Terahertz photomixer

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Abstract. The paper gives a review of continuous wave optical devices called THz photomixers used for excitation and detection of the terahertz radiation. Possible structures of the terahertz photomixers are classified and described.

Key words: continuous wave optical devices, THz photomixers, terahertz radiation.

1. Introduction

Among many terahertz wave sources, as synchrotrons [1–3], FELs (Free Electron Lasers) [4], BWO tubes (Backward-Wave Oscillators) [5], Smith-Purcell emitters [6], IMPATT diodes (IMPact Ionization Avalanche Transit-Time) [7], Gunn diodes [8], THz lasers [9] a THz photomixer seems to be cheap, simple, and quite prospective [10, 11]. Even so sophisticated semiconductor device as a Quantum Cascade Laser (QCL), where a terahertz wave is produced directly [12–14], last time has been rearranged into three technologically integrated elements necessary to set up the photomixer: both two mid-infrared cascade lasers and a nonlinear element for photomixing in one chip [15].

Basically, a THz photomixer consists of two independent tunable laser sources yielding the difference frequency in a desired terahertz region by heterodyning. Two laser beams with different frequencies light a photoconductive antenna PA – see Fig. 1, where running fringes with the terahertz difference frequency excite carries in the semiconductor material. The device serves as a terahertz coherent wave emitter. Usually, the solid state (diode) lasers are used as elements of a laser heterodyne. As it is known, they show a relatively wide gain curve – hundreds gigahertz or more [16]. The value of the beat frequency can be easily regulated by changing the temperature of the laser diodes, or laser current operation.
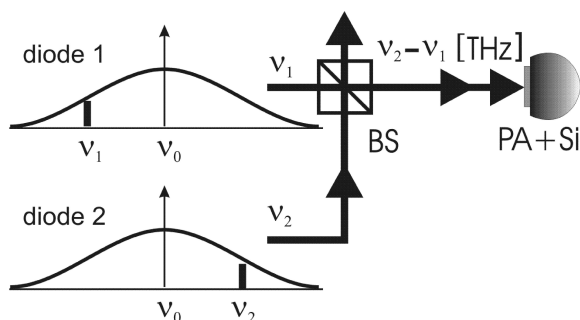

Fig. 1. Illustration of the two laser diode heterodyne operation with the same central frequencies ν_0. Each diode operates on different frequencies ν_1 and ν_2 tuned by temperature or current. BS – cubic beam-splitter, PA+Si – photoconductive antenna and Si lens

The method is very useful, but it is necessary to ensure a single-mode operation of both lasers. It is the most important property of the used diode lasers. There are different methods to eliminate multimode operation of diodes which allow to reach the goal. The most known popular technologies are so called DFB (distributed feedback) or DBR (Bragg diffracted) structures. The single mode selection is done using the diffraction grating technologically etched close to the p-n junction of the diode structure. It works like an optical filter [17]. As aforementioned, the band of the photomixer depends on the spectral width of the diodes used in the experiment. To enlarge the band or to move the band of the photomixer into higher frequencies the diodes with different central frequencies are applied (see Fig. 2).
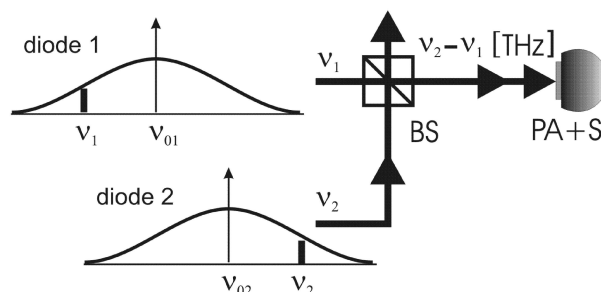

Fig. 2. Illustration for the two laser diode heterodyne operation with slightly moved central frequencies ν_{01} and ν_{02}

The "heart" of the terahertz photomixer is a photoconductive antenna. The photoconductive antenna (PA) consists of an electrical dipole (the simplest solution) and suitable semiconductor quick enough to produce carriers in time with the beat frequency (it means, in order of picoseconds). This condition is fulfilled by many technologically elaborated semiconductor materials. One of them is a Low Temperature grown Gallium Arsenide (LT-GaAs) [18, 19]. When the heterodyned laser beams light the surface of the semiconductor, than carriers appear in the material. Let us focus the beam between arms, at the gap of the dipole antenna technologically fixed to the surface of the semiconductor. Then, so called "dark" photocurrent appears (free-charge carries). If the metal antenna

