Polarization-Insensitive Plasmonic Photoconductive Terahertz Emitters

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Terahertz waves have great potentials for security screening, medical imaging, and chemical identification. The use of plasmonic contact electrodes in photoconductive terahertz emitters has been very effective in enhancing terahertz radiation power and signal-to-noise ratio levels of terahertz imaging and sensing systems. However, previously demonstrated plasmonic photoconductive terahertz emitters have all utilized grating-based plasmonic contact electrodes, which are sensitive to the polarization state of their optical pump beam. This polarization sensitivity can degrade the performance of plasmonic photoconductive terahertz emitters in
practical application settings. In this thesis, we develop a polarization-insensitive plasmonic photoconductive terahertz emitter, which utilizes a periodic array of subwavelength cross-shaped apertures as the plasmonic contact electrodes. By using cross-shaped aperture arrays, surface plasmon waves can be excited near the metal contact-substrate interface, bringing more photo-generated carriers close to this interface, which reduces the carrier transport path length to the contact electrodes. The two-dimensional symmetry of the cross-shaped apertures leads to a polarization-insensitive interaction between the plasmonic contact electrodes and optical pump beam. The geometry of the cross-shaped aperture arrays is selected to achieve maximum optical pump absorption in the photo-absorbing substrate at the metal-contact interface. Prototypes of this plasmonic photoconductive emitter are fabricated. The fabricated emitter prototypes show an excellent polarization insensitivity to the optical pump. The terahertz radiation power and efficiency of this emitter are comparable to those of a grating-based plasmonic photoconductive emitter with the same terahertz radiating elements.
The thesis of Xurong Li is approved.

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To my beloved family.
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Chapter 1: Introduction

Terahertz regime is a portion of the electromagnetic spectrum covering wavelengths between the microwave and infrared regimes (Figure 1.1). Usually the terahertz frequency range covers frequencies between 0.1 THz and 10 THz. Radio frequency (RF) community often refers to terahertz waves as submillimeter waves, while optical community often calls these waves far infrared waves. The terahertz range is also referred to as terahertz gap, since historically the efficient generation and detection of terahertz waves have been extremely difficult. From RF point of view, the resistive-capacitive (RC) parasitic effects and relatively long carrier transit times in transistors cause a high-frequency roll off in the efficiency of electronic terahertz sources and detectors. From optical point of view, terahertz frequencies correspond to photon energies of several milli electron volts. There is no natural semiconductor with a bandgap energy matching the terahertz photon energies, making the design of traditional optoelectronic devices operating at terahertz frequencies difficult. However, with recent developments in terahertz technology, scientists have managed to introduce new modalities for high-efficiency generation and detection of terahertz waves, enabling new terahertz imaging, sensing, and communication applications.

Figure 1.1 The electromagnetic spectrum from radio waves to gamma rays.
1.1 Applications of terahertz waves

Terahertz waves have a number of unique properties enabling plenty of potential applications. They can penetrate into many optically opaque materials. Compared to X-rays, they are non-destructive and non-ionizing. As a result, they can be used for security screening [1], medical diagnosis [2,3], and industrial quality control [4,5]. Some plastic factories have already adopted terahertz technology to measure the thickness of plastic pipes.

Terahertz waves can also be used for chemical identification. Many molecules have strong rotational and vibrational resonances at terahertz frequencies, resulting in a unique spectral signature in this frequency range. Terahertz waves are also very important for astronomical studies. It is estimated that 98% of the electromagnetic radiation since the Big Bang fall in the terahertz range [6]. Therefore, terahertz waves can reveal a lot of information about the formation of planets and stars as well as evolution of galaxies. Terahertz waves can also be used for environmental monitoring, since many pollutant and hazardous gas molecules have unique spectral signatures in the terahertz range [7]. Terahertz waves can also be used for various biosensing and biological studies, enabling label-free monitoring of various biological processes [8].

