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APPLICATION OF SURFACE PLASMON POLARITONS ON CHARGED PARTICLE BEAM DIAGNOSTICS

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Abstract

In Recent years, the Cherenkov light radiation transformed from surface plasmon polaritons has been found and proposed for a compact and adjustable light source. As the process is motivated by charged particle beam, the characteristics of the light are not only related with the device but can also reflect certain characteristics of the beam. In this paper, a beam position and energy measurement method has been proposed based on the Cherenkov light radiation transformed from surface plasmon polaritons. Early-stage numerical and analytical investigations are also presented for a planar structure device.

INTRODUCTION

The rapid development of advanced accelerators and their applications puts higher demands on the beam diagnostic technology, such as, size of the devices, resolution, etc. [1, 2]. In recent years, progress in nanotechnology, photonics, and manufacturing technology may lead to new forms of diagnostic method and device [3, 4]. Surface Plasmon Polaritons (SPPs) have the advantages of high coupling efficiency, compactness, ease of integration, etc., and are widely used in fields of biosensing, communication, optics and so on [5, 6]. It can also be excited by both photons and charged particles with specific energies. When the phase velocity of SPPs is larger than that of the light in dielectric, the SPPs can transform into Cherenkov radiation at the metal-dielectric interface [7, 8]. Compared with traditional Cherenkov radiation excited by free electrons directly, the band of the radiation light is narrowly confined by the overlapping resonance. The wavelength of the radiation light is not only determined by the dispersion relation of the device itself but also related to the characteristics of the free electrons, which can be developed into a good diagnostic method.

In this paper, we present two new concepts for beam energy and position monitors based on Cherenkov radiation transformed from SPPs, which is capable of converting the beam information to the wavelength of the radiation light. Benefit from the mature spectroscopic technique and micro-nano technology, it holds the potential to increase the dynamic range, improve resolution, and reduce the size of these kinds of devices. The planar structure and electron beam are adopted in this paper to evaluate the performance of these devices. The concepts are general for other charged particle beams.

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PRINCIPLE AND CHARACTERISTICS OF THE RADIATION

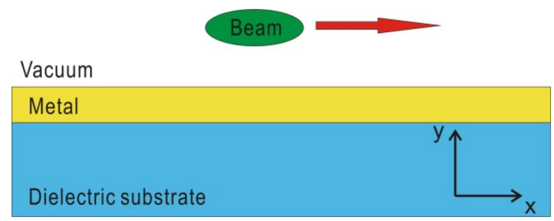

Figure 1: Schematic diagram of the IMI-structure device.

In order to make good use of the radiation to diagnose beam, the characteristics of the radiation needs to be studied. A planar structure (Insulator/Metal/Insulator, IMI) is taken as an example. The geometry is shown in Fig. 1. When the free electron beam satisfying with the dispersion relation of the structure transmits in the vacuum, the surface plasmon polaritons can be excited at two interfaces. If the beam velocity is also larger than the light propagation in the dielectric ($\beta > \frac{1}{\sqrt{\varepsilon_d}}$, here, β is the ratio of the electron beam velocity to the speed of light in vacuum, ε_d is the permittivity of the dielectric), the electromagnetic waves will transform into radiation mode. So the Cherenkov radiation transformed from SPPs is an overlapping resonance, including two steps.

Figure 2 presents a dispersion relation of an IMI-structure device obtained by numerical calculation whose parameters are shown in Table 1. k_x represents the wave vector in x direction in Fig. 2 [5]. The red lines represent the dispersion curve of the device. The black line is the light line in vacuum. The blue line is the light line in the dielectric medium. The cyan area shows the area where the wave vector satisfies with the Cherenkov radiation condition. The dash magenta line represents the line of the electron beam with total energy of 1 MeV. The intersection between the beam line and the dispersion line indicates that the SPPs can be excited. As it locates in the cyan area, the SPPs can transform to Cherenkov radiation. It can be concluded that the frequency of the radiation light is determined by the dispersion curve of the device and beam energy. The permittivity of the dielectric medium determines the minimum beam energy that allows the SPPs to transform into Cherenkov radiation.

