Operation of quantum dot based terahertz photoconductive antennas under extreme pumping conditions

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Photoconductive antennas deposited onto GaAs substrates that incorporate InAs quantum dots have been recently shown to efficiently generate both pulsed and CW terahertz radiation. In this Letter, we determine the operational limits of these antennas, and demonstrate their extreme thermal breakdown tolerance. Implanted quantum dots serve as free carrier capture sites, thus acting as life-time shorteners, similarly to defects in low-temperature grown substrates. However, unlike the latter, defect-free quantum-dot structures possess perfect lattice quality, thus not compromising high carrier mobility and pump intensity stealth. Single gap design quantum dot based photoconductive antennas are shown to operate under up to 1 W of average pump power ($\sim$1.6 mJ cm^{-2} energy density), which is more than 20 times higher than the pumping limit of low-temperature grown GaAs based substrates. Conversion efficiency of the quantum dot based photoconductive antennas does not saturate up to 0.75 W of pump power ($\sim$1.1 mJ cm^{-2} energy density). Such thermal tolerance suggests glowy prospects for the proposed antennas as a perspective candidate for intracavity optical-to-terahertz converters.

Terahertz (THz) photoconductive antenna (PCA) technology, first demonstrated just over 30 years ago[1], has matured into a solid industrial solution, the first choice in pulsed and CW spectroscopic and imaging systems[2–4]. Most recent developments report over 600 μW of output THz power and over 3% optical-to-THz conversion efficiency from a single gap PCA[5]. Large area array PCAs were shown to generate even higher powers, up to several mW[6]. Alongside these significant advances, there is still a great demand for further minitiaturisation of THz time domain spectrometers and imaging systems. Currently, the larger constituent of such setups is usually the pump source – a Ti:Sapphire or ultrafast fibre laser.

Recently, we proposed more compact setups that use quantum dot (QD) based compact semiconductor lasers in conjuction QD based PCAs for generation of both pulsed and CW THz radiation[7–10]. Indeed, semiconductor materials incorporating InAs QDs in bulk GaAs possess all the properties required for efficient optical-to-THz conversion, such as short carrier lifetimes enabled by carrier capture into the dots[11], while maintaining high carrier mobility[8], unlike low temperature grown materials[2]. Similar materials were used also as active media in diode lasers[12], laser amplifiers[13], or saturable absorbers[14]. Employment of these laser pumps in compact THz setups now looks as native as it can be, due to the natural matching of the operational wavelength of such lasers with the permitted states of the wafer[9,15]. Moreover, these PCAs support not only resonant pumping with photons possessing the energy of the QD excited state (but not the ground state![15]), but also operate efficiently under pumps with photon energies over the GaAs bandgap.

Here, we determine the operational limits of the QD based PCAs, and outline further research and application directions towards the development of ultra compact turn-key room temperature operating THz spectroscopy and imaging systems.

The QD-based PCA used in this work consisted of electrodes deposited onto a heterostructured wafer containing self-assembled QDs. A schematic illustration of the complete PCA structure is presented in Fig. 1. The wafer was grown by molecular beam epitaxy in the Stranski-Krastanov regime, on a semi-insultating GaAs substrate. First, an AlAs/GaAs multilayer distributed Bragg reflector with overall thickness

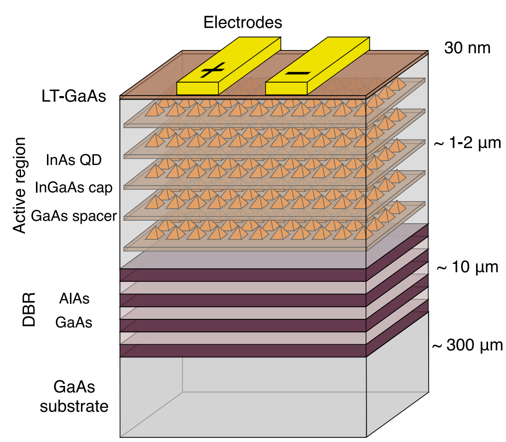

FIG. 1. Schematic of the quantum dot based photoconductive antenna (QD-PCA). An AlAs/GaAs distributed Bragg reflector (DBR) is deposited onto a GaAs substrate, and an active region comprising 25 layers of InAs QDs is grown on top by molecular beam epitaxy. A low-temperature-grown GaAs (LT-GaAs) layer covers the active region, and Ti/Au electrodes are lithographically deposited in a stripline geometry with a 50 μm gap between them.