Terahertz waves are also considered as the data carriers for future wireless communication systems to meet the ever-increasing demand for communication data rates. However, the transmission distance of terahertz waves is limited by the strong atmospheric attenuation, especially at high terahertz frequencies (>1 THz) [9]. Therefore, terahertz waves are more suitable for short-distance communication [10] but can be used for long-distance communication in the space where little atmospheric molecules exist [11].
1.2 Terahertz sources

Generating electromagnetic waves in the terahertz range is extremely difficult compared to the other parts of the electromagnetic spectrum. The earliest studied terahertz radiation was from a blackbody radiation source, which is very low-power and inefficient. Later on, scientists tried to generate terahertz waves by accelerating free electrons, which radiate electromagnetic waves with frequencies proportional to the acceleration. Synchrotrons are one of the most straightforward sources in this category, which cover the frequency range from microwave to X-ray [12]. Their radiation power can be very high, from several watts to kilowatts, and very broadband. But their setup is too bulky and expensive for commercial applications. Other electron beam devices, such as backward wave oscillators [13] and traveling wave tubes [14], can produce reasonable power levels. However, their operation is limited to low frequencies (<1.5 THz). In addition, their requirement for a vacuum environment and high magnetic fields limits their potential applications.

Extending the frequency of RF sources to terahertz frequencies is another solution, which can offer compact terahertz sources (Figure 1.2). Resonant tunneling diodes (RTD) [15], Gunn diodes [16], and frequency multipliers are some of the commonly used terahertz sources in this category. These electronic sources can offer high powers in the low-frequency terahertz region (0.1 THz to 1 THz). However, their radiation power dramatically drops at higher frequencies. They are also limited in frequency tunability and bandwidth.

Numerous efforts have been made by the optical community to generate terahertz waves. Quantum cascade lasers have been investigated extensively in the past decade. Their output power can exceed 200 mW [17]. However, their requirement of cryogenic cooling restricts the scope of
their potential applications. Another optical method used for generating terahertz waves is optical down-conversion by using nonlinear optical effects [18]. For example, by mixing two optical beams with a terahertz frequency difference, a terahertz wave can be generated with a wide frequency tuning range. But the phase mismatch between the optical and terahertz beams limits their interaction length and the radiation efficiency. Moreover, because of the one-to-one photon interaction in nonlinear processes, the maximum efficiency of this category of terahertz sources cannot exceed the ratio between the energy of the terahertz photon and optical pump photon. This limitation is often referred to as the Manley-Rowe limit.

![Terahertz emission power as a function of frequency](image)

Figure 1.2 Terahertz emission power as a function of frequency [19].
1.3 Photoconductive terahertz sources

Another very promising optical tool used for terahertz wave generation is a photoconductive source. Since their first demonstration in 1984 [20], an extensive research has been conducted on photoconductive terahertz sources. A photoconductive terahertz source is comprised of an ultrafast photoconductor and a terahertz radiating element driven by an external optical pump (Figure 1.3). Depending on the application, the photoconductive terahertz source can work in a pulsed or continuous-wave (CW) mode.

In the pulse mode of operation, an ultrafast (usually sub-picosecond) optical beam is incident on the photoconductor. The photoconductor absorbs the light and generates electron-hole pairs. When an external bias voltage is applied to the contact electrodes connected to the photoconductor, an electric field is generated inside the substrate. Therefore, the photo-generated electrons and holes drift toward their corresponding contact electrodes, inducing an ultrafast photocurrent containing terahertz frequency components. After reaching the contact electrodes, the collected ultrafast photocurrent drives the terahertz antenna and generates terahertz radiation.

