# Monolithically Integrated Balanced Uni-Traveling-Carrier Photodiode with Tunable MMI Coupler for Microwave Photonic Circuits

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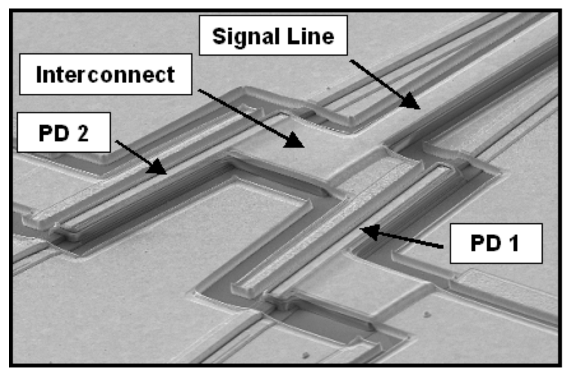
***Abstract*—A monolithically integrated balanced uni-traveling-carrier photodiode (UTC-PD) with a tunable 2x2 multimode interference (MMI) coupler has been fabricated and tested. Two waveguide UTC-PDs are electrically isolated using high-energy Helium implantation, and then connected in series using a monolithic metal interconnect. On chip metal-insulator-semiconductor (MIS) capacitors provide some DC decoupling. The tunable MMI coupler allows for tuning of the power balance in the PDs. Output saturation currents greater than 40 mA at 1 GHz are demonstrated for a single 10 μm x 150 μm UTC-PD. The third order intermodulation distortion (IMD3) is also measured and exhibits an output intercept point (OIP3) of 43 dBm at 20 mA and 34 dBm at 40 mA for this same UTC-PD. In the balanced configuration, the OIP3 values are therefore 49 dBm and 40 dBm. The balanced UTC-PD is also highly symmetric; the common mode rejection ratio (CMRR) was measured to be around 40 dB.**

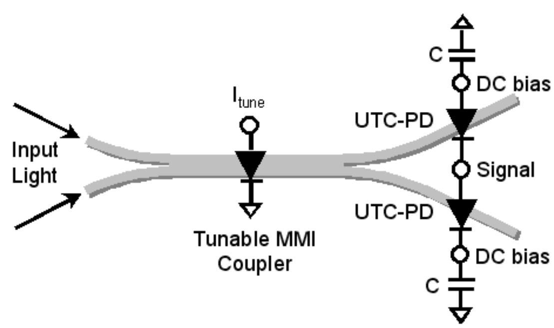
***Keywords-balanced photodiode (BPD), common mode rejection ratio (CMRR), fiber-optic link, linearity, saturation current, third order intermodulation distortion (IMD3), third order output intercept point (OIP3), uni-traveling-carrier photodiode (UTC-PD).***

## I. INTRODUCTION

Phase modulated coherent fiber-optic links have the potential for greatly enhanced spur free dynamic range (SFDR) [1]. The backbone of a coherent link is the coherent optical receiver used to demodulate the phase of the received signal. A coherent receiver consists of a coupler for mixing the incoming signal with a local oscillator (LO) signal, and a balanced photodiode (BPD) for detecting the phase difference between the two waves. BPDs are employed because of their ability to suppress laser relative intensity noise (RIN) [2]. Some of the desired attributes for a coherent receiver are high power, high linearity, and large CMRR. A pin BPD has been reported with more than 20 dB CMRR [3]. UTC-PDs are attractive for BPDs because of their high saturation current capabilities made possible by reduced space charge effects [4]. Recently an advanced device architecture has been developed allowing for the monolithic integration of waveguide UTC-PDs with other optical components [5]. A monolithically integrated coherent receiver is advantageous because the optical power coupled to the PDs can be maximized. In this work, we have fabricated and tested a monolithically integrated BPD consisting of two series connected UTC-PDs,




(a)




(b)

Fig. 1. (a) SEM image of UTC-PD pair connected in series and (b) schematic of balanced UTC-PD with integrated tunable MMI coupler.

a tunable 2x2 MMI coupler, and DC decoupling capacitors. With a single regrowth process, several optical components have been monolithically integrated to form a highly functional microwave photonic circuit. The UTC-PDs exhibit both high saturation current and high linearity. The MMI can be fine tuned to a 50:50 splitting ratio allowing for accurate control of the power balance in the PDs. The BPD is also highly symmetric lending to a large CMRR.

