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Abstract

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Mediated coupling of surface plasmon polaritons by a moving electron beam

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Abstract: The mediated coupling of surface plasmon polaritons (SPPs) by a parallel moving electron beam is demonstrated in this paper. The theoretical analysis shows that the electron beam excited spoof surface plasmon polaritons (SSPs) on the grating placed above the metal films play the role as the excitation source in the mediated coupling. The numerical calculations and particle-in-cell simulations demonstrate the significant advantages of the SSPs mediately coupled SPPs in contrast with that coupled by the parallel moving electron beam directly. The photo density of the mediately coupled SPPs reaches up to 10^6 per cm^2 for the electron beam with the charge density 100 nC/cm, which is two orders of magnitude larger than that of the directly coupled SPPs. The tuning band of the mediately coupled SPPs reaches up to 9% for the beam energy ranging from 10 keV to 30 keV, while it almost cannot be tuned for the direct coupling. The lifetime of the mediately coupled SPPs, which reaches up to hundreds of femtoseconds, is also much longer. Accordingly, the mediated coupling may bring great significances for the applications of SPPs.

OCIS codes: (240.6680) Surface plasmons; (230.6080) Sources.

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1. Introductions

Surface plasmon polartions (SPPs), which arise from the collective oscillations of the free electrons in noble metals, are electromagnetic waves highly confined on the metal dielectric interface [1,2]. The properties of SPPs have led to various applications in modern science and technology, such as the biological and chemical sensing [3–5], the near field imaging [6,7], and the enhanced optical transmission [8], etc. As the nature link between optics and electronics, SPPs are recently used to combine the two subjects to generate radiation waves ranging from terahertz to ultra-violet [9–13]. It has been regarded as a promising approach to overcome the terahertz gap, and opens a new way for integrated radiation sources and SPPs applications [14].

The excitation of SPPs have been studied for a long time. The incident plane waves can be coupled into SPPs by the wavevector compensation with lens or gratings [15–17]. Another SPPs excitation approach often used is the electrical dipoles, and the propagation direction of the excited SPPs can be controlled by the arrangement and polarizations of the dipoles [18–20]. SPPs can also be coupled by moving electron beams [21–27], and the experimental and theoretical analysis show that SPPs coupled by parallel moving electron beams have their unique properties compared with that excited by the perpendicular electron beam: they are coherent, tunable, and propagating along the electron beam without attenuation or the additional transition radiation [24]. However, there are also many challenges for the parallel moving electron beam coupling. For example, the tuning band of the coupled SPPs depends on the dispersion relation of metal film, and it almost cannot be tuned when beam energy is under 100 keV; due to the Ohm loss in the metal, the lifetime of the coupled SPPs is very short.

In this paper, we demonstrate the mediated coupling of SPPs by a parallel moving electron beam and show that the above mentioned shortcomings can be overcome. In this scheme, an electron beam moving parallel to the grating placed above the metal films excites spoof surface plasmon polartions (SSPs) [28, 29]. When the excited SSPs satisfy the boundary conditions of SPPs excitation, they will be coupled into SPPs on the metal surfaces. The results of numerical calculation and particle-in-cell (PIC) simulation reveal many significant advantages of this mediated coupling. The photo density of the SSPs mediately coupled SPPs reaches up to 10^6 per cm^2 for 100 nC/cm electron beam, which is two orders of magnitude larger than that of SPPs coupled by parallel electron beam directly. The tuning band of the mediately coupled SPPs reaches up to 9%, or even better, when the beam energy is under 100 keV. The lifetime of the mediately coupled SPPs, which reaches up to hundreds of femtoseconds, are also much longer.

The paper is organized as following: the theoretical and numerical investigation of the mediated coupling of SPPs on a single metal layer are given in section 2. Section 3 demonstrates the physical mechanism of this coupling based on the results of the single metal layer. According to this mechanism, the SSPs mediated coupling of SPPs by a parallel moving electron beam on multilayers is presented in section 4. Section 5 is the effect of the insertion of a sustaining dielectric layer. Section 6 is the conclusion.

