Hybrid Continuous-Wave Demodulating Multipixel Terahertz Imaging Systems

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***Abstract*—We present an electrooptic (EO) terahertz imaging technique providing a demodulating detector array for phase-sensitive multipixel terahertz detection. The terahertz radiation from a quartz-stabilized microelectronic emitter is mixed with the synchronized laser beat signal of a continuous-wave distributed-feedback diode laser pair. A fast laser current control loop provides stable phase locking between the terahertz emitter and the laser difference frequency, whereby a demodulating near-infrared photonic-mixer-device camera is used for depth-resolving EO terahertz imaging. Alternatively, a femtosecond laser is used for the EO read-out.**

***Index Terms*—Demodulating detector array, electrooptic (EO) terahertz detection, laser synchronization, photonic-mixer device, terahertz imaging.**

I. Introduction

RECENTLY, we demonstrated continuous-wave (CW) terahertz detection with a hybrid system using either a femtosecond laser [1]–[3] or a synchronized CW distributed-feedback diode laser pair [4] for electrooptic (EO) read-out. Hereby the incident terahertz radiation from a quartz-stabilized microelectronic emitter is electrooptically mixed [5] with a higher harmonic of the femtosecond laser's pulse repetition rate or the laser beat signal of the diode laser pair, respectively. By suitable system settings, the mixing generates an IF signal in the megahertz range. Both systems consists of a reference and a measurement branch, enabling phase-sensitive lock-in detection. A 2-D topographic image can be retrieved by raster-scanning of an object within the focal plane of the terahertz beam, as shown in Fig. 1, whereby the data acquisition took around 15 min, due to the stepwise pixel-by-pixel detection. The 3-D image was obtained by applying a phase-unwrap algorithm on the measured phase information.

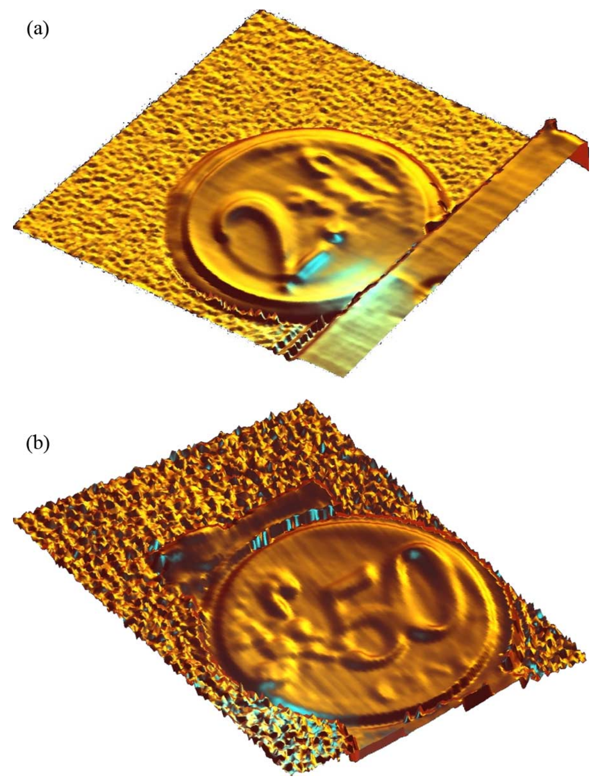

Fig. 1. Topographic raster-scan image of a: (a) 2-Euro coin using a femtosecond laser for EO read-out and (b) 50-Euro cent coin using synchronized two-color laser radiation for read-out.

While both systems perform phase-sensitive terahertz measurements with a high signal-to-noise ratio (SNR), the CW diode lasers are more cost effective, highly compact, and less maintenance intensive compared to most femtosecond lasers with the possible exception of fiber lasers. However, in order to achieve image frame rates close to real time, in both cases, the number of pixels measured simultaneously has to be increased. This can be achieved by parallel EO detection [6]–[9], which, in the case of CW radiation and unamplified femtosecond lasers, requires long integration times due to the small terahertz-induced birefringence [9], [10]. A lock-in functionality featured by each pixel has the potential to resolve this insufficiency while maintaining the capability of phase-sensitive measurements. A device with integrated basic lock-in data processing per pixel is the demodulating detector array, introduced for terahertz detection by Spickermann *et al.* in [11].

