Low pump irradiance to modulate THz waves driven by photogenerated carriers in an InAs slab

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***Abstract*—We theoretically and experimentally study the THz electromagnetic properties of an undoped-InAs slab whose permittivity is optically modified by a photo-generation process. The modulation of the permittivity is calculated by solving the ambipolar rate equation for the free carriers. Experiment results demonstrate that InAs is a promising semiconductor to manufacture fast and efficiently on-chip THz components. We show a high modulation of the THz transmission up to 100% from 0.75 to 1.1THz at very low pump fluence in the continuous wave regime. We also demonstrate a high-speed transmission modulation rate up to the MHz range with a modulated pump.**

I. INTRODUCTION

Terahertz electromagnetic waves with frequencies lying from 0.3 to 10 THz attract much interest owing to their potential applications in several domains ranging from medicine, telecommunication or security. Recent developments of bright terahertz (THz) sources and efficient detectors accelerate the progress of non-destructive THz systems. However, the demand for versatile THz components able to address a wide range of frequencies is high. Among the envisaged approaches, artificial structures named metasurfaces based on subwavelength electromagnetic resonators were used to control THz waves [1]. Real-time and dynamical control have been demonstrated with photo-generated metasurfaces [2,3]. Here, the metasurfaces are optically printed into a semiconductor layer. However, several issues must be bypassed in terms of modulation rate or pump irradiance before this approach might be implemented in the application domain.

II. DESCRIPTION OF THE STUDY

In this work, we theoretically study the THz electromagnetic properties of photo-generated carriers in an undoped-InAs slab as presented in Fig. 1. The modifications of the permittivity induced by an optical pump are calculated by solving the ambipolar rate equation for the photo-carriers. Photo-carrier diffusion plays a crucial role in the search of an optimal geometry [4]. To understand and to reveal the real impact of the photo-carrier diffusion in the InAs material, we have created a multiphysics code to calculate the electromagnetic properties of the InAs slab illuminated by a THz plane wave. We have analyzed the electromagnetic properties of the InAs slab as a function of the thickness "*h*", the pump fluence and the polarization (TE and TM) of the THz wave and demonstrated a high modulation of the THz radiations.

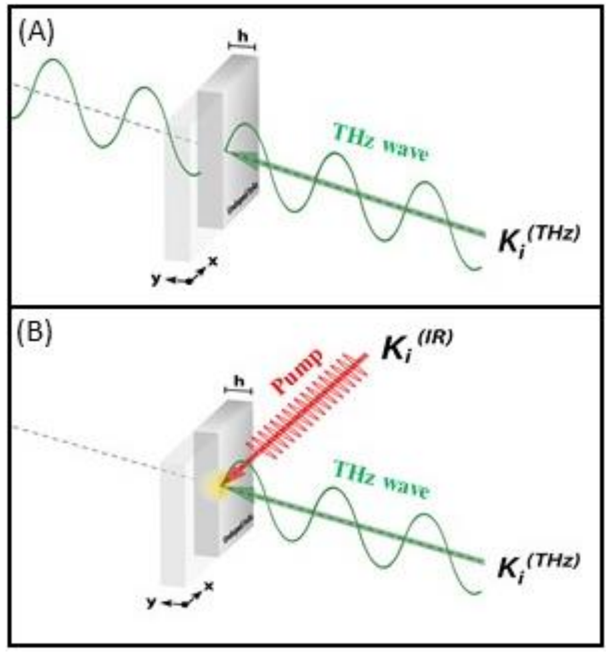

Fig. 1. (A) Schematic of the Undoped-InAs slab of thickness "*h*" radiated by a THz plane wave from 0.75 to 1 THz. (B) The radiated InAs material is pumped by an IR plane wave which allows to obtain a modulation in transmission of the THz radiation.

