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Cyclotron electron beam excited surface plasmon polaritons coherent radiation

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Abstract

A physical mechanism of electron beam excitation of surface plasmon polaritons (SPPs) on the circular cylindrical structure and transformation into coherent radiation is proposed. Here SPPs on the circular cylindrical structures are excited by a cyclotron electron beam (CEB) rather than by the linearly moving electron beam (LEB). This change leads to an essential consequence due to the natural periodicity of 2π in structure and CEB, and this dual natural periodicity makes the SPPs transformation possible and brings significant excellences. HEM hybrid modes and TM_{0n} modes SPPs can be excited and propagate along a cyclotron trajectory together with the CEB to attract energy from CEB continuously to compensate the energy loss; the phase velocity of SPPs synchronizes the CEB; the process of the excitation and transformation is longer. Therefore, the transformed power density is enhanced and reaches up to 10^{10}W/cm^2 . The cyclotron frequency of the electron beam is 1THz, but the frequency regime of the SPPs and the radiation are much higher, up to hundreds of terahertz. The mechanism presented in this letter opens the way for developing the desired room temperature, powerful and coherent light radiation sources from the infrared to the ultraviolet frequency regime.

Keywords

plasmon, polaritons, coherent, cyclotron, radiation, electron, beam, excited, surface

Disciplines

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Cyclotron electron beam excited surface plasmon polaritons coherent radiation

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Abstract – A physical mechanism of electron beam excitation of surface plasmon polaritons (SPPs) on the circular cylindrical structure and transformation into coherent radiation is proposed. Here SPPs on the circular cylindrical structures are excited by a cyclotron electron beam (CEB) rather than by the linearly moving electron beam (LEB). This change leads to an essential consequence due to the natural periodicity of 2π in structure and CEB, and this dual natural periodicity makes the SPPs transformation possible and brings significant excellences. HEM hybrid modes and TM_{0n} modes SPPs can be excited and propagate along a cyclotron trajectory together with the CEB to attract energy from CEB continuously to compensate the energy loss; the phase velocity of SPPs synchronizes the CEB; the process of the excitation and transformation is longer. Therefore, the transformed power density is enhanced and reaches up to 10^{10} W/cm². The cyclotron frequency of the electron beam is 1 THz, but the frequency regime of the SPPs and the radiation are much higher, up to hundreds of terahertz. The mechanism presented in this letter opens the way for developing the desired room temperature, powerful and coherent light radiation sources from the infrared to the ultraviolet frequency regime.

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Introduction. – In this letter, a physical mechanism of electron beam excitation of surface plasmon polaritons (SPPs) on the circular cylindrical structure and the transformation of the excited SPPs into enhanced coherent radiation are proposed and investigated. Here the cyclotron electron beam (CEB) excitation of SPPs on the circular cylindrical structures is used to replace the linearly moving electron beam excitations, on which many literatures have been published [1–9]. We have found that this change leads to the essential consequence in physics for which there is a natural periodicity of 2π in both circular cylindrical structure and CEB, and the combination of this dual natural periodicities not only makes the excited SPPs

transformation possible, but also brings many significant excellences to the mechanism. The results of the theoretical analyses and numerical calculations show that both the HEM hybrid modes and the TM_{0n} modes of SPPs can be excited by CEB. And the excited SPPs propagate along a 3-dimensional cyclotron trajectory inside or outside the circular cylindrical structure together with the CEB. So the cyclotron SPPs can attract energy from the electron beam continuously to compensate the energy loss due to the radiation and decay of propagation. The physics is that the phase velocity of the excited SPPs is in synchronization with the CEB, so the process of the excitation and transformation is longer. The impressive results of investigation show that the power density of the radiation transformed from the cyclotron SPPs reaches up

