Photodetection noise reduction of a 10 GHz fiber-laser-based photonic microwave generator

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***Abstract*—We demonstrate reduced photodetection noise floor of a 10 GHz fiber laser-based photonic microwave generator by using a pulse repetition-rate-multiplier in combination with a modified Uni-Traveling-Carrier (MUTC) photodiode that features high power handling and linearity. This enables a residual phase noise floor of -170 dBc/Hz at 10 GHz, which is a 5-25 dB improvement over earlier results. Photodiode flicker noise is measured to be near -133/f dBc/Hz.**

I. INTRODUCTION

Photonically-generated microwaves [1] provide unprecedented close-to-carrier phase noise and short term stability by taking advantage of the performance of ultra-stable laser cavities [2] and optical frequency dividers [3]. The basic structure of this type of photonic microwave generator includes: a continuous-wave (CW) laser that is frequency-stabilized to an ultra-stable optical cavity, a self-referenced mode-locked laser that is phase-locked to the CW laser, and a photodiode detecting the mode-locked laser repetition rate. The mode-locked laser transfers the stability of the optical signal into its repetition frequency. We are interested in microwave generation near 10 GHz, which is a harmonic of the laser repetition rate.

Self-referenced Er:fiber mode-locked lasers are commercially available, relatively cheap, compact, and robust, making them convenient to be used in such an approach to generate ultra-low phase noise microwave signals. However, when compared with other self-referenced lasers, such as a gigahertz Titanium-sapphire (Ti:S) [4], the Er:fiber laser has a lower repetition rate (a few hundred megahertz) and correspondingly higher pulse energy that results in more rapid saturation of the microwave signal from the photodiode detecting the repetition rate. This leads to a relative high detection noise floor induced by shot and thermal noise. The details of the photodiode (PD) saturation depend on the repetition rate, pulse length, bias voltage and photodiode design. But for common parameters and devices, saturation typically begins with only ~1 mW average power for a laser with 250 MHz repetition rate. This limits the power generated in the 10 GHz harmonic to approximately -20 dBm, which currently results in a shot- or thermal-noise limited phase noise floor of about -140 to -150 dBc/Hz on the 10 GHz photodetected harmonic [5, 6].

In order to reduce the detection noise floor, we employ pulse rate multipliers and modified Uni-Traveling-Carrier (MUTC) photodiodes [7] which feature high power handling and linearity. The saturation power of the 10 GHz harmonic at the output of the photodiode increases by 35 dB above that of the previous case. Consequently, the detection noise floor is dramatically reduced.

II. PHOTODETECTION NOISE FLOOR AND PHOTODIODE SATURATION

The detection noise floor has been studied in detail, and can be found in the literature [8]. Here we provide a brief overview of the specific case relevant for our experimental approach.

For ultra-narrow periodic current pulses, the average signal power is $2I^2R$, where I is the average current and R (=50 Ω) is the impedance. The thermal noise is given by 4 k_BT, where k_B is the Boltzmann constant and T (=300 K) is the temperature in Kelvins. The shot noise is given by $2eIR$, where e is the electron charge.

In ideal conditions (PD never saturated), the single-sideband detection phase noise floor is the thermal and shot noise limited signal-to-noise ratio, which can be written as:

$$L(f)= -161 +10 \log (1/I+1/I^2) \quad [\text{dBc/Hz}] \qquad (1)$$

where I is in mA.

Note that this calculation is based on an assumption that shot noise equally contributes to the phase and amplitude quadrature of the signal [9], and no other effect, such as amplitude modulation to phase modulation conversion (AM-PM), is considered. The calculated data, shown in Fig. 1, indicates that the noise floor decreases when the average current increases.