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is polarized with some voltage carriers give a periodical short circuit for the antenna (see Fig. 3). In other words, the antenna PA converts the photocurrent into a THz wave. The described device is often called an Auston switch [20–22]. In that way an optical switch designed is the base for the operation of the terahertz emitter.
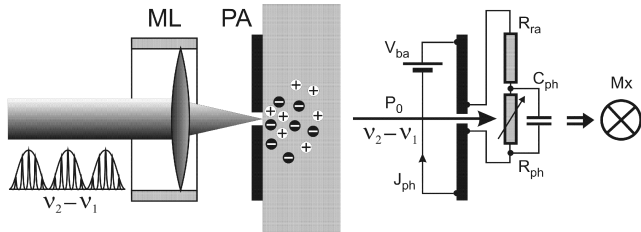

Fig. 3. Illustration of the Auston switch operation. Left: a laser beam (with some beat frequency ν_2–ν_1) is focused at the gap in the dipole antenna creating carriers at the plate of the semiconductor. If the antenna is polarized, than as a consequence, carries create a short circuit. ML – microscopy *lens*, PA – photoconductive antenna. Right – equivalent circuit: V_{ba} – bias voltage, P_0 – incident power, J_{ph} – photocurrent, $\nu_2 - \nu_1$ – optical beat frequency, R_{ph} – photoresistance of the antenna PA, C_{ph} – capacitance of the photoconductive gap, R_{ra} – radiation resistance of the antenna PA, Mx – symbol of the photomixer used in the paper

THz photomixer – classification attempt. The most popular THz photomixer consists of two independent laser sources. The frequency band of both lasers should give possibility to tune the lasers yielding the frequency difference in the THz range. Figure 4 shows the scheme of the THz photomixer. Both laser sources give a beating frequency $\nu_2 - \nu_1$. Both laser beams create an interference signal at the surface of the semiconductor (exciting beam). The fringes obtained in that way run along the semiconductor material giving the modulated intensity of the electrical field at the semiconductor with the frequency of $\nu_2 - \nu_1$ (e.g. terahertz frequency). If the semiconductor is enough "quick", it works like an optical switch AS – Auston switch [20]. The terahertz wave emitted via a simple, biased with some voltage, dipole antenna can be applied for imaging or spectroscopy. The THz signal is detected by a cryo-bolometer, Golay cell or semiconductor devices.
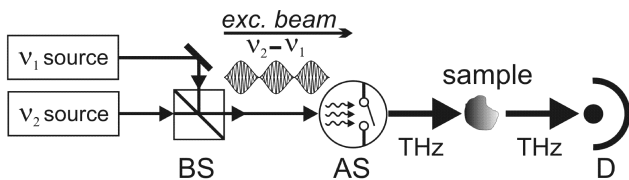

Fig. 4. Two separate diode laser sources of a frequency difference $\nu_2 - \nu_1$ excite an optical Auston switch AS including a photoconductive antenna and Si lens. BS – beam splitter, D – detector

The detection of the THz signal can be accomplished without the detectors aforementioned. The method bases on so called coherent homodyne detection (explanation in the further part) [23]. Homodyne, means here the arrangement,

where the same laser beam operates as an exciting beam and probing one – see Fig. 5.
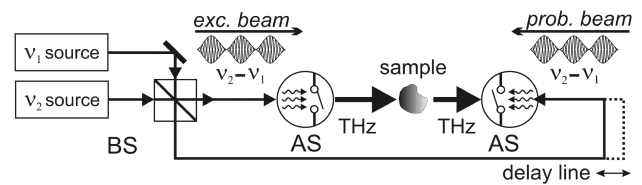

Fig. 5. THz photomixer with coherent homodyne detection arrangement. BS – beam splitter, AS – Auston switch

It is possible to apply, instead of two lasers, a cheap, multimode laser diode (MDL) as a source of the frequency difference for excitation of the photoconductive antenna AS (see Fig. 6). To obtain a beat frequency between two adjusted modes, some optical selectors OS (e.g. a Fabry-Perot filter) are used [24].
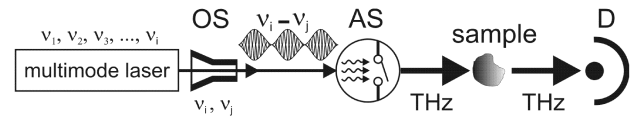

