

RESEARCH ARTICLE

Giant Broadband Electric Field Enhancement Mediated by Ω -Shaped Antenna and Its Application on Ultrasensitive Terahertz Detectors

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ABSTRACT

Receiving antennas that concentrate the free-space electromagnetic energy into the deep sub-wavelength feed gaps can significantly improve the performance of terahertz (THz) detectors. However, narrow bandwidths of traditional resonant antennas limit the response bandwidth of THz detectors. Here, we propose Ω -shaped split ring (OSR) antennas and demonstrate their application in THz detectors. First, the inductive-capacitive and the fundamental dipole resonances of OSR antennas are systematically investigated. Owing to the shrinkage of frequency interval and the resultant synergistic effects between the two resonant modes, the OSR antenna demonstrates a high designed electric field enhancement factor of larger than 40 within a wide bandwidth of 0.4 THz. Subsequently, we design and realize an asymmetrically OSR-antenna-integrated THz photothermoelectric (PTE) graphene detector on a flexible polyimide substrate. The OSR-antenna-induced giant THz electric field enhancement greatly improves THz free-carrier absorption in the graphene channel and drives a fast and sensitive PTE response. In room temperature and zero-bias working conditions, the flexible THz detector demonstrates an excellent detection performance with a fast response (8 μ s), a high responsivity (908 V/W), and a high sensitivity (5.8 pW/Hz^{1/2}). Our research shows that the OSR antennas have great potential to realize high-performance flexible THz sensing devices.

1 | Introduction

Antennas are key components for electromagnetic wave emitting and receiving, and can significantly improve the performance of detection systems [1–7]. Split ring resonators (SRRs) and dipole antennas are two common types of resonant antennas, featuring high gains and narrow bandwidths [8–17]. However, for most resonant antennas, there is a trade-off between gain and bandwidth. Although SRRs exhibit the inductive-capacitive (LC) resonance

and fundamental dipole resonance, there is a large frequency interval between the two resonances [18, 19]. As a variation of SRRs, Ω -shaped split ring (OSR) antennas can overcome this limitation by designing the LC and dipole resonant frequencies separately. An OSR antenna consists of a pair of metal strips with a narrow gap between them and a metal square loop (having three edges), which is symmetrically connected with the two metal strips. In 2020, Altıntaş et al. developed an X-band sensor incorporating an OSR antenna fabricated on an FR4 substrate for

industrial detection [20]. In the same year, Abdulkarim et al. used Ω -shaped metamaterial resonators integrating with microstrip transmission lines to fabricate a sensor operating in the 1–20 GHz frequency range for liquid detection [21]. In 2022, Attariabad et al. proposed a metasurface structure with OSR nanoantenna as unit cells on a graphene photodetector to improve light absorption efficiency [22]. However, the majority of published studies have not explored the resonant behaviors of OSR antennas, particularly the small frequency interval between two fundamental resonant modes generates a synergistic effect, enabling the high gain and broadband response for applications in sensing and detection. Specifically, by changing the dimensions of the metal loop and the length of the two metal strips, the LC and dipole resonant frequencies can be separately designed to reduce the resonant frequency interval.

For most ring-shaped antennas, the LC resonant is excited in the electric excitation configuration (EEC, electric field parallel to the dipole arms and the magnetic field parallel to the loop plane). If a low dielectric constant and low-loss polymer substrate is used, the OSR antenna can be excited in the magnetic excitation configuration (MEC, magnetic field crossing the loop vertically, and the substrate being along the propagation direction of the incident electromagnetic waves). By leveraging the strong electric field enhancement effect of OSR antennas in the feed gap and integrating the excellent PTE effect of 2D materials such as graphene [23, 24], Bi_2Te_3 [25, 26], and PtSe_2 [27], it is expected that high-sensitivity and broadband electromagnetic sensing devices can be realized.

In this article, we systematically studied the resonant characteristics of OSR antennas on flexible polyimide (PI) substrates and demonstrated a high-performance flexible THz PTE detector asymmetrically integrated with an optimized OSR antenna structure, which was designed to operate near 0.1 THz for use in the main frequency band of 6G communications. First, the OSR structural parameters were theoretically evaluated according to the designed operation frequency range. Subsequently, numerical simulations were performed to explore the resonant behaviors and further optimize the structural parameters, enabling the OSR antenna to have a smaller resonant frequency interval. Due to the synergistic effect between the neighboring modes, the local electric field intensity in the gap was strengthened. Then, the resonant characteristics of the OSR antenna in EEC and MEC (with the magnetic field parallel (EEC) or perpendicular (MEC) to the plane of the OSR antenna, and the electric field aligned along the OSR arms) were thoroughly analyzed through theoretical analysis and numerical simulations. The transmission spectra of the OSR antenna array were measured using a terahertz time-domain spectroscopy system (THz-TDS), and the measured spectral data were highly consistent with the simulation results. Finally, employing the mechanical exfoliation and the precise positioning transfer techniques, a graphene flake with nanometer-scale thickness was transferred to one side of the OSR feed gap, realizing an asymmetrically coupled OSR antenna-integrated flexible THz PTE detector. Benefiting from the giant broadband field enhancement of the OSR antenna, this detector achieves high responsivity and low noise equivalent power (NEP) at the LC and dipole resonances, both in EEC and MEC. The findings indicate that the OSR antennas on flexible substrates

are very useful for the development of high-performance THz detectors and other electromagnetic sensing devices.

2 | Resonant Principles and Antenna Design

As shown in Figure 1a, the OSR antenna is composed of two dipole arms with the same length close to each other and a square split ring in connection with them, the two components of which share the same narrow feed gap. When the electric field of incident THz plane wave is along the two dipole arms and the wave vector is perpendicular (defined as the electric excitation configuration, EEC) and parallel (defined as the magnetic excitation configuration, MEC) to the OSR antenna plane, it is expected that the OSR antenna can support multiple resonant modes (the LC and the fundamental dipole resonances). In the EEC, the transmission spectrum of the OSR antenna array shown in Figure 1b indicates that the antenna mainly supports two fundamental resonances. The resonant mode at the low frequency exhibits a high quality factor, while the other one at the high frequency features a large full width at half maximum (FWHM). The two resonances are the high-gain and narrow-bandwidth LC resonance and the broadband fundamental dipole resonance mainly supported by the split ring and the two dipole arms, respectively.

