Continuous Wave Terahertz Systems Based on 1.5 μm Telecom Technologies

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Abstract Terahertz systems can profit from technologies developed originally for telecom
applications. Recent developments on telecom-based key devices are summarized and ways
towards CW systems with highest flexibility and excellent performance at reasonable costs
are sketched.

1 Introduction

A lot of attractive applications in various fields like security or non-destructive materials
testing have been demonstrated for THz sensor systems and THz spectroscopy [1, 2].
Terahertz has not yet found the way from scientific labs to the field use, however. One key
reason is that the first generation of optical THz systems was expensive, bulky, and not
turn-key ready for unskilled persons. Changing from 800 nm to the 1.5 μm wavelength of
optical fibre telecommunications marks an essential step towards systems for practical use.
In this paper, advantages and challenges of telecom technologies for terahertz applications
are discussed, and the progress towards next generation compact, flexible and cost effective
THz systems is described.

In part 2 we will define "1.5 μm Telecom Technologies" and point out their
benefits for THz. Part 3 discusses emitter-receiver pairs and the special challenges and
advantages of 1.5 μm telecom based photomixers. The optical control unit containing
the two tuneable beat lasers including their delay modulation are topic of part 4. Part
5 give examples where the CW systems are especially advantageous compared to
pulsed systems.

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2 Telecom technologies for terahertz systems

2.1 Building blocks for optical CW THz systems

The basic building blocks for CW THz systems are sketched in Fig. 1. Two single mode lasers with a wavelength offset corresponding to the target THz frequency are required. In order to generate two beat signals (i.e. pump and probe beam) the laser outputs are interfered via an optical network. The two beat signals are tuneable in their relative phase by means of optical delay lines. The beat signals drive so called photomixers. In the emitting photomixer the optical beat signal is used to modulate the electrical current, generating a THz wave at the corresponding THz frequency. In the detector, the incident THz wave and the optical signal are coherently mixed and the resulting electrical signal is recorded versus the tuned time delay. Hence, THz amplitude and phase can be accessed. The THz beam between emitter and receiver can be build up by lenses or mirrors, in transmission or reflection, adapted to the application and independently from the optical block. For generating the optical beat signals any wavelengths can be used - if the according photomixers are available. The wavelength range close to 1.5 μm appears especially very advantageous because components and technologies developed for fibre-optical telecommunications can be exploited for THz applications.

2.2 Fibre devices - from bulky free space optics to flexible fibre setups

The introduction of fibre-based telecommunications has paved the way for the internet. The fibres have lowest loss at 1.5 μm, the Erbium doped fibre amplifiers (EDFA) are operating at this wavelength, and thus the telecom systems have been designed around 1.5 μm. A huge variety of fibre devices have been developed and are now available at reasonable costs, thanks to their high production volumes. EDFAs give plenty of power to drive photomixers. Lasers and detectors are commercially available with fibre pigtails. Even if devices internally contain free space optics (for example isolators, filters, delay lines) they can be used practically for assembly of "all-fibre" circuits. The big advantages of fibre connections for assembly of THz systems are

–   stability of the light paths without the need for heavy and bulky optical benches
–   optical control unit separated from THz setup
–   fibre coupled emitter and receiver heads flexibly movable along large objects.
–   perfect spatial overlap of modes at fibre output (important for CW systems based on individual lasers).
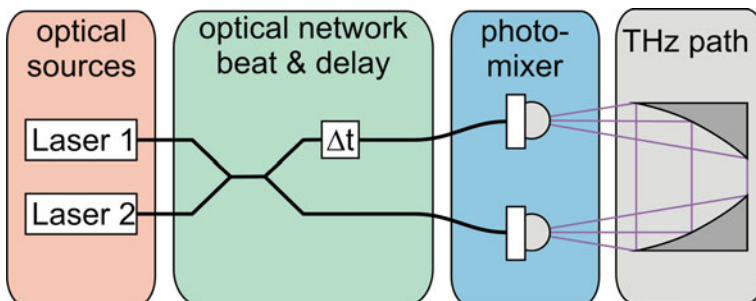
Fig. 1 Schematic building blocks of a CW THz system.

However, these advantages of fibre technologies are connected with the need to move to 1.5 μm wavelengths. The traditional semiconductor for THz Systems, low temperature (LT) grown GaAs, is operated at 800 nm and transparent at 1.5 μm. Thus the development of photomixers adapted to longer wavelengths is needed.