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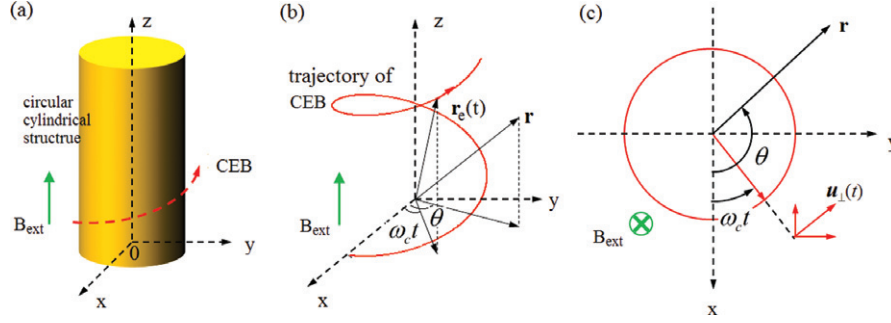


Fig. 1: (Colour on-line) (a) The schematic of CEB excitation. (b) The 3-dimensional cyclotron trajectory of CEB. (c) The trajectory of the CEB on the X - Y plane.

to 10^{10} W/cm². Therefore, the mechanism presented in this letter may open the way for developing the desired room temperature, powerful and coherent light radiation sources.

Electromagnetic fields produced by CEB. – In this letter, CEB is used to excite the cyclotron SPPs on the circular cylindrical structures, and the schematic is shown in fig. 1(a). To deal with the CEB excitation of cyclotron SPPs, at first we study the electromagnetic fields produced by CEB, as shown in fig. 1(b) and (c).

The electron beam moves along a 3-dimensional cyclotron trajectory with radius r_0 , the velocity along the Z -direction and the cyclotron frequency of the electron beam are u_z and ω_c , respectively. The cyclotron velocity and charge quantity of CEB are $u_\perp = \omega_c r_0$ and q , respectively. The permittivity and permeability in vacuum are ϵ_0 and μ_0 , respectively.

We have considered the spread of the electron beam along the parallel direction, and the velocity distribution function of the electron beam is [10]

$$(f_0(\vec{u}))_{spread} = \frac{1}{\sqrt{\pi}\Delta u_z} \delta(u_\perp - u_{\perp 0}) e^{-\frac{(u_z - u_{z0})^2}{(\Delta u_z)^2}}. \quad (1)$$

Then the current density of the CEB along the Z -direction is

$$(J_z)_{spread} = q \int_0^\infty u_z f_0(\vec{u}) d\vec{u} = q \int_0^\infty u_z \frac{1}{\sqrt{\pi}\Delta u_z} e^{-\frac{(u_z - u_{z0})^2}{(\Delta u_z)^2}} du_z. \quad (2)$$

The integral of eq. (2) could not be completed analytically, but we can do it by means of numerical calculations.

Without consideration of the spread, the velocity distribution function and the current density of CEB along the Z -direction can be written as

$$f_0(\vec{u}) = \delta(u_\perp - u_{\perp 0}) \delta(u_z - u_{z0}), \quad (3)$$

$$J_z = q \int_0^\infty u_z f_0(\vec{u}) d\vec{u} = qu_{z0}. \quad (4)$$

The results of the numerical calculations of $(J_z)_{spread}$ and J_z (for the case $u_{z0} = 0.55c$ and $\Delta u_z = 0.02c$) show

that the influence of the velocity spread is very small, less than $1/1000$. Similarly, it can be shown that the influence of the perpendicular velocity u_\perp spread is also quite small [10]. So we use the velocity distribution function in eq. (3) to simplify the mathematical manipulation in this letter. By solving the Maxwell equations together with the boundary conditions, the electromagnetic fields produced by CEB can be obtained.

