High power telecommunication-compatible photoconductive terahertz emitters based on plasmonic nano-antenna arrays

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We present a high-power and broadband photoconductive terahertz emitter operating at telecommunication optical wavelengths, at which compact and high-performance fiber lasers are commercially available. The presented terahertz emitter utilizes an ErAs:InGaAs substrate to achieve high resistivity and short carrier lifetime characteristics required for robust operation at telecommunication optical wavelengths. It also uses a two-dimensional array of plasmonic nano-antennas to offer significantly higher optical-to-terahertz conversion efficiencies compared to the conventional photoconductive emitters, while maintaining broad operation bandwidths. We experimentally demonstrate pulsed terahertz radiation over 0.1–5 THz frequency range with the power levels as high as 300 μ W. This is the highest-reported terahertz radiation power from a photoconductive emitter operating at telecommunication optical wavelengths. *Published by AIP Publishing.* [<http://dx.doi.org/10.1063/1.4967440>]

Photoconductive emitters are widely used for generating sub-picosecond pulses in the time-domain terahertz imaging and spectroscopy systems.^{1–6} Telecommunication wavelengths (e.g., 1550 nm) are one of the most desired regimes for pumping photoconductive emitters due to the availability of high-performance, low-cost and compact fiber lasers.^{7,8} However, the performance of previously demonstrated photoconductive terahertz emitters operating at telecommunication wavelengths has been limited by low resistivity of photo-absorbing semiconductor substrates at these wavelengths (e.g., InGaAs). This is because efficient operation of photoconductive terahertz emitters requires accelerating photo-generated carriers by high bias electric fields, which results in high dark currents and thermal breakdown when using low resistivity substrates.

Various different techniques have been proposed to overcome the low resistivity limitation of photo-absorbing substrates at telecommunication wavelengths.^{9–12} One of the most promising solutions is the use of a superlattice of monolayers of ErAs in an InGaAs substrate. Since the ErAs layers act as deep recombination centers inside the superlattice, the resistivity and carrier lifetime of such superlattice structures can be controlled by the number and thickness of ErAs layers.^{13–16} Although the high resistivity and short carrier lifetime characteristics of ErAs:InGaAs substrates can enable a more reliable device operation at telecommunication wavelengths, the radiation power of previously demonstrated ErAs:InGaAs photoconductive terahertz emitters operating at 1550 nm pump wavelengths has been limited by low quantum efficiency of conventional ultrafast photoconductors.

In this work, we present a large-area photoconductive terahertz emitter based on a two-dimensional array of plasmonic nano-antennas fabricated on an ErAs:InGaAs substrate. The use of plasmonic nano-antennas allows absorption and concentration of the majority of incident pump photons in close proximity to the nano-antennas. As a result, most of the photo-generated carriers drift to the nano-antennas within a sub-picosecond

time-scale and contribute to enhanced terahertz radiation.^{17–24}

The enhanced terahertz radiation is maintained over broad bandwidths by the use of nano-antenna sizes much smaller than the terahertz wavelengths.²⁴ Additionally, using the large device active areas allows efficient operation at high optical pump power levels without being limited by the carrier screening effect and thermal breakdown. By using this powerful technique, we demonstrate the terahertz radiation power levels as high as 300 μ W over a 0.1–5 THz frequency range, exhibiting the highest reported terahertz radiation power compared to the previously demonstrated photoconductive terahertz emitters operating at telecommunication optical pump wavelengths.

Schematic diagram and operation concept of the presented photoconductive terahertz emitter is shown in Fig. 1. It is fabricated on a 1 μ m thick ErAs:InGaAs layer, epitaxially grown on an InP substrate, with a carrier lifetime of 1.24 ps. The device has interdigitated bias lines. A two-dimensional array of plasmonic nano-antennas is connected to anode bias lines within every other gap between the anode and cathode bias lines. The other gaps between the anode and cathode bias lines are shadowed by a second metal layer deposited on top of an Si₃N₄ antireflection coating layer. This blocks optical transmission into the substrate and prevents forming an optically-induced terahertz-radiating dipole moment in the opposite direction to that of the nano-antennas.^{25,26} Geometry of the plasmonic nano-antennas, which are in the form of Au gratings, is chosen to excite surface plasmon waves when illuminated by the optical pump beam.^{27–29} The excitation of surface plasmon waves concentrates a large portion of the optical pump photons and photo-generated carriers in close proximity to the nano-antennas. By reducing the average distance of the photo-generated carriers from the nano-antennas, a larger number of photocarriers are drifted to the nano-antennas in a sub-picosecond time scale and significantly higher optical-to-terahertz conversion efficiencies are achieved compared to non-plasmonic photoconductive emitters.¹⁹ In order to maintain high

FIG. 1. Schematic diagram of the presented photoconductive terahertz emitter based on a large-area plasmonic nano-antenna array fabricated on an ErAs:InGaAs substrate.

optical-to-terahertz conversion efficiencies over broad bandwidths, the length of nano-antennas is chosen to be much smaller than the terahertz wavelengths ($5 \mu\text{m}$).

A Finite Element Method-based multi-physics solver (COMSOL) is used to analyze the interaction between the plasmonic nano-antennas and a TM-polarized optical pump beam. The analysis shows that using the Au nano-antennas with 50 nm height, 90 nm width, and 180 nm periodicity and a 250 nm Si_3N_4 antireflection coating layer offers 96% optical transmission into the ErAs:InGaAs substrate at a 1550 nm pump wavelength (Fig. 2). Since optical transmission into the substrate is accompanied by the excitation of surface plasmon waves, optical absorption is significantly enhanced at the edges of the plasmonic nano-antennas (Fig. 2 inset).