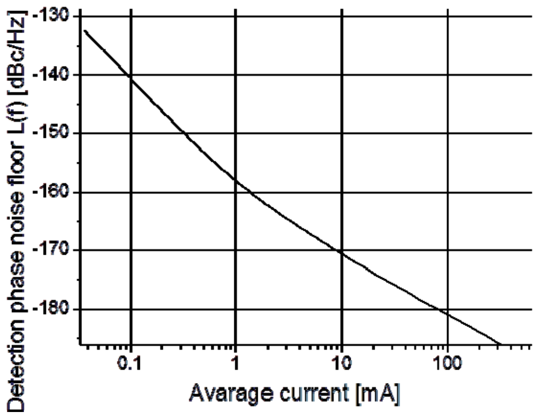

Figure 1. Detection phase noise floor versus average photo-current.

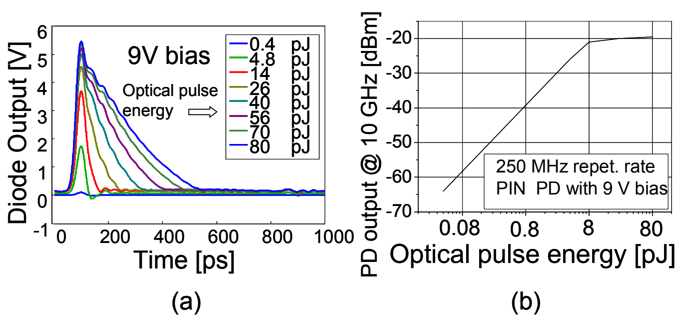

Figure 2. Saturation behavior of a PIN PD, a: time domain PD response and b: frequency domain PD response.

However, the photodiode always saturates beyond certain pulse energy. Fig. 2 shows the saturation behavior of a PIN PD in the time and frequency domains. It indicates that the saturation of a photodiode is directly related to input optical pulse energy. Once the photodiode is saturated, the noise floor cannot be further improved, as shown in Fig. 2. The noise floor reduction is equivalent to the increase of PD saturation current, which is the product of pulse power and the pulse repetition rate. Thus, one approach to reduce the noise floor is pulse rate multiplication. The other method is improvement of the pulse saturation power by using a high power handling PD and high bias voltage.

III. EXPERIMENTAL SETUP AND MEASURMENT RESULTS

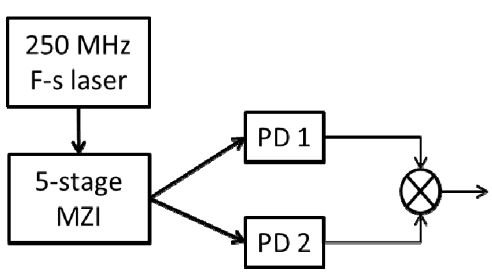

Figure 3. Experimental setup, where MZI is a Mach-Zehnder Interleaver.

Fig. 3 shows the experimental setup of measuring the residual detection phase noise of the photodiode. The laser source is a commercial Er:fiber based femtosecond laser with a repetition rate of 250 MHz.

The laser pulse rate multiplier is a fiber-based cascaded Mach-Zehnder interleaver as shown in Fig. 4 [9,10].

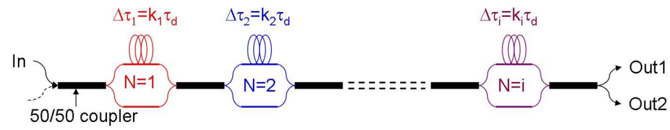

Figure 4. Scheme of the fiber-based cascaded MZI, where k_1, k_2 and k_i are integers, τ_d (=100 ps) is the period of the desired frequency signal. No pulse overlapping happens at the output.

The fiber couplers split optical pulses, then delay and temporally interleave the pulse trains from the two arms. Thus, each stage of MZI can multiply the pulse rate by a factor of 2. We employ standard four-port 50/50 fiber couplers with the two outputs of each stage serving as the inputs to the next stage. As a result, even with inexpensive off-the-shelf couplers the transmission efficiency from a single output after a few stages can easily reach > 40 %. Compared with the Fabry-Perot cavity pulse rate multiplication method [9,11], this approach has much higher transmission efficiency, is simpler, and even has lower residual noise. Although these generated pulses are not synchronized in optical phase, this does not affect the microwave signal generation.

