# Optical Millimeter-Wave Generation using 1.55µm Photodiodes with and without Integrated Antennas

**(invited paper)**

***A. Stöhr*[1], *C.C. Renaud*[2], *D. Moodie*[3], *A.G. Steffan*[4], *L. Pavlovic*[5], *D. Jäger*[1], *A.J. Seeds*[2], *M. Robertson*[3], *A. Umbach*[4], *M. Vidmar*[5], *M. Weiß*[1], *V. Rymanov*[1], *S. Fedderwitz*[1], *G. Tsianos*[4], *L. Naglic*[5]**

[1]Universität Duisburg-Essen, Lotharstr. 55, 47057 Duisburg, Germany, andreas.stoehr@uni-due.de

[2] University College London, Gower Street, WC1E 6BT London, United Kingdom, c.renaud@ee.ucl.ac.uk

[3] Centre for Integrated Photonics, Adastral Park, Ipswich IP5 3RE, United Kingdom, dave.moodie@ciphotonics.com

[4]u[2]t Photonics AG, Berlin, Reuchlinstr. 10-11, 10553 Berlin, Germany, steffan@u2t.de

[5]University Lubljana, Kongresni trg 12, 1000 Ljubljana, Slovenia, leon.pavlovic@fe.uni-lj.si

## Abstract

We report on optical synthesizer concepts for low phase-noise and high output-power optical millimeter-wave generation up to 300GHz. Different types of photodetectors including waveguide *pin*, travelling-wave and waveguide UTC photodetectors have been developed and investigated. By utilizing those photodetectors in conjunction with dual-wavelength laser set-ups we present photonic synthesizer concepts for broadband ($f_{3dB}$>100GHz), w-band (75-110GHz) as well as for wideband (30-300GHz) millimeter-wave generation. The maximum output power level in the w-band exceeds 0dBm and minimum phase noise level is below -85dBc/Hz @ 100kHz offset. We furthermore present novel fiber-optic photodiode packages for broadband operation with a 1mm coaxial (w1) output as well as packages for antenna integrated photodetectors enabling 30-300GHz operation.

## 1. Introduction

Starting from early pioneering experiments in the 1970s, Microwave Photonics today has now become an enabling technology for various commercially emerging applications in the millimeter-wave and even THz frequency range such as fixed and broadband wireless services, in-house communications, instrumentation, remote sensing, radar, radio astronomy, spectroscopy or imaging. This rise is being backed by technological advances on the component and sub-system level achieved worldwide. In view of this, the European Commission has recently funded an integrated project entitled IPHOBAC [1] to coordinate and strengthen European activities in this field of interest. IPHOBAC aims at developing innovative millimeter-wave photonic components and integrated photonic millimeter-wave sources for applications in communication, security/radar and instrumentation. One of the key challenges in that regard is the development of ultra-wideband photodiodes or photomixers for high-power millimeter-wave generation which we will report here. In detail we will present and discuss various types of high-output power PDs developed in the IPHOBAC project. This includes evanescent coupled pin waveguide PDs [2], waveguide coupled UTC PDs [3] as well as partially-doped partially nonabsorbent TWPDs [4]. All of the presented PDs are capable of generating output power levels of 0dBm or higher. We further report on package developments including a broadband package with 1mm coaxial output connector for DC-110GHz operation as well as quasi-optical packages for wideband operation (30-300GHz) using antenna integrated PDs [5]. We finally demonstrate broadband signal generation (DC-110GHz) as well as w-band (75-110GHz) and wideband 50-300GHz millimeter-wave generation using the developed PDs.

## 2. High-speed 1.55µm Photodiode Fabrication

Within the IPHOBAC project different types of photodiode chips are developed, fabricated and investigated with respect to their high output power performances in the mm-wave frequency range. Among the different types of photodetectors developed are waveguide travelling-wave type PD, evanescent coupled pin photodiodes and waveguide UTC photodiodes. Besides developing PD chips with a 50Ω coplanar output, as shown in Fig. 1 (left) for broadband

operation up to 110GHz, the project has also developed waveguide photodiodes with integrated planar antennas for wideband operation up to 300GHz (Fig. 1(right)).