In the CW mode of operation, two continuous-wave optical beams with a terahertz frequency difference are incident on the photoconductor. An external bias voltage is applied to the contact electrodes to induce a photocurrent. Since the photocurrent magnitude is proportional to the photo-generated carrier density, it contains the same terahertz frequency as the frequency difference of the two optical beams. This photocurrent drives the terahertz antenna and produces terahertz radiation. To achieve maximum efficiency, the intensity of the two optical beams should be the same.
With the development of solid-state and fiber laser technology, photoconductive terahertz emitters have become very promising. The ultrashort pulse width of femtosecond fiber lasers enables a broad bandwidth for pulsed operation, and the high spectral stability, tunability and purity of CW fiber lasers enable a broad frequency tunability for CW operation. Moreover, photoconductive terahertz emitters can work at room temperature, which makes them more practical for commercial applications compared to quantum cascade lasers, which need a cryogenic setup. A major advantage of photoconductive terahertz sources over sources relying on nonlinear optical processes is that the optical-to-terahertz conversion efficiency is not constrained by the Manley-Rowe limit. In nonlinear optical processes, the maximum conversion efficiency is set by the ratio of the terahertz photon energy to the optical photon energy. However, in photoconductive terahertz sources, the optical-to-terahertz conversion efficiency can theoretically exceed 100%. When the photoconductor absorbs one photon, it can generate one electron-and-hole pair. Under an external electric field, this electron-and-hole pair drifts to the respective electrodes and drives the terahertz antenna, which can generate multiple terahertz photons. Therefore, theoretically photoconductive terahertz sources have a substantially higher upper optical-to-terahertz conversion efficiency limit than sources based on nonlinear optical processes.

However, conventional photoconductive terahertz emitters still suffer from a poor quantum efficiency. Only the ultrafast photocurrent that reaches the terahertz antenna can contribute to the terahertz radiation. This requires the transport time of the photocarriers to the contact electrode to be within a fraction of the terahertz oscillation period (1 ps for 1 THz). For example, for GaAs substrates, only the photocarriers within the first 100 nm of the substrate depth can efficiently generate radiation at frequencies above 1 THz. The rest of the photocarriers only contribute to a
low-frequency photocurrent, which can heat the device and degrade its efficiency and reliability. The low-frequency photocurrent can also result in an inverse electric field that lowers the acceleration of the photocarriers moving toward the antenna electrodes. To address this problem, short-carrier-lifetime semiconductors are usually used as the photoconductor, such as low-temperature grown GaAs (LT-GaAs). Because of the short carrier lifetime (<1 ps), most of the photocarriers recombine before they can reach the contact electrodes, so they cannot contribute to the terahertz radiation. Only the photocarriers that are very close to the contact electrodes can be collected and routed to the terahertz antenna. However, short-carrier-lifetime semiconductors usually have a lower mobility than the intrinsic semiconductors due to the defects inside their lattice. Apart from the carrier mobility limitation, the minimum spot size of the optical pump beam is diffraction limited. Therefore, only a small portion of the photocarriers are generated very close to the contacts, limiting the overall quantum efficiency of conventional photoconductive terahertz emitters.

Figure 1.3 A conventional photoconductive terahertz emitter.
One of the solutions to improve the quantum efficiency of photoconductive terahertz emitters is the use of plasmonic contact electrodes (Figure 1.4) [21-24]. By focusing the optical beam directly on the plasmonic contact electrodes, surface plasmon waves are excited near the metal contact-substrate interface, which increases both the optical density and the photo-generated carrier density in close vicinity to the contact electrodes. By reducing the average transport path length of the photo-generated carriers to the contact electrodes, a significantly larger number of photo-generated carriers drifts to the terahertz antenna in a sub-picosecond timescale. Therefore, higher terahertz power levels are generated. Up to 2 orders-of-magnitude and 3 orders-of-magnitude enhancements in the optical-to-terahertz conversion efficiency of photoconductive emitters have been demonstrated by using two-dimensional (2D) and three-dimensional (3D) plasmonic contact electrode gratings [24], respectively. The concept of plasmonic contact electrodes has also been used in large-area photoconductive terahertz emitters, and terahertz radiation powers up to 6.7 mW have been achieved [25].