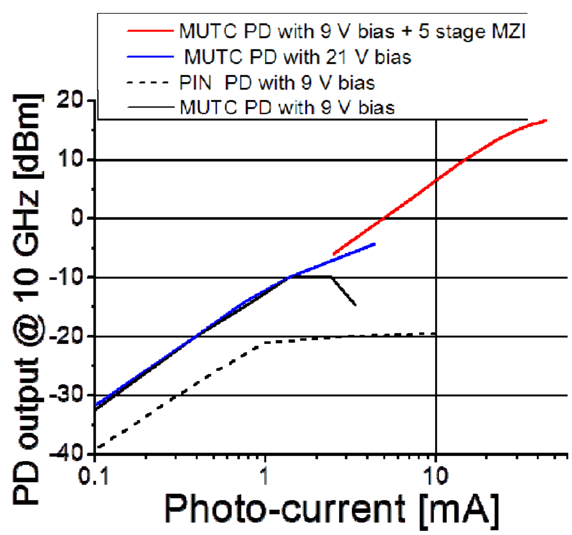

Figure 5. MUTC photodiode output power @ 10 GHz versus photo-current.

The saturation feature of the MUTC photodiode is shown in Fig. 5. Compared with the PIN PD without multiplication, the MUTC PD with multiplication has much higher saturation output power @ 10 GHz (17dBm). This allows us use this signal to directly drive mixer and other components without using a microwave amplifier.

As shown in Fig. 5, the saturation current increases by more than 30x, which directly corresponds to a reduction of the noise floor (see Fig. 1). We measured the lowest residual detection noise floor at 10 mA as shown in Fig. 6. With higher optical power, the measurement results are limited by the amplitude to phase conversion (AM-PM) [12,13] of the femtosecond laser noise. Actually, the noise for frequency between tens of kilo-Hz to 2 MHz is attributed to the AM-PM conversion. The detection noise floor is about -170 dBc/Hz at Fourier frequencies higher than 2 MHz. The flicker noise floor of the photodetection is near -133/*f* dBc/Hz.

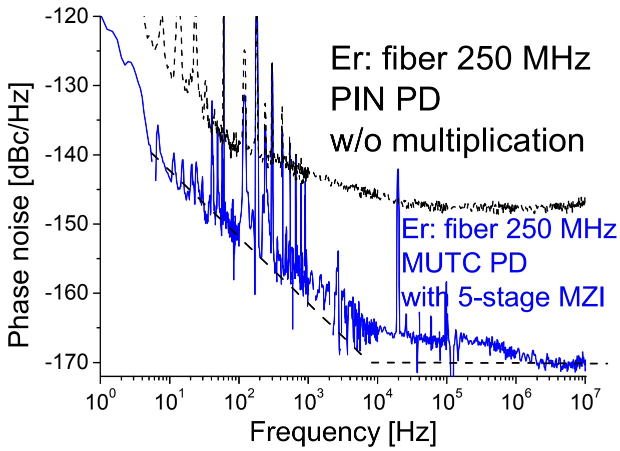

Figure 6. residual photodetection phase noise of a PD with/without multiplier.

IV. CONCLUSION AND PERSPECTIVE

By means of the pulse rate multiplication and high power handling modified MUTC PD, we reduce the photodetection noise floor of a photonic microwave generator to a level of -170 dBc/Hz with –133/*f* dBc/Hz flicker noise at low frequencies.

This approach has enabled further improvements in absolute phase noise [14]. An additional advantage to be realized is to combine both outputs of the MZI to generate microwave signals. We expect to gain another 3 dB signal-to-noise improvement.

REFERENCES

[1] T. M. Fortier, M. S. Kirchner, F. Quinlan, J. Taylor, J. C. Bergquist, T. Rosenband, N. D. Lemke, A. D. Ludlow, Y. Y. Jiang, C. Oates, and S. Diddams, "Generation of ultrastable microwaves via optical frequency division," *Nat. Photonics* 5, 425-429 (2011).

