J Infrared Milli Terahz Waves
DOI 10.1007/s10762-010-9751-8

Compact cw Terahertz Spectrometer Pumped at 1.5 μm Wavelength

Dennis Stanze · Anselm Deninger · Axel Roggenbuck · Stephanie Schindler · Michael Schlak · Bernd Sartorius

Received: 20 April 2010 / Accepted: 2 December 2010

Abstract A compact and low-cost continuous wave terahertz spectrometer operating at an optical wavelength of 1.5 μm is presented. The spectrometer employs high power distributed feedback (DFB) laser diodes in integrated "butterfly" packages. No further optical amplification of the beating signal is required. An integrated photodiode antenna with an output power of 5 μW at 500 GHz is used as efficient terahertz emitter. Employing low-temperature grown (LT-) InGaAs/InAlAs photoconductive receivers as coherent detectors, SNR values of the terahertz power up to 75 dB are attained at an integration time of 300 ms. Accurate characterization of the thermal tuning behavior of the DFBs and precise thermal control yield an absolute accuracy of 1 GHz and a resolution of better than 5 MHz, without any on-line monitoring of the optical frequency. Due to the high frequency resolution no delay line is needed to vary the terahertz phase.

Keywords Continuous wave terahertz system · Distributed feedback laser · Photodiode terahertz emitter · Photoconductive terahertz receiver · Terahertz spectroscopy

1 Introduction

Continuous-wave (cw) terahertz spectrometers based on GaAs photomixer technology [1–3] have demonstrated superior signal-to-noise ratios (SNR) and a wide bandwidth [4, 5]. Frequency-domain terahertz spectroscopy has been successfully applied to the study of gases [6, 7] and solids [8], and first industrial applications have been evaluated [9]. However, these systems require an excitation wavelength below 870 nm and thus an intricate laser technology, with optical components (mode-hop free lasers, free-space optical

D. Stanze (✉) · M. Schlak · B. Sartorius
Fraunhofer Institute for Telecommunication, Heinrich Hertz Institut, Einsteinufer 37, 10587 Berlin, Germany
e-mail: dennis.stanze@hhi.fraunhofer.de

A. Deninger · A. Roggenbuck · S. Schindler
TOPTICA Photonics, Lochhamer Schlag 19, 82166 Gräfelfing, Germany

Published online: 22 December 2010

isolators with Terbium Gallium Garnet crystals and customized fiber-optic arrays) being the major cost drivers.

In the telecom wavelength band (1.5 μm), mature distributed feedback (DFB) laser technology is available in reliable, highly integrated packages. Unfortunately, there has long been a lack of cw terahertz emitter and receiver modules. Recently, some of us have realized a prototype cw terahertz system operating at 1.5 μm, combining for the first time an InGaAs/InGaAsP photodiode emitter and an InGaAs/InAlAs photoconductive receiver [10]. While demonstrating the overall feasibility of this approach, the prototype system employed expensive external cavity lasers and fiber amplifiers as optical source, and a mechanical delay line for phase-sensitive terahertz measurements.

In this work we transfer the precise frequency control technique developed for 850 nm lasers [5], to state-of-the-art DFB lasers at 1.5 μm. Then we combine this with the 1.5 μm THz emitter / coherent receiver concept outlined in [10] in order to build a potentially compact and low cost cw terahertz spectrometer. On the source side, an all-fiber-based two-color laser is controlled by a digital driver unit, which, via thermal tuning of the individual DFB diodes, precisely addresses any desired terahertz frequency. This system is described in detail in section 2. Section 3 deals with the photodiode-based terahertz emitters, section 4 describes the improvements of the photoconductive receiver for cw applications. The complete system is presented in section 5, including an evaluation in terms of the SNR performance attained. We show that the high frequency stability enables us to vary the terahertz phase by controlled frequency steps at fixed optical paths, omitting any mechanical delay line.

2 Laser source

Almost all coherent cw terahertz systems published in the literature utilized GaAs based emitters and detectors, and thus laser sources at either 780 nm or 850 nm. Despite the availability of compact, precisely tunable DFB diodes at near-infrared wavelengths [5, 8, 11, 12], the lasers have remained relatively large (typical size 20×8×8 cm per laser), and optical components such as bulk Faraday isolators or fiber-optic splitters contribute both to the large size and high manufacturing costs.

