Generation of 10.2 dBm millimeter-wave power at 100 GHz using soliton microcomb and modified uni-traveling carrier photodiode

Fatemehsadat Tabatabaei[1,*], Jesse S. Morgan[1], Shuman Sun[1], Samin Hanifi[1], Ruxuan Liu[1], Steven Estrella[2], Madison Woodson[2],
Steven M. Bowers[1], Xu Yi[1], and Andreas Beling[1]

1. Department of Electrical and Computer Engineering, University of Virginia, 22903, Charlottesville, VA, USA
2. Freedom Photonics LLC, 93117, Santa Barbara, CA, USA
*ft4xx@virginia.edu

***Abstract*—We demonstrate photonic generation of millimeter-wave power by detecting a soliton pulse train with an InGaAsP/InP modified uni-traveling carrier photodiode. The maximum output power reaches 10.2 dBm at 27 mA, surpassing the maximum power of 9.1 dBm at 34 mA obtained from 2-laser line heterodyning.**

***Keywords*—photodiode, microcomb, microwave photonics**

I. INTRODUCTION

High-speed photodiodes (PDs) are key components in photonic systems that can address emerging applications in the microwave and millimeter-wave (mmWave) regime [1-3]. These systems are often limited by the PD's saturation effects and suffer from the power roll-off associated with the PD's bandwidth. Leveraging recent progress in integrated microresonators, we have shown that the PD's output power in the linear regime can approach the theoretical limit of conventional 2-laser line heterodyne detection at 100 GHz when the PD is illuminated with soliton microcomb [4]. This is possible due to the constructive interference of the many comb lines that produce mmWave power at the repetition rate when detected in the PD [5]. In this work we demonstrate that the maximum power generated from soliton microcomb in a charge-compensated modified uni-traveling carrier (CC-MUTC) PD can exceed the maximum power available from heterodyne detection while at the same time the PD dissipates less power.

II. EXPERIMENTAL RESULTS

The PD used in this experiment is an 8-µm diameter back-illuminated CC-MUTC PD with 0.19 A/W responsivity at 1550 nm and a dark current of 0.5 nA at -3 V. Operating mostly under the mechanism of single carrier transport, CC-MUTC PDs are prime candidates for high-speed and high-power applications [6]. The fact that the photocurrent is mainly based on fast electrons enables short carrier transit and thus high bandwidth. The transparent drift layer is lightly n-type doped for charge compensation. The charge from the ionized donors pre-distorts the electric field and can counteract the space charge effect at a high photocurrents and thus reduce saturation. More details about the CC-MUTC PD's layer structure can be found in [7]. To further improve thermal management and thus power handling, the PD die is flip-chip bonded to a gold-plated coplanar waveguide (CPW) on a high thermal conductive aluminum nitride (AlN) submount [8]. The short CPW serves as probe pad and was designed to have a characteristic impedance of 50 Ω with minimal impact on the PD's frequency response. A cross sectional view of the device is shown in Fig. 1(a). The frequency response of the PD was measured with an optical heterodyne setup consisting of two free-running external cavity lasers that produce a tunable beatnote with near 100% modulation depth. As shown in Fig. 1(b), the PD has a 3 dB-bandwidth of 75 GHz, 73 GHz, and 68 GHz at 15 mA, 5 mA, and 3 mA respectively. At 15 mA, the roll-off in power is only

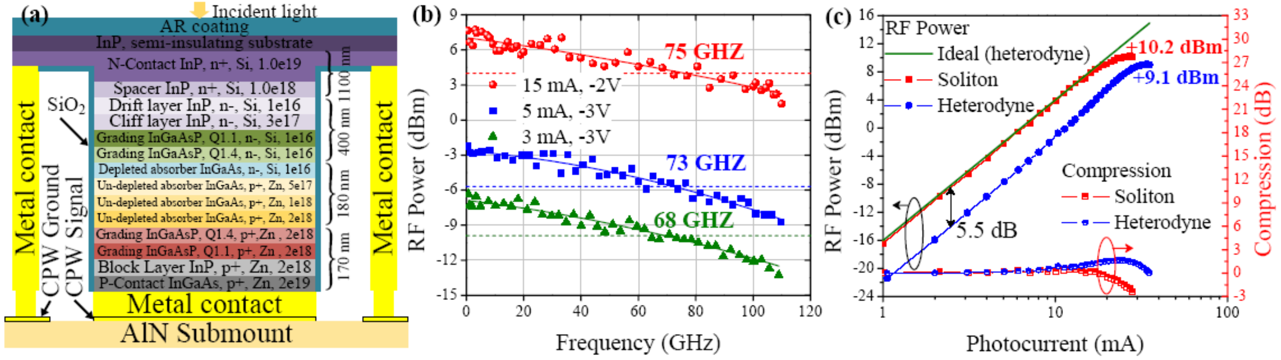

Fig. 1. (a) CC-MUTC PD. Doping concentrations in cm^{-3}. (b) Frequency responses. (c) PD output power at 100 GHz for heterodyne and soliton detection at -2 V.