Prototypes of the presented plasmonic terahertz emitter with $0.5 \times 0.5 \text{ mm}^2$ active area are fabricated on an ErAs:InGaAs substrate. The plasmonic nano-antennas are patterned by electron-beam lithography followed by 5/45 nm Ti/Au deposition and liftoff. The interdigitated bias lines are patterned by optical lithography followed by 40/360 nm Ti/Au deposition and liftoff. A 250 nm-thick Si_3N_4 antireflection coating layer is deposited next by plasma-enhanced chemical vapor deposition. After this step, shadow metals are patterned

FIG. 2. Optical transmission spectrum through the plasmonic nano-antennas into the ErAs:InGaAs substrate; the inset shows optical absorption inside the ErAs:InGaAs substrate at 1550 nm pump wavelength.

by optical lithography followed by 10/90 nm Ti/Au deposition and liftoff. Contact vias are patterned by optical lithography and opened by reactive ion etching of the Si_3N_4 layer. Optical microscope image of the device and scanning electron microscope image (SEM) of the plasmonic nano-antennas are shown in Figs. 3(a) and 3(b), respectively.

The fabricated terahertz emitters are mounted on the semi-hemispherical Si lenses and characterized in response to 1550 nm optical pump pulses with 170 fs width and 76 MHz repetition rate, generated by an optical parameter oscillator (OPO) pumped by a Ti:sapphire laser. The optical pump spot size is adjusted to illuminate the entire device active area, and its polarization is set to be normal to the plasmonic nano-antennas.

Figure 4(a) shows the induced photocurrent in a fabricated emitter prototype as a function of the optical pump power and bias voltage. The observed asymmetry in the photocurrent characteristics is due to the asymmetry in the photoconductor contact electrode areas as well as the higher drift velocities of photo-generated electrons compared to photo-generated holes under the same bias electric fields. As illustrated in Fig. 4(a), higher dark currents are induced compared to the photocurrent levels at optical pump powers ranging from 100 mW to 400 mW. The high dark current levels are due to the low resistivity of the ErAs:InGaAs substrate that could result in thermal breakdown at high bias voltages.

FIG. 3. Optical microscope image of the plasmonic terahertz emitter and scanning electron microscope image of the plasmonic nano-antennas are shown in (a) and (b), respectively.

FIG. 4. (a) The induced photocurrent and (b) terahertz radiation power from a large area plasmonic photoconductive emitter prototype as a function of the optical pump power and bias voltage.

A calibrated pyroelectric detector (Spectrum Detector, Inc. SPI-A-65 THz) is used to measure the radiated terahertz power from the emitter prototype. Figure 4(b) shows the radiated terahertz power from the emitter prototype as a function of bias voltage and optical pump power. A non-quadratic relation between the radiated power and optical pump power is observed, indicating that the emitter efficiency is degraded by the carrier screening effect. The impact of the carrier screening effect is more dominant at higher optical pump powers, since a larger number of photo-generated electrons and holes are separated from each other by the bias electric field. The negative impact of the carrier screening effect can be easily mitigated by using larger area plasmonic nano-antenna arrays. Terahertz radiation powers as high as $300 \mu\text{W}$ are achieved at 400 mW optical pump power, exhibiting the highest-reported terahertz radiation power from the photoconductive terahertz emitters operating at telecommunication wavelengths.

A time-domain terahertz spectroscopy setup is used to measure the radiated electric field from the emitter prototype (Fig. 5(a)). For this purpose, the 1550 nm optical beam from

FIG. 5. (a) Experimental setup used for measuring the radiated electric field from the terahertz emitter prototype in the time domain. The radiated electric field in the time domain and radiated power in the frequency domain are shown in (b) and (c), respectively.

the OPO is split into two beams. One beam is used to pump the emitter prototype to generate terahertz radiation. The other beam is first frequency-doubled by a periodically-poled Lithium Niobate crystal and then focused onto a 0.6 mm-thick GaAs (110) crystal for electro optic detection of the generated terahertz radiation. The bias voltage of the terahertz emitter is modulated between +15 and -15 V with a 3 kHz modulation frequency. Figure 5(b) shows the radiated electric field in the time domain at an optical pump power of 300 mW with a radiation pulse width of ~ 0.7 FWHM. Radiation spectrum is obtained from the Fourier

transform of the measured radiated electric field. Figure 5(c) shows the calculated radiation spectrum, indicating radiation bandwidths of more than 5 THz and signal-to-noise ratio levels of 80 dB.

In summary, we present a high-power and telecommunication-compatible terahertz emitter based on large-area plasmonic nano-antenna arrays fabricated on an ErAs:InGaAs substrate. The use of plasmonic nano-antenna arrays offers a significant enhancement in the optical-to-terahertz conversion efficiency compared to the conventional photoconductive terahertz emitters while maintaining broad radiation bandwidths. The use of ErAs:InGaAs substrate offers the high resistivity and short carrier lifetime characteristics required for robust device operation at telecommunication pump wavelengths. We experimentally demonstrate radiation powers as high as 300 μ W over 0.1–5 THz frequency range. This is the highest-reported terahertz radiation power from the photoconductive terahertz emitters operating at telecommunication wavelengths. Therefore, the presented terahertz emitter is a very promising candidate for high-performance and compact time-domain terahertz imaging and spectroscopy systems.

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