Optical Submillimeter-Wave Generation Employing Antenna Integrated Ultra-Fast Travelling-Wave 1.55μm Photodetectors

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***Abstract* — Optical heterodyne submillimeter-wave (submmw) generation using waveguide and antenna coupled 1.55μm travelling-wave photodetectors (TW-PD's) is experimentally investigated up to about 500GHz.**

I. INTRODUCTION

Ultra fast photodetectors have become key components for many domains. In terms of frequency, applications range from wireless access networks operating at microwaves and lower millimeter-waves over millimeter-wave instrumentation and sensors up to millimeter and sub-millimeter radio astronomy. Especially, in the last years the developments have significantly been pushed from the application side i.e. from interest in developing systems such as large (sub-)mm-wave antenna arrays [1] or mm-wave fiber-radio systems [2,3]. In such systems, high-frequency (sub-)mm-wave local oscillator (LO) signals must be distributed to remote antenna stations. Since this is not feasible by electrical means due to the high propagation loss of electrical waveguides at (sub-)mm-wave frequencies, so-called "photonic LOs" are required. Photomixers employing low-temperature grown GaAs (LT-GaAs) have firstly been reported to generate sub-mm-wave signals in excess of 1THz [4]. However, LT-GaAs photomixer operate at around 800nm whereas for the distribution of optical heterodyne signals in large antenna arrays, long-wavelength fibre-coupled photomixers operating at around 1.55μm wavelength are preferred due to the minimum transmission loss of the optical fiber and the availability of high-power erbium-doped fiber amplifiers, tunable laser diodes and other required fiber components [1]. Recently, remarkable improvements in the maximum operating frequency and the maximum electrical output power of 1.55μm photodetectors have also been achieved and reported [5]-[13].

In this paper high-power ultra-broadband frequency response of InAlAs/InGaAs travelling-wave photodetectors is demonstrated up to 120GHz mm-wave frequency. Further we report on waveguide (WR10, WR8 and WR5) coupled TW-PD's and present experimental results up to 1THz. Finally, photonic THz transmitters with integrated planar slot and bow-tie antenna structures for quasi optical free space coupling will be presented. The resonant slot antenna coupled transmitter exhibited a generated power level sufficiently large to pump the SIS junction of an astronomical receiver at 460GHz. An equivalent device with integrated bow-tie antenna that we developed and recently fabricated shows a very broadband characteristic. Using this device we demonstrate optical heterodyne generation between 30 and 350GHz.

II. 1.55μm TRAVELLING-WAVE PHOTODETECTOR

The ultra high-frequency travelling-wave photodetectors investigated in this work were designed for operation at 1.55μm wavelength. The optimised p-i-n waveguide structure of the detector[6] is based upon InP substrate. The frequency response of the TW-PD was characterised using an experimental set-up for optical heterodyning [5]. Cleaved TW-PD without antireflection coating and mode transformer were measured by on-wafer probing. The length and width of the investigated devices were 50μm and 6μm, respectively. The detector exhibits a DC responsivity of 0.08A/W at a reverse bias of 1.5V. Fig. 1 shows the characteristic impedance of the TW-PD up to 1THz that was calculated and extrapolated using an analytical model[13] on the basis of S parameter measurements made with an 110GHz network analyser. As it can be seen, the characteristic impedance of the TW-PD at 110GHz is approximately 10Ω. Fig. 2 shows the broadband frequency response of the TW-PD from DC to 120GHz with a total signal roll-off of about 13dB. Fig. 2 also shows the measured mm-wave output power at a fixed beat frequency of 110GHz versus the photocurrent. As can be seen from Fig. 2 the maximum mm-wave power level achieved is -7.9dBm. Due to the impedance mismatch between the 10Ω characteristic impedance of the

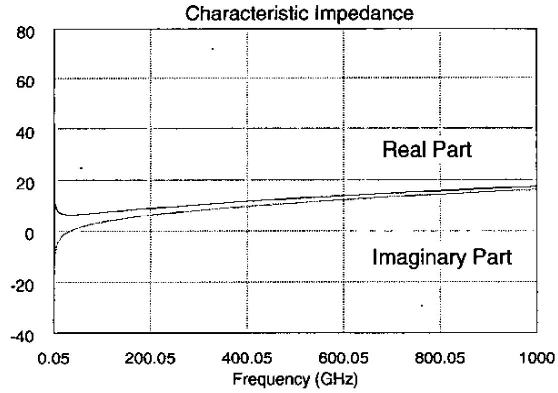

Fig. 1. Characteristic impedance of the 1.55μm TW-PD

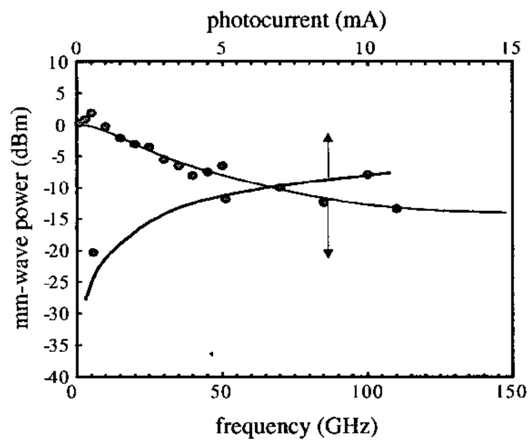

Fig. 2. Broadband frequency response of the TW-PD and maximum generated power versus photocurrent at 110GHz mm-wave frequency

TW-PD and the 50Ω probe we estimate the maximum available power at the same photocurrent to be about 8dB larger. Thus, the maximum available power level at 110GHz is expected to be larger than 1mW.