Over the past 20 years, SRR and dipole antennas have been extensively investigated [28–35]. Early studies indicated that the resonant modes supported by SRR antennas include one LC resonance and multiple dipole resonances [18, 36–39]. The LC resonance occurs at the lowest frequency, while the dipole resonances occur at higher frequencies [19]. The frequency of the LC resonance is determined by the dimension of the loop structure (determining the inductance) and the width of the feed gap (determining the capacitance) [40]. For the LC resonance, a circular oscillating current will be generated in the loop structure, resulting in the same amounts of positive and negative charges accumulating at the two feed gap edges, respectively, and forming a strong local electric field in the feed gap (Figure 1a). The fundamental resonant frequency f of a dipole antenna, that is mainly related to the arm length along the electric field direction, is

$$f = c / (2n_{\text{eff}}L)$$

where $n_{\text{eff}} = (n_{\text{sub}} + 1)/2$ is the effective refractive index with n_{sub} the refractive index of the substrate [41], L is the length of a single dipole arm [42], and c is the speed of light in vacuum.

As shown in Figure 1c, at the dipole open-circuit resonant frequency, the electric-field-induced currents in the dipole arms make the charges inside the dipole arms move toward both ends and accumulate at the metal terminals. The charges accumulated at the two edges of the feed gap will reach the maximum value at resonance, which significantly enhances the electric field intensity in the feed gap. For an SRR antenna, due to the large frequency separation, the LC and the fundamental open-circuit dipole resonant modes are treated as two completely separate ones. However, for the OSR antenna with the same loop dimension, because the dipole arm length can be solely designed,

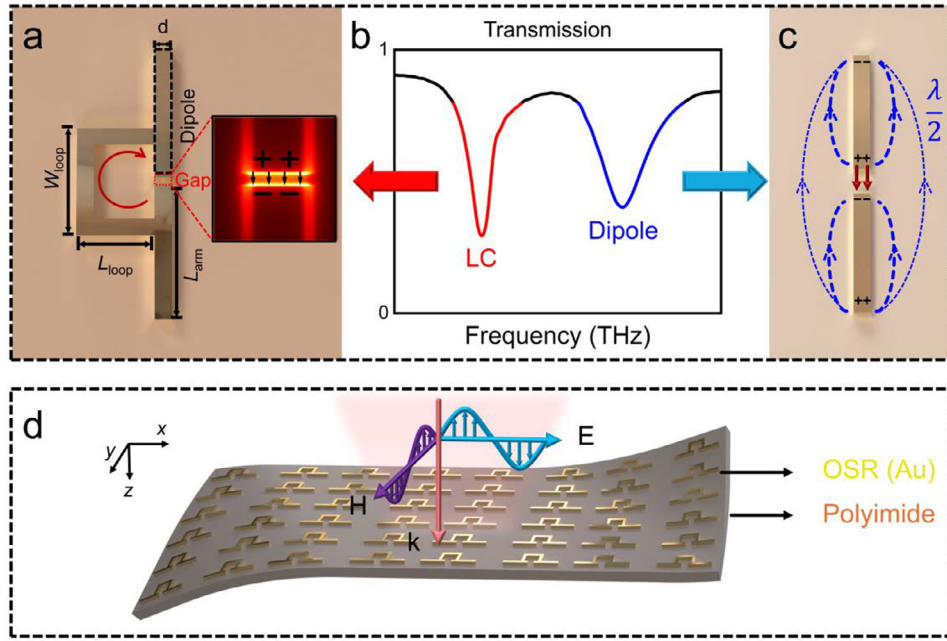


FIGURE 1 | The schematic diagram of the OSR antenna structure and the resonant principles. a) Schematic diagram of the OSR antenna and the simulated local electric field enhancement in the feed gap at the LC resonant frequency. b) Transmission spectrum of the OSR antenna array. c) Schematic diagram of the dipole resonant principle. d) Schematic diagram of the flexible OSR antenna array.

the frequency interval between the LC and the fundamental dipole resonances of OSR antennas can be effectively reduced, which enables the large electric field enhancement in the feed gap within a wide bandwidth.

Flexible polymer substrates have the advantages of low refractive index and low loss, which will significantly reduce the parasitic substrate effects [43, 44], especially for the MEC. As shown in Figure 1d, in order to explore the resonant behaviors of OSR antennas, a periodic OSR array was fabricated on a polyimide (PI, Kapton, 300–HN, 75 μm thickness) substrate. As shown in Table S1, in comparison with the other flexible polymer materials, PI has the advantages of high mechanical flexibility and thermal stability. Therefore, PI was chosen as the substrate. Within the frequency range of 0–1 THz considered in this work, the refractive index is approximately 1.9, and the loss can be ignored (Figure S1). Based on the considered frequency range (0–1 THz), the structural parameters of the OSR antenna were preliminarily determined as follows: the length of each dipole arm L_{arm} is 158 μm , the loop width W_{loop} is 75 μm , the loop length L_{loop} is 80 μm , and the feed gap width W_{gap} is 4 μm . The width of all metal strips d is 10 μm , and the thicknesses of the Ti/Au layers are 15/35 nm. Subsequent numerical simulations and THz–TDS measurements will be performed on the OSR array.

3 | Simulations and Measurements of the OSR Array

We systematically investigated the electric field enhancement in the feed gap at resonant frequencies for three similar OSR antenna structures (Figure S2) using the commercial software (Lumerical Solution) [45] based on the finite–difference time–domain (FDTD) method. The results indicate that the OSR

antenna structure shown in Figure 1a exhibits the most significant electric field enhancement. Consequently, this structure was selected for subsequent theoretical and experimental studies.

In the simulation, the OSR antenna is placed on an infinitely thick PI substrate to eliminate the influence of guided resonance modes. The refractive index of the PI substrate is set to 1.9, and its loss is neglected. The Floquet periodic boundary conditions are adopted for the antenna array along the x and y directions, and the periods in the x and y directions are $P_x = 640 \mu\text{m}$ and $P_y = 160 \mu\text{m}$, respectively. The excitation port is 800 μm away from the OSR plane, and the incident pulsed plane waves propagate along the z direction with the electric field parallel to the x direction. The complex dielectric constant of Au is given by the Drude model:

$$\epsilon = 1 - \omega_p^2 / (\omega^2 + i\gamma\omega)$$

where the plasma frequency ω_p is 1.12×10^{16} rad/s, the scattering coefficient γ is 8.67×10^{13} rad/s, ω is the angular frequency of the incident electromagnetic wave, and i is the imaginary unit.

