Compact Photonic Millimeter Wave (200-300 GHz) Transmitters Based On Semicircular Bow-Tie Antenna-Integrated 1.55 μm Triple Transit Region Photodiodes

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Abstract—In this work, we present an on-chip integrated continuous wave (cw) photonic transmitter (PT) covering frequencies within 200-300 GHz in the millimeter wave (mmW) range. The compact PT (2x2 mm²) is realized by merging a planar broadband semicircular bow-tie antenna (SCBTA) structure (featuring hole slots) with a passive optical waveguide (POW) integrated high-speed 1.55 μm waveguide (WG) triple transit region photodiode (TTR-PD). In addition, an advanced PT concept with a monolithically integrated ridge-type semiconductor optical amplifier (SOA) WG is introduced. This is to reduce optical input power density at the PT chip facet and further to compensate optical losses in the POW. Based upon the method of moments (MoM) calculations, a peak return loss of ~27 dB and antenna directivities (even without a silicon lens) exceeding 10 dBi were obtained in the frequency range of interest. Experimentally, a tunable frequency range of 200-300 GHz, along with a 6-dB bandwidth, was achieved for fabricated SCBTA-integrated PT chips, which provide output power levels in excess of -10 dBm.

Index Terms—Broadband antennas, millimeter wave devices, optical waveguides, radio frequency, triple transit region photodiodes.

I. INTRODUCTION

Recently, the research community and numerous emerging markets engaged in wireless radio-over-fiber (RoF) communications spark raised interest in photonic millimeter wave (mmW) technology for generation and detection of ultra-high capacity data signals within 30-300 GHz [1],[2]. A matter of special importance is the upward trend of operating carrier frequency essential for various application areas such as wireless point-to-point or rather point-to-multipoint multi-gigabit communication systems. Concerning wireless use, the entire mmW frequency band, e.g. covering the license-free 7 GHz bandwidth within the 60 GHz band (57-64 GHz) or the recently regulated 10 GHz bandwidth within both the 70 GHz (71-76 GHz) and 80 GHz (81-86 GHz) bands, has been partly allocated by regulatory bodies throughout the world [3]. In particular, the frequency range of 200-300 GHz provides relatively low atmospheric absorption losses (e.g. in comparison to the 60 GHz band) for transmission of multi-gigabit capacities. Here, fixed wireless transmission systems for overcoming spans of >1 km are able to achieve up to 100 GHz bandwidth [2].

Though, high-capacity wireless transmission systems capable of optical access and metro networks necessitate more and more extremely compact devices, which permit wideband tunability in combination with ultra-broadband modulation capabilities and further utilize optical fiber approaches for low-loss mmW propagation. Therefore, a great deal of attention is also attracted to overcome the bulky assembling of costly single devices. At this point, photonic integration of a component with several devices on one chip is a key approach. For instance, an essential component employed in wireless RoF systems is a PD or rather a WG PD, e.g. consisting of POW and PD sections as part of a wireless PT with an integrated antenna.

In this work, we report on a compact on-chip integrated cw SCBTA-PT operating at mmW frequencies within 200-300 GHz. Furthermore, monolithic integration of a SOA structure in the POW section of the high-speed and high-power 1.55 μm WG TTR-PD for reduction of optical input power density at the front coupling surface and compensation of optical losses up to the light absorption in the active WG TTR-PD section is presented.

II. POW-INTEGRATED WG TTR-PD

Approaching analog applications within a wide frequency range, high-speed InP-based mushroom-type 1.55 μm WG TTR-PDs with an integrated POW for efficient optical fiber coupling were developed and introduced in [4],[5]. A schematic showing the operation principle of the WG TTR-PD with a coplanar waveguide (CPW) circuitry and further an output microstrip feed line for the connection with a planar antenna is presented in Fig. 1.
For discrete TTR-PD chips, a 3 dB bandwidth beyond 110 GHz and a return loss exceeding 20 dB were demonstrated besides high-output power levels in excess of 0 dBm. Beyond that, DC responsivities of up to 0.5 A/W have been experimentally achieved for fabricated TTR-PDs without anti-reflection coatings. This was attained by three transit layers of the applied TTR structure, in which velocity saturation or even velocity overshoot emboss the electron drift, and by the high-frequency mushroom-type WG PD architecture. More details can be found in [5].