2.3 Optical integration

In the traditional GaAs technology, high power lasers are the main optoelectronic product. There has been virtually no need for integration of various optical functionalities. In InGaAsP grown on InP, the 1.5 μm material systems, telecom applications have driven the development of many more different and much more complex device types. Photodiodes as high speed detectors and amplitude- and phase modulators are such examples, which are also useful for THz, as will be shown later. Monolithic integration of different devices and functionalities on one chip is a second result from the demands of telecom applications. Fabrication of lasers of different and well defined wavelengths on one chip, and integration of waveguides and couplers for combining the laser emissions to a common output port are well established techniques. However, the needs for telecom- or for THz-applications differ, and thus the required opto-electronic THz-devices are not available off the shelf. The specialized devices for 1.5 μm operated THz systems have to be developed, with the mature InP-technology offering an excellent platform.

3 Photomixer emitter - receiver pairs

Photomixers build the interface between optics and THz. They are the key devices for exploiting optical technologies at given wavelengths for THz applications.

3.1 Conventional configurations with photoconductive emitters and receivers

First CW systems have been assembled at 800 nm [3, 4]. It looked very promising to replace the expensive Ti:Sapphire lasers by more simple CW lasers while using the low temperature grown (<200°C) LT GaAs photoconductive antennae (PCA) available from pulsed systems also as photomixers. However, conditions in pulsed or in CW operation are quite different: At a similar mean power, the peak powers in 100 fs pulses at 100 MHz repetition rate are five orders of magnitude higher than the peak powers of CW modulated light, and the semiconductor has four orders of magnitude longer time (compared at 1 THz) to recover from the excited into a dark state with high resistivity (Fig. 2). Operation with optical beat signals appears as a very smooth modulation compared to the very strong and short excitation in pulsed systems. Taking this into account it is not surprising that photoconductive antennae work differently in CW operation than in pulsed systems. Consequently, in spite of their simple laser units, CW systems were significantly later introduced on the market (by companies Emcore [5], Toptica [6]), and in many aspects - for example bandwidth - the performance cannot compete with pulsed systems.

At 1.5 μm, the development of photoconductive antennae was much more difficult than for LT GaAs. Similar to GaAs, low temperature growth of InGaAs on InP creates the required fast recombination centres. But the LT-growth of InGaAs on InP increases the dark conductivity by orders of magnitude, which is not acceptable for the targeted THz applications. Several other techniques have been tried to incorporate fast recombination centres without inducing a high dark conductivity. Implanting or doping with Fe [7,8]
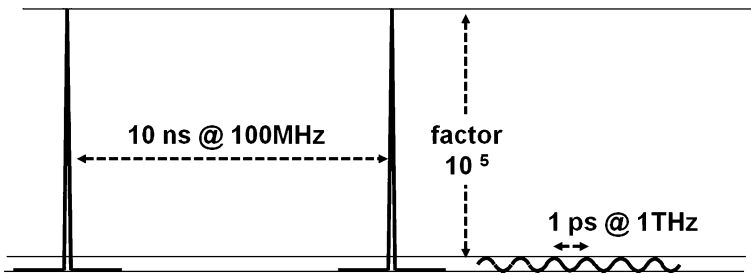
Fig. 2 Pulsed versus CW excitation: higher peak power, longer time for relaxation into dark state.

during the growth is a first approach which has been used for generating fast recombination centres, while a second technique has been the bombardment of the grown layers with ions [9]. The according photoconductive antennae worked in pulsed systems, but only the emitters developed recently in [8] could compete with LT GaAs devices. Attempts for applying the according Fe-doped InGaAs also in CW systems are not described so far. Such investigations have been performed for the ion bombarded InGaAs. However, used for CW emitters, the output power was 15 dB below that of GaAs devices [10]), and 10nW@1THz was achieved in improved photomixers [11]. Applications for coherent receivers are not reported yet.

