Vertically Illuminated TW-UTC Photodiodes for Terahertz Generation

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***Abstract*—More efficient continuous-wave photonic near-infrared mixers as terahertz sources are investigated with the motivation to develop a universal photonic local oscillator for astronomical submillimeter/terahertz receiver systems. For this, our group has developed new concepts for vertically illuminated traveling-wave (TW) photomixers. The new device called TW-Uni-Travelling Carrier photodiodes (TW-UTC PD) was simulated, modeled and shall be optical/terahertz tested at the Electrical Engineering Department of the University of Chile, whereas device fabrication is performed at the MC2 cleanroom facility at Chalmers University of technology. We are reporting on first progresses in this direction.**

I. Introduction

Development of terahertz frequencies systems has been widely studied during the last years and this, has lead to a wide range of applications in astronomy, biology, medicine, imaging, communications and security. For radio astronomy applications more efficient continuous-wave photonic mixers as terahertz sources are being developed with the motivation to fabricate a universal photonic local oscillator for THz radio astronomy receivers. Two new concepts are been integrated to develop these new types of photomixers. The first concept is called large area vertical illuminated travelling-wave (TW) photomixing and the second one involves Uni-Travelling Carrier Photodiodes (UTC-PD). The final device, called TW-UTC photodiode, has been simulated and modeled and shall be optically tested in the new terahertz photonics laboratory at the Electrical Engineering Department of the University of Chile, whereas device fabrication is being conducted at the MC2 clean room facility at Chalmers University of Technology. This paper describes design and developments made so far, for a TW-UTC photomixer between 200 GHz and 2 THz.

II. Vertical Illuminated TW-UTC PD Concept

The main goal behind fabrication of these new types of photomixers is to achieve better efficiency, which is measured with higher power at high frequencies and larger bandwidth. It is well known that the main advantage of travelling-wave photodetectors (TWPD's) is to avoid the parasitic RC constant limitation of the corresponding lumped element [1], this means that bandwidth and power can be improved with TW devices. Tavelling-wave photomixers can be divided in two classes depending of the effective absorption coefficient (α) of the devices structure [2], low effective $\alpha << 1\mu m^{-1}$ leads to edge coupled (fiber-illuminated), whereas high absorption leads to vertically illuminated designs. In fiber illuminated devices, the output power is proportional to the square of the photocurrent and the bandwidth depends inversely on the photocarrier life-time and electrode capacitance, therefore, photomixers have been usually designed for small areas. In order to get a higher power capability large-area travelling-wave photomixers is in our case a better option, due to in these types of devices bandwidth is not limited for the electrode capacitance and also it has higher-power handling capacity. In a general case of photomixing when a photomixer is illuminated by two single mode CW lasers beams, the THz output power may be written as [3].

$$P(\omega) = \frac{I_0^2 R_A}{2[1 + (\omega\tau_c)^2][1 + (\omega R_A C)^2]} \tag{1}$$

where $I_0(= GV_0)$ is the photocurrent, G is the DC photo-conductance, V_0 is the bias DC voltage, R_A is the antenna resistance, τ_c is the carrier life time, and C is the device capacitance. In the case of TW devices the time constant $\tau_{RC}(= R_A C)$ is ideally bypassed, thus the output power roll-off is proportional to ω^{-2}. In addition to improve even more the THz power, and achieve wide bandwidth, the carrier life time must be improved. One way to do it, is using Uni-travelling Carrier Photodiodes (UTC-PD). The main feature of the UTC-PD proposed by Ishibashi et al. [4] is that only electrons work as active carriers optimizing the $R_A C$ and transit time constants. Thus, bandwidth and output saturation current are both increased in comparison with PIN PD's and therefore higher output powers can be obtained at high frequencies [3],[4].