## II. Device Design and Fabrication

The device structure is grown on a semi-insulating InP substrate by MOCVD. The optical waveguide consists of unintentionally doped (UID) InGaAsP QWs and barriers sandwiched between two InGaAsP waveguide layers. The bandgap wavelength of the QWs is significantly detuned from the input wavelength in order to minimize optical losses in the passive sections of the device. The UTC-PD structure is grown above the optical waveguide. This consists of a highly n-doped InP layer, followed by a UID InP collection layer, some band smoothing layers, and a highly p-doped InGaAs absorbing layer. Photodetection regions are formed by selectively removing these UTC-PD layers. The highly n-doped InP layer ensures that the electric field drops only across the collection layer in the photodetection regions. After formation of these regions, a blanket InP cladding regrowth is performed. Following regrowth, ridges and mesas are etched. Topside n- and p-contacts are then deposited and annealed. Benzocyclobutene (BCB) dielectric is used for reducing parasitic pad capacitance. The UTC-PDs are electrically isolated with a series of high energy Helium implants ranging in energy from 40 keV to 1.325 MeV. This provides a sheet resistance of 5.28 MΩ/square on the n-side and 2.46 MΩ/square on the p-side of the diodes as determined by transmission line model (TLM) measurements. A SEM and schematic of the balanced UTC-PD are shown in Fig. 1. The PDs are connected in series with a monolithic metal interconnect. This electrical isolation and series connection technique has been used in previous work for the fabrication of tunable bipolar cascade lasers and photonic integrated circuits (PICs) [6]. The MIS capacitors are fabricated by sandwiching a thin layer of dielectric between the p-metal and a buried n-contact layer. The capacitance is around 30 pF but can be varied simply by adjusting the dielectric thickness.

The 2x2 MMI coupler is a general interference type MMI [7]. It is 8 μm wide and 336 μm long. For tuning, current is injected uniformly across the width and into a region 70 μm long in the center of the MMI. In a MMI, the input field is reproduced in single or multiple images at periodic intervals. By modifying the refractive index around a selected area within one interval of the MMI, new phase relations between self-images are produced in the next interval resulting in a modified output image [8]. Therefore locally injecting current to change the refractive index can be used to tune the splitting ratio of the MMI.

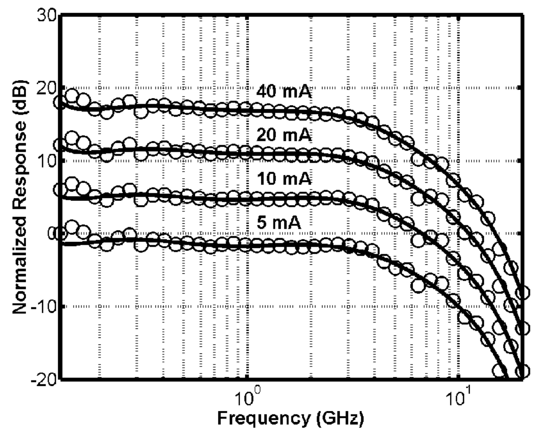



Fig. 2. Normalized response of a 10 μm x 150 μm UTC-PD at varying photocurrent levels. The bias is –5 V.

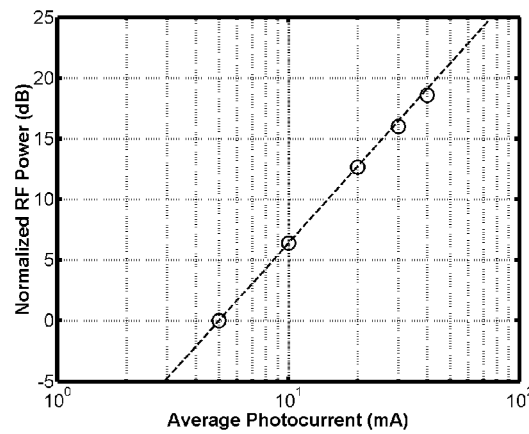



Fig. 3. Normalized RF power as a function of average photocurrent at 1 GHz for a single 10 μm x 150 μm UTC-PD. The bias is –5 V.

## III. Results

To characterize the saturation current and linearity of the UTC-PDs, they were measured discretely. The optical-to-electrical frequency response was measured using a lightwave component analyzer. Fig. 2 shows the normalized response for up to 40 mA of average DC photocurrent for a single 10 μm x 150 μm UTC-PD. Fig. 3 shows the normalized RF power as a function of average DC photocurrent. The saturation current is greater than 40 mA at a bias of –5 V. The IMD3 was measured using a two-tone setup similar to that in [9]. Two DFB lasers were externally modulated to generate two tones, and the signals were combined in a 3 dB coupler.

