Control of terahertz emission in photoconductive antennas through an additional optical continuous wave

A. Bockelt,* J. Palací, and B. Vidal

Nanophotonics Technology Center, Universidad Politécnica de Valencia, Camino de Vera s/n 46022 Valencia, Spain
**Corresponding author: abockelt@ntc.upv.es*

Received May 23, 2013; revised July 18, 2013; accepted July 19, 2013;
posted July 22, 2013 (Doc. ID 191124); published August 13, 2013

The manipulation of the operating conditions of photoconductive antennas by means of an additional continuous wave (CW) is reported. It is used to control a fiber-based terahertz (THz) time-domain-spectroscopy system at telecom wavelengths. The injection of an optical CW into the transmitter allows the control of the THz amplitude without causing major degradation to the system performance. This, for instance, can be exploited to perform modulation of the THz signal.

OCIS codes: (040.2235) Far infrared or terahertz; (160.5140) Photoconductive materials; (300.0300) Spectroscopy.
http://dx.doi.org/10.1364/OL.38.003123

Terahertz (THz) technology has remarkably advanced in recent years, and nowadays it is a powerful tool in many scientific fields, such as biomedical sensing and imaging, nondestructive material testing, and security applications as well as telecommunications and spectroscopy [1–3]. Whereas in the early childhood of THz technology the equipment for THz spectroscopy was expensive, cumbersome, and hardly commercially available, in the last decade, simpler systems have emerged on the market, thanks to photonic schemes of THz generation and detection. Because of various limitations, i.e., mainly the complexity of reaching high frequencies with pure electronic solutions and the necessity of cryogenic cooling for the operation of, e.g., quantum cascade lasers, most widely disseminated implementations for broadband THz-generation are photoconductive antennas (PCA) operating as ultrafast switches [4] and nonlinear optic crystals performing frequency-conversion by optical rectification [5]. Components for both approaches have been recently redesigned to use optical wavelengths typically employed in the telecommunication industry. Thus the cost and complexity of optical sources are reduced as well as fiber-based implementations being allowed [6,7]. Typically, THz sensing systems can be divided in THz time-domain spectroscopy (THz-TDS) where sub-picosecond pulses are used to generate broadband THz radiation and frequency domain spectroscopy (FDS), where a pair of continuous-wave (CW) optical signals are tuned to generate a beat in the THz region. In this report, the effect of a single CW optical signal on a fiber-based pulsed THz-TDS system based on PCA is studied. It is also examined if this CW can be used for amplitude modulation necessary for lock-in detection.

Photoconductive switches for THz generation are built up by a semiconductor material and a pair of metallic electrodes on their surface. Illumination of the gap between these electrodes by ultrashort optical pulses of appropriate energy liberates charge carriers formerly bound in the bulk material, which build up a photocurrent when facing an accelerating bias field. This transient current is the source of the radiated THz field. The magnitude of the radiated field is proportional to the variation of the transient current [8]. This current is proportional to the amount of available free charge carriers, which in turn has a nonlinear dependency on the optical power. Regarding the response function of the transmitter module, the antenna shows a saturation behavior, i.e., equal increments of optical power lead to smaller changes in free carrier population at high optical powers compared with low powers. If a CW of sufficient energy is applied to the antenna, a constant population level of free charge carriers would be created, since typical carrier lifetimes in semiconductors largely exceed the duration of optical cycles. Bearing in mind the nonlinear response with its saturation tendency, the presence of a CW yields a smaller total variation of the free carrier population. As a consequence, resulting photocurrents and THz amplitudes are expected to be lower. The principle of optical control by such a CW carrier is illustrated in Fig. 1. The experimental setup shown in Fig. 2 has been used to investigate the combination of a CW signal and the conventional THz-TDS system.

A mode-locked 1550 nm femtosecond laser was used as optical pulsed source to feed a pair of PCA based on an InGaAs/InAlAs hetero-structure via an optical fiber patchwork. The laser operates at a repetition rate of 100 MHz, and the output pulse is specified to be shorter than 45 fs. The power at the input of the transmitter and receiver antennas is about 10 mW. Initially the bias voltage applied to the transmitter PCA was kept constant at 12 V. Time traces of the generated THz transients were

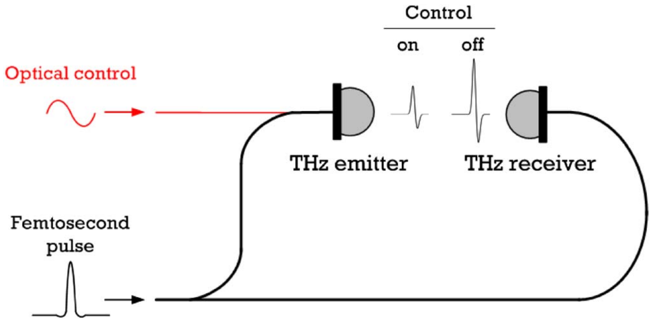

Fig. 1. Principle of optically controlling the THz radiation.

