Terahertz Radiation Generated from Graphene Hyperbolic Metamaterial

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***Abstract*—We demonstrate an on-chip terahertz emitter based on Cherenkov radiation in terahertz band generated in graphene-based hyperbolic metamaterials. Terahertz radiation with power of 60-100nW at 8THz is observed experimentally, which is valuable in terahertz technology.**

Keywords—terahertz radiation, Cherenkov radiation, hyperbolic metamaterial

I. Introduction

Cherenkov radiation (CR) is a kind of electromagnetic radiation generated by moving charged particles passing through the medium at a velocity exceeding the phase velocity of light [1]. By using hyperbolic metamaterials (HMMs), a kind of artificial materials with anisotropic permittivity with different sign in different directions [2], the kinetic energy of electrons for exciting CR could be greatly reduced due to the threshold-less CR effect [3]. Namely, the electron velocity u_0 lower than $c/\varepsilon_x^{1/2}$ could excite CR, where ε_x represents the positive permittivity orthogonal to the metamaterial layer [3].

In recent years, many HMMs-based CR emitters were theoretically studied in different special frequency ranges such as visible light [3], deep ultraviolet [4], and THz [5]. Only the THz CR from HMMs has not been observed in experiment yet because of the difficulties in material preparation and device fabrication [6]. On the other hand, the low-energy THz free electron source remains one of the most important issues in THz technology with promising applications in wireless communication, composition detection, and medicine [7].

Here, we demonstrate an on-chip terahertz radiation source based on graphene hyperbolic metamaterial. Low-energy electron beam (E=1.5-2.5keV) generated by Mo planar electron emitter passes above the graphene-hexagonal boron nitride (hBN) layered HMM and generates 1-10THz CR within the material. After extracted by Au grating, the THz radiation with power about 60-100nW and frequency at ~8THz has been derived. This work provides a kind of new method for integrated THz sources.

II. Device Design And Fabrication

Fig. 1(a) is the sketch of the on-chip terahertz free electron source which contains three important parts. The on-chip Mo electron emitter could emit free electron beam to excite CR in HMM, graphene-hBN HMM is adopted as the THz CR medium, and the Au grating with narrow slots is for extracting the CR mode in HMM to free space THz radiation due to wave vector compensation and localized surface plasmon (LSP) enhancement [8]. During device preparation, the Mo electron emitter is patterned using ultraviolet lithography and deposited by magnetic sputtering. The cathode is a 40μm-wide and 550nm-thick trapezoid with several tips at the end to enhance the local electric field for electron beam emission, and the distance between the cathode and anode is set as 50μm for the space of the HMM. The grating with period of 3μm and slot width of 1μm is etched in the ~50nm-thick Au area between the Mo electrodes. Above the grating, 4-layer graphene-hBN HMM is prepared layer by layer through the polydimethylsiloxane (PDMS) dry transfer method [9] and the overall thickness is about 150-200nm. Fig. 1(b) shows the photo of the device under the optical microscope and Fig. 1(c) is the image of the chip.

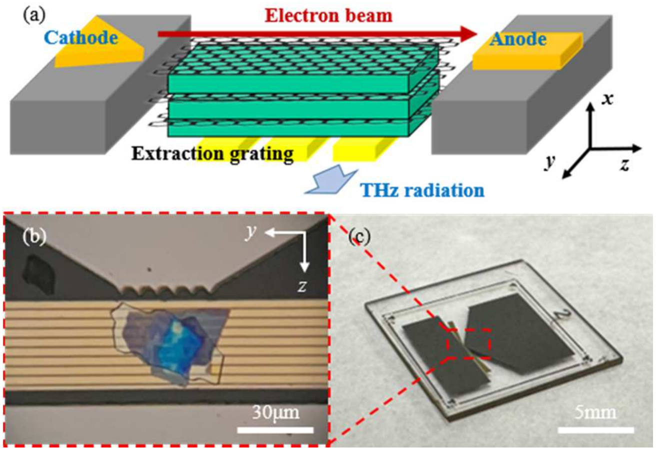

Fig. 1. Integrated terahertz source. (a)Sketch of the structure of the source, (b) Optical microscope image of the core area in the device, (c)Image of the device.

