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Optical efficiency enhancement methods for terahertz receiving photoconductive switches

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ABSTRACT

We improve the efficiency of THz receiving photoconductive switches by improving the conversion of the optical pump to signal current. This is achieved by both optimizing the incident excitation beam polarization and spatial profile of excitation. Due to boundary conditions of the electric field at the electrode edge, a nanometer-sized polarization-dependent shadow is created in the substrate at the electrode edge where most picosecond lifetime photocarriers are collected. This edge effect is further harnessed by elongating the excitation beam next to the stripline electrode. The effects of excitation beam polarization and spatial profile were experimented with InGaAs/InAlAs quantum-well-based photoconductive switch. In both cases notable enhancement in the signal is observed—30% with polarization optimization and up to 100% with beam elongation. Both techniques preserve the pulse quality and are applicable with readily available optical elements.

1. Introduction

There are various methods for detecting radiation within the terahertz (THz) frequency range [1]. Among these methods, the heterodyne time-domain-terahertz-spectrometer (TDTS) using a pair of THz photoconductive switches (PC switches) offers many advantages over other methods that have led to its popularity (Fig. 1(a)). PC switches are affordable, compact, compatible with common femtosecond pulse and continuous wave lasers, and operate both as THz transmitters and THz receivers at room temperature. Despite these advantages, low efficiency has been a concern and has limited the realization of many potential applications [2]. Increasing the efficiency of a THz PC switch in converting the optical pump to THz radiation (at the transmitter) or to low frequency signal current (at the receiver) has a significant positive effect on all THz applications, motivating substantial research into increasing the efficiency of these devices.

Efficiency can be improved in three different directions: material enhancement, antenna design optimization, and optical excitation efficiency enhancement. Material studies have been successful at the price of reduced bandwidth or excessive fabrication complexity [2–5]. Nanomaterials and quantum engineering have been applied to tune the properties of substrate materials in photoconductive switches. Due to band gap tunability, multi-quantum-well (MQW) based semiconducting substrates are increasingly used to fabricate more efficient PC switches for desired excitation wavelengths [6] (Fig. 1(b)).

Antenna designs have been improved with conventional resonant dipoles and log-periodic toothed structures as the body of the antenna. Additionally, the tip-to-tip nanogaps and interlaced structures in the gap of the antenna have been found to increase the efficiency [5,6]. The optical excitation efficiency has also been improved by antenna arrays, and integrated microlenses [7–9]. However, the optical excitation can also be enhanced externally.

In this study we explore two practical techniques that can notably improve the signal level detected in the THz receiving stripline PC switches. Both techniques preserve the detection bandwidth and are applicable with readily available optical elements. We first explain and study the causes of previously reported polarization dependence efficiency of THz PC switches [10–12]. The obtained insight is then used to enhance the excitation beam profile experimentally.

2. Subwavelength effects of polarization variations

2.1. Theory

There are numerous theories that describe THz emission in photoconductive switches. However, THz detection via PC switches is less explored [10]. THz PC switches on both sides require similar optical excitation; a gating femtosecond pulse that excites carriers. The photocarriers are then modulated through the THz pulse that impinges on the receiver structure. Carrier dynamics and photo-physics of the substrate material enter the calculations and then the performance of the device is predicted through proper circuit model for the considered antenna design

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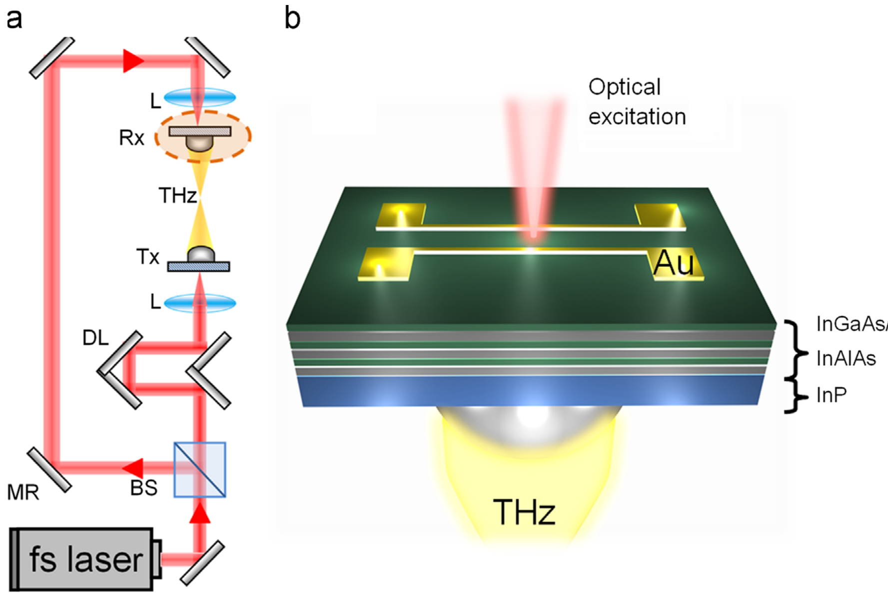