Fig. 6. THz photomixer with multimode laser, OS mode selector, AS Auston switch, and D detector

Figure 7 presents another example where a sophisticated optical selector is used [25]. It is so called a V-shape mirror VSM and diffraction grating DG, as a specific optical selector OS – see Fig. 6. These two optical elements create an output selecting mirror of the laser diode. The V-shape mirror reflects only radiation of chosen frequencies possible to generate by the laser. We can switch the system by displacement of the mirror VSM (see the figure) perpendicularly to the laser beams. In that way the laser diode generates on chosen frequencies ν_i and ν_j.
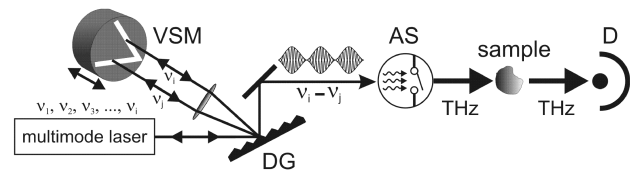

Fig. 7. The arrangement with a multimode laser and V-shape total reflecting mirror VSM. DG – diffraction grating, AS – Auston switch, D – detector

Another concept of using a multimode frequency diode laser is similar to that in comb lasers [26]. The pulses obtained (see Fig. 8) can be applied in the same way as in Time Domain Spectroscopy (TDS) [27, 28] or THz imaging [29].
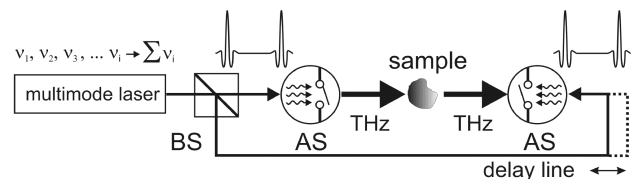

Fig. 8. Multimode laser comb in TDS measurements

A dual wavelength laser diode using the hopping mode is possible to use in THz technique and worth to consider [30]. The mode hop in the multimode laser diode MLD is obtained by the use of a laser diode current control (as known the wavelength of the MLD varies with the injection current). Figure 9 illustrates schematically the method. The system requires no external optical parts but only current and temperature control.
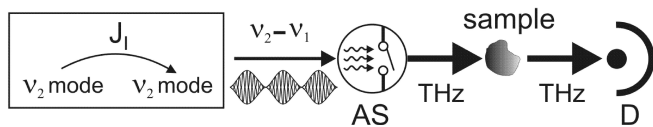

Fig. 9. The system where the laser diode injection current J_I releases the inter-mode hops

Integrated laser diodes, instead of two separate ones, can also be used in the THz photomixer arrangement (see Fig. 10).
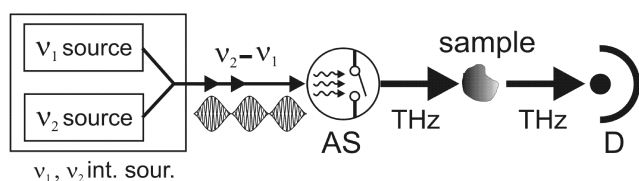

Fig. 10. THz photomixer with technologically integrated two laser sources

The most mature device, where all three elements are technologically integrated in one chip are two cascade mid-infrared lasers with nonlinear medium Mx monolithically integrated in the active medium (Fig. 11) [31].
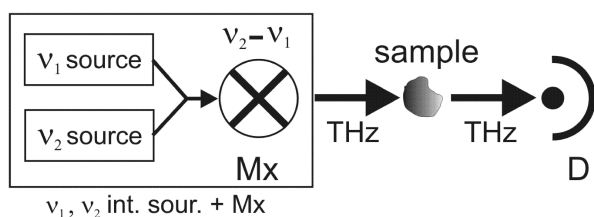

Fig. 11. Technologically integrated three elements: two mid-infrared cascade lasers or photodiodes with some frequency difference and suitable nonlinear material as a mixer Mx