2. SSPs mediated coupling of SPPs on a single layer

As shown in Fig. 1(a), a grating is placed above a metal film with distance d, and the electron beam is moving parallel to this grating. And this structure can be divided into 5 regions. Based on the Maxwell equations and Floquet theorem, the dispersion equation of this structure is given as:

$$\frac{\left(\frac{a}{D}\sum_n\left[-j\frac{k_0\varepsilon_3}{k_{3n}\eta}\right]\chi_n \sin c^2\frac{k_{zn}a}{2}\right)-\sqrt{\frac{\varepsilon_0}{\mu_0}}}{\left(\frac{a}{D}\sum_n\left[-j\frac{k_0\varepsilon_1}{k_{1n}\eta}\right]\sin c^2\frac{k_{zn}a}{2}\right)-\sqrt{\frac{\varepsilon_0}{\mu_0}}}\frac{e^{j2k_0d_2}}{e^{j2k_0d_1}}=\frac{\left(\frac{a}{D}\sum_n\left[-j\frac{k_0\varepsilon_3}{k_{3n}\eta}\right]\chi_n \sin c^2\frac{k_{zn}a}{2}\right)+\sqrt{\frac{\varepsilon_0}{\mu_0}}}{\left(\frac{a}{D}\sum_n\left[-j\frac{k_0\varepsilon_1}{k_{1n}\eta}\right]\sin c^2\frac{k_{zn}a}{2}\right)+\sqrt{\frac{\varepsilon_0}{\mu_0}}} \quad (1)$$

where $k_{zn}=k_z\pm(2\pi/D)n$, $k_{in}=\sqrt{k_{zn}{}^2-\varepsilon_i k_0{}^2}$, $\eta=\sqrt{\mu_0/\varepsilon_0}$, the subscript n represents the orders of the space harmonics, and subscript i represents each region of the structure. The coupling between the SSPs and SPPs leads the factor χ_n, which is:

$$\chi_n=\left(\eta_{SPPs}e^{-k_{3n}d}-\eta_{SSPs}e^{k_{3n}d}\right)/\left(\eta_{SPPs}e^{-k_{3n}d}+\eta_{SSPs}e^{k_{3n}d}\right) \quad (2)$$

where

$$\eta_{SPPs}=\left(\varepsilon_4k_{5n}-\varepsilon_5k_{4n}\right)\left(\varepsilon_3k_{4n}+\varepsilon_4k_{3n}\right)e^{-k_{4n}d_3}-\left(\varepsilon_4k_{5n}+\varepsilon_5k_{4n}\right)\left(\varepsilon_3k_{4n}-\varepsilon_4k_{3n}\right)e^{k_{4n}d_3},$$

$$\eta_{SSPs}=\left(\varepsilon_4k_{5n}-\varepsilon_5k_{4n}\right)\left(\varepsilon_3k_{4n}-\varepsilon_4k_{3n}\right)e^{-k_{4n}d_3}+\left(\varepsilon_4k_{5n}+\varepsilon_5k_{4n}\right)\left(\varepsilon_3k_{4n}+\varepsilon_4k_{3n}\right)e^{k_{4n}d_3}.$$

The increasing distance d leads to the decoupling between the SSPs and SPPs, and this factor approaches to −1, and then Eq. (1) becomes the dispersion equation of the grating without the metal film.

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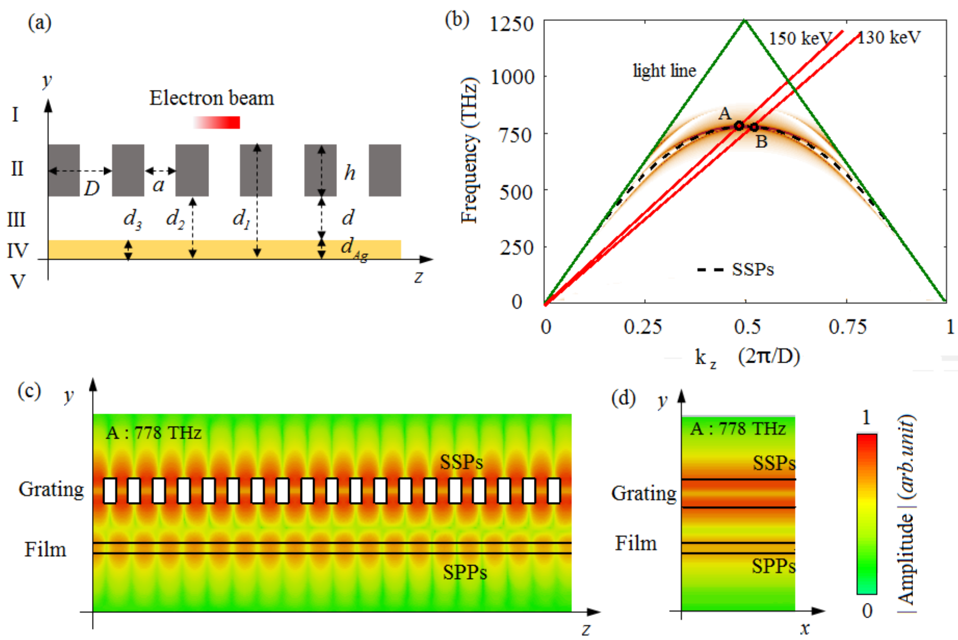

