Instruction manual and data sheet iPCA-21-05-300-800-h

Broad area interdigital photoconductive THz antenna with microlens array and hyperhemispherical silicon lens for laser excitation wavelengths λ ~ 800 nm

iPCA – interdigital Photoconductive Antenna

Table of contents:

1. PCA applications

The PCA can be used as terahertz (THz) emitter or detector in pulsed laser gated broadband THz measurement systems for time-domain spectroscopy in the frequency region from 0.1 to 3 THz. The emitter conversion efficiency of optical laser power into THz power is very high.

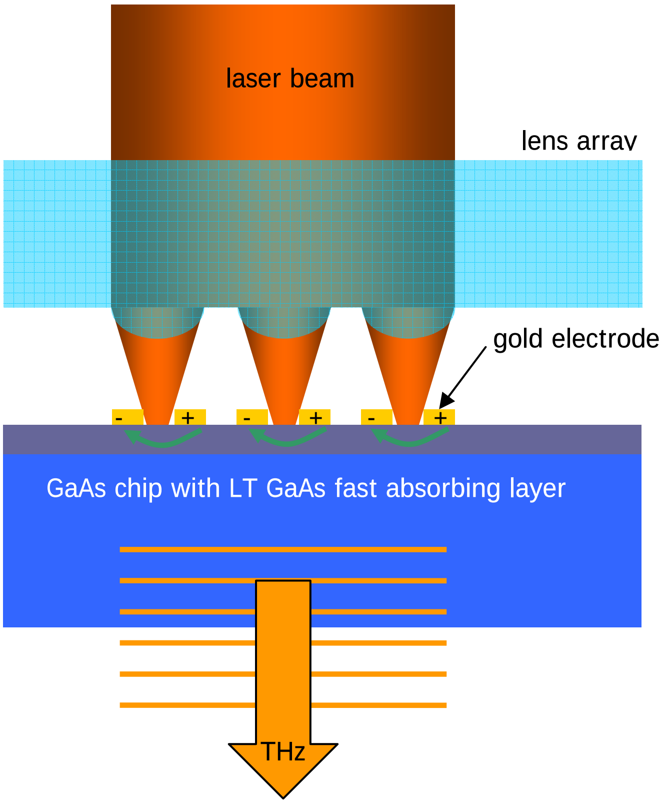
The preferred application is as THz emitter antenna for mean optical laser power > 100 mW.

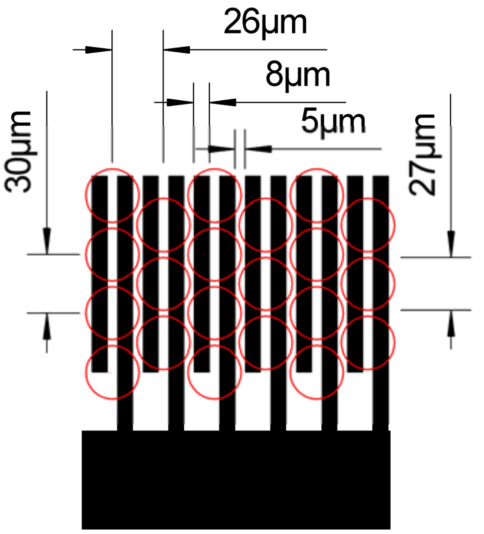
Main iPCA data

Laser excitation wavelength	λ ~ 800 nm
Antenna resonance frequency	2 THz
Active antenna area	300 µm x 300 µm
Emitted THz spectrum	0.1 THz … 3 THz
Emitter conversion efficiency	2 µW THz / 100 mW optical power
Maximum mean THz power	10 µW @ 500 mW laser power
Recommended optical power	50 mW … 500 mW

2. iPCA working principle

Instead of a single small antenna gap an extended gap along the finger electrodes of the iPCA can be illuminated by a short pulse laser beam. By using the microlens array only every second gap between the finger structure is excited by the laser beam with a photon energy $h\nu$ larger than the energy gap E_g of the semiconductor antenna material. The fill factor of the lens array of 73.5 % ensures, that nearly the total optical laser energy is used for excitation of carriers. Despite of the large emitting area the needed voltage for the carrier excitation is low (~ 25 V) because of the small gap of only 5 µm.

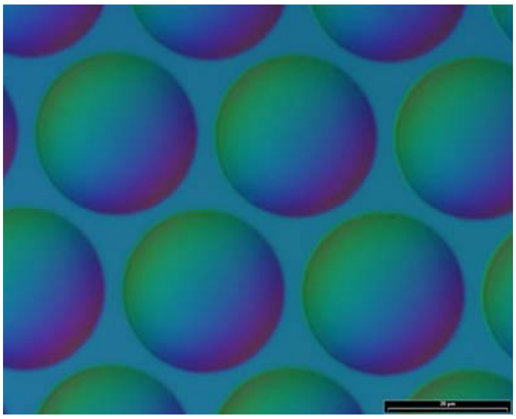




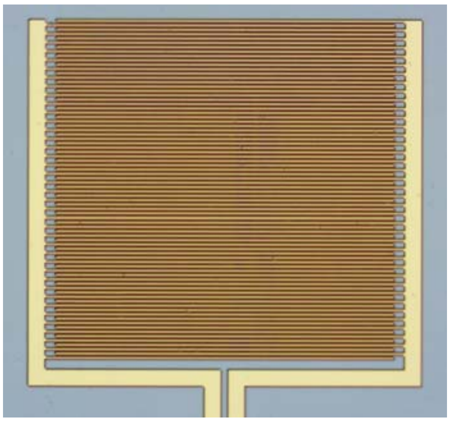
The coherent excitation of the single emitters, located at every microlens spot results in a constructive interference of the radiated THz waves in the far field. The laser beam has to be adjusted in such a way, that the spots are on the GaAs surface between the finger electrodes (minimum electrical resistance of the antenna).