2. THz photomixer. Design

The terahertz wave created in the dipole antenna shows tendency to be reflected from the walls of the semiconductor plate. The wave leaves the semiconductor if it is joined to some material with similar refractive index (about 3.4). The condition fulfils high resistivity silicon (about 10 kΩcm). It is formed as a lens, which collimates the wave. But hemispherical shape of the lens still creates problems with internal reflections (see Fig. 12).
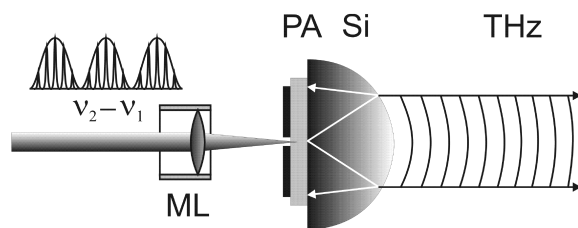

Fig. 12. Photoconductive antenna PA fixed to a hemispherical lens Si. ML – microscopy lens

The problem is solved when a hyperhemispherical Si lens is applied (Fig. 13).
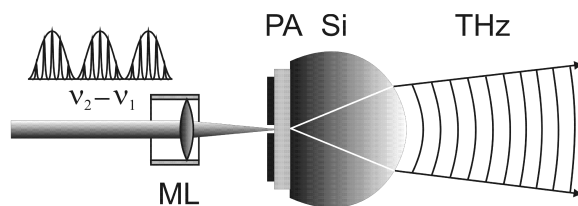

Fig. 13. Hyperhemispherical Si lens apllied to a photoconductive antenna PA

Many problems with the correct adjusting of the photomixing system can be solved by the application of fibers guiding the infrared radiation (exciting and probing beams) to photoconductive antennas PA (see Fig. 14). Professional products on the market are equipped with fibers [32].
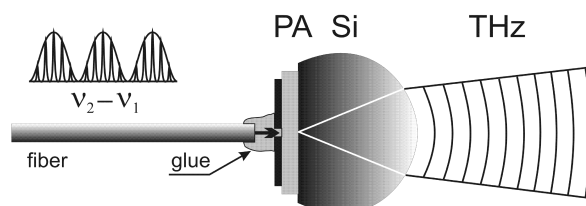

Fig. 14. The exciting beam is delivered to a photoconductive antenna with a fiber fixed directly to PA. The same solution is applied to the probing beam

The complete arrangement of the THz photomixer is shown in Fig. 15. The photoconductive antenna PA is polarized with some dc voltage or (much better solution) with square voltage pulses (a few tens of Volts) with relatively low frequency (from hundreds Hz to a few kHz). The THz wave is collimated and focused with polyethylene lenses PL on the sample. The set of lenses focuses the THz beam on cryo-detector BC.
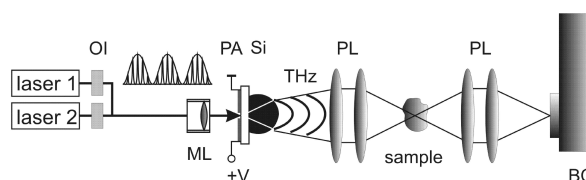

Fig. 15. Photomixer with a cryo-bolometer BC. Laser heterodyne is protected against parasitic back-scattering with optical isolators OI. PA – photoconductive antenna, Si – silicon lens, ML – microscopy lens, PL – polyethylene lens

The cryo-detector gives a good signal-to-noise ration but is not comfortable and not portable. One of the solution is a room temperature detector (Golay cell) or using so called coherent homodyne detection. The same laser beam modulated with THz frequency (exciting beam) is used as a probing beam – see Fig. 5. It excites another (very often identical) photoconductive antenna AS creating carriers, and, as a result, giving not zero average voltage signal at the receiving dipole antenna [10, 23].
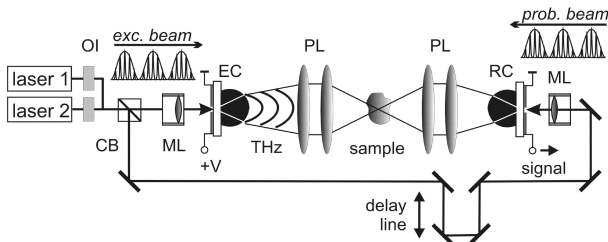

Fig. 16. Coherent homodyne detection. OI – optical isolator, ML – microscopy lens, EC – emitting chip, RC – receiving chip, PL – polyethylene lens

