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Electrically-Driven THz-wave Demodulation with a Photomixer : Theory and Experiment

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Abstract: Phase-sensitive demodulation of the signal from a modulated THz-wave is theoretically and experimentally demonstrated by using the detection with a low-temperature grown GaAs photomixer that is electrically-driven with an alternative voltage at the modulation frequency.

I. INTRODUCTION

The terahertz waves have been broadly exploited for fundamental and technological applications in precision spectroscopy, astrophysics and atmospheric sciences, medical imaging, high-speed wireless communications, chemical sensing, and security screening [1]. The optical frequency down-conversion with an ultrafast photodetector coupled to an antenna (photomixer) driven by the optical beat of two continuous-wave (cw) lasers enabled cw THz generation with broadband tuning [2]. Compact, room-temperature operated, cost-effective and low-power consuming THz photonic systems based on photomixers with optical frequency control provided narrow spectral linewidth, wide frequency tunability, high dynamic range and high signal-to-noise ratio. This contribution exploits the nonlinear electrical response of a low temperature grown GaAs (LTG-GaAs) photoconductor to demonstrate frequency conversion between the radiofrequency, terahertz and optical signals in a photomixer. Precisely, the heterodyne detection technique is exploited to down-convert to the microwave domain a radiofrequency-modulated THz-wave with a suitably tuned optical beat [3]. The photomixer, electrically driven with an alternative voltage oscillating at the modulation frequency of the THz-wave, provides a DC response signal indicating phase-sensitive demodulation of the THz-wave.

II. RESULTS

The photomixing technique is based on two spatially superposed coherent optical waves, detuned by an angular frequency ω and with the same optical power P , that enter at normal incidence in a LTG-GaAs photoconductor. The photomixing is theoretically investigated by assuming an uniform unidimensional carrier transport driven by an electric field applied in parallel with the surface of the photoconductor. The continuity equations allow to derive the expression of the current density inside the photoconductor :

$$j(t) = \frac{2e\eta P}{\hbar\omega Ad} \left[\begin{array}{l} \tau_n(E)v_n(E) \left(1 + \frac{\omega\tau_n(E)\sin(\omega t) + \cos(\omega t)}{1 + (\omega\tau_n(E))^2} \right) \\ + \tau_p(E)v_p(E) \left(1 + \frac{\omega\tau_p(E)\sin(\omega t) + \cos(\omega t)}{1 + (\omega\tau_p(E))^2} \right) \end{array} \right] \quad (1)$$

Two laser beams carrying photons with nearly the same energy $\hbar\omega$ are focused on a photoconductive area A , absorbed within a depth d , with a quantum efficiency η . The dependences of the carrier lifetimes $\tau_{n,p}(E)$ with the electric field [4] are linearized here, by taking into account only the carrier heating :

$$\tau_{n,p}(E) \approx \tau_{0n,0p} [1 + 3\lambda eE / (2k_B T)] \quad (2)$$

in function of the Boltzmann constant k_B , the electron charge e , the room temperature $T = 300$ K, the low-field carrier lifetimes $\tau_{0n,0p}$ and the distance λ between Coulomb barriers in the LTG-GaAs photoconductor. The carrier drift velocities have a nonlinear dependence on the electrical field [5,6], that reads :

$$v_{n,p}(E) = v_{sn,sp} / [1 + v_{sn,sp} / (\mu_{0n,0p} E)] \quad (3)$$

where $v_{sn,sp}$ are the saturation velocities and $\mu_{0n,0p}$ are the low-field mobilities for electrons and holes. The total electric field applied to the photoconductor is expressed as the sum between a radiofrequency field (amplitude $E_{RF} = V_{RF}/r$, angular frequency ω_{AC} , phase ϕ_{RF}) from an radiofrequency voltage applied to the photomixer electrodes, and a THz field (spectral components with amplitudes $E_{THz,n}$, angular frequencies $\omega_{THz} + n\omega_{RF}$, phases $\phi_{THz,n}$) induced by a THz-wave modulated at ω_{RF} that is detected with the photomixer :

$$E(t) = E_{RF} \cos(\omega_{RF} t + \phi_{RF}) + \sum_n E_{THz,n} \cos((\omega_{THz} + n\omega_{RF})t + \phi_{THz,n}) \quad (4)$$

