem associated with the desired radiation sources remains to be solved. Until now, in this frequency regime, vacuum electronic technology has still played an important role in the high power radiation sources with a high efficiency. Therefore, the present paper aims to find an appropriate way to combine the vacuum electronics with photonics by means of plasmon waves, for they are slow waves and hence an interaction between the electron beam and plasmon wave may possibly take place.

We indicate that the SP can interact with the electron beam efficiently under a certain condition. The interaction between the electron beam and MSP has also been explored both theoretically and numerically. The rest of the present paper is organized as follows. In Section 2, theoretical analyses including dispersion equations and a growth rate curve are described to discuss the condition of the interaction between an SP and the electron beam. In Section 3 the dispersion relation and growth rate of effective MSP mode are presented. In Section 4 are shown the surface plasmon modes excited by the electron beam passing just above the surface of the structure. Finally, the interaction between the electron beam and

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the SP wave based on computer simulation is presented in Section 5.

2. Theoretical analysis of the interaction between an SP and the electron beam

As mentioned above, an SP on a metal surface can be excited by electrons and light. The SP can be excited by an electron beam when the electron beam passes closely along the surface of the metal. A schematic diagram of the interaction between the electron beam and the SP is shown in Fig.1. The eigenvalue approach is used to deduce the dispersion equation. The surface plasmon is assumed to be excited, and then the field components can be obtained by solving the Helmholtz equations. Considering the boundary conditions, the dispersion equation is derived as follow:

$$\frac{k_{x1}}{k_{x2}}\left(1-\frac{\omega_{\mathrm{psilver}}^2}{\omega^2}\right)=-\frac{(1+\alpha)+\mathrm{i}\cdot 2\sqrt{\alpha}\cot\left(k_{x2}\sqrt{\alpha}(b-a)\right)+(\alpha-1)\mathrm{e}^{\mathrm{i}k_{x2}\cdot a}}{(1+\alpha)+\mathrm{i}\cdot 2\sqrt{\alpha}\cot\left(k_{x2}\sqrt{\alpha}(b-a)\right)-(\alpha-1)\mathrm{e}^{\mathrm{i}k_{x2}\cdot a}},$$

where $\alpha = 1-\dfrac{\omega_{\mathrm{pe}}^2}{(\omega-k_z v)^2}, k_z = \dfrac{\omega}{v}, k_{x1}^2 = k_z^2 - \varepsilon_1 k_0^2, k_{x2}^2 = k_z^2 - k_0^2, \varepsilon_1 = \varepsilon_0\left(1-\dfrac{\omega_{\mathrm{psilver}}^2}{\omega^2}\right)$, $\omega_{\mathrm{psilver}}$ and ω_{pe} are the plasma frequencies of metal silver and the electron beam respectively: they are related by relation $\omega_{\mathrm{pe}} = 10^{-4}\omega_{\mathrm{psilver}}$. If the imaginary part of the frequency ω, which is known as the growth rate of the SP wave, is higher than the loss of the SP wave in the metal silver, the surface plasmon can be excited and amplified by the electron beam.

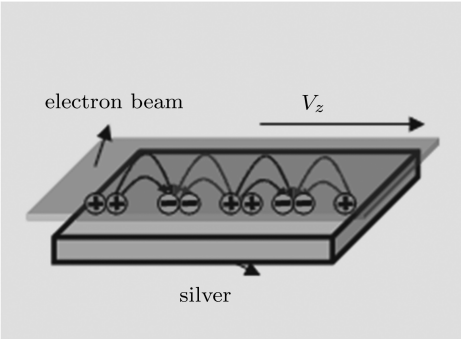


Fig.1. Schematic diagram of the interaction between the SP and an electron beam.

The dispersion and the growth rate of this interaction are drawn in Fig.2. It shows that such an interaction can provide an exponential growth rate according to the data given in Ref.[1]. For silver at 0.6 μm wavelength, the loss of the SP wave in silver is calculated to be 0.133%, which is lower than the growth rate of the SP wave (0.231%). It indicates that the growth rate is much higher than the attenuation coefficient, and then the light can be amplified by the electron beam. However, the density of the electron beam needed is up to 10^6 A/cm^2 and the radiation generated is located in an infrared region.