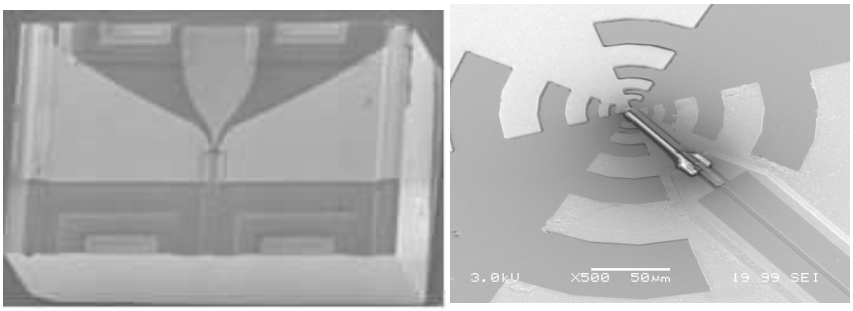


Fig. 1: UTC type waveguide photodetector (left) and waveguide photodiode with integrated planar antenna (right).

## 3. Package Developments

For broadband demonstrations such as optical mm-wave generation up to 110GHz, it is necessary to package the developed PDs. Thus, the project has developed a small form factor, hermetic housing with a coaxial RF output connector. The general concept of the developed housing is based upon a PD package with a V-connector for operation up to 50 GHz. Based upon this concept a package with a w1-connector had been developed (Fig. 2 (left)). Here, a critical point is the RF connection from the photomixer chip to the outer coaxial connector, which must be very broadband, highly efficient, low loss and without resonances. A specially designed grounded coplanar wave (CPW) substrate acts as connecting part between photomixer chip and coaxial connector. Packaged devices show a 3dB cut-off frequency of about 100GHz.

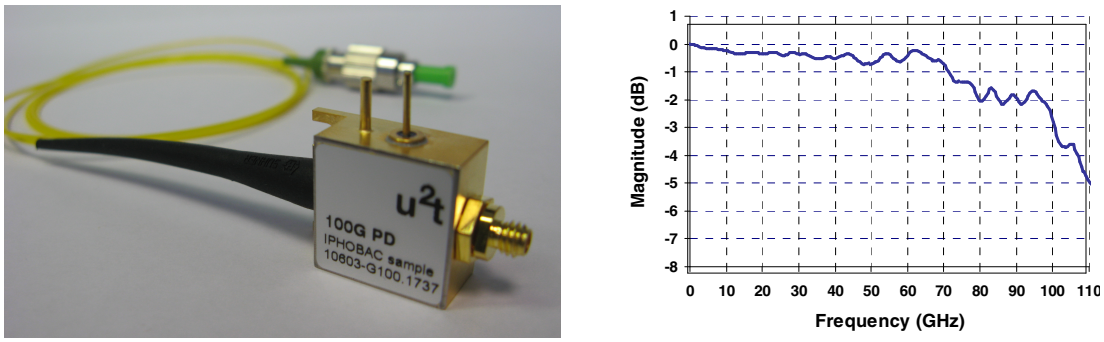


Fig. 2: Packaged photodiode (left) using a package with w1 coaxial output connector and frequency response (right).

We further present a highly-compact fiber-optic package for 30-300GHz wireless transmitter modules with integrated antenna. The overall module size is only 22x17x8.5mm and comprises fiber-chip coupling, electrical beam forming as well as techniques for low millimeter-wave losses. FEM-simulations show that the operational frequency range of the package is at least within 30-300GHz. Furthermore, the package allows a high flexibility in terms of possible chip dimensions. Using this approach, external mm-wave components like antennas or cables can be avoided thus offering a low-cost small-scale solution. A small-series of the presented package has already been constructed. Results with in-house fabricated photomixers with integrated antenna are further presented.