The setup used in this work comprised two DFB lasers with center wavelengths of 1537 nm (“laser 1”) and 1535 nm (“laser 2”). We used off-the-shelf butterfly packages with built-in thermo-electric cooler (TEC), optical isolator and polarization-maintaining fiber pigtail. The fiber output power was 50 mW per laser, and both lasers were packaged, together with an additional in-line fiber isolator each, in a small metal box (15 cm x 10 cm x 5 cm).

The laser linewidth was examined with a self-heterodyne beat setup, employing a 20 km fiber delay. We measured a linewidth of ~1 MHz on a time scale of ~100 μs. Tuning curves (wavelength vs. temperature) were recorded for each laser, using a precise wavelength meter (HighFinesse Ångstrom WS6-IR1, absolute accuracy ~1 pm). As evident from figure Fig. 1, the dependence of the lasing wavelength on the adjusted temperature was not exactly linear, in particular at high temperatures, where the response of the thermistor within the butterfly package becomes non-linear. To account for this behavior, the calibration curves of figure Fig. 1 were stored in a look-up table. In the actual terahertz experiment, this look-up table served to select the appropriate temperature settings for any desired terahertz frequency. A digital interface unit (“TeraControl 110”, Toptica Photonics) converted the temperature settings into analog control voltages for the respective TECs,

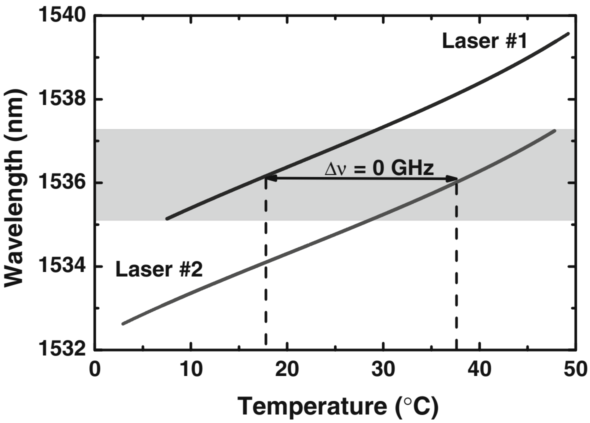


Fig. 1 Wavelength calibration curves. A variation of the chip temperature tuned the emission wavelength of the DFB lasers. Equal wavelengths were reached at temperature settings of 18°C and 37.5°C for laser 1 and 2, respectively. At extreme temperatures, a maximum difference frequency of 885 GHz was attained.

using two cascaded digital-analog converters (DACs) per channel with a total resolution of 21 bit. Thus we achieved an absolute accuracy of the difference frequency of ~1 GHz and a resolution of less than 5 MHz. A higher resolution up to the linewidth of the lasers requires an additional frequency measurement and stabilization system.

We note that the difference frequency range of these DFB lasers was limited to 900 GHz because of the large overlap region of the tuning range of nearly 2 nm (grey region in Fig. 1). This can be enhanced by selecting two DFB lasers with a larger wavelength offset. If both laser wavelengths overlapped at the extreme ends of the temperature spectrum, the continuous difference frequency range would broaden to ~ 1.25 THz. By using a third laser with a further wavelength offset an even broader tuning range can be envisaged, e.g. from 1 THz to 2.25 THz.

3 Terahertz emitter: waveguide integrated photodiode antenna (WIN-PDA)

Photoconductive antennas for 1.5 μm— the workhorse in pulsed terahertz systems—deliver only sub-microwatt power, when used in cw operation. In contrast, terahertz powers of several ten microwatts have been reported for photodiode emitters, e.g. of Uni-Travelling Carrier (UTC) type [13, 14]. Our setup employed photodiodes originally developed for high speed telecommunication at 1.5 μm [15, 16]. Unlike the UTC types of [13, 14], these devices have a standard P-I-N structure. The advantage of our photodiodes is their integrated waveguide (Fig. 2a).The absorbing layer is located on top of the waveguide, so

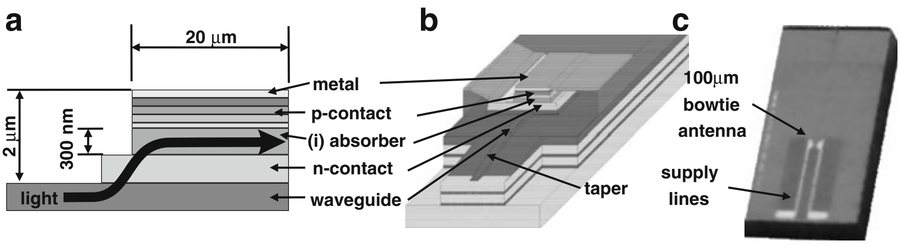


Fig. 2 (**a**, *left*) sideview of photodiode with integrated waveguide, (**b**, *middle*) scheme of WIN-PDA structure with taper, (**c**, *right*) photograph of photodiode chip.