From simulations employing an analytical model for TW-PD [13], the frequency roll-off is identified to be

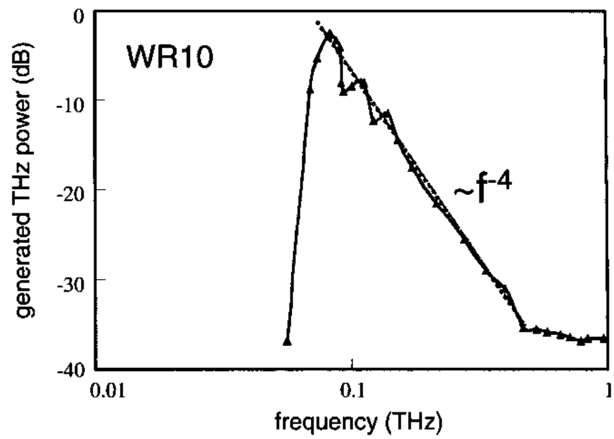

Fig. 3. Measured (sub)mm-wave output power of a waveguide (WR10) coupled 1.55μm TW-PD.

mainly caused by transit time effects and electrical transmission losses. Further penalties arise from intrinsic effects resulting from carrier transport in the doped sections of the TW-PD and velocity mismatch.

III. Waveguide Coupled THz Photonic Transmitter

To investigate the submm-wave performance of waveguide coupled photonic transmitters the fabricated TW-PD were contacted by a 50Ω coplanar transmission lines with a transition to a WR10 waveguide at its end. The submm-wave output of the WR10 waveguide was free-space coupled to a Golay cell for measuring the generated power up to THz frequencies. In this first experiment, no impedance matching techniques nor any imaging quasi optical lenses were employed. Fig. 3 shows the measured relative output power versus sub-mm wave frequency up to 1THz. As can be seen, no power is detected at lower frequencies, since no mode can propagate below the cut-off frequency of the waveguide (59,01 GHz for WR10). Furthermore, it can be observed that the measured power decreases with f^{-4}. We do not consider this to be caused by the TW-PD only, but especially by the appearance of

TABLE I

Calculated cut-off frequencies of the various TE_{MN} and TM_{MN} modes in WR8 and WR5 waveguides.

waveguide modes TE_{mn}, TM_{mn}	TE_{10}	TE_{20}, TE_{01}	TE_{11}, TM_{11}	TE_{21}, TM_{21}	TE_{30}	TE_{31}, TM_{31}
cut-off frequency[GHz] (WR8)	73.8	147.6	165.1	208.8	221.5	266.2
cut-off frequency[GHz] (WR5)	115.8	231.6	258.9	327.5	347.4	417.5

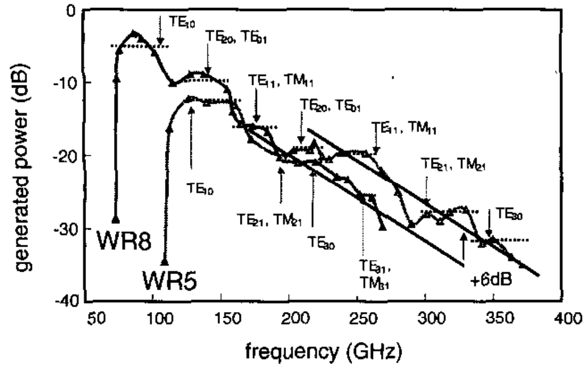

Fig. 4. Measured frequency response of waveguide (WR8 & WR5) coupled photonic transmitter employing 1.55µm TW-PD.

higher order modes and increasing waveguide losses. To confirm this, TW-PD coupled to a WR8 and WR5 waveguides were investigated which both exhibit only a few higher order modes up to 400GHz in contrast to the WR10 waveguide. The measured output power of these waveguide coupled transmitters is shown in Fig. 4. In Tab. 1, the calculated cut-off frequencies are listed. As can be seen from Fig. 4, for both waveguide types, a step-like frequency response is observed where the different steps appear in the vicinity of the cut-off frequencies of the higher-order modes. It also can be observed that at higher frequencies the coupling to the WR5 waveguide is about 6dB more efficient than that to WR8. This implies that not only the frequency dependence of the TW-PD causes the total roll-off of f^{-4} but also the frequency dependent coupling, impedance and loss of the waveguides.