3. Antenna design

iPCA-21-5-300-800 with lens array



27 µm ∅ lenses, 30 µm pitch



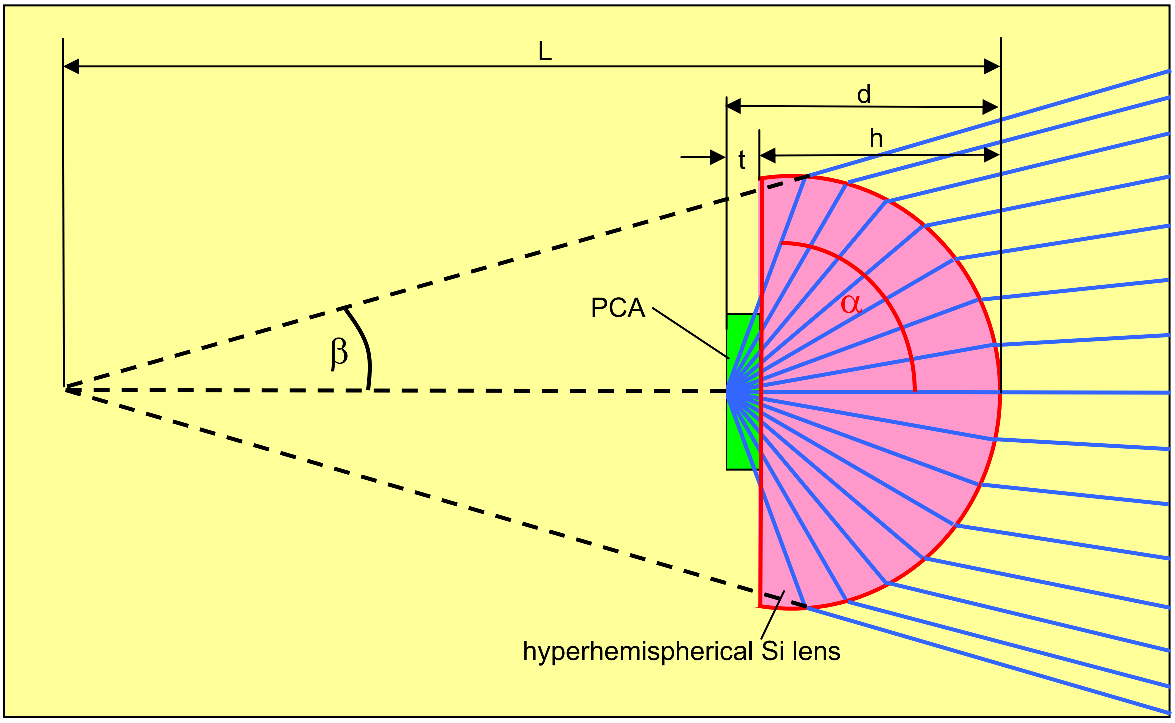
Survey on iPCA

Photoconductive antenna	substrate	semi-insulating GaAs
	chip area	4 mm x 4 mm
	thickness t	650 µm
	active area	300 µm x 300 µm

Hyperhemispherical lens	material	undoped HRFZ-silicon,
	specific resistance ρ	>10 kΩcm
	refractive index n	3.4
	diameter	12 mm
	height h	7.1 mm
	distance d	7.7 mm

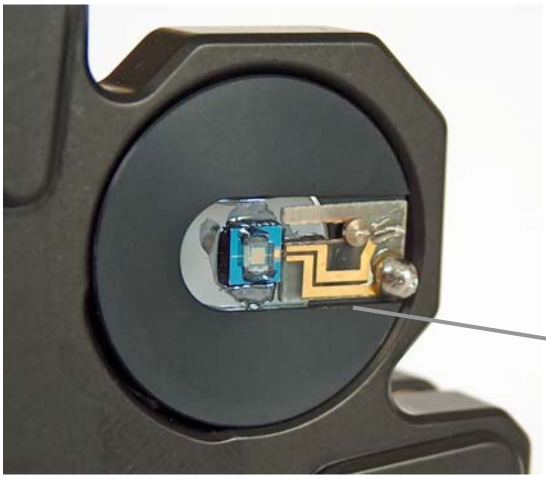
Terahertz beam	collection angle α	57°
	divergence angle ß	15°
	virtual focus length L	26.4 mm

Aluminum mount	25.4 mm diameter, 6 mm thick
Coaxial cable	type RG178 B/U, impedance 50Ω, capacitance 96pF/m, 1 m long
Connector type	BNC

