Millimetre-wave Photonic Emitter Featuring a PIN-PD with WR-12 Output

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2021 International Topical Meeting on Microwave Photonics (MWP) | 978-1-6654-2610-7/21/$31.00 ©2021 IEEE | DOI: 10.1109/MWP53341.2021.9639424

***Abstract*— We present a photonics based compact broadband emitter module for millimetre-wave signal generation, operating in the E-Band (60 - 90 GHz). A low-loss RF hybrid integration technique is developed to assemble a high-speed and high-power InGaAs/InGaAsP PIN photodiode (PIN-PD) chip into a rectangular waveguide package with WR-12. We demonstrate achieving an output RF power of more than -0.985 dBm (797 µW) at 70 GH frequency.**

Keywords—optoelectronics, microwave photonics, photonic emitters, mm-Wave, PIN-PD, WR-12

I. Introduction

In the recent years, the millimetre wave (mm-Wave, 30 – 100 GHz) and terahertz (THz, 0.1 – 3 THz) frequencies have been exploited for various application such as spectroscopy, imaging, and wireless communications. For the generation of carrier signals in these frequencies, microwave photonics is a key technique, due to its inherent advantage of ultra-broad tunability and ultra-wide modulation bandwidths. As a result, photonics-based wireless transmitters are crucial components to enable the direct conversion of optical to radio frequency (RF) domain, for realising compact RF front-end in radio-over-fibre (RoF) architecture for wireless communication systems [1].

Among the photomixers for mm-Wave and sub-THz generation, the uni-traveling carrier photodiode (UTC-PD) structure, with its variants, is widely used due to its ability to yield high power and bandwidth. In contrast, the PIN photodiode (PIN-PD) structure, which is simpler than its UTC counterpart [2], was thought to have lower bandwidth and output power [3]. For packaging of PDs into the mm-Wave/THz RF front-end modules, three main approaches are used; rectangular waveguide [4], [5], dielectric lens [3], [6] and planar antennas [7], [8]. While each offers its own advantage and application, the former technique allows using standard components such as amplifiers and horn antennas. Among the packaging challenges is the efficient RF integration for minimising the coupling losses. In the best of our knowledge, no such emitter have been reported operating in the E-band (60 – 90 GHz) frequency range using a PIN-PD.

In this work, we present a compact mm-Wave photonic emitter working in the E-band. It features a high speed and high power PIN photodiode (PIN-PD) integrated in a rectangular waveguide package with custom assembly. The output interface is a standard WR-12 waveguide. By using a low-loss RF coupling technique, the developed emitter module yields a continuous wave (CW) RF power of more than -0.985 dBm at frequency of 70 GHz. The performance demonstrated matches with that of the emitters integrating complex PD structures.

II. PIN-PD Emitter Design

A. Emitter Module

The developed photomixing emitter device is shown in Fig. 1(a). We designed a custom aluminium housing for the optoelectronic assembly and integration of active and passive components. It allows optical coupling and DC biasing of the PD chip. The output port is a WR-12 waveguide, placed at the bottom side of module, with a UG-387/U flange for connecting standard waveguide-based components. The dimensions of the module are 40 × 33 × 12 mm^3. The emitter is specifically designed to feed a four-port E-band rectangular orthogonal mode multiplexing (ROM) antenna, we reported recently [9], for spatial multiplexing in wireless communications.

(a)

(b)

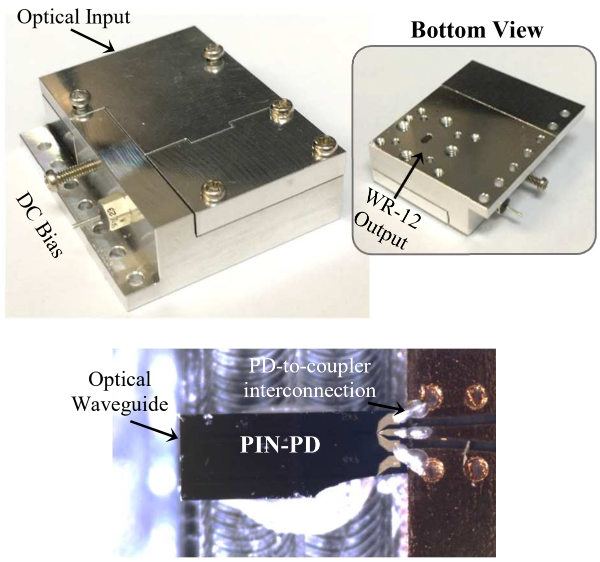

Fig. 1: (a) Picture of packaged photonic emitter for mm-Wave generation with rectangular waveguide WR-12 output and (b) integration of a PIN-PD chip with planar RF circuit using silver-filled epoxy.