Figure 16 explains the method. In the case of the unbalanced arms of a difference Δd, when we change the beat frequency ν_{THz}, or in other words, the frequency of the THz wave, we observe a periodical signal I_{det} at the receiving chip due to variable phase relations between the THz ray E_{THz} and detecting beam P_{opt} – the consequence of the coherent detection – see Eq. 1 [10, 18]:

$$\langle I_{\text{det}} \rangle \propto P_{\text{opt}} \cdot E_{\text{THz}} \cdot \cos\left(\frac{\nu_{\text{THz}}}{c} \Delta d\right). \qquad (1)$$

When the receiving chip RC is illuminated with heterodyned laser beams, than it works like an optical switch. It gives a short circuit for the antenna it means it increases and decreases periodically (with the heterodyne frequency) a detectivity of the antenna. In that way, the non zero average signal $\langle I_{\text{det}} \rangle$ is obtained at the receiving chip (see Fig. 17). The signal can be easy detected using a conventional synchronous detection method using a lock-in amplifier [21, 33].
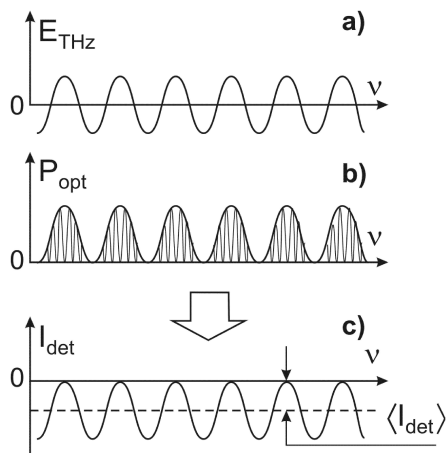

Fig. 17. The idea of coherent homodyne detection. a) E_{THz} – THz ray, b) P_{opt} – detecting beam, c) I_{det} – signal at the receiving chip, $\langle I_{\text{det}} \rangle$ – nonzero average signal

3. THz photomixer. Adjusting

The terahertz photomixer, as many optic devices, needs careful adjusting. A first problem is a suitable lens to focus infrared radiation of the laser diodes at the surface of the photoconductive antenna PA. Usually it is a good quality microscopy lens ML. The next problem is correct placing of the antenna PA at the surface of the silicon lens Si, what is illustrated and explained in Fig. 18.
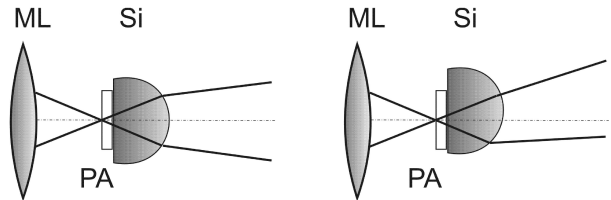

Fig. 18. Adjusting of the chips: left – correct, right – wrong. PA – photoconductive antenna, ML – microscopy mirror, Si – silicon lens

The material of the lens should suit the refractive index of the antenna PA (in the case of the LT-GaAs it is about 3.40). It fulfills a high resistivity silicon: about 10 kΩ·cm. So high refractive index creates the focus for the terahertz beam in a different place than the focus of the infrared beam. Figure 19 explains the problem. It is why the pair lenses (ML and Si), like at the figure, should be moved of the distance d to the direction of the THz part of the photomixer.
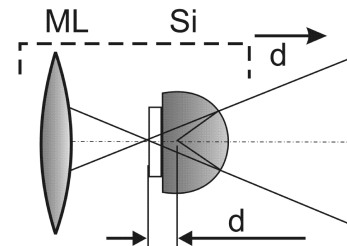

Fig. 19. Position of the setup: ML – microscopy lens, Si – silicon lens, d – displacement of the THz beam focus

The terahertz beam, to make it useful, can be led to a measurement place of the THz system with polyethylene lenses (Fig. 20). It is a common solution. The advantage of the lenses is a low cost of the optical system; the disadvantage – relatively high spot of the beam in the focus.
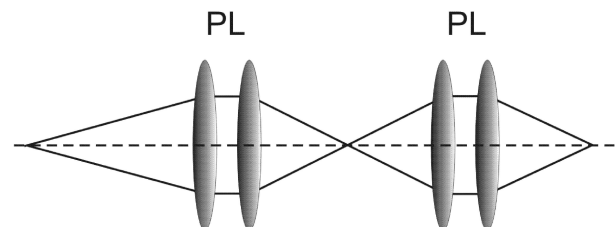

