Invited Paper

Electron beam excitation of surface plasmon polaritons and transformation into electromagnetic radiation

Shenggang Liu [1*, 2], Min Hu [1, 2], Renbin Zhong [1, 2], Xiaoxing Chen [1, 2], Ping Zhang [1, 2], Sen Gong [1, 2], Tao Zhao [1, 2]
[1] Terahertz Science and Technology Center, School of Physical Electronics,University of Electronic Science and Technology of China, Chengdu, Sichuan, China, 610054
[2] Cooperative Innovation Center of Terahertz Science, Chengdu, Sichuan, 610054,
[*1] Email: liusg@uestc.edu.cn

(Received 16 June, 2015)

Abstract: The results of many years' research show that only by means of electronics (both vacuum and semiconductor electronics) or only by means of photonics, the whole Terahertz gap could not be covered. Therefore, to look for a way to remove the difficulties is certainly a big challenge. Recently, a novel physical phenomenon has been found: in a structure of nano-scale metal film with dielectric medium loading, the Surface Plasmon Polaritons excited by electron beam can be transformed into enhanced electromagnetic radiation. Based on this physical phenomenon, a concept of combining the electronics and photonics to generate electromagnetic radiation comes up. In this paper, we show that this concept leads to a novel approach, which can not only cover the whole THz gap, but also generate enhanced coherent radiation from THz to ultraviolet.

Keywords: Electron beam, Surface plasmon polaritons, Terahertz Source, Graphene

doi: 10.11906/TST.069-084.2015.06.08

I. Introduction

The Terahertz (THz) gap in electromagnetic wave spectrum is shown in Fig.1. It can be seen that only by means of Electronics (both Vacuum and Semiconductor electronics) or only by means of Photonics, the whole THz gap could not be covered till now [1, 2].

Nevertheless, based on the obtained achievements in 0.3-3 *THz*, recently, THz science and technology has become one of the most attractive research areas in modern science and technology because of its unique characteristics and potential applications. It is a very important frequency regime for physics, chemistry, biology, medicine, astronomy and material science, etc.

THz science and technology are paid wide attention all over the world. The series international conference, IRMMW-THz, usually held for 5 days, including presentations form IR, MMW and THz fields, and there are 2 plenary talks in the morning each day. So, totally there are 10 plenary talks for the whole conference. Usually only 2-3 plenary talks were on THz even at the beginning of 21st century. However, in the 38th IRMMW-THz conference held in Germany (2013) and the 39th IRMMW-THz conference held in USA (2014), total 10 plenary talks were all on THz science and technology. It clearly shows that the main subjects of the IRMMW-THz conference have been shifted to THz.

In the 38th IRMMW-THz conference (2013): besides 10 plenary talks the 44 invited keynote talks were on THz also, accounting for 83% of the total invited keynote talks. And in the 39th IRMMW-THz conference (2014): 545 papers were accepted, in which 493 paper were on THz, accounting for about 90%. Obviously, the subject of the IRMMW-THz conference has fast focusing on THz. In particular, after the 38th conference, *Nature Photonics* published a special issue "Focus THz-Optics" with 6 important papers. It shows that with obtained achievements in the (0.3-3.0) THz frequency regime, people are able to do much for the development of THz science and technology and their applications. This frequency regime is remarkably interesting owing to its potential applications in imaging and spectroscopy for medical diagnostics and biology, high-bandwidth communication, security and defense, and non-destructive evaluation [3].

However, the THz source which can cover the whole THz gap is still an urgent challenge. Tom Lee gave a Plenary talk at IRMMW-THz 2014 “Bridging the Terahertz Gap: Progress and Challenges” [2]. It shows that it is hard for Electronic (including vacuum electronic and semiconductor devices) and Photonic methods to completely satisfy the requirement in THz region.

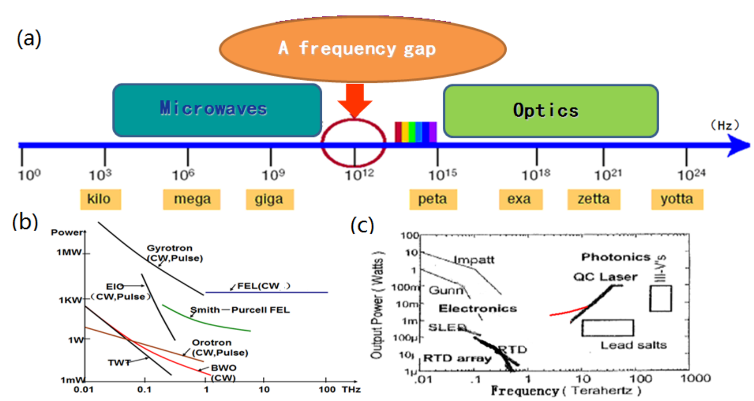

Fig. 1 (a) THz gap in electromagnetic wave spectrum. (b) The output power of vacuum electronic devices. (c) The whole THz gap can not be covered only by means of electronics or only by means of photonics [1-3].