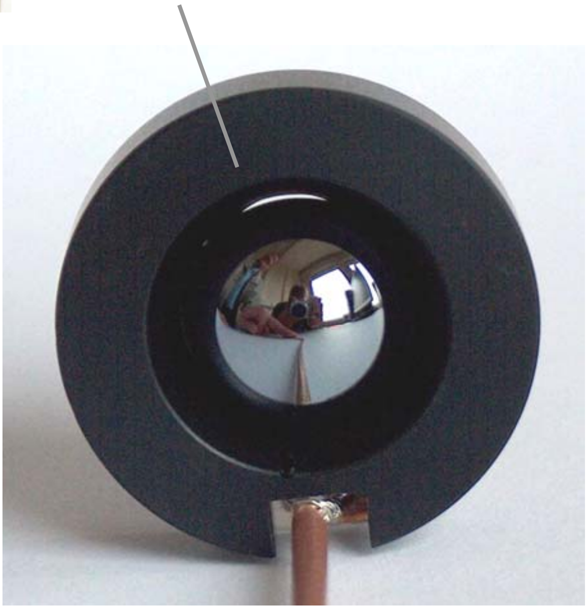


- The iPCA chip is optically adjusted and glued on the hyperhemispherical silicon lens with a thermal conducting glue.
- The silicon lens is fixed on the aluminum mount with a thermal conducting glue.
- The two antenna contacts are wire bonded on a printed circuit board, which provides the connection to a 1m long coaxial cable with BNC or SMA connector
- A central hole in the aluminum mount allows the Terahertz radiation to escape from the hyperhemispherical silicon lens

iPCA with hyperhemispherical silicon lens, coaxial cable RG 178 and BNC connector



Front side with microlens array

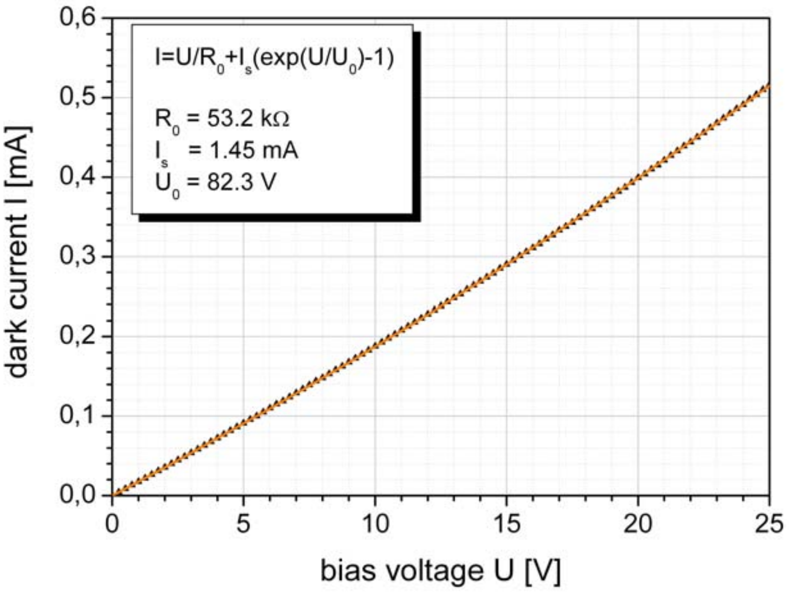


Back side with silicon lens

4. Antenna parameters

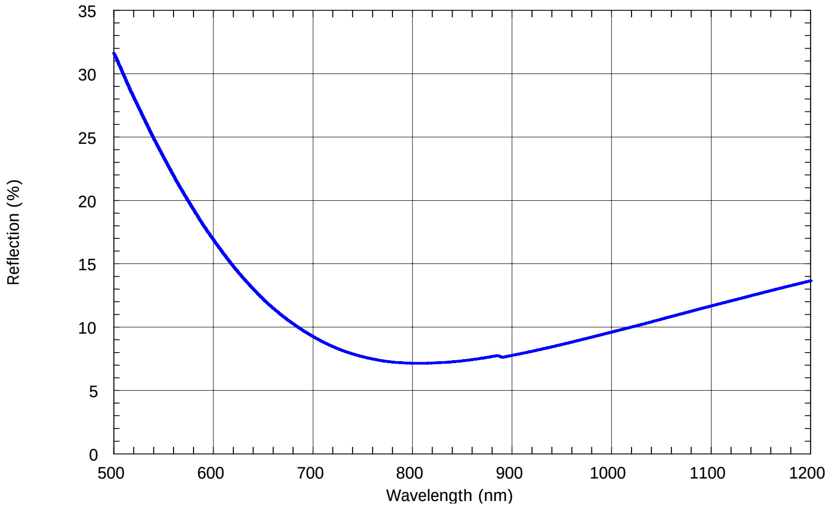
Electrical parameters	value	units
Dark resistance	50 ± 10	kΩ
Dark current @ 10 V	200	µA
Maximum voltage	20	V