In the region $r < r_0$, the electromagnetic fields are

$$\begin{cases} E_z^i = \frac{1}{2\pi} \left(\sum_m \left(j\omega\mu_0 q - \frac{jk_z q}{\omega\epsilon_1\epsilon_0} \left(\frac{m}{r} \frac{u_\perp}{u_z} + k_z \right) \right) I_m(k_c r) \right. \\ \quad \times K_m(k_c r_0) e^{jm\theta} \Big) e^{jk_z z}, \\ H_z^i = \frac{1}{2\pi} \left(\sum_n \frac{qu_\perp}{ru_z} (I_m(k_c r) + rI'_m(k_c r)) K_m(k_c r_0) \right. \\ \quad \times e^{jm\theta} \Big) e^{jk_z z}. \end{cases} \quad (5)$$

In the region $r \geq r_0$, they are

$$\begin{cases} E_z^i = \left(\frac{1}{2\pi} \right) \sum_m \left(j\omega\mu_0 - \frac{k_z}{\omega\epsilon_i\epsilon_0} \left(\frac{m}{r} \frac{u_\perp}{u_z} + k_z \right) \right) \\ \quad \times I_m(k_c r_0) K_m(k_c r) e^{jm\theta} \Big) e^{jk_z z}, \\ H_z^i = \left(\frac{1}{2\pi} \right) \frac{qu_\perp}{ru_z} \sum_m \left(I_m(k_c r_0) (K_m(k_c r) + rK'_m(k_c r)) \right. \\ \quad \times e^{jm\theta} \Big) e^{jk_z z}, \end{cases} \quad (6)$$

where $k_c = \sqrt{k_z^2 - k_0^2}$, $\omega - k_z u_z - \omega_c = 0$, $I_m(k_c r)$ and $K_m(k_c r)$ are the m order modified Bessel functions. It can be seen that the electromagnetic fields produced by CEB contain plenty of modes, including TM mode ($m = 0$) and HEM modes ($TM_{mn} + TE_{mn}$) with $m \neq 0$. And they are evanescent waves, which decay exponentially along the R -direction without phase delay.

Now we should notice how to produce the CEB. It is well known that the electron cyclotron resonance stimulated

emission of radiation has been investigated, and high-power microwave-millimeter wave generators (so-called gyrotrons) have been developed and applied intensively by using the CEB [10]. With an adiabatic varying magnetic field in a uniform longitudinal section, the CEB can be produced [10]. The energy of the electron beam used in this letter is rather low, so the direct radiation by the CEB is neglected [10,11]. In this letter, the permanent magnetic field used to produce CEB is only a few tesla. The electron beam of the scanning electron microscopy (SEM) is often used as the electron beam source to excite SPPs [1,12,13]. Due to the excellent electro-optical system in SEM, the electron beam is very good, and it can be focused by the external magnetic field B_{ext} , to guarantee that CEB moves in the structure.

Excitation of SPPs on circular cylindrical structure by CEB. – Now we deal with the CEB excitation of cyclotron SPPs on circular structure. The schematic is shown in the inset of fig. 2(a), and CEB moves along the structure with radius r_0 . In the presence of the external permanent magnetic field B_{ext} , the dielectric function of the metal is a tensor [10,14–16]. But in our letter, the external magnetic field B_{ext} is parallel to the Z-direction of the structure, as shown in the inset of fig. 2(a), and the cyclotron frequency ω_c^* of the free electron in the metal is much smaller than the operating frequency ω , $\omega_c^* \ll \omega$. In this case, the metal can be considered as an isotropic medium, and its dielectric function can be described by the modified Drude model, for Ag, which is [17–20]

$$\varepsilon_{Ag}(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 - j\gamma\omega}, \quad (7)$$

where ε_∞ is 5.3, ω_p is 1.39×10^{16} rad/s and γ is 3.21×10^{13} Hz. Also the size quantization due to the only 20 nm thick Ag tube will not affect the dielectric function within the application range of the operating frequency ω , since the size quantization energy is only of the order of 1 meV.