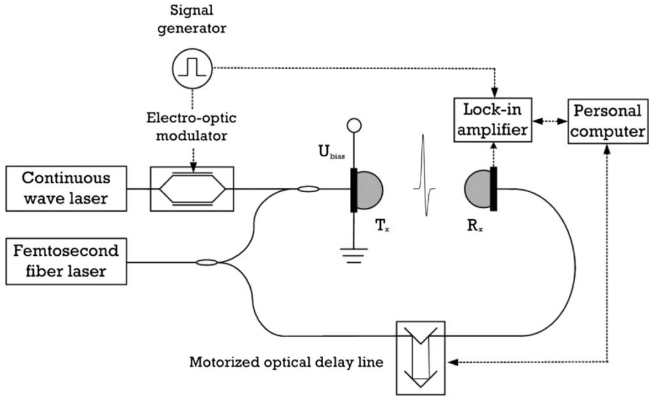

Fig. 2. Architecture of a THz-TDS setup with optical control by a CW carrier. For reference measurements with antenna bias modulation, the generator signal is applied to the transmitter PCA, and the CW source is switched off.

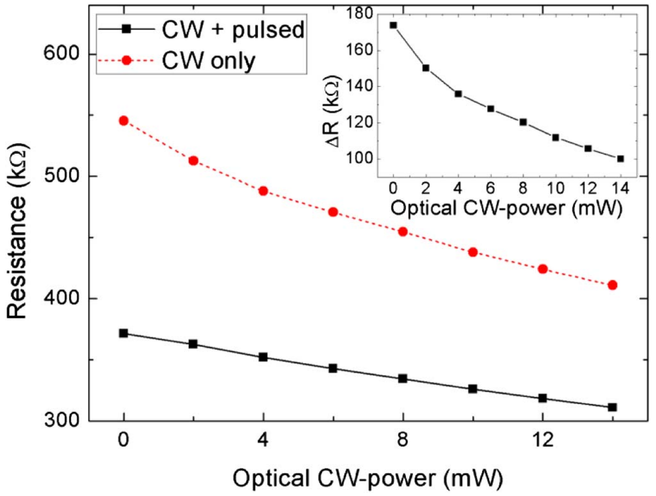

Fig. 4. Resistance of the receiver photoconductive switch versus incident CW power with and without applying the pulsed source, Inset: Resistance difference between both cases.

captured delaying the pulses that reach the receiver module's switch by using a computer-controlled motorized optical delay line. In the transmitter path, a second fiber coupler was introduced to add CW light.

Figure 3 shows the dependence of the detected THz signal on the power of the optical CW. A decrease in the THz signal can be appreciated. This result contrasts with [9], where Ryu and Kong observed an increase in the detected THz amplitude proportional to the CW power at 780 nm using a free-space setup. The reduction of the THz amplitude we observe is attributed to the constant population level of free charge carriers generated by the CW signal that reduces the carrier population variation when optical pulses arrive at the photoconductive switch. This is reflected in the average resistances that were measured for the transmitter PCA at different optical CW powers. These are shown in Fig. 4. The red dashed line represents the resistance if only the CW is applied, and the black solid line the resistance when the pulsed laser is added. It decreases in both cases and is assumed to be inversely proportional to the amount of free charge carriers. The difference between both graphs is directly proportional to the difference of the corresponding free carrier population, which is a measure for the THz amplitude. With increasing optical CW power, this difference becomes smaller, and the efficiency in terms of THz power is diminished. The wavelength of the CW was changed, and no dependence with wavelength was found as long as the photon energy remains large enough to generate carriers in the material.

The optical control of the signal's amplitude can be used for modulation. THz modulation for lock-in detection can be implemented through mechanically chopping the THz beam in free-space, amplitude modulation of the optical pulses (by means of a chopper in free-space or using an external modulator in fiber-based schemes), by electronic modulation of the antenna voltage or even using free-space THz modulators [10,11]. Adding a CW to the THz-TDS system provides an alternative approach that allows high-frequency modulation since low-cost directly modulated CW lasers at 1550 nm with bandwidths up to the GHz range are commercially available. Additionally, all-optical modulation is convenient for fiber-based remote THz sensing heads.