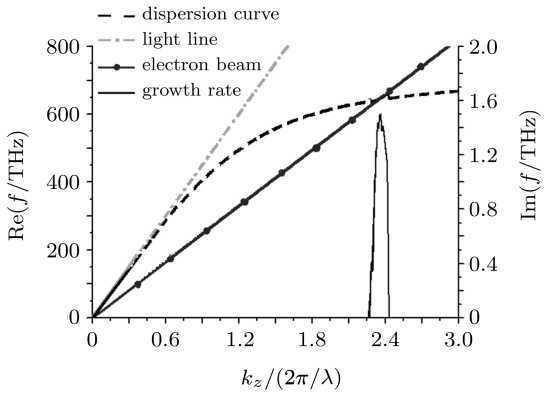


Fig.2. Dispersion and growth rate curves: the black dashed line is the dispersion curve corresponding to the left frequency axis; and the grey solid line is the growth rate curve corresponding to the right frequency axis.

3. Theoretical analysis of MSP and electron beam interaction

In the present work, a new perspective is taken to study theoretically the surface plasmon modes on a structured perfect-conductor. The surface plasmon modes are assumed to be the electromagnetic surface eigenmodes supported by the structured perfect-

conductors. Therefore, in the theoretical analysis the eigenvalue solving approach is used to solve Maxwell's equations with suitable boundary conditions. In this case, due to the fact that the frequency is in a lower terahertz frequency region, the real surface plasmon in metal cannot be excited, and ohmic loss is ignored in this paper.

Figure 3 shows the geometry of an MSP structure of periodical units of a square perfect-conductor with rectangular hole arrays. We consider the case of rectangular holes with size $s \times a$ and period d on a perfect-conductor structure called the MSP structure. In this case, the slow wave structure has rectangular holes. So the fundamental mode TE_{10} is considered because of the least loss in the holes.[2] Using Floquet theory, the field components of E_z and H_y in region I are expressed as

$$\begin{aligned} E_z^{\mathrm{I}} &= \left(A\mathrm{e}^{-\mathrm{i}k_x x} + B\mathrm{e}^{\mathrm{i}k_x x}\right)\sin\left(k_y y\right), \\ H_y^{\mathrm{I}} &= -\mathrm{j}\frac{k_x^{\mathrm{I}}}{\omega\mu_0}\left(A\mathrm{e}^{-\mathrm{i}k_x x} + B\mathrm{e}^{\mathrm{i}k_x x}\right)\sin\left(k_y y\right), \end{aligned} \quad (1)$$

where $k_x^{\mathrm{I}2} = k_y^2 - k_0^2$, $k_y = \pi/s$, s is the width of the hole, k_x and k_y are plane wave vectors at the x- and the y-positions respectively.

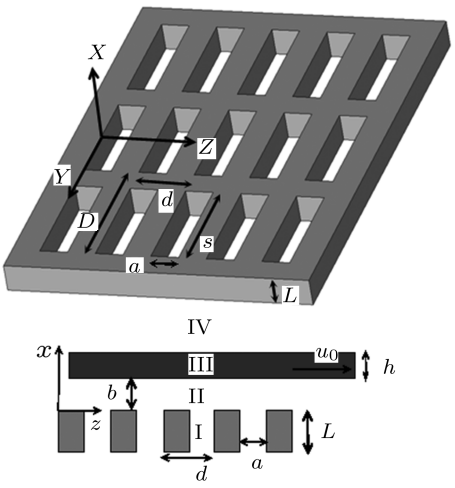


Fig.3. Geometry of the MSP structure: a rectangular-hole array in a perfect metal of thickness L. The periods are d in the z-direction and D in the y-direction, while the sides of the holes are $a = 0.5d$, $s = 2d$, and $d = 0.6$ mm. The distance between the line current with velocity u_0 and the upper surface of the structure is z_0.