Making use of the boundary conditions of the continuity of the tangential components of electric and magnetic fields at $r = r_a$, the dispersion equation and the excited cyclotron SPPs can be obtained. The dispersion curve of the cyclotron SPPs for hybrid modes ($m = 1$) on an Ag wire excited by CEB is shown in fig. 2(a). The operating frequencies and other behaviours of the excited cyclotron SPPs are determined by the working points, which are the intersection points of the dispersion curve and beam lines. The equation of the beam line is $\omega - k_z u_z - \omega_c = 0$, the physics of this equation shows the phase of the SPPs propagation is synchronized with the cyclotron electron beam. As shown in fig. 2(a), the working points for $\beta = 0.4$ and $\beta = 0.6$ ($\beta = u_z/c$, c is the light speed in vacuum) are A and B, respectively. Figure 2(b) shows that for spectra of E_z and H_z , the corresponding operating frequencies are 862 THz and 831 THz, respectively. This indicates that the cyclotron SPPs excited by CEB are coherent and the operating frequency can be tuned by adjusting the energy

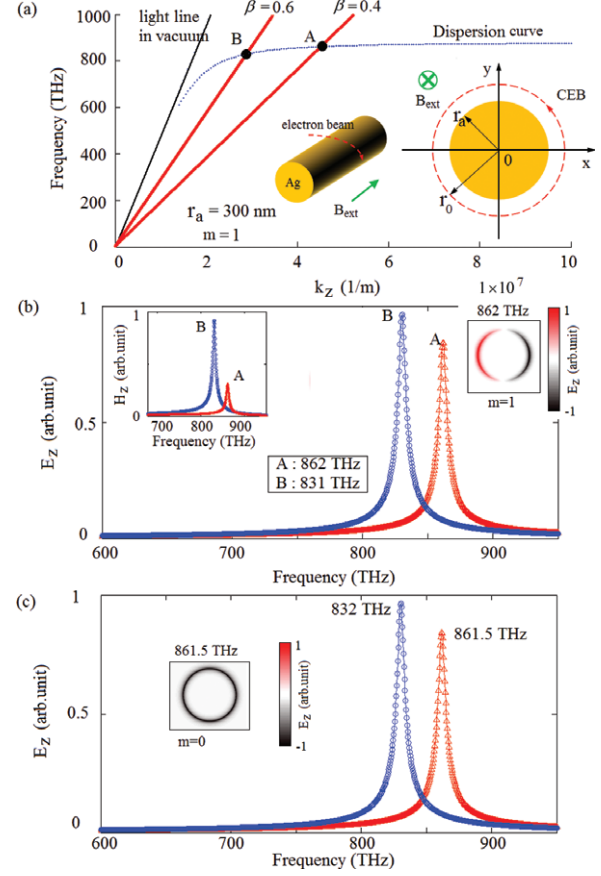


Fig. 2: (Colour on-line) (a) The dispersion curves of cyclotron SPPs excited by CEB, and the inset is the schematic of this excitation. (b) The E_z fields spectra of the cyclotron SPPs at $m = 1$, and the insets are the spectra of the H_z field and the contour map of the E_z field, respectively. (c) The E_z fields spectra of the excited SPPs at $m = 0$, and the inset is the contour map of excited SPPs.

of CEB. The excited cyclotron SPPs propagate along a 3-dimensional cyclotron trajectory around the Ag wire together with the CEB. So the cyclotron SPPs can attract energy from CEB continuously to compensate the energy loss due to the radiation and decay of propagation. It also can be seen from the spectra that the excited cyclotron SPPs contain both HEM modes and TM ($m = 0$) modes, as shown in fig. 2(b) and (c).

Radiation transformation of cyclotron SPPs. – Now we move on to the radiation transformation of the excited cyclotron SPPs. Two kinds of structures, structure I and structure II, are proposed. By matching the boundary conditions at $r = r_a$ and $r = r_b$ in structures I and II, the dispersion curves and the transformed radiation in the two structures can be obtained.

In structure I, the CEB is moving outside the Ag film, and the loading dielectric is inside, as shown in the inset of fig. 3(a). The dispersion curves of structure I for $m = 1$ are shown in fig. 3(a). The outer radius r_a is 120 nm, the inner radius r_b is 100 nm, and the permittivity of the loading