Manuscript received October 30, 2009; revised February 04, 2010; accepted March 10, 2010. Date of publication June 14, 2010; date of current version July 14, 2010. This work was supported by the Federal Ministry of Education and Research Germany (BMBF) under the LYNKEUS Project and by the German Research Foundation (DFG).

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Digital Object Identifier 10.1109/TMTT.2010.2050390

In this study, we apply the same demodulating detector array as in [11] to the coherent hybrid terahertz imaging system of [1]–[4] to extend this system from single-pixel to multipixel operation. Such devices have originally been developed for 3-D imaging with near-infrared radiation in applications such as obstacle identification, distance measurements, and object recognition [12]. In our setup, we use a PMDtec PMD[vision] 3 k-S camera comprising a PhotonICs PMD 3 k-S sensor with a resolution of 64×48 pixels and 0.1-mm pixel pitch.[1] Each pixel comprises two transparent modulation electrodes between two read-out channels. By modulating the applied voltage, the pixel acts like a charge swing, controlling the charge carrier transport to the two output nodes. While incident light with a modulation according to the pixel's modulation frequency generates a voltage difference between both read-out channels, unmodulated light creates equal read-out voltages on both nodes. This leads to very efficient suppression of background radiation. The suppression is further enhanced electronically because every pixel contains an integrated circuit designed to cancel out the background signals. The circuit drains the integration capacitors of the output nodes from charge carriers accumulated because of the background radiation, and thus prevents saturation over an extended range of illumination intensities, whereas the dynamic range for the measurement of modulated light can be preserved [13]. In the conventional applications of the PMD camera, the correlation between the modulated laser radiation and modulated voltage on the electrodes encodes the time-of-flight information. In our case, though, we employ the PMD camera in combination with an EO crystal and exploit that the camera pixels are equipped with independent inherent lock-in capabilities for phase-sensitive EO multipixel terahertz imaging.

II. Experimental Approach

Here, we report PMD camera integration into the hybrid terahertz imaging system. Our system setup employs a CW quartz-stabilized microelectronic terahertz emitter from Radiometer Physics GmbH[2] providing the same amount of terahertz radiation for both a reference and an imaging branch. Each branch contains a fiber-coupled EO read-out unit, which is driven by the fiber-combined radiation of two tunable distributed-feedback diode lasers (Fig. 2). The diode lasers provide a power of 100 mW each and operate at a center wavelength of 852 and 855 nm, respectively. A 2×2 fiber array is used to combine the laser radiation of the diodes, which provides 50 mW of power at each fiber output. Besides a $\langle 110 \rangle$-oriented ZnTe EO crystal, both read-out units contain a dichroic indium–tin–oxide reflector [14] to couple the incident terahertz radiation onto the free-space optical beam path of the two-color laser radiation. The reference branch is required to provide a stable phase correlation between the difference frequency of the diode laser pair and the frequency of the terahertz source.

Within the reference branch, the incident terahertz radiation, as well as the optical beam, are focused into the EO crystal. While the laser diode pair provides a mode-hop-free tunability

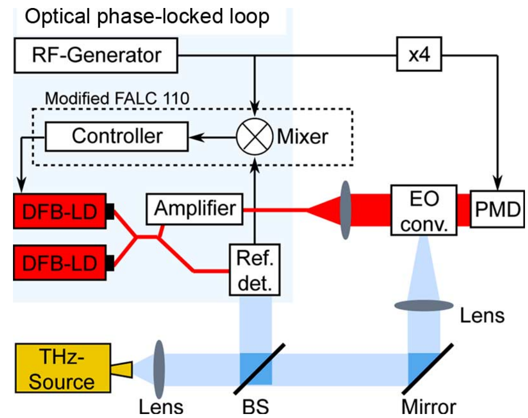

Fig. 2. Hybrid system setup with synchronized CW diode lasers and PMD camera.

of the difference frequency from zero up to nearly 2 THz, the employed terahertz emitter operates at a fixed frequency of 0.62 THz. The lasers' difference frequency is detuned by several tens of megahertz relative to the terahertz frequency. This detuning frequency results in an IF signal by EO sampling of the incident terahertz radiation. The IF signal is detected by a photodiode pair providing balanced detection. The IF signal has to be stabilized. For this purpose, it is fed into a modified version of TOPTICA's FALC 110 linewidth controller,[3] which receives its reference frequency from an RF generator operating at 10 MHz. The controller adjusts the electrical current of one of the lasers, whereas the other one remains free running. Hereby we achieve a phase lock between the reference EO signal and the signal of the RF generator, enabling phase-sensitive measurements. The frequency control loop is described in detail in [4].