Package simulations with different broadband antenna types (e.g. bow-tie, log-periodic, log-spiral) as well as antenna/quasi-optics sizes have been carried out to analyze the operational frequency range of the package with applied antenna. Best results have been achieved by applying a 2x2mm log-periodic antenna within the package. Sample results achieved with CST Microwave Studio are shown in Fig. 3 (right). The radiation patterns for 60GHz and 300GHz are presented as samples, showing directivities of 12.9dBi and 25.4dBi, respectively. The maximum directivity within the whole targeted operation range is further shown in the figure. Within 30-300GHz, directivity raises from about 8dBi to more than 25dBi.

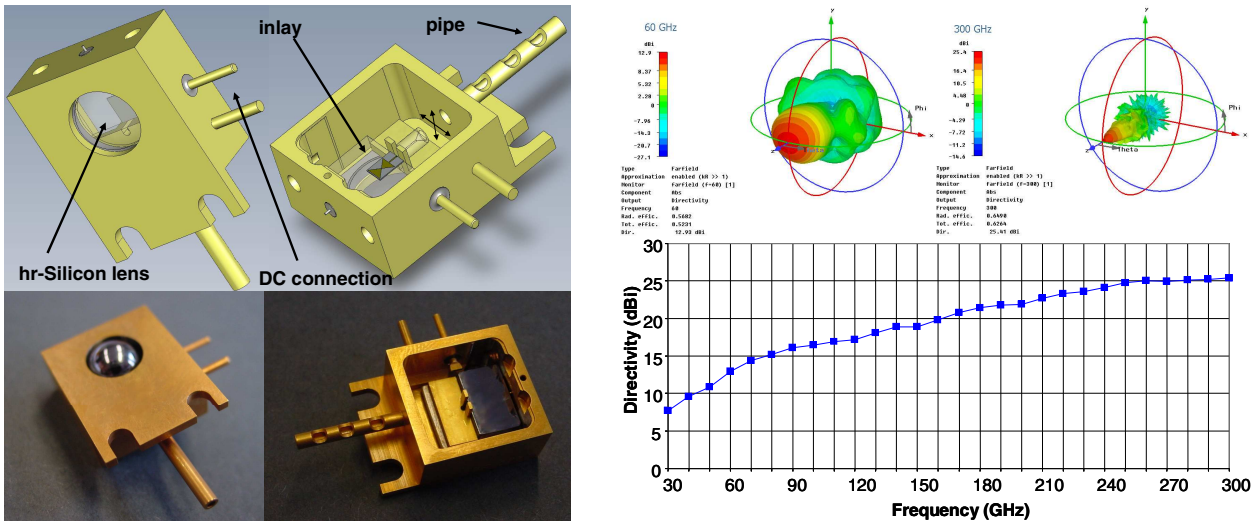


Fig. 3: Quasi-optical package for PDs with integrated planar antennas (left) and simulated antenna directivity (right).

## 4. Optical Millimeter-Wave Generation

For experimentally demonstrating optical mm-wave generation we have used an optical heterodyne set-up with two separate lasers and a packaged photodiode. This enabled a full frequency span from DC to 110GHz. At first, the frequency behavior within a frequency range from DC to 220GHz has been investigated (see Fig. 4 (left)). The measurement results from DC to 110GHz were achieved by using only calibrated devices. As can be seen, a flat and wideband frequency response was achieved with a total signal roll off of about 6dB and output power levels up to -3.23dBm. Considering a frequency range from 20 to 110GHz, total signal roll off is about 3dB. For frequencies larger than 110GHz, uncalibrated probes and mixers were used. Within a span of 110 to 220GHz, signal roll off is about 40dB. For w-band operation the PD was coupled to a WR10 waveguide and a limiting amplifier has been integrated in the synthesizer consisting of two stages and an interstage isolator. The mm-wave signal coupling is performed by WR10 rectangular waveguides. Corresponding to Fig. 4 (right), the frequency response is extremely flat with a power fluctuation of less than 3dB within a frequency range from 69GHz to 112GHz.