Since it is very hard to cover the whole THz gap only by means of electronics or only by means of photonics, an idea comes up: could we find a way which can combine the electronics and photonics? What we have carried on is that by means of the Surface Plasmon Polaritons (SPPs), we may combine the photonics and electronics for the generation of THz radiation. Our studies show that such combination is really a good promising way.

2. SPPs in Subwavelength hole arrays excited by plane wave and electron beam

Firstly, we start from the extraordinary transmission of the subwavelength hole arrays (SHA). In 1998, T.W. Ebbesen et al. [4] found that SHA display highly unusual zero-order transmission spectra at wavelengths larger than the array period. In particular, sharp peaks in transmission are observed at wavelengths as large as ten times that of the diameter of the cylinders. The maxium peak is orders of magnitude greater than that predicted by standard aperture theory (the transmission efficiency of a single subwavelength aperture is predicted by Bethe [5] to the scale of $(r/\lambda)^4$, where r is the hole radius, λ is wavelength).

Ebbesen's experiments [4, 6] provided evidence that these unusual optical properties are due to the coupling of light with plasmons on the surface of the SHA.

We explore the physics of the electromagnetic diffraction radiation of a SHA excited by a set of evanescent waves generated by a line charge of electron beam moving parallel to the array [7-12].

Activated by a uniformly moving line charge, numerous physical phenomena occur such as the diffraction radiation on both sides of the array as well as the electromagnetic penetration or transmission below or above the cut-off through the holes. Under the excitation, the SHA become Diffraction radiation arrays. Each hole emits its own radiation and the radiation from all the holes together form the entire diffraction radiation, as shown in Fig.2. And the simulation results of contour map shown in Fig.2(b) and 2(c) agree well with those of the analytical results. Moreover, these two figures were selected as the kaleidoscope of PRE (Phys. Rev. E., 80, 2009) [7].

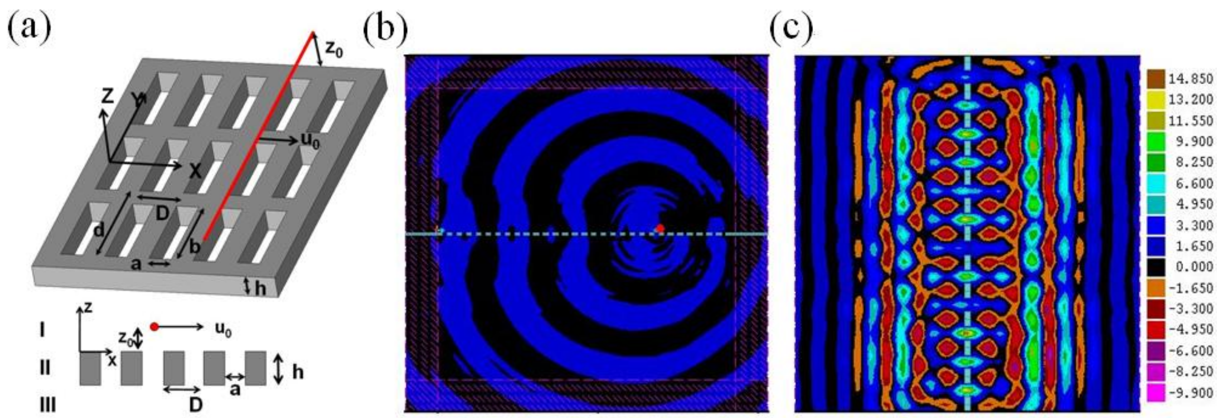

Fig. 2 (a) Schematic structure of holes array excited by line electron beam; (b)Simulation results of contour map of Bz on x y plane; (c) Simulation results of contour map of B_z on y z plane. [7]

The structure can be divided into three regions: (1) upper half space, (2) lower half space and (3) the holes array. By using the following integral equations with relevant Green's functions the analytical theory for such system can be worked out.

$$\vec{E}\left(x,y,z\right)=\iint_{s}\left(\vec{G}\nabla\vec{E}-\vec{E}\nabla\vec{G}\right)d\vec{s} \tag{1}$$

where $\vec{E}(x,y,z)$ is the field in each region, $\vec{G}(x,y,z;x_0,y_0,z_0)$ is the Green function in each region, (x,y,z) are the coordinate of the observe points, and (x_0,y_0,z_0) are the coordinate of the source points. The results of the theoretical calculations and that of the computer simulation are well agreed with each other. The details of the mathematical manipulations can be found in [7].

If the lower half space is filled with dielectric medium, another novel diffraction radiation occurs in the lower half space and it becomes very complicated one. In the case that Cherenkov radiation condition is satisfied in the dielectric medium, the Cherenkov radiation occurs and keeps the Cherenkov cone, and the surface wave is transformed into radiation waves in the dielectric medium [11].