The photodiode chip is shown in Fig. 1(b). It is a InGaAs/InGaAsP PIN-type device [3], fabricated on a 500 µm thick InP susbtrate, with 50 Ω coplanar waveguide (CPW) contact pads. These PIN diodes are developed to deliver high output power at mm-Wave and sub-THz frequencies, comparable to that of more complex UTC diodes [10]. We recently demonstrated a PIN-PD based THz emitter in J-band frequency with rectangular waveguide WR-3 interface [11].

The active part of the chip used in this work has dimensions of 5×7 μm². The RF coupling is a critical step in the packaging of high frequency signal sources, which results in considerable loss in signal power. Recently, we integrated the PIN-PD with a planar antenna using a two-wire bond technique, resulting in a more than 6 dB measured loss [12]. In this work, the interconnection is achieved using a silver-filled epoxy. These silver-bonds are expected to less inductive than wire-bonds and improve the RF coupling.

B. *CPW to WR-12 Coupler*

To achieve the transition from CPW input to WR-12 waveguide, a coupler circuit is designed. It converts the QTEM mode into TE_{10} dominant mode of the waveguide. This is achieved by an E-plane probe, with a length L_p equal to the quarter of guided wavelength λ_g in the substrate at central frequency of 75 GHz, which radiates the propagating signal. An aperture of width W, 1.5 mm, and length L, 3.1 mm, in the ground layer guides the radiation into the waveguide section underneath. The overall planar circuit is shown in Fig. 2. A band-stop filter is inserted in the DC line, to block the RF leakage into bias port. The passive circuit is designed on a 127 μm thick commercial low-loss substrate Duroid® 5880 ($\varepsilon_r = 2.2$).

The coupler is simulated using finite element method (FEM) simulator Ansys HFSS. The S-parameters of three-port circuit are shown in Fig. 3 over the entire E-band frequency range. The reflections (S11) at input port are lower than -15 dB from 65 GHz onwards, while the RF-block filter provides better than 20 dB isolation (S31) between the RF and DC ports input ports. The coupler is expected to provide better and insertion loss (S21) of less than 1 dB over 25 GHz of bandwidth.

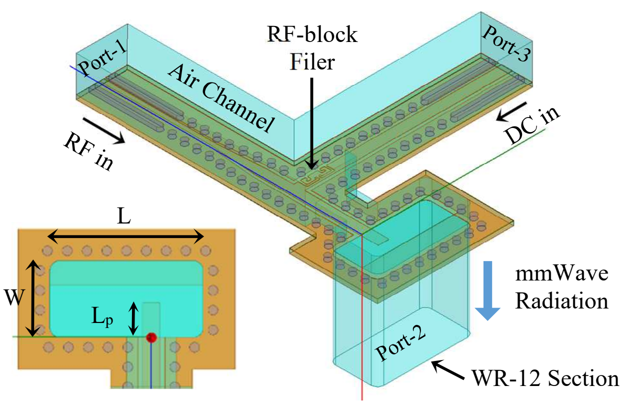

Fig. 2: 3D model of the planar RF circuit including a CPW to rectangular waveguide mode transition and an RF-block filter. Inset: WR-12 coupler parameters.

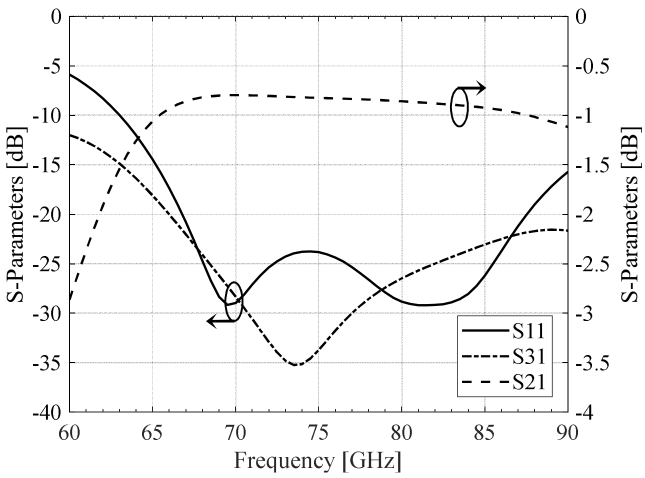

Fig. 3: Simulated performance for CPW to WR-12 coupler circuit showing reflection coefficient (S11), RF isolation at DC port (S31) and insertion loss (S21).

