Enhanced THz generation from interdigitated quantum dot based photoconductive antenna operating in a quasi-ballistic regime

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***Abstract*—In this paper, we present a new approach for the enhancement of pulsed terahertz (THz) generation in quantum dot (QD) based photoconductive antennas (PCA). We demonstrate the benefits of the combination of a QD substrate based PCA and an interdigitated electrodes topology which allows the photocarriers to reach the antenna terminals in a quasi-ballistic regime and immediately contribute to the THz emission. A 50-fold increase in the generated THz power is observed. Such enhancement is made possible by unique combination of QD substrate properties, such as very high electric and thermal breakdown ruggedness, high carrier mobility, and yet short carrier lifetimes, compared to typical low temperature grown materials. We expect this solution to become favourable for development of powerful compact THz emitters.**

I. Introduction

The quest for efficient yet compact source of the terahertz (THz) radiation started almost 40 years ago and still remains a pending issue, despite numerous solutions proposed to date [1]. Photoconductive antennas (PCAs) have shown themselves as the most efficient sources for pulsed THz spectroscopy and imaging [2] applications. Nevertheless, pulsed PCA setups, despite reaching considerable powers and efficiency [3], are still relatively bulky and are barely operational outside the labs, as they require extensive and expensive ultrafast lasers as pump sources [4]. The placement of optical nanoantennas in the PCA gaps, suggested about a decade ago [5], showed some exciting results, boosting the generation and detection efficiency by up to two orders of magnitude [6], [7]. The plasmonic THz mesh at the output of the PCA can also significantly enhance the emitted THz power [8]. Further steps towards compactness of the pulsed THz spectroscopic and imaging setups were taken with the introduction of the quantum-dot (QD) based PCAs (QDPCAs) [9]. The QD based photoconductive substrate provides an inherent compatibility [10] with the QD ultrafast lasers [11]. Since introduction, QDPCA have proven to be an efficient THz emitters capable of generating tunable CW [12] and pulsed [9], [13] THz radiation. Due to high-quality, defect-less QD substrates, such PCAs demonstrate exceptional thermal and electrical breakdown tolerance, allowing for up to 1 W of pump power into a single gap antenna [14]. Moreover, these antennas were shown to be efficiently enhanced by introduction of silver plasmonic nanoantennas [15].

Important to note that one of the crucial features of the QD structures is the unique combination of the sub-ps photocarrier lifetime τ_c [16] with increased mobility [9] compared to low-temperature grown GaAs and ternary photoconductive compounds as InGaAs [17]. The mobility vs. lifetime trade-off is essential for the THz power enhancement and stable operation of the PCA-emitter. Nevertheless, since the photocarrier mobility is proportional to the momentum relaxation time τ_s, the decrease of τ_c causes the degradation of τ_s [18], [19]. Recently it was shown that this contradiction can be overcome using thin (~200 nm) and high-mobility photoconductive substrates in combination with plasmonic nanoantennas, providing sub-ps transit time τ_b of photocarriers, that is actually a ballistic time, and thus mitigating the requirement of the shortening of τ_c [20], [21] by shortening the τ_b.

Here, we report an alternative approach, i.e. without plasmonic effects, to enhance the THz pulsed emission using the QDPCA with an interdigitated (ID) electrodes topology. Such topology is considerably easier in production than plasmonic grating, due to the larger spatial size of the topology elements. The observed THz boost occurs predominantly due to a number of reasons residing in the ID topology: (1) increased antenna perimeter, and as a consequence, increased photocurrent; (2) increased electrical capacitance of the IDQDPCA's gap, as the ID electrodes form a series of parallel connected capacitors. Moreover, the developed emitter might operate in a quasi-ballistic regime with a characteristic time $\tau_b \sim 3$ ps thanks to the combination of the unique properties of a QD structure with ID topology, that allows the photocarriers to reach the electrodes immediately. Importantly, that the strong electric fields between the fingers do not cause the breakdown of the antenna due to the QD based photoconductive substrate. Enhancement of the THz power manifests predominantly in the lower frequency part of the spectrum, where it exceeds 50-

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fold mark at lower pump powers. Interestingly, up to date only ID PCAs with a microlens array [22] and plasmonic large-area THz emitters with a shadow Au layer [23] have been reported as efficient pulsed THz transceivers.