We have carried out the experimental demonstration described in Fig. 1. We have evaluated the transmission of a THz-wave through a micrometric-thick slab of undoped-InAs using a continuous-wave (CW) and modulated by an IR laser of 805nm wavelength. In the experimental set-up, the collimated THz wave radiates the InAs membrane located in the sample holder of the optic set-up, which in turns is traversed by the IR laser. The maximum power is 500mW and the spot diameter is 2mm when it is collimated. The rest of the optic set-up is composed of two THz wave systems: source and receiver. The THz source system is composed of a synthesizer which is used as a source, then its signal is multiplied in frequency by diodes and other amplifiers by a factor (x81). The THz receiver system is composed of an electric spectrum analyzer that sends its local oscillator (LO) on the head of an heterodyne detection, which is multiplied in frequency (x96) by diodes and other amplifiers in order to reach in the range 0.75THz to 1.1THz (RF signal). This signal is mixed with the signal measured on a diode which returns the frequency difference (IF frequency), that goes into the bandwidth of the electric spectrum analyzer, which displays this measurement. The measurement is calibrated in terms of system losses and frequency (factor x96).

Fig. 2 illustrates the optical characterization of an intrinsic InAs slab of thickness *h*=3.8um illuminated. Fig. 2(A) illustrates the transmitted power (in dBm) for a frequency ranging from 0.75THz to 1.1THz with different pump irradiances. The spectrum shows that low-pump irradiance in the continuous regime of only a few W/cm^2 is enough to modulate the transmission of the THz waves up to 20dB. Fig. 2(B) presents the normalized THz transmission, where the spectrum shows that low irradiance (**Φ**=6.6W/cm^2) in the CW pump is enough to modulate the transmission of the THz waves from 70% to 0% on a broad band frequency range. At last, Fig. 2(C) illustrates the THz transmission ratio intensity in dB between the InAs slab at different pump fluences $T_{\mathbf{\Phi}}$ and the reference measurement T_0 when the laser pump is turned-off (**Φ**=0W/cm^2). We observed that an irradiation of only **Φ**=2.7W/cm^2 allows a modulation of the transmitted waves up to 6dB (blue color), and with an irradiance of **Φ**=4.7W/cm^2 is modulated up to 15dB (red color). Higher pumps overcome 20dB. The highest transmission modulation obtained is around 30dB with a very low-pump equal to **Φ**=8.1W/cm^2. This is enough to modulate the transmission of the THz waves up to 100% at a frequency ranging from 0.75THz to 1.1THz.