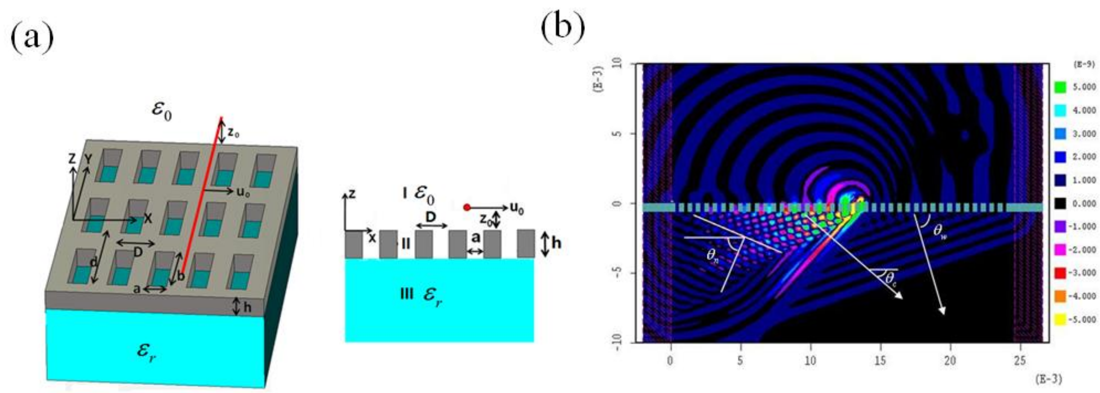

Fig. 3 (a) Schematic structure of SHA with dielectric medium loading in the lower half-space excited by line electron beam. (b) The simulation results of contour map B_y. [11]

For the case with beam energy 60 *kV*, and ε_r=9, the simulation result is given in Fig.3(b). The diffraction radiation in the upper half-space remains unchanged basically. However, in the lower space, the loading dielectric medium brings essential changes to the behavior of the radiation. At first, in the periodical structure, the surface wave can be expanded into space harmonics, and the zeroth-order space harmonic can be transformed into the Cherenkov radiation in the lower half-space provided the Cherenkov condition is fulfilled. Secondly, the negative space harmonics can also become diffraction radiation, and the negative first space harmonic radiation is the strongest one, and/but here this component is a backward wave. Therefore, an interference happens and the interferential spots have an obvious angle θ_n, as shown in Fig.3(b). It also clearly shows that they are formed and determined by interference of the diffraction radiation and Cherenkov radiation.

In additional, we have also studied the interaction between the electron and mimicking surface plasmon [9-12]. The electromagnetic penetration behaviour in the array of subwavelength holes gives the advantage of using two beams to enhance the efficiency.

3. Surface plasmon polaritons excited by electron beam

Till now we have studied the electron beam excitation of SHA. Now we are going to deal with the electron beam excitation of a uniform surface of a film.

Surface plasmon polaritons (SPP) are slow waves due to the collective oscillations of the free electron gas in noble metals [13, 14]. Making use of Fermi-Dirac distribution and Sommerfeld theory of the metal, the dielectric function of such metals can be expressed as modified Drude model [13-16]:

$$\varepsilon_m = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 - i\gamma\omega} \tag{2}$$

Here, γ is the collision frequency, ω_p is plasma frequency and $\omega_p = \sqrt{\frac{ne^2}{m}}$, n is the free electron gas density, e and m are charge and quality of electron. It can be seen that for noble metal (Ag or Au), ω_p is very high, reaching 10^{16} rad/s, and the equivalent dielectric medium may have negative real part. Therefore, it can support SPPs in visible light regime.

SPPs can be excited by incident plane waves and electron beam (e-beam) [17-19]. It should be noticed that the wave vector of SPPs is larger than that of plane wave, so special experimental arrangements have to be designed to provide conservation of the wave vector, such as Krestschmann and Otto geometry as shown in Fig 4 [18, 19].

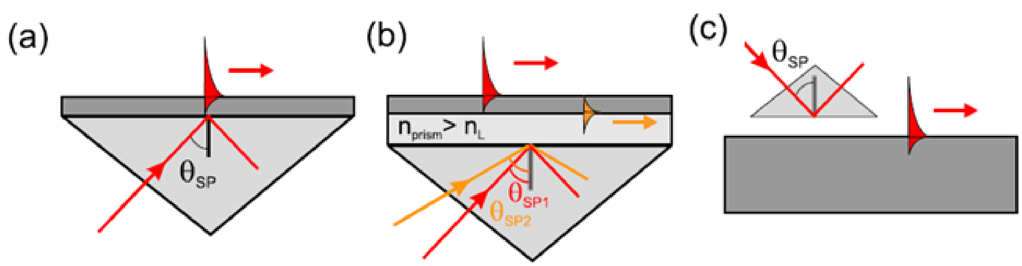

Fig. 4 (a) Kretschmann geometry, (b) two-layer Kretschmann geometry, (c) Otto geometry. [19]

Different from plane wave excitation, SPPs can be excited directly by e-beam moving both perpendicularly and parallel to the metal surface [17-23]. Perpendicular excitation of SPPs has been wildly studied, and the high quality e-beam of scanning electron microscope (SEM) is often used [18-21]. This study has greatly enriched the applications of SEM. Parallel excited SPPs have also potential applications in modern science and technologies. It has been found that parallel excited SPPs can be transformed into coherent and tunable radiation with greatly intensity enhancement [24]. The investigation and comparison of SPPs excited by perpendicular and parallel e-beam indicate that the mechanisms of these two excitation methods are essentially different, and each of them has its own unique behavior and properties [17].