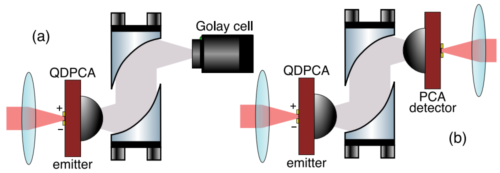

FIG. 2. THz section of the setups for intensity measurement with Golay cell (a) and coherent characterisation with the PCA (b).

of about 10 µm designed to reflect the pump wavelength corresponding to the QD excited state[15] was deposited. On top of it was grown the active medium, comprising 25 layers containing InAs QDs. Each QD layer was capped by a 4 nm to 5 nm thick $In_{0.15}Ga_{0.85}As$ wetting layer and separated by a 35 nm to 36 nm GaAs spacer layer, resulting in a total active region thickness of about 1 µm. On top of the active layer structure, a 30 nm layer of low-temperature-grown GaAs (LT-GaAs) was grown, to reduce the dark conductivity and enhance the Ohmic contact between the antenna electrodes and the wafer. Lastly, 250 nm thick Ti/Au electrodes were deposited with standard lithographic techniques and further wet etching. For power measurements, a bowtie electrodes with 8 µm gap were used, while for coherect characterisation, stripline-shaped electrodes with a 50 µm were studied.

In all experiments, the pump beam was focused with a 25 mm lens, resulting in a spot diameter of around 30 µm

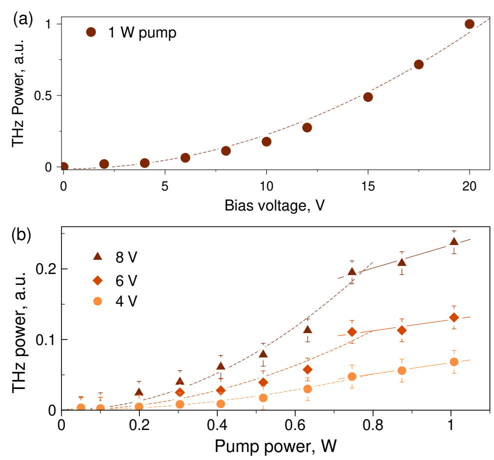

FIG. 3. (a) Emitted THz power by a bow-tie QD-PCA as function of the applied bias voltage. The average optical pump power is 1 W at the $\lambda = 800$ nm wavelength. (b) Emitted THz power as function of the average optical pump power, for varying bias voltages. Dashed lines represent quadratic and solid lined show linear fits, respectively.

measured as $1/e^2$ power decay. We used an easily accessible 800 nm wavelength from a femtosecond Ti:Sapphire laser, delivering up to 1.5 W of average power in 120 fs pulses with an 80 MHz repetition rate. The electrodes were electrically biased, and the pump beam was modulated with a mechanical chopper, to allow lock-in detection of the generated THz power. The optical pump intensity was controlled by two polarisers. The emitted THz radiation from the QD-PCA was pre-collimated by a mechanically attached hyperhemispherical Si lens, and guided to the detector by two off-axis parabolic mirrors (Fig. 2).

In the first set of experiments, the relative THz power was measured by a Golay-cell detector. Both pump intensity and bias voltage dependences were characterised. The results of this characterisation are presented in Fig. 3. We observe that the QD-PCAs allow pumping with intensities up to 1.1 W (156 $\mathrm{kW\,cm^{-2}}$) biased at 20 V, without reaching thermal breakdown. This exceeds both previously demonstrated results of 300 mW[8] (42 $\mathrm{kW\,cm^{-2}}$) and 700 mW[10] (99 $\mathrm{kW\,cm^{-2}}$), for PCAs of similar type, and is about 20 times higher than the typical limits of conventional LT-GaAs based single gap PCAs[16]. Both bias voltage and pump intensity dependences are superlinear, and can be decently traced with quadratic fits. However, at higher power intensities, regardless the applied bias, the trend comes to a saturation (Fig. 3 (b)) . Carrier screening effect[17], Joule heating of the substrate[18,19], or carrier concentration reaching its maximum – any combination of these factors can be the reason for such saturation.

