Coherent terahertz imaging with synchronized distributed-feedback diode lasers

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***Abstract*—We present a heterodyne hybrid terahertz imaging system, which combines electronic narrow-band emitters, operating at 0.2 THz and 0.62 THz respectiveley, with a continuous-wave two-color laser system for electro-optic detection. The laser system employs two distributed-feedback laser diodes, providing a tunable difference frequency which is phase-locked to the emitted terahertz frequency with an offset of 10 MHz.**

I. Introduction and Background

RECENTLY, we have demonstrated hybrid terahertz imaging setups, based on electro-optic detection[1] using either femtosecond pulsed[2] or continuous-wave[3] (CW) laser radiation. Both imaging techniques readily enable multi-pixel terahertz detection and promise phase-resolved two-dimensional real-time imaging capabilities. While we successfully established amplitude and phase imaging with a high dynamic range using an ultra-short pulsed laser system, synchronization of the CW diode lasers to the electronic terahertz radiation source was yet unsatisfactory.

The CW hybrid terahertz imaging system consists of a high-power frequency-multiplier-chain-based micro-elec-tronic emitter combined with two frequency-tunable distributed-feedback (DFB) laser diodes for electro-optic detection. The difference frequency of the lasers becomes mixed with the frequency of the terahertz radiation to derive an intermediate frequency (IF) for data processing. The challenge of this system is the need for stabilization of the laser difference frequency and its synchronization with the terahertz radiation. Spatial hole burning effects within the active region of the laser diodes are continuously changing the local charge carrier density and therefore the effective refractive index of the laser cavities. This broadens the spectrum of the laser beat signal and has to be compensated with a laser-current control loop which needs a very large bandwidth to work properly. With the scheme implemented here, we achieve not only frequency stabilization but even stable phase-locking. Offset frequency locking to a local-oscillator (LO) signal enables phase-sensitive measurements via lock-in detection. The phase information hence can be employed directly for evaluating the time of flight of the terahertz waves.

II. Experimental Approach and Results

The system setup is shown in Figure 1. Two different types of highly stable narrow-band micro-electronic sources from Radiometer Physics[4] are used for generation of the terahertz radiation to take advantage of the frequency tunability of the used diode lasers. One type is a synthesizer-driven W-band source combined with an amplifier and a six-times multiplier-chain achieving 0.62 THz at more than 1 mW output power. The other type is a frequency-doubled Gunn-oscillator operating at 0.2 GHz with 2.5 mW output power.

The terahertz radiation is mixed with the two-color laser beam from the diode-laser pair in electro-optically active ZnTe crystals. The lasers are two temperature-stabilized DFB laser diodes operating at ~855 nm with a tunable difference frequency of up to 2 THz.

The laser beams are combined with a 2x2 polarization-maintaining fiber combiner whose output drives both a reference and a signal electro-optic mixer. Each laser emits on the order of 100 mW, of which about half is available behind the fibers at the detectors. The detectors contain a 2-mm-thick <110>-oriented ZnTe crystal followed by a pair of photodiodes with a 100-MHz bandwidth for balanced detection.

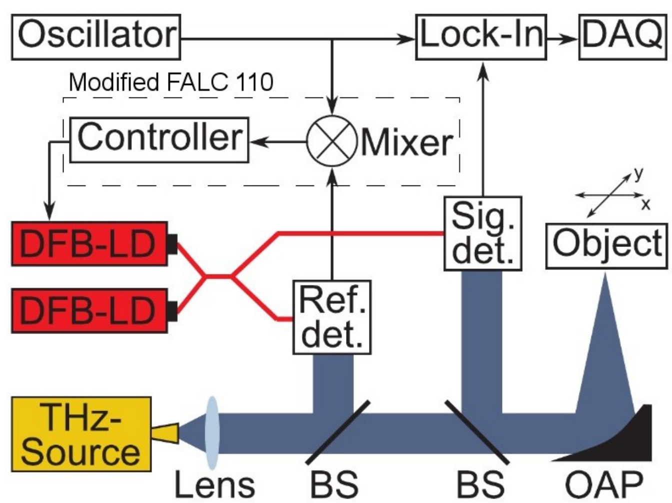

Fig.1: Illustration of the continous-wave hybrid terahertz imaging setup with the fast laser current control loop.

A portion of the terahertz beam is directed to the reference branch in order to determine the detuning of the difference frequency of the two lasers relative to the frequency of the terahertz radiation. Hereby, the terahertz beam is guided to the reference detector and is electro-optically sampled with the two-color laser radiation resulting in an IF-signal.