that the 1.5 μm light (black arrow) couples evanescently into the absorber layer. The active region can be extended up to a length of 20 μm, and consequently the light absorption and thus the efficiency is high even for thin absorbing layers (e.g. 300 nm). Thin layers are beneficial for fast transit times and high terahertz bandwidths. A critical issue is the coupling from the optical fiber into the waveguide structure. We integrated a tapered part of the waveguide (schematically shown in Fig. 2b) to minimize the losses at the fiber-chip interface.

The original off-the-shelf telecom photodiodes were upgraded to terahertz emitters by modifying the contacts and integrating a bowtie antenna (length 100 μm, 90 degree) onto the chip (Fig. 2c). We call this device "Waveguide INtegrated PhotoDiode Antenna" (WIN-PDA).

The WIN-PDAs were characterized by injecting the two-color laser light into the device. The photodiode was reverse biased at 2.5 V. The radiation emitted by the WIN-PDA was measured using a factory calibrated Golay Cell (Tydex, model GC-1P). Results for a beat frequency of 0.5 THz are shown in Fig. 3. The terahertz output power first increased in a super-linear way with the injected optical power, and then saturated. A maximum terahertz output power of about 5 μW at 0.5 THz was achieved with an optical pumped power of 25 mW coming out of the fiber. The terahertz emission obtained using this first WIN-PDA is less than reported in [14] for UTC diode emitters with highly resonant antennas, but it has higher output power than typical values reported for GaAs photoconductive antennas with comparable optical input power at similar frequencies [5].

4 Coherent receiver: LT-InGaAs/InAlAs PCA

Photoconductive antennas (PCAs) operating at 1.5 μm have long been a problem, due to the high dark conductivity of LT InGaAs grown on InP which incapacitates the material for terahertz applications. Alternative techniques like Fe-doping [17] or ion irradiation [18] have been suggested for high speed 1.5 μm photoconductors, however up to now with limited success in terms of the terahertz emission power and the coherent detected signal.

Recently the problem of the high dark currents of LT InGaAs has been solved [19]. Beryllium-compensated, 12 nm thin LT-InGaAs layers were embedded between InAlAs trapping layers. 100 periods were grown to form a multi-layer stack (Fig. 4a). In time-

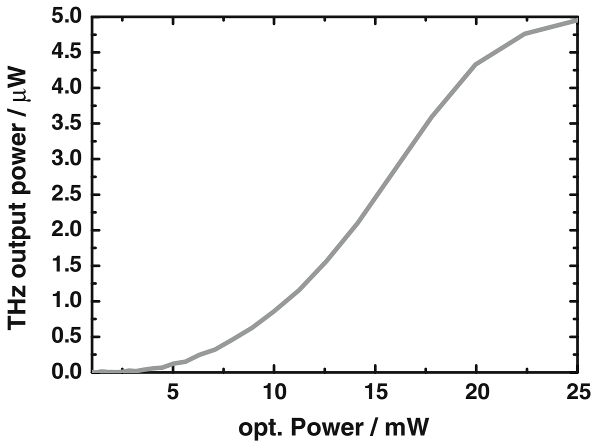


Fig. 3 THz output power vs. optical input power of a WIN-PDA with 100 μm bowtie antenna.

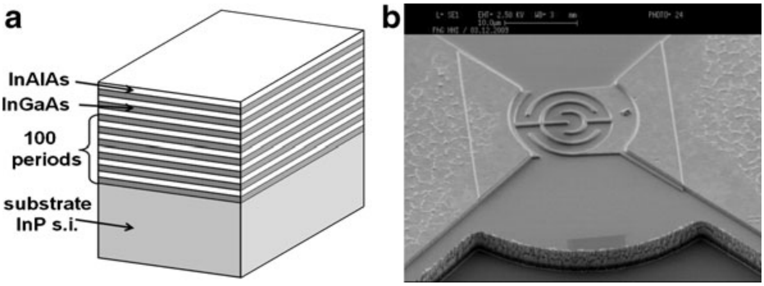


Fig. 4 (**a**, *left*) InGaAs-InAlAs multi-nanostructure, (**b**, *right*) SEM picture of the interdigitated electrodes on the pc matrial, used in the cw terahertz receiver modules.