A coherent detection scheme was used to analyse the emission spectrum of the QD-PCA. The setup comprises a THz time-domain spectroscopy system, where a commercial LT-GaAs PCA (Teravil Ltd.) is used as the detector. The results of coherent measurement are shown in Fig. 4. Similarly to the Golay cell measured power dependence, the amplidude of the THz pulse first grows linearly with the pump power and saturates at intensities above 500 mW. The other noticeable effect is the pulse duration shortening from 2.3 ps to 1.7 ps, outlined in the inset of Fig. 4(a). Such pulse contraction is explained by the carrier lifetime duration at higher pump powers, reported earlier[11,14], and carrier screening effects of different nature[17,20,21]. Broadening of the corresponding signal spectra, shown in Fig. 4(b), is another evidence of this effect.

Thus, QD based PCAs not only withstand significant pump intensities reaching $\sim$1600 $\mathrm{\mu J\,cm^{-2}}$, but also operate efficiently, converting optical pump into the THz signal, with some signs of saturation revealed only at pump powers above 0.7 W, which is 15 times higher than typical single gap PCAs available to date. Moreover, this signal increases in bandwidth with growing pump power. Such thermal tolerances, together with the demonstrated saturation behaviour, opens a new pathway for the further development of compact setups. In an intracavity arrangement, these QD-PCAs could not only generate THz radiation employing all the intracavity laser power – typically hundreds of times higher than laser output – but also serve as an extra saturable absorber in the cavity while still maintaining lasing, owing to their saturation characteristics.

In this Letter, we have broadened the known operational

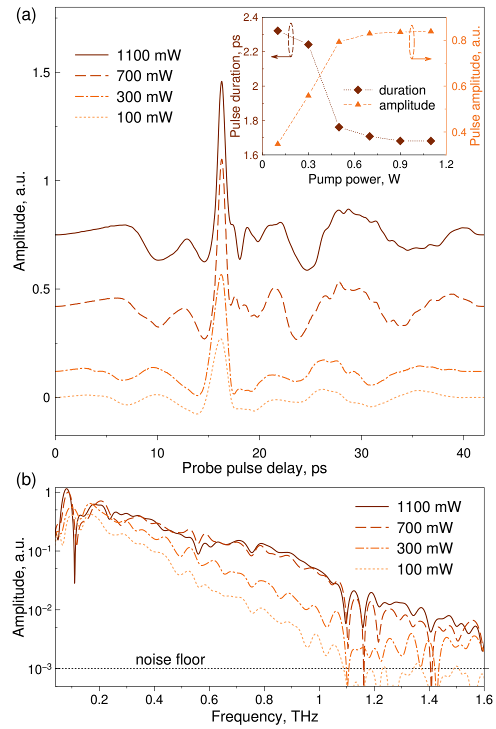

FIG. 4. (a) Time-domain traces detected from a QD-PCA at different optical pump powers (shifted vertically for improve readability). The inset shows the amplitude and duration of the THz pulses as function of pump power. (b) Corresponding spectra calculated from the time-domain signals, shown in logarithmic scale.

limits of the QD-based PCAs by showing their successful operation at pump powers exceeding 1 W, corresponding to a $\sim$1.6 mJ cm^{-2} energy density. The conversion efficiency starts saturating at pump powers over 0.7 W ($\sim$1.1 mJ cm^{-2} energy density). This extremely high operational tolerance allows us to propose intracavity placement of the QD based PCAs into the cavity of compact semiconductor lasers. Upon such layout, QD-based PCAs will employ the pump power contained inside the laser cavity and serve as additional saturable absorbers, while generating coherent pulsed broadband THz signals. Erbium QDs in GaAs bulk demonstrated unprecedented conversion efficiency of 0.2% due to superradiance effect in very homogenius nanostructures[22], suggesting that further tailoring of growth conditions to achieve higher homogeneity, can potentially lead to similar effect. This approach will allow even more efficient and compact room temperature operating THz setups than those demonstrated to date.