3.2 Photodiodes as photomixers - benefits and limits

Fortunately, another option comes up at 1.5 μm: Photodiode based photomixers. Similar to photoconductors they can be integrated with THz antennae (photodiode antenna, PDA). The important advantage versus photoconductors: The latter are lifetime limited, thus fast recombination centres have to be incorporated to get fast photoconductors. These recombination centres, however, reduce the efficiency of the photoeffect. One can optimize speed or efficiency, not both. In contrast, the speed of photodiodes is transit time limited, which is the time the photocarriers need to travel to the p- or n-contacts. Here one has options to optimize the speed without minimizing the efficiency. In the next chapter concepts for high speed photodiodes will be described and results on improved THz emitters will be given.

   If photodiodes can be used for improved emitters - can they also be used for improved coherent detection? To answer this question, one has to examine the optical behaviour of both components, which are schematically explained in Fig. 3. It is well known that an illuminated photodiode creates a -relatively high (~V) - photovoltage, and photocurrents are obtained without any external voltage. In contrast, photoconductors need a voltage to generate a photocurrent. This behaviour is exploited in using photoconductors as coherent detectors: The electromagnetic field received by the antennae is applied to the photoconductor as bias voltage. The measured photocurrent is now the product of the THz field and the optical power, which just gives the mixing signal needed for coherent detection of the THz field. For the photodiode the (weak) field of the electromagnetic THz wave adds only to the (high) photovoltage, it is a sum and not the product needed for a mixing process. From this point of view photodiodes seem to be no candidates for coherent detection. However, we have to mention recent work on exploiting non-linearities in special photodiodes for coherent detection [12]. But the achieved signal noise ratio (58 dB @ 300 GHz, 110 μW THz power) is far away from that of typical LT GaAs photoconductive receivers (>70 dB @ 300 GHz, ~1 μW THz power). Therefore, in our opinion, the best photomixer pair is a photodiode antenna as high power emitter combined with a photoconductive antenna for highly sensitive coherent detection.
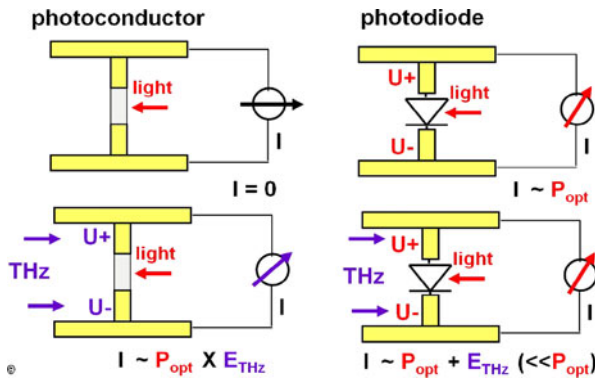
Fig. 3 Comparison of photoconductive versus photodiode antennae in case of coherent detection. Illuminated photoconductors give currents only if the THz fields apply a voltage to the antennae. Illuminated photodiodes create voltages and currents, the THz fields create only a small add on.

3.3 Photodiode based emitters

The switching speed (i.e. optical modulation speed) of p-i-n photodiodes is limited by the transit time of the photocarriers to the p- or n-contacts. A first approach towards high speed is the uni-travelling-carrier (UTC) design [13]. The basic scheme of the according band structure is shown in Fig. 4. The UTC-diodes consist of a high/moderate p-doped InGaAs absorbing layer and an undoped/slightly n-doped InP collection layer. Generated holes in the absorbing layer diffuse via collective motion to the p-contact. The corresponding electrons diffuse/drift partly with overshoot velocity into the collection layer and then to the n-contact. The switching speed is therefore defined by the velocity of the fast electrons, not by the slow holes, which gives this device type the name. NTT in Japan has been exploited the UTC-photodiode as terahertz emitter at first and has been demonstrated a terahertz emission of about 10 µW at 1 THz [14]. By optimizing the UTC concept and combining it with resonant antennae, other institutions have published THz emission powers of more than 530 µW at 350 GHz [15].