Fig. 20. Polyethylene lenses PL

Another popular system uses off-axis parabolic total reflecting metal mirrors (Fig. 21). It gives acceptable focus (especially for terahertz imaging applications), but it is relatively

difficult to adjust. One of the method is to use a standard single mode laser (a He-Ne laser or one of the laser diodes of the laser heterodyne) and so called "zero" diaphragm. In that way it is possible to obtain easy observable pattern of the diffraction fringes. The mirrors should be adjusted so long to obtain not disturbed pattern of the fringes along all path of the terahertz beam. The figure explains the procedure.
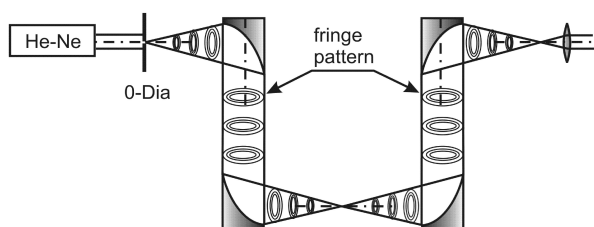

Fig. 21. Off-axis parabolic mirrors PM. 0-Dia – "zero" diaphragm

4. Other solutions

One of possible method to design a dual source of frequencies is a multimode laser with a pre-selection of two modes. Other solution bases on more or less integrated dual sources of the laser radiation. We can recognize two general kinds of the devices: laser-microchips with external photomixing (two in one plus photomixing), and microchips with internal photomixing (three in one).

Multimode laser. The application of the multimode laser diode MLD as a source for the terahertz photomixing seems to be the simplest and the cheapest. As known, we can expect many optical beats between different modes. Mixing many laser modes creates sharp envelops of the mixed frequencies with some repetition rates depending on the mode distance [34–36]. A number of the beats depends on the optical spectrum of the laser diode used in the experiment. The method uses just a rich contents of the multimode beats [27]. In that way it is possible to obtain a broad spectrum in THz band as a broadband radiation source for THz-TDS (Terahertz Time Domain Spectroscopy) [28]. The THz radiation is detected in a classical way using the cross-correlational heterodyning between the generated THz waves and the multimode laser beam on the photoconductive antenna PA in the setup like in Fig. 8.

Multimode laser with a pre-selection. The multimode laser can be preselected to obtain a dual mode laser. Figure 22 shows the idea in a schematic way. The beat frequency $\nu_2 - \nu_1$ is applied in the same way as it is illustrated in Fig. 6. The selection of the two modes can be accomplished with a suitable mode selector (e.g. an etalon) [24].
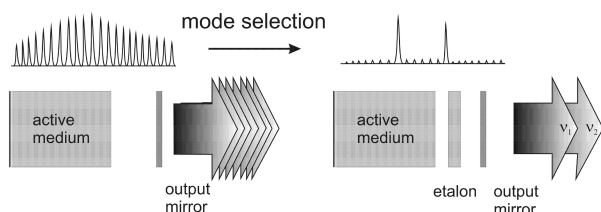

Fig. 22. Illustration for multimode laser diode with mode selection using an etalon

Dual color laser diodes. A dual-color laser diode is an integrated structure of two diodes. Each of the diodes operate on slightly different wavelengths and in that way the desired difference frequency is obtained and applied as a source for the photomixer [17, 37]. The advantage is simplicity of the photomixer arrangement. As they report [37], the monolithic semiconductor element consists of two DFB laser sections and one phase section between the lasers in one chip. The big advantage of the device is possibility of independent tuning each of the laser by adjusting currents. In that way the frequency band from 170 to 490 GHz was reached. Figure 23 schematically illustrates the idea.
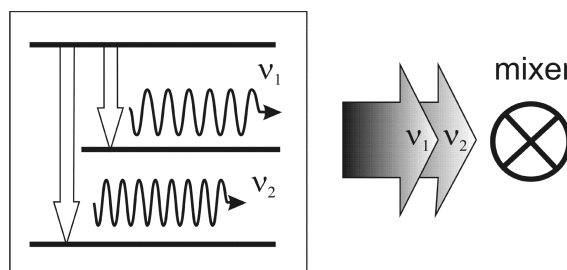