The transmission spectra of the OSR antenna array are obtained by FDTD simulations. As shown in Figure 2a, the OSR antenna exhibits two resonant valleys at 0.22 and 0.56 THz, corresponding to the two fundamental resonant modes. To elucidate the origins of these resonant modes, the OSR antenna was decomposed into the SRR and dipole antenna structures, and numerical simulations were performed separately under the same simulation conditions for each structure. The results show that the first resonant (LC) frequency of the SRR antenna with the same loop dimension appears at 0.33 THz, and the second resonant (dipole) frequency appears at 1.0 THz (Figure S3). The resonant frequency of the dipole antenna with the same length appears at 0.57 THz, which is almost the same as the second resonant frequency of

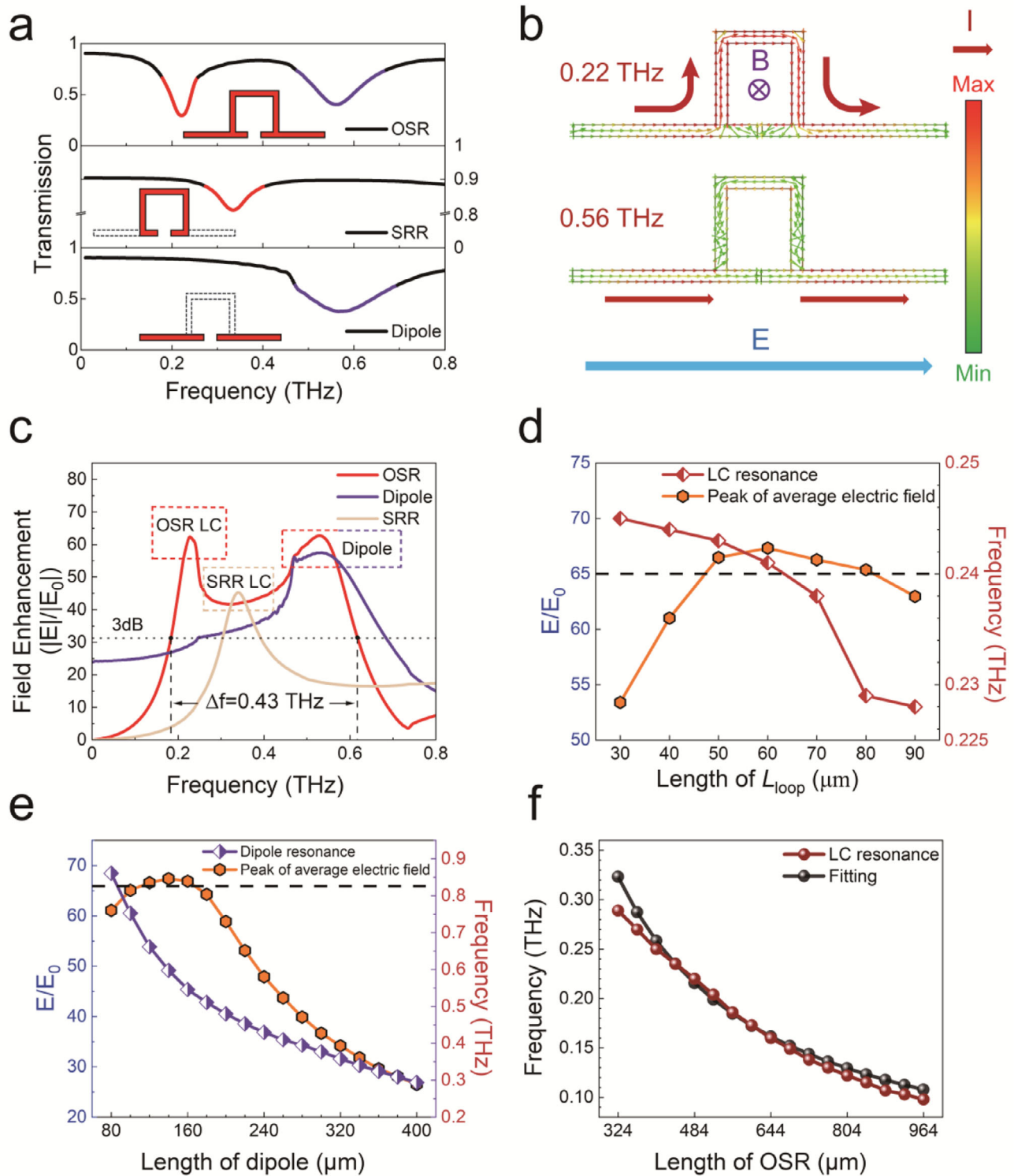


FIGURE 2 | a) Transmission spectra of the OSR, SRR, and dipole antennas. b) The simulated current patterns at the LC and dipole resonances. c) Surface-averaged electric field enhancement in the feed gap for the OSR, SRR, and dipole antennas. d) LC resonant frequencies and the corresponding field enhancement factors with respect to L_{loop} . e) Dipole resonant frequencies and the averaged electric field enhancement factors at the LC resonant frequency with respect to the dipole arm length. f) Comparison of the LC resonant frequency and the half-wave resonant frequency of the OSR antenna.

the OSR antenna. Furthermore, the FWHM of the first resonant valley of the OSR antenna is much smaller than that of the second one. The length of the dipole arm along the electric field direction of the OSR antenna is longer than that of the SRR antenna with the same loop size. This leads to a larger equivalent inductance L in the equivalent circuit model of the OSR antenna, which results in a redshift of the LC resonant frequency compared to the SRR antenna. In addition, the dipole resonant frequency is only related to the arm length along the electric field direction, so the dipole resonance does not shift significantly [17, 46]. Therefore, we can conclude that the two valleys in the transmission spectrum of the OSR array correspond to the LC and the fundamental dipole resonant modes.

