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Surface plasmon polaritons light radiation source with asymmetrical structure

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An asymmetrical surface plasmon polariton (SPPs) light radiation source with double metal films (SPLRD) is presented and studied. SPPs modes can be excited on the double metal films by a parallel traveling electron beam and then transformed into enhanced Cherenkov radiation in the substrate. Tunable dual-frequency radiation ranging from infrared to ultraviolet can be realized. In comparison with a single-metal-film structure, the efficiency, tunability, and output power density of the SPLRD are greatly increased, with up to eight times higher radiation power intensity being achievable. The radiation performance of a cylindrical SPLRD is enhanced to an even greater extent, with reductions in the required exciting electron-beam energy and the dielectric substrate permittivity. These novel properties due to the asymmetry of the structure and the SPPs excitation pattern are significant for furthering the understanding of electron beam–SPPs interaction and for the development of efficient wideband light radiation sources. © 2018 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/1.5000779

I. INTRODUCTION

Surface plasmon polaritons (SPPs) can be excited on a metal film by a parallel traveling electron beam, and can be transformed into enhanced Cherenkov radiation in a dielectric substrate under the metal film, as long as their velocity exceeds that of light in the substrate.1–8 The radiated electromagnetic waves are coherent and can be enhanced, and the frequency can be tuned by adjusting the energy of the exciting electron beam.1

In this paper, an SPP light radiation source with asymmetrical double metal films (SPLRD) in the configuration shown schematically in Fig. 1 is presented and investigated. As can be seen from the figure, the structure consists of two dielectric substrates separated by a gap, with two metal films of different thicknesses deposited on the opposing surfaces of the substrates. When an electron beam of definite thickness propagates through the gap, asymmetrical and symmetrical SPPs modes can be excited simultaneously on the double metal films, and are then transformed into enhanced Cherenkov radiation in the substrates. The efficiency and output power of this SPLRD are dramatically increased in comparison with the single-mode radiation from a single-metal-film structure (SMFS).

II. THEORETICAL ANALYSIS OF THE SPLRD

In the SPLRD, the charge density and current density of the exciting electron beam with definite thickness 2de can be expressed as follows:1

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FIG. 1. Configuration of the SPLRD.

\[
\rho = q\theta(y)\delta(z - u_0t) \quad (1)
\]

\[
J = qu_0\theta(y)\delta(z - u_0t) \quad (2)
\]

Where \(\theta(y) = \begin{cases} 
\frac{1}{2d_e} & |y| < d_e \\
0 & \text{otherwise}
\end{cases} \)

where \(q\) and \(u_0\) are the total charge and velocity of the beam, respectively. Throughout this paper, the condition for generation of Cherenkov radiation, \(u_0 > c/\sqrt{\varepsilon_d}\), is assumed to be satisfied.

On satisfying the boundary conditions, the dispersion relation and radiation power spectrum of the SPLRD can be obtained as the following complex expressions:

\[
\left\{ \left( \frac{\varepsilon_m}{k_{y_1}} + \frac{\varepsilon_d}{k_{y_2}} \right) e^{-ik_{y_1}d_1'} - \left( \frac{\varepsilon_d}{k_{y_2}} - \frac{\varepsilon_m}{k_{y_1}} \right) e^{ik_{y_1}d_1} \right\}
\]

\[
\left\{ \frac{\varepsilon_{m}k_{y_0}}{k_{y_1}} \right\} \left( e^{-2\kappa_0d_0} + e^{2\kappa_0d_0} \right) \left( \frac{\varepsilon_d}{k_{y_2}} + \frac{\varepsilon_m}{k_{y_1}} \right) e^{ik_{y_1}d_1}
\]

\[
-\left\{ \frac{\varepsilon_{m}k_{y_0}}{k_{y_1}} \right\} \left( e^{-2\kappa_0d_0} + e^{2\kappa_0d_0} \right) \left( \frac{\varepsilon_d}{k_{y_2}} - \frac{\varepsilon_m}{k_{y_1}} \right) e^{-ik_{y_1}d_1} \right\} = 0 \quad (3)
\]

and

\[
P(\omega) = P_1(\omega) + P_2(\omega) \quad (4)
\]