THz HMM is the most important part of the device where THz CR is excited by electron beam emitted by the Mo cathode. To develop the THz HMM, graphene is adopted to be the plasmonic layer to support the THz surface plasmon polaritons (SPP) [10], and hBN is adopted to be the dielectric material for its low-loss dielectric properties in THz region [11]. Fig. 2(a) depicts the anisotropic permittivity dispersion of a 40-layer metamaterial alternately stacked by 1nm graphene and 50nm hBN in THz band. The orthogonal component is positive while the parallel component stays negative within 1-10THz, which means the multilayer-structure has hyperbolic properties. Fig. 2(b) depicts the effective refractive index of the excited CR modes when electron energy is E=0.1keV, 1keV and 10keV. The results indicate that the CR modes in HMM are strongly confined within several micrometers which facilitates device integration. Fig. 2(c) depicts the simulated field distribution

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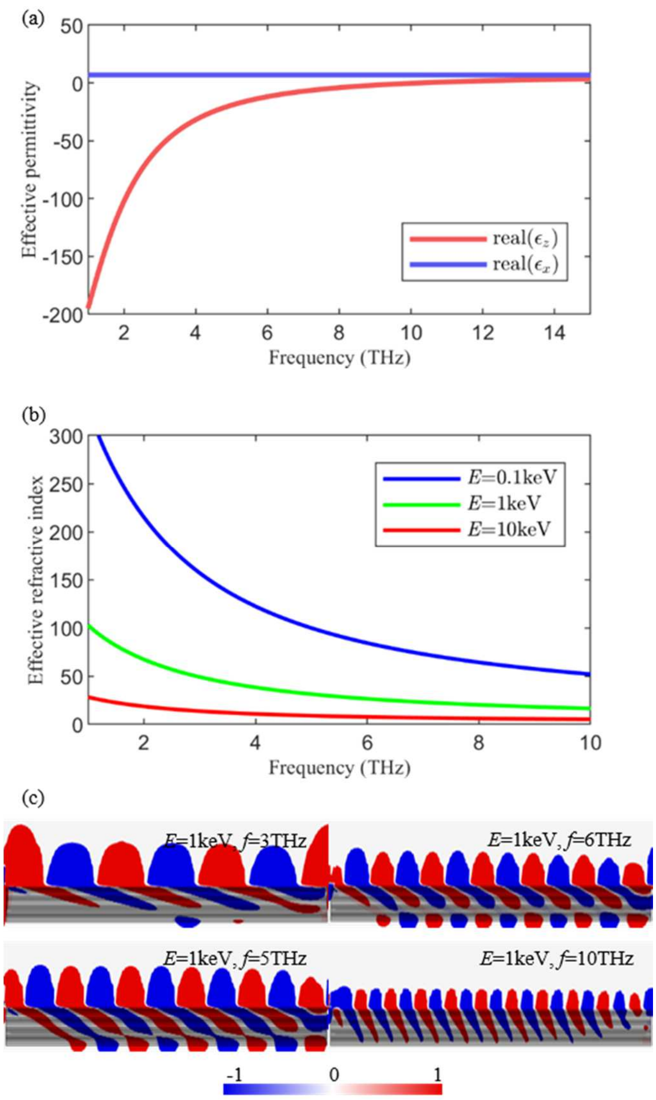

Fig. 2. Calculated and simulated CR properties in the metamaterial. (a)Anisotropic permittivity of the metamaterial in THz band. (b)Effective refractive index of CR modes in the metamaterial with different electron energy. (c)Simulated CR field contour (component parallel to the electrons trajectory) when E=1keV in different frequency.

(electric field component E_z) of the CR modes in HMM at frequencies f=3THz, 5THz, 6THz and 10THz.

III. Experiment Set-up And Results

Fig. 3 gives the sketch of experiment set-up for the radiation spectrum measurement. The source chip is fixed in a vacuum chamber with vacuum degree <10^{-6} Pa while two electrode probes connect the Mo cathode and anode for the load of accelerating voltage. Poly-4-methyl-1-pentene (TPX) lens and quartz window are adopted to focus and export the THz radiation from the chip and out of the chamber, respectively. A chopper operating at 15Hz is adopted to modulate the radiation into sine style which can be detected by the THz detector directly. Radiation is detected and analyzed by Golay THz detector equipped with THz scanning Fabry-Perot interferometer (TSFPI). When the cavity length is scanned continuously, the THz transmission intensity would change accordingly and the spectrum can be calculated by Fourier transformation.