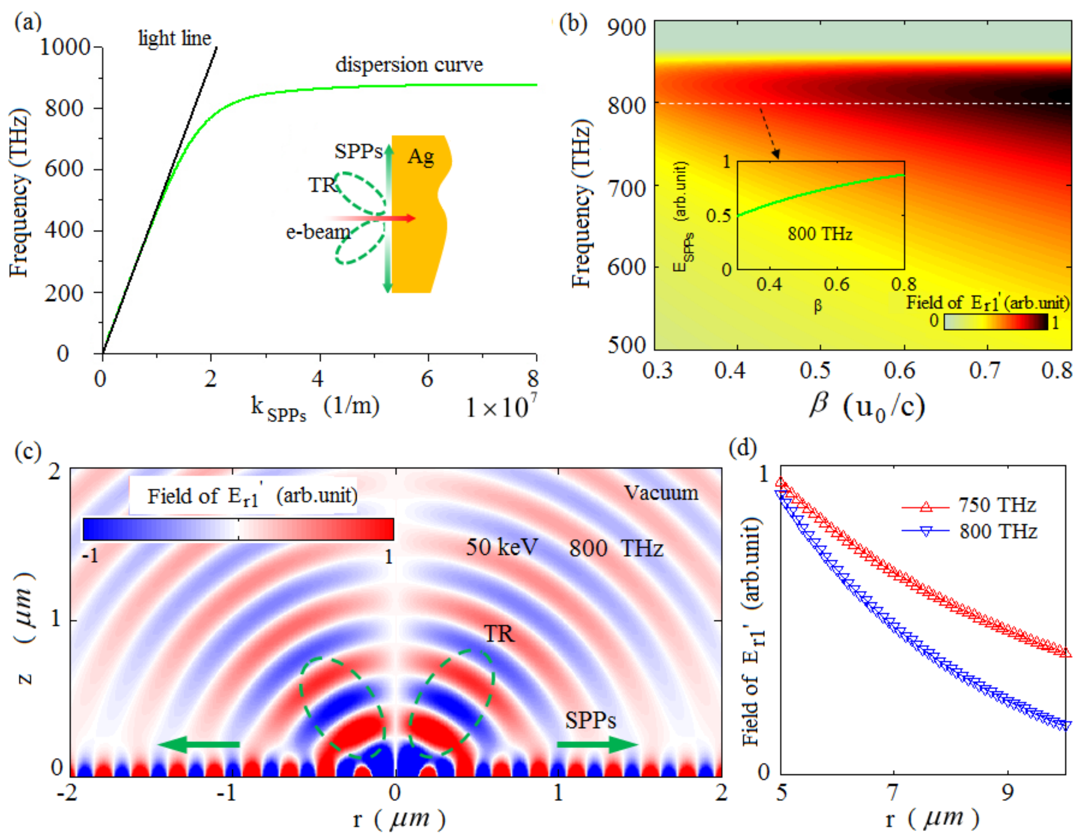

Fig. 5 (a) The dispersion curve of SPPs for perpendicular excitation. (b) The dependence of frequency and SPPs field amplitude on the beam energy and the inset is the field amplitude at fix 800 *THz* VS. Beam energy (β). (c) The contour map of *r*1 *E* 2 of SPPs and TR at 800 *THz* in the vacuum. (d) The SPPs amplitude distribution of field E'_{r1} at 800 *THz* and 750 *THz* along the surface for beam energy 50 *keV*. [17]

In the case of perpendicular excitation, there is no intersection point of beam line and SPPs dispersion curve in Brillouim diagram, and hence there is no working point, as shown in Fig.5 (a). The excited SPPs are not coherent, and contain plenty of frequency components, as shown in Fig. 5(b). The contour map of SPPs and Transition Radiation (TR) fields at 800 *THz* in the vacuum is shown in Fig. 5(c). The excited TR radiate into the vacuum and the excited SPPs are confined to the surface and propagate along the R direction. The amplitude distributions of SPPs E'_{r1} field along the surface at 750 *THz* and 800 *THz* are shown in Fig. 5(d), respectively. It can be seen that different frequency components of SPPs have different decay lengths depending on the imagery part of k_r [17].