II. Sample Growth, Antenna Fabrication and Experimental Setup

The substrates containing InAs QDs in the GaAs bulk used as the PCA photoconductive medium were MBE grown in the Stranski-Krastanow regime. Structure with 25 equally spaced unform QD layers were grown on 30 layer AlAs/GaAs Distributed Bragg Reflector (DBR) and capped with 30 nm thick layer of LT-GaAs. This layer is thin enough not to contribute to the photoconductivity, yet its presence increases the dark resistance of the resulting PCA samples and facilitates the ohmic contact between PCA electrodes and the substrate. More detailed information on the QD substrated design and growth can be found in our earlier papers [9], [10].

The samples of IDQDPCA and bare QDPCA (for comparison) were fabricated within one technological routine similar to that reported in our previous works [24], [25]. The PCAs utilize a 60° bow-tie topology with a photoconductive gap of 20 μm. The 50/450 nm thick Ti/Au metallization was deposited on the PCAs surface using thermal evaporation. Finally, the 150 nm height ID electrode fingers were fabricated using electron-beam nanolithography and covered with a 130 nm thick Al_2O_3 antireflection and protection layer. The 200 nm wide electrode fingers are separated by a 1.2 μm gap and placed within a 20-μm wide area. Bare QDPCA was also covered with a 130 nm thick Al_2O_3 layer to provide more fair comparison. The SEM image of the IDQDPCA design is shown in Fig.1 (a).

The PCA were used as THz emitters in our laboratory THz time-domain spectrometer (THz-TDS) pumped with a compact fiber EFOA-SH fs-laser (by AVESTA) featuring a central wavelength of 780 nm, pulse duration $\sim$ 100 fs and the repetition rate of 70 MHz. The wrapped-dipole PCA TERA-8 (by Menlo Systems) was used as a THz detector. Both PCA-emitters under the comparison were biased with rectangular pulses with amplitude U_b = 0-5 V (adjustable) and a repetition rate of 20 kHz. The laser radiation was focused onto the antennas gap by a plano-convex lens with a 10 mm focal length to provide a tight focusing of the laser beam. The optical pump power in the PCA-emitter channel was adjusted by the programmable attenuator in the range of $P_{\rm opt} = 0.1 - 10$ mW. A pair of plano-convex high-resistivity float-zone silicon hyperhemispheric lenses with a 12 mm diameter and a 7.1 mm height HSL-12 (by Batop) were used to match the THz radiation with free space; two 2-inch-diameter off-axis parabolic mirrors with 4-inch focal length were employed to collect THz waves from the PCA-emitter and focus them onto a PCA-detector. The current from the PCA-detector was pre-amplified and then demodulated at 20 kHz in order to obtain a signal-to-noise ratio of the THz-TDS $\sim$ 70 dB. The collection time for one spectrum measurement with frequency resolution of $\sim$ 0.02 THz was about 20 s, which was achieved by using a 150 mm high speed linear delay stage with optical feedback, Parker Daedal MX80 (by Parker Hannifin). For simplicity, we limited ourselves to THz measurements in non-dried room air and at room temperature. Nevertheless, this does not prevent measurement, analysis and comparison of the detected THz signal from the PCAs under study. The detected THz pulse waveform signal was collected 20 times; then we applied the Fast Fourier Transform with Tukey (tapered cosine) signal window. During comparative measurements, we only substituted and adjusted the PCA-emitters, while keeping the rest of the THz beam path unchanged.

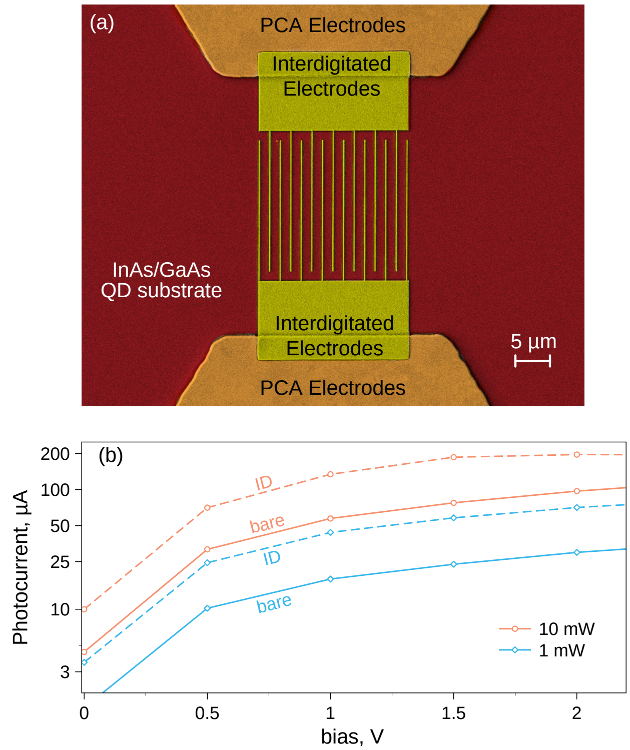

Fig. 1. (a) SEM image of the fabricated IDQDPCA design, and (b) the PCA photocurrent vs. bias voltage in log-scale for IDQDPCA and bare QDPCA for pump powers of $P_{\rm opt}$ = 1 and $P_{\rm opt}$ = 10 mW.

