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# Optically-pumped continuous-wave terahertz sources

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## ABSTRACT

Recently we have improved the efficiency and the output power of our optically pumped continuous-wave THz sources. These sources are based on the beating of two laser lines in a wide bandwidth photodetector. Its intrinsic nonlinear behaviour is used to produce a beatnote at the frequency difference between the two laser lines (photomixing). These photomixers are continuously tunable THz sources working at room temperature. We have developed two kinds of photomixers: GaAs-based for 0.8  $\mu\text{m}$  pumping and InP-based for 1.5  $\mu\text{m}$  pumping. On GaAs the best results has been obtained thanks to low-temperature-grown GaAs (LTG-GaAs) photoconductors (PC). Efficiency and power were optimized by designing a new type of thin PC placed in a Fabry-Pérot resonator. The high impedance of the PC is a well-known limitation of this device but with our approach it was possible to reduce its impedance by a factor 100. Moreover by designing an impedance matching network it was possible to obtain 1.8 mW at 252 GHz with a total efficiency of 0.5 %. On InP the best results are obtained with uni-travelling-carrier photodiodes (UTC-PD). The device was improved by designing a new heterostructure and new semi-transparent contacts with sub-wavelength apertures. The active layer was also bonded to a silicon substrate thanks to metal thermocompression. It is demonstrated that with this approach it is possible to obtain a power of 0.7 mW at 300 GHz with a total efficiency of 0.7 %. More generally the efficiency of optically pumped terahertz sources will be discussed.

**Keywords:** Terahertz sources, photomixing, photomixer, photoconductor, low-temperature-grown GaAs, uni-travelling carrier photodiode, thermocompression bonding

## 1. INTRODUCTION

Powerful room-temperature terahertz sources are key elements for promising applications such as spectroscopy, imaging and high data rate wireless transmissions. Several approaches have been published: Schottky diodes harmonic generation, quantum cascade lasers and transistor oscillators. But it is still a challenge to obtain high power, wide tunability and good efficiency. Terahertz optoelectronic generation has a specific advantage: the tunability and/or the bandwidth can be very large. The main drawbacks are the limited amount of power generated and the low efficiency<sup>1</sup>. We present here our progress concerning the improvement of THz CW photomixers.

In part 2 we present the general definitions of the efficiency of a photomixer. In part 3 we present our improvements concerning high efficiency LTG-GaAs PC pumped at 0.78  $\mu\text{m}$ . In part 4 we present our last results concerning UTC-PD pumped at 1.55  $\mu\text{m}$ . In part 5, we conclude this study.

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## 2. EFFICIENCY OF PHOTOMIXING SOURCES

### 2.1 General considerations

In our study two kinds of wide bandwidth photodetectors are used to generate THz power: PC and PD. In the first case no internal electric field exists and the device can be modelled as a time-varying resistance (or conductance). A dc bias is then needed in order to produce a THz current in the load. In the case of a PD, an internal electric field exists and separate electron-hole pairs even if an external dc bias is not applied. In general this device can be modelled as a current source.

In general, the photomixer can be modelled as a device that converts dc power ( $P_{dc}=V_0I_0$  where  $V_0$  is the bias voltage and  $I_0$  the dc current) and optical power ( $P_{opt}$ ) into THz power that is delivered to a resistive load  $R_L$ :

$$P_L = \frac{1}{2} R_L I_L^2 \quad (1)$$

where  $I_L$  is the ac current circulating into the load. The total efficiency is equal to:

$$\eta_{tot} = \frac{P_L}{P_{dc} + P_{opt}} \quad (2)$$

It is also interesting to define the electrical efficiency:

$$\eta_e = \frac{P_L}{P_{dc}} \quad (3)$$

### 2.2 Efficiency of PC

If we consider a PC illuminated by two lasers beating at the pulsation  $\omega$  as a perfectly linear time-varying resistance connected to a resistive load short-circuited in dc, and by neglecting generated harmonics, the power delivered to the load is:

$$P_L = \frac{1}{2} \frac{G_L}{(G_0 + G_L)^2} I_0^2 \frac{1}{(1 + \omega^2 \tau_c^2)(1 + \omega^2 \tau_{RC}'^2)} \quad (4)$$