A second approach for high speed photodiodes applies thin absorbing layers. This obviously reduces the transit time of the carriers, but also the absorption and the efficiency. In order to get both, high switching speed and high efficiency, waveguide integrated photodiodes have been developed. The thin absorbing layer is located on top of a waveguide. The light couples into the thin (for example 0.3 µm) absorbing layer which has typically a length of 20 µm and width of 5 µm. Efficient absorption can be achieved in such structures. Waveguide integrated photodiodes with taper for improved fibre-chip coupling (Fig. 5) developed at HHI [16] are a qualified product for telecommunication applications with a high market share in presently
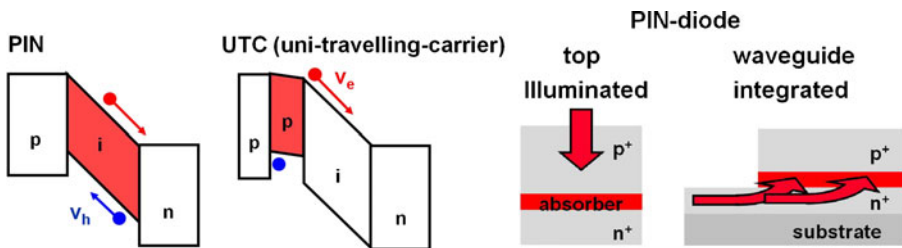
Fig. 4 Approaches to high speed photodiodes. Left: band structure of PIN versus uni-travelling-carrier (UTC) diode. Right: side view on top illuminated and waveguide integrated photodiode with thin absorption layer.
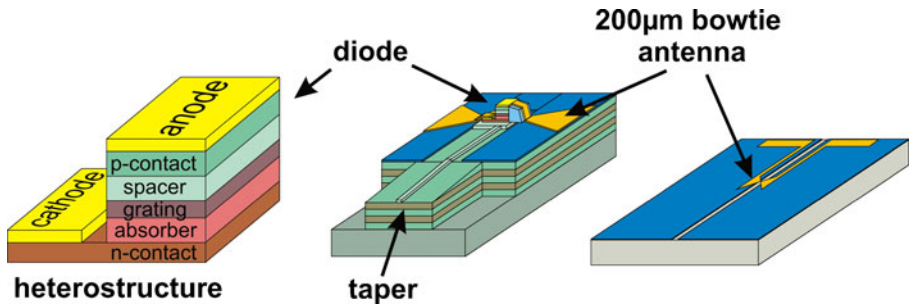
Fig. 5 Scheme of waveguide integrated telecom photodiode with integrated bow tie antenna.

installed 40 Gb/s systems. It is a straightforward step to integrate these telecom photodiodes with THz antennae (Fig. 5). Driven by an optical beat signal of 30 mW and using a factory calibrated Golay cell we measured THz powers of 14 μm at 200 GHz and 5 μW at 500 GHz [17]. These values are below those of the UTCs. However, we consequently use broadband (bow tie) antennae, and in addition we have not modified the design of the qualified telecom photodiodes yet. Adapting the design for THz applications without changing the qualified processing steps will result in higher power from robust devices.
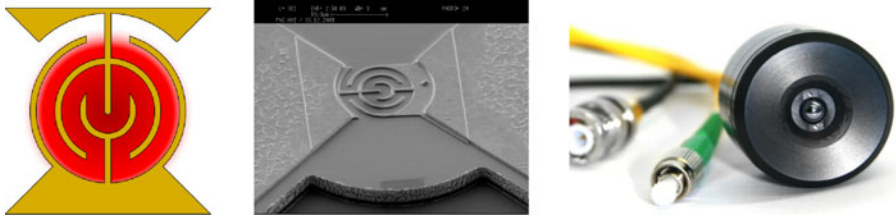
3.4 Photoconductive receivers

In the beginning the benefits of 1.5 μm photodiode based emitters could not be exploited because the fast photoconductors needed for highly sensitive coherent detection were not available for 1.5 μm wavelengths. Several techniques had been tried for getting photoconductors with a performance comparable to LT GaAs. A big step forward has been achieved by the LT InGaAs/InAlAs nano-film photoconductors [18] in a multi-layer stack. Even in Be-compensated LT InGaAs the carrier concentration is too high for application as photoconductive THz antennae. The InAlAs now contains deep trapping centres which capture the residual electrons from the photoconductive layer (Fig. 6, left) and increase so the dark resistivity of the InGaAs. But the trapping effect works only for very thin layers (10 nm). Therefore the InGaAs/InAlAs layers must be grown as a multilayer stack of typical 100 periods to get a sufficient light absorption.