Dark current voltage characteristic at T = 300 K

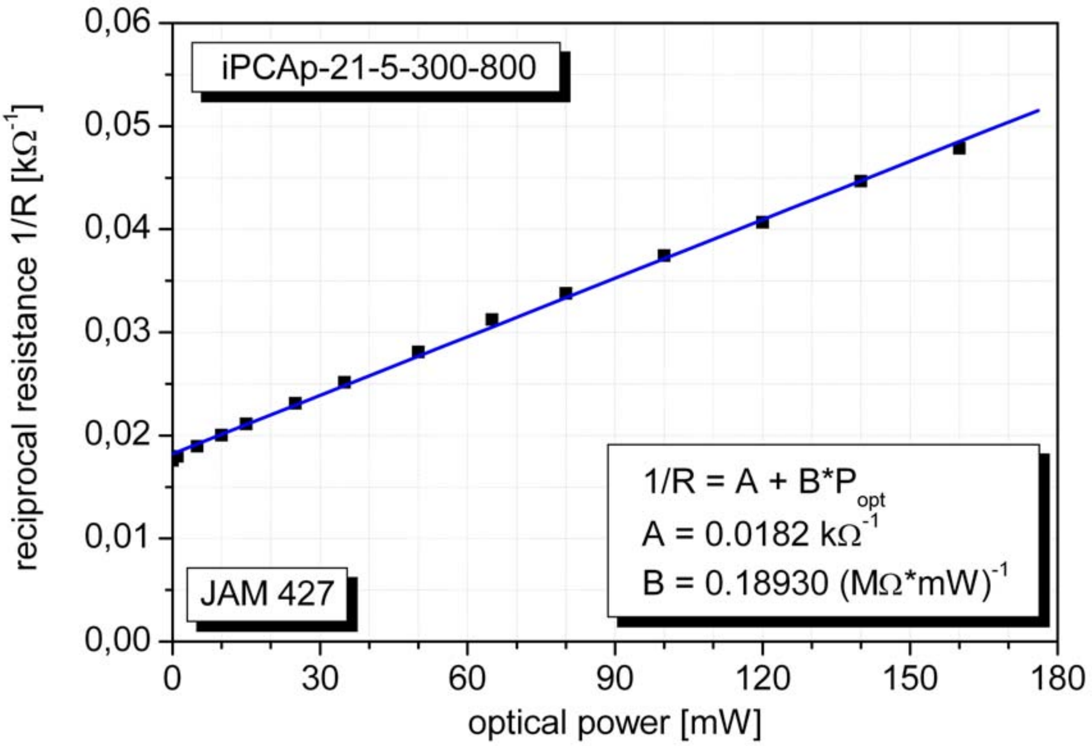


Optical excitation parameters	value	units
Excitation laser wavelength	< 850	850 nm
Optical reflectance @ 800 nm	7	%
Maximum mean optical power	1	W
Carrier recovery time	200	fs

Spectral reflectance of the iPCAwithout the microlens array

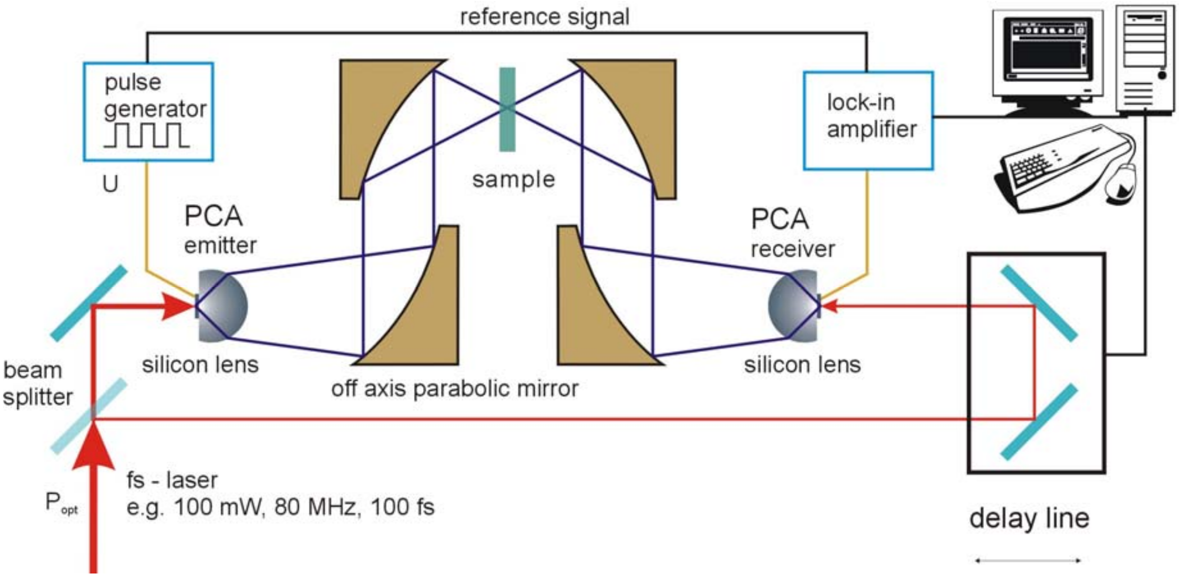


Illumination dependent resistance R



5. Instructions for use of the iPCA-21-05-300-800-h

The antenna can be used as terahertz emitter or detector in pulsed laser gated broadband THz measurement systems for time-domain spectroscopy and as photomixing emitter or detector in tunable cw THz measurement systems in the frequency region from 0.1 to 4 THz (see schematics below).