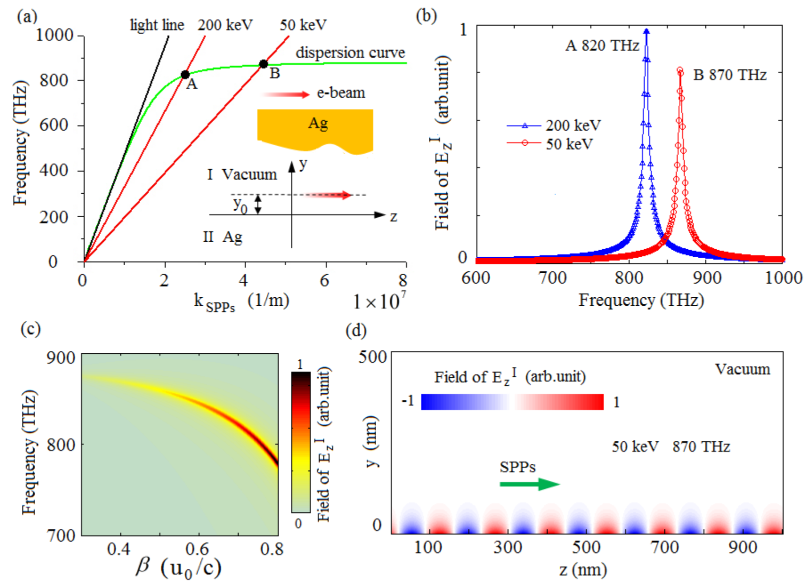

Fig. 6 (a) The dispersion curve of SPPs for parallel excitation. (b) The frequency spectrum of the excited SPPs for beam energy 200 *keV* and 50 *keV*. (c) The dependence of frequency and filed amplitude on the beam energy.(d)The contour map of parallel excited SPPs field in the vacuum.[17]

In the case of parallel excitation, there is an intersection point of beam line and SPPs dispersion curve, so the working point exists. And the frequency and the propagation behavior of SPPs depend on the working point. So coherent SPPs can be excited. Therefore, the parallel excited SPPs waves are coherent and the operating frequency of SPPs can be tuned by adjusting the beam energy, shown in Fig. 6. It is illustrated in Fig. 6(b) that the operating frequency of SPPs is 820 *THz* for beam energy of 200 *keV* and 870 *THz* for 50 *keV*. As shown in Fig. 6(c), the increase of the beam energy leads a lower working point and, in turns, a lower operating frequency. It can be seen that the operating frequency of SPPs can be tuned in a large frequency range. The contour map of the SPPs field at 870 *THz* in vacuum for beam energy 50 *keV* is shown in Fig. 6(d). It can be seen that SPPs are excited by parallel moving e-beam without TR accompanied. Furthermore, the parallel excited SPPs propagate on the Ag surface together with the beam, and then they are able to get energy from the beam continuously to compensate the energy loss due to the metal. Accordingly, there is no attenuation for SPPs excited by the parallel moving e-beam along the propagation direction for a rather long distance [17].

The above results indicate that there are important differences between parallel and perpendicular excitations [17]:

(1) SPPs excited by perpendicular electron beam are always accompanied by transition radiation, but parallel electron beam does not excite transition radiation, etc.

(2) SPPs excited by perpendicular electron beam are decay waves along the propagating direction, and the propagation length is very short, but SPPs excited by parallel electron beam can propagate longer without decay along the propagating direction.

(3) SPPs excited by perpendicular electron beam are not coherent waves and contain plenty of frequency components, but those excited by parallel electron beam are coherent waves.

4. **SPPs Cherenkov Light Source (SPCLS)**

A physical phenomenon has been found: in a structure of nano-scale metal film with dielectric medium loading, the SPPs excited by an electron bunch can be transformed into enhanced Cherenkov radiation [24], as shown in Fig.7. What is even much more interesting is the cylindrical structure, with a dielectric rod coved with a thin metal film, two-colors SPPs Cherenkov light radiations can be generated.

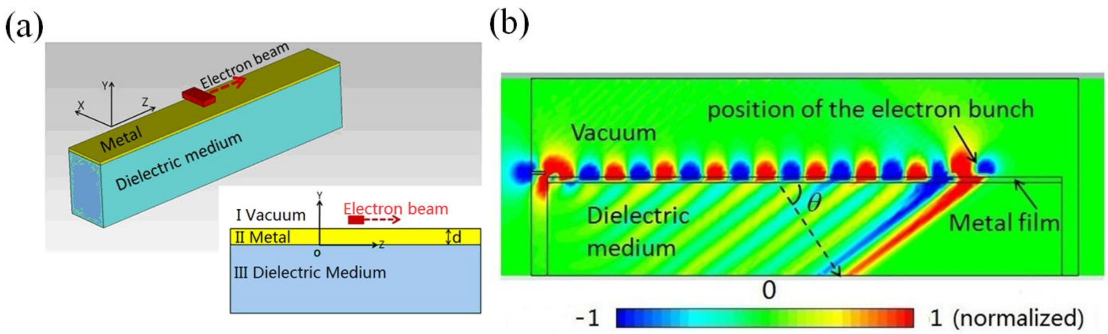

Fig. 7 (a) A schematic of the planar structure SPCLS. (b) A contour map of electrical field E_z excited by electron beam in the planar structure SPCLS. The angle of the Cherenkov cone is θ. [24]