Fig. 1. (a): The schematic of the SSPs mediated coupling of SPPs; (b): The dispersion curves of the mediated coupling; (c) and (d): The contour maps of the E_z field at working point A (778 THz) in y-z plane and x-y plane, respectively.

For the SSPs mediated coupling of SPPs, the dispersion curve of SSPs should be close to that of SPPs. However, a small distance d leads to a strong coupling between SSPs and SPPs, and causes the mismatch of the excited SSPs with the boundary conditions of SPPs coupling. On the other hand, a large d leads to the decoupling between the SSPs and SPPs and results in a low efficiency of the mediated coupling. The dispersion curves based on Eq. (1) with parameters D = 120 nm, a = 60 nm, h = 100 nm, d_{Ag} = 50 nm, and d = 200 nm are shown in Fig. 1(b). The permittivity of the Ag film is adopted from the Ref [30]. The dispersion realtion of the SPPs is shown as the gradual changed yellow part in Fig. 1(b). It can be seen that the dispersion curve of the SSPs is close to that of SPPs, which indicates that the excited SSPs satisfy the boundary conditions of SPPs coupling, and can be coupled into SPPs on the metal film. This is confirmed by the contour maps given by PIC simulation shown in Fig. 1(c) and 1(d), in which the excited SSPs are coupled to the SPPs at the operating frequency 778 THz for electron beam energy 150 keV, corresponding to the working point A shown in Fig. 1(b).

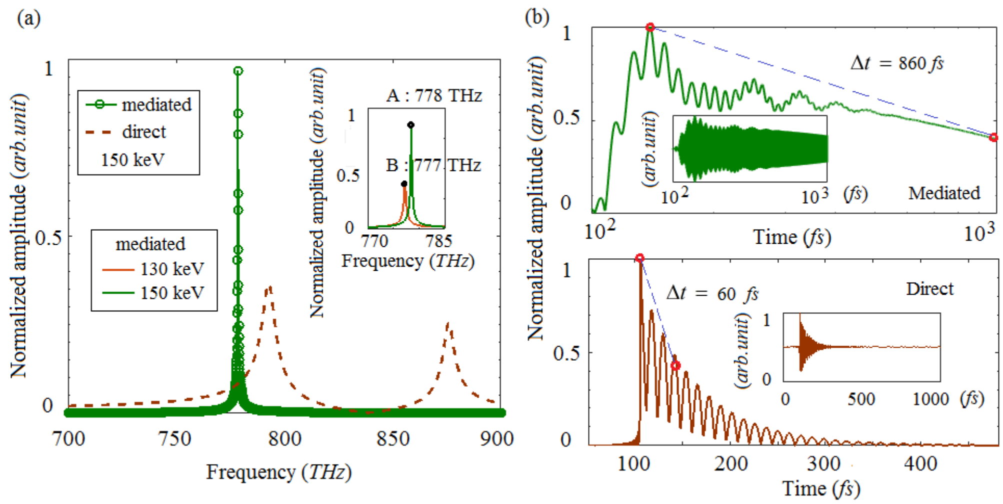

Fig. 2. (a). The spectra of E_z fields of the SSPs mediated and direct coupling, and the inset is that of the mediated coupling for beam energy 130 keV and 150 keV. (b). The E_z fields of the mediated and direct coupling in time domain.