Schematic of a time-domain spectroscopy setup

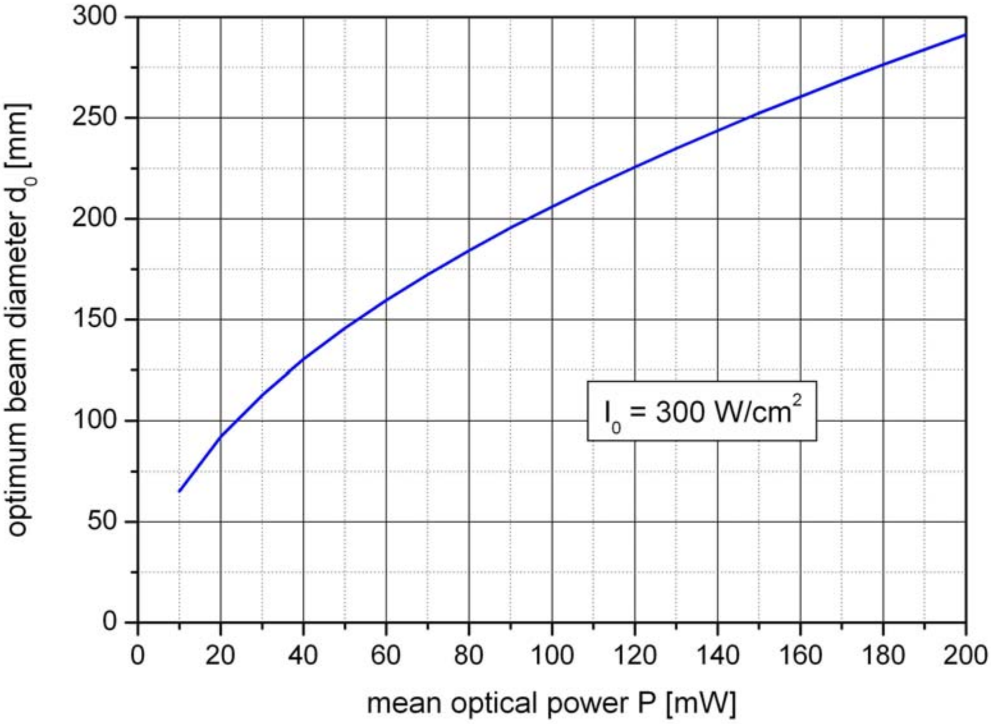
Emitter:

A pulsed laser parallel beam has to be directed onto the antenna microlens array in such a way, that the spots are on the antenna surface between the finger electrodes. In this case the electrical resistance of the illuminated antenna has a minimum value. The microlens array is pre-aligned for an incident laser beam normal to the surface of the microlens array.

The optimum incidence angle can be adjusted by using a common hand held resistance meter connected with the antenna during a slightly change of the angle of incidence of the laser beam with the goal of the lowest possible antenna resistance.

The laser beam diameter has to be adjusted to the active area of the antenna by using a telescope or a focusing lens. To ensure, that all the illuminated microlenses focus the laser light into the gap of the interdigital structure, a parallel beam is needed on the surface of the microlens array. To get a high conversion efficiency from optical into THz power a careful adjustment of the optical beam diameter is needed.

The main point is, that the conversion efficiency increases quadratically with the optical power density (intensity) up to the onset of a saturation. This optimum (mean) optical intensity I_0 is about 300 W/cm^2. The optimum beam diameter d_0 on the surface of the microlens array can be estimated by using the formula $d_0 = 2\ (P/(\pi\ I_0))^{1/2}$. P is the mean optical laser power. In the figure below the optimum beam diameter d_0 in dependency on the mean optical laser power P is shown.



After beam adjustment a voltage U of ~ 15 V (maximum 20 V peak voltage) has to be supplied on the antenna by connecting the BNC connector cable to a voltage source.

Receiver:

The pulsed laser beam has to be directed onto the microlens array of the antenna. For the beam diameter the same rule holds as for the emitter antenna, but the power density can be lower. The angle of incidence of the parallel laser beam has to be adjusted in the same way as it is described above for the emitter antenna.

The phase of the laser beam with respect to the beam on the emitter site has to be adjusted by using of an optical delay line in such a way, that the measured value of the THz field on the antenna meets a maximum of the optical beam. By changing the phase difference between the emitter and receiver antenna the time-dependent shape of the THz field can be measured.

The cable with the BNC connector must be connected with a sensitive electronic current amplifier.

Lock-in detection

Because of the small detector signal a lock-in detection scheme is recommended. The following two possibilities for lock-in detection can be used:

- An optical chopper can be used in front of the emitter antenna to chop the optical beam with a frequency ~ 1 kHz. The result is a chopped emitted THz signal, which meets the detector antenna. The output of the detector antenna is than a chopped current, which can be amplified using an ac amplifier and rectified using a standard lock-in system. The disadvantage of this system is the loss of 50 % of the optical excitation power on the emitter antenna.

- A square wave voltage generator with an output voltage U of maximum +/- 20 V and a frequency of some kHz can be used as supply for the emitter antenna. The result is an emitted alternating THz signal, which meets the detector antenna. The output of the detector antenna is than an alternating current, which can be amplified using an ac amplifier and rectified using a standard lock-in system. This setup is shown in the figures above.