The theoretical analyses and computer simulations are carried out, and their results agree well with each other [24]. Making use of the Maxwell equations, we get a nonhomogeneous Helmholtz equation for electromagnetic fields induced by the electron bunch. Then, solving the nonhomogeneous Helmholtz equation by means of the Wronskian approach, we obtain the electromagnetic fields for each region shown in Fig. 7(a). Matching the boundary conditions, we get the dispersion equation of the SPPs and the Cherenkov radiation power. The numerical calculation results of dispersion relation and output power spectrum are shown in Fig. 8(a). They are well agreed with the computer simulation results shown in Fig. 8(b).

Our results show that the mechanism of SPCLS is essentially different from that of all other kinds of Cherenkov radiation: In the ordinary cases, Cherenkov radiation is a broad and continuous spectrum radiation, and the maximum radiation frequency depends on the highest response frequency of the medium. For Cherenkov radiation in a waveguide filled with dielectric medium, the radiation frequency is determined by the wave band of the waveguide. In the case that the electron beam vertically incidents to a metal film, the excited Cherenkov radiation might be accompanied by transition radiation. As for SPCLS, the uniformly moving electron bunch does not excite Cherenkov radiation in the metal film directly, instead, it excites the SPPs at first, and then the SPPs are to be transformed into Cherenkov radiation with intensity enhancement automatically in the dielectric medium on which the metal film is embedded. Therefore, the velocity of the moving electron beam is not required to be higher than, but just equals to the phase velocity of the SPPs. And the frequency of the radiation is determined by the intersection of the beam line with the SPPs dispersion curve, which means the SPPs in SPCLS serves as a "Tunable Frequency Filter" [24].

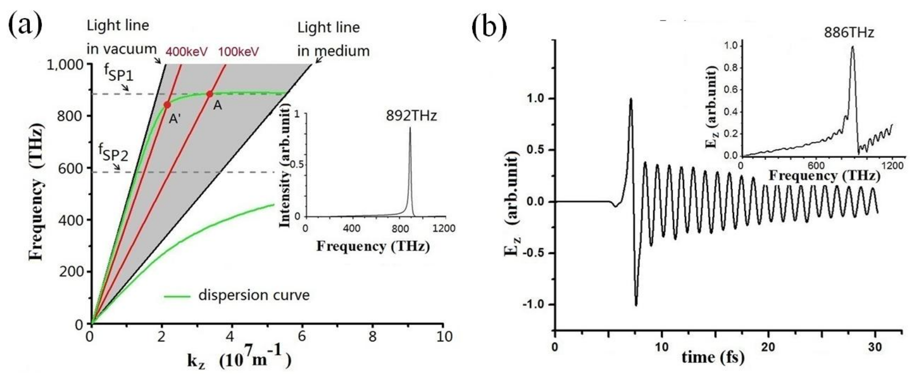

Fig. 8 (a) Dispersion curves of d=20 *nm* thick Ag film covering the dielectric medium ($\varepsilon_d = 9$). The intersection is A or A' for electron beam lines with energy of 100 or 400 *keV*. f_{SP1} and f_{SP2} are the surface plasmon frequencies at the vacuum-metal and metal-dielectric interfaces, respectively. The inset of Fig. 7(a) shows the calculated power spectrum. (b) Field E_z of the simulation and its Fourier spectrum. [24]

SPCLS has following unique characteristics: It can generate radiation from visible light to ultraviolet regime; it is a broad band tunable coherent light radiation source; for the cylindrical structure, it may generate two-color light with the same Cherenkov cone; its power density is high, up to 10^8 *W/cm*^{2} or even higher, depending on the beam energy and current density. It is of micro/nano-scale size, so it can be integrated on chip and can be built into the light radiation array to increase the output power.

This work is reviewed by *Nature Physics* as “a welcome surprise, indeed, that the same physical phenomenon could prove valuable for both detectors and sources of light ”[25] before publication.

5. Graphene SPPs excited by E-beam

Recently, graphene has become the most attractive research area in modern science and technology because of its exceptional properties and great potential applications. We have noticed that the real party of equivalent dielectric function of a graphene sheet is negative, so it supports SPPs, and the plasmon frequency of graphene lies in the 1-50 *THz* frequency regime [26, 27]. From the point of view of SPPs behavior and the excitation, graphene sheet is similar to the thin noble metal film. For example, graphene SPPs can also be excited by incident plane wave, strong near-field and electron beam, etc. Moreover, graphene SPPs have many advantages over metal film SPPs because the conductivity and permittivity of graphene can be controlled by adjusting external gate voltage, chemical doping, etc. Based on graphene SPPs excited by a parallel moving electron beam, a novel approach for generation of THz radiation is explored [28].