IV. Solt Antenna Coupled Photonic Transmitter

To investigate the potential of a high-frequency TW-PD for generating sufficient output power at submm-wave frequencies to pump an astronomical receiver, antenna integrated photonic transmitter modules have been fabricated (see Fig. 5). The original transmitter employs a TW-PD (same layer structure as above) monolithically integrated with a planar full-wave slot antenna resonant at 460GHz. Furthermore, a passive bias-T was integrated employing radial stubs as low-pass filters. The integrated transmitter chip was mounted on a hemispherical silicon lens with a diameter of 10 mm. This lens couples the antenna to free space, producing a near Gaussian submm wave beam, that can be re-imaged on any receiver optics.

In the experiment, we first used a 460GHz solid state oscillator chain consisting of a Gunn oscillator with a subsequent tripler to pump the SIS-junction. The output power of the solid state oscillator was adjusted for

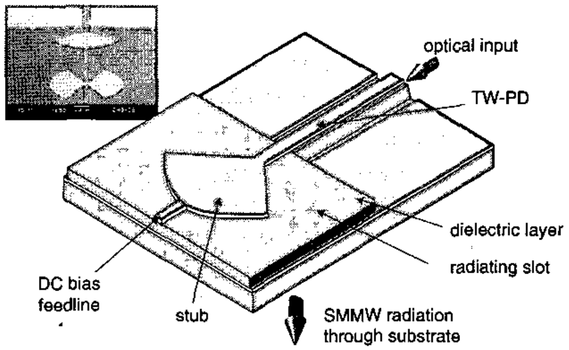

Fig. 5. Schematic of a slot antenna integrated photonic transmitter employing a travelling-wave PD, abowe the SEM picture of a fabricated photonic transmitter chip.

optimum sensitivity (i.e. lowest noise temperature) of the SIS-receiver and the corresponding DC bias curve of the SIS-junction was recorded. Hereafter, the solid state oscillator signal was replaced by the photonic transmitter module. Different DC bias curves of the SIS-junction were recorded as a function of laser input power level, i.e. as a function of the detector's photocurrent[5]. For a photocurrent of about 20mA the submm-wave power generated by the photonic LO was sufficient for optimal pumping of the SIS-junction. Thus, the developed photonic transmitter clearly fulfils the power requirements of a local oscillator for SIS-receivers at this frequency.

V. Bow-Tie Antenna Coupled Photonic Transmitter

The last photonic transmitter that we present consists of a TWPD and a broadband bow-tie antenna (see Fig. 6). This integrated chip was also mounted on a hemispherical silicon lens but the quasi optical beam was in this case coupled to a Golay cell. This device allows us to demonstrate optical heterodyne generation between 30 and 350GHz and as it can be seen in Fig. 7, the roll off is about two times smaller compared to the results presented in section III. The lowest operating frequency is given by the dimensions of the bow-tie antenna.

VI. Conclusion

We reported on travelling-wave 1.55µm photodetectors for heterodyne submm-wave generation. A maximum power level of -7.9dB, at 110GHz has been achieved indicating that the maximum available power at 110GHz is in excess of 1mW. Waveguide coupled photonic THz transmitter are experimentally investigated up to 1THz. A step-like frequency response was found which is believed

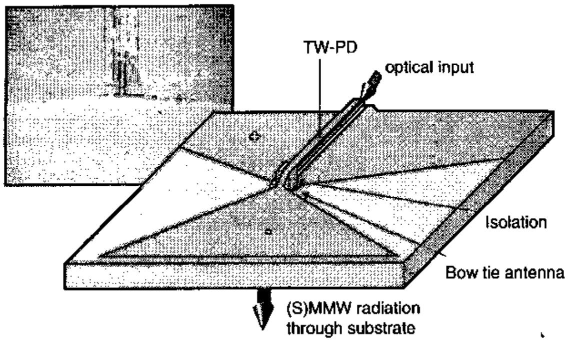

Fig. 6. Schematic of a bow-tie antenna integrated photonic transmitter employing a travelling-wave PD

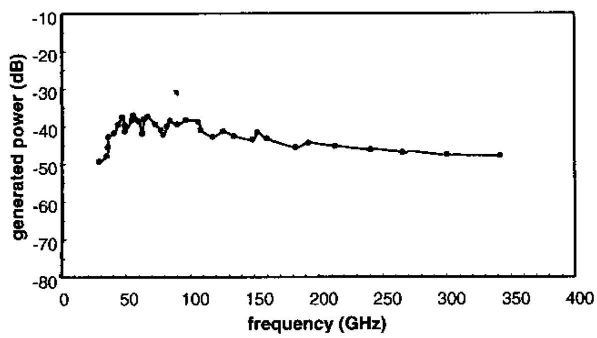

Fig. 7. Broadband optical signal generation employing Bow-Tie antenna integrated TW-PD

to depend on higher order waveguide modes. Finally broadband quasi optic measurements over slightly more then one decade were done with a bow-tie antenna coupled transmitter.

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