By solving the inhomogeneous Maxwell equations, the coupled SPPs fields can be found as:

$$\left(E_{SPPs}\right)_z = \frac{a}{D}\left(E_2{}^a e^{jk_0d_2} + E_2{}^b e^{-jk_0d_2}\right)\sum_n\left(\sin c\frac{k_{zn}a}{2}\frac{\eta_{SPPs}e^{k_{3n}d_3}}{\eta_{SPPs}e^{-k_{3n}d_3}+\eta_{SSPs}e^{k_{3n}d_3}}e^{-k_{3n}y}e^{jk_{zn}z}\right)e^{-j\omega t} \tag{3}$$

where

$$E_2{}^a = \left(\frac{a}{D}\sum_n\left[-j\frac{k_0\varepsilon_3}{k_{3n}\eta}\right]\chi_n \sin c^2\frac{k_{zn}a}{2}+\sqrt{\frac{\varepsilon_0}{\mu_0}}\right)e^{-jk_0d_2}\left(\left[-j\frac{k_0\varepsilon_1}{k_{1n}\eta}\right]_{n=0}E_e{}^0\sin c\frac{k_{z0}a}{2}-H_e{}^0\right)\zeta^{-1},$$

$$E_2{}^b = \left(\frac{a}{D}\sum_n\left[-j\frac{k_0\varepsilon_3}{k_{3n}\eta}\right]\chi_n \sin c^2\frac{k_{zn}a}{2}-\sqrt{\frac{\varepsilon_0}{\mu_0}}\right)e^{jk_0d_2}\left(\left[-j\frac{k_0\varepsilon_1}{k_{1n}\eta}\right]_{n=0}E_e{}^0\sin c\frac{k_{z0}a}{2}-H_e{}^0\right)\zeta^{-1},$$

$$\zeta = \begin{pmatrix} +\left(\frac{a}{D}\sum_n\left[j\frac{k_0\varepsilon_1}{k_{1n}\eta}\right]\sin c^2\frac{k_{zn}a}{2}+\sqrt{\frac{\varepsilon_0}{\mu_0}}\right)\left(\frac{a}{D}\sum_n\left[j\frac{k_0\varepsilon_3}{k_{3n}\eta}\right]\chi_n\sin c^2\frac{k_{zn}a}{2}-\sqrt{\frac{\varepsilon_0}{\mu_0}}\right)e^{jk_0h} \\ -\left(\frac{a}{D}\sum_n\left[j\frac{k_0\varepsilon_3}{k_{3n}\eta}\right]\chi_n\sin c^2\frac{k_{zn}a}{2}+\sqrt{\frac{\varepsilon_0}{\mu_0}}\right)\left(\frac{a}{D}\sum_n\left[j\frac{k_0\varepsilon_1}{k_{1n}\eta}\right]\sin c^2\frac{k_{zn}a}{2}-\sqrt{\frac{\varepsilon_0}{\mu_0}}\right)e^{-jk_0h} \end{pmatrix},$$

$E_e{}^0$ and $H_e{}^0$ are the incident waves generated by the parallel moving electron beam [24,29].

The spectra of the SPPs fields calculated from Eq. (3) for the SSPs mediated coupling are shown in Fig. 2(a). The amplitude of the mediately coupled SPPs is two times larger than that of SPPs coupled by electron beam directly, in which the electron beam is placed at the surface of the film. The inset of Fig. 2(a) shows that the operating frequencies of the mediated coupled SPPs are 778 THz and 777 THz for beam energy 150 keV and 120 keV, respectively.

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It also can be found in Fig. 2(b) that the lifetime of the mediately coupled SPPs reaches up to 860 femtoseconds, but that of direct coupling is only tens of femtoseconds for the same parameters.

3. The mechanism of the SSPs mediated coupling

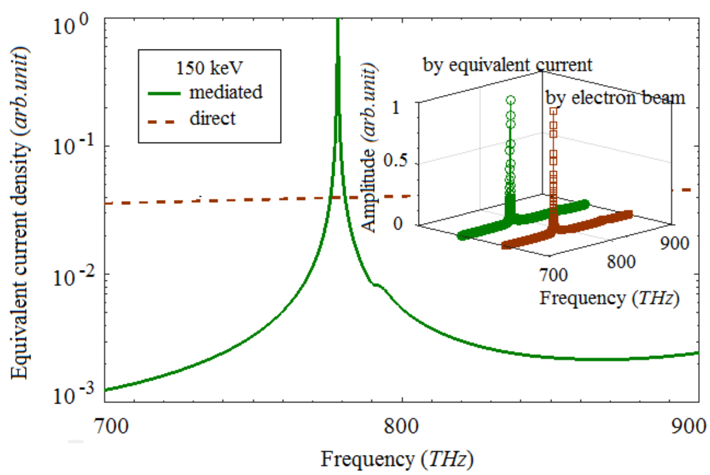

Fig. 3. The equivalent current densities for the mediated and direct coupling. The inset is the spectra of SPPs based on the equivalent current and the electron beam.