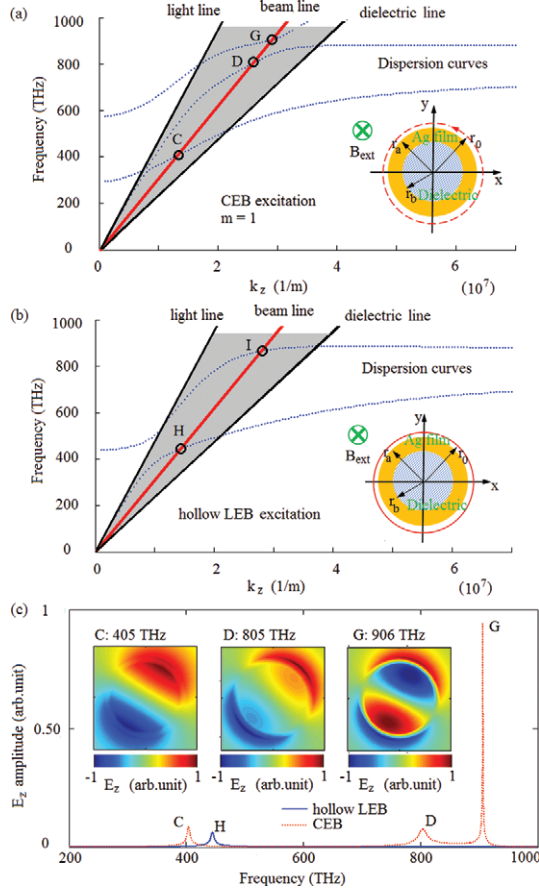


Fig. 3: (Colour on-line) (a) The dispersion curves of structure I excited by CEB, and the inset is the schematic of this structure. (b) The dispersion curves of structure I excited by the hollow electron beam. (c) The spectra of the radiation fields, the red line is for CEB excitation, the blue line is for hollow electron beam excitation, and the insets are the contour maps of the radiation fields excited by CEB.

dielectric is 4. Due to the dual natural periodicity of 2π of the structure and CEB, some dispersion curves lie in the shaded region (radiation region), in which the excited cyclotron SPPs can be transformed into radiation [1]. For the CEB with $\beta = 0.65$ and $\omega_c = 1$ THz, the working points C, D and G in fig. 3(a) are within the radiation region, and the field spectrum is illustrated by the red line in fig. 3(c). This shows that there are three operating modes, and their frequencies are 405 THz, 805 THz and 906 THz corresponding to the three working points C, D and G, respectively. The contour maps for these operating frequencies in the insets of fig. 3(c) show that the radiation fields are confined in the dielectric.

For making a comparison, the radiation transformation of SPPs excited by hollow LEB in structure I is also studied. For CEB excitation, there are many SPPs modes, but for hollow LEB excitation, only TM_{0n} SPPs modes can be excited. So their dispersion curves are different. Consequently, the working points are different at different frequencies. The essential difference is that the radiation density transformed from the cyclotron SPPs gets the