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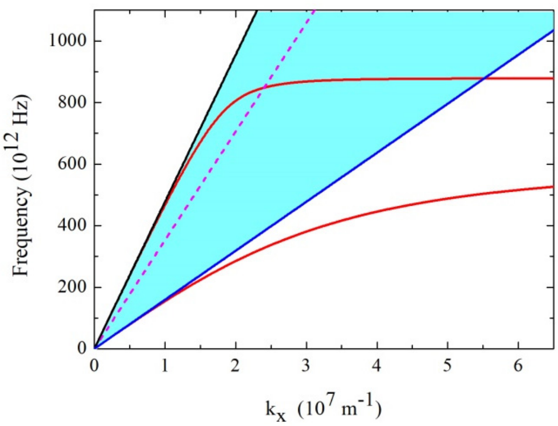

Figure 2: Dispersion relation of the surface plasmon polaritons.

Table 1: Device Parameters.

Parameter	
Metal thickness	30 nm
Metal	Ag
Permittivity of dielectric	9

BEAM ENERGY MONITOR

Based on the mechanism of the radiation, the wavelength of the light radiated by the device can reflect the energy of the beam for a specific device. The dispersion properties of SPPs can be derived from Maxwell's equations [5]. Combined with relativistic mass energy relation and assuming the motion of the electrons parallel to the interface, the relation between the light frequency and the beam energy can be expressed as formula (1). Where E is the beam energy, E_0 is the rest energy of electron, ε_d is the permittivity of the medium, d is the thickness of the metal, $k_0 = \frac{\omega}{c}$ is the wave vector of light in the vacuum. The dielectric function of the metal $\varepsilon_m = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 - i\gamma\omega}$ can be given by the modified Drude mode [7], ε_∞ is the permittivity at infinite frequency, ω_p is plasma frequency of metal, γ is damping constant.

Figure 3 indicates that the wavelength of the Cherenkov radiation transformed from SPPs is a function of beam energy. In the calculation, the metal is Ag whose thickness is 50 nm. The permittivity of the medium is 9. With increase of the beam energy, the radiation is from visible light to infrared light. So the beam energy can be measured with mature spectrometers in this regime. The measurement resolution is also evaluated with this device, as shown in Fig. 4. The vertical axis represents the variation of the radiation wavelength caused by the beam energy change. It can be seen that the variation of the radiation wavelength is 0.28 nm/keV under the beam enrgy of 5 MeV. Assuming the resolution of the spectrometer is 0.1 nm, the theoretical energy resolution for this device is estimated to be 357.14 eV with electron beam of 5 MeV. With the increase of the beam energy, the measurement resolution is improved, which can be explained by the slope change of the dispersion curve. Moreover, it is worth to mention that both the measurement range of the device and the measurement resolution under specific beam energy are adjustable by designing the device to modulate the dispersion relation.

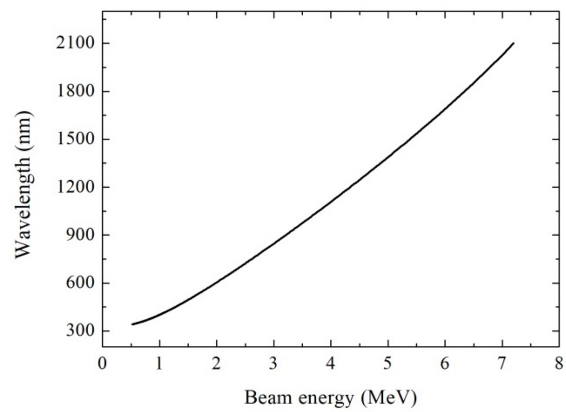

Figure 3: Relation between the beam energy and the light wavelength radiated by the device. The metal is Ag. Its thickness is 50 nm.

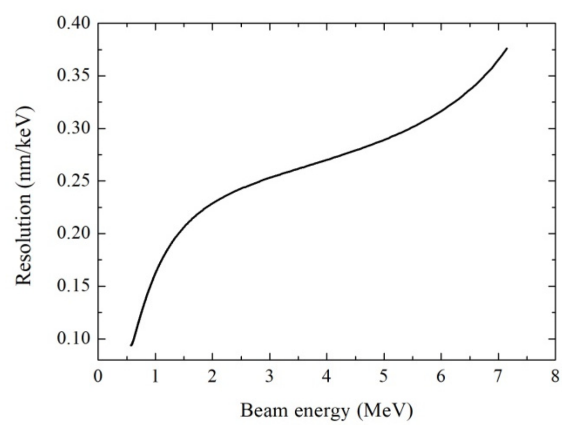

Figure 4: Measurement resolution under different beam energies.

