Terahertz Radiation with a Cylindrical Mimicking Surface Plasmons Structure

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Abstract—**Mimicking surface plasmons modes are important for THz science and technology for it opens the tools that are necessary to construct devices at this frequency regime. Here, a cylindrical mimicking surface plasmon is proposed to interact with electron beam to generate terahertz radiation. The exploration on such interactions is presented. The results of the theoretical study and computer simulation show that the cylindrical mimicking surface plasmons waves can be excited by and can interact with the electron beam with relative high efficiency.**

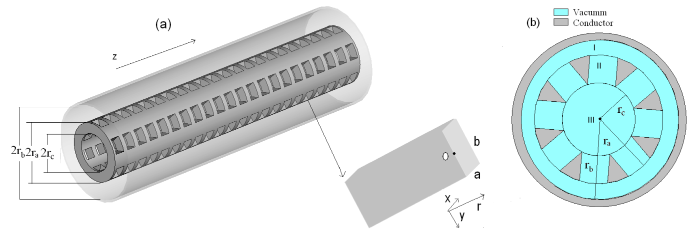
I. Introduction And Background

Recently, mimicking surface plasmons modes (MSP) open new tools to design and construct devices operating at terahertz frequency regime, a very important and rapidly developing area of modern science and technology. Making use of the MSP, the development of some active terahertz devices including the THz modulator, switching device etc, has been proposed [1-2]. However, in order to fill the "THz gap", THz radiation sources are extremely important. Nowadays although strong efforts have been made and some progresses have been achieved in these aspects, there are still many problems associated with the THz radiation sources remain to be solved. It seems that looking for a proper way to combine the electronics and photonics is one of the promising approaches. Now the successful exploration of MSP may bring a bright perspective for THz radiation sources [1]. The MSP supports the slow propagating surface waves which give the possibility of electron beam-MSP interactions, and hence it enables to produce THz radiation sources operating at room temperature [3, 4].

Now, the cylindrical MSP structure with a×b rectangle holes array is proposed and studied, making use of this MSP, the electron beam-MSP interactions are suggested to generate and amplify THz radiation.

II. Cylindrical Mimicking Surface Plasmons modes

The cylindrical mimicking surface plasmons structure is shown in Fig.1 (a) which consists of inner and outer circular conductor, the former conductor is perforated with rectangular holes array uniformly in z and azimuthal directions, the cross section is shown in Fig.1 (b). Then the outer and inner conductors together form a waveguide for the MSP modes.



（Fig 1. (a) cylindrical mimicking surface plasmons structure, the size of the hole is a×b where a is the wide and b is the length; (b) the cross section, where grain area is conductor.）

Now we deal with dispersion relation of MSP modes propagating along the z axis. Because the diameter is much longer than the width of holes, for simplicity, each hole can be considered as a rectangular waveguide. Therefore, the fields in the holes can be expressed in Cartesian system with origin point O and in the regions $r_a<r<r_b$ and $0<r<r_c$ the fields can be expressed in cylindrical system. MSP modes are evanescent waves outside the surface of holes array [1], so the fields in $r_a<r<r_b$ and $0<r<r_c$ regions should take the form of Modified Bessel functions. The Maxwell's equations together with the periodic boundary conditions leads to the following electromagnetic fields in the region I $r_a<r<r_b$：

$$E_{z1}=\sum_{m=-\infty}^{m=+\infty}\sum_{n=-\infty}^{n=+\infty}\left[A_{2nm}I_\Gamma(k_{c1n}r)+C_{2nm}K_\Gamma(k_{c1n}r)\right]e^{j\omega t-jk_{zn}z-j\Gamma\theta};$$
$$H_{z2}=\sum_{m=-\infty}^{m=+\infty}\sum_{n=-\infty}^{n=+\infty}\left[B_{2nm}I_\Gamma(k_{c2n}r)+D_{2nm}K_\Gamma(k_{c2n}r)\right]e^{j\omega t-jk_{zn}z-j\Gamma\theta} \quad (1)$$

Where $\Gamma=l+mN;k_{c1n}=\sqrt{k_{zn}^2-k_0^2};k_{zn}=k_z+\dfrac{2n}{d}\pi$, N is the number of holes in the azimuthal direction, l is the azimuthal order of modes, m is azimuthal spatial harmonic number and n is z axial spatial harmonic number. The size of hole is a×b and the period is d.