Based on the results of the SSPs mediated coupling of the single metal layer, further research is carried out to reveal the physical mechanism of the mediated coupling of SPPs. For this excitation, the parallel moving electron beam excites SSPs on the grating first, and then they are coupled into SPPs on the metal films when they satisfy the boundary conditions of SPPs coupling. This indicates that the excitation sources of SPPs for the mediated coupling are the SSPs, not the incident waves generated by the moving electron beam. As shown in the inset of Fig. 3, the result agrees with the numerical results based on the equivalent currents given in Eq. (4).

$$\iint_s \left(J_{SSPs}^{\;\;eff}\right) dS = \oint_l \sum_n \left[j\frac{k_0 \varepsilon_3}{k_{3n}\eta} \right] \left(E_{SPPs}\right)_z \, dl \tag{4}$$

Figure 3 shows the sources of the mediated and direct coupling by electron beam. Firstly, it can be seen that the amplitude of the source of the mediated coupling is larger than that of direct coupling at the operating frequency, and this leads a larger amplitude of the mediately coupled SPPs compared to that of direct coupling. Secondly, Fig. 3 shows that the source of the mediated coupling has a operating frequency, which is determined by the intersection point of the beam line and the dispersion curve of the grating. Accordingly, the operating frequency of the mediately coupled SPPs can be tuned by varying the beam energy. There is a qualitative difference in operating frequency between two types of couplings, the operating frequency of the mediately coupled SPPs is determined by that of SSPs, while for direct coupling, it is determined by the intersection point of the beam and the SPPs lines [24]. At last, the SSPs, which are the sources for the mediated coupling, are continuous signals, while the incident waves generated by moving electron beam are only pulses. Therefore, the mediately coupled SPPs can get energy continuously from SSPs in the whole period of coupling to compensate the energy loss of SPPs due to propagation. Accordingly, the SSPs mediately coupled SPPs have a much longer lifetime than that of SPPs directly coupled by moving electron beam.

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4. SSPs mediated coupling of SPPs on multilayers

Based on the mechanism presented in section 3, SPPs in multilayers can also be mediately coupled by SSPs, and it can be resolved into two simplified processes: the excitation of SSPs on the grating, and the mediated coupling between the excited SSPs and SPPs in multilayers.

The schematic of the mediated coupling of SPPs on multilayers is shown in the inset of Fig. 4(a), in which a grating is placed above the multilayers formed by the alternate metal films and dielectric films. Due to the coupling of each metal film, the dispersion curves of SPPs on multilayers exhibits a wide band characteristic. Consequently, SPPs on multilayers can be excited in a much broader operating frequency region. When the dispersion curve of the SSPs on the grating is located in this band, the excited SSPs satisfy the boundary conditions of SPPs coupling, and then are coupled into SPPs on the multilayers.