Figure 1.4 Photoconductive terahertz emitter with plasmonic gratings.
Despite the great promise of plasmonic photoconductive terahertz emitters, the performance of the previously demonstrated plasmonic photoconductive emitters has been very sensitive to the polarization state of the optical pump beam due to the use of grating-based plasmonic contact electrodes (Figure 1.5). This polarization sensitivity could be a major problem for future terahertz imaging, spectroscopy, and communication systems. For most terahertz systems used in research laboratories with stationary and bulky lasers, the polarization state of the laser is stable. Therefore, it is very easy to control the polarization angle of the optical pump incident on plasmonic photoconductive terahertz emitters. However, for more practical terahertz systems used in industrial environments and field settings, we need to use compact, lightweight, and low-cost pump lasers, such as various types of semiconductor lasers and fiber lasers. Many of these systems are not necessarily stationary. For example, a terahertz scanner used for imaging paintings in a museum or scanning the tiles on the outer surface of a spacecraft needs to move from one place to another. These movements and environmental conditions can change the polarization state of many compact lasers. For example, most high-power fiber lasers cannot use polarization-maintaining fibers to handle high power levels. When moving and bending the fibers during scanning, the polarization state of the output beam can easily change. Consequently, the terahertz radiation power from a grating-based plasmonic photoconductive terahertz emitter pumped by such a laser can change dramatically. Therefore, polarization-insensitive plasmonic contact electrode structures are in high demand to maintain high optical-to-terahertz conversion efficiencies under various optical polarization conditions.
Figure 1.5 Terahertz radiation power as a function of the polarization angle of the optical pump in a photoconductive terahertz emitter with grating-based plasmonic contact electrodes [22].
Chapter 2: Theory and Design

2.1 Optical transmission through periodic metallic structures

For a plane wave normally incident on a planar dielectric surface, the optical transmission obeys the Fresnel equation. The optical absorption inside the dielectric substrate depends on both the optical intensity and the absorption coefficient. For GaAs, the absorption coefficient at 800 nm is \(~10^4\) cm\(^{-1}\) (Figure 2.1), which means that most of the transmitted optical waves are absorbed within the first 1 \(\mu\)m depth in GaAs. As discussed in Chapter 1, only the photocarriers generated within the first 100 nm distance from the contact electrodes can efficiently contribute to terahertz radiation. The rest of the optical energy is wasted.

![Figure 2.1 Absorption coefficients of several semiconductors at 300 K [41].](image-url)
With subwavelength periodic metallic structures, surface plasmon waves can be generated near the metal-substrate interface. When the light is incident on the subwavelength metallic structures, the extra momentum provided by the periodic structures can couple the incident light to the surface plasmons on the metal (Figure 2.2). Localized surface plasmons are induced around the metallic structure, and redistribute optical waves inside the substrate, enhancing the optical absorption near the surface.

![Figure 2.2 Surface plasmon dispersion diagram (green line). The excitation of a surface plasmon wave requires an additional momentum, G.](image)

For metallic gratings, only the electromagnetic waves with an electric field normal to the grating direction can transmit through the gratings; the parallel component of the electric field is blocked
by the metal. On the other hand, 2D symmetric periodic metallic structures can provide extra momentum in either direction, therefore an incident wave with various polarization directions can transmit through the metallic structures.

2.2 Design of polarization-insensitive plasmonic contact electrodes

There are numerous periodic subwavelength metallic structures that can be used to generate surface plasmon waves. In our case, the periodic metallic structures are used as the plasmonic contact electrodes, so they also serve to collect the ultrafast current from the photoconductor. Therefore, isolated metallic structures cannot be used as the plasmonic contact electrodes. Extensive theoretical and experimental studies have investigated the transmission spectrum of various periodic subwavelength metallic structures and its dependence on the geometric parameters [26-37]. A recent study showed that cross-shaped hole arrays inside a metal sheet can provide a larger transmission of light than square-shaped and rectangular-shaped hole arrays [38]. Therefore, we choose cross-shaped aperture arrays for our plasmonic contact electrodes.