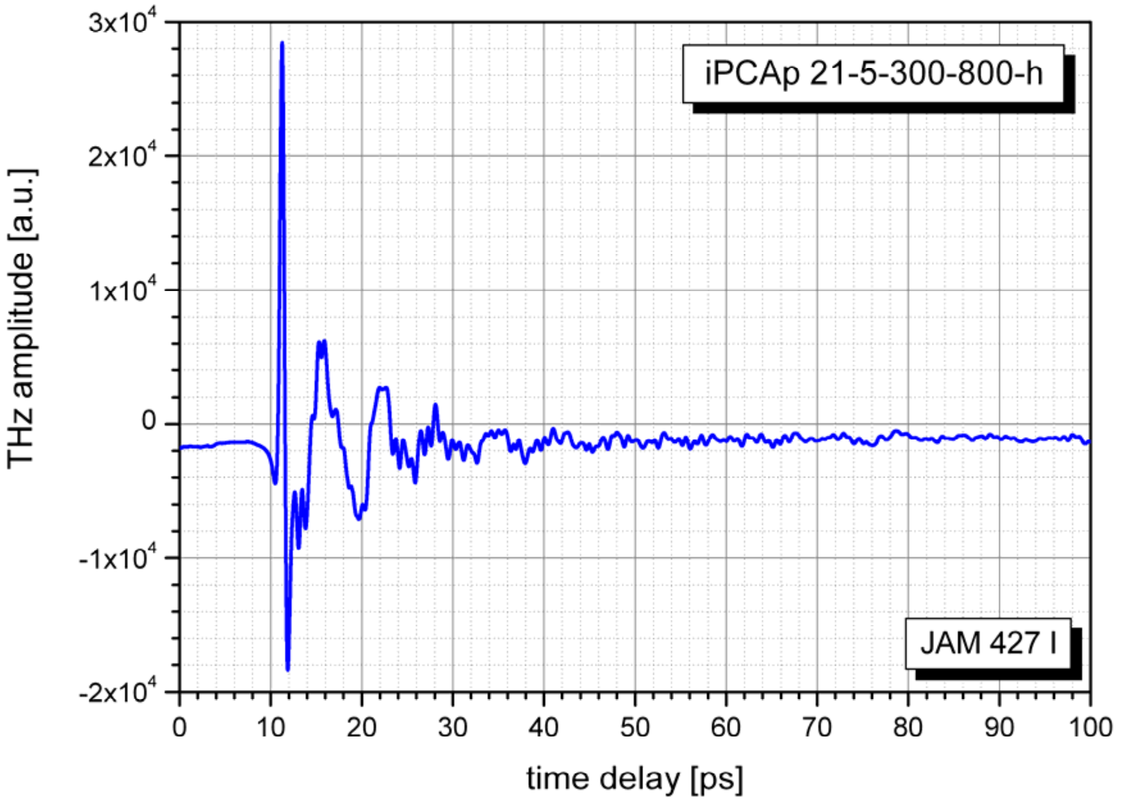
Direct voltage detection

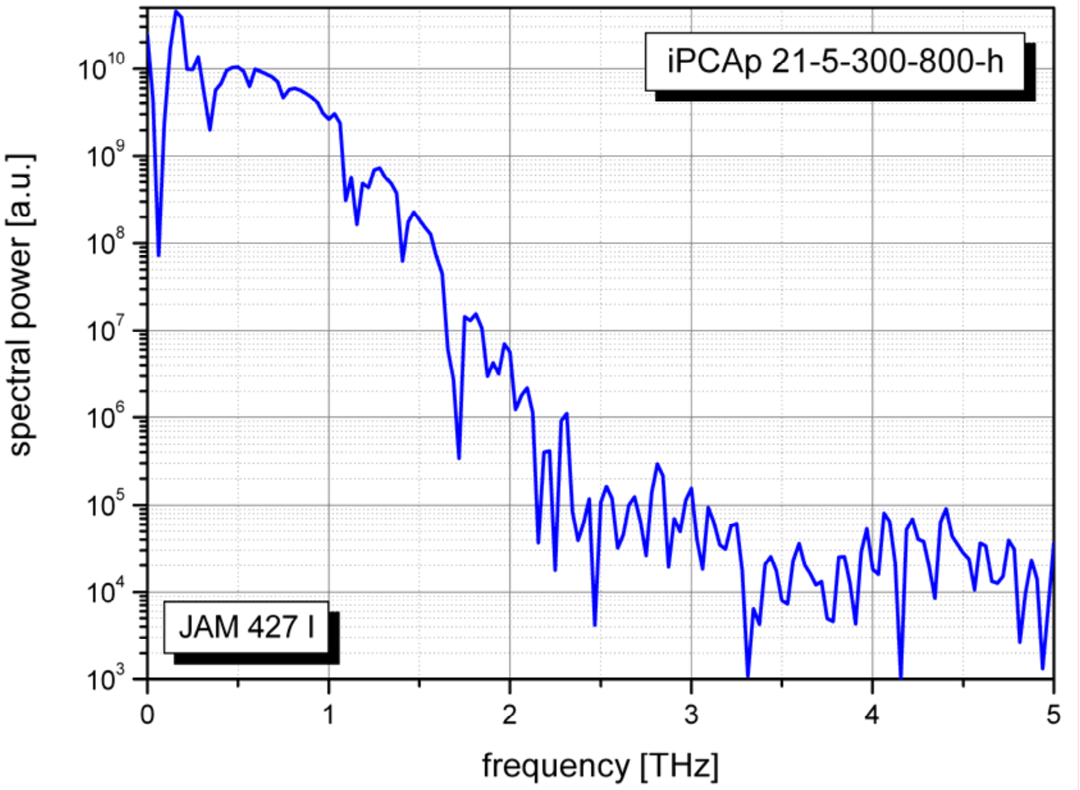
If the THz signal is large enough, a direct dc voltage detection scheme can be used. In this case the emitter antenna has to be supplied by a dc voltage U of up to 20 V. The detector antenna rectifies the THz signal like in a lock-in system using the delay line for adjusting the optical reference signal. The maximum antenna output voltage is in the region of ~ 10 mV and the current ~ 1 nA. In this case a low drift dc current amplifier is needed to increase the signal level for registration.