$$\frac{\varepsilon_m E_0 - \sqrt{E^2(1-\varepsilon_m) + E_0^2\varepsilon_m}}{j\varepsilon_m\sqrt{E^2(\varepsilon_d - 1) - E_0^2\varepsilon_d} - \varepsilon_d\sqrt{E^2(1-\varepsilon_m) + E_0^2\varepsilon_m}} e^{-k_0 d\sqrt{\frac{E^2(1-\varepsilon_m)+E_0^2\varepsilon_m}{E^2-E_0^2}}}$$
$$= \frac{\varepsilon_m E_0 + \sqrt{E^2(1-\varepsilon_m) + E_0^2\varepsilon_m}}{j\varepsilon_m\sqrt{E^2(\varepsilon_d - 1) - E_0^2\varepsilon_d} + \varepsilon_d\sqrt{E^2(1-\varepsilon_m) + E_0^2\varepsilon_m}} e^{k_0 d\sqrt{\frac{E^2(1-\varepsilon_m)+E_0^2\varepsilon_m}{E^2-E_0^2}}} \quad (1)$$

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BEAM POSITION MONITOR

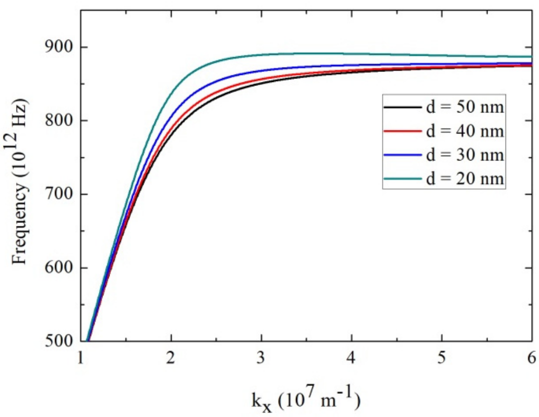

Figure 5: Dispersion relation of IMI-structure with different metal thickness.

As mentioned above, the radiation wavelength is also determined by the dispersion relation of the device. If a device is designed with position-dependent dispersion relation, the beam position information can be encoded in the frequency spectrum of the radiation. Figure 5 presents the dispersion curve of the IMI-structure device with different metal thicknesses. It shows that the dispersion relation changes with the metal thickness. So an IMI-structure device with varying metal thickness perpendicular to beam transmission direction can be designed to measure beam position information for charged particle beam. The geometry of the device is shown in Fig. 6. The beam is transmitted along the X-axis. When the beam energy is constant, only the location of the beam in Z-axis determines the wavelength of the radiation.

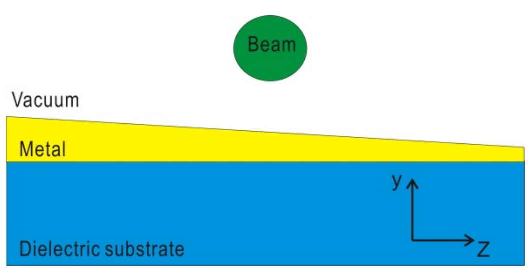

Figure 6: Schematic diagram of beam position monitor.

Figure 7 presents relation of the radiation wavelength and metal thickness for the electron beam of 7 MeV, which is nonlinear. With the decrease of the metal thickness, the slope becomes higher, which means the detector becomes more sensitive.

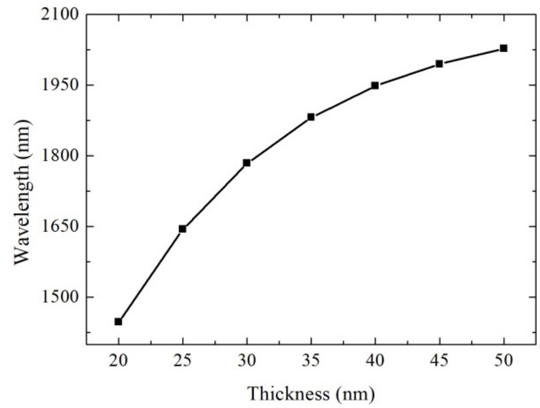

Figure 7: Relation of the radiation wavelength and metal thickness for the electron beam of 7MeV.

CONCLUSION

In this paper, the Cherenkov radiation transformed from surface plasmon polaritons has been studied. Based on the characteristics of the radiation, two new concepts for beam energy and position monitor have been proposed, both of which are non-destructive. The specific case of planar IMI-structure has been adopted to carry on the early-stage demonstration of the radiation used in diagnostics, which presents great application potential. In the future, as a variety of structures can be used to generate the radiation with different dispersion properties, targeted optimization needs to be done for a specific application based on the concepts.

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