The performance of multipixel EO detection is fundamentally limited by the laser shot noise. In order to increase the SNR, we use a fiber-coupled tapered amplifier (up to 300-mW output power) for the two-color laser radiation of the imaging branch to provide a reasonable dynamic range for parallel read-out. The out-coupled beam is expanded and illuminates the large-area ZnTe crystal, before being imaged onto the PMD camera's demodulating detector array. The camera is fed with the fourth harmonic of the signal from the RF generator for the internal generation of four 90°-shifted reference signals, which are required for the retrieval of the phase information [11].

Alternatively, we use a femtosecond laser for EO read-out instead of the synchronized diode laser pair. Hereby the fourth harmonic of the IF signal detected in the reference branch is fed into the camera, while the inherent stability of the pulsed system eliminates the need of an active synchronization scheme [1].

III. First Results

We recorded a terahertz focal spot on the EO crystal, in the read-out unit of the imaging branch. Fig. 3 shows the amplitude and the phase image of the terahertz focal spot using either the femtosecond laser [see Fig. 3(a)] or the diode laser pair [see Fig. 3(b)]. The provided laser power was roughly 200 mW

[1]PMDtec, Siegen, Germany. [Online]. Available: http://www.pmdtec.com

[2]Radiometer Phys. GmbH , Meckenheim, Germany. [Online]. Available: http://www.radiometer-physics.de

[3]TOPTICA Photon. AG, Munich, Germany. [Online]. Available: http://www.toptica.com

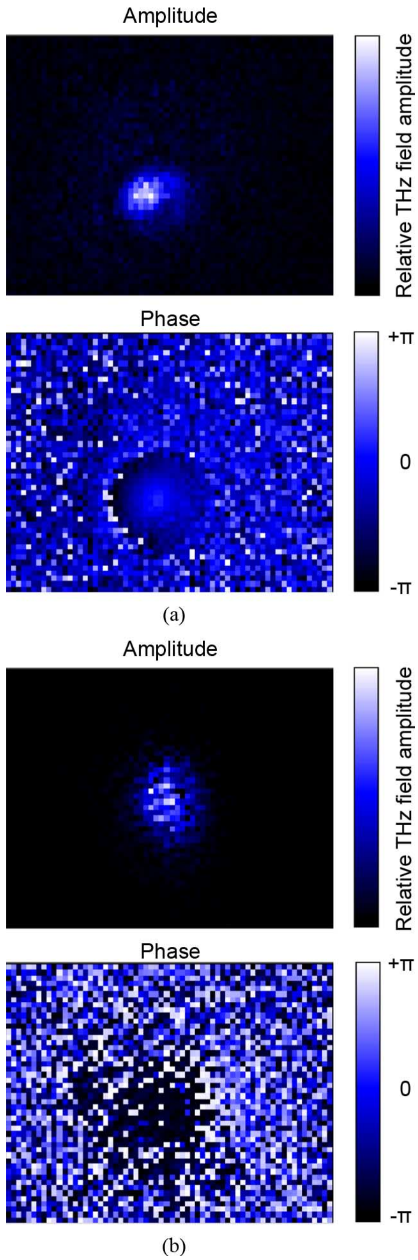

Fig. 3. Measurements of a terahertz focal spot using a: (a) femtosecond laser with a magnification factor of one and (b) a synchronized laser diode pair with a magnification factor of two for EO read-out. The detector array has a size of 6.4 mm × 4.8 mm.

in both cases. The image taken by the pulsed laser setup was effectively recorded within 2.5 s and shows a dynamic range of 24 $\mathrm{dB}/\sqrt{\mathrm{Hz}}$ of the measured signal. The terahertz source was operating at 1.1 mW. The total integration time using the two-color laser system was 5.5 s, but at a power level of the terahertz emitter of 0.5 mW. The dynamic range amounted to 12 $\mathrm{dB}/\sqrt{\mathrm{Hz}}$. The value is considerably lower than that of the setup with the femtosecond laser system. This is explained in part by the reduced terahertz power. In addition, the terahertz focus was imaged with a magnification factor of two onto the PMD sensor, whereas in the case of the pulsed laser, the magnification factor was one. Finally, mixing of CW terahertz radiation with a CW laser beat signal leads to a 6-dB lower EO signal than mixing with femtosecond laser pulses. The measurements were taken close to the camera's saturation limit to achieve the best possible SNR.