In region II, TM-polarized surface waves are considered as follows:

$$E_x^{\mathrm{II}} = \sum_{p=-\infty}^{\infty}\left(C_p\mathrm{e}^{-\mathrm{i}k_x^{\mathrm{II}}x} + D_p\mathrm{e}^{\mathrm{i}k_x^{\mathrm{II}}x}\right)\mathrm{e}^{-\mathrm{i}k_z z},$$

$$H_y^{\mathrm{II}} = \sum_{p=-\infty}^{\infty} -\mathrm{j}\frac{\omega\varepsilon}{k_x^{\mathrm{II}}}\left(C_p\mathrm{e}^{-\mathrm{i}k_x^{\mathrm{II}}x} - D_p\mathrm{e}^{\mathrm{i}k_x^{\mathrm{II}}x}\right)\mathrm{e}^{-\mathrm{i}k_z z}, \quad (2)$$

where $k_z = \dfrac{\omega}{u_0} + \dfrac{2\pi p}{d}$, $k_x^{\mathrm{II}2} = k_z^2 - k_0^2$, and p is any integer.

Also in regions III and IV,

$$\begin{aligned} E_z^{\mathrm{III}} &= \sum_{p=-\infty}^{\infty}\left(E_p\mathrm{e}^{-\mathrm{i}k_x^{\mathrm{III}}\cdot x} + F_p\mathrm{e}^{\mathrm{i}k_x^{\mathrm{III}}x}\right)\mathrm{e}^{-\mathrm{i}k_z z}, \\ H_y^{\mathrm{III}} &= \sum_{p=-\infty}^{\infty} -\mathrm{j}\frac{\omega\varepsilon}{k_x^{\mathrm{III}}}\left(E_p\mathrm{e}^{-\mathrm{i}k_x^{\mathrm{III}}x}\right. \\ &\quad \left. -F_p\mathrm{e}^{\mathrm{i}k_x^{\mathrm{III}}x}\right)\mathrm{e}^{-\mathrm{i}k_z z}, \end{aligned} \quad (3)$$

where $k_x^{\mathrm{III}2} = \left(k_z^2 - k_0^2\right)\alpha,\ \alpha = 1 - \dfrac{\omega_p^2}{\left(\omega - k_z u_0\right)^2}$,

$$\begin{aligned} E_z^{\mathrm{IV}} &= \sum_{p=-\infty}^{\infty} G_p\mathrm{e}^{-\mathrm{i}k_x^{\mathrm{II}}x}\mathrm{e}^{-\mathrm{i}k_z z}, \\ H_y^{\mathrm{IV}} &= \sum_{p=-\infty}^{\infty} -\mathrm{j}\frac{\omega\varepsilon}{k_x^{\mathrm{II}}}G_p\mathrm{e}^{-\mathrm{i}k_x^{\mathrm{II}}x}\mathrm{e}^{-\mathrm{i}k_z z}, \end{aligned} \quad (4)$$

where

$$\begin{aligned} k_z &= k_{z0} + \frac{2\pi p}{d}, \\ k_x^{\mathrm{II}2} &= k_z^2 - k_0^2. \end{aligned}$$

Together with the boundary conditions, the dispersion of the MSP can be expressed as

$$\frac{k_x^{\mathrm{I}}}{k_0^2} = \frac{a}{d}\sum_{p=-\infty}^{\infty}\sin c^2\left(\frac{k_z a}{2}\right)\frac{1}{k_x^{\mathrm{II}}}\frac{C_p - D_p}{C_p + D_p}, \quad (5)$$

where C_p and D_p are parameters and expressed as

$$\begin{aligned} C_p &= \mathrm{e}^{\mathrm{i}k_x^{\mathrm{II}}b}\left[\left(\sqrt{\alpha} + 1/\sqrt{\alpha}\right)\cdot\mathrm{i}\cdot\sin(k_x^{\mathrm{II}}\sqrt{\alpha}h)\right. \\ &\quad \left. +2\cos(k_x^{\mathrm{II}}\cdot\sqrt{\alpha}\cdot h)\right], \\ D_p &= \mathrm{e}^{-\mathrm{i}k_x^{\mathrm{II}}b}\left(\sqrt{\alpha} - 1/\sqrt{\alpha}\right)\cdot\mathrm{i}\cdot\sin(k_x^{\mathrm{II}}\sqrt{\alpha}h). \end{aligned}$$