where

\[
P_1(\omega) = \sqrt{1 + \left( \frac{k_z}{k_{y_2}} \right)^2 \omega \varepsilon_0 \varepsilon_d \left| \frac{D_2}{D} \right|^2} \quad (5)
\]

and

\[
P_2(\omega) = \sqrt{1 + \left( \frac{k_z}{k_{y_2}} \right)^2 \omega \varepsilon_0 \varepsilon_d \left| \frac{D_8}{D} \right|^2} \quad (6)
\]

are the radiation power spectra in the upper and lower half spaces, respectively. \(k_0 = \omega/c\), \(k_{y_0} = \sqrt{k_z^2 - k_0^2}\), \(k_{y_1} = \sqrt{\varepsilon_m k_0^2 - k_z^2}\), \(k_{y_2} = \sqrt{\varepsilon_d k_0^2 - k_z^2}\), and \(\beta = u_0/c\). The longitudinal wave vector \(k_z\) is taken as an independent variable in the dispersion relation (3), but to be equal to \(\omega/\beta u_0\) in the radiation power spectrum equations (4)–(6) to match the phase of the electron beam. \(D\) is the
determinant of the coefficients in the boundary condition equations, and $D_7$ and $D_8$ are the numerators in Cramer’s rule; expressions for $D_7$ and $D_8$ are derived in Appendix I in the supplementary material. $\varepsilon_d = 9$ is the permittivity of the substrate, and $\varepsilon_m$ is the dielectric parameter of the metal films, which for silver films can be expressed by the modified Drude model\textsuperscript{10,11}

$$\varepsilon_m = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\gamma\omega}$$  \hspace{1cm} (7)

with $\varepsilon_\infty = 5.3$, $\omega_p = 1.39 \times 10^{16}$ rad/s and $\gamma = 3.2 \times 10^{13}$.

III. RADIATION PROPERTIES OF THE SYMMETRICAL SPLRD

Figure 2 shows the dispersion curves obtained from Eq. (3) in the case where the thicknesses $d_1 = 20$nm and $d_1' = 21$nm of the two silver films are similar (symmetrical SPLRD); the other structural parameters are $d_e = 15$nm and $d_0 = 30$nm. It can be seen that two SPPs modes are excited: the symmetrical mode and the asymmetrical mode. The dispersion curve of the asymmetrical mode lies below the dielectric light line, while the curve of the symmetrical mode intersects both the dielectric light line and the vacuum light line. As is well known, a radiated wave is possible only for frequencies in the band between the two light lines (the radiation region, shown shaded in Fig. 2). Thus, for the symmetrical mode, only the frequency band in the radiation region can be transformed into radiation. That is, the symmetrical SPLRD can work only with single-frequency radiation. Furthermore, the very flat dispersion curve of the symmetrical SPP mode indicates a relatively narrow radiation frequency tuning band for the symmetrical SPLRD, since the radiation frequency is determined by the point of intersection of the electron-beam line and the dispersion curve, such as point A, which represents 911 THz radiation excited by an electron beam of energy 100 KeV, or point B, which represents 928 THz radiation excited at 400 KeV. For comparison, the corresponding points of intersection for an SMFS with the same structural parameters are shown as $A_1$ and $B_1$, with lower radiation frequencies than those for the SPLRD.

Figure 3(a) and (b) show the radiation power spectra of the symmetrical SPLRD and the SMFS excited by electron beams of energy 100 KeV and 400 KeV, respectively. The peak radiation frequencies correspond to the respective intersection points A, B and $A_1$, $B_1$ in Fig. 2. It is clear that the SPLRD can generate a radiation amplitude several times higher than that from the SMFS, with the contrast becoming even greater when the energy of the exciting electron beam is increased, reaching a factor of 2.8 in the case of a 400 KeV electron beam [Fig. 3(b)], indicating the higher efficiency of the SPLRD compared with the SMFS.

FIG. 2. Dispersion curves of the symmetrical SPLRD with $d_1 = 20$nm, $d_1' = 21$nm, and an SMFS with the same structural parameters. The radiation region is shaded. A, $A_1$ and B, $B_1$ are the radiation frequencies defined by the points of intersection of the dispersion curves and the electron-beam lines for energies of 100 KeV and 400 KeV, respectively.
FIG. 3. Radiation power spectrum for the symmetrical SPLRD with $d_1 = 20\text{nm}$ and $d_1' = 21\text{nm}$ when excited by an electron energy of (a) 100\text{KeV} and (b) 400\text{KeV}. The amplitude of the spectrum is normalized by the peak radiation power of the SMFS, which is depicted by the dashed curves.

