Integrated Ψ-Type Photonic Polarization Diversity Receivers for Wireless Radio-over-Fiber Communication Links

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Abstract
In this work, we present novel integrated Ψ-type photonic polarization diversity receivers (PPDRs), comprising two high-frequency 1.55 µm photodiodes (PDs) applicable in wireless radio-over-fiber (RoF) communication links. Therefore, geometries in the overall optical beam splitter (OBS) output section, e.g. optical mode-guiding stripe height, gap between the optical waveguides (WGs), WG widths and coupling length, are considered to obtain high polarization diversity for the developed PPDRs. Moreover, we demonstrate first experimental achievements based on the coupling length variation. In comparison to a conventional 3-dB Y-coupler-integrated device, the experimental results show a polarization-dependent behavior of the PPDR with a maximum polarization dependent loss (PDL) of >3 dB (e.g. measured at the WG-PDs) due to the integrated Ψ-type OBS output section. Taking further geometry parameters of the PPDR into consideration, an increased PDL is expected for the monolithically integrated WG-PDs.

Key words
Compact photonic packages, high-speed photodiodes, integrated optical mode transformers, passive optical waveguides, photonic polarization diversity receivers, polarization multiplexing, radio-over-fiber applications

I. Introduction
Nowadays, photonic millimeter wave (mmW) generation and detection systems are most welcome for plenty of emerging markets. For example, applications cover broadband mmW transmitters and receivers for wireless RoF communications, e.g. within the E-band (60-90 GHz) [1].

By means of a dual wavelength light source, radio frequency (RF) mmW generation can be attained by light excitation of a photodetector responsible for optoelectronic mmW signal conversion, commonly used in a photonic approach. Afterwards, the generated mmW signal can be radiated, e.g. via an external horn antenna [2]. Nevertheless, appropriate mmW modules mostly used in wireless communication systems still consist of numerous costly and bulky mmW components, e.g. coaxial cables, rectangular or circular waveguide connectors, adapters or rather transitions, entailing undesirable effects like power losses and expanded module dimensions. For this reason, photonic realization of an all-embracing integrated device within a single package would be key.

Here, we report on novel integrated Ψ-type PPDRs for application in wireless RoF communication systems within the mmW frequency range.

II. Principle of Operation
For operation at optical communication wavelengths around 1.55 µm (e.g. within the conventional band), Fig. 1 shows a schematic diagram of the developed PPDR featuring two WG-coupled high-speed (>30 GHz) 1.55 µm PDs. Efficient optical fiber-chip coupling is accomplished between a conventional cleaved single-mode fiber (SMF) and a monolithically integrated optical mode transformer (OMT), which is the initial part of an InGaAsP/InP-based passive optical waveguide (POW). The entire POW section is based on a mono-mode ridge-type WG approach. The POW is employed for guiding the optical mode to the OBS, e.g. after low-loss coupling of the optical mmW
signal from the SMF thanks to the OMT. In the OBS section, which is based on studies presented in [3], the POW is extended by an additional bi-mode WG for polarization-sensitive directional splitting of the propagating transversal electric (TE) and transversal magnetic (TM) modes. For effective directional splitting, the polarization dependency can be obtained by the alignment of geometry parameters such as the mode-guiding stripe height, the gap between the mono- and bi-mode WGs, the mono-mode WG width ($w_{\text{mono}}$), the bi-mode WG width ($w_{\text{bi}}$) and the coupling length ($l_c$).

Hereafter, both the TE-mode and the TM-mode independently propagate in the Ψ-type optical output section (OOS). Thus, the TM-mode guiding waveguide (WG$_{\text{TM}}$) is connected to the photodetector (PD$_{\text{TM}}$) shown in the upper part of Fig. 1. For the TE-mode propagation, two guiding WGs are introduced. The intersection between the OBS and OOS is applied as a further mode transformer [3]. The dominating mono-mode waveguide (WG$_{\text{TE}}$) is connected to the photodetector (PD$_{\text{TE}}$) shown in the lower part of Fig. 1 and supported by the non-leading second WG. The photodetectors comprise two high-speed (>30 GHz) InP-based 1.55 μm WG-PDs. Consequently, two electrical mmW signals are generated simultaneously after optoelectronic conversion and coupled to related output coplanar waveguide (CPW) circuitries (see Fig. 2). For biasing the PDs, an integrated bias-T is implemented for each PD. Details on integrated PDs can be found in [4], [5]. The mmW signals can be further fed to external (metallic) rectangular waveguides (such as WR-12) by the use of hybrid integration, e.g. on a RF laminate submount in the module package [6]. For directional mmW radiation, additional horn antennas are required.

III. Design and Fabrication

For calculating the optical mode splitting efficiency, the beam propagation method (BPM) was used for numerical analyses. First results based on the coupling length variation showed a polarization-dependent splitting behavior within the OBS and OOS. Moreover, non-leading behavior was clearly shown in the supporting WG. Details have been presented in [7].