The field components of E_z and H_y in region IV are evanescent waves and decay exponentially into the air. Due to the finite depth of the holes, the wave modes in region I should be considered to be not only decaying mode but also growing mode, thus the expression of $A\mathrm{e}^{-\mathrm{i}k_x x} + B\mathrm{e}^{\mathrm{i}k_x x}$ holds true. The computer numerical simulations, shown subsequently in Figs.5 and 6, can prove that the SP waves excited by the electron beam are not evanescent waves into the holes any more.

Figure 4 shows the different dispersion curves of MSP structures along with kinds of rectangular holes. In Fig.2 it is demonstrated that the frequency of the

MSP is tunable by changing the shape of the holes. The frequency of the SP wave increases with the decrease of the long side s that is always longer than the short side a ($s \geq a$) due to the excited fundamental mode TE_{10}. When the long side of the rectangular hole, s, is large enough, expression (5) can be expanded into a grating structure. As is known, the excited fundamental mode in the grating is TEM which is also shown in Fig.4.

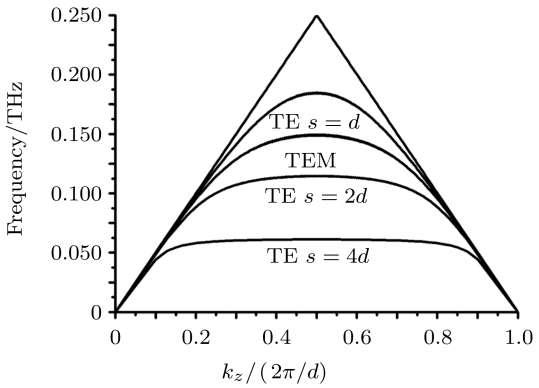


Fig.4. Dispersion curves of an SP wave with different structures.

4. Surface plasmon excited by electron beams

An electron beam above the structure surface is introduced to excite the SP modes shown in Figs.5 and 6. The demonstration simulated by FDTD software shows clearly that when the electron beam at a voltage of 65 kV just passes above the surface of the structure, TE_{10} mode is excited, which means $k_z = \pi/d$ where the group velocity vanishes. As is known, from the dispersion, different electron beam voltages lead to different values of k_z. For other values of k_z, the surface field coupling between neighbouring holes becomes very complicated and the pattern should no longer be identified as a particular mode pattern. From Figs.5 and 6, the plot of the E_z contour in the x plane indicates that the field E_z is highest at the surface of the structure and decays exponentially into just air, but it becomes a transmissible mode in the holes. Due to the small thickness of the holes, the SP wave whose frequency is just below the cutoff frequency of the hole can even penetrate into the holes without evanescence as shown in Fig.7. These results reveal the characteristics of the MSP modes excited by the electron beam passing above the surface of subwavelength hole array conductors.

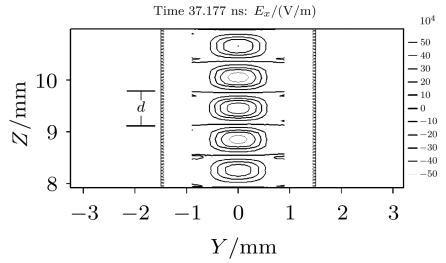


Fig.5. SP modes in the hole array, excited by an electron beam.