The time-independent photocurrent, i.e. the photocurrent in antenna-emitter circuit under fs-laser pump, was measured at bias voltage U_b = 0-2 V in order to prevent the IDQDPCA breakdown at high pump power due to substantial Joule heating due to small gap between fingers in the ID topology. This dependence is shown in Fig.1 (b) illustrating the impact of ID electrodes on the photocurrent enhancement. As seen, for the chosen U_b range, no current saturation effects for the both PCAs are observed.

III. Results and Discussion

Fig. 2 demonstrates the THz spectra for the bare QDPCA and IDQDPCA, respectively. The observed numerical narrow lines in the spectra are associated with the resonant THz absorption by water vapour along the THz beam path. As it can be seen from the plots, the spectra generally keep their shape with the change of pump power across the whole frequency

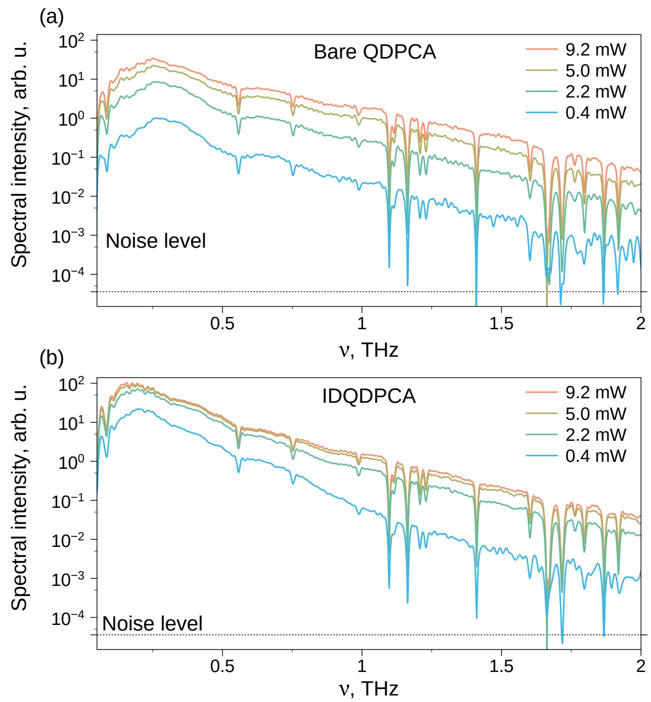

Fig. 2. THz spectra for the laser pump powers of $P_{\text{opt}} = 0.4 - 9.2$ mW for (a) bare QDPCA and (b) IDQDPCA

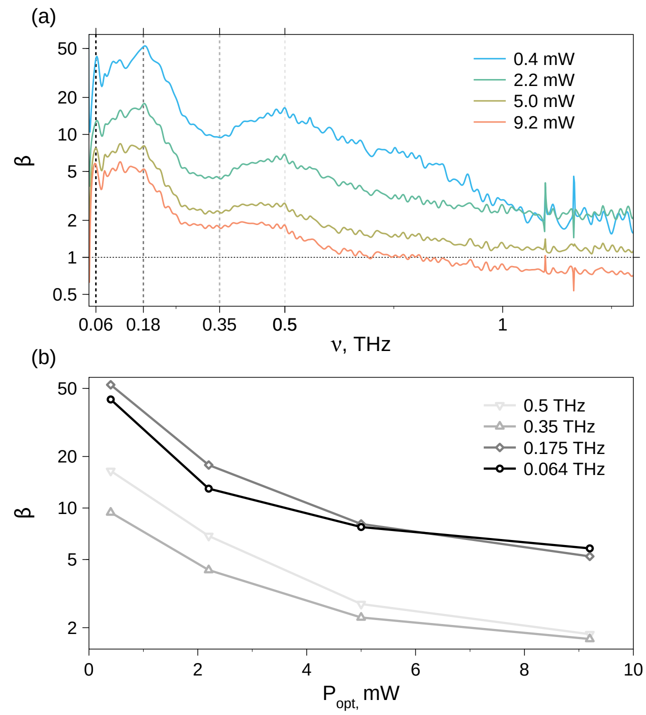

Fig. 3. (a) Spectral power boost factor β characterising the enhancement of THz power in the IDQDPCA over QDPCA, and (b) β vs. P_{opt} dependence for the frequencies marked in (a).

domain for both bare and IDQDPCA, and IDQDPCA has a spectral maximum at lower frequencies.