Significant further improvements have been achieved by mesa-structured antennae [19] with electrical side contacts (Fig. 6, right). Thanks to the side contacts, one gets homogeneous field distributions in the depth of the photoconductors, and the photocarriers have not to cross several interfaces and barriers on their way to the contacts. Time domain systems with a bandwidth up to 4 THz had been demonstrated. Related antennae designs appear also as good candidates for coherent detection in the CW systems. Mesa-structured bow-tie antennae have

Fig. 6 Left: scheme for capturing of carriers from an InGaAs photoconductive film by InAlAs deep trapping centres. Right: improved mesa-structure with electrical side contacts for homogeneous fields and barrier-free current flow.

Fig. 7 Photoconductive receiver with circular finger electrodes for CW operation. Left: scheme. Centre: SEM photograph, showing the etched trench between the bow tie contacts. Right: fibre coupled module with PCA chip.

been selected as receivers, and for the first time a CW system combining photodiode emitters with coherent photoconductive detection could be demonstrated [17].

However, it is well known that interdigitated finger electrodes are very advantageous in CW systems. But it is very challenging to realize interdigitated fingers in mesa technique. One has to etch 0.3 μm wide groves 2 μm deep into the multilayer stacks, subsequently adding the side contacts. Hence, planar top contacts with a circular design were processed at first. The circular design minimizes the polarization sensitivity to the laser light and matches better with the beam profile (Fig. 7, left). In addition trenches between the bow-tie wings were etched to minimize parasitic dark currents [20]. An SEM photo of such a fabricated photoconductive antenna is shown in Fig. 7, centre. As last step the photoconductive antennae (PCA) are packaged into fibre coupled modules (Fig. 7, right).

4 Optical control units and system setups

4.1 Conventional laboratory setups

A laboratory CW terahertz setup at 1.5 μm can be assembled as it is schematically shown in Fig. 8. Two external cavity lasers (ECL) with wide tuning ranges (100 nm) are used to generate the beating signal. Via a 50:50 fibre coupler both wavelengths of the lasers were combined to the beating signal, which is split up into the emitter and receiver branch. Two EDFAs, one for each branch, boost the optical beating signal up to the required power (typ. 20 - 40 mW) for the photodiode emitter and the photoconductive receiver. The bias of the photodiode emitter is modulated at 100 kHz between 0 V and -2 V (reverse bias) for lock-in detection. The THz signal is directed via mirrors or lenses to the photoconductive receiver. A delay line (commercial fibre delay for example) in the receiver link is used to vary the time correlation between THz wave and optical beat signal. The according photocurrent is measured
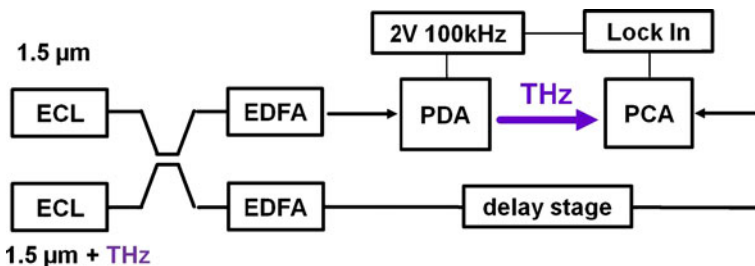
**Fig. 8** Laboratory setup of a 1.5 μm fibre coupled CW system.
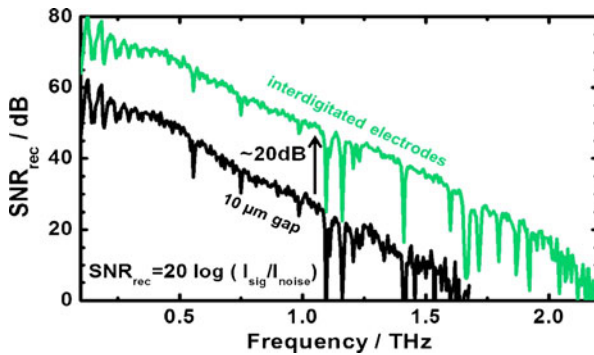
Fig. 9 Performance of 1.5 μm CW systems combining photodiode emitters with photoconductive coherent receivers. Compared to the simple mesa-antennae the interdigitated finger electrodes give better signal-noise ratios, and the system can be operated up to 2 THz.

using lock-in detection. Figure 9 shows measurements for two different receivers, a mesa antenna with a 10 μm gap, and an antenna with interdigitated finger electrodes, as described above. The improved performance of the latter can be noticed. The SNR is 70 dB at 0.5 THz, and the according system can be operated up to 2 THz [20].