III. SOA-INTEGRATED WG TTR-PD

Besides wideband tunability in the frequency band of interest, the PT should offer high output radio frequency (RF) power levels for wireless transmission. Thus, high external quantum efficiency of the WG TTR-PD for high-current operation under relatively low optical input power conditions is desired. Given that a defined absorption length of the active TTR-PD section is of particular interest for high-frequency operation, integration of a POW for coupling the optical signal from a single-mode fiber (SMF) to the WG TTR-PD chip is essential. However, residual optical losses such as fiber coupling or propagation losses of a long POW somewhat limit the external quantum efficiency of the TTR-PD. For this reason, internal amplification of the optical signal seems to be useful to compensate these losses. Additionally, a reduction of the optical input power density at the coupling facet of the PT chip could be achievable.

Therefore, adapted from the InGaAsP/InP-based POW approach, e.g. reported in [6], a shallow ridge-type SOA-WG with a quaternary core material (i.e. InGaAsP) was designed, which leaves an external optical signal amplification out (e.g. by a SOA module). A model of the SOA-integrated WG TTR-PD is schematically shown in Fig. 2.

As further shown in Fig. 4, the integrated SOA is able to exhibit unsaturated gain levels of up to 21 dB dependent on the active layer thickness ($D$). Furthermore, maximum optical output power levels of up to +17.5 dBm are achievable but result in suffering gain levels at the 3 dB power drop-off saturation point.

In addition, SOA characteristics have been investigated, adapting the analytic model reported in [7],[8]. In contrast to the presented approach utilizing a buried SOA structure, the employed shallow ridge approach was implemented. For example, selected parameters used for considerations of the WG TTR-PD with an integrated SOA featuring a 50 nm active layer thickness are summarized in Tab. 1.

![Fig. 1. Schematic of the InP-based WG TTR-PD with an integrated POW.](image1)

![Fig. 2. Schematic of the SOA-integrated WG TTR-PD.](image2)

![Fig. 3. Optical mode propagation (BPM).](image3)

![Fig. 4. Overall gain plotted against optical input power as well as optical output power.](image4)
Considering the trade-off between gain and optical output power, a compromise has to be made (see Fig. 5). Thus, the SOA with an appropriate active layer thickness of 50 nm, which is sufficient to achieve an optical output power of around +12 dBm at the saturation point, is chosen. Accepting somewhat lower output power levels in the order of +11 dBm but in return obtaining higher gain, active thicknesses of up to 100 nm can be taken into account. Assuming that an optical power level of around +12 dBm would be directly applied to the active TTR-PD, a clearly increased responsivity (>0.5 A/W) is expected. Experimental results will be presented elsewhere.

IV. SCBTA-INTEGRATED WG TTR-PD

As illustrated in Fig. 1, the compact cw mmW PT with a chip area of 2x2 mm² is realized by merging a broadband SCBTA with a high-speed 1.55 μm WG TTR-PD.

The WG TTR-PD (in combination with a ridge-type POW for optical coupling) is integrated at the feeding point of the planar SCBTA structure (see also [6]). Here, a peak return loss of ~27 dB was simulated using the MoM and is presented in Fig. 7.

Thus, antenna directivities exceeding 10 dBi were obtained in the frequency range of interest even without a HRFZ-silicon lens. Experimentally, a tunable frequency range of 200-300 GHz, along with a 6-dB bandwidth, was achieved for fabricated SCBTA-PT chips, which permit output power levels in excess of -10 dBm.
V. CONCLUSION

In this paper, we introduced compact cw mmW (200-300 GHz) SCBTA-integrated PTs featuring 1.55 μm WG TTR-PDs. Besides, we presented a compact SOA-integrated WG TTR-PD design targeting at high output RF power levels at mmW frequencies beyond 200 GHz (even at low optical excitation). Furthermore, mmW generation was demonstrated within the 200-300 GHz range for SCBTA-PTs comprising hole slots in the antenna structure.

ACKNOWLEDGMENT

The authors wish to acknowledge the contributions of M. Kost and T. Schroeder from Universität Duisburg-Essen for device simulation and M. Wachholz from Universität Duisburg-Essen for support in device fabrication.

REFERENCES