Fig. 23. Illustration for the dual laser diode operation. The mixer is still outside of the dual color chip

Two-color cascade lasers with internal photomixing. Cascade lasers (QCL) needs cooling to about 150 K if they operate in THz region. It is due to relatively thin layers of the semiconductor designed for that band of the frequency. The problem is illustrated in Fig. 24. Very often even both devices, the THz QCL and the detector, are cooled to helium temperature. The problem is less difficult in the medium frequency band, when the cascade lasers operate at room temperature, and this idea was the base for the successful solution.
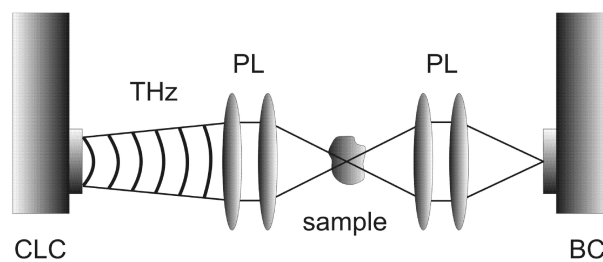

Fig. 24. Illustration for the arrangement with a cascade laser CLC and detector (bolometer) BC – both in cryostats, PL – polyethylene lens

A Federico Capasso group of the Harvard School of Engineering and Applied Sciences and colleagues from Texas A&M University and ETH Zurich demonstrated in 2008 year a sophisticated structure of two integrated room temperature mid-infrared cascade lasers. The lasers worked on 33.7 THz (8.9-micron wavelength) and 28.5 THz (10.5-micron wavelength) yielding a difference frequency of 5.2 THz. This dual frequency cascade laser chip was technologically equipped with a nonlinear material, which generated the frequency difference (see Fig. 25). In that way a "room-temperature terahertz laser" was invented [31].
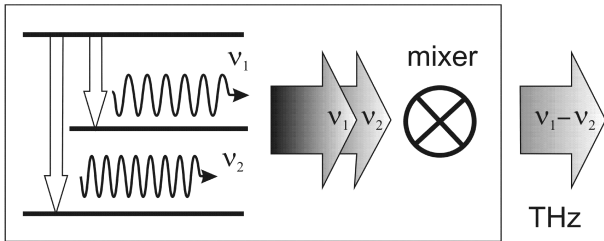
Fig. 25. Scheme of two room temperature medium frequency cascade lasers (or laser diodes) technologically integrated with a frequency mixer

Frequency stability aspects. A frequency stability of THz photomixer systems depends on many factors. The main factor which influences the stability is temperature of diodes or other lasers used in the system. The system shown in Fig. 4 is equipped with two separated and independently cooled laser diodes. Theoretically they can be tuned with temperature with a step of 0.002°C, what gives tuning of appr. 50 MHz. In practice the frequency stability reaches the values between 1 GHz and 5 GHz. For THz imaging applications it does not have any meaning. For spectroscopy applications it allows to recognize most of investigated spectral lines. Systems shown in Fig. 10, 11, 23, and 25 are more stable by technological integration of the lasers.

5. Some results

The terahertz photomixer consists of two optical arms: an exciting beam (including a terahertz path) and probing beam (Fig. 26). Typically, the both arms are of the same length, what is ensured by tuning the delay line. We consider another case, where the lengths of the arms are unbalanced. It is obvious, that such a system behaves like an interferometer. It

means, when the frequency of the source (laser diode heterodyne) is changed, than we observe a quasi-sinusoidal signal (see Fig. 27)
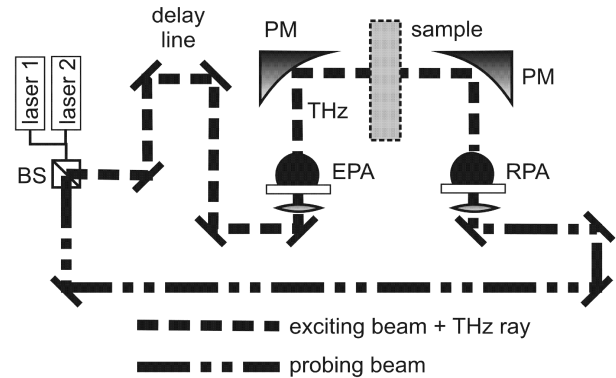

Fig. 26. A typical arrangement of a THz photomixer, where the coherent detection method is applied. EPA – emitting photoconductive antenna, RPA – receiving photoconductive antenna, BS – cubic beamsplitter, PM – parabolic mirrors

The length difference Δd between the probing and exciting beams could be easy calculated from the period in the frequency domain measurement shown in Fig. 27. When we place the sample in the THz arm of the system, than the length difference Δd is different. The difference between both measurements can be easy recalculated into the value of the refractive index of the measured sample.