To further verify the two resonant modes of the OSR antenna, the surface current patterns of the OSR antenna shown in Figure 2b were obtained using the finite element-based commercial COMSOL Multiphysics software [47]. At both of the two resonant frequencies, a large amount of charges are accumulated at the two edges of the feed gap, forming a strong electric field in the feed gap region. At the first resonant frequency, significant currents appear in the middle of the two dipole arms, and the maximum current occurs in the loop structure. Since the loop currents and the dipole currents near the two edges of the feed gap have opposite directions, they partially cancel each other in this region. At the second resonant frequency, electromagnetic field-induced currents are only in the middle regions of the two dipole arms, which is in accordance with the characteristic of the fundamental dipole open-circuit resonance [48]. The strong electric field enhancement in the feed gap is fully consistent with the fundamental dipole open-circuit resonance. Hence, it can be confirmed that the OSR antenna exhibits the LC and dipole resonances, and there is only a small frequency interval between the two resonances compared to the SRR antenna. Further, to some extent, the frequency interval between the LC and dipole resonances can be designed by changing the loop dimension and the length of the dipole arm separately.

The electric field enhancement in the feed gap describes the gain of a receiving antenna, resulting in the concentration of the free-space electromagnetic energy into the deep subwavelength feed gap region [16, 49]. As illustrated in Figure 2c, the average electric field intensities of the OSR, SRR, and dipole structures in the feed gap regions are derived from the numerical simulations, and the OSR antenna exhibits the largest electric field enhancements at the two resonances. At the LC resonance, the peak of the average electric field amplitude of the OSR antenna is 38% higher than that of the SRR antenna, while the FWHM is only 43% of that of the SRR antenna. At the fundamental dipole resonance, the peak of the average electric field amplitude of the OSR antenna is 9% higher than that of the dipole antenna. Based on the THz electric field-driven current pattern on the Ω -shaped antenna (Figure 2b), a qualitative explanation for the synergistic effect between the LC and dipole resonances can be given. In comparison with a standard SRR antenna, in the Ω -shaped antenna, the THz electric field-driven currents in the two dipole arms enter into the loop, leading to the larger circular current and the resultant magnetic energy. At the LC resonant frequency, the magnitude of magnetic energy equals that of electric energy, which results in a larger electric field enhancement in the feed gap of the Ω -shaped antenna. Further, because of the elongated

length of the circular current on the Ω -shaped antenna, Figure 2c shows that the LC resonant mode shifts from 0.33 to 0.22 THz. However, at the dipole resonant frequency, due to the small current amplitude on the loop, the fundamental dipole resonant frequency of the Ω -shaped antenna is nearly unchanged, and the electric field enhancement in the feed gap is slightly increased. Moreover, the OSR antenna exhibits a 3 dB bandwidth of 0.43 THz, demonstrating its broadband performance. Therefore, in comparison with the SRR and dipole antennas, the OSR antenna has significant improvements in gain and bandwidth.

The width of the feed gap, the dimension of the loop structure, and the length of the dipole will affect the gain and bandwidth of the OSR antenna. The LC resonant frequency of the OSR antenna is not sensitive to W_{gap} compared to the SRR antenna (Figure S3), which should be attributed to the small currents near the feed gap region (Figure 2b). When the total length of the loop structure remains constant, the frequency of the LC resonance in Figure 2d redshifts within a extremely small range as L_{loop} increases, which is due to the fact that the length change of the upper three edges of the loop accounts for a small percentage in the total perimeter of the OSR antenna, so the frequency of the LC resonance does not shift significantly. The peak of field enhancement amplitude at the LC resonance initially increases and then decreases as L_{loop} increases, reaching a maximum at $L_{\text{loop}} = 60 \mu\text{m}$. Considering that there are strong electric field enhancements and the enhancement amplitude is nearly a constant in the feed gap with L_{loop} in the range of 50–80 μm , we still choose the loop length of 75 μm and the loop width of 80 μm . The field enhancement in the feed gap will change with dipole length and reaches the maximum value with the dipole length in the range of 120–160 μm , as shown in Figure 2e. Here, the dipole length of 158 μm is chosen.

To further investigate the LC resonant characteristics of the OSR antenna, L_{arm} and W_{loop} (Figure S3) were varied in the numerical simulations to analyze the LC resonant frequency characteristics of the OSR antenna length (defined as $L_{\text{OSR}} = 2L_{\text{arm}} + W_{\text{gap}} + 2L_{\text{loop}}$). Figure 2f demonstrates that the LC resonant frequency of the OSR antenna is approximately inversely proportional to the L_{OSR} . The surface current in the middle region of the overall OSR antenna is strongest at the LC resonant frequency shown in Figure 2b, which exhibits a half-wave resonant characteristic. The half-wave resonant frequency of the total length of the OSR antenna (L_{OSR}) is almost identical to the LC resonant frequency, where the half-wave resonant frequency is expressed as: $f = c/(2n_{\text{eff}}L_{\text{OSR}})$. Therefore, it can be concluded that the LC resonant frequency of the OSR antenna can be calculated using the expression of half-wave resonance over the entire structure.

In summary, the resonant modes of the OSR antenna are mainly composed of the LC and the fundamental dipole resonances. Compared with the SRR antennas, the OSR antenna can reduce the resonant frequency interval of the two resonant modes by adjusting the size of the loop and the length of the metal strips to design the LC resonance and the dipole resonance frequencies, respectively. As shown in Figure S4, the spatial gain profiles at the LC and fundamental dipole resonant frequencies were simulated using the ANSYS HFSS package [50]. Due to the synergistic enhancement effect between the two neighboring modes, a larger bandwidth and a stronger electric field enhancement are

achieved, which are beneficial for realizing high-performance THz sensing devices.

In order to compare with experimental results, 75- μm -thick PI substrates were used in the numerical simulations, as shown in Figure 3a. The structural parameters of the fabricated OSR antenna were measured by using a scanning electron microscope (SEM). The length of each dipole arm L_{arm} is 160.55 μm , the loop width W_{loop} is 75.02 μm , the loop length L_{loop} is 80.03 μm , the feed gap width W_{gap} is 3.66 μm , and the width of all metal strips d is 10.48 μm . All the structural parameters of the fabricated OSR antenna are in good agreement with the designed values. The THz waves are incident perpendicular to the plane of the OSR antenna array along the z direction in the EEC (red coordinates in Figure 3b). The numerical transmission spectrum of the OSR antenna on the finite thickness PI substrate (gray curve in Figure 3c) exhibits not only the resonant valleys corresponding to the LC and dipole resonances appearing in Figure 2a, but also several additional sharp transmission dips. This phenomenon is primarily attributed to two factors: first, the Fabry-Pérot (FP) interference effect arising from reflections between the top and bottom surfaces of the finite substrate; second, the guided resonant modes excited by the composite structure of the antenna array and the finite thickness substrate [51, 52].