For technological realization, a completely monolithic integration was applied to the device. The fabricated InP-based Ψ-type PPDR chip is illustrated in Fig. 2, including the guiding waveguides, e.g. WG$_{\text{TE}}$ and WG$_{\text{TM}}$, and the corresponding WG-PDs (PD$_{\text{TE}}$ and PD$_{\text{TM}}$). Selective chemical etching was applied to the POWs and the active WGs. Conventional metal deposition techniques were used for direct current (DC) and RF circuitries. The fabrication was performed within the European collaborative projects euroPIC [4] and PARADIGM [5]. For comparison, chip bars have been fabricated comprising five PPDRs varying in the coupling length and an additional device integrated with an optical 3-dB Y-coupler instead of the OBS and the OOS (see Fig. 3).

IV. Experimental Results

For characterizing the polarization diversity of the PPDR chips, PDLs at both the PD$_{\text{TE}}$ and the PD$_{\text{TM}}$ were measured. The setup used for characterization is shown in Fig. 3. For this purpose, one of the devices from the chip bar was biased by four needles. A drive voltage of -2.8 V was applied to each PD of the device. For fiber-chip coupling, a cleaved optical SMF was used. The optical input power level was in the order of -4.2 dBm. The chip bar was placed on a thermoelectrically cooled device-under-test (DUT) submount.

Fig. 1: Operation principle of the integrated Ψ-type photonic polarization diversity receiver

Fig. 2: Fabricated Ψ-type PPDR chip featuring two high-speed (>30 GHz) InP-based 1.55 μm WG-PDs [4], [5]
Fig. 3: Measurement arrangement for characterization of PPDR chip bars

Fig. 4 shows PDL measurements of different Ψ-type PPDRs at an optical wavelength of 1.55 µm. Here, devices with different coupling lengths of the OBS section, e.g. between 200 µm and 600 µm, are investigated. A clear polarization-sensitive behavior can be identified for the PD_{TE}. As a result, a maximum PDL (~3 dB) and a minimum PDL (~0.9 dB) are measured for devices comprising coupling lengths of 200 µm and 600 µm, respectively.

Fig. 4: PDL measurements of Ψ-type PPDRs with varying coupling lengths at a wavelength of 1.55 µm

By comparison, WG-PDs integrated in devices with conventional 3-dB Y-couplers showed a PDL in the order of 0.8 dB, which confirmed the given PDL of a discrete PD [5]. Detailed experimental characterization can be found in [7]. Since the maximum PDL is found at the PD_{TE} of a PPDR with a coupling length of 200 µm, further investigations covering a wider wavelength range have been carried out. The results are presented in Fig. 5. At this point, a PDL even higher than 3 dB was observed at a 1.57 µm wavelength.

Fig. 5: PDL measurements of a Ψ-type PPDR featuring a coupling length of 200 µm at different wavelengths

In the next steps, further geometry parameters will be taken into consideration, promising an increased PDL for both WG-PDs of the integrated PPDRs.

V. Packaging

For packaging the PPDR chips, a compact module housing was designed. A schematic of the photonic package is presented in Fig. 6, giving a general overview of means and techniques to obtain wireless mmW generation. As shown in Fig. 6, the module design provides a dual WR-output introducing two rectangular waveguides (e.g. WR-12) for coupling out of the generated mmW signals and thus utilizing polarization multiplexing (PolMUX). A RF laminate platform is contemplated for hybrid integration of the PPDR chip in the packaged module. A similar integration approach for a single PD was already presented in [6]. The related packaging approach will be also presented at the conference [8].

Fig. 6: Package design of a compact dual WR-output module for integration of PPDR chips

The module further comprises a DC feed for biasing the PPDR chip and an optical input, which offers means for an optical (cleaved) SMF to accomplish fiber-chip coupling.
IV. Conclusion

Here, we reported on novel photonic integrated Ψ-type PPDRs for wireless RoF communication links (e.g. using PolMUX techniques). Utilizing integrated high-speed (>30 GHz) 1.55 µm PDs, first experimental results showed a polarization-dependent behavior of the devices with maximum PDLs of >3 dB (PD_{TE}) due to the monolithically integrated OBS and Ψ-type OOS. For instance, devices integrated with conventional 3-dB Y-couplers provided PDLs in the order of 0.8 dB. Furthermore, the concept of a compact photonic dual WR-output package was presented for the PPDRs.

Acknowledgment

This work was supported by the European collaborative projects euroPIC (grant no. CP-TP 228839-2 EuroPIC) and PARADIGM (grant no. 257210). The authors wish to acknowledge the support of Andreas G. Steffan and Sascha Fedderwitz from u’t Photonics AG in device measurements.

References