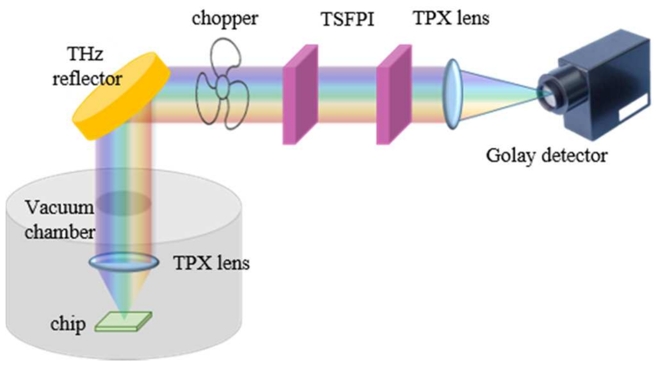

Fig. 3. Experiment set-up for the measurement of radiation spectrum.

Fig. 4 depicts the measured radiation spectrum of the device with the spectrum intensity normalized by the maximum value of both the two figures. Fig. 4(a) shows the normalized noise spectrum when the voltage between cathode and anode is not loaded, which reveals the background noise and the internal noise of the detector (affected by the vibration and temperature or other factors). The noise power detected by Golay cell is about 10-15nW. Fig. 4(b) depicts the obvious signal peak in $f \approx 8.06$THz when voltage is set to 2kV and grating period is 3μm, which is significantly different from the noise spectrum in Fig. 4(a). The measured result is in good agreement with the calculated radiation frequency $f_{calculated}$ =8.815THz in the range of allowable error considering the inevitable insufficient electron-acceleration in experiment and fabrication errors of the HMM. The maximum detected power in this case is about 60-100nW which is over 4 times stronger than that of the noise. This result is experimentally repeatable in different devices with the same structure parameters. The measured results confirm that the HMM-based on-chip free electron source could generate THz radiation with frequency lying in 1-10THz range, which is hard to realize in minimized free electron devices. Moreover, if the grating period or the

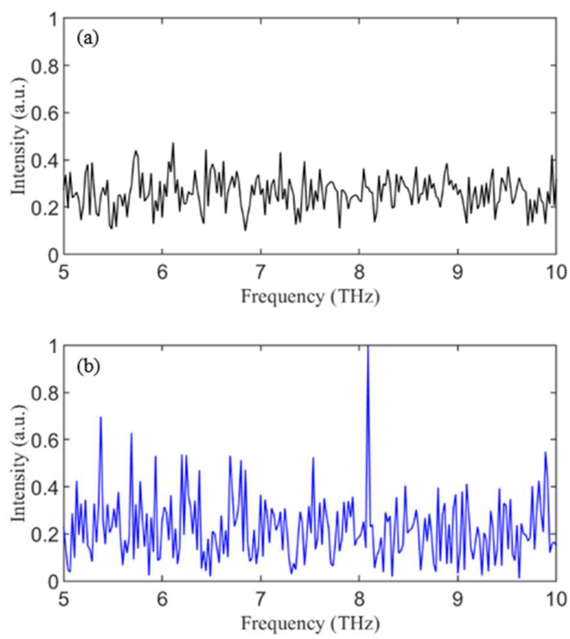

Fig. 4. Measured spectrum of the device. (a) Noise spectrum when the voltage is not loaded. (b) Signal spectrum when voltage between cathode and anode is 2kV.

electron energy (decided by the accelerating voltage) is changed, the radiation frequency could be tuned in a wide range, which is promising for tunable terahertz sources.

IV. CONCLUSION

In conclusion, by constructing THz HMM with graphene and hBN multilayers, we developed an on-chip integrated THz free electron source based on the CR in HMM. The THz radiation with power 60-100nW at frequency of ~8THz is observed in experiment which is consistent with calculation and simulation. The device size is 3 orders of magnitude smaller than the previous THz free electron sources which has the application potential for THz communication and imaging. In the future, arrayed tunable THz source might also be realized by adopting the HMM-based integrated THz source.

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