Temperature dependence of nonlinearity in high-speed, high-power photodetectors

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***Abstract*—We present an experimental study of the nonlinearity of modified uni-traveling carrier (MUTC) photodiodes at cryogenic temperatures. At 120 K, the amplitude-to-phase (AM-to-PM) conversion nonlinearity is reduced by up to 10 dB, resulting in nearly 40 dB AM-to-PM rejection over a broad photocurrent range.**

***Keywords*— High speed photodiodes; Low noise photonic microwave generation**

I. Introduction

Fast photodiodes enable the conversion of optically carried microwaves into the electrical domain, and have therefore become key to multiple applications such as microwave photonics [1], synchronization of large-scale science facilities [2] and generation of low-noise stable microwaves from optical references via optical frequency division (OFD) [3-6]. Among these applications, perhaps the most demanding is optical frequency division, since it requires high linearity, efficiency and power handling to provide sufficiently low residual noise [6] and long term stability [7] to support high fidelity division of optical signals to the microwave domain. Photodiodes based on MUTC structures have demonstrated state-of-the-art performance in each of these metrics [8].

Continued improvement of photodetector performance requires deeper understanding of their physics and limitations. Insight into device operation may be obtained by operating at low temperatures, especially as it relates to the bandgap energy and electron-phonon interaction. Furthermore, cryogenic microwave systems such as Josephson junction circuits could benefit from microwave regeneration directly in the cryogenic environment [9]. In this case, a single optical fiber could replace several coaxial cables, reducing cost, complexity and heat load. Previous studies have shown that photodiodes retain their high-speed operation at low temperatures [10] and that the dark current is significantly reduced [11]. However, we are not aware of any investigations of the nonlinearity or noise of high speed photodetectors in cryogenic environments. Here we present measurements of AM-to-PM conversion in MUTC devices at temperatures varying from 300 K down to 120 K. Our preliminary results show an improvement of up to 10 dB in the linearity of the MUTC photodiodes.

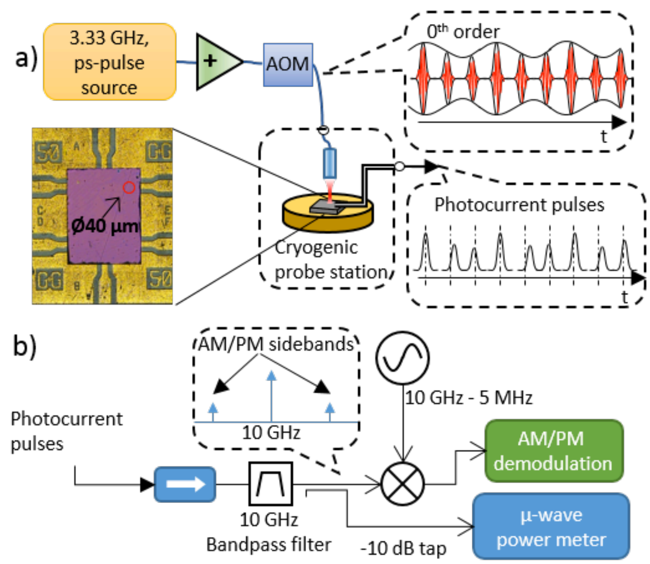

Fig. 1. Measurement setup. **a)** A pulse-train from an Er:fiber mode-locked laser is interleaved up to a repetition frequency of 3.33 GHz and a final interleaving stage generates pulse pairs separated by 100 ps. ~150 kHz amplitude modulation is written unto the beam using the 0th order of an acousto-optic modulator (AOM). **b)** The AM-to-PM demodulation is achieved by first mixing the 10 GHz harmonic down to 5 MHz and then using a FFT analyzer to demodulate the AM and PM quadratures of the 150 kHz tone. **Inset**: Photograph of the MUTC diodes, flip-chip bonded on an aluminum nitride substrate with patterned co-planar waveguides for microwave transmission. The active area of the device under test is shown in the red circle.