There are several design strategies for plasmonic contact electrodes. We choose to maximize the optical absorption in a 100 nm-deep GaAs layer under the plasmonic contact electrodes. To further increase the optical absorption, we add a silicon nitride layer on top of the substrate to serve as an anti-reflection layer. We use gold as the metal to achieve strong plasmonic enhancement factors at an 800 nm optical pump wavelength. Because gold does not adhere well to the GaAs surface, we need to use a thin layer of Ti as the adhesion layer. Our optimized cross-shaped
aperture array possesses a 200 nm periodicity, a 150 nm arm length, and a 50 nm arm width. The thicknesses of the Au, Ti, and silicon nitride layers are 45 nm, 3 nm, and 340 nm, respectively.

We use a finite-element-method-based software package (COMSOL) to analyze the interaction of an 800 nm optical pump beam with the designed cross-shaped aperture arrays. Figure 2.3 shows that the excitation of surface plasmon waves by the cross-shaped aperture arrays bends the direction of the transmitted optical pump beam through the apertures. The surface plasmon waves enhance the photocarrier concentration near the contact electrode-substrate interface, where the electric field is strongest under an external bias. The analysis also shows that the optical transmission through the cross-shaped plasmonic contact electrodes and the photocarrier concentration in the substrate are not affected by the polarization state of the optical pump beam.

Figure 2.3 Top-view color plot of the optical absorption inside the GaAs substrate at a depth of 1 nm below the surface (left) and cross-sectional-view color plot of the optical absorption inside the GaAs substrate (right) at an optical pump wavelength of 800 nm. The white arrows show the optical power flow direction.
Figure 2.4 compares the optical absorption in a 100 nm-deep GaAs region beneath the designed cross-shaped plasmonic contact electrode with that of a plasmonic contact electrode grating. The geometry of the plasmonic contact electrode grating (3 nm Ti/45 nm Au, periodicity = 225 nm, width = 125 nm) is chosen to maximize the optical absorption in a 100 nm-deep GaAs region beneath the contact electrodes for an 800 nm optical pump beam polarized normal to the gratings. While the optical absorption beneath the cross-shaped plasmonic contact electrode remains constant at all optical pump polarizations, it varies significantly for the plasmonic grating. Our analysis estimates an ~2.5 times reduction in optical absorption beneath the plasmonic grating, which corresponds to ~6 times reduction in the generated terahertz power level, when the optical pump polarization direction is changed from the normal to the parallel orientation relative to the grating.

Figure 2.4 Normalized optical absorption in a 100-nm-deep GaAs region beneath the designed cross-shaped plasmonic contact electrode (purple data) and a plasmonic contact electrode grating (blue data) as a function of the optical pump polarization.
We also compare our designed cross-shaped aperture array with other aperture arrays of different shapes. Figure 2.5 shows the optical absorption inside the GaAs substrate within various regions under cross-shaped, circle-shaped, and square-shaped aperture arrays with the same area. We can see that the cross-shaped aperture array has the highest optical absorption within the first 100 nm of the GaAs substrate depth compared to the other two structures.

Figure 2.5 The optical absorption inside the GaAs substrate as a function of the depth under the periodic metallic structures with different shapes.
2.3 Terahertz antenna design

The terahertz antenna should be chosen according to the terahertz emitter mode of operation and the desired application. For our first proof-of-concept polarization-insensitive plasmonic terahertz emitter, pulsed mode of operation is chosen, which necessitates the use of a broadband antenna. We choose logarithmic spiral antenna as the terahertz radiating element (Figure 2.6) [21]. This antenna is designed to offer a broadband radiation resistance of 70-100 Ω and a reactance close to 0 Ω over the 0.1-2 THz frequency range.