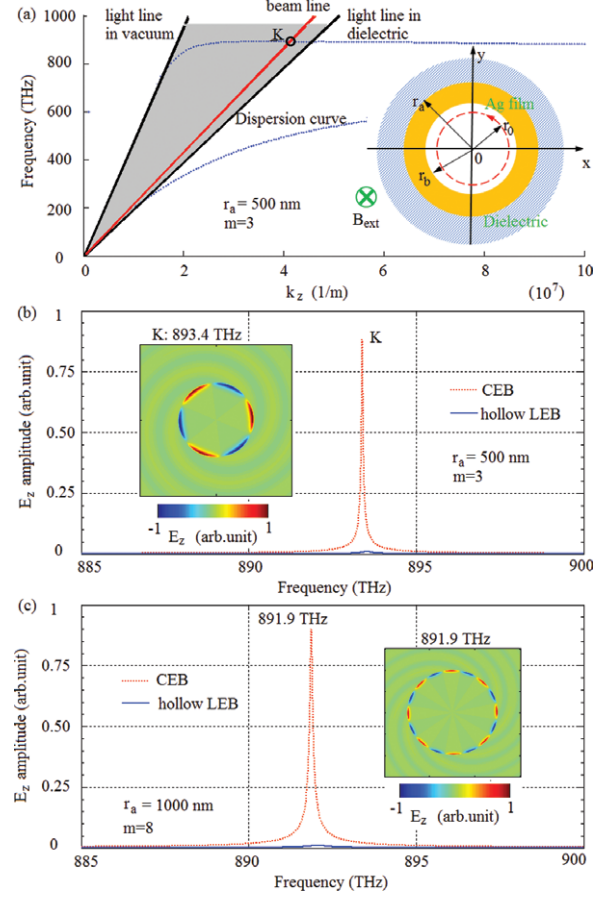


Fig. 4: (Colour on-line) (a) The dispersion curve of the SPPs transformation into radiation in structure II, and the inset is the schematic of this structure. (b) The spectra of the radiation field excited by CEB and hollow electron beam, and the inset is the contour map of the radiation field excited by CEB. (c) The spectra of the radiation field by CEB and hollow beam when r_a is 1000 nm, the inset is the contour map of the radiation field by CEB.

largest amplitude at the operating frequency equal to 906 THz (working point G), and it is much higher (more than 10 times) than that by hollow LEB in fig. 3(c), reaching up to 10^{10} W/cm² with the charge quantity of 0.1 pC.

In the structure II, the CEB is moving inside the Ag film, and the loading dielectric is outside, as shown in the inset of fig. 4(a). The dispersion curve of structure II for $m = 3$ is shown in fig. 4(a). The outer radius r_a is 500 nm, the inner radius r_b is 480 nm, and the permittivity of the loading dielectric is 6. For $\beta = 0.45$ and $\omega_c = 1$ THz, the working point K is located in the shaded region, and the excited cyclotron SPPs can be transformed into coherent radiation. The radiation-field spectrum (red line) and its contour map are shown in fig. 4(b) and its inset, respectively. It can be seen that the transformed radiation propagates in the loading dielectric. For making a comparison, the radiation transformation of SPPs excited by hollow LEB in structure II is also studied, and its radiation field spectrum at the same parameters as CEB

excitation is illustrated by the blue line in fig. 4(b). The result in fig. 4(b) shows that the radiation density transformed from cyclotron SPPs is much higher than that by hollow LEB, reaches up to 10^9 W/cm^2 with the charge quantity of 0.1 pC.

The spectra of the radiation fields transformed from SPPs excited by CEB and the hollow beam in structure II with inner radius r_a 1000 nm are shown in fig. 4(c). This shows that the high mode $m = 8$ for cyclotron SPPs can also be excited by CEB and transformed into radiation. And the amplitude of the radiation field is still much higher than that by the hollow electron beam. This indicates that the geometrical size of structure II in this mechanism can be much larger than a nano-meter, and this is of significance from the viewpoint of practical manufacture.

A more interesting phenomenon is that the electron cyclotron frequency is just about 1 THz, but the frequency region of the excited SPPs and the transformed radiation are much higher, up to hundreds of THz. The physics is that the radiation frequency mainly depends on the frequency of the free-electron gas in the metal film, and the role of the electron cyclotron frequency is to keep the synchronization of the excited SPPs and the electron beam over all the interaction time to guarantee that the excitation and transformation process goes on.

Summary. – The dual nature periodicity of 2π of both the circular structure and CEB not only makes the immediate transformation of the excited SPPs into radiation possible, but also brings significant excellences to the mechanism as follows:

- 1) the hybrid modes of SPPs can be excited by CEB, and the excited SPPs propagate along a 3-dimensional trajectory together with the CEB;
- 2) the density of the radiation transformed from cyclotron SPPs is stronger than that by hollow LEB, and up to 10^{10} W/cm^2 can be achieved;
- 3) it is very interesting that the electron cyclotron frequency is just about 1 THz, but the frequency regime of the excited SPPs and the transformed radiation is much higher, up to hundreds of THz;
- 4) the size of the structures becomes much larger than a nano-meter, this is of significance from the viewpoint of practical manufacture and applications.

Therefore, the mechanism presented and investigated in this letter opens a promising way for developing the desired room temperature coherent radiation sources in the frequency regime from infrared to ultraviolet.

* * *

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