III. Emitter Characterisation

The emitter module is tested to characterise the output power performance using lock-in detection. A picture of the experimental arrangement is shown in Fig. 4, used for measuring the generated mm-Wave power in free-space. The setup uses is a typical optical heterodyne setup, consisting of two CW tunable laser sources (TLS) to obtain two optical tones spaced accordingly, corresponding to the desired carrier frequency f_0. A WR-12 standard horn antenna is connected with the emitter, which has 26 dBi gain and 7° 3-dB beamwidth in E-plane. The emitted radiation is detected by means of a wide-aperture calibrated THz power sensor (Thomas Keating). The narrow-beam antenna and wide area of the detector make sure that most of the radiated power is collected on the sensor window. The output signal is finally detected by means of a lock-in amplifier.

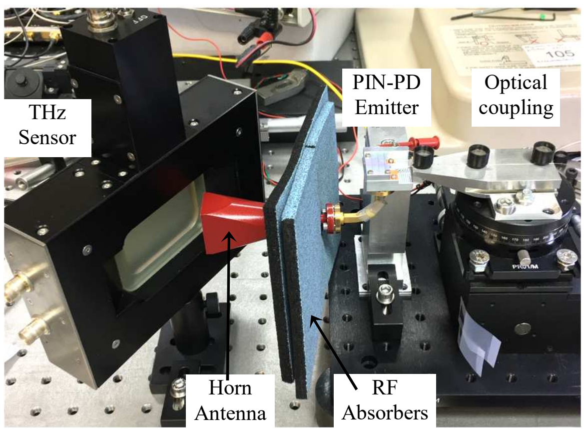

Fig. 4: Experimental setup for measuring the RF power generated by the emitter module.

The measured output power is plotted in Fig. 5 at carrier frequency of 70 GHz. The graph shows the dependence of RF power on the DC photocurrent, with PIN-PD biased at -2 V. As can be seen, the power increases quadratically and no saturation is observed. Due to the limited optical power available and losses in optical coupling, the photocurrent is limited to 9.5 mA while the diode saturates at 12 mA. Nonetheless, a decent CW power of -0.985 dBm (797 μW) is achieved. The peak saturated power is expected to be over 0-

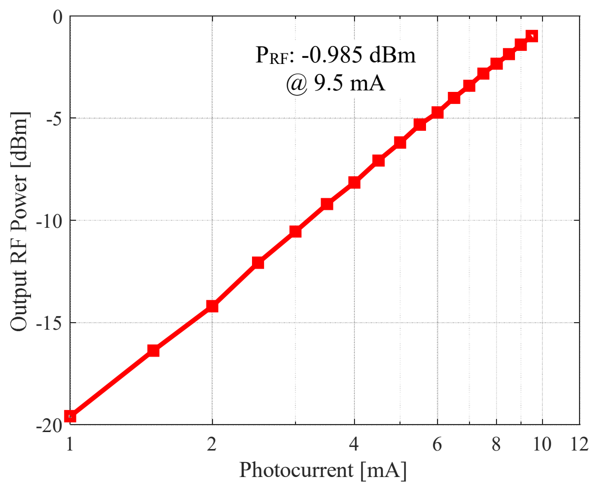

Fig. 5: Measured RF power vs. DC photocurrent at carrier frequency of 70 GHz at bias voltage of -2 V.

dBm. For comparison, our previous emitter module employing wire-bonds [12] produced -7.1 dBm of radiated power for the same frequency and photocurrent. As a result, significant improvement can be achieved in the emitter module by employing the epoxy-coupling technique. It is worth noting that in terms of output power, our PIN-PD module performs as good as other integrated photomixing emitter modules devices in presented in literature, working in similar frequency range using UTC-PD and other modified structures [4], [5][13].

IV. Conclusion

We have demonstrated a photonic wireless emitter integrating a high-speed and high-power PIN photodiode with a wideband CPW to WR-12 coupler. A CW radiated power of -0.985 dBm was achieved for the PIN-PD module, which is comparable to the emitters employing its UTC counterparts. The low-loss RF coupling was achieved by means of epoxy-bonding technique. This technique, along with our PIN-PD, can be used to develop waveguide-based efficient sub-THz emitters using 2D hybrid integration.

Acknowledgement

This work has been supported by European Cooperation in Science and Technology (COST) under action EUIMWP CA16220, as well as by TERAWAY project, (https://ict-teraway.eu/) under grant agreement No. 871668. Author Muhsin Ali thanks Philipp Meyer at Fraunhofer HHI for assisting in cleaving InP chips.

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