The proposed OSR antenna array was prepared by ultraviolet photolithography, thermal evaporation, and lift-off technology (Figure S5). The transmission spectrum of the OSR antenna array in the EEC was verified by using a THz-TDS (Figure S6). As shown in Figure 3c, the two main resonant valleys and some secondary dips closely match the numerical simulation results. The small and sharp features at 0.45, 0.67, and 0.79 THz on the simulated transmission spectrum cannot be well resolved in the experiment, which may have contributed to the low frequency resolution (15 GHz) of the THz-TDS, the finite OSR array sample, and the excess loss that cannot be precisely considered in simulations. Next, we investigated the electric field enhancement in the MEC (blue coordinates in Figure 3b). According to Faraday's law of electromagnetic induction, the harmonic oscillation magnetic field will induce a circular harmonic oscillation current, further enhancing the electric field intensity in the feed gap. Figure 3d presents the numerical transmission and absorption spectra of the OSR antenna array in the two excitation configurations, where the absorption spectra are derived from the transmission spectra T and reflection spectra R : $A = 1 - T - R$. The results show that in the MEC (blue curve), the frequency of the LC resonance redshifts about 0.006 THz compared to the case of the EEC (red curve), and the electromagnetic energy absorption is enhanced. Specifically, the field enhancement peak in the feed gap of the OSR antenna in the MEC is 232% of that of the EEC, as shown in Figure 3e.

The transmission spectrum of the OSR antenna in the MEC was verified using the THz-TDS. The Gaussian beam emitted by the THz emitter can be regarded as a plane wave for the sample placed near the focus region, so that the equiphase surface is nearly a plane (Figure S7). Initially, the transmission spectrum of a PI flexible substrate without the OSR antenna array was measured in Figure 3f (black curve). Subsequently, a PI flexible substrate of the same size with an OSR antenna linear array was placed in the same position, and its transmission spectrum was

measured (blue curve). The result shows that the transmission spectrum of the OSR antenna array exhibits a valley near 0.22 THz. Considering the numerical transmission spectrum in the MEC shown in Figure 3d, it can be concluded that the valley corresponds to the LC resonance induced by the THz electric and magnetic fields. Based on these findings, we can utilize the OSR antenna in EEC and MEC to enhance the performance of THz sensing devices.

4 | Terahertz Detector Asymmetrically Integrated with an OSR Antenna

It has been widely reported that the THz spectral regime of 0.1–0.3 is the main electromagnetic band for the future 6G communications [53–58]. Here, we demonstrated an OSR antenna-integrated THz detector. By optimizing the structural parameters of the OSR antenna, a resonant frequency of 0.1 THz was designed for the potential application in 6G communications. The structural parameters of the OSR antenna can also be modified to enable operation in the other target frequency band. The optimized parameters of the OSR are as follows: the length of each dipole arm is $L_{\text{arm}} = 598 \mu\text{m}$, the loop width is $W_{\text{loop}} = 80 \mu\text{m}$, the loop length is $L_{\text{loop}} = 204 \mu\text{m}$, the feed gap width is $W_{\text{gap}} = 4 \mu\text{m}$, and the width of all metal strips is $d = 4 \mu\text{m}$. The periodicities in the x and y directions are $P_x = 2400 \mu\text{m}$ and $P_y = 176 \mu\text{m}$, respectively. The structural parameters of the fabricated OSR antenna were verified using the SEM (SIGMA 300, ZEISS). The transmission spectrum shows that the LC resonant frequency of the modified OSR antenna is at 65 GHz, and the fundamental dipole resonant frequency is at 122 GHz (Figure S8). Next, we used the modified OSR antenna as a coupling antenna for the THz detector.

Semiconductor planar fabrication and 2D material precise positioning transfer techniques are utilized to fabricate the graphene THz detector [59]. The multi-layer graphene flake was transferred to the OSR antenna feed gap region by using the polydimethylsiloxane (PDMS)-assisted method, where one side of the graphene flake was contacted with one edge of the feed gap for electrical connection, and the other side of the graphene flake was connected to another electrode to realize the asymmetrically coupled structure. During the transfer process, a higher temperature (373 K) and longer heating time (5–10 min) are required to transfer the graphene from the PDMS film to the feed gap due to the excellent thermal insulation property of the PI substrate (Figure S9). Figure S8 shows the current-voltage curve, the atomic force microscopy (AFM, MultiMode 8-HR, BRUKER) image, and the Raman spectrum (home-made, 520 nm laser wavelength) of the transferred graphene. The resistance of the graphene channel is 1621 Ω . The thickness of 30 nm of the graphene flake was verified by the AFM system. The Raman spectrum of the transferred graphene flake exhibits two characteristic peaks at 1580 cm^{-1} (G peak) and 1721 cm^{-1} (2D peak). Due to the strong electric field enhancement effect of the OSR antenna, the THz absorption of the graphene channel in the feed gap is significantly enhanced, generating a large number of hot carriers and resulting in the asymmetric temperature gradient along the graphene channel. According to the Seebeck effect (thermoelectric effect), this produces an open-circuit voltage