![Figure 2.6 Radiation resistance and antenna reactance of the designed logarithmic spiral antenna [21].](image)
The structure of the designed polarization-insensitive plasmonic photoconductive terahertz emitter is shown in Figure 2.7. The cross-shaped plasmonic contact electrodes are connected to the logarithmic spiral antenna and serve as the current source feeding the antenna. The emitter is mounted on a silicon lens to collect and collimate the terahertz radiation from the back-side of the GaAs substrate.

Figure 2.7 Schematic diagram of the polarization-insensitive plasmonic photoconductive emitter with cross-shaped aperture array contact electrodes fabricated on an SI-GaAs substrate.
Chapter 3: Fabrication

The general fabrication process of the polarization-insensitive plasmonic photoconductive terahertz emitter can be divided into three parts: (1) the fabrication of plasmonic contact electrodes, (2) the fabrication of the logarithmic spiral antenna, and (3) the device packaging. For the first polarization-insensitive plasmonic photoconductive terahertz emitter prototype, we choose to use a semi-insulating (SI)-GaAs substrate.

3.1 Plasmonic contact electrode fabrication

(a) Clean the GaAs wafer by immersing the sample in acetone (10 min), isopropanol (10 min), and deionized water (10 min).

(b) Dry the sample with nitrogen.

(c) Bake the sample on a hot plate at 70 °C for 1 min.

(d) Spin coat MicroChem 950K PMMA A4 on the sample at 3,000 rpm for 60 sec.

(e) Bake the resist on a hot plate at 180 °C for 3 min.

(f) Perform electron-beam lithography of the cross-shaped aperture arrays.

(g) Develop the electron-beam resist by immersing the sample in an MIBK:IPA 1:3 mixture for 60 sec.
(h) Remove the developer by immersing the sample in pure isopropanol and deionized water immediately after (g).

(i) Remove the surface oxide layer by immersing the sample in hydrochloric acid (15%) for 15 sec.

(j) Remove the HCL by deionized water.

(k) Deposit metal (3/45 nm Ti/Au) on the sample using a CHA Solution electron-beam evaporator.

(l) Lift-off the deposited metal by immersing the sample in acetone for 12 hours. Then put the sample in an ultrasonic agitator for 3 min.

(m) Remove acetone by immersing the sample in isopropanol (3 min) and deionized water (1 min).

(n) Dry the sample with nitrogen.

To fabricate the cross-shaped aperture arrays with a 200 nm period, a 150 nm arm length, and a 50 nm arm width, the electron-beam (e-beam) lithography pattern needs special design. With the original designed pattern (Figure 3.1a), the fabricated metal does not show the designed cross shape (Figure 3.1c) due to the nonuniform electron beam accumulation. By specially designing the e-beam lithography pattern (Figure 3.1b), the sharp corners compensated the e-beam distribution, and the fabricated metal shows a clear cross shape (Figure 3.1d).
Figure 3.1 (a) The original electron-beam lithography pattern for cross-shaped aperture arrays. (b) The modified electron-beam lithography pattern. (c) A scanning-electron microscope (SEM) image of the cross arrays obtained using the e-beam pattern in (a). (d) An SEM image of the cross arrays obtained using the e-beam pattern in (b).

### 3.2 Antenna fabrication

(a) Spin coat AZ nLOF 2020 photoresist on the sample at 3,000 rpm for 60 sec.

(b) Bake the resist on a hot plate at 110 °C for 1 min.

(c) Perform optical lithography of the logarithmic spiral antenna.
(d) Develop photoresist by immersing the sample in AZ 300MIF for 90 sec.

(e) Remove the developer by immersing the sample in deionized water immediately after (d).

(f) Deposit metal (20/400nm Ti/Au) on the sample using CHA Solution electron-beam evaporator.

(g) Lift-off the deposited metal by immersing the sample in acetone for 12 hours. Then put the sample in an ultrasonic agitator for 1 min.