4.2 Towards compact systems

The CW system above works well in the laboratory, but ECLs, EDFAs and delay lines are expensive and bulky devices, and thus the next step concerns the simplification of the
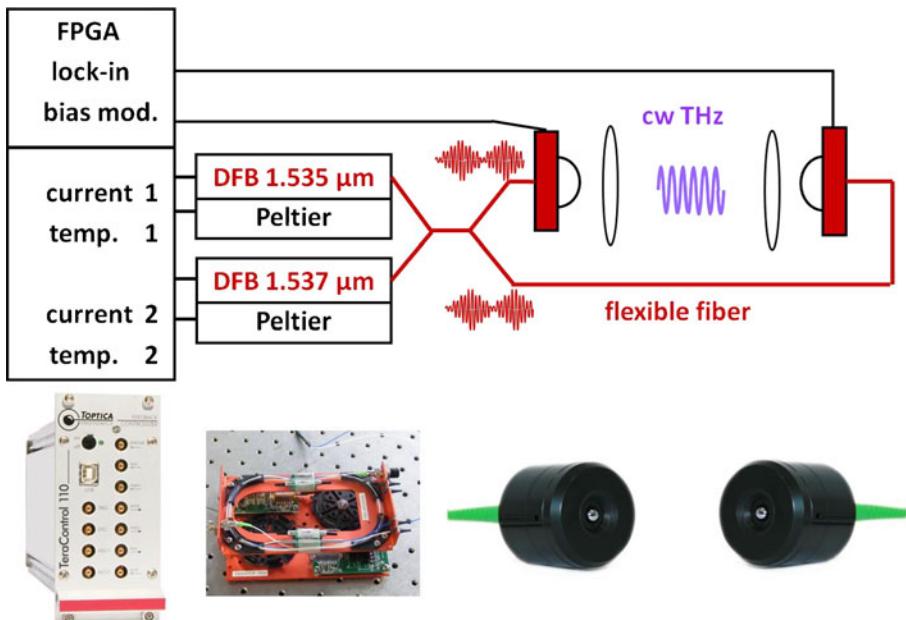
Fig. 10 Scheme of a simplified and compact system with DFB lasers, no EDFAs, no delay line. Lower: photographs of used components: electronic control unit, DFB laser and fibre network, fibre coupled PDA emitter and PCA receiver modules.

optical control unit. Instead of the ECLs one can use compact DFB lasers, which can be tuned continuously in wavelength (typically ~5 nm, corresponding to 600 GHz, doubled by tuning both lasers) via the temperature of the Peltier-cooled heat sinks. The lasers are packaged in butterfly modules and are equipped with polarization maintaining fibres. Their output power of 50 mW is sufficient for driving the photomixers without the need for EDFA boosters. The delay line can be avoided by applying a technique described in [21]: the fibre branches to emitter and receiver have an offset in their length, and this converts the continuously wavelength tuning into the needed phase variation. The good function of this all-fibre setup (Fig. 10) with a similar performance as the previous laboratory setup could be demonstrated already [22]. This system with a minimum of optical devices marks a significant step towards ultra-compact and cost efficient THz systems.

4.3 Integrated laser/modulator chips

Integration of the beat lasers on one chip is the next step towards ultra-compact optical control units, supported by the mature InP technology. In one advantageous concept two DFB lasers - both with micro-heaters for wavelength tuning - are not arranged in parallel but in line, using one common waveguide running through both lasers. The rear laser transmits through the front laser, and at the front laser facet one obtains the joint dual-mode beat signal without need for any coupler. The function of this extreme compact and flexible device has been demonstrated already [23].

However, the most important advantage of integration is the potential to replace the mechanical delay lines. The system described in 4.2 operates already without a delay line. However, the disadvantages of this solution are the coupling of wavelength and phase tuning, and the limited speed of the phase tuning function. Both can be overcome if electro-optical phase modulation can be applied. Phase modulation of one individual light wave - easily performed using phase modulators from telecom developments - converts directly and proportional into delay modulation of the beat signal [24]. However, having one individual wavelength in one fibre, all phase instabilities in this fibre (based on temperature and vibration) convert also very strongly into phase instabilities in the beat signal. These phase instabilities cancel out only if both optical waves are guided through the same fibre. The individual light paths including the phase modulator must be very short, very stable arranged on a chip. Figure 11 shows the scheme of an integrated chip solving this problem [25].