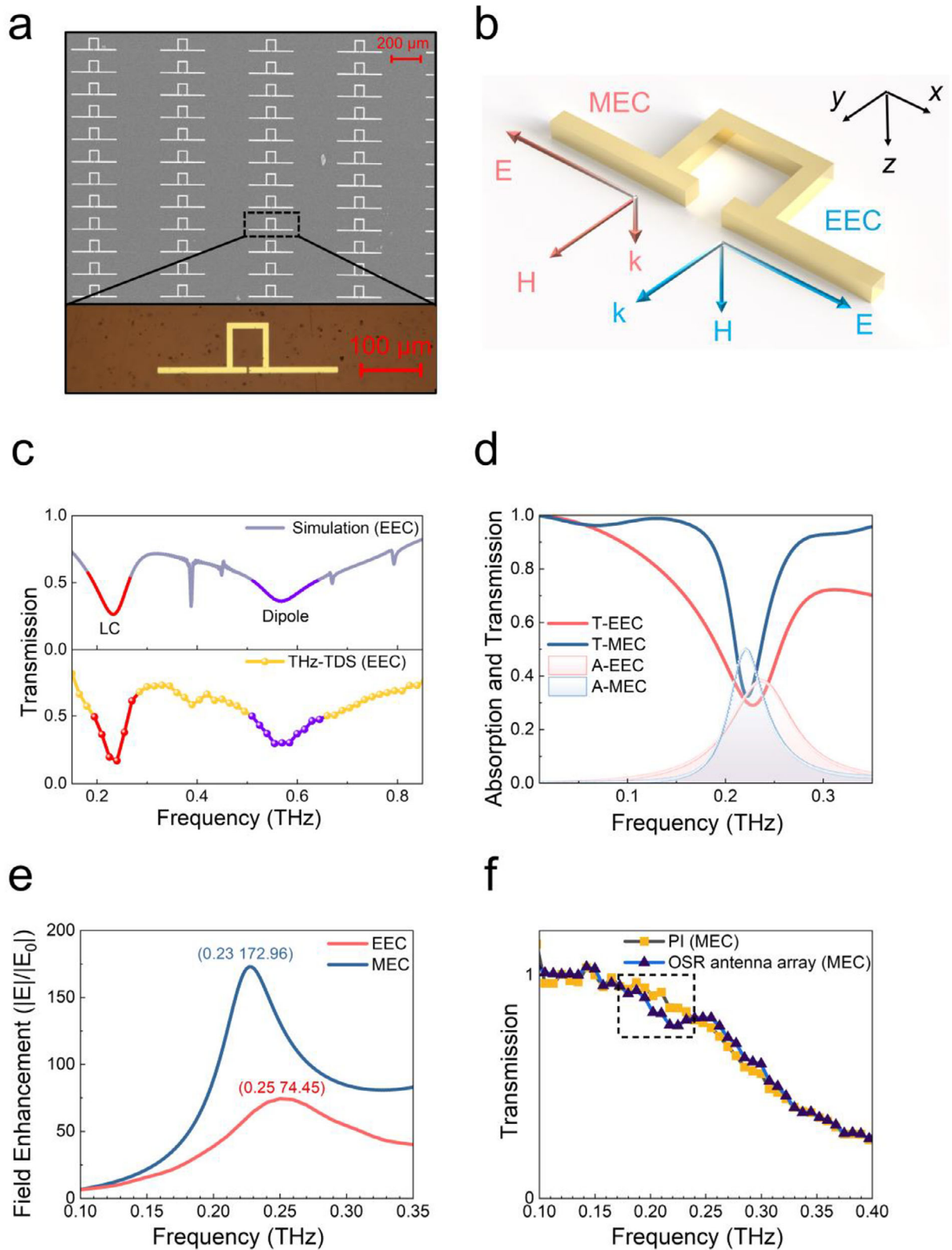


FIGURE 3 | Resonant properties of the flexible OSR antenna array excited in different configurations of incident electromagnetic waves. a) Optical photograph and optical micrograph of the OSR antenna array. b) Schematic diagrams of the EEC (red curve) and MEC (blue curve). c) Comparison of numerical and experimental transmission spectra of the OSR antenna array in the EEC. d) Numerical transmission and absorption spectra of the OSR antenna array excited in the two excitation configurations at the LC resonant frequency. e) Average field enhancements in the feed gap of the OSR antenna in the two excitation configurations. f) Transmission spectra of the OSR antenna array and the PI substrate measured by using a THz-TDS in the MEC.