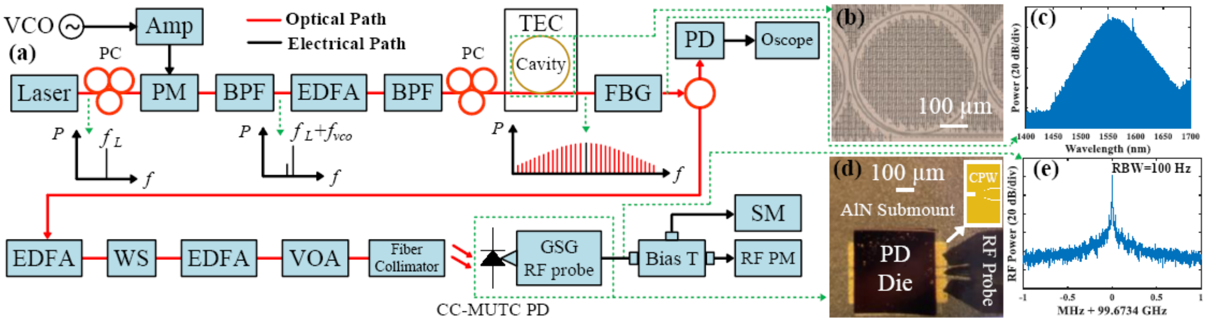

Fig. 2. (a) Experimental setup for soliton microcomb generation and detection. VCO: voltage-controlled oscillator, PC: polarization controller, TEC: thermoelectric cooler, SM: DC source meter. (b) Microscope image of the microring resonator. (c) Optical spectrum of microcomb. (d) Microscope image of PD with RF probe and schematic top view of the CPW. (e) Electrical spectrum of down-converted PD output signal. RBW: resolution bandwidth.

4.2 dB between DC and 100 GHz. At higher photocurrents, an electric field is induced by the photogenerated carriers that accelerates electron transport in the un-depleted absorber resulting in higher bandwidth [7]. This bandwidth enhancement is also visible from the blue curves in Fig. 1(c) which show the output power and compression as a function of the average photocurrent at a fixed heterodyne beatnote frequency of 100 GHz. The maximum output power reached 9.1 dBm at 34 mA, which is slightly below the 9.6 dBm that we previously reported for a CC-MUTC at a bias of -3.5 V in [7]. Here the bias was -2 V to reduce the dissipated power (reverse bias × photocurrent) and prevent PD thermal failure. The experimental setup for soliton microcomb generation is illustrated in Fig. 2(a). Light from a continuous wave laser with frequency f_L is modulated in the phase modulator (PM) whereby the pump for the microresonator is derived from the first phase-modulated sideband f_L+f_{VCO} after passing through a band pass filter (BPF) and an erbium doped fiber amplifier (EDFA). We used an integrated Si_3N_4 bus-waveguide coupled microring resonator with a radius of 228 µm (Fig. 2(b)), an intrinsic quality factor of 4.3×10^6, and a free spectral range of 100 GHz [3]. The soliton microcomb had a 3 dB-bandwidth of 4.6 THz and a pulse width <40 fs. After microcomb generation, a fiber Bragg grating (FBG) is used to filter out the pump laser line as shown in Fig. 2(c). A programmable wave shaper (WS) is used to compensate for the group velocity dispersion due to the 70-meter-long optical fiber between the two EDFAs. Further information about the soliton generation can be found in [4]. The microcomb can then be attenuated using a variable optical attenuator (VOA) before it is launched into the PD via a fiber collimator. To achieve uniform illumination in our measurements (soliton and heterodyne detection), the incident light spot was expanded to overfill the active area until the responsivity decreased from its maximum value by 50%. The output signal of the PD is then extracted using a radio frequency (RF) probe (Fig. 2(d)) with 1 mm coaxial connector followed by a short cable and a bias-T. The power was measured with a DC to 110 GHz RF power meter (RF PM). It should be mentioned that we used the same RF components (RF probe, cable, etc.) in both, heterodyne and soliton experiments, and that their losses were subtracted from the measured powers. To verify the repetition rate of the microcomb, we also down-converted the PD output signal with an RF mixer [3], and determined the repetition rate to be 99.673 GHz as shown in Fig. 2(e). The PD output power and compression curve for soliton detection are shown in red in Fig. 1(c). For photocurrents below 10 mA, we found a 5.5 dB power enhancement compared to heterodyne detection, which is close to the expected value of 6 dB. The fact that the soliton detection shows onset of compression at a lower photocurrent than heterodyne can be explained by the much larger optical peak powers in the ultrashort solitons. Likewise, we believe that saturation suppresses the bandwidth enhancement. Remarkably, this disadvantage is fully compensated by the power enhancement leading to a maximum power of 10.2 dBm at an average photocurrent at 27 mA which is 1.1 dB higher than the maximum power for heterodyne detection that was obtained at a higher photocurrent of 34 mA. Our results show that detection of soliton microcomb is a promising candidate for the generation of stable, high-power mmWave signals at reduced dissipated power which allows the PD to be operated further below the point of thermal failure.

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