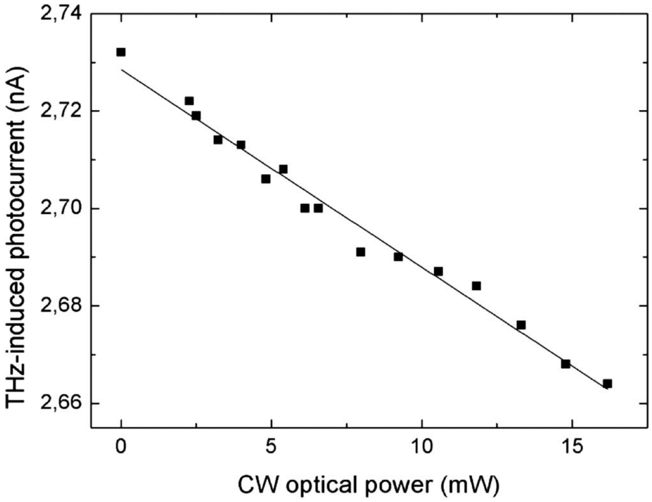

Fig. 3. Effect of a CW optical signal on the THz amplitude.

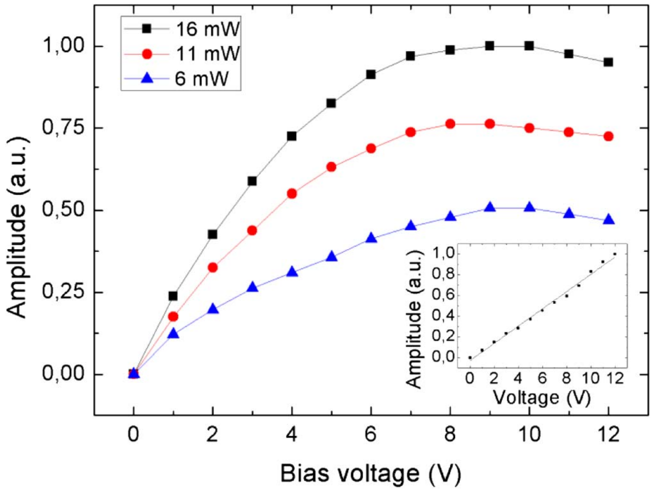

Fig. 5. Amplitude of the THz signal as a function of the bias voltage for different values of the CW optical power. Inset: Dependence of the THz signal on the bias voltage of the antenna.