However, the measurements suffer from slight inhomogeneities of the pixels, obstructing the detection of the weak EO signal by a considerable background signal, which varies from pixel to pixel. This enforces dark measurements, subsequent to terahertz image recording, for spatial-noise subtraction. Thereby the measurement is repeated with the incoming terahertz signal blocked. In Fig. 3(a), the images are composed of 5000 frames (2500-THz image frames followed by 2500 dark-image frames), and in Fig. 3(b) of 11 000 frames, each recorded within an integration time of 0.5 ms. Due to the restricted size of the pixel capacitances, longer integration times were not possible. The limited speed of the camera's embedded computer for data pre-processing and IEEE-1394-Firewire communication extends the total data acquisition time of the image to several minutes.

Despite these insufficiencies, one has to take into account that the camera is a commercial device for time-of-flight measurements of directly modulated near-infrared radiation and thereby not optimized for highly demanding coherent terahertz measurements. In order to increase the SNR, one could take advantage of pixel binning. However, the application of a correction algorithm would be necessary because of the variation of the sensitivity from pixel to pixel. In our applications, we would avoid the complications that arise from the fact that the pixel sensitivity depends on the illumination intensity [15]. While this property is an important issue for the conventional use of the camera due to strongly varying light conditions encountered in many situations, we profit from the nearly constant read-out illumination. Finally, larger pixel capacitances and identical read-out channels of the detector array would increase the camera's usefulness for terahertz applications.

Compared to imaging with photoconductively generated terahertz pulses—as investigated in [11]—the dynamic range achieved by us with CW radiation and heterodyne EO detection is considerably smaller due to the lower terahertz field amplitude. However, in order to improve the sensitivity of EO detection, one could change to organic nonlinear crystals with a higher nonlinearity such as DAST [16] or related materials such as OH1 [17]. This measure would probably necessitate a change of the laser sources in order to operate at the wavelengths optimal for the nonlinear mixing process.

IV. Conclusions and Outlook

In conclusion, the presented system has the capability to record terahertz images with 3072 pixels including phase information within seconds. The hybrid system concept provides high compactness and enables coherent terahertz measurements, while the demodulating detector array of the PMD camera offers inherent lock-in capabilities for parallel EO detection. Furthermore, the system can be easily adapted to other terahertz frequencies, due to the EO read-out. The system is ready for multipixel terahertz detection, but at present falls short of achieving image frame rates close to real time. In order to enhance the dynamic range and lower the effective recording time of the image, a digital correction of the pixel inhomogeneities for proper pixel binning should be applied. Faster data

communications and large camera-integrated read-out buffers would allow to omit extensive data post-processing on external hardware and thereby reduce the total image acquisition time drastically.

At present, the camera's demodulating detector array is not optimized for the needs of terahertz measurements. We expect this technique to offer phase-sensitive real-time terahertz imaging under the premise that the pixel sensitivity becomes shot-noise limited by operation close to saturation.

Acknowledgment

The authors are grateful for the support of G. Schuricht, TOPTICA Photonics AG, Munich, Germany, T. Löffler, Synview GmbH, Bad Homburg, Germany, and Radiometer Physics GmbH, Meckenheim, Germany.

References

[1] T. Löffler, T. May, C. am Weg, A. Alcin, B. Hils, and H. G. Roskos, "Continuous-wave terahertz imaging with a hybrid system," *Appl. Phys. Lett.*, vol. 90, Mar. 2007, Art. ID 091111.

[2] T. May, C. am Weg, A. Alcin, B. Hils, T. Löffler, and H. G. Roskos, "Towards an active real-time THz camera: First realization of a hybrid system," *Proc. SPIE*, vol. 6549, May 2007, Art. ID 654907.