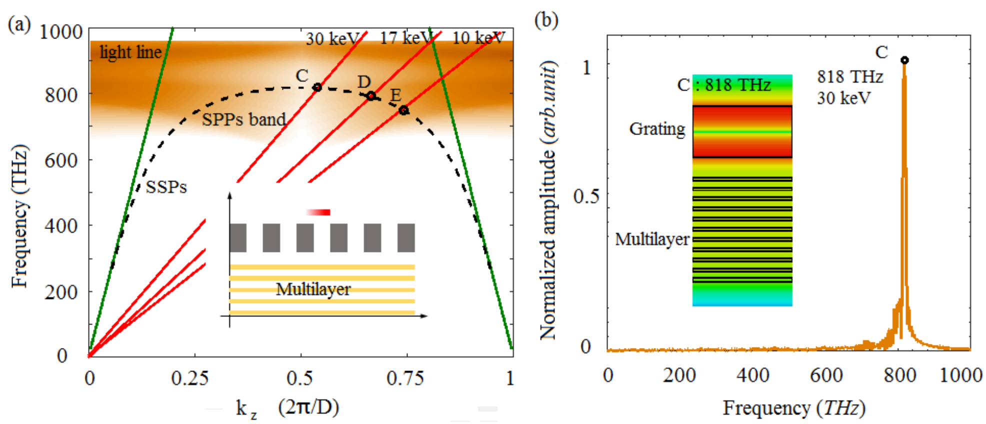

Fig. 4. (a): The dispersion curves of the SSPs mediated coupling of SPPs for multilayers, and the inset is the schematic of this mediated coupling; (b): PIC results of the mediated coupling for multilayers, and the inset is the contour map at the working point C (818 *THz*).

By means of fields matching, the dispersion curves of SPPs in multilayers (11 metal layers) are illustrated in Fig. 4(a) with the following parameters: the metal layer thickness 10 *nm,* and dielectric layer thickness 20 *nm* (considered as vacuum in the calculation and simulation). It demonstrates that the dispersion curves of SPPs in the multilayers are extended in a wide band ranging from 700 *THz* to 850 *THz* and 900 *THz* to 950 *THz* approximately, shown as the gradual changed yellow part in Fig. 4(a). The distance *d* between the grating and the multilayers is set as the sum of the skin depth of SSPs and SPPs, 60 *nm*, to avoid the mismatch of the SSPs with SPPs coupling boundary conditions and the low efficiency of the mediated coupling. As shown in Fig. 4(a), the dispersion curve of the SSPs, the black dashed line, at the grating parameters $D = 60$ *nm*, $a = 30$ *nm*, $h = 150$ *nm,* is located in the SPPs band. Accordingly, the SPPs in the multilayers can be coupled by the excited SSPs. The spectrum of the SSPs mediately coupled SPPs field given by PIC simulation is shown in Fig. 4(b). It suggests that the operating frequency of the mediately coupled SPPs is 818 *THz* for 30 *keV*, which agrees well the working point C shown in Fig. 4(a). The contour map of SPPs by PIC simulation at the operating frequency 818 *THz* is illustrated in the inset of Fig. 4(b), showing the mediated coupling of SPPs in the multilayer by the excited SSPs.

By making use of the equivalent current of the excited SSPs and the boundary conditions, the photo density of the mediately coupled SPPs in the multilayers can be found as:

$$N_{SPPs} = \frac{1}{2\hbar\omega}\int\left(\vec{E}_{SPPs} \times \vec{H}_{SPPs}\right)dS \tag{5}$$