6. Time-domain measurements

Emitted THz pulse by 800 mW optical excitation at 800 nm wavelength

THz pulse measured by Gabor Matthäus, Institute of Applied Physics, University of Jena, Germany





Power conversion efficiency and saturation effect

THz emission

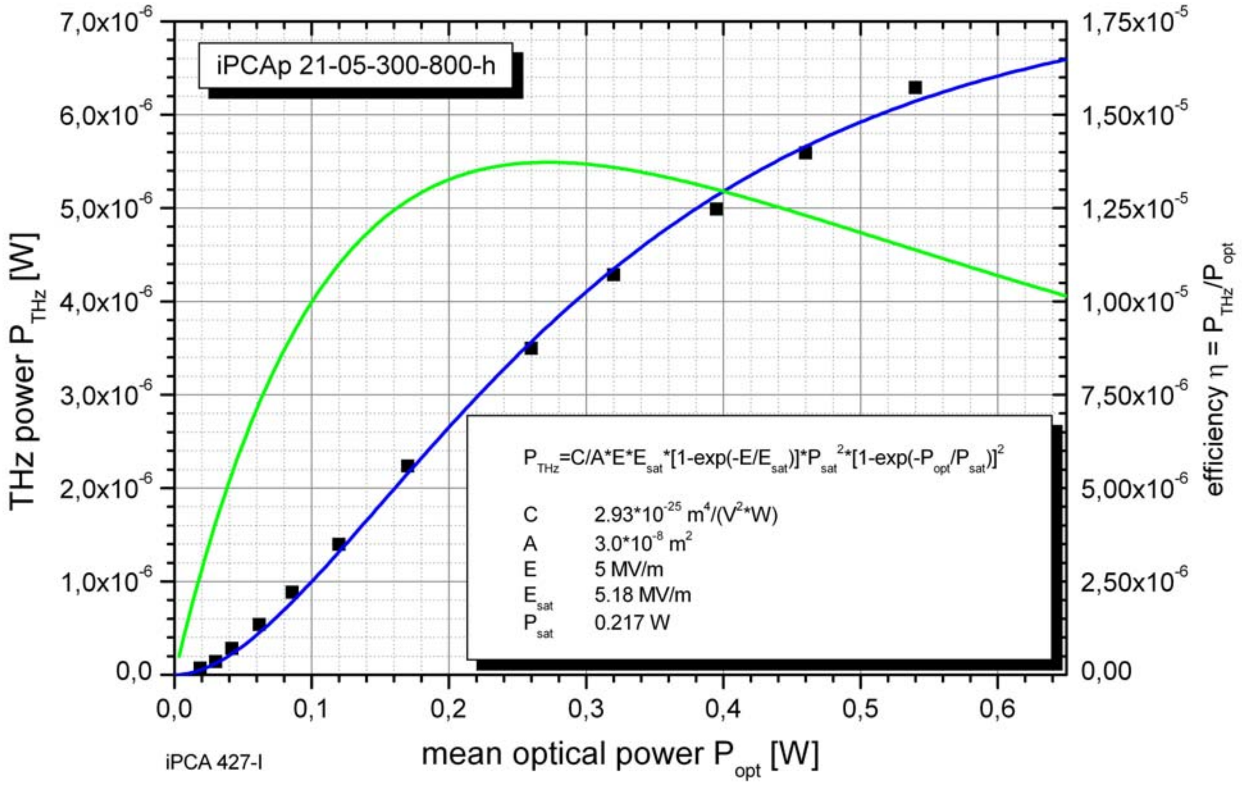
Between the emitted THz electrical field strength E_{THz}, the excited carrier density ρ, the electrical dc field strength E in the antenna gap, the current density j, the laser illuminated area A, and the exciting optical power P_{opt} holds the following proportionalities

$$E_{THz} \sim j \sim \rho \cdot E \sim P_{opt} \cdot E \qquad (1)$$

Thus, for the emitted THz power P_{THz} holds

$$P_{THz} = C \cdot (E \cdot P_{opt})^2 / A \qquad (2)$$

The THz power increases quadratic with the electrical field strength and the optical power. But this parabolic dependency is only valid for optical power densities and field strengths below saturation. The electrical field strength is limited to about 25 V / 5 µm = 5 MV/m for 5 µm gap distance.



measured by Gabor Matthäus, Institute of Applied Physics, University of Jena, Germany

Saturation

The graph above shows the measured mean THz power P_{THz} and the power conversion efficiency η as a function of the mean optical power P_{opt}. The following graph displays the measured mean THz power P_{THz} versus the electric field strength E. The visible saturation effects are of different nature. The saturation with increasing electric field strength is a result of the band structure of GaAs. The ballistic acceleration of the excited electrons is limited by their saturation velocity and the scattering in a higher valley. The saturation due to the mean optical power is a result of the screening of the electric field.

These saturation effects can be described using the equation

$$P_{THz} = \frac{C \cdot E \cdot E_{sat}}{A} \cdot \left[1 - e^{-E/E_{sat}}\right] \cdot P_{sat}^2 \cdot \left[1 - e^{-P_{opt}/P_{sat}}\right]^2 \qquad (3)$$

with

$C = 2.93 \cdot 10^{-25} \cdot m^4 \cdot A^{-1} \cdot V^{-3}$ - specific coefficient