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DATA AVAILABILITY STATEMENT

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

REFERENCES

[1] D. H. Auston, K. P. Cheung, and P. R. Smith, "Picosecond photoconducting hertzian dipoles," Appl. Phys. Lett. **45**, 284–286 (1984).
[2] D. R. Bacon, J. Madéo, and K. M. Dani, "Photoconductive emitters for pulsed terahertz generation," J. Opt. **23**, 064001 (2021).
[3] S. S. Dhillon et al., "The 2017 terahertz science and technology roadmap," J. Phys. D. Appl. Phys. **50**, 043001 (2017).
[4] P. Jepsen, D. Cooke, and M. Koch, "Terahertz spectroscopy and imaging - Modern techniques and applications," Laser Photon. Rev. **5**, 124–166 (2011).
[5] R. B. Kohlhaas, S. Breuer, L. Liebermeister, S. Nellen, M. Deumer, M. Schell, M. P. Semtsiv, W. T. Masselink, and B. Globisch, "637 μ W emitted terahertz power from photoconductive antennas based on rhodium doped InGaAs," Appl. Phys. Lett. **117**, 131105 (2020).
[6] N. T. Yardimci, S. Cakmakyapan, S. Hemmati, and M. Jarrahi, "A High-Power Broadband Terahertz Source Enabled by Three-Dimensional Light Confinement in a Plasmonic Nanocavity," Sci. Rep. **7**, 4166 (2017).
[7] T. Kruczek, R. Leyman, D. Carnegie, N. Bazieva, G. Erbert, S. Schulz, C. Reardon, and E. U. Rafailov, "Continuous wave terahertz radiation from an InAs/GaAs quantum-dot photomixer device," Appl. Phys. Lett. **101** (2012).
[8] R. R. Leyman, A. Gorodetsky, N. Bazieva, G. Molis, A. Krotkus, E. Clarke, and E. U. Rafailov, "Quantum dot materials for terahertz generation applications," Laser Photon. Rev. **10**, 772–779 (2016).
[9] K. A. Fedorova, A. Gorodetsky, and E. U. Rafailov, "Compact All-Quantum-Dot-Based Tunable THz Laser Source," IEEE J. Sel. Top. Quantum Electron. **23**, 1–5 (2017).
[10] A. A. Gorodetsky, A. Yadav, S. V. Smirnov, N. Bazieva, and E. U. Rafailov, "Quantum dot photoconductive antenna-based compact setups for terahertz spectroscopy and imaging," in *SPIE Proc.*, Vol. 11499 (2020) p. 1149905.
[11] A. Gorodetsky, N. Bazieva, and E. U. Rafailov, "Pump dependent carrier lifetimes in InAs/GaAs quantum dot photoconductive terahertz antenna structures," J. Appl. Phys. **125**, 151606 (2019).
[12] E. U. Rafailov, M. A. Cataluna, and W. Sibbett, "Mode-locked quantum-dot lasers," Nat. Photon. **1**, 395 – 401 (2007).
[13] E. U. Rafailov, P. Loza-Alvarez, W. Sibbett, G. S. Sokolovskii, D. A. Livshits, A. E. Zhukov, and V. M. Ustinov, "Amplification of femtosecond pulses over by 18 db in a quantum-dot semiconductor optical amplifier," IEEE Photon. Technol. Lett. **15**, 1023–1025 (2003).
[14] E. U. Rafailov, S. J. White, A. A. Lagatsky, A. Miller, W. Sibbett, D. A. Livshits, A. E. Zhukov, and V. M. Ustinov, "Fast quantum-dot saturable absorber for passive mode-locking of solid-state lasers," IEEE Photon. Technol. Lett. **16**, 2439–2441 (2004).
[15] A. Gorodetsky, A. Yadav, E. Avrutin, K. A. Fedorova, and E. U. Rafailov, "Photoelectric Properties of InAs/GaAs Quantum Dot Photoconductive Antenna Wafers," IEEE J. Sel. Top. Quantum Electron. **24**, 1–5 (2018).
[16] "Batop GmBH. PCA - photoconductive antenna for THz waves," `www.batop.com/products/terahertz/photoconductive-antenna/`

photoconductive-terahertz-antenna.html, (Accessed: 20 January 2016).