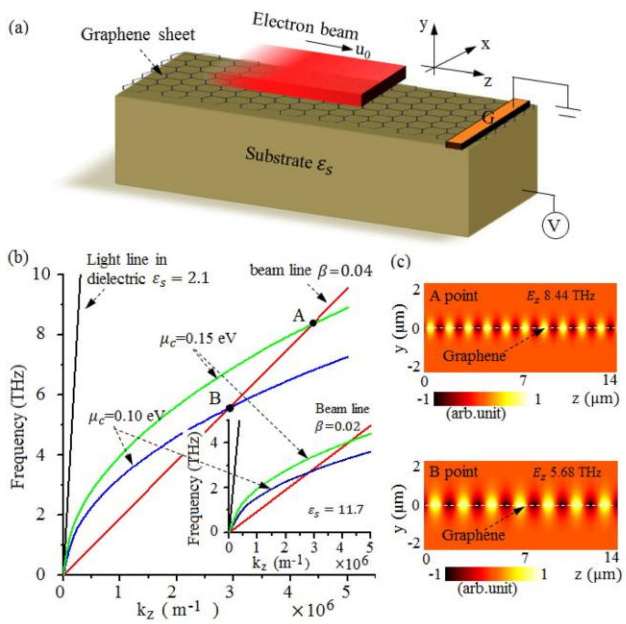

Fig. 9 (a) A monolayer graphene is on a dielectric substrate and an electron beam uniformly moves parallel above the graphene. (b) The dispersion curves of the structure with the substrate (TPX). The light line in vacuum almost coincides with that in dielectric. The inset is the dispersion curve for the substrate (Si).(c) The contour map of graphene SPPs at working points A and B.s [28]

In the case of parallel electron beam excitation shown in Fig. 9(a), graphene SPPs can propagate together with the electron beam for that their phase velocity equals the velocity of electron beam. The SPPs can obtain energy continuously from electron beam to compensate their energy loss during propagation. Fig. 9(c) clearly shows the graphene SPPs propagation and SPPs are tightly confined to the both sides of graphene sheet.

The SPPs cannot radiate directly from the graphene sheet. It could be transformed into Cherenkov radiation, if the working points are in the radiation region, and a cone is formed by the vacuum light line. However, the SPPs dispersion curves shown in Fig. 9(b) are always below the dielectric light line, so the intersections of SPPs dispersion curves and the beam line are always below the radiation region, irrespective of whether the permittivity of the dielectric substrate is lower or higher. Therefore, it is not possible to transform graphene SPPs into Cherenkov radiation.

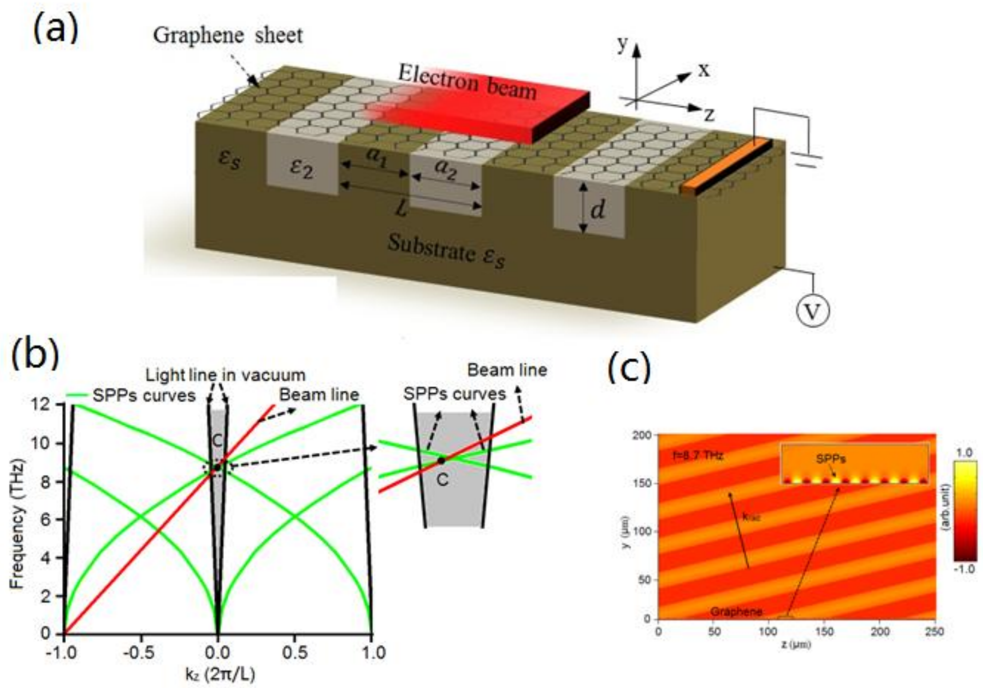

Fig. 10 (a) The schematic of graphene sheet with a micrometer dielectric slits array substrate. (b) The dispersion curves. (c) The contour map of Ez field at working point C (8.7 *THz*), and the inset is enlarged view near the graphene sheet. [28]