To demonstrate the effect of the incorporated ID electrodes on the PCA-emitter performance, we introduce the spectral power boost factor $\beta(\nu) = \dfrac{P_{\text{IDQDPCA}}(\nu)}{P_{\text{QDPCA}}(\nu)}$, which is derived as a ratio between the THz spectral power of IDQDPCA and QDPCA, respectively.

As it can be seen from Fig.3 (a), β is dependent on the optical pump power P_{opt}, while the THz boost is predominantly concentrated in a low-frequency region of $\nu \leqslant 1$ THz. The very similar phenomenon we observed in plasmonic PCA-emitters earlier [26], [27]. Nevertheless, plasmonic-assisted technology is much more complicated when compared to ID topology. The boost in the latter is associated with the increased perimeter of the ID electrodes topology, that results in the rise of the photocurrent compared to bare sample, as well as with a $\sim$ 30-fold increase of the electric capacitance of the antenna's gap C, as the ID electrodes form multiple capacitors connected in parallel, while the emitted THz power is proportional to the electric energy stored in the gap as $P_{THz} \sim CU^2$.

The two humps are also clearly seen in Fig.3 (a) at $\nu = 0.175$ THz and $\nu = 0.5$ THz. The reason of their appearance might arise from frequency-dependent impedance mismatching between photoconductor and antenna [28]. Overall, the non monotonous behaviour of $\beta(\nu)$ is associated with the change in conductivity of the antenna's gap, since the incident light accelerates a discharge of a capacitor. At a small pump power, β slowly changes within wide frequency region, while at highest value of P_{opt} = 9.2 mW, the spectral power boost factor begins to dramatically decrease. There are several reasons for this. For a more clear illustration, we plotted the β dependence on pump power for the chosen frequencies outlined in Fig.3 (a), corresponding to the absolute maximum of β at $\nu = 0.175$ THz, for the local minimum of of β at $\nu = 0.35$ THz, and the second maxima of β at $\nu = 0.06$ THz and $\nu = 0.5$ THz, respectively. These power dependences are shown in Fig.3 (b). As one can see from the plot, all the curves demonstrate a decreasing behaviour with increase of P_{opt}. The first reason of this is an overheating of the IDQDPCA due to significantly increased photocurrent under higher pump power, that impacts the operation of the QDs as carrier capture sites, decreasing their capability to efficiently localise photocarriers. The second reason is the intervalley scattering in InAs-related materials [29], [30], as well as intensified screening effects in PCAs, and the increase of charge carriers effective mass.

We note that similarly to plasmonic PCA [31], the ID electrodes allow the antenna to operate in a quasi-ballistic regime, featuring the characteristic time $\tau_b \sim 3$ ps thanks to the unique properties of the QDs, hence allowing the photocarriers to immediately reach the antenna electrodes. This enables one to work with small bias voltages (and even at low pump power), avoiding the breakdown of the emitter. Another important advantage of IDQDPCA over plasmonic antenna [26] is the feasibility and relative ease of its fabrication technology, and a more uniform THz spectrum as well. Moreover, the selected ID topology does not require the second Au metallization layer to mask the incident laser radiation, and can easily be scaled to a higher operational area of the photoconductive gap.

IV. Conclusion

In this paper, we demonstrated a quasi-ballistic operation of a quantum dot (QD) photoconductive antenna (PCA)-emitter with interdigitated electrodes (ID) providing a 50-fold enhancement of the spectral THz power compared to the bare QD PCA with similar geometrical and physical parameters, but with conventional topology. The enhancement is predominately associated with a huge increase of the electric field in the PCA gap, and its non-uniform spectral response is defined by the $\sim$30-fold increase of electric capacitance of the antenna's gap due to ID electrodes, that form an array of capacitors connected in parallel. Overall demonstrated THz power enhancement recorded by the Golay cell is almost 10-fold for lower laser pump powers. By combining the unique properties of the QD photoconductive substrates, such as as short carrier lifetime and high mobility with the ID topology, we showed that the IDQDPCA demonstrates low saturation compared, for example, to plasmonic antenna-emitter on a LT grown substrates. We also note that the use of microlens array similar to that reported in ref [22], can potentially suppress the parasitic current, thus further enhancing the conversion efficiency of the proposed emitter.

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