Where  $G_L$  is the load conductance,  $I_0$  is the dc photocurrent into the photoconductor,  $G_0=I_0/V_0$ ,  $\tau_c$  is the carrier lifetime,  $\tau_{RC}'=C/(G_0+G_L)$ , and  $C$  is the photoconductor capacitance. The maximum efficiency is obtained when  $\omega \ll 1/\tau_c$ ,  $1/\tau_{RC}'$  and when the matching condition is achieved ( $G_L = G_0$ ). In this ideal case:

$$\eta_e = \frac{P_L}{P_{dc}} = \frac{1}{8} \quad (5)$$

The maximum electrical efficiency is then equal to 12.5 %.

### 2.3 Efficiency of PD

In the case of PD the situation is generally more complicated than for PC but as in the case of photoconductors the power delivered to the load can be expressed as:

$$P_L = r_{eff} I_0^2 \quad (6)$$

The  $r_{eff}$  parameter is an effective resistance that depends on the load resistance but also on the frequency (it contains transit times and RC time constants). The electrical efficiency is:

$$\eta_e = \frac{P_L}{P_{dc}} = \frac{r_{eff} I_0}{V_0} = r_{eff} G_0 \quad (7)$$

### 3. HIGH EFFICIENCY LOW-TEMPERATURE-GROWN GAAS PHOTOCONDUCTORS

#### 3.1 Standard LTG-GaAs photomixers

Standard LTG-GaAs PC are planar interdigitated structures. In this case, LTG-GaAs layers of thickness close to 1  $\mu\text{m}$  are needed to absorb the light and the digit-to-digit distance is also close to 1  $\mu\text{m}$ . The capacitance of such structures is very low (few fF). For a carrier lifetime close to 1 ps, a low responsivity of 10 mA/W at 10 V is observed around 800 nm<sup>2</sup>. Due to the low thermal conductivity of LTG-GaAs, the maximum optical power is generally limited to 100 mW before destruction. It corresponds to a photocurrent of 1 mA and to a dc resistance of 10 k $\Omega$ . Under these conditions, impedance matching is very difficult to achieve and the electrical efficiency is very low (< 0.1 % at 300 GHz). The total efficiency is even lower (<0.01 % at 300 GHz).

#### 3.2 Fabry-Pérot cavity based LTG-GaAs photomixers

Since several years we have developed new photomixers based on LTG-GaAs layers sandwiched between two gold layers which serve at the same time as bias electrodes and optical mirrors of a Fabry-Pérot (FP) resonator. This structure can actually be seen as a lossy FP resonator. The PC exhibit quantum efficiency peaks for particular thicknesses corresponding to the FP destruction interference condition. An optical absorption close to 80 % can be obtained in layers of a few 100's nm thickness. Technologically, this structure is fabricated thanks to metallic bonding on a silicon wafer (thermoccompression).

Compared to the standard structure almost the same number of carriers are photocreated in a smaller volume, the conductance is then higher. Consequently the responsivity of these PC is higher. The electrodes are planes with a separation distance of a few 100's nm (equal to the LTG-GaAs layer thickness) the electric field is then more uniform and higher (at identical voltage). In summary, the responsivity is higher at a lower voltage, so the impedance is lower<sup>3</sup>.

A responsivity of about 0.1 A/W at 3.5 V has been measured on a 280 nm thick FP photomixer (carrier lifetime: 500 fs). The corresponding impedance is 240  $\Omega$  (figure 1). This lower impedance allows to increase the efficiency of conversion. A maximum power of 350  $\mu\text{W}$  @ 305 GHz has been measured at 3.5 V bias<sup>4</sup>. The corresponding electrical efficiency is 0.7 % and the total efficiency is 0.16 %.