The frequency of the radiation from the SPLRD is shifted to the blue compared with that from the SMFS [as shown by the corresponding frequencies at points A and A$_1$ in Fig. 3(a)], and this blue shift becomes stronger with increasing beam energy [as shown by the corresponding frequencies at points B and B$_1$ in Fig. 3(b)], which is in good agreement with the results shown in Fig. 2 for the different trends of the dispersion curves. It should be noted that with high exciting electron energy, the spectrum of the SMFS becomes broader, whereas the SPLRD maintains a perfectly narrow spectrum under the same excitation, thereby guaranteeing a more coherent radiation source over a wider frequency band.

IV. RADIATION PROPERTIES FOR ASYMMETRICAL SPLRD

A dramatically different situation occurs when the thicknesses $d_1$ and $d_1'$ of the two silver films are significantly different (asymmetrical SPLRD). Figure 4 shows dispersion curves for such a case in which $d_1 = 20\text{nm}$ and $d_1' = 350\text{nm}$. It can be seen that, in general, three SPPs modes are excited on the silver films, and although one of the asymmetrical modes cannot radiate because its dispersion curve lies below the dielectric light line, radiation can still be emitted for the symmetrical mode and another asymmetrical mode simultaneously in the radiation region. For the lower location of the
dispersion curve of the asymmetrical mode, the radiation frequency is always lower than that of the symmetrical mode under the same excitation. The radiation power increases with increasing exciting electron energy and can reach values many times that of the SMFS, as shown in Fig. 5.

The gap width between the two metal films has an important influence on the dispersion behavior of the excited SPPs modes for the asymmetrical SPLRD.

When the gap width is small ($d_0 = 30$nm), as shown in Fig. 4(a), the dispersion curve of the symmetrical mode initially rises steeply but then becomes very flat with increasing $k_z$, whereas the trend of variation is gentler for the asymmetrical mode, leading to separation of the two dispersion curves. Therefore, the symmetrical and asymmetrical modes can be excited simultaneously by an electron beam with energy $E = 100$KeV and transformed into Cherenkov radiation, as shown by the intersection points C and E, with the radiation of the symmetrical mode being dominant, as shown in Fig. 5(a). However, at higher electron energies, such as $E = 400$KeV as shown in Fig. 5(b), only the symmetrical mode can be excited, corresponding to the intersection point D. In comparison with the radiation from the SMFS, as indicated by the intersection points $C_1$ and $D_1$, a 3.5-times greater radiation amplitude can be obtained from the asymmetrical SPLRD.

When the gap becomes wide ($d_0 = 150$nm), it can be seen from Fig. 4(b) that the dispersion curve of the asymmetrical mode approaches that of the symmetrical mode and they exhibit similar trends in the radiation region, so they can always be excited simultaneously to obtain two radiation modes.
FIG. 5. Radiation power spectra for the asymmetrical SPLRD. The electron-beam energy and gap width are (a) 100\text{KeV}, \(d_0 = 30\text{nm}\); (b) 400\text{KeV}, \(d_0 = 30\text{nm}\); (c) 100\text{KeV}, \(d_0 = 150\text{nm}\); (d) 400\text{KeV}, \(d_0 = 150\text{nm}\). The amplitudes of the spectra are normalized by the peak radiation power of the SMFS, which is depicted by the dashed curves.

For low beam energy (100\text{KeV}), the two radiation modes are indicated by the intersection points \(F\) and \(H\), and their radiation spectra in Fig. 5(c) show that the radiation of the symmetrical mode is still dominant, with its frequency and power (point \(F\)) behaving just like those of the SMFS (point \(F_1\)), because the wide gap greatly weakens the interaction between the fields of the upper and lower films at low exciting beam energy. However, at higher beam energy (400\text{KeV}), as can be seen from Fig. 5(d), the asymmetrical-mode radiation (point \(I\)) becomes overwhelmingly dominant, reaching eight times the radiation power intensity of the SMFS, owing to the strong interaction between the upper and lower fields.

