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Demodulation of a THz Waveform with a Photomixer

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Abstract: The response at alternative electric fields of a low-temperature-grown GaAs photomixer driven with the optical beat of two continuous-wave lasers is exploited with the optical frequency down-conversion approach for THz-wave heterodyne detection and demodulation.

1. Introduction

The terahertz-waves have a recognized potential in various fields including precision spectroscopy, remote sensing, medical imaging and high-speed wireless communications [1]. The optical frequency down-conversion with an ultrafast photodetector coupled to an antenna (photomixer) enabled to generate continuous THz-waves with broadband tuning [2]. Implementation of the optical frequency control allowed to build compact THz photonic systems with narrow spectral linewidth, wide frequency tunability, high dynamic range and high signal-to-noise ratio. The response of a low temperature grown GaAs (LTG-GaAs) photoconductor to electric fields in the radiofrequency, terahertz and optical domains enable broadband frequency conversion using the photomixing approach. The heterodyne detection with a photomixer is exploited here to down-convert a radiofrequency-modulated THz-wave to the microwave domain by using a suitably tuned optical beat [3]. The photomixer is electrically driven with an alternative voltage oscillating at the modulation frequency of the THz-wave and provides a phase-sensitive DC response signal indicating the demodulation of the THz-wave [4].

2. Results

The photomixing model assumes two coherent optical waves, detuned by an angular frequency ω , and with the same optical power P and linear polarization that are spatially superposed and enter at normal incidence in a LTG-GaAs photoconductor. The photomixing signal is derived by assuming uniform unidimensional carrier transport driven by an electric field E with a slow time dependence that is directed in parallel with the surface of the photoconductor. The quadratic response of the photoconductor to the optical fields and the continuity equations yield the current density in the photoconductor :

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

expressed in terms of the energy $\approx \hbar\omega$ of the photons of the optical beams, the electron charge e , the photoconductive area A , the absorption depth d , and the quantum efficiency η . The carrier lifetimes $\tau_{n,p}$ depend on the electric field. The carrier heating is assumed here and yields a linear dependence expressed as [5] :

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

in function of the Boltzmann constant k_B , the room temperature $T=300$ K, the low-field carrier lifetimes $\tau_{0n,0p}$ and the optical phonon mean free path λ in the LTG-GaAs photoconductor. The saturation of the carrier drift velocities may be described with nonlinear dependences in function of the electric field [6,7]:

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

where $v_{sn,sp}$ are the saturation velocities and $\mu_{0n,0p}$ are the low-field mobilities for the electrons and holes.

The electric field applied externally to the photoconductor is assumed to be the sum between a radiofrequency field (amplitude E_{RF} , angular frequency ω_{AC} , phase ϕ_{RF}), from an radiofrequency signal applied to the photomixer electrodes, and a THz electric field (spectral components with amplitudes $E_{THz,n}$, angular frequencies $\omega_{THz} + n\omega_{RF}$, phases $\phi_{THz,n}$, with n integer), induced by the detection of a THz-wave modulated at ω_{RF} :

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

The electrical nonlinearity enables frequency mixings between the optical beat frequency, the THz-wave frequency and the modulation frequency. The amplitudes of the spectral components of the current density may be calculated with eq. (1-4) using Fourier analysis of the power series expansions in terms of E_{RF} and $E_{THz,n}$. The results in the case of the heterodyne detection and the demodulation of a THz-wave with three spectral components are shown in Fig. 1.(a). The current density has 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.

The experimental setup (Fig. 1.(b)) exploits a LTG-GaAs photomixer with a log-spiral antenna that is driven by the optical beat of two extended cavity laser diodes (DL1 and DL2) emitting by 820 nm. The extremities of the antenna are connected to a microwave line addressed with a bias-T that allows, on one hand, to couple the signal from a radiofrequency synthesizer (RF) to the photomixer and to measure the demodulation signal with a lock-in detection (Lock-in), and, on the other hand, to measure the heterodyne detection signal with a microwave spectrum analyser

(SA). First, a THz-wave is generated in the 75-110 GHz range with an electronic frequency multiplier driven by a microwave synthesizer (MW). The synthesizers and the spectrum analyser are phase-referenced to a 10 MHz signal from a GPS-disciplined quartz. The modulation of the THz-wave is performed 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 and the spectrum of the detected signal is shown in the inset of Fig. 1.(c). Next, a phase-delayed signal from the RF synthesizer (amplitude 1.5 V, frequency 15 MHz) is capacitively coupled to the photomixer. The signal at DC is recovered with a 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 phase-sensitive demodulation of the signal from the THz-wave with the electrically-driven photomixer.

This work demonstrates reconfigurable photomixing and integration of the detection and demodulation functions in a single photonic circuit for THz signal processing.

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Figure captions

Fig. 1.(a) Calculated amplitudes of the spectral components of the current density in the photomixer for the heterodyne detection of a modulated THz-wave (blue bars), and the demodulation of the THz-wave (red bars). Optical power 2×20 mW and optical beat at $\omega = 2\pi \times 1$ THz. The THz-wave, modulated at $\omega_{RF} = 2\pi \times 10$ MHz, has spectral components at ω_{THz} , $\omega_{THz} + \omega_{RF}$, $\omega_{THz} + 2\omega_{RF}$ with amplitudes $E_{THz,n} = 10^5$ V/m, phases $\phi_{THz,n} = 0$ rad, and $\omega_{THz} = 2\pi \times 1.001$ THz. For demodulation, the photoconductor is driven with a radiofrequency signal at ω_{RF} with an amplitude $E_{RF} = 10^5$ V/m and phase $\phi_{RF} = 0$ rad. The photomixer parameters used in the calculations are $d = 2$ μm , $A = 12.6$ μm^2 , $\hbar\omega/e = 1.5$ V, $\eta = 0.68$ and the LTG-GaAs parameters from [5-7] (b) The experimental setup. The signal from RF modulates the THz-wave and, upon application of an adjustable phase offset Φ , is coupled to the photomixer electrodes. (c) Phase-sensitive dependence of the demodulated signal. Sinusoidal adjustment shown in magenta. Inset : Spectrum of the heterodyne detection signal of a THz-wave with carrier frequency at 102.072 GHz and modulated at 15 MHz. Optical beat power 2×14 mW. RBW=1 MHz, sweep time 4 ms, 16 video averages.