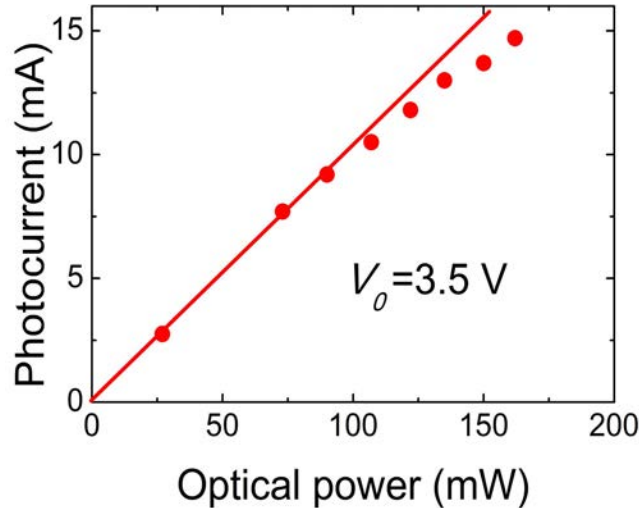


Figure 1. Photocurrent through a FP resonator LTG-GaAs PC versus optical power at a bias voltage of 3.5 V.

In order to further improve the efficiency of the photomixer, a new design was studied with an impedance matching circuit<sup>5</sup> (figure 2). The LTG-GaAs layer thickness was also reduced to 160 nm (carrier lifetime: 400 fs).

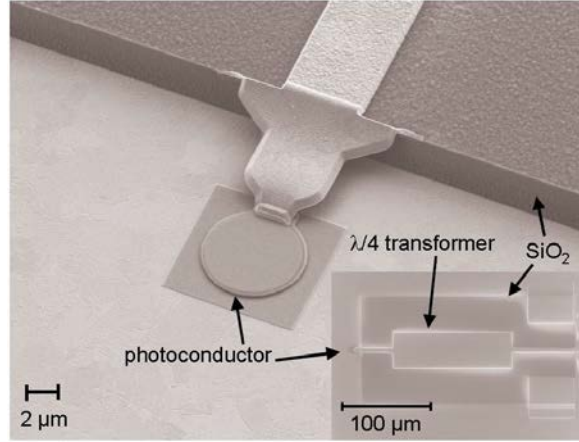


Figure 2. SEM image of a LTG-GaAs metallic-mirror-based resonant PC linked to a 50  $\Omega$  thin film microstrip line. Inset: top view of the photoconductor coupled to the impedance matching circuit.

A maximum photocurrent of 24 mA was measured at 3 V. A maximum power of 1.8 mW was measured at 252 GHz (figure 3). The corresponding electrical efficiency was 2.5 % and the total efficiency was 0.52 %.

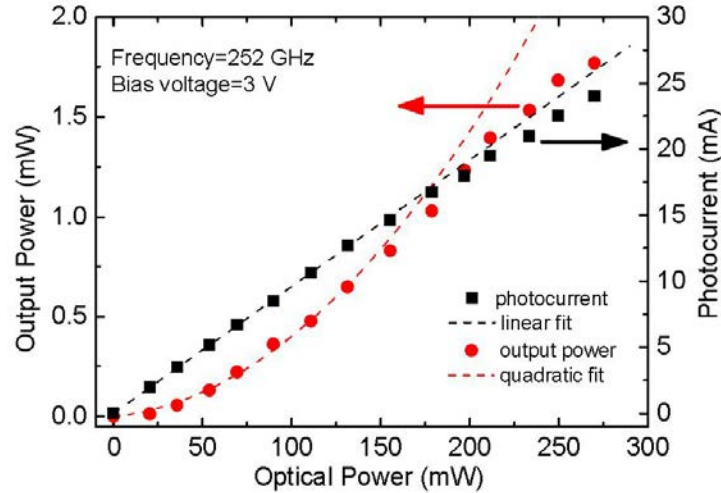


Figure 3. Photocurrent and output power of the matched photomixer as a function of the optical power.

These high figures are also explained by the improved heat evacuation of these devices: the LTG-GaAs layer (which has a low thermal conductivity) is thinner, the silicon substrate has a higher thermal conductivity than the standard GaAs substrate and the bonding metal layer (gold) acts as a heat spreader. Standard interdigitated photomixers are destructed for power densities close to 100 kW/cm<sup>2</sup>, in the case of the FP photomixer, dissipated power density close to 1.2 MW/cm<sup>2</sup> have been observed before destruction.