978-1-4244-5417-4/09/$26.00 ©2009 IEEE

This signal serves as feedback for stabilization of the laser beat signal via the very fast laser-current control loop. It consists of a fast control amplifier (a modified version of the FALC 110 from TOPTICA Photonics) including an integrated mixer which uses an externally provided 10-MHz LO-signal to define the offset frequency and enable the mixer to act as a phase discriminator. In our experiments the LO-signal is given by a function generator. The output signal of the control amplifier is fed to one of the lasers whereas the other laser remains free-running. Hence, while both laser frequencies can vary with time, the difference frequency of the laser radiation is phase-locked to the terahertz frequency of the emitter with an offset of 10 MHz.

The other part of the terahertz beam is delivered to the signal (imaging) branch. The terahertz beam is focused onto the object. The reflected as well as the backscattered terahertz radiation is then guided to the electro-optic signal detector, which is connected to the signal input of the lock-in amplifier, whose reference signal is provided by the function generator. Therefore the amplitude and relative phase of the detected signal can be measured.

A two-dimensional image with phase information can be generated by scanning the object within the focal plane using an x-y-translation stage. Figure 2 displays raster-scan intensity images at a frequency of 0.2 THz, while comparable results at 0.62 THz are not shown. Despite the different power of the applied terahertz sources the field amplitude within the crystal is similar due to the diffraction limit of the terahertz focal spot. Hence the lower power of the 0.62 THz-emitter can be compensated.

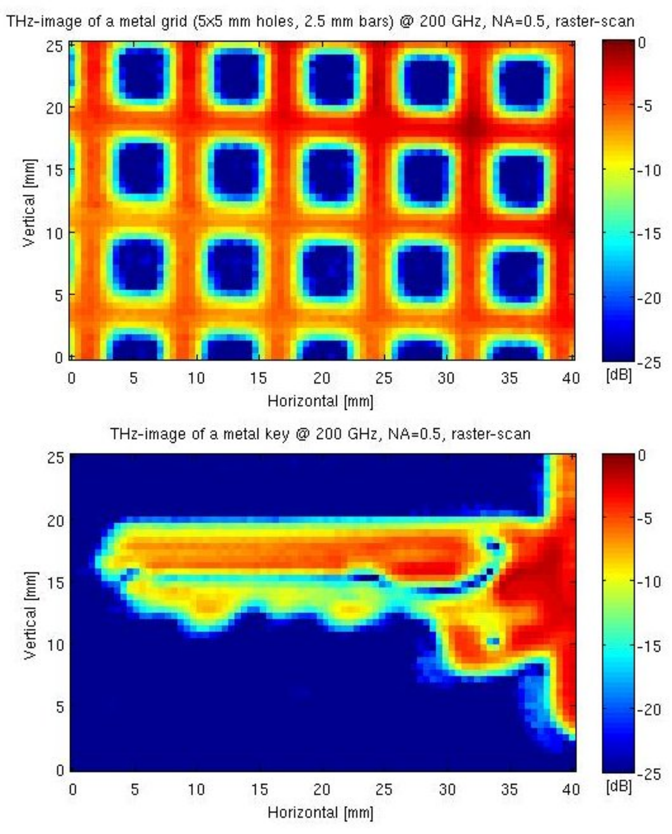

Fig.2: THz images at a lock-in time constant of 100 ms.

III. Conclusion and Outlook

We have developed a CW hybrid terahertz imaging system combining a micro-electronic emitter and two distributed-feedback diode lasers for electro-optic detection. The challenge in the development of this CW hybrid terahertz imaging system has been the need of an active stabilization of the lasers difference frequency to enable phase sensitive lock-in detection. Therefore, we setup a fast laser-current control loop, which not only provides frequency stabilization but even stable phase-locking to the terahertz frequency. The system has been employed for coherent terahertz imaging. It represents an alternative for heterodyne imaging using ultrashort pulsed lasers for electro-optic detection, as we have done in earlier studies. There we have seen that the performance of multi-pixel electro-optic imaging is limited by the laser shot noise. In order to enhance the number of pixels which can be measured simultaneously, one needs more laser power. In the case of the CW diode lasers one can take advantage of tapered laser amplifiers which permit to achieve power levels of several hundred mW while maintaining fundamental-mode operation[5]. Furthermore, the system can be adapted to other terahertz frequencies, mainly limited by the difference frequency tunability of the two-color laser radiation and the detection capabilites of the electro-optic crystal. Beyond that, the stabilization scheme itself is highly attractive for narrow-band spectroscopy applications.

IV. Acknowledgements

This work is funded by the LYNKEUS Project of the Federal Ministry of Education and Research Germany (BMBF).

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