(h) Remove acetone by immersing the sample in isopropanol (3 min) and deionized water (1 min).

(i) Dry the sample with nitrogen.

Figure 3.2 An optical microscope image of the fabricated logarithmic spiral antenna. The two middle metal pads are cross-shaped plasmonic contact electrodes.
### 3.3 Device package

1. Deposit silicon nitride as the anti-reflection coating
   
   (a) Clean the sample with acetone (3 min), isopropanol (3 min) and deionized water (1 min).

   (b) Deposit a 340-nm-thick silicon nitride layer by plasma-enhanced chemical vapor deposition (PECVD).

2. Open contact vias through the silicon nitride layer
   
   (c) Spin coat AZ nLOF 2020 photoresist on the sample at 3,000 rpm for 60 sec.

   (d) Bake the resist on a hot plate at 110 °C for 1 min.

   (e) Perform optical lithography of the contact vias.

   (f) Develop photoresist by immersing the sample in AZ 300MIF for 90 sec.

   (g) Remove the developer by immersing the sample in deionized water immediately after (d).

   (h) Etch the silicon nitride layer by reactive-ion etching using an Oxford 80 Plus.

   (i) Remove the photoresist by immersing the sample in acetone (10 min), isopropanol (3 min) and deionized water (1 min). Dry the sample with nitrogen.

   (j) Dice the sample into individual devices.

   (k) Glue the device on a 12 mm hyper-hemispherical silicon lens.

   (l) Bond wires onto the device.
Chapter 4: Characterization and Results

4.1 Terahertz radiation power measurement

4.1.1 Experimental setup

A mode-locked Ti:Sapphire laser with an 800 nm wavelength, 135 fs pulse width, and 76 MHz repetition rate was used as the pump source to characterize the radiation properties of the fabricated polarization-insensitive plasmonic photoconductive terahertz emitter (Figure 4.1). The optical beam from the laser was linearly polarized. To control the polarization direction of the optical pump, we first used a quarter-wave plate to convert the linearly polarized optical beam into circularly polarized beam. Then we placed a linear polarizer with a controllable polarization angle after the quarter-wave plate to control the polarization angle of the optical pump. The beam was focused by an objective lens onto the anode plasmonic contact electrode to maximize the induced ultrafast photocurrent and optimize the impedance loading to the logarithmic spiral antenna.

![Experimental setup for measuring the terahertz radiation power from the polarization-insensitive plasmonic photoconductive terahertz emitter.](image)

Figure 4.1 Experimental setup for measuring the terahertz radiation power from the polarization-insensitive plasmonic photoconductive terahertz emitter.
The terahertz radiation power was measured by a calibrated pyroelectric detector (Spectrum Detector Inc., SPI-A-65 THz). For each measurement, the polarization direction of the optical beam was recorded, and the optical pump power incident on the terahertz emitter was measured and adjusted to the same value by an optical attenuator. An optical chopper and a lock-in amplifier were used to eliminate the background noise and amplify the pyroelectric detector output signal.

4.1.2 Result and analysis

The measured radiation power as a function of the optical pump power and bias voltage are shown in Figure 4.2. The measured terahertz radiation power increases as the bias voltage is increased. This is because the electric field across the anode and cathode contacts accelerates the photogenerated electrons and holes. At higher optical pump powers, a larger number of photocarriers is generated, which results in a higher terahertz radiation power. At an 8 mW optical pump power and 20 V bias voltage, the terahertz radiation power can reach 28.8 uW. This is comparable with the power of the previously demonstrated grating-based plasmonic photoconductive terahertz emitter with identical logarithmic spiral antenna at the optimum polarization angle [21]. Higher terahertz radiation powers are achieved at higher optical pump powers.

