Compact Phase Detector for Optical-Microwave Synchronization Using Polarization Modulation

Juan Wei, Shuangyou Zhang, Jungwon Kim, *Senior Member, IEEE*, and Shilong Pan, *Senior Member, IEEE*

***Abstract*—We propose and demonstrate a compact optical-microwave phase detector taking advantage of polarization modulation. The proposed polarization modulator-based phase detector (PolM-PD) shows 460-attosecond residual timing jitter integrated from 1 Hz to 100 kHz when synchronizing an 8-GHz dielectric resonator oscillator to a free-running 250-MHz mode-locked Er-fiber laser. The absolute single-sideband phase noise of the locked 8-GHz DRO is –138 dBc/Hz (–165 dBc/Hz) at an offset frequency of 10 kHz (10 MHz). The proposed PolM-PD has a compact structure implemented by all commercially available components. Because no fiber loop and delay line are used, the proposed PolM-PD can be potentially integrated on a chip.**

***Index Terms*—Microwave generation, optical polarization, optical pulses, phase detection, phase locked loops.**

I. Introduction

WITH the advances of femtosecond mode-locked lasers (MLLs), a variety of applications have been enabled in areas such as spectroscopy [1]–[3], arbitrary waveform generation [4], analog-to-digital conversion (ADC) [5], [6], and optical measurement [7]–[9]. Among them, microwave signal generation based on MLLs shows high phase stability and large tunability [10]–[13], which attracts great interests for radars [14] and satellite communications [15]. Although direct photodetection of optical pulses using high-speed photodetector (PD) is a simple and efficient method to extract microwave frequencies from a MLL [16]–[24], the amplitude noise of the optical pulses would convert to the phase noise of the generated microwave signal during photodetection. Besides, in the directly-detected signal, there are a huge number of frequency tones spanning from DC to the bandwidth of the PD with an interval of the repetition rate of the MLL, so narrow-band electrical filters are required to select the desired frequency component. As an alternative, optical-microwave phase detectors that detect the phase difference between the optical pulses and the microwave signal can be applied to achieve ultralow noise synchronization of microwave oscillators and MLLs for microwave generation. In addition, optical-microwave phase detectors also play an important role to synchronize RF subsystems and optical pulses in linear accelerator-based x-ray light sources (x-ray free-electron lasers, XFELs) [25]–[27], especially when the XFELs are used to observe ultrafast phenomena with pump-probe techniques.

As early as 2004, an optical-microwave phase detector based on a free-space Sagnac loop was implemented to achieve synchronization of MLLs and microwave references, as well as microwave frequency extraction from MLLs [28]. The Sagnac loop contains a phase modulator driven by the microwave signal to be detected. The location of the phase modulator is carefully selected, so that the counter-propagating pulses experience opposite phase modulation and thus the phase error between the microwave signal and the optical pulses manifests itself as the amplitude imbalance of the Sagnac interferometer's two outputs, which could be detected by a balanced photodetector (BPD). Later, an improved implementation with a much lower phase noise floor, referred to fiber-loop optical-microwave phase detector (FLOM-PD), was achieved using a fiber Sagnac loop [29]–[31]. A nonreciprocal quarter-wave bias unit is inserted to induce a constant $\pi/2$ phase difference between the counter-propagating pulses in the Sagnac loop, which however causes slow phase drift because of the temperature-dependent birefringence change in the quarter-wave plate and therefore limits the long-term stability of the entire system. As an alternative, balanced optical-microwave phase detector (BOM-PD) was proposed, in which the phase error between the optical pulses and microwave signal is mapped to the amplitude modulation depth of the optical pulse train. Then, the amplitude modulation depth is converted into the baseband by utilizing an auxiliary signal generated from the optical pulses [32]–[34]. BOM-PD shows distinct performance in term of long-term stability, but the use of the auxiliary signal necessitates a series of RF components such as band-pass filters, phase shifters and a frequency divider with operating frequencies specified for the MLL's repetition rate. Recently, an optical-microwave phase detector based on a dual-output Mach-Zehnder modulator (MZM) was demon-

Manuscript received January 8, 2018; revised March 9, 2018; accepted May 12, 2018. Date of publication May 18, 2018; date of current version August 30, 2018. This work was supported in part by the National Natural Science Foundation of China under Grants 61422108 and 61527820, in part by the National Research Foundation of Korea under Grant 2013M1A3A3A02042273, and in part by the Encouragement Program for the Industries of Economic Cooperation Region, Ministry of Trade, Industry and Energy of Korea, under Grant R0003976. The work of J. Wei was supported by the Chinese Scholarship Council for visiting research at KAIST. *(Corresponding authors: Jungwon Kim and Shilong Pan.)*

J. Wei and S. Pan are with the Key Laboratory of Radar Imaging and Microwave Photonics, Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China (e-mail: weiweifreedom@nuaa.edu.cn; pans@nuaa.edu.cn).

S. Zhang was with the Korea Advanced Institute of Science and Technology, Daejeon 34141, South Korea. He is now with the National Physical Laboratory, Teddington TW11 0LW, U.K. (e-mail: shuangyou.zhang@npl.co.uk).

J. Kim is with the School of Mechanical and Aerospace Engineering, Korea Advanced Institute of Science and Technology, Daejeon 34141, South Korea (e-mail: jungwon.kim@kaist.ac.kr).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JLT.2018.2837671

strated [35]. Optical pulses from an MLL are interleaved with their replica that are delayed by a quarter of the pulse period, and then sent to the MZM driven by the microwave signal to be detected. In the MZM, the optical pulse train is amplitude modulated with a modulation depth that is proportional to the phase error between the optical pulses and the microwave signal. A synchronous detection method similar to that in the BOM-PD is adopted in order to obtain the phase error signal in the baseband. This scheme showed very good long-term stability by carefully controlling the environmental humidity and temperature, and was working very well in the XFEL [36]. However, accurate optical delays and bias stabilization are required, dramatically increasing the complexity of the system.