A comparison of the radiation spectra of the SPLRD and the SMFS in Fig. 5(b) and (d) reveals the contrast between the perfectly narrow spectrum of the former and the clearly broadened spectrum of the latter. The narrow spectrum of the SPLRD ensures its better frequency tunability at high excitation energies.

The above results confirm that the SPLRD with its asymmetrical structure is not only able to work at dual frequencies, but also has a much higher radiation efficiency and better frequency tunability than the SMFS, owing to the high excitation efficiency of the electron beam and the strong interactions between the SPPs modes excited on the two metal films with different thicknesses.

V. STUDY OF A CYLINDRICAL SPLRD

Even more interesting results can be obtained for an asymmetrical SPLRD with cylindrical structure (cylindrical SPLRD). It is formed by rolling up the lower and upper silver films with both of the dielectric substrates of an asymmetrical planar SPLRD, as shown in Fig. 6, with \(r_0 = 100\text{nm}\), \(r_1 = 120\text{nm}\), \(r_2 = 180\text{nm}\), \(r_3 = 530\text{nm}\) and \(\varepsilon_d = 4\). In the cylindrical SPLRD, the annular exciting electron beam is located in the gap between the inner and outer metal film layers of different thicknesses, and the central and outer spaces are filled with dielectric substrate.

A detailed mathematical analysis of the cylindrical SPLRD is given in Appendix II in the supplementary material. The dispersion curves in Fig. 7 indicate that three SPPs modes are excited
in the cylindrical SPLRD. Modes 2 and 3 can always radiate, but mode 1 can do so only at low exciting beam energy (e.g., 100 KeV). The corresponding radiation power spectra are shown in Fig. 8. At a beam energy of 100 KeV, as shown in Fig. 8(a), although three modes are excited, and radiate at frequencies indicated by the intersection points $J_1$, $J_2$, and $J_3$, the radiation from mode 3 ($J_3$) is relatively weak [see the inset in Fig. 8(a)], so there are primarily two output frequencies, at $335 THz$ ($J_1$) and $753 THz$ ($J_2$), corresponding to modes 1 and 2, respectively, with mode 2 being predominant. At a beam energy of 150 KeV, only modes 2 and 3 can radiate, at frequencies indicated by points $K_2$ and $K_3$, with the radiation intensity at $K_2$ being overwhelming. In comparison with a cylindrical SMFS with the same structural parameters, the radiation intensity of a cylindrical SPLRD is remarkably enhanced, by a factor of eight. Furthermore, in comparison with the planar SPLRD structure, to achieve a radiation intensity of the same order of magnitude, the exciting electron-beam energy required for the cylindrical SPLRD can be significantly reduced from 400 KeV to 150 KeV, which reveals the excellent energy transfer efficiency of the cylindrical SPLRD resulting from its larger interaction area between the electron beam and the metal films. The permittivity of the dielectric substrate required for successful operation of the cylindrical SPLRD, $\varepsilon_d = 4$, is also less than that required in the planar case, $\varepsilon_d=9$, which is of benefit to practical applications.
VI. CONCLUSION

A novel structure for a SPPs light radiation source, the SPLRD, has been presented to generate radiation in a range from infrared to ultraviolet. With a planar structure, symmetrical and asymmetrical SPPs modes can be excited simultaneously and be transformed into enhanced Cherenkov radiation. The efficiency, tunability, and output power density are greatly increased in comparison with an SMFS, and a power intensity eight times higher can be obtained when an exciting electron energy of 400\,KeV is used. With a cylindrical structure, excited by an annular electron beam, the radiation performance is even better than in the planar case, with up to eight times the radiation power intensity of an SMFS being achievable at low electron energy (150\,KeV) and small permittivity of the dielectric substrate ($\varepsilon_d = 4$). These enhanced properties of the SPLRD are due to the superior excitation mechanism of the asymmetrical structure: both sides of the electron beam can excite SPPs on the double metal films of different thickness, and differences in gap width have an important influence on the performance of the SPLRD. The results presented here will help advance understanding of electron beam–SPPs interactions and will also be of benefit to the development of high-efficiency wideband light radiation sources.

SUPPLEMENTARY MATERIAL

See supplementary material for Detailed theoretical analyses of the planar and cylindrical SPLRDs are presented in Appendices I and II, respectively.
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