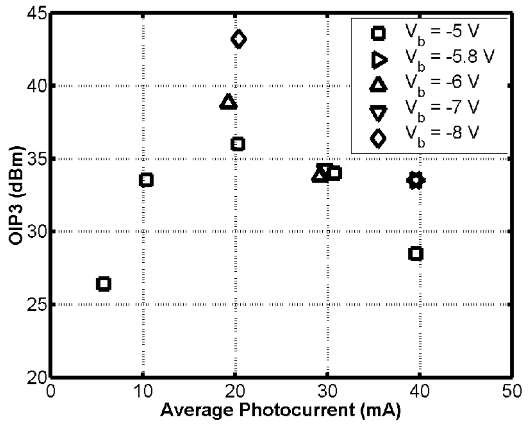



Fig. 4. OIP3 as a function of average photocurrent for varying biases. This is for a single 10 μm x 150 μm UTC-PD.

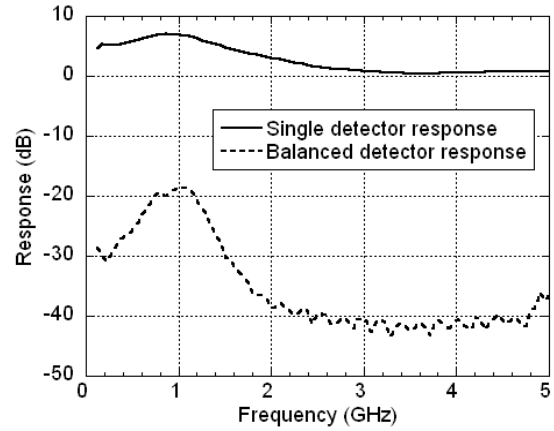



Fig. 6. Frequency response measurement with optical input to single PD and with balanced optical input.

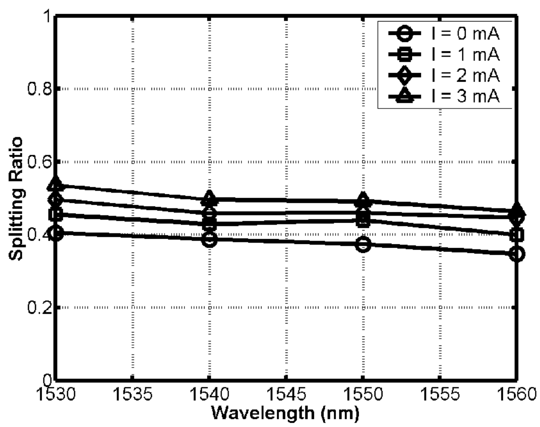



Fig. 5. Tunable MMI coupler splitting ratio as a function of wavelength for several current injection levels.

An EDFA was used to vary the optical power input to the UTC-PD. Fig. 4 shows a plot of the extracted OIP3 as a function of average DC photocurrent for several biases. For a fixed photocurrent level, say 20 mA, increasing the reverse bias enhances the OIP3 by reducing space charge effects in the PD [10]. The OIP3 at 20 mA and a bias of –8 V was 43 dBm and at 40 mA and a bias of –5.8 V was 34 dBm. This corresponds to 49 dBm and 40 dBm in the balanced configuration. To the best of our knowledge, these are some of the highest OIP3 values reported for a waveguide PD.

To characterize the tunability of the MMIs, the splitting ratio was measured over a wide wavelength range for varying levels of injected current. Fig. 5 shows that with just a few milliamps of injected current, the splitting ratio can be adjusted in order to balance the power in the output arms of the MMI. This indicates that only slight changes in refractive index are necessary for tuning the splitting ratio. If higher refractive index changes and thus higher levels of injected current were necessary, the device performance could degrade [8]. The CMRR was measured by comparing the measured electrical response with light input to one UTC-PD to that with light input to both UTC-PDs with a balance of optical power. To do this, the tunable MMI coupler was used to achieve a maximum power imbalance and then an optimized power balance. Fig. 6 shows the corresponding measured frequency responses. The CMRR is 40 dB for frequencies above 2 GHz.

## IV. CONCLUSIONS

We have fabricated and characterized a waveguide balanced UTC-PD where adjacent UTC-PDs are electrically isolated using high energy Helium implants and series connected with a metal interconnect. The BPD has been monolithically integrated with a tunable 2x2 MMI coupler using a simple single regrowth fabrication process. By injecting current into a section of the MMI to locally change the refractive index, the splitting ratio can be tuned to balance the power in the PDs. A single UTC-PD has a saturation current greater than 40 mA and OIP3 values of 43 dBm and 34 dBm at DC photocurrent levels of 20 mA and 40 mA respectively. These correspond to 49 dBm and 40 dBm for the balanced configuration. The splitting ratio of the MMI coupler can be tuned with just a few milliamps of injected current. The BPD has a CMRR of 40 dB as measured by comparing the electrical response with light input to a single PD to that with a balanced optical input. This BPD can be used for enhancing the performance of coherent fiber-optic links as well as other microwave photonic links.

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