[17]J. E. Pedersen, V. G. Lyssenko, J. M. Hvam, P. U. Jepsen, S. R. Keiding, C. B. Sørensen, and P. E. Lindelof, "Ultrafast local field dynamics in photoconductive THz antennas," Appl. Phys. Lett. **62**, 1265 (1993).

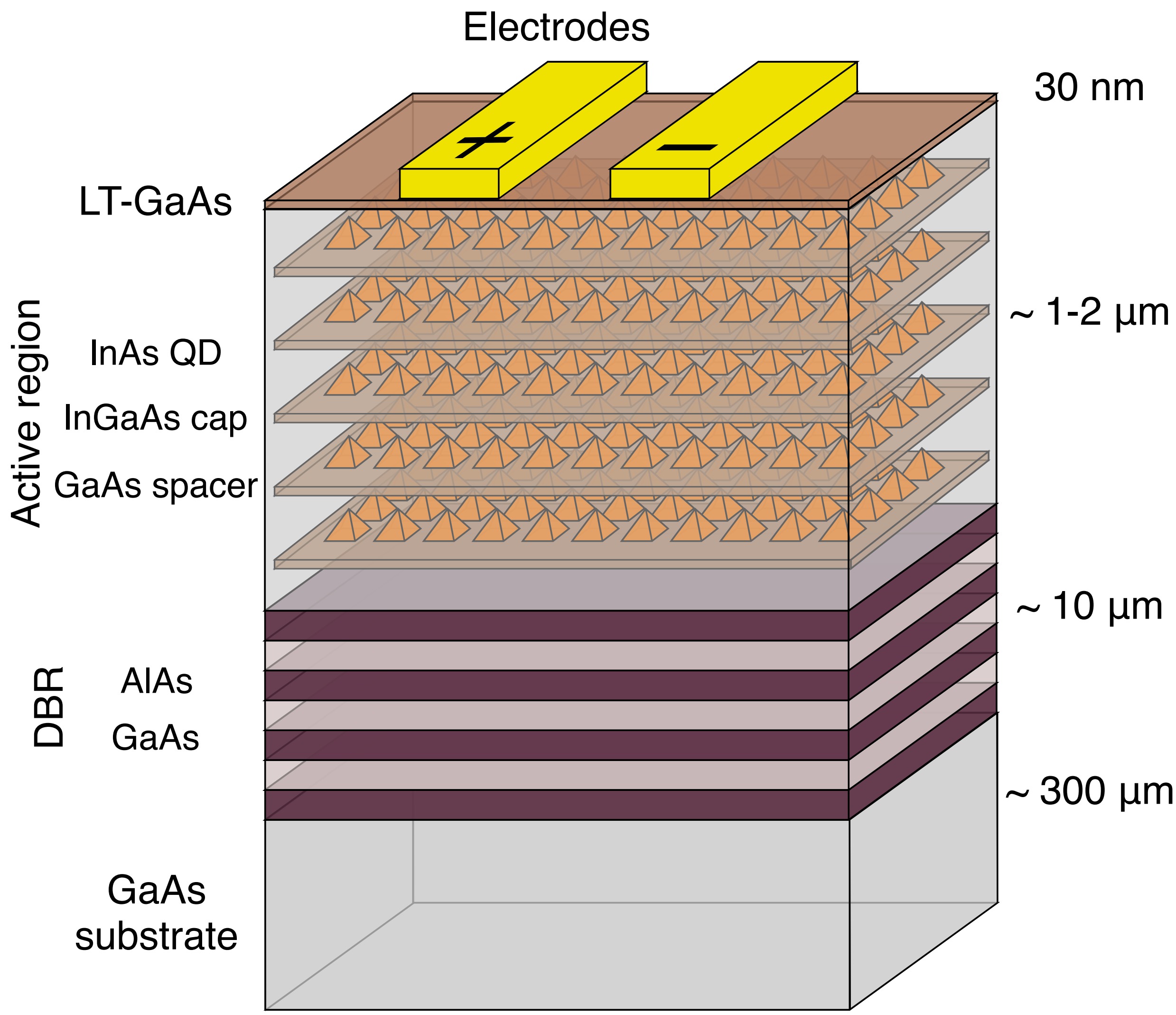
[18]M. Xu, M. Mittendorff, R. J. B. Dietz, H. Künzel, B. Sartorius, T. Göbel, H. Schneider, M. Helm, and S. Winnerl, "Terahertz generation and detection with InGaAs-based large-area photoconductive devices excited at 1.55 μ m," Appl. Phys. Lett. **103**, 251114 (2013).