Two DFB lasers with e-beam defined detuned gratings for a target wavelength offset and with integrated heaters for further wavelength tuning are located in an interferometer-type structure. Integrated multi mode interference (MMI) couplers and waveguides generate and lead two beat signals (identical in their wavelength-pairs) to two output ports at opposite chip facets. The essential point is the integration of a phase tuning section between one laser and one coupler. This modulates the phase of one beat signal relative to the other one - the needed function is achieved.

The delay modulation can work electro-optically with up to MHz or even GHz speed, and this allows exploiting very advantageous modulation techniques, for example the "single-sampling-point" [26]. Saw-tooth modulation of the phase-modulator with a modulation-amplitude corresponding to a 2π shift of the beating signal converts the beating signal and the terahertz wave into an endless sine modulation. Using a lock-in synchronized with the phase modulation one can detect in real time amplitude and phase of the THz wave.
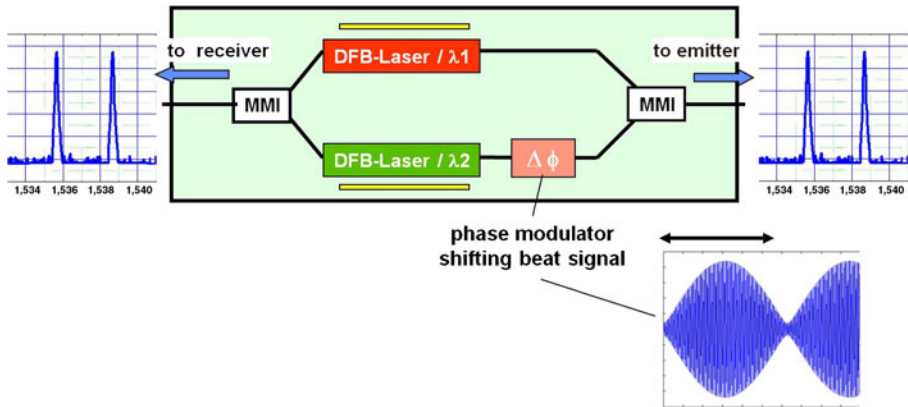
Fig. 11 Integrated chip with two tuneable DFB lasers and phase modulator. The beat signal can be controlled electro-optically via phase modulation of an individual wavelength.

In summary compact, cost effective, high performance and high speed terahertz CW systems are no longer a contradiction. The next generation will combine all this merits in one solution.

## 5 Advantageous applications of CW THz systems

Up to this point the development on 1.5 μm fibre coupled CW terahertz was motivated by reducing cost and size of systems and by improving stability and simplicity of operation. In the following we point out applications where CW operation in general offers advantages compared to pulsed systems.

5.1 Highly resolved spectroscopy

In time domain systems the spectral resolution is determined by the tuning range of the time delay. This causes long measuring times (up to hours), and in the end the resolution is limited by the repetition rate of the used fs laser. In CW systems, the resolution is limited by the linewidths of the used lasers (DFB: ~ MHz) and the investigations can be restricted on the frequency range of interest. Figure 12 shows a study on an absorption line of water vapour using a system as described in 4.1. The step width was 250 MHz, and the shape of the line - broadened by temperature/pressure effects - can clearly be observed [17].