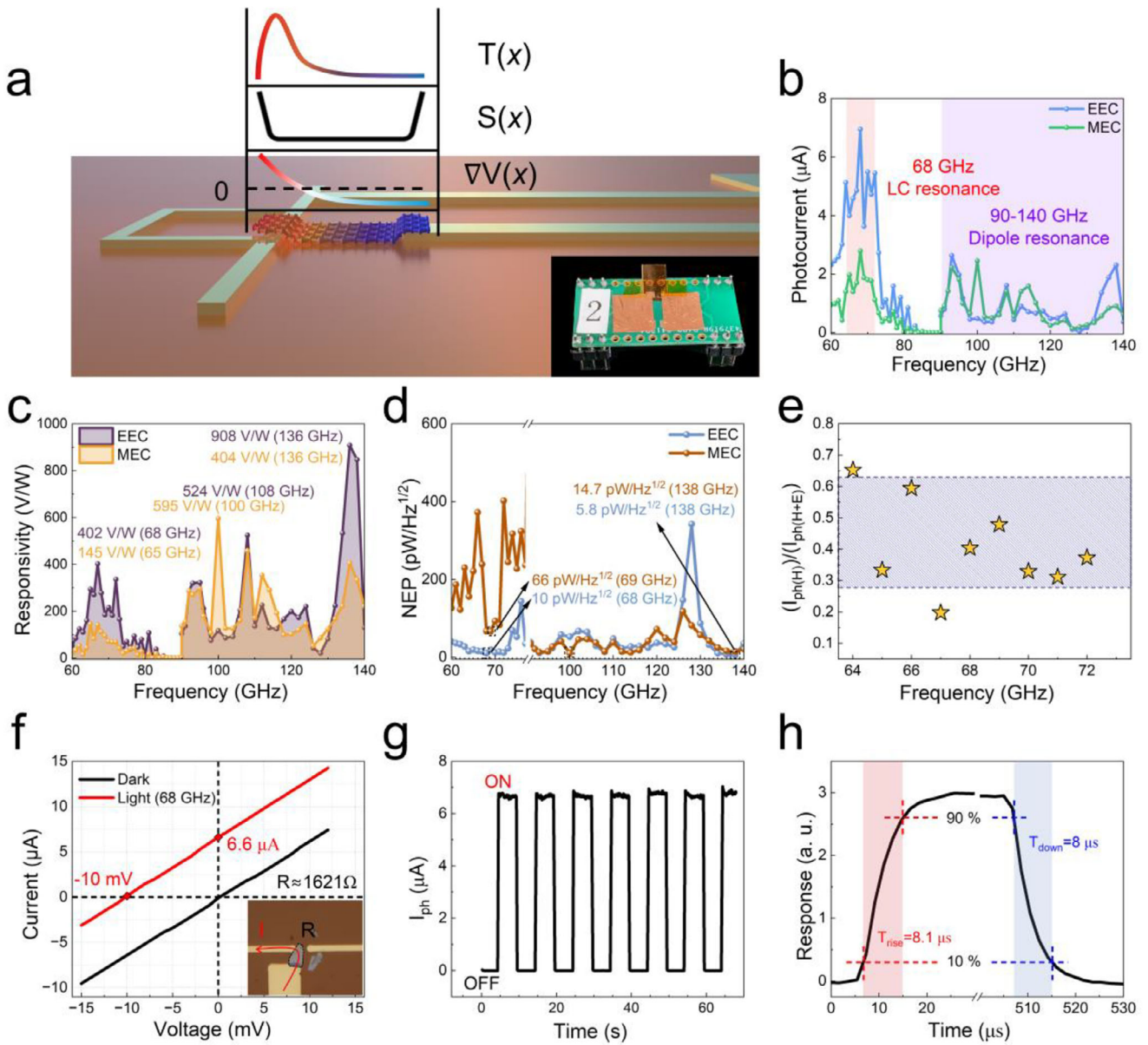


FIGURE 4 | The photocurrent response characteristics of the flexible THz PTE detector. a) Schematic diagram of the PTE detection principle and the optical image of the detector. b) Photocurrent spectrum of the detector. c) Voltage response spectrum of the detector. d) NEP spectra of the detector. e) Relative contribution of the magnetic field in the MEC. (f) Current-voltage curves of the THz detector in dark conditions and illuminated by 68-GHz electromagnetic waves, respectively. g) Pulse response of the detector at the LC resonance. h) Response times of the detector.

[27]:

$$V_{OC} = - \int S \times \nabla T(x) dx \quad (1)$$

where V_{OC} is PTE open-circuit voltage, S is the Seebeck coefficient, and T is temperature.

The schematic diagram and optical image of the fabricated flexible THz PTE detector are shown in Figure 4a. Two conductive copper tapes were used to connect the electrode pads on the PI substrate with a PCB plate to realize circuit connection. The photoresponse of the detector was tested in the 60–140 GHz frequency range at room temperature (300 K) (Figure S10). The photoresponse signal was recorded by a lock-in amplifier (MFLI 500 kHz/5 MHz, Zurich Instruments) and an oscilloscope

(MSO2024B, Tektronix) after a low-noise current preamplifier (SR570, Stanford). As shown in Figure 4b, with the incident power density of terahertz radiation ranging from 0.49 to 4.99 mW/cm², the detector produces the maximum photocurrents of 6.95 and 2.79 μA at 68 GHz in EEC (blue curve) and MEC (green curve), respectively. The transmission spectrum of the OSR antenna shows that the LC resonance frequency is at 65 GHz, which corresponds to the maximum photocurrent generated by the detector at 68 GHz. This confirms that the enhanced photoresponse of the detector near 68 GHz originates from the LC resonance. Moreover, a broadband response, characterized by multiple discrete peaks, was observed between 90 and 140 GHz. This corresponds to the dipole wideband resonance near 122 GHz in the numerical simulations, indicating that the photoresponse in this range is primarily induced by the dipole resonance.

The voltage responsivity can be expressed as [60]:

$$R_v = \frac{I_{ph}R}{A_e P} \quad (2)$$

where I_{ph} is the short-circuit photocurrent, R is the resistance of the detector, A_e is the effective area of the detector, and P is the power density. The power densities at each frequency point were measured with a pyroelectric meter (Vector H410). The power densities of the THz source ranged from 0.49 to 4.99 mW/cm² and 1.10–2.49 mW/cm² in the 60–90 GHz and 90–140 GHz frequency ranges, respectively. Since the detector employed an antenna-coupled structure, the effective area of the detector is given by the effective receiving area of the antenna [61]:

$$A_e = \frac{3\lambda_{eff}^2}{8\pi} \quad (3)$$

where $\lambda_{eff} = 2\lambda_0/(n+1)$ is the effective wavelength, and λ_0 is the wavelength in vacuum. Figure 4c presents the voltage responsivity spectra in the EEC (purple curve) and MEC (orange curve). Within the 60–90 GHz frequency range, the voltage responsivity reaches a maximum value of 402 V/W at 68 GHz in the EEC and a maximum value of 145 V/W at 65 GHz in the MEC. Within the frequency range of 90 to 140 GHz, the detector exhibits multiple strong voltage response peaks in both excitation configurations, enabling the detector to achieve a wider response range. These properties indicate that the flexible graphene detector integrated with an OSR antenna can achieve strong responses with a wide bandwidth through the LC and the fundamental dipole resonances.

In practical applications, NEP is usually used to evaluate the sensitivity of THz detectors. Under zero-bias condition (zero dark current) and considering only thermal noise (Johnson–Nyquist noise [19, 62, 63]) given by:

$$V_n = \sqrt{4k_B T R}$$

where V_n is the noise voltage and k_B is the Boltzmann constant, the calculated V_n is 5.18 nV/Hz^{1/2}. The value of the NEP is calculated as [60]:

$$NEP = \frac{V_n}{R_v} \quad (4)$$

Figure 4d shows the NEP spectra in the two excitation configurations. It can be seen that the NEP reaches 10 pW/Hz^{1/2} (68 GHz) and 66 pW/Hz^{1/2} (69 GHz) in the EEC (blue curve) and MEC (orange curve) at LC resonance, respectively. Within the dipole resonant frequency range, the NEP values in the two configurations reach their minimum values of 5.8 pW/Hz^{1/2} (138 GHz) and 10.4 pW/Hz^{1/2} (100 GHz), respectively. This further indicates that in the two configurations, the detector achieves high sensitivities, demonstrating excellent device performance.