[2] Y. Y. Jiang, A. D. Ludlow, N. D. Lemke, R. W. Fox, J. A. Sherman, L. S. Ma, and C. W. Oates, "Making optical atomic clocks more stable with 10-16-level laser stabilization," *Nat Photon* 5, 158-161 (2011).

[3] D. J. Jones, S. A. Diddams, J. K. Ranka, A. Stentz, R. S. Windeler, J. L. Hall, and S. T. Cundiff, "Carrier-envelope phase control of femtosecond mode-locked lasers and direct optical frequency synthesis," *Science* 288, 635-639 (2000).

[4] T. M. Fortier, A. Bartels, and S. A. Diddams, "Octave-spanning Ti : sapphire laser with a repetition rate > 1 GHz for optical frequency measurements and comparisons," *Optics Letters* 31, 1011-1013 (2006).

[5] F. Quinlan, T. Fortier, M. Kirchner, J. Taylor, M. J. Thorpe, N. D. Lemke, A. D. Ludlow, Y. Y. Jiang, C. Oates, and S. Diddams, "Ultralow phase noise microwave generation with an Er:fiber-based optical frequency divider," *Optics Letters*, 36, 3260-3262 (2011).

[6] J. Millo, M. Abgrall, M. Lours, E. M. L. English, H. Jiang, J. Guena, A. Clairon, M. E. Tobar, S. Bize, Y. Le Coq, and G. Santarelli, "Ultralow noise microwave generation with fiber-based optical frequency comb and application to atomic fountain clock," *Applied Physics Letters* 94 (2009).

[7] Z. Li, H. Pan, H. Chen, A. Beling, and J. C. Campbell, "High-saturation-current Modified Uni-Traveling-Carrier Photodiode With Cliff Layer," *IEEE J. Quantum Electron*. 46, 626-632 (2010).

[8] B. E. A. Saleh and M. C. Teich, *Fundamentals of Photonics* Wiley, New York, (1991)

[9] H. Jiang, J. Taylor, F. Quinlan, T. Fortier, and S. Diddams, "Noise floor reduction of an Er:Fiber laser-based photonic microwave generator," *IEEE Photonics Journal* 3, 1004-1012 (2011).

[10] A. Haboucha, W. Zhang, T. Li, M. Lours, A. Luiten, Y. L. Coq, and G. Santarelli, "An optical fiber pulse rate multiplier for ultra-low phase noise signal generation," *Optics Letters*, 36, 3654-3656 (2011).

[11] S. A. Diddams, M. Kirchner, T. Fortier, D. Braje, A. M. Weiner and L. Hollberg, "Improved signal-to-noise ratio of 10 GHz microwave signals generated with a mode-filtered femtosecond laser frequency comb," *Optics Express*, 17, 3331-3340 (2009)

[12] J. Taylor, S. Datta, A. Hati, C. Nelson, F. Quinlan, A. Joshi, and S. Diddams, "Characterization of Power-to-Phase Conversion in High-Speed P-I-N Photodiodes," *IEEE Photonics Journal* 3, 140-151 (2011).

[13] W. Zhang, T. Li, M. Lours, S. seidelin, G. Santarelli, and Y. le Coq, "Amplitude to phase conversion of InGaAs pin photo-diodes for femtosecond lasers microwave signal generation," *Applied Physics B: Lasers and Optics* 106, 301-308 (2011).

[14] T.M. Fortier, C.W. Nelson, A. Hati, F. Wuinlan, J Taylor, H. Jiang, C.W. Chou, M. Thorpe, N. Lemke, T. Rosenband, A. Ludlow, D. Howe, C. Oates and S.A. Diddams, “Sub-femtosecond time jitter with a hybrid photonic-microwave oscillator” in *this proceeding* (2012)