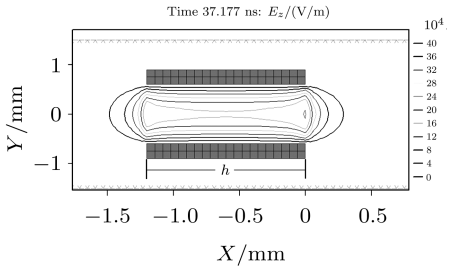


Fig.6. SP modes in one hole.

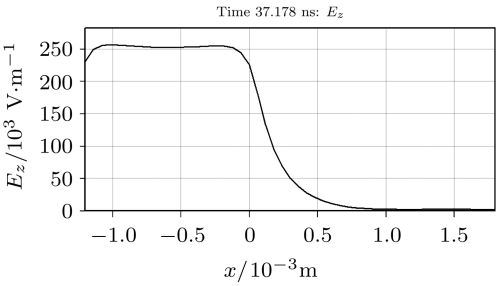


Fig.7. E_z field in the x-plane.

5. Interaction between surface plasmon and electron beams

Computer simulations are carried out by using the commercial software MAGIC (FDTD). We use a perfect conductor with rectangular holes as the MSP structure shown in Fig.1. The period equals 0.6 mm, with 1.2 by 0.3 by 1.2 mm rectangular holes, and the number of periods is 30 at the z position.

Figure 8(a) shows the electron beam emitted just above the holes, along with the distribution in P–z phase space. Figure 8(a) clearly shows that the electron beam with a voltage of 65 kV is modulated and interacts with the surface plasmon wave. To illustrate the evanescent wave interacting with the electron beam, we show in Fig.10(a) the magnitude of E_z along the z-axis just at the beam position. The observed

spectrum frequency of the E_z field is 121.76 GHz below the cutoff frequency 125 GHz.

It is interesting to note that the wave field is evanescent and decays exponentially in the sub-wavelength holes as expected from the MSP concept,[2] but in the subwavelength hole array with finite depth, electromagnetic penetration occurs, and there are no longer evanescent waves similar to the light transmission predicted in Refs.[4] and [5]. Because of the penetration phenomena explained above, two electron beams are suggested to be used to enhance the interaction. The modulated electron beam, the observed current and the E_z field are given in Figs.8(b), 9(b) and 10(b) respectively. The electron beam is divided into two beams with the same beam density, and they are emitted into both sides of the structure. It has been clearly shown that the MSP and the electron beam interact with each other at a higher efficiency.

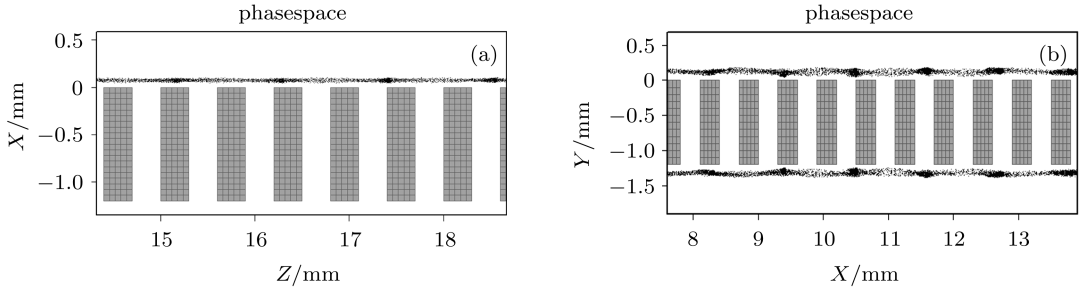


Fig.8. Modulated electron beam in the Y-plane.