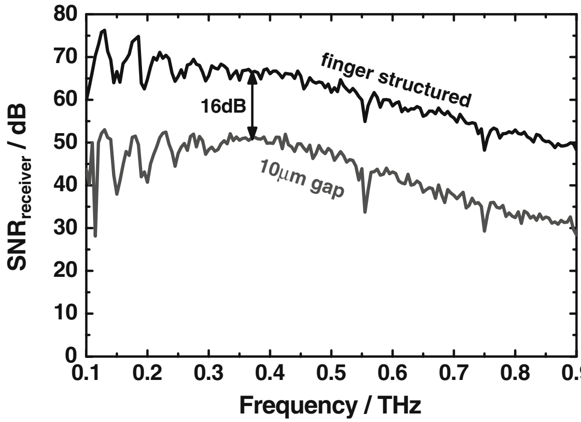
domain terahertz systems, stripline PCAs as emitter and dipole type PCAs as receiver have successfully been applied [19].

For the cw setup we chose a 90 degree bowtie antenna design, adapted to the diode emitter antenna. In order to achieve higher sensitivities, we replaced the simple photoconductive gap of the pulsed devices by a digitated finger structure, shown in the SEM picture in Fig. 4b. Direct e-beam lithography was used to define these small contact electrodes. The photoconductive gaps in this structure have a width of 1 μm; the electrical contacts of less than 0.5 μm. Thus the design combines short gaps and more homogenous illumination between two fingers. Also the interaction length between the optical signal and the THz signal is increased.

The dark currents in our device were reduced by etching away the photoconductive layer outside the illuminated region. The resulting trench can be seen on the bottom of the SEM picture in Fig. 4b. The technique we used for this process is identical to the process for mesa etching presented in [20].

The results of these improvements compared to a standard bowtie antenna with a 10 μm gap are shown in Fig. 5, which compares both device types in a twin-ECDL setup described in [19]. The signal to noise ratio of the digitated finger receiver increases by about a factor 6 (16 dB), compared to the 10 μm gap device, at identical terahertz power levels of the WIN-PDA emitter. The modified receiver chips were packaged into fiber coupled modules (shown in Fig. 6, bottom right).

Fig. 5 Signal to noise ratio of the terahertz signal, measured with two external cavity diode lasers. Grey trace; bowtie antenna with 10 μm gap black trace: improved design with interdigitated electrodes. The SNR is given by 20× $\log_{10}(I_{sig} / I_{noise})$, where I_{sig} denotes the receiver photocurrent and I_{noise} is the noise current, measured with a blocked terahertz beam. The frequency resolution is ~5 GHz.



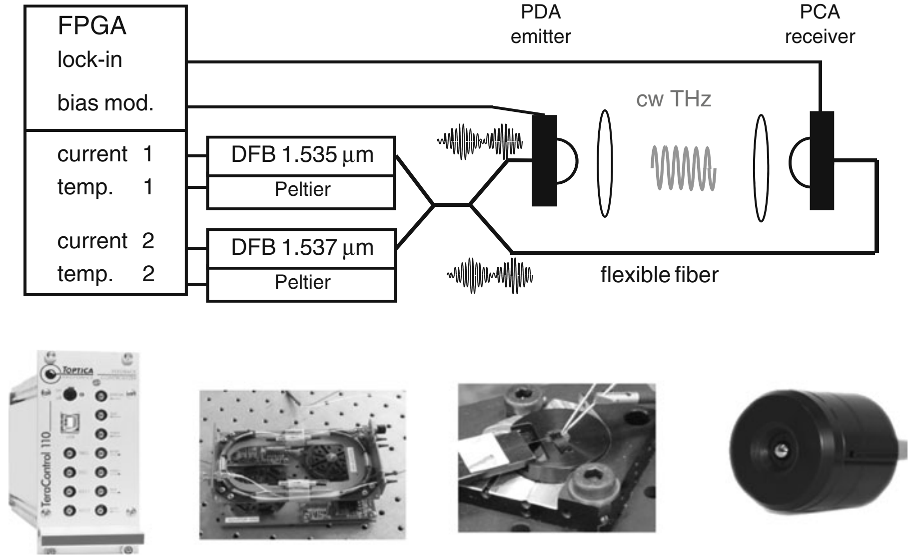


Fig. 6 Schematic setup of the ultra compact cw terahertz system and photographs of its key components.