By using UTC-PD's as vertical illuminated travelling-wave devices, it is feasible to improve simultaneously bandwidth and output power, the latter would increase by a factor of $(1 + (\omega R_A C)^2)$. Hence output power and bandwidth in TW-UTC PD may be rewritten as,

$$P_{THz}(\omega) = \frac{1}{2} R_A \frac{I_0^2}{1 + (\omega\tau_c)^2} \tag{2}$$

$$f_{3dB} = \frac{1}{2\pi\tau_c} \tag{3}$$

Using the fact of I_0 is equal to [8]:

$$I_0 = \eta P_0 \frac{e}{h\nu} \frac{\tau_{tr}}{2} v_{e,dr} A_{ill} \quad (4)$$

where $P_0 = \sqrt{P_1 P_2}$ is the beat part of the interference of both laser powers, η is the quantum efficiency, $v_{e,dr}(= \mu_e \frac{V_0}{W})$, is the drift velocity of the electrons, $W(= W_A + W_c)$ is the spacing between the electrodes, A_{ill} is the effective illuminated area, and $\tau_{tr}/2$ is the effective life time of the photoelectrons in the photoconductive gap.

In order to optimize THz power, not only the above parameters must be tunned, we also need optimize the transit time. The travelling time in the collection layer can be defined as $\tau_c = W_c/v_d$, where W_c is the collection layer width and v_d is the drift velocity of electrons [6], thus transit time in UTC-PDs can be defined as [7].

$$\tau_{tr} = \tau_A + \tau_c = \frac{W_A^2}{3D_e} + \frac{W_A}{v_{th}} + \frac{W_c}{v_d} \quad (5)$$

where, τ_{tr} is the total transit time and τ_A is the transit time in the absorption layer, τ_c is the transit time in the collection layer, W_A, D_e and v_{th} are the abortion layer thickness, diffusivity of electrons in the absorption layer and the electron thermionic emission velocity, respectively. For absorption layer thickness larger than 100 nm (our case), transit time of electrons is dominated mainly for the first term in the equation (5), then transit time can be approximated as $\tau_{tr} \approx W_A^2/3D_e$.

III. TW-UTC PHOTOMIXER MODELLING

A. Layer Structure

The layer structure chosen for the UTC-PD is based in the optimization made for Biddut Banik et al. [7] using TCAD simulator from Synopsys (table 1). The epitaxial layer of an InGaAs/InP was optimized for 340 GHz, the simulation result predicted $\approx 1\ mW$ of output power assuming a maximal allowable optical excitation of 0.25 W, thereby assuming $R_A \approx 50\ \Omega$, the fact of bypassing the factor $(1+\omega^2\tau_{RC}^2)$ using TW scheme could increase the output power approximately in a factor 6 at 1 THz.

B. Antenna Integration

1) Bow-tie slot antenna : The UTC-PD must be integrated with antennas for THz generation and emission.
Different types of antennas such a log spiral and log periodic have been reported [7], but the impedance of those broadband antennas is low for our propose.
Due to terahertz power is proportional to antenna impedance higher impedance antennas are desirable. One of our antennas is a bow-tie slot antenna designed to reduce the reflections and minimize standings waves (Fig. 1). In this design the UTC-PD is placed in a coplanar wave guide (CPW) integrated with a slot bow-tie antenna, photomixer is back illuminated and coupled to hemispherical GaAs lens (2).
The electromagnetic performance of the scheme shown in figure 2, was optimized using CST Microwave Studio. The S_{11}

TABLE I
OPTIMIZED UTC-PD LAYER STRUCTURE FOR 340 GHZ [7]

LAYER	MATERIAL	THIKNESS	DOPING
12	$In_{0.53}Ga_{0.47}As$	50	3e19 p+
11	$In_{0.53}Ga_{0.47}As_{0.80}P_{0.20}$	20	2e19 p+
10	$In_{0.53}Ga_{0.47}As$	125	1e18 p
9	$In_{0.53}Ga_{0.47}As$	8	1e15 i
8	$In_{0.76}Ga_{0.24}As_{0.54}P_{0.28}$	16	1e15 i
7	InP	6	1e15 i
6	InP	7	1e18 n
5	InP	150	1e16 n-
4	InP	50	5e18 n
3	$In_{0.53}Ga_{0.47}As$	10	1e19 n+
2	InP	500	$>$ 2e19 n+
1	$In_{0.53}Ga_{0.47}As$	10	I
Sub	InP	SI	SI

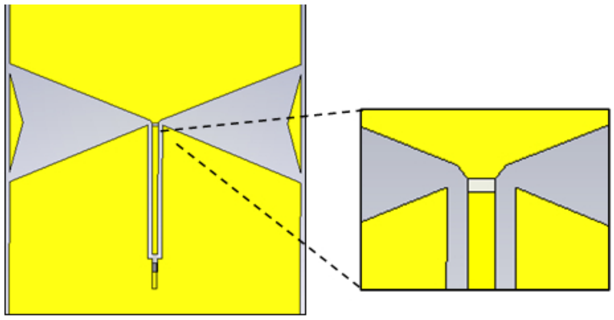

Fig. 1. Bow-tie slot antenna integrated to CPW.