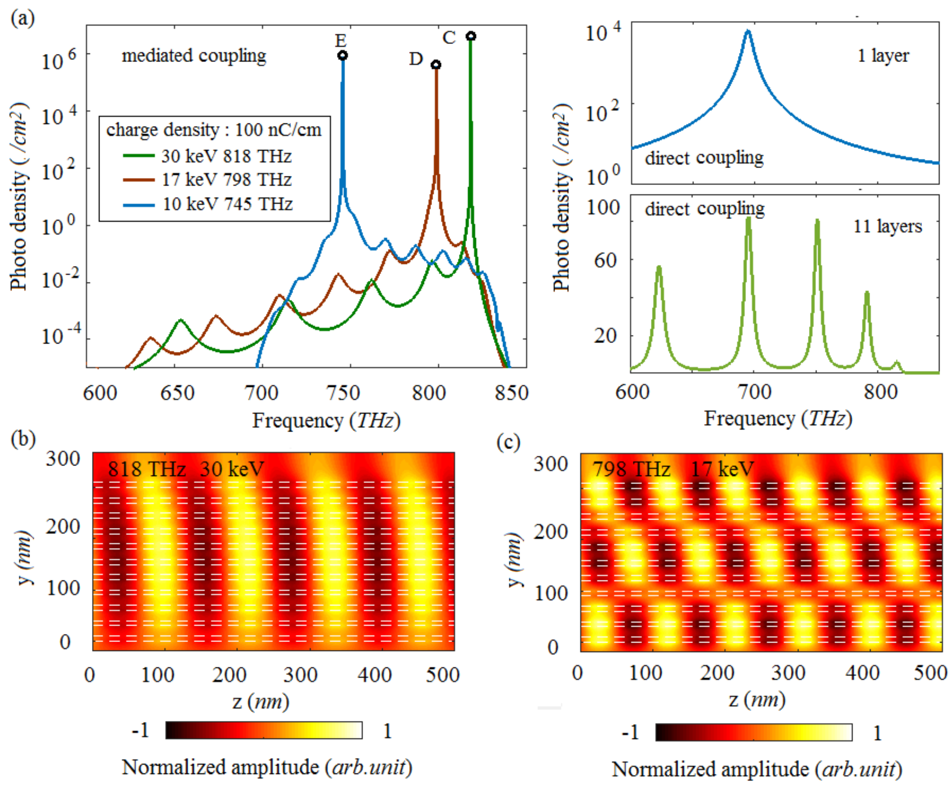

Fig. 5. (a): The photo densities of the mediated and direct couplings; (b) and (c): The contour maps of the mediately coupled SPPs in the multilayers.

The numerical results of photo density are shown in Fig. 5(a). It can be seen that the mediately coupled SPPs photo density reaches up to 10^6 per cm^2 for the electron beam with charge quantity 100 *nC/cm*, and it is 2 orders larger than that of the direct electron beam coupling. It also shows that the operating frequencies of the mediately coupled SPPs are 818 *THz*, 798 *THz* and 745 *THz*, corresponding to the working points C, D and E for beam energy 30 *keV*, 17 *keV* and 10 *keV*, respectively. This indicates that the tuning band of the mediately coupled SPPs reaches up to 9% for the beam energy ranging from 10 *keV* to 30 *keV*. Furthermore, the tunability of the mediately coupled SPPs on multilayers depends on the dispersion relation of the grating and it can be optimized by adjusting the parameters of the grating. However, the directly coupled SPPs in multilayers contain many frequency components as shown in Fig. 5(a), and that on single layer almost cannot be tuned in the same beam energy range. The contour maps of the mediately coupled SPPs at operating frequencies 818 *THz* and 789 *THz* are shown in Figs. 5(b) and 5(c), respectively. They suggest that SPPs on multilayers are coupled with different electromagnetic modes for different beam energies.

The photo densities of the mediately coupled SPPs vs. the metal layer number and the layer gap (dielectric layer thickness) are presented in Figs. 6(a) and 6(b), respectively. It is found that the photo density increases with the metal layer number first and then decreases. This is because that the increasing layer number makes more SPPs can be coupled, but this also results in more Ohm loss. The photo density vs. the layer gap experiences the same trend, for the reason that the rising layer gap not only turns less Ohm loss, but also decouples the SPPs on each film, which makes SPPs cannot be coupled by SSPs in the multilayers, such as the case of layer gap 30 *nm* shown in Fig. 6(b).

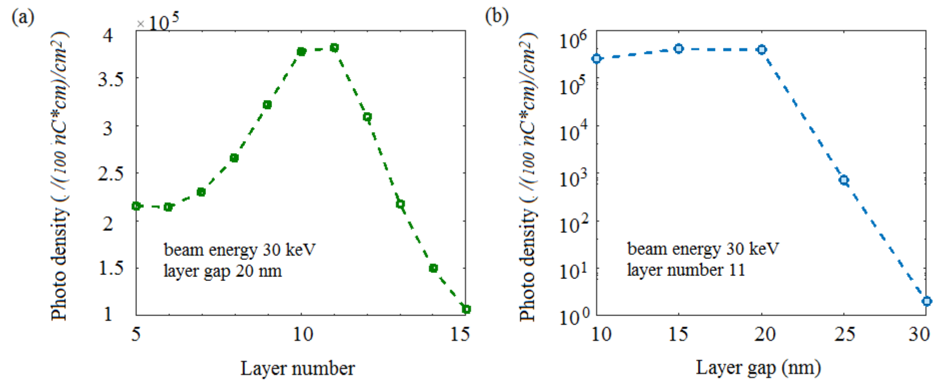

Fig. 6. (a) The photo density vs. metal layer number; (b) The photo density vs. layer gap.