5 Assembly and evaluation of the cw spectrometer system

The aforementioned building blocks— compact DFB lasers, photodiode based terahertz emitter, and the coherent photoconductive receiver— were assembled into an ultra-compact cw terahertz system. The scheme of the setup and the individual components are shown in Fig. 6.

The frequencies of the two DFB lasers were thermally tuned by the digital "TeraControl 110" module. The laser beams were combined in a 50:50 fiber coupler, the outputs of which were connected to the terahertz emitter and receiver, respectively.

At this stage, the WIN-PDAs were not packaged, and we constructed a test platform with an inserted silicon lens on which the WIN-PDA chips were centered (photo in Fig. 6). The optical fiber was adjusted to the tapered waveguide using piezo controllers. The AC bias voltage for the terahertz emitter (0/−2.2 V, ~7 kHz) was provided by the TeraControl 110 and fed to the WIN-PDA via contact needles. The terahertz signal was guided through two PE-lenses to the receiver module, where the resulting photocurrent was measured by the digital lock-in part of the TeraControl unit.

In contrast to previous work [8, 10], this system featured no semiconductor or fiber amplifiers. Also, no delay line was used. Rather, the terahertz phase was varied by changing the frequency in small, well-controlled steps; a method described in [8] by "scanning an interference pattern in frequency".

The performance of the system was evaluated at a moderate optical power of 25 mW per two-color fiber output. The terahertz frequency was varied in steps of 30 MHz, covering a range from 50 GHz to the tuning limit of 886 GHz. The resulting photocurrent was preamplified by a factor of 10^6 and measured with a lock-in integration time of 300 ms per frequency point. The measurement of the whole spectrum requires over 2 hours due to the high resolution of 30 MHz. The high resolution is needed to measure the phase oscillations of the terahertz signal with high resolution. The results of the measurements are summarized in Fig. 7, where the SNR is extracted from the envelope of the phase oscillations of the receiver photocurrent [8].

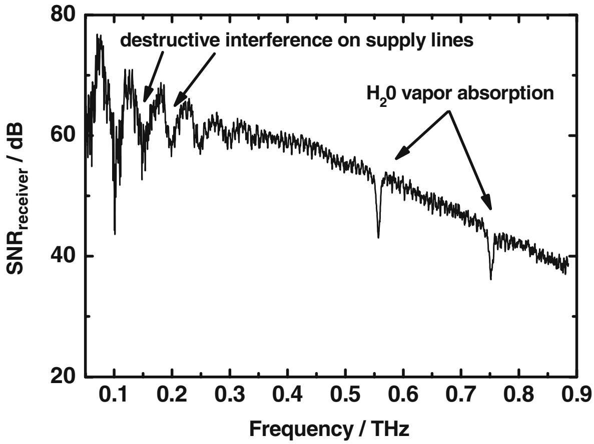


Fig. 7 SNR spectrum of the ultra compact cw terahertz system. The frequency step width was 30 MHz, analyzing the envelope of the phase oscillation yields an effective resolution of ~180 MHz.

The signal to noise ratio of the system was ~75 dB at 75GHz and 40 dB at ~900GHz. The signal oscillations between 50 GHz and 400 GHz result from destructive interference of the terahertz signal on the electrical supply lines of the WIN-PDA. These oscillations will be minimized by improving the supply lines.

We emphasize that the bandwidth of the spectrum in Fig. 7 is not limited by the WIN-PDA emitter and PCA receiver, but merely by the frequency range of the DFB diodes available at the time of the experiment. A higher terahertz bandwidth can easily be realized with a different pair of laser diodes. For the emitter / receiver combination itself, operation up to 2 THz has already been demonstrated in a twin-ECDL driven system [21].

Compared to the GaAs-based system described in [8], the present SNR values are 15-20 dB lower, at comparable lock-in integration times and with nearly the same modulation frequency. Tentatively, the SNR can be further improved by modifying the antenna design of the emitter and receiver for more efficient terahertz emission and detection. Also the optimization of the multilayer structure of the receiver could increase the sensitivity. The key advantages of the 1.5 μm system presented here are its ultra-compact footprint, and the low cost of the utilized telecom components.