## 4. INP UNI-TRAVELLING-CARRIER PHOTODIODES

### 4.1 Uni-travelling-carrier photodiodes (UTC-PD) for terahertz generation

LTG-GaAs PC are limited to wavelengths close to 0.8  $\mu$ m. Longer wavelengths close to the telecom range are ideal for photomixing since abundant components can be found at low price (lasers, modulators, amplifiers etc..). The most straightforward approach is to develop PC with smaller bandgaps<sup>1</sup>. But performances are generally rather limited due to the fact that the breakdown field is lower and the dark current is higher compared to LTG-GaAs. Another approach is based on PD: conventional *pin*-PD has the inevitable trade-off between responsivity and bandwidth. The UTC-PD is a structure that provides a high bandwidth and a high saturation power simultaneously<sup>6,7</sup>.

## 4.2 Sub-wavelength grid window UTC-PD

We have designed new UTC-PD InP/InGaAs structures with grid anode windows (figure 4). This window is based on sub-wavelength metallic apertures that allows good optical transmission and simultaneously low contact resistivity.

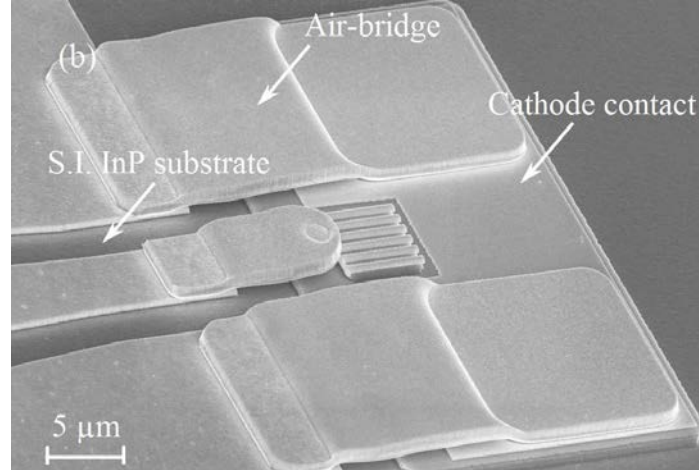


Figure 4. SEM image of a  $6 \times 6 \mu\text{m}^2$  UTC-PD integrated with a  $50 \Omega$  coplanar waveguide.

An output power of  $400 \mu\text{W}$  at 300 GHz have been measured for a  $3 \times 3 \mu\text{m}^2$  UTC-PD. The optical power was 200 mW and the photocurrent 12.7 mA (figure 5). The corresponding electrical efficiency was 2.1 % and the total efficiency was 0.18 %.

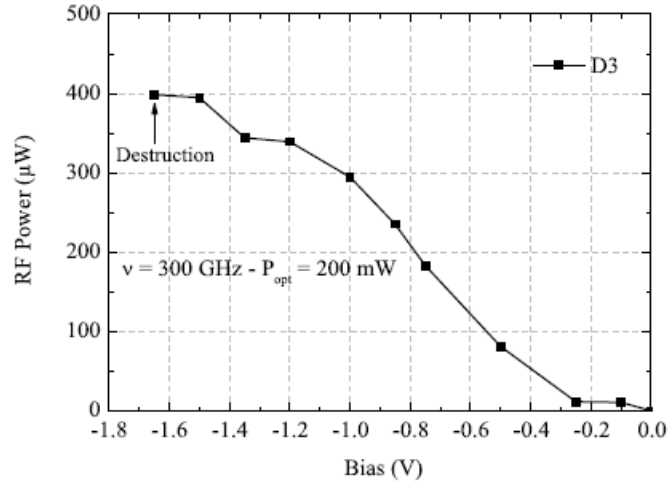


Figure 5. THz power as a function of the bias voltage for a  $3 \times 3 \mu\text{m}^2$  UTC-PD.

Recently an active UTC-PD layer was also bonded to a silicon substrate thanks to metal thermocompression bonding. With this approach an output power of 0.7 mW at 300 GHz with a total efficiency of 0.7 % has been demonstrated.

## 5. CONCLUSION

In conclusion, we have demonstrated that CW THz powers close to the mW level at 300 GHz can be generated with two families of photomixers: FP resonator LTG-GaAs PC ( $\lambda = 0.78 \mu\text{m}$ ) and sub-wavelength grid window UTC-PD ( $\lambda = 1.55 \mu\text{m}$ ). The total efficiency of the conversion process is in the 0.5-0.7 % range which is an excellent value for a room-temperature widely tunable THz source.

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