5. Effect of the insertion of a sustaining dielectric layer

The past years have witnessed the progress of the techonolgy of the nano fabrication [31–33]. It is reported that a nanometric grating with a period 200 *nm* can be fabricated in large area by a cost-efficient process [32]. Even more, the period of the nanometric grating consisting of MoS_2 layers is only several nanometers [33]. On the other hand, the progress of the scanning electron microscope provides a promising electron beam to couple SPPs [21]. Accordingly, all these give an opportunity to make a device based on the mechanism of the SSPs mediated coupling of SPPs.

From the point view of practice, for the mediated coupling, there should be a dielectric layer on the metal films to sustain the grating or metal films. Figure 7(a) shows the dependences of the photo densities and operating frequencies on the permitivitty of the inserting dielectric layer. Here, D = 60 *nm*, a = 30 *nm*, h = 150 *nm*, the beam energy is 9 *keV*, and the perimitivitties of all the dielectric layers, including that sustain the grating and multilayer metal films, are the same. It can be seen in Fig. 7(a) that the photo density reaches up to 10^5 per cm^2. It also shows that the operating frequencies of the mediately coupled SPPs is lower than that without dielectric layer insertion. This is because that the dispersion relation of both the SSPs and SPPs are pulled down by the insertion of the dielectric layers [24]. Figure 7(b) demonstrates that the operating frequencies of mediately coupled SPPs with dielectric layers insertion are 634 *THz* and 683 *THz* for electron beam energy 7 *keV* and 10 *keV*, respectively. And this indicates that the tuning band also reaches up to 7.4% for the beam energy ranging from 7 *keV* to 10 *keV*.

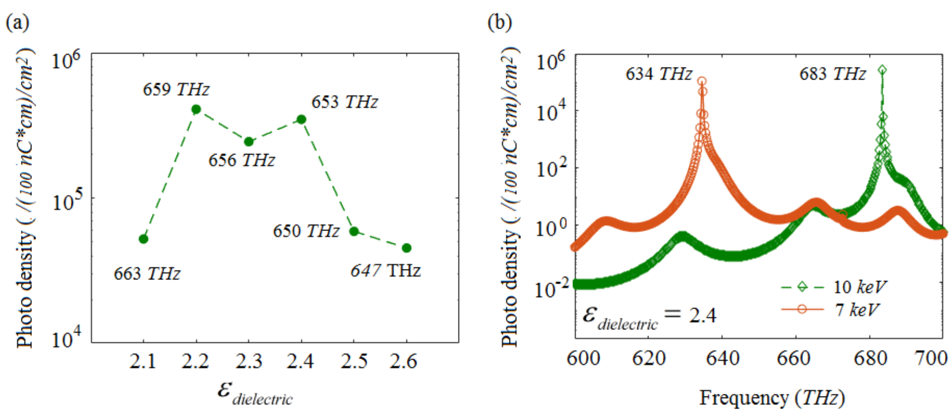

Fig. 7. (a) The photo density vs. permitivitty of dielectric layer; (b) The spectra of the mediately coupled SPPs.

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6. Summary

In summary, the SSPs mediated coupling of SPPs is analysed in this paper. The physical mechanism of this coupling is that the parallel moving electron beam excites the SSPs on the grating first. When the excited SSPs satisfy the boundary conditions of SPPs coupling, they can be coupled into coherent and tunable SPPs on metal surfaces efficiently. In the SSPs mediated coupling of SPPs, the excited SSPs, not the incident waves generated by the electron beam in the direct coupling, play the role as the excitation sources. Compared with the incident waves, the excited SSPs have many unique characters and bring many significant advantages to the mediately coupled SPPs: Firstly, the photo density of the mediately coupled SPPs reaches up to 10^6 per cm^2 for the electron beam with charge density 100 nC/cm, about two orders of magnitude larger than the direct electron beam coupling. Secondly, the tuning band of the mediately coupled SPPs reaches up to 9% for the beam energy ranging from 10 keV to 30 keV, while for direct coupling, it almost cannot be tuned within the same electron beam energy range. Finally, the lifetime of the mediately coupled SPPs reaches up to hundreds of femtoseconds. Based on mechanism of the mediated coupling, SPPs on graphene sheet, semi-conductor and other materials can also be coupled by the SSPs excited by moving electron beams or current pulses on gratings, sub-wavelength holes arrays, spiral lines, meta-materials and other periodical structures. Accordingly, the mediated coupling by a moving electron beam may significantly advance the applications of SPPs, such as the integrated radiation sources, the biological and chemical sensing, and so on.

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