Available online at www.sciencedirect.com
ScienceDirect
Optics Communications 281 (2008) 1473–1475
OPTICS COMMUNICATIONS
www.elsevier.com/locate/optcom

Real-time nondestructive imaging with THz waves

LiangLiang Zhang [a,c,*], Nick Karpowicz [b], CunLin Zhang [c], YueJin Zhao [a], XiCheng Zhang [b]

[a] Department of Optical Engineering, Beijing Institute of Technology, No. 5 ZhongGuanCun NanDaJie, Beijing 100081, China
[b] Center for Terahertz Research, Rensselaer Polytechnic Institute, 110 8th Street, Troy, NY 12180, USA
[c] Beijing Key Laboratory for Terahertz Spectroscopy and Imaging, Capital Normal University, No. 105 XiSanHuan BeiLu, Beijing 100037, China

Received 17 September 2007; received in revised form 6 November 2007; accepted 14 November 2007

Abstract

We present a real-time imaging measurement in the terahertz (THz) frequency region. The dynamic subtraction technique is used to reduce long-term optical background drift. The reflective images of two targets, a Nikon camera's lens cap and a plastic toy gun, are obtained. For the lens cap, the image data were processed to be false-color images. For the toy gun, we show that even under an optically opaque canvas bag, a clear terahertz image is obtained. It is shown that terahertz real-time imaging can be used to nondestructively detect concealed objects.

PACS: 42.30.Sy; 42.30.Va

Keywords: Real-time imaging; Dynamic subtraction; False color images

Conventional THz imaging was realized by raster scanning of the object; only one point was measured at one time [1,2]. This scanning involves mechanical movement of the source or sample and therefore is very time consuming. The acquisition time of an image is typically on the order of minutes to hours, depending on the size of the target, the total number of the pixels, and required frequency resolution [3,4]. In this letter, we present an optoelectronic terahertz imaging system with a real-time approach. We are able to measure the two-dimensional electric-field distribution of terahertz radiation without target movement. In principle, the acquisition speed is limited only by the frame rate of the camera [5,6]. Comparing with the terahertz continuous wave imaging which is an amplitude imaging technique [7], the real-time imaging method can provide large bandwidth information. However, because the lock-in amplifier cannot be used with the CCD camera to suppress noise dramatically, the dynamic subtraction technique is used to reduce long-term optical background drift [8].

The experimental diagram of the THz real-time reflective imaging system is illustrated in Fig. 1. In this system, we use optical rectification to generate THz pulses and electro-optic sampling for detection. The laser being used is a Spectra Physics Hurricane with 1 kHz repetition rate, 75 fs pulse duration, 650 mW average output power, and 795 nm center wavelength. The expanded THz beam has a diameter of about 25 mm, and is generated with a 2.5 mm thick ZnTe crystal. The incident angle of the THz beam on the sample's surface is 15°. A polyethylene lens with 150 mm focal length is used to image the sample target onto a large size ZnTe sensor crystal ($40 \times 40 \times 2\ mm^3$). The THz beam is collected by the lens in a 2F–2F geometry. The probe beam has an expanded diameter of 25 mm and co-propagates with the THz beam through the sensor crystal. A Princeton Instruments CCD camera is used to capture the image, with an exposure time of 32 ms. The signal to noise ration of the system is larger than 200 and the spatial resolution of the image is 2 mm.

* Corresponding author. Address: Beijing Key Laboratory for Terahertz Spectroscopy and Imaging, Capital Normal University, No. 105 XiSanHuan BeiLu, Beijing 100037, China. Tel./fax: +86 10 68902178.
E-mail address: zhlliang@126.com (L. Zhang).

0030-4018/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.optcom.2007.11.063

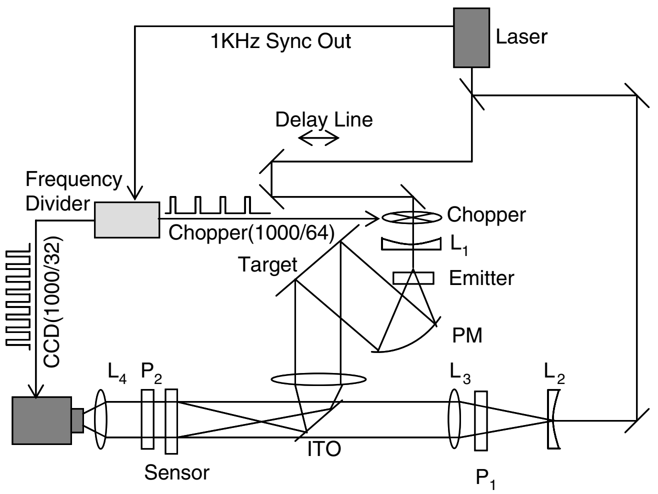

Fig. 1. Experimental setup for the terahertz real-time imaging with dynamic subtraction.