In comparison with numerical simulations, there is a discrepancy that at the LC resonance, the photocurrent in the MEC is smaller than that in the EEC. Nevertheless, the photoresponse mechanism, which is jointly dominated by electric and magnetic fields, can still be effectively demonstrated in experiments. To evaluate the enhancement in detector response performance

attributed to the magnetic field component, the ratio of the photocurrents when the magnetic field is perpendicular to the detector but the electric field is not aligned with the dipole arms to that in the MEC is examined. Figure 4e presents the ratio of the photocurrents at the LC resonance frequency for the two incidence configurations (only magnetic field across the loop plane and in the MEC). The results show that the magnetic field contributes about half of the photoresponse of the detector in the MEC. This suggests that the introduction of the magnetic field can nearly double the responsivity of the detector compared to the case of EEC, which is consistent with the numerical results shown in Figure 3e. These findings further confirm that the THz PTE detector based on OSR antennas can operate effectively in various incidence configurations and exhibits excellent performance.

As shown in Figure 4f, in order to confirm the photoresponse mechanism of the detector, a semiconductor parameter analyzer (4200A-SCS) was used to measure the dark I-V curve (black) and the I-V curve under the 68 GHz illumination (3.67 mW/cm²) in the EEC (red). A large short-circuit current (responsive photocurrent) of 6.6 μ A was measured at the LC resonance (68 GHz), and the value of open-circuit photovoltage is –10 mV. The two I-V curves show a good linear relationship and are parallel to each other, demonstrating a good PTE response of the detector. Subsequently, by illuminating with the electrically square-modulated THz radiation, the photocurrent waveform of the detector was recorded, as shown in Figure 4g. The square photocurrent waveform shows that the detector has a strong photocurrent of 6.95 μ A at the LC resonance (68 GHz) and has good stability over a long time period (~1 min). The response time of the THz detector can be evaluated from the rise and fall times of the square photocurrent waveform. The rise time is defined as the duration required for the photocurrent to increase from 10% to 90% of its maximum amplitude, while the fall time corresponds to the decay from 90% to 10% of the maximum amplitude. As shown in Figure 4h, the rise and fall response times of the detector are 8.1 and 8.0 μ s, respectively. This indicates that the detector has a fast response speed.

Finally, we evaluated the thermal and mechanical stabilities of the flexible detector. Different from a thermal energy harvesting device, a terahertz detector is usually operated with a low incident terahertz power density of about 1 mW/cm². If the frequency of the incident terahertz wave is 0.1 THz, the receiving area of the detector is about 0.01 cm² ($3\lambda^2/8\pi$ [27]), and the incident power onto the detector is about 10 μ W. At the same time, due to the strong hot carrier effect in graphene, the incident terahertz energy is effectively transferred into the electron system through free carrier absorption. Finally, the excess energy in the electron system is dissipated into the electrodes. For such a low incident terahertz energy, two-temperature simulations indicate that the rise of crystal temperatures of electrodes, graphene channel, and the substrate is negligible [63].

The mechanical stability is important for flexible devices in applications. In our devices, the metallic structures, including antenna, transmission lines, and electrode pads, composed of a 15-nm Ti layer (adherent layer) and a 35-nm Au layer (conducting layer), were deposited on the flexible PI substrate using the electron beam-assisted thermal evaporation method. Several tens nanometer-thick Au/Ti films have been widely used in various

TABLE 1 | Performance comparison of room temperature and fast response THz graphene detectors on different substrate materials.

Substrate	Operating frequency [GHz]	Voltage Response [V/W]	NEP [pW/Hz ^{1/2}]	Response time [μ s]	References
PI	65–69	402 (145)	10 (66)	8	This work
	136–138	908 (404)	5.8 (14.7)		
Quartz	110	764	34	/	[68]
PET	487	2	3×10^3	/	[69]
Si/SiO ₂	103/275	410/400	12/13	~ 1	[70]
Si/SiO ₂	2800	/	$\sim 1 \times 10^3$	5×10^{-3}	[71]
Si/SiO ₂	100	0.62 [A/W]	19.6	4.5×10^{-3}	[27]
Si/SiO ₂	84	138	25	3.7	[19]
Si/SiO ₂	99	976	2.87	0.3	[63]
Si/SiO ₂	280	22	21	4.7	[72]
Si/SiO ₂	100	1.3	340	250	[73]
Si/SiO ₂	120	0.0429 [A/W]	7	7.4	[74]
Si/SiO ₂	300	264.6	280	1	[75]
Si/SiO ₂	100	279.15	9	4.7	[76]

flexible devices [64, 65], and the good mechanical stability of these metallic structures is well identified. Multilayer graphene flakes used in our devices have excellent mechanical strength and flexibility [66]. They are widely used in flexible devices [67]. Further, the mechanical stability of the OSR antenna-integrated graphene detectors was measured. As shown in Figure S11, when an OSR-integrated graphene detector was bent with about a 5-mm radius of curvature, all the metal structures are neither detached from the substrate nor cracked, and the transferred graphene flake remains bonded to the electrodes. The electrical properties of the device have not changed.

As summarized in Table 1, we presented a performance comparison of room-temperature THz detectors based on various 2D materials on different substrate materials in recent years. The comparisons indicate that the detector demonstrated in this work has higher sensitivity, lower NEP, and can be operated at room temperature and in zero-bias mode.

5 | Conclusion

In this work, we proposed and demonstrated a dual resonant OSR THz receiving antenna and its application as a light coupler for a THz detector. We systematically investigated the LC and the fundamental dipole resonant characteristics of the OSR antenna in theory and experiment. Compared to conventional SRR and dipole antennas, the OSR antenna generates a stronger electric field enhancement in the feed gap and a broader response bandwidth by the synergistic enhancement effect between the two neighboring modes. Furthermore, due to Faraday's law of electromagnetic induction, the electric field enhancement effect is further enhanced at the LC resonance in the MEC. The transmission spectra of the OSR antenna in EEC and MEC were measured by the THz-TDS, which are in good agreement with the simulation results. Subsequently, we presented a

room-temperature flexible graphene-based THz PTE detector. By employing the OSR antenna as an asymmetric coupler for the THz PTE detector, the incident THz electromagnetic energy is effectively concentrated in the feed gap, significantly improving the PTE responsivity. The results show that both the LC resonance and the dipole resonance enhance the PTE response in the two configurations. We believe that OSR antennas can provide a useful platform for realizing high-performance and wide-bandwidth THz detectors and other electromagnetic sensing devices.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting file: lpor70630-sup-0001-SuppMat.docx