To make results more precise we can calculate a Fourier transform from the signal like in Fig. 27 (but the method is reliable for non-dispersive materials of the measured samples) [38].
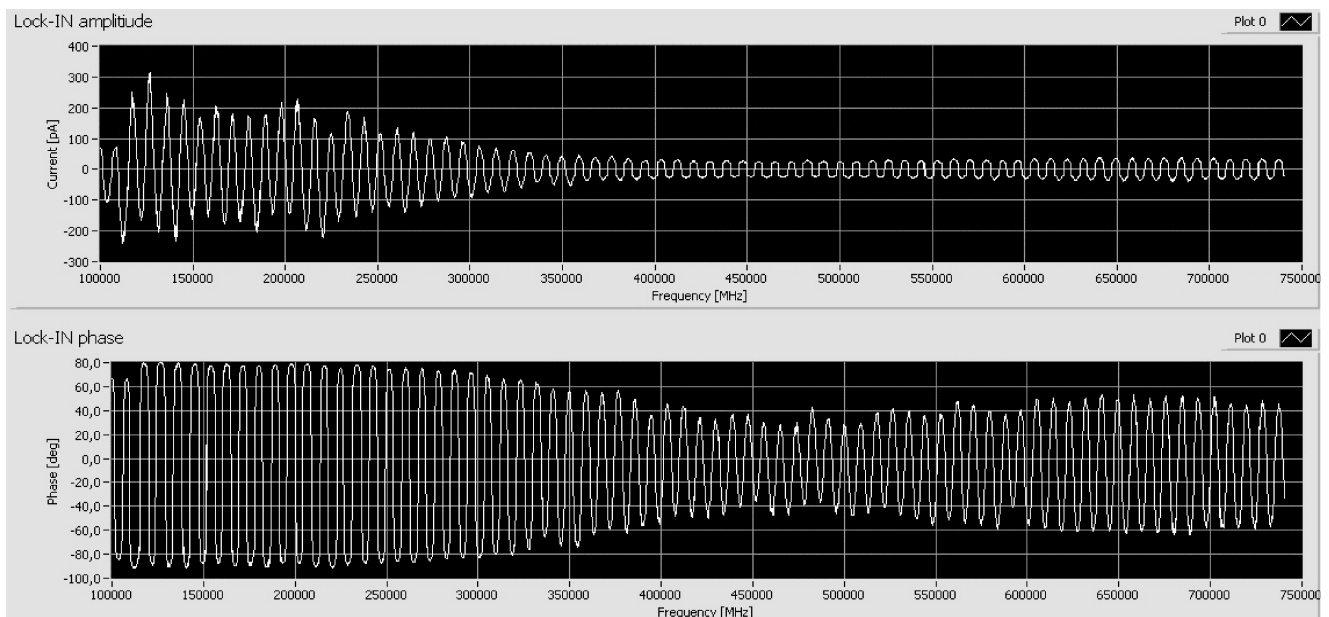

Fig. 27. A typical signal (amplitude – top, and phase – bottom) obtained from the lock-in amplifier when the frequency of the photomixer is tuned from appr. 0.1 to 0.75 THz

6. Conclusions

The terahertz photomixer, as a continuous wave spectrometer, can be competitive for pulse arrangements. Firstly, pulse THz spectrometers using the method of THz-TDS (Time Domain Spectroscopy) are relatively expensive because of the femtosecond laser as the element of the arrangement. Secondly, continuous wave setups can show a better resolution comparing to pulse systems (see e.g. cw systems equipped with quantum cascade lasers) [12–14]. It can be relatively easily applied to terahertz wide-band communications [39]. On the other hand, pulse systems achieve wide band of the terahertz spectrum including medium infrared [40].

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