We propose micrometer dielectric slits array substrate structure in which the wave vector mismatch can be removed and the SPP-beam line intersection can be brought back within the cone region formed by the light lines. The schematic of graphene sheet with a micrometer dielectric slits array substrate are shown in Fig. 10(a). SPPs in graphene are excited by a uniformly moving electron beam and it propagate with the electron beam. Then making use of the periodicity of the dielectrics the SPPs can be transformed into radiation waves, and the enhanced coherent SPPs radiation can be achieved [28].

The dispersion curves of the structure are plotted as green lines and blue lines shown in Fig.10(b). The beam line intersects dispersion curves at points c. Fig.10(b) indicates that the intersections of dispersion curves and beam line can get in the radiation region between the two vacuum light lines, and hence SPPs can be transformed into coherent radiation in free space. The radiation pattern is shown in Fig.10(c). The radiation frequency is in the THz frequency regime, and it is tunable by changing the beam energy, and the tunability can reach $\Delta f / f_0 = 5\%$.

6.THz radiation from Nonlinear Graphene SPPs

Let's consider a graphene embedded on a dielectrics with a dielectric constant ε_1. The above mentioned graphene is a different type of dielectrics with dielectric constant ε_2, as shown in Fig.11(a). When the field amplitude is greater than 5 *kV/cm*, the conductivity is dominated by the nonlinear term. The nonlinear effect increases with both decreasing the frequency and increasing the temperature.

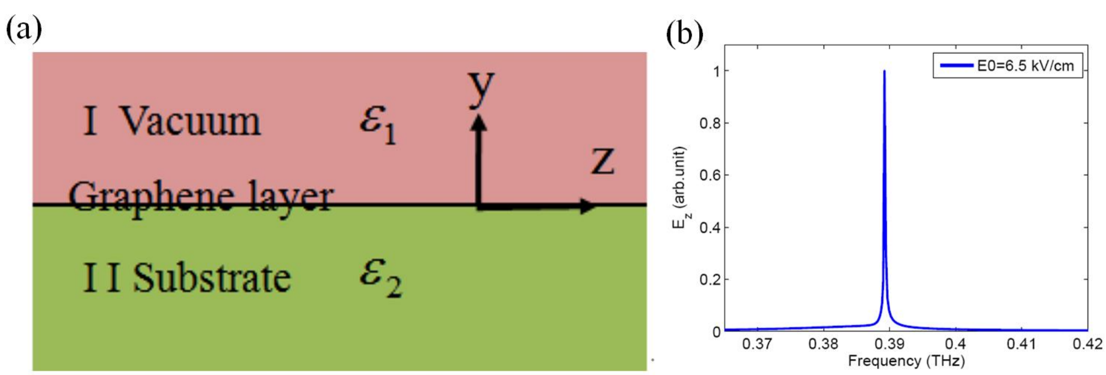

Fig. 11 (a) A layer of graphene is sandwiched between two dielectrics. (b) Radiation field distribution due to the nonlinear SPP in dielectrics, and the peak frequency is 0.39 *THz*. [29]

Due to a nonlinear current in the graphene, the SPP mode has a higher phase velocity than the phase velocity of the light in the dielectrics. When excited by an electron beam moving at speed faster than that of the light in the dielectrics, the SPP can be transformed into Cherenkov radiation. Fig. 11(b) shows that the radiation field is directly transformed from the nonlinear SPP [29].

7. Conclusion

In conclusion, a novel physical phenomenon has been found in a system. while excited by parallel moving electron beam in noble metal thin film with dielectric loading, the excited SPPs can be transformed into electromagnetic radiation. Consequently, new approaches with the concept of combining the electronics and photonics to generate electromagnetic radiation are presented. If the thin metal film is used, the radiation frequency from infrared to ultraviolent frequency regime can be achieved. If the graphene sheet is used to replace the noble metal thin film in a periodical dielectrics loading structure, the SPPs of graphene can be transformed into radiation waves, and the entire THz gap can be covered. Moreover, due to the nonlinear conductivity of graphene sheet, the electron beam excited SPPs can be transformed into THz radiation directly.

Therefore, this concept and the approach may open a way to develop tunable, room temperature and miniature sources which can cover a large frequency regime from THz to ultraviolet with very high power density. Moreover, it is of micro- or nanoscale size, so it can be integrated on a chip and built into a radiation array. The experimental study for both metal film and graphene sheet is progressing. The preliminary results verify the theory.

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