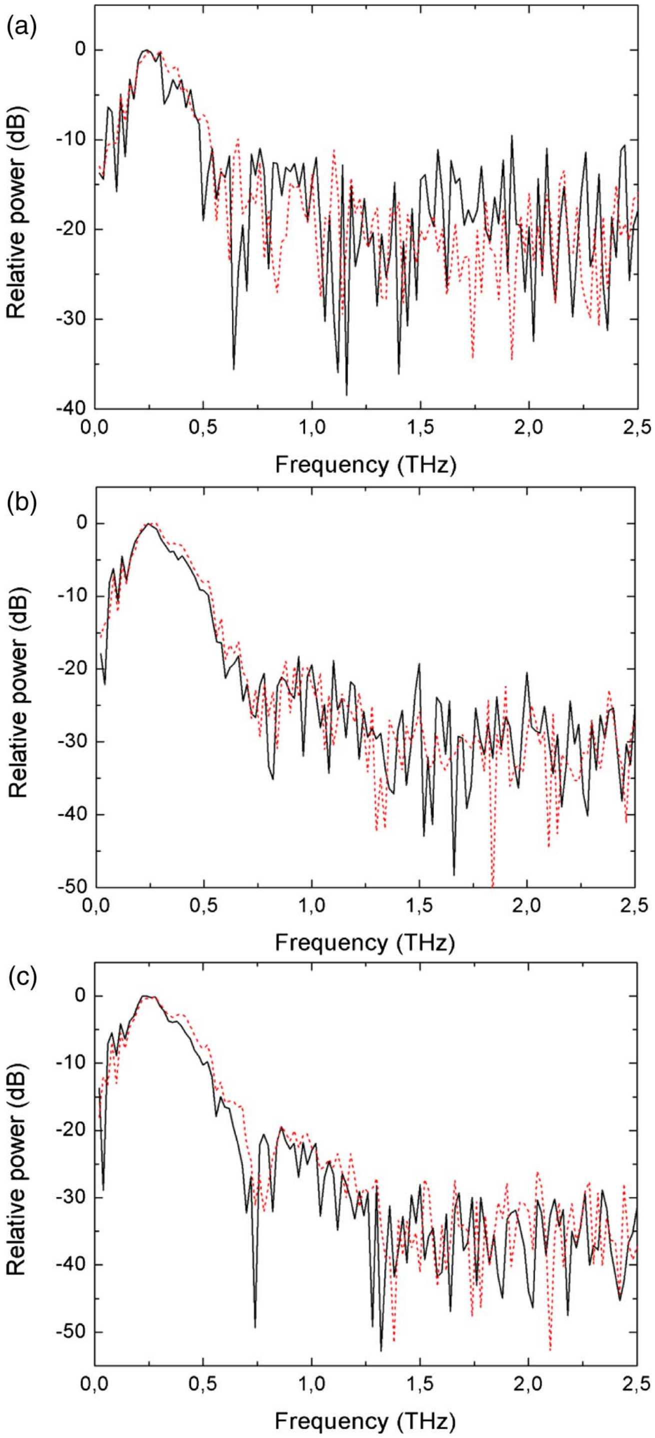

Fig. 6. Comparison between Fourier spectra captured with antenna bias modulation (black solid line) and optical modulation (red dotted line) for equal THz amplitudes at (a) 6 mW, (b) 11 mW, and (c) 16 mW CW optical power. The SNR increases from 20 to 35 dB.

The dependence of the modulation efficiency on the antenna bias was investigated. The THz amplitude was measured as a function of the bias voltage applied to the transmitter PCA for three different values of power for the modulated CW laser. As illustrated in Fig. 5, it turned out that the optical modulation method leads to saturation in the examined range up to 12 V, whereas modulation of the antenna bias shows a linear behavior (inset of Fig. 5). The optimum modulation frequency for both modulation techniques was found to be around 30 kHz and is determined by the PCAs' electrodes' bandwidths.

To assess the feasibility of optical modulation of the PCAs, the spectra obtained when using this technique have been compared with the ones from antenna bias modulation. Since a different amount of energy is modulated in the two distinct ways, spectra corresponding to time traces with equal amplitudes have to be compared. The modulation of the antenna bias was performed with a square-wave pattern superimposed with the same DC bias applied during the optical modulation measurements, not to fundamentally change the accelerating field. Figure 6 shows spectra for three different CW optical powers. No major degradation is observed between both methods. The signal-to-noise (SNR) increases as a function of the power of the modulated CW laser.

In conclusion, we show optical control of the THz power generated by PCA operating in the telecom band. The injection of an additional optical signal can be exploited to manipulate the operating conditions of the photoconductive switch in the THz emitter. A potential benefit is to gain the option of optically modulating the THz beam. This method has the advantage that several THz heads could be remotely modulated using a single additional device. Although the efficiency of such modulation is reduced, the THz spectra obtained using this technique show no degradation when compared with conventional approaches.

This work was supported by the Spanish Ministerio de Economía y Competitividad through project TEC2012-35797. The work of Alexander Bockelt is supported by the Formación de Profesorado Universitario (FPU) grant program of the Ministerio de Economía y Competitividad.

References

1. P. H. Siegel, IEEE Trans. Microw. Theory Tech. **50**, 910 (2002).
2. M. Tonouchi, Nat. Photonics **1**, 97 (2007).
3. P. U. Jepsen, D. G. Cooke, and M. Koch, Laser Photon. Rev. **5**, 124 (2011).
4. P. R. Smith, D. H. Auston, and M. C. Nuss, IEEE J. Quantum Electron. **24**, 255 (1988).
5. B. B. Hu, X.-C. Zhang, D. H. Auston, and P. R. Smith, Appl. Phys. Lett. **56** 506 (1990).
6. B. Sartorius, H. Roehle, H. Künzel, J. Böttcher, M. Schlak, D. Stanze, H. Venghaus, and M. Schell, Opt. Express **16**, 9565 (2008).
7. B. Sartorius, M. Schlak, D. Stanze, H. Roehle, H. Künzel, D. Schmidt, H.-G. Bach, R. Kunkel, and M. Schell, Opt. Express **17**, 15001 (2009).
8. Y.-S. Lee, *Principles of Terahertz Science and Technology* (Springer, 2010), pp. 62–64.
9. C. Ryu and S. G. Kong, Electr. Lett. **46**, 359 (2010).
10. J. Kyoung, M. Seo, H. Park, S. Koo, H.-S. Kim, Y. Park, B.-J. Kim, K. Ahn, N. Park, H.-T. Kim, and D.-S. Kim, Opt. Express **18**, 16452 (2010).
11. F. Fan, W.-H. Gu, S. Chen, X.-H. Wang, and S.-H. Chang, Opt. Lett. **38**, 1582 (2013).