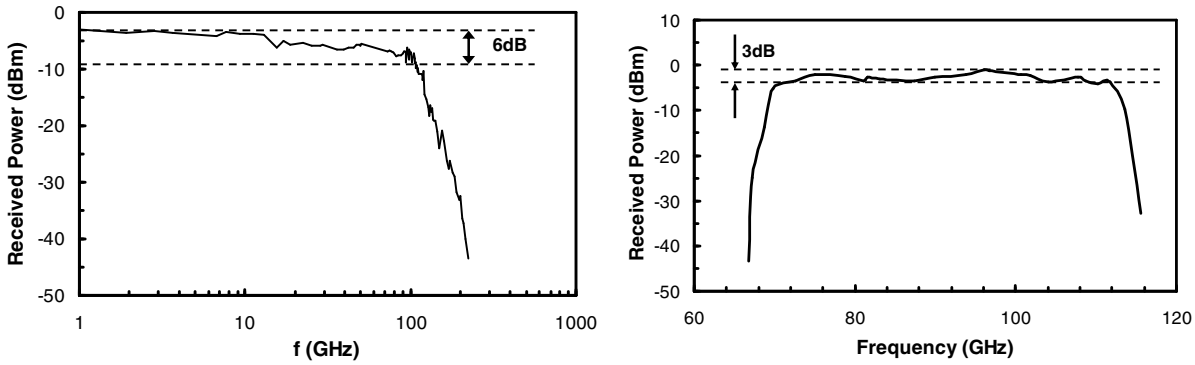


Fig. 4.: Broadband optical mm-wave generation using w1-packaged PD (left) and w-band optical mm-wave generation using PDs coupled to rectangular WR10 waveguides (right).

Using an RF reference signal and external modulation we have furthermore studied low-phase noise generation using the developed PD. At an offset of 100kHz from a 100GHz mm-wave carrier, a low spectrally pure signal with a phase noise level as low as -87dBc/Hz has been achieved.

One of the fabricated photodetectors integrated with antenna was tested for emission at frequencies up to 300 GHz. The emitter was excited with a heterodyne signal coming from two tuneable lasers that have been locked to a reference optical frequency comb generator (Optical injection locking) [6]. The resulting high purity signal was at frequencies ranging from 17 GHz up to 1.5 THz, which was the span of the comb generator. The emitted signal was collected through a lens and measured using a Golay cell, which was calibrated at 110 GHz using standard components and power meters. The device was emitting 1 mW at 50 GHz showing a relatively similar power up to 120 GHz and then the power goes down to 5 µW at 300 GHz (Figure 5).

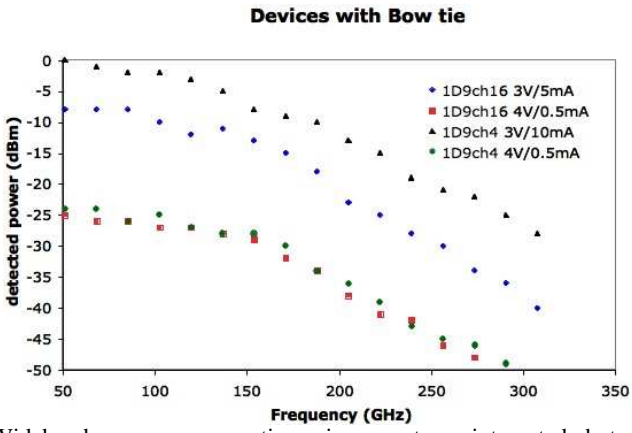

Fig. 5: Wideband mm-wave generation using an antenna integrated photodetector.

## 5. Conclusion

We reported on broadband (DC-110GHz), w-band (75-110GHz) and wideband (30-300GHz) optical mm-wave generation using different types of photodetectors developed in the IPHOBAC project. High mm-wave output power of 0dBm and low phase noise of -87dBc/Hz @ 100kHz offset from a 100GHz mm-wave signal were experimentally demonstrated.

## 6. Acknowledgments

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