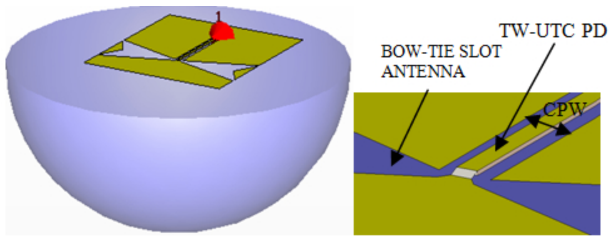

Fig. 2. Bow-tie antenna fed with CPW and integrated in a hemispherical GaAa lens.

parameter is shown in the figure 3, which is better than around -10 dB. Its oscillating shape is due to the presence standing waves which are consequences of the impedance mismatch between the CPW and the bow-tie antenna. The matching process is still under research.

2) Butterfly metal antenna: Due to the preferred small gap between inner and outer conductors (a larger one would just produce ohmic losses), the impedance of the CPW is below 50 Ohms.
Therefore, a metal bowtie antenna with its lower impedance around 70 Ohms matches much better than a bowtie slot which has a much higher impedance.around 150 Ohms.
It is well known that the terahertz output power is proportional to the antenna impedance and in the general case the impedance of a planar antenna is at most a few hundreds of ohms [3] and usually is bigger than the impedance of

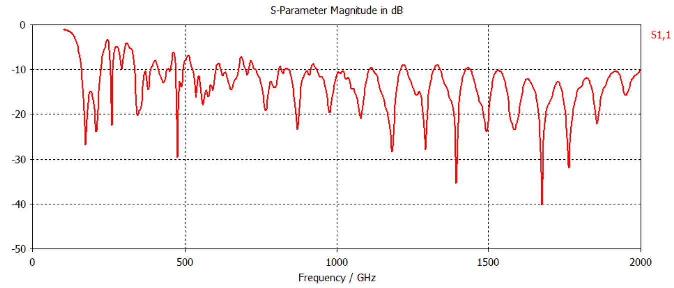

Fig. 3. S_{11} parameter for modified bow-tie slot antenna with 25○ of aperture and 120 um length.

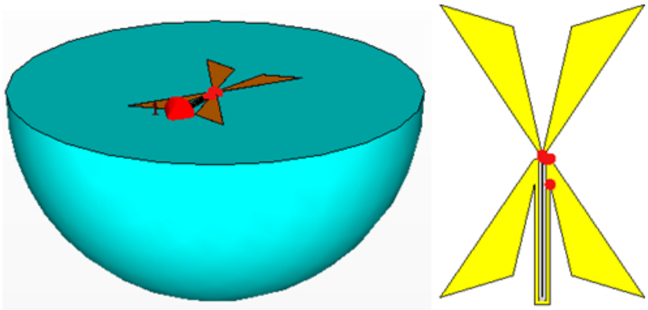

Fig. 4. Butterfly metal antenna over a GaAs lens.

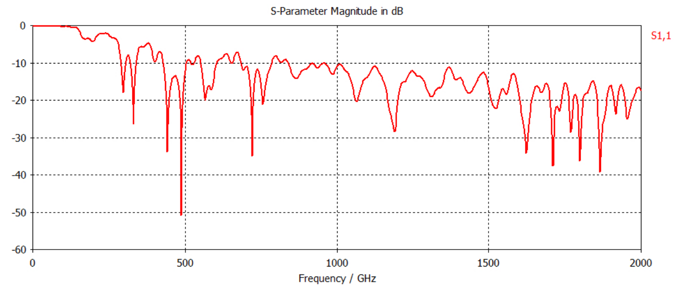

Fig. 5. S_{11} parameter for metal Butterfly antenna with mesa width of 0.5 μm, and slot lines of 2 μm.

our CPW. Thus the photomixer works under mismatched condition, therefore a lower impedance antenna is another alternative to reduce the mismatch shown in Fig. 3, where the oscillating shape of the S_{11} parameter is a consequence of this mismatch.