6 Conclusion

An ultra compact and low cost cw terahertz system operating at the telecom wavelength band of 1.5 μm has been assembled and characterized. Key components are a pair of thermally tunable DFB lasers, a photodiode based terahertz emitter, and a photoconductive InGaAs/InAlAs coherent receiver. The system exploits low cost fiber components developed for telecom applications. Neither an optical amplifier nor a mechanical delay line is used. The system achieves an excellent SNR of the terahertz power of up ~ 75 dB at 75 GHz, and 40 dB at ~ 900 GHz. The frequency range of the present setup is only limited by the tuning range of the DFB lasers and an extension of the bandwidth up to 2 THz seems feasible [21]. This new cw system represents a significant step in bringing terahertz technologies from the laboratory to "real world" applications.

References

1. E. R. Brown *et al.* , "Photomixing up to 3.8 THz in low-temperature-grown GaAs," Applied Physics Letters 66, pp. 285–287, 1995
2. S. Matsuura *et al.*, "Generation of coherent terahertz radiation by photomixing in dipole photoconductive antennas," Applied Physics Letters 70, pp. 559–561, 1997
3. S. Verghese *et al.*, "Generation and detection of coherent terahertz waves using two photomixers," Applied Physics Letters 73, pp. 3824–38261 1998
4. I.S. Gregory *et al.*, "Continuous-wave terahertz system with a 60 dB dynamic range", Applied Physics Letters 86, pp. 204104–204104-3, 2005
5. A.J. Deninger *et al.*, "Precisely tunable continuous-wave terahertz source with interferometric frequency control", Review Science Instruments 79, pp. 44702–44702-6, 2008
6. S. Pine etal., "A Terahertz Photomixing Spectrometer: Application to SO2 Self Broadening," Journal of Molecular Spectroscopy 175(1), pp. 37–47, 1996
7. G. Mouret *et al.*, "Far-infrared cw difference-frequency generation using vertically integrated and planar low temperature grown GaAs photomixers: application to H2S rotational spectrum up to 3 THz," Applied Physics B 79, pp. 725–729, 2004
8. A. Roggenbuck *et al.*, "Coherent broadband continuous-wave terahertz spectroscopy on solid-state samples", New Journal of Physics 12, pp. 043017–043017-13, 2010
9. A. Majewski, "Terahertz Spectroscopy: High-resolution terahertz spectrometer sniffs out chemicals," Laser Focus World, 44:4, 2008
10. D. Stanze *et al.*, "Coherent CW terahertz systems employing photodiode emitters," Proceedings IRMMW 2009, 2009,
11. I.S. Gregory *et al.*, "Analysis of photomixer receivers for continuous-wave terahertz radiation," Applied Physics Letters 91, pp. 154103–154103-3, 2007
12. T. Göbel *et al.*, "Single-sampling-point coherent detection in continuous-wave photomixing terahertz systems," Electronics Letters 45(11), pp 65–66, 2009
13. H. Ito *et al.*, "Photonic Generation of Continuous THz Wave Using Uni-Traveling-Carrier Photodiode," Journal of Lightwave Technology 23, pp. 4016–4021, 2005
14. C.C. Renaud, *et al.*, "A high responsivity, broadband waveguide uni-travelling carrier photodiode," Proceedings SPIE, Vol. 6194, 61940C, 2006
15. H.-G. Bach *et al.*, "InP-Based Waveguide-Integrated Photodetector With 100-GHz Bandwidth," IEEE Journal of Selected Topics in Quantum Electronics 10(4), pp. 668–672, 2004
16. A. Beling *et al.*, "Miniaturized Waveguide-Integrated p-i-n Photodetector With 120-GHz Bandwidth and High Responsivity," IEEE Photonics Technology Letters 17(10), pp. 2152–2154, 2004
17. M. Tonouchi *et al*, "THz emission properties of Fe-implanted InGaAs Photoswitch exited with 1.5 μm femtosecond fiber laser," Proceedings IRMMW 2007, pp. 146–147, 2007
18. M. Martin *et al.*, "Gigahertz modulation of tunable terahertz radiation from photomixers driven at telecom wavelengths," Applied Physics Letters 93, pp. 131112–131112-3, 2008
19. B. Sartorius *et al.*, "All-fiber terahertz time-domain spectrometer operating at 1.5 μm telecom wavelengths," Optics Express 16 (13), pp. 9565–9570, 2008
20. H. Roehle *et al.*, "Next generation 1.5 μm terahertz antennas: mesa-structuring of InGaAs/InAlAs photoconductive layers," Optics Express 18 (13), pp. 2296–2301, 2010
21. D. Stanze *et. al.*, "Improving Photoconductive Receivers for 1.5 μm CW THz Systems," Proceedings IRMMW 2010, 2010