[19]D. S. Ponomarev, R. A. Khabibullin, A. E. Yachmenev, A. Y. Pavlov, D. N. Slapovskiy, I. A. Glinskiy, D. V. Lavrukhin, O. A. Ruban, and P. P. Maltsev, "Electrical and thermal properties of photoconductive antennas based on In x Ga1 − x As (x > 0.3) with a metamorphic buffer layer for the generation of terahertz radiation," Semiconductors **51**, 1218–1223 (2017).

[20]G. Rodriguez and A. J. Taylor, "Screening of the bias field in terahertz generation from photoconductors," Opt. Lett. **21**, 1046 (1996).

[21]Z. Piao, M. Tani, and K. Sakai, "Carrier Dynamics and Terahertz Radiation in Photoconductive Antennas," Jpn. J. Appl. Phys. **39**, 96–100 (2000).

[22]W. Zhang, E. R. Brown, A. Mingardi, R. P. Mirin, N. Jahed, and D. Saeedkia, "THz Superradiance from a GaAs: ErAs Quantum Dot Array at Room Temperature," Appl. Sci. **9**, 3014 (2019).


Electrodes
+
−
30 nm
LT-GaAs
~ 1-2 μm
Active region
InAs QD
InGaAs cap
GaAs spacer
~ 10 μm
DBR
AlAs
GaAs
~ 300 μm
GaAs
substrate