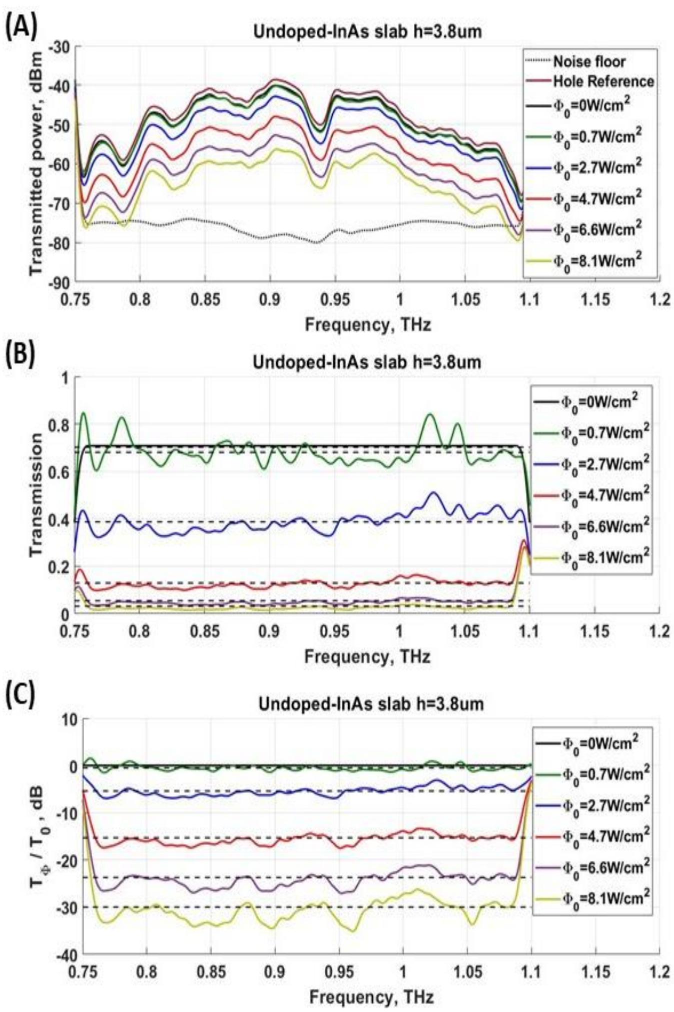

Fig. 2. Experimental results of an irradiated intrinsic InAs slab of thickness *h=3.8um* radiated with a THz plane wave at a frequency ranging from 0.75THz to 1.1THz. (A) THz transmitted power in dBm. (B) Normalized THz transmission. (C) THz transmission ratio intensity ($T_{\mathbf{\Phi}}$ / T_0).

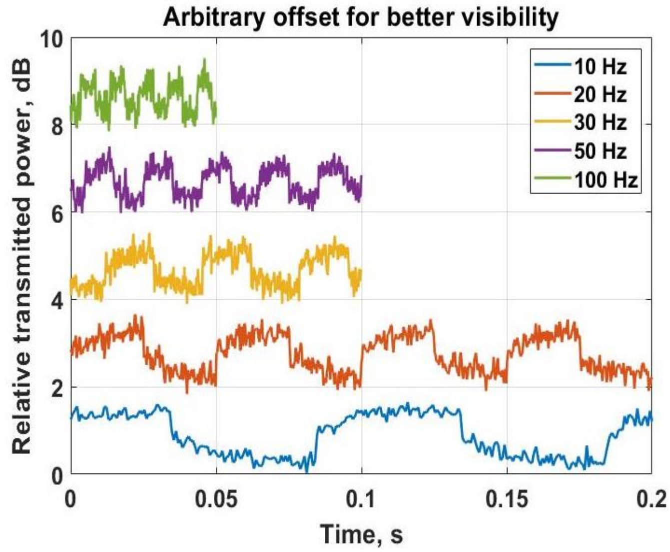

Fig. 3. Transmitted power observed at the spectrum analyzer in a zero-span mode for a pump irradiance modulated using an on/off amplitude modulation at increasing frequencies.

We have also performed experiments using a modulated pump where we demonstrate a frequency modulation up to the MHz range. In this case, to perform the amplitude modulation of the laser pump, we use an acousto-optic modulator (AOM). The THz frequency was set to 925GHz, we set a pump irradiance of **Φ**=8.1W/cm^2 at the laser output and the zero-order of the AOM diffraction output is used to photo-generate the InAs slab. Fig. 3 presents the transmitted power as a function of time, showing the dynamic response of the THz modulation around 925 GHz. These results are limited by the zero-span operation of the spectrum analyzer. Present work consists in the observation of the modulation sidebands amplitudes of the transmitted power, and shows evidences of a possible cut off frequency close to 1MHz.

III. CONCLUSION

We have demonstrated that the undoped-InAs is a promising semiconductor for the development of on-chip fast and efficiently THz components. A modulated pump at an irradiance of few W/cm^2 is enough to dynamically control the THz transmission over a frequency range from 0.75 THz to 1 THz and with a high-speed modulation rate up to the MHz range.

REFERENCES

[1]. K. Fan and W. J. Padilla, "Dynamic electromagnetic metamaterials", *Materials Today* **18**, 1 (2015).

[2]. T. Okada and K. Tanaka, "Photo-designed terahertz devices", *Scientific Reports* **1**, 121 (2011).

[3]. G. Georgiou, *et al*. "Photo-generated THz antennas", *Scientific Reports* **4**, 3584 (2014).

[4]. E. Alvear-Cabezón, *et al*. "Photogenerated metasurfaces at terahertz frequencies induced by a continuous wave low-pump", *Phys. Rev. B*. **98** 035305 (2018).

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