The electric fields in the photoconductor are calculated with the parallel-plate approximation, and the photomixer electrode spacing is r . The alternative electric field induced by an incoming THz-wave on the antenna electrodes $E_{THz} = \vec{E}_{THz}^{inc} \cdot \vec{l}_{eff} / r$ depends on the incident THz-electric field \vec{E}_{THz}^{inc} and the effective vector length \vec{l}_{eff} of the antenna. The electrical nonlinearity arising from the $v_{n,p}(E)$ and $\tau_{n,p}(E)$ dependences enables frequency mixings, leading to a current density with spectral components at DC arising from rectification and demodulation of the THz-wave, at harmonics of the modulation frequency, and around the optical beat and THz-wave carrier frequencies. In the case of the demodulation of a THz-wave with three spectral components, the amplitudes of the spectral components of the current density are calculated with eq. (1-4) using power series expansions in terms of E_{RF} and $E_{THz,n}$, and displayed in Fig. 1(a).

The experiment (Fig. 1.(b)) is based on a LTG-GaAs photomixer with a log-spiral antenna driven by the optical beat of two extended cavity laser diodes (DL1 and DL2) emitting at 820 nm. The extremities of the antenna are connected to a microwave line addressed with a bias-T that allows coupling the signal from a radiofrequency synthesizer (RF) to the photomixer, to measure the demodulation signal with a lock-in detection technique (Lock-in) and the heterodyne detection signal with a microwave spectrum analyser (SA). The THz-wave is generated with a 75-110 GHz electronic frequency multiplier driven by a microwave synthesizer (MW). The synthesisers and the spectrum analyser are phase-referenced to a 10 MHz GPS-disciplined quartz. First, a multifrequency THz-wave is generated by modulating the MW synthesizer with a 15 MHz signal provided by the RF synthesizer. The THz-wave is then down-converted using the heterodyne detection scheme. The spectrum of the detected signal is shown in the inset of Fig. 1(c). A phase-delayed signal from the RF synthesizer (amplitude 1.5 V, frequency 15 MHz) is then capacitively coupled to the photomixer. The signal at DC is recovered with the lock-in detection by using 100% amplitude modulation of the RF synthesizer at 1 kHz. The Fig. 1.(c) presents the dependence of the detected signal in function of the relative phase between the THz-wave modulation signal and signal applied to the photomixer. The sinusoidal dependence indicates the demodulation of the THz-wave with the photomixer.

III. SUMMARY

The photomixing approach enables integration of the functions of the optoelectronic detection and the electrically-driven demodulation in a single photonic circuit for THz signal processing.

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Figure captions

Fig. 1. (a) Amplitudes of the spectral components of the current density in the photomixer. Optical power 2×20 mW, optical beat at $\omega = 2\pi \times 1$ THz, THz-wave at $\omega_{THz} = 2\pi \times 1.001$ THz. The THz-wave has spectral components at ω_{THz} , $\omega_{THz} + \omega_{RF}$, $\omega_{THz} + 2\omega_{RF}$ with the same amplitude $E_{THz,n} = 10^5$ V/m, and phase $\phi_{THz,n} = 0$. Radiofrequency modulation of the photomixer at $\omega_{RF} = 2\pi \times 10$ MHz, with amplitude $E_{RF} = 10^5$ V/m and phase $\phi_{RF} = 0$. Photomixer parameters used in the calculations: $r = 2 \mu\text{m}$, $d = 2 \mu\text{m}$, $A = 12.6 \mu\text{m}^2$, $\hbar\omega/e = 1.5$ V, $\eta = 0.68$. The LTG-GaAs photoconductor parameters are taken from [4-6].

(b). The experimental setup. The signal from RF is exploited to modulate the THz-wave and, upon application of an adjustable phase offset Φ , to drive the photomixer electrodes. (c). Phase-sensitive dependence of the demodulated signal. Inset : Spectrum of the heterodyne detection signal of a THz-wave at 102.072 GHz modulated at 15 MHz. Optical beat power 2×14 mW. RBW=1 MHz, sweep time 4 ms, 16 video averages.