The dynamic subtraction technique is used in this system to reduce long-term optical background drift. The synchronization frequency is from the femtosecond laser and equal to the 1 kHz repetition rate of the laser pulse. It is divided by 32 and 64 by a frequency divider. The two output frequencies are used to trigger optical chopper and CCD camera, respectively. When the CCD camera captures two consecutive frames, one of them is with the THz beam blocked by the chopper and the other one is with the terahertz signal. Suppose that the odd-number frame that the CCD captures contain signal with the background, but the even-number frames contain the background only; then the signal can be extracted dynamically from the equation below:

$$S = \frac{\sum_{n=1}^{N} I_{2n-1} - I_{2n}}{\sum_{n=1}^{N} I_{2n}}$$

since the signal and the background frames are captured alternatively in the millisecond time scale, the long-term background drift is greatly reduced.

Another component of the noise is caused by the short-term drift of the laser, which is not removed by the dynamic subtraction technique. This arises from the pulse-to-pulse variation in probe beam power, which can induce a difference between signal and reference frames independently of the presence of the THz field. However, since this affects the entire power of the probe beam in a uniform manner, it leads to an homogenous offset of the entire frame. Therefore, by subtracting the mean value of the pixels at the edge of the frame (where no THz detection takes place) from the rest of the image, this can be effectively removed as well.

We obtained reflective images of different targets including a part of a Nikon lens cap and a plastic toy gun. For the lens cap, only the area in the red square is detected and the image data were processed to be false color images for comparison with the terahertz image visible in real-time. The optical and terahertz images are shown in Fig. 2. The real-time image shows the electric field distribution on the sensor crystal at a fixed time delay, whereas the color image was produced by scanning the time delay and performing a Fourier transform to each pixel.

There are three response functions for the false color image, one function for each color. Here we define the three colors as red, green and blue. We also separated the terahertz images corresponding to different spectral regions. The three images illustrated in Fig. 3 are the

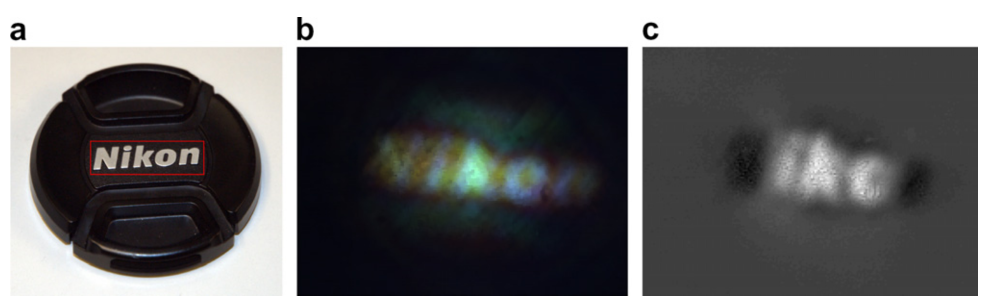

Fig. 2. Images of a lens cap: (a) Optical image; (b) False-color THz image; (c) real-time THz image.

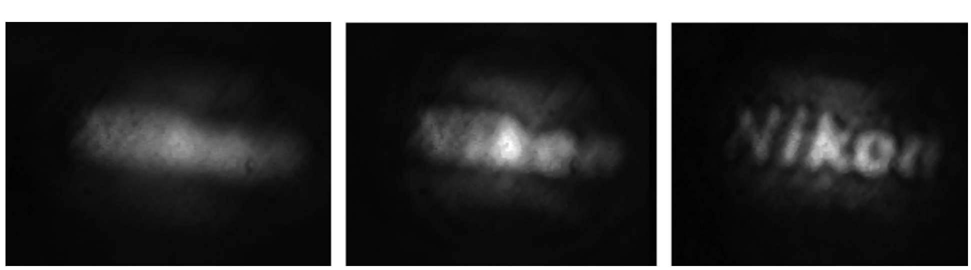

Fig. 3. Terahertz images corresponding to separated color. The images from left to right are within the red, green and blue frequency region.