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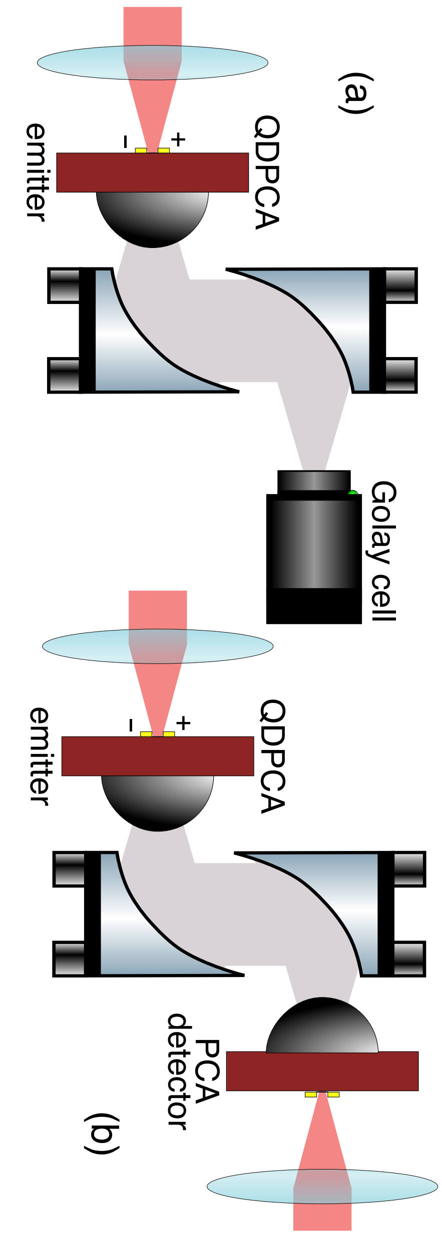
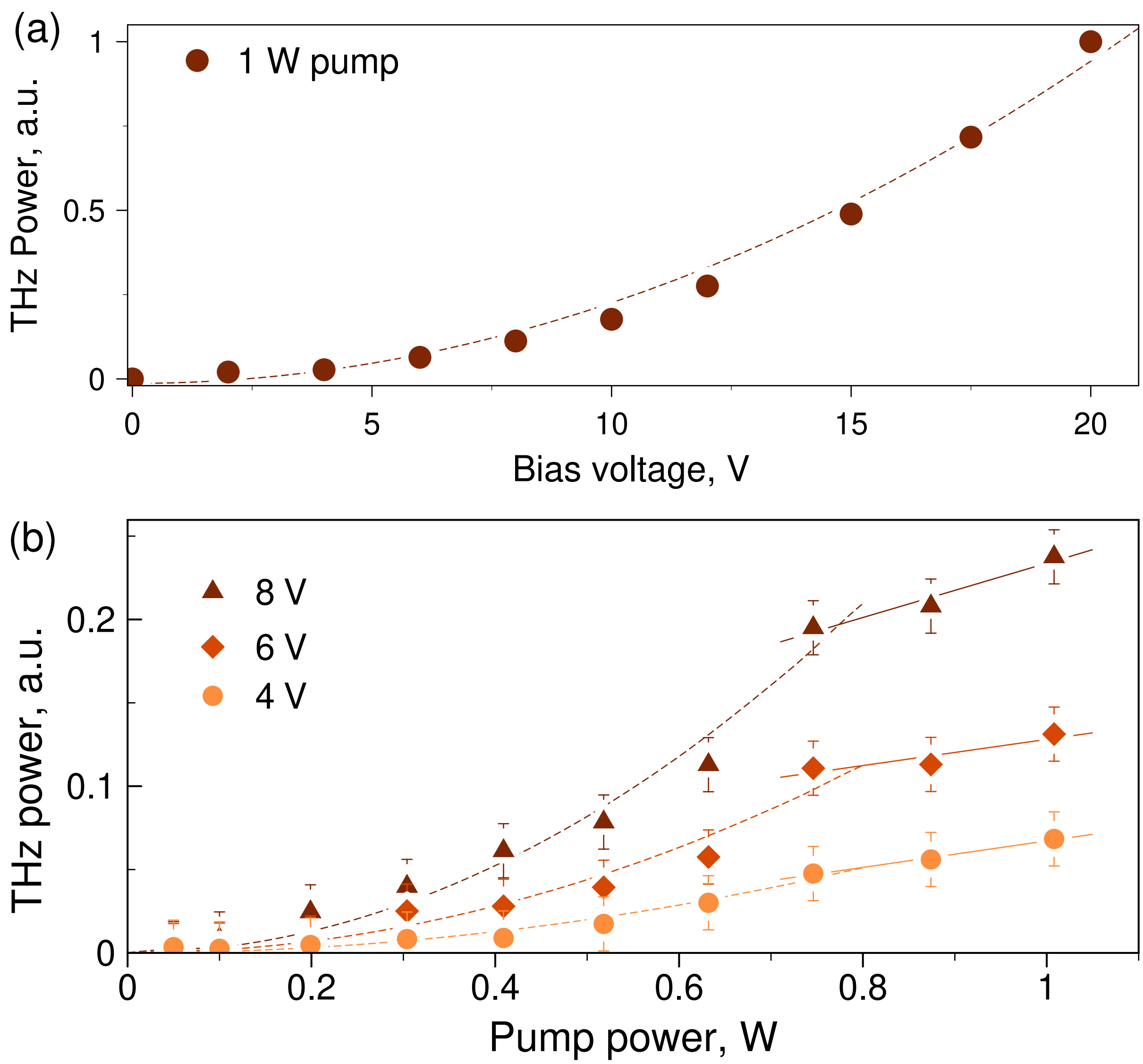
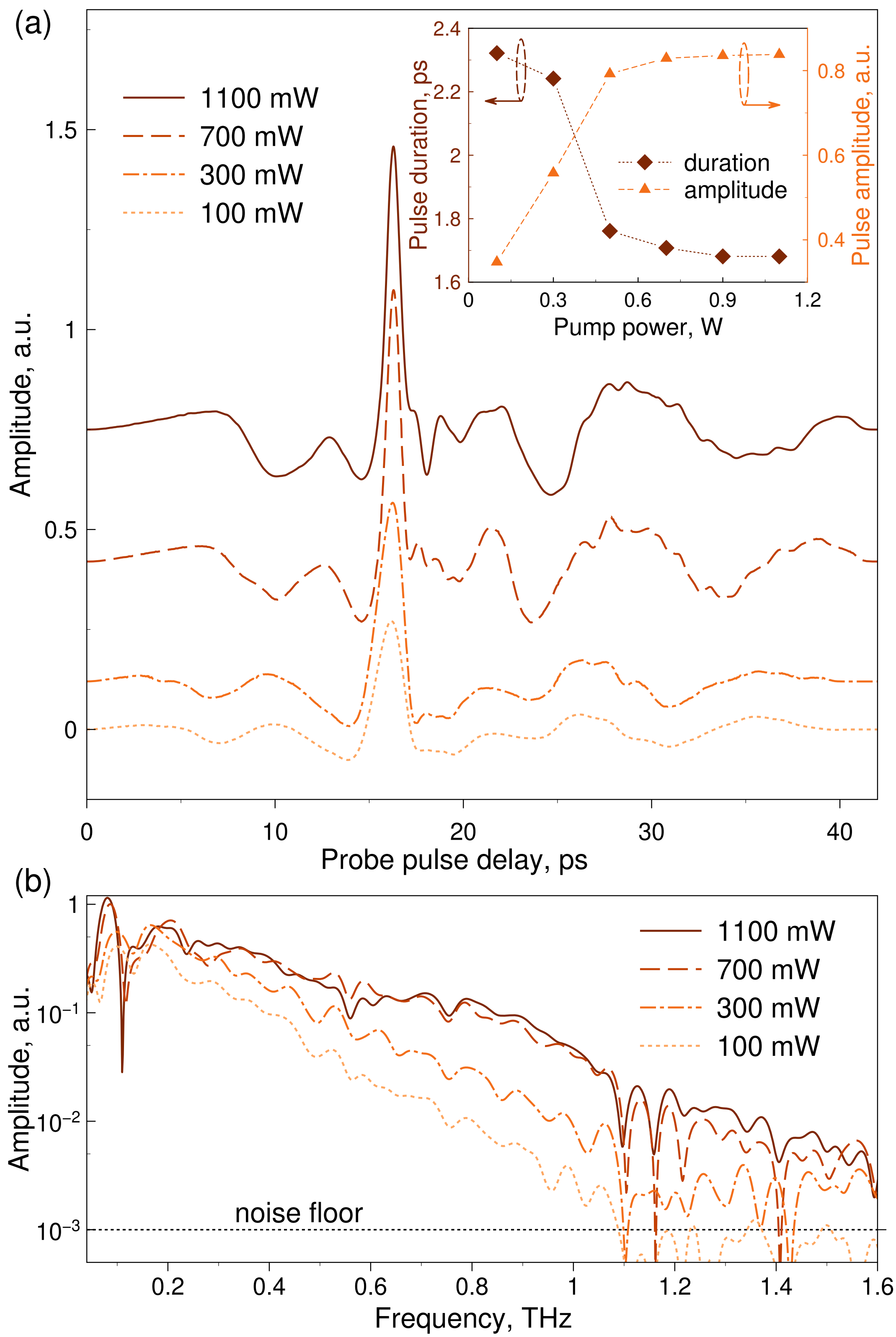



(a)
1 W pump
THz Power, a.u.
Bias voltage, V
(b)
8 V
6 V
4 V
THz power, a.u.
Pump power, W


(a)
1100 mW
700 mW
300 mW
100 mW
Amplitude, a.u.
Probe pulse delay, ps
Pulse duration, ps
Pulse amplitude, a.u.
duration
amplitude
Pump power, W
(b)
1100 mW
700 mW
300 mW
100 mW
Amplitude, a.u.
noise floor
Frequency, THz