Antenna simulations in CST microwave studio show that the mismatch of this antenna (Fig. 5) is lower than the previous one but it drawback is that the output power shall be slower.

IV. DEVICE FABRICATION

The firsts back side illuminated TW-UTC PDs are being fabricated at Chalmers University. First devices have been developed using 150-300 μm slot bow-tie antenna integration and 600 μm CPW length structures with mesa structure width of 3 μm and slot lines of 3-6 μm. Three solvents are used in the process of wafer cleaning, acetone, methanol and IPA, all of them heated at 60^0C in a sequence of 10 min, 30 s and 2 min respectively. After this step standard optical lithography is used to fabricate antenna integration and the CPW mesa structure, the first p-contact on the top of the mesa structure

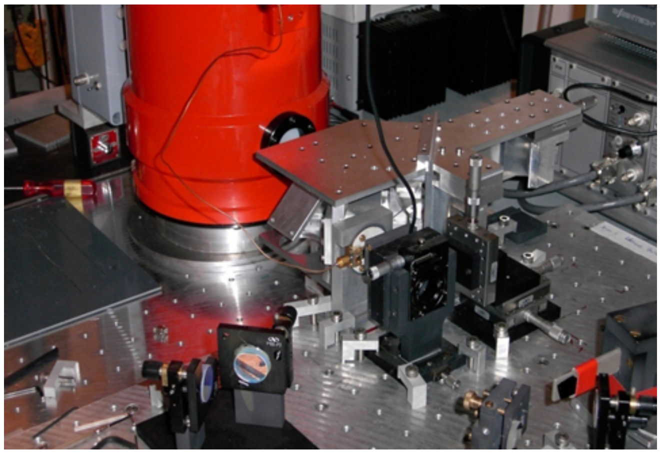

Fig. 6. Optical set-up used for 800 nm testing system.

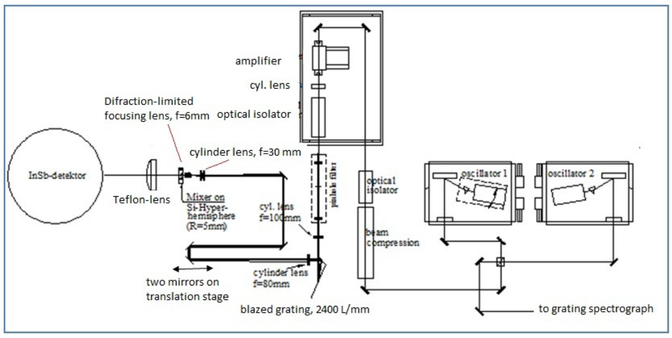

Fig. 7. Schematic of set-up used for 800 nm testing, the 1550 nm fiber system is being set up similarly.

is built using an image reversal resist AZ5214E, the contact is deposited using standard vapour deposition technique. In order to have a ohmic contact the sequence of Pt/Ti/Pt/Au was used, for the n-contact and a similar sequence of Ti/Pt/Au was used for the n-contact. For wet etching two different etches are needed, one for etching InGaAs/InGaAsP, and another for InP. The InGaAs/InGaAsP etch is H_3PO_4:H_2O_2:H_20 (1:1:25), this etch is selective to InP and its stops when it reach an InP layer, HCL:H_3PO_4:H_2O_2 (3:1:6) is used for InP and also is highly selective to InGaAs.The process of fabrication also use dry etching for etch InP and InGasAs/InGaAsP, but in another part of the process. The final fabricated device shall be placed on a hyper-hemispherical Si lens, and the front part of the device will be antireflection coated for 1550 nm.

V. DEVICE TESTING SET UP

Device testing will be performed at our terahertz photonics laboratory at the Electrical Engineering Department at University of Chile Fig. 6

Schematic set-up of the optical testing system is shown in Fig. 7, the IR-optic developed by Ernest Michael [8], was designed using an optic ray-tracing software (ZEMAX). The idea is to exploit the grating dispersion to design an optical set-up with frequency independent alignment which does the proper transformation from the grating dispersion to the phase-match angle frequency dependence on the mixer.

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