The terahertz radiation power from the fabricated plasmonic photoconductive emitter was measured at different optical pump polarization angles, while maintaining a 4 mW optical pump power. Unlike grating-based plasmonic photoconductive emitters [22], whose terahertz radiation power drops by more than one order of magnitude when the optical polarization changes from the optimum angle to the worst angle, a negligible variation in the terahertz radiation power was
observed when varying the optical polarization angle from 0 degree to 180 degrees (Figure 4.3). This demonstrates an effective polarization insensitive solution for practical applications.

Figure 4.2 Average terahertz radiation power from the fabricated terahertz emitter as a function of the bias voltage and optical pump power.
4.2 Terahertz spectrum measurement

4.2.1 Experimental setup

A time-domain spectroscopy setup was used to characterize the spectral properties of the polarization-insensitive plasmonic photoconductive terahertz emitter (Figure 4.4). The optical beam from the Ti:sapphire laser was first split into two beams using an optical beam splitter. One of the optical beams was used to pump the terahertz emitter. The generated terahertz pulse was focused onto a plasmonic photoconductive terahertz detector based on nano-antenna arrays [39]. The other optical beam was used to probe the terahertz detector. By moving the delay stage, the time delay between the optical probe pulses and the incident terahertz pulses on the terahertz detector is varied to observe the change in terahertz power as a function of polarization angle.
detector changes. Therefore, we can sample the incident terahertz field by recording the response of the terahertz detector at different delay-stage positions.

Figure 4.4 Experimental setup for time-domain spectroscopy.
4.2.2 Result and analysis

Figure 4.5 The radiated electric field in the time domain from the fabricated plasmonic photoconductive terahertz emitter with cross-shaped contact electrodes.

Figure 4.6 The radiation power in the frequency domain from the fabricated plasmonic photoconductive terahertz emitter with cross-shaped contact electrodes.
The radiated terahertz field from the fabricated plasmonic photoconductive emitter with cross-shaped contact electrodes was characterized at a 4 mW optical pump power using the described time-domain terahertz spectroscopy setup (Figure 4.4). Figure 4.5 shows the time-domain radiated electric, which has a full width at half maximum of 0.4 ps. By taking the Fourier transforms of the radiated field, the terahertz radiation spectrum is calculated (Figure 4.6). The terahertz radiation bandwidth can go up to 3 THz.
Chapter 5: Conclusion and future work

The purpose of this work was to develop a polarization-insensitive photoconductive terahertz emitter to address the problem of polarization variability of pump lasers in practical terahertz imaging and sensing systems. A two-dimensional nanoscale cross-shaped aperture array was chosen as the plasmonic contact electrodes and its design optimization was investigated. The two-dimensional symmetry of the cross-shaped apertures offers a polarization-insensitive interaction between the plasmonic contact electrodes and the optical pump beam. The geometry of the cross-shaped apertures was set to maximize the optical pump absorption in close proximity to the contact electrodes. Prototypes of the polarization-insensitive plasmonic photoconductive terahertz emitter were fabricated and characterized. The emitter prototypes show an excellent polarization insensitivity and similar terahertz radiation powers compared to previously demonstrated polarization-sensitive photoconductive terahertz emitters with plasmonic contact electrode gratings at the optimum optical pump polarization.

The use of two-dimensional symmetric plasmonic contact electrodes is not limited to the demonstrated photoconductive emitter. Depending on the application, different types of antennas can be used for terahertz wave radiation. For continuous-wave terahertz radiation, we can use resonant antennas to offer higher radiation resistance at the desired frequency, such as dipole antennas. For broadband terahertz radiation, large-area photoconductive antenna arrays can provide higher terahertz radiation powers. The polarization-insensitive plasmonic contact electrodes can be easily integrated with these terahertz antennas. Furthermore, the two-dimensional symmetric plasmonic contact electrodes can be used in photoconductive terahertz...
detectors to offer a polarization-insensitive operation. In addition, the geometry of the polarization-insensitive plasmonic contact electrodes can be easily adjusted for operation at different optical pump wavelengths.
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