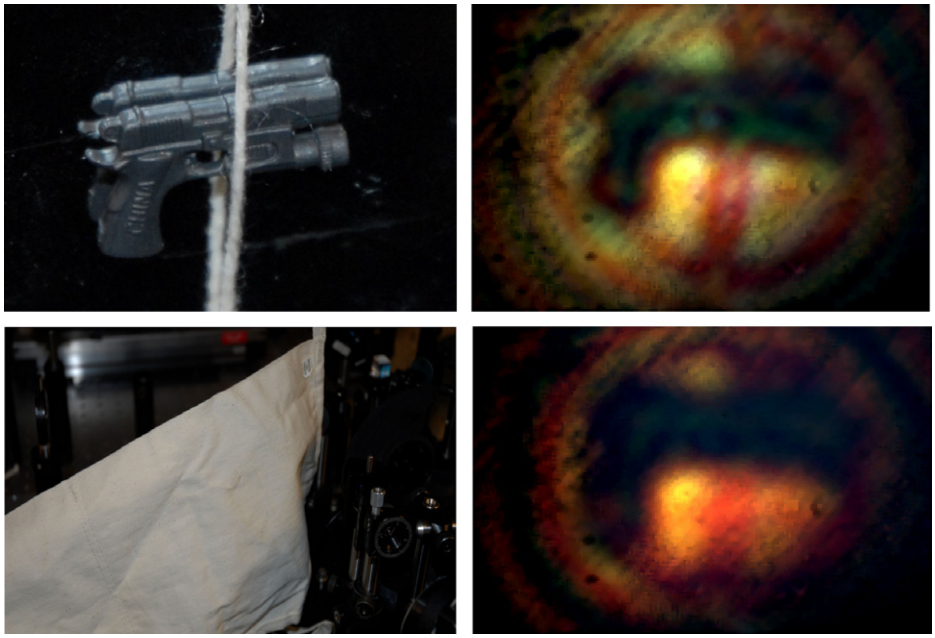

Fig. 4. The top are terahertz real-time images of the toy gun. The bottom is the images of the toy gun that is covered by a canvas bag. The images on the left side are optical image and the images on the right side are THz image.

images in the red, green and blue frequency region, respectively. At each frame of the frequency domain image, we multiply by each color's response function and add the result to that color's frame. This method can effectively eliminate the phase mismatching pattern caused by the spherical THz wavefronts overlapping with the collimated probe beam. From Fig. 3, it is clear that the third image, which contains the highest frequency region, is the most legible, in accordance with the Rayleigh criterion.

Next, we display the ability of this imaging method to detect concealed targets. A plastic toy gun is hidden under cloth materials which is made of fabric and with 1 mm thickness. The thread that crosses the gun is used to fix it within the focal plane. Both the optical and terahertz images are show in the top section of Fig. 4. We can clearly see the profile of the gun even the hole at the center of it and the effect of the thread. Then we covered the toy gun with a canvas bag which is opaque to visible light but transparent in the THz frequency region. The profile of the target can be easily seen in Fig. 4, despite a shift to lower frequencies due to scattering in the material [9]. That means a very promising and valuable application of terahertz real-time imaging is the noninvasive detection of concealed objects.

In conclusion, we demonstrated that dynamic subtraction technique in a real-time imaging system is a very effective method to reduce long-term optical background drift, and that dark region subtraction is effective at eliminating short-term drift. Combining the two techniques allows for a significant improvement of the signal-to-noise ratio, allowing the acquisition of good quality terahertz images of the lens cap and the toy gun, with and without a cloth cover. We believe that terahertz real-time imaging will be a valuable tool in the nondestructive detection field.

Acknowledgement

This work has been supported by the Natural Science Foundation of China under Grant Nos.10390160 and 10474067, National Keystone Basic Research Program (973 Program) under Grant Nos. 2007CB310408 and 2006CB302901. It is also supported by State Key Laboratory of Functional Materials for Informatics, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences.

References

[1] B.B. Hu, M.C. Nuss, Opt. Lett. 20 (1995) 807.
[2] W.L. Chan, J. Deibel, D.M. Mittleman, Rep. Prog. Phys. 70 (2007) 1325.
[3] M.C. Nuss, Circ. Dev. 12 (1996) 25.
[4] Q. Wu, T.D. Hewitt, X.-C. Zhang, Appl. Phys. Lett. 69 (1996) 1026.
[5] L. Zhang, Y. Zhang, C. Zhang, Y. Zhao, X. Liu, Opt. Lett. 31 (2006) 3668.
[6] Z.G. Lu, X.-C. Zhang, SPIE 3491 (1998) 334.
[7] N. Karpowicz, H. Zhong, C. Zhang, K.-I. Lin, J.-S. Hwang, J. Xu, X.-C. Zhang, Appl. Phys. Lett. 86 (2005) 054105.
[8] Zhiping Jiang, X.G. Xu, X.-C. Zhang, Appl. Opt. 39 (2000) 2982.
[9] A. Ishimaru, Wave Propagation and Scattering in Random Media, Academic, New York, 1978.