II. Experiments and Results

The diodes used for this study are 40 µm diameter MUTC devices as demonstrated in [12]. The photodiode is illuminated with ~1 ps pulses at 1550 nm obtained from an erbium:fiber mode-locked laser. The laser has 208.33 MHz repetition rate and is followed by a 4-stage pulse interleaver that produces a 3.33 GHz pulse-train. A final interleaving stage produces pulse pairs separated by 100 ps to maximize the power contained in the 10 GHz harmonic of the microwave spectrum. This pulse train is then delivered through a 70-m fiber link to the laboratory where the cryogenic probe station is located. At the remote site, dispersion compensation is performed with normal dispersion fiber and the pulses are subsequently amplified with an erbium-doped fiber amplifier. Autocorrelation traces confirmed the picosecond pulse width delivered through a fiber optic vacuum feedthrough.

To study the photodiodes at cryogenic temperatures, we place them in a cryogenic probe station fitted with both fiber optic and microwave feedthroughs. The pulses are focused on the photodiode with a fiber-pigtailed graded index lens inside the vacuum chamber. Lateral alignment is optimized by maximizing the dc photocurrent. The focusing condition has been systematically explored, as the diode's nonlinearity is aggravated by tight focusing [13]. We observe that the diode's nonlinearity increases for beam waists much smaller than the size of the active area. For best AM-to-PM performance, we ensure that the beam size is slightly larger than the active area to overfill it. Such configuration has the advantage of maximizing the diode's linearity with the trade-off of a slight reduction in the overall responsivity.

To analyze the AM-to-PM conversion we use a standard technique [14, 15], shown in Fig 1 (b). A small amount of 150 kHz amplitude modulation is written on the optical pulse-train by modulating the driving power of an acousto-optic modulator. AM-to-PM conversion in the photodetector converts a fraction of this modulation to the phase of the generated 10 GHz microwave. To measure the resulting phase modulation, the 10 GHz signal is first mixed down to 5 MHz with a microwave synthesizer and then demodulated with an FFT analyzer. The AM-to-PM conversion is given by ratio of the phase modulation to the imparted amplitude modulation (radians per fractional optical power change).

We have measured both the microwave power in the 10 GHz harmonic and the AM-to-PM conversion in the photodiode as a function of photocurrent for several temperatures between 300 K and 120 K and reverse bias voltages between 4 and 8 V. The results for 7 V bias are shown in Fig. 2. We observe that while the null in the AM-to-PM conversion coefficient does not shift significantly with temperature, the nonlinearity over a broad photocurrent range is reduced at lower temperatures. Reasons for the improved linearity are currently under investigation.

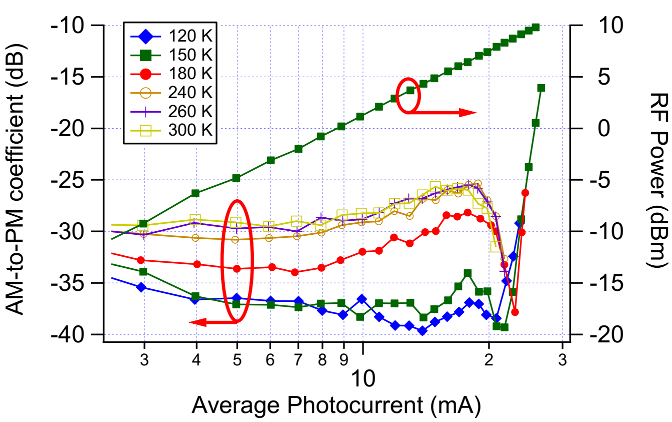

Fig. 2. **(left)** AM-to-PM conversion measured in the photodiode at 7 V bias. The null in the AM-to-PM conversion does not shift significantly, but the non-linearity at low photocurrent is significantly reduced at lower temperatures, extending the useability range of the photodiode. **(right)** 10 GHz microwave power at the bias tee at 150 K. Power levels do not change significantly with temperature.

III. Outlook

We have begun studying MUTC photodiodes at cryogenic temperatures and have found that the linearity can improve. Additionally, we intend to study the noise performance of these photodiodes to elucidate the contribution of the various mechanisms that contribute to the phase noise added by the photodiode in optically-derived low noise microwave signals.

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