The frequency of MSP propagating along z axis is always below the cutoff frequency of the holes. Hence, in the holes (region II) the fields take the form as:

$$E_{z2}=-\frac{j\omega\mu}{k_\varphi}\sin k_\varphi(y+b)\left[A_{11}\sin(k_r r)+A_{12}\cos(k_r r)\right]e^{j\omega t}; \quad (2)$$

Where $k_\varphi=\dfrac{\pi}{b},k_r=\sqrt{k_0^2-k_\varphi^2}$ At the region 0<r< rc, we assume the fields can couple with each other to form an inner mode and also can support a surface spatial harmonic wave, so the fields can be expressed:

$$E_{z3}=\sum_n\sum_m\left[A_{3m}I_\Gamma(k_{c3}r)\right]e^{j\omega t-j\Gamma\theta-jk_{zn}z};$$
$$H_{z3}=\sum_n\sum_m\left[B_{3m}I_\Gamma(k_{c3}r)\right]e^{j\omega t-j\Gamma\theta-jk_{zn}z} \quad (3)$$

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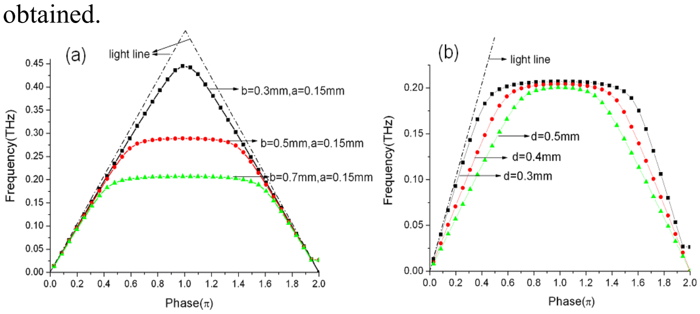
In this cylindrical MSP structure, it is noted that at the azimuthally symmetric case (l=0), TE and TM modes can be decoupled, however at non-symmetrical case($l \neq 0$), the TE and TM modes can not exist independently. Following this procedure and boundary matching condition yields the dispersion equations for fundamental MSP modes and high order modes.

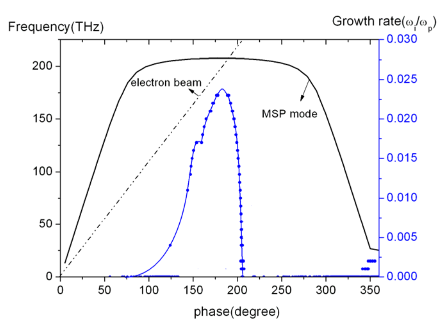
III. RESULTS

By numerical calculation, the dispersion characteristics of cylindrical MSP mode can be found shown in Fig.2. The cutoff frequency of the MSP mode is dramatically depended on the length (parameter b) of holes. And it is shown that period d affects the cutoff frequency of MSP modes slightly, however strongly depended on the top band of the MSP dispersion relation curve. So we can design the cylindrical mimicking surface plasmons mode at the THz regime by adjusting the length and period of the holes array.

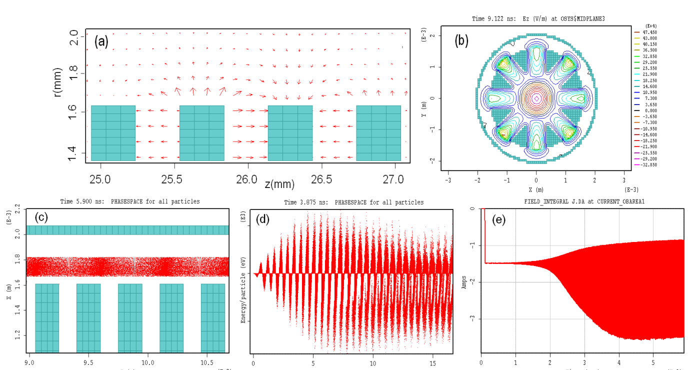
Fig.3 shows when the electron beam synchronizes with the MSP modes, the interaction occurs and the growth rate can be obtained.



(Fig2 Dispersion relation of MSP of the cylindrical MSP structure.(a) the dispersion lines of MSP with different length (b) the dispersion lines of MSP with different period)



（Fig3 Growth rate of the beam-wave interaction.）



(Fig4 Computer simulation results)

Fig.4 is the results of computer simulations which show when the electron beam passes closely through the surface of this structure the MSP mode can be excited (Fig.4 (a)-(b)). The process of momentum-energy coupling between MSP and beam is shown in Fig.4(c)-(e). Figure.4(c) shows that the electron beam bunching very well during the process of interaction, and note that in Fig.4 (d-e), the efficiency of such electron beam–MSP interaction is very attractive and the modulation depth of electron beam can reach 20% when the current density is about 100A/cm^2, and at the case of 40A/cm^2 the modulation depth also can reach 13%.

IV. CONCLUSION

In this paper, a cylindrical MSP and the interaction of electron beam-MSP wave are presented. Summarizing the results, we can conclude:

1. This cylindrical MSP structure has axial and azimuthal periodic holes array so the nonsymmetrical TE and TM modes can not exist independently, they always coupled each other to produce hybrid mode.
2. The cylindrical MSP wave can be exited by the electron beam, which leads to the forward wave/backward wave instabilities, and the instabilities could occur at the terahertz frequency regime.
3. The efficiency of cylindrical MSP-electron beam interaction is attractive (the modulation depth can reach 20%). And by using this interaction the starting current density can be reduced dramatically, at 0.215THz frequency the starting current density is below 20A/cm^2.

The results given in this paper show that MSP-electron beam interaction is of significance for the combination of electronics and photonics to develop terahertz radiation sources.

V. ACKNOWLEDGMENTS

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