Fig. 1. (a) Schematic of a TDTS setup. In this setup, the pulsed laser beam is split into two beams; one excites the transmitter and the other excites the detector. The path of the excitation beam for THz transmitting PC switch is varied via a delay line so that the THz pulse and the optical pulse arrive in phase at the detector side. This phase is then varied finely to obtain the temporal profile of the detected THz pulse. (b) Schematic view of the optical excitation of a MQW-based stripline PC switch. The stripline (25 μm gap and 2 mm length) is fabricated on a substrate that is composed of 100 layers of InGaAs/InAlAs (20 nm each layer). These are grown on the InP wafer. A silicon lens is attached to the other side of the wafer to focus the incident THz radiation.

[2,10]. While THz radiation polarization is of interest to different applications [11] the polarization of the optical excitation pulse is less investigated [12]. The polarization of the incident optical pulse should enter at the first step of the PC switching mechanism where the photocarriers are excited via the femtosecond optical pulse. However, the effect of polarization is not directly expressed even in most rigorous Monte-Carlo carrier simulations [13]. This is because the effect of polarization is usually hidden in other parameters that are related to both substrate material and electrode design. Eq. (1) shows the relation between the incident optical pulse and the excited photocarrier density n_{abs}:

$$n_{abs} \approx \frac{\eta(\nu_0)\int_0^T p_i(t,\nu_0)dt}{h\nu_0 V}, \tag{1}$$

where ν_0 is the center frequency of the radiation, $p_i(t,\nu_0)$ is the power at the instant t and frequency ν_0, V is the part of sample volume actively engaged in the phenomena, $h\nu_0$ is the incident photon energy, and $\eta(\nu_0)$ is the quantum efficiency of the material at frequency ν_0. Eq. (1) reveals that an increase in quantum efficiency can directly compensate for a low-level incident optical power at the linear regime. The effect of polarization is implicit in the quantum efficiencyη. It is difficult to come up with an exact formulation for quantum efficiency in a PC switch, as it depends on numerous simultaneous mechanisms Eq. (2). However, there are several major factors that can be addressed.

$$\eta \approx \eta_i \eta_e \eta_t \eta_a \tag{2}$$

In Eq. (2), η_i is the internal quantum efficiency or number of electron–hole pairs generated per photon absorbed. η_e is the excitation sweep-out efficiency, that is the portion of carriers contributing to the generated photocurrent. This coefficient is a function of carrier lifetime, substrate defects, and also relative illuminated spot location on the gap. η_t is the substrate transmissivity that depends on the reflection of the beam from the substrate and electrodes. This is a function of refractive index of the substrate and the surrounding medium and also the electrode design. η_a is the absorption efficiency that depends on the wavelength, the intensity and polarization of the incident beam, and the thickness of the absorbing layer.

The excitation polarization can directly affect η_a and η_t. However, as we will see, η_e will also be indirectly affected. The coefficient η_a depends on polarization of the excitation since the absorption coefficient is polarization dependent for some substrates such as MQW structures [14]. The dependence of η_t on polarization is rather implicit. In the case of an ordinary coplanar stripline structure (Fig. 1), numerical simulations are necessary to investigate the effect of polarization on optical coupling. Fig. 2 shows the FDTD results as a 2D profile of the optical power for a pulsed plane wave (800–830 nm bandwidth) illuminating the electrode structure on an InP substrate. This figure shows the cross section of one of the electrodes where the beam is focused (Fig. 2(a), (b)). The optical power distribution is polarization dependent in the substrate as clearly shown in Fig. 2(c)–(e). We used the Lumerical FDTD solutions software; the mesh accuracy is 2 nm × 2 nm, and perfectly-matched-layer (PML) boundary conditions are used. Also, Johnson–Christy [15] and Palik permittivity values [16] are used for gold and InP material respectively. We used InP as this is the substrate material that is usually used beneath the InGaAs/InAlAs QW structures. Therefore, in this simulation we have approximated the refractive index of the MQW structure by its matching InP substrate layer.

Fig. 2(c) shows the optical power profile for TE mode, where the E-field is parallel with the x-axis and is thus perpendicular to the electrode edges. Since the tangential component of the electric field is zero on the surface of the electrode, the field is intensified at the vertical edge of the electrode and thus higher power is penetrating the substrate right next to the electrode edge. This is an important contribution – due to short carrier lifetime in PC switches most of the viable (accessible) photocarriers are collected right at the edge of the electrode. These are the short-lived carriers that are collected by the electrodes and can contribute to the detected current. For our sample of InGaAs/InAlAs the carrier lifetime is approximately 1.5 ps [17] and the saturation velocity is $V_s = 0.75 \times 10^7$ cm/s [18], which results in a 112.5 nm active distance from the electrodes. This is the average distance of survival for the photocarriers considering an exponential distribution for the carrier lifetime [11]. When the structure is excited with TM polarization there is a submicrometer-sized shadow close to