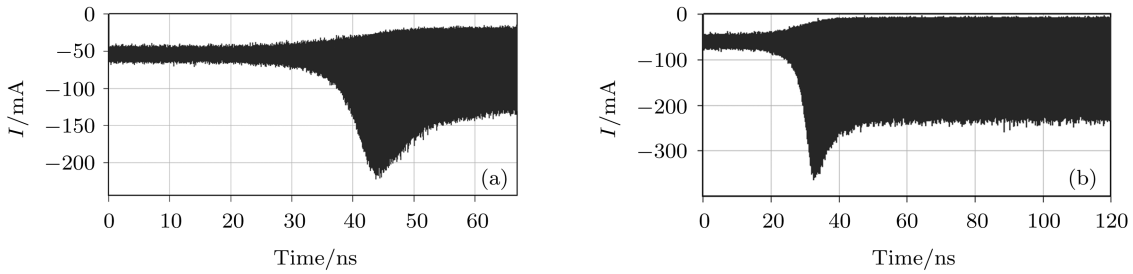


Fig.9. Observed current.

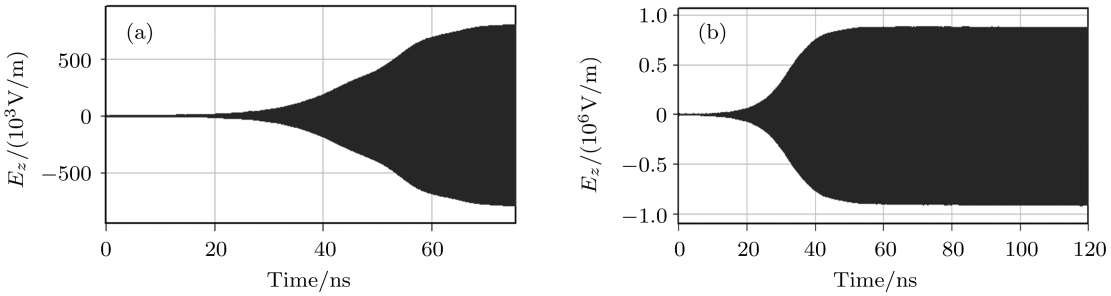


Fig.10. E_z field observed at the surface.

6. Conclusion

From the discussion above, the electron beam sheet can provide sufficient momentum and energy to excite the surface plasmon modes in a structured perfect-conductor surface, and the MSP wave can interact with the electron beam. This mechanism can

be used to design novel electromagnetic devices from the microwave to terahertz regions. All of the results herein not only provide an insight into the characteristics of the surface plasmon mode on a mimicking perfect-conductor surface, but also demonstrate a new and valuable approach to designing electromagnetic devices and meta-materials with special surface mode characteristics.

References

[1] Heinz Raether 1988 *Surface Plasmons on Smooth and Rough Surfaces and on Gratings* (Berlin: Springer-Velag) p4

[2] Pendry J B, Martin-Moreno L and Garcia-Vidal F J 2004 *Science* **305** 847

[3] Hibbins A P, Evans B R and Sambles J R 2005 *Science* **308** 670

[4] Ebbesen T W, Lezec H J, Ghaemi H F, Thio T and Wolff P A 1998 *Nature* **391** 667

[5] Martin-Moreno L, Garcia-Vidal F J, Lezec H J, Pellerin K M, Thio T, Pendry J B and Ebbesen T W 2001 *Phys. Rev. Lett.* **86** 1114

[6] Garcia de Abajo F J and Saenz J J 2005 *Phys. Rev. Lett.* **95** 233901

[7] Lan Y C 2006 *Optics Express* **14** 11339

[8] Shin Y M, So J K, Jang K H, Won J H, Srivastava A and Park G S 2007 *Phys. Rev. Lett.* **99** 147402

[9] Shen J T, Cartrysse P B and Fan S H 2005 *Phys. Rev. Lett.* **94** 197401

[10] Zhou R L, Chen X S, Zeng Y, Zhang J B, Chen H B, Wang S W, Liu W, Li H J, Xia H and Wang L L 2008 *Acta Phys. Sin.* **57** 3506 (in Chinese)

[11] Chen H T, Padilla W J, Zide J M O, Gossard A C, Taylor A J and Averitt R D 2006 *Nature* **444** 697

[12] Mikhailov S A and Savostianova N A 1997 *Appl. Phys. Lett.* **71** 1308