Fig. 12 Advantageous CW application highly resolved spectroscopy. Example: absorption of water vapour.
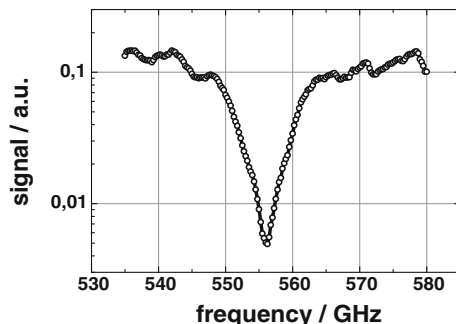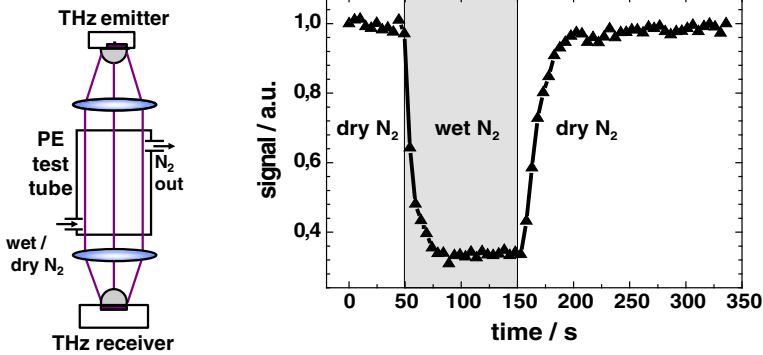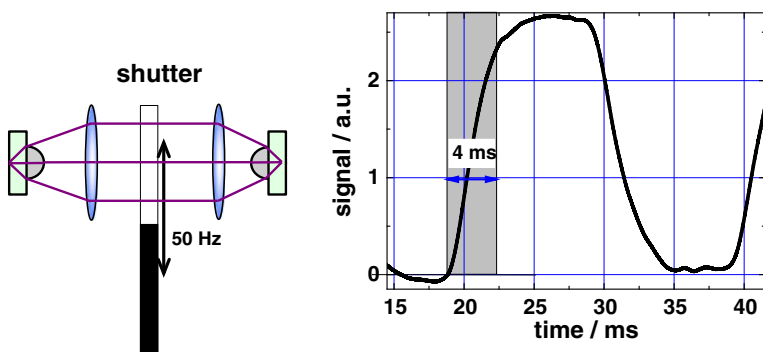
Fig. 13 Advantageous CW application monitoring on fixed frequency. Example: contamination of dry nitrogen flow by water vapour, monitoring at 557 GHz through the walls of a plastic tube.

5.2 Monitoring on selected wavelengths

Pulsed systems measure the complete spectrum. However, often monitoring on a selected line is preferred, for example in process control of a gas stream. Figure 13 illustrates such an application. A gas stream of dry N_2 is contaminated with water vapour. The THz transmission on a fixed frequency of 557 GHz is measured and recorded (Fig. 12). The contamination with water vapour can clearly and easily be monitored through the walls of the plastic tube [17].

5.3 High speed measurements

Observation at fixed frequency also allows high speed measurements if the signal noise ratio is sufficient. In Fig. 14 this is studied at a frequency of 1 THz using a conventional setup. A lock in with an integration time of 1 ms is used. The THz beam is blocked and opened using a shutter at 50 Hz. The detected signal follows the shutter with rise and fall times of 4 ms [27]. That is not matching the demands for video rate, but it is sufficient for a lot of imaging applications.

Fig. 14 Advantageous CW application high speed data acquisition. Example: analysis of rise and fall times at 1 THz radiation. Rise and fall times of 4 ms can be resolved.

6 Summary and conclusions

Telecom technologies offer a lot of laser and fibre components for assembling the optical parts of THz systems very flexibly and cost effectively. Missing key devices had been the photomixers for operation at 1.5 μm wavelengths. The breakthrough towards usable photoconductive antennae for 1.5 μm has been achieved by InGaAs/InAlAs nano-film multi-layer-structures which can be applied for highly sensitive coherent detection. Having reached this point, the 1.5 μm systems have best chances to surpass the conventional 800 nm systems in performance and in functionality, thanks to the mature semiconductor technology. Photodiode-antennae based emitters provide more power then photoconductive photomixers, and the combination with the coherent photoconductive receivers gives the best emitter-receiver pair. Integration of pairs of tuneable lasers results in very compact beat sources. The on-chip integration of phase modulators replaces the mechanical delay lines. This is not only reducing significantly size and costs. The greatest advantage is the high speed electro-optical delay modulation. Any electrical signal from a function generator is impressed on the optical beat signal and subsequently on the emitted THz wave. Thus one can get full control on the THz wave, in frequency, phase, and amplitude. New and very useful detection schemes become possible, like for example the single-sampling-point technique.

In summary, telecom technologies offer flexible fibre coupled setups, improved photomixer emitter-receiver pairs, and high functionality based on compact integrated chips. Telecom starts to bring its slogan to terahertz-applications: for everybody, everywhere, anytime.

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