[3] B. Hils, M. D. Thomson, T. Löffler, W. von Spiegel, C. am Weg, H. G. Roskos, P. de Maagt, D. Doyle, and R. D. Geckeler, "Terahertz profilometry at 600 GHz with 0.5 μm depth resolution," *Opt. Exp.*, vol. 16, pp. 11289–11293, Jul. 2008.

[4] F. Friederich, A. Deninger, G. Schuricht, A. Roggenbuck, F. Lison, G. Spickermann, P. H. Bolìvar, and H. G. Roskos, "Phase-locking of the beat signal of two distributed-feedback lasers to oscillators working in the MHz to THz range," *Opt. Exp.*, accepted for publication.

[5] Q. Wu and X.-C. Zhang, "Free-space electro-optic sampling of terahertz beams," *Appl. Phys. Lett.*, vol. 67, pp. 3523–3525, Dec. 1995.

[6] F. Z. Meng, M. D. Thomson, V. Blank, W. von Spiegel, T. Löffler, and H. G. Roskos, "Characterizing large-area electro-optic crystals toward two-dimensional real-time terahertz imaging," *Appl. Opt.*, vol. 48, pp. 5197–5204, Sep. 2009.

[7] Q. Wu, T. D. Hewitt, and X.-C. Zhang, "Two-dimensional electro-optic imaging of THz beams," *Appl. Phys. Lett.*, vol. 69, pp. 1026–1028, Aug. 1996.

[8] T. Yasuda, T. Yasui, T. Araki, and E. Abraham, "Real-time two-dimensional terahertz tomography of moving objects," *Opt. Commun.*, vol. 267, pp. 128–136, Nov. 2006.

[9] A. Nahata, J. T. Yardley, and T. F. Heinz, "Two-dimensional imaging of continuous-wave terahertz radiation using electro-optic detection," *Appl. Phys. Lett.*, vol. 81, pp. 963–965, Aug. 2002.

[10] D. Crawley, S. Withington, and J. Obradovic, "Area-scan camera for terahertz holography," *Rev. Sci. Instrum.*, vol. 77, May 2006, Art. ID 053106.

[11] G. Spickermann, F. Friederich, H. G. Roskos, and P. H. Bolívar, "A high signal-to-noise ratio electrooptical THz imaging system based on an optical demodulating detector array," *Opt. Lett.*, vol. 34, pp. 3424–3426, Nov. 2009.

[12] T. Ringbeck, "A 3D time of flight camera for object detection," in *8th Opt. 3-D Meas. Technol. Conf.*, Zurich, Switzerland, Jul. 2007. [Online]. Available: http://www.pmdtec.com/fileadmin/pmdtec/downloads/publications/200705_PMD_ETHZuerich.pdf, [accessed: Jun. 7, 2010]

[13] T. Ringbeck, T. Möller, and B. Hagebeuker, "Multidimensional measurement by using 3-D PMD sensors," *Adv. Radio Sci.*, vol. 5, pp. 135–146, 2007.

[14] T. Bauer, J. S. Kolb, T. Löffler, E. Mohler, H. G. Roskos, and U. C. Pernisz, "Indium–tin–oxide-coated glass as dichroic mirror for far-infrared electromagnetic radiation," *J. Appl. Phys.*, vol. 92, pp. 2210–2212, Aug. 2002.

[15] S. May, S. Fuchs, D. Droeschel, D. Holz, and A. Nuechter, "Robust 3D-mapping with time-of-flight cameras," in *IEEE/RSJ Int. Intell. Robots Syst. Conf.*, St. Louis, MO, Oct. 2009, pp. 1673–1678.

[16] M. Jazbinsek, L. Mutter, and P. Günter, "Photonic applications with the organic nonlinear optical crystal DAST," *IEEE J. Sel. Top. Quantum Electron.*, vol. 14, pp. 1298–1311, Sep. 2008.

[17] F. D. J. Brunner, O. P. Kwon, S. J. Kwon, M. Jazbinsek, A. Schneider, and P. Günter, "A hydrogen-bonded organic nonlinear optical crystal for high-efficiency terahertz generation and detection," *Opt. Exp.*, vol. 16, pp. 16496–16508, Oct. 2008.

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