$A = 3.0 \cdot 10^{-8}\ m^2$ - illuminated area of the PCA

$E = V/g$ - electrical field strength within the gap

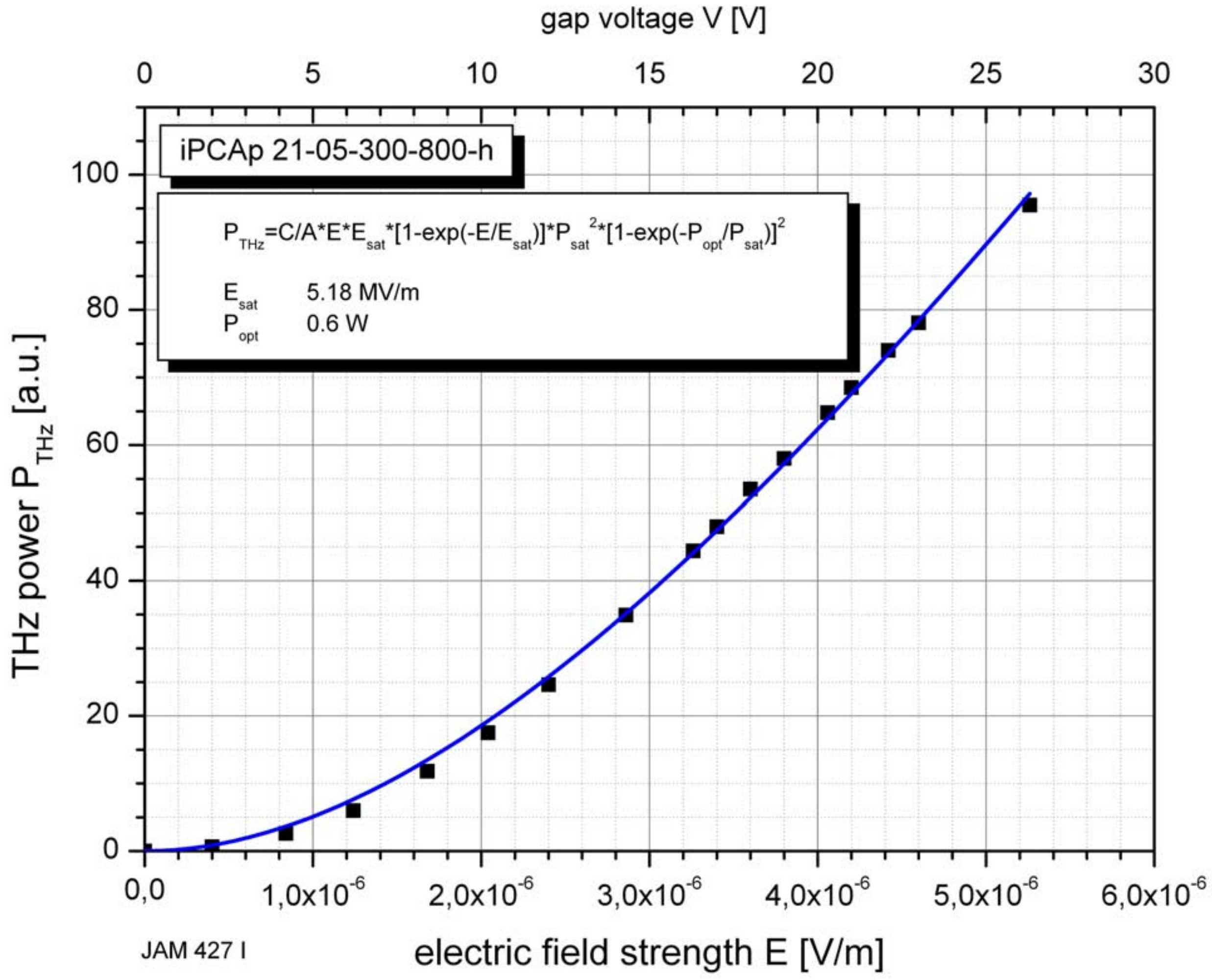
E_{sat} = 5.18 MV/m - saturation electric field strength

P_{opt} - mean optical power

P_{sat} = 0.217 W - saturation optical power

V - gap voltage

g = 5 µm - gap distance



The specific coefficient C contains a factor ½ due to the THz emission in two main directions and also a factor T = 0.7 due to the extraction loss of the THz power from the high refractive index semiconductor emitter.

Power conversion efficiency η

The power conversion efficiency $\eta = P_{THz} / P_{opt}$ describes the formula

$$\eta = \frac{P_{THz}}{P_{opt}} = \frac{C \cdot E \cdot E_{sat}}{A \cdot P_{opt}} \cdot \left[1 - e^{-E/E_{sat}}\right] \cdot P_{sat}^2 \cdot \left[1 - e^{-P_{opt}/P_{sat}}\right]^2 \qquad (4)$$

The maximum power conversion efficiency of $\eta = 1.37 \cdot 10^{-5}$ is obtained at about $P = 1.26 \cdot P_{sat} = 273$ mW.

Low optical power and low voltage

For optical power and electric field strength level below the saturation the equation (3) simplifies to

$$P_{THz} = \frac{C}{A} \cdot \left(E \cdot P_{opt}\right)^2 \qquad (5)$$

and equation (4) to

$$\eta = \frac{C}{A} \cdot E^2 \cdot P_{opt} \qquad (6)$$

Thus, the power conversion efficiency increases continuously with the optical power and the electric field strength up to the onset of saturation effects.

Optimum working conditions

Optical power density

The physical relevant value for the power saturation is the saturation power density $P_{sat}/A = 7.23\cdot10^6$ W/m^2. For optimum power conversion efficiency $\eta = P_{THz} / P_{opt}$ the optical power density must be $P_{opt}/A = 1.26 \cdot P_{sat}/A = 9.11\cdot10^6\ W/m^2$. Thus, the full width of half maximum (FWHM) of the laser beam on the PCA surface has to be adjusted to about

$$FWHM = 3.74 \cdot 10^{-4}\, m \cdot \sqrt{\frac{P_{opt}}{W}} \qquad (7)$$

Antenna voltage

Because of the increasing power conversion efficiency η with increasing electric field strength $E = V/g$ the antenna voltage V has to be adjusted to the maximum possible value of ~ 20 V.