In this paper, we propose and demonstrate a compact optical-microwave phase detector based on polarization modulation (referred to PolM-PD hereafter), which could achieve femtosecond-level synchronization between MLLs and microwave signals. The PolM-PD consists of a polarization modulator (PolM), a polarization controller, a polarization beam splitter (PBS) and a balanced photodetector (BPD), which are all commercially available. When the PolM-PD is applied to detect the phase error between a MLL and a voltage-controlled oscillator (VCO), we can (1) directly generate a high-power and ultralow-noise microwave signal without any electrical filter or electrical amplifier, by establishing a feedback loop to control the VCO based on the phase error, or (2) stabilize the repetition rate of a MLL with a reference microwave standard by establishing a feedback loop to control the MLL based on the detected phase error. In [37], we reported some preliminary measurement result of the proposed PolM-PD, i.e., the residual phase noise at an offset frequency of 1 Hz to 100 kHz. Here, we perform a comprehensive study of the PolM-PD, and demonstrate its capability in extracting an 8-GHz low-noise microwave signal from a MLL. The factors that limit the performance of the PolM-PD are discussed.

II. Principles

Fig. 1(a) shows the schematic diagram of the proposed PolM-PD, which consists of a polarization modulator (PolM), a polarization controller, a polarization beam splitter (PBS) and a balanced photodetector (BPD). Mathematically, an ultrashort optical pulse train from a MLL can be written as

$$P_i(t) = P_{\text{pulse}}\tau_p \sum_{n=0}^{\infty} \delta(t - nT_R) \tag{1}$$

where P_{pulse} is the peak power of the pulse, τ_p is the duration of the pulse and T_R represents the pulse period. The optical pulse train is directed to the PolM, which is an integrated device with the equivalent scheme shown in Fig. 1(b) [38]. The PBS in the PolM divides the incident optical pulse train into two paths (denoted as E_x and E_y), which are orthogonally polarized. The two signals are phase modulated in the two paths with opposite phase modulation indices by the microwave signal. Meanwhile, the static phase difference φ between E_x and E_y can be tuned by a direct current (DC) voltage applied on the PolM. Then, the two modulated optical pulse trains are combined by a PBC.

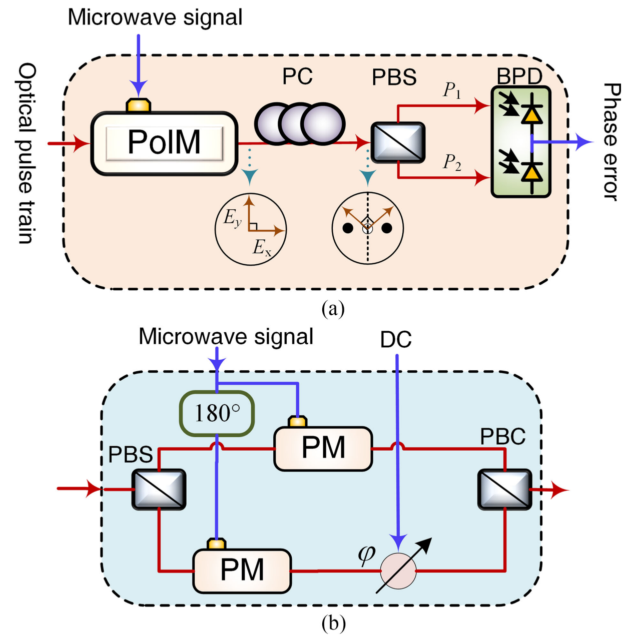

Fig. 1. (a) Schematic diagram of the proposed PolM-PD. (b) Equivalent scheme of a polarization modulator [38]. PBS: polarization beam splitter; PM: phase modulator; PBC: polarization beam combiner; DC: direct current voltage; PolM: polarization modulator; PC: polarization controller; BPD: balanced photodetector.

A polarization controller (PC) following the PolM is used to adjust the polarization direction of E_x (or E_y) to have an angle of 45 degrees with one of the principal axes of the PBS. Note that the outputs of PBS are insensitive to this angle in a small range around 45 degrees since the gradient here is zero. Besides, the PC can also introduce a static phase difference between E_x and E_y. When E_x and E_y interfere with each other in the PBS, the phase modulation of the optical pulse trains is converted into amplitude modulation, so we can get the amplitude modulated optical pulse trains at the outputs of the PBS, given by

$$\begin{cases} P_1(t) = P_{\text{pulse}}\tau_p \sum\limits_{n=0}^{\infty} \cos^2\left(\frac{\beta}{2}\sin(\omega_0 t + \theta_e) + \frac{\varphi}{2}\right)\delta(t - nT_R) \\ P_2(t) = P_{\text{pulse}}\tau_p \sum\limits_{n=0}^{\infty} \sin^2\left(\frac{\beta}{2}\sin(\omega_0 t + \theta_e) + \frac{\varphi}{2}\right)\delta(t - nT_R) \end{cases} \tag{2}$$

where β and ω_0 are the phase modulation index and the angular frequency of the microwave signal to be measured, respectively, θ_e indicates the phase error (i.e., relative temporal position information) between the optical pulses and the microwave signal zero crossings. Since the angular frequency of the microwave signal ω_0 is an integer multiple of the repetition rate of the optical pulse train (i.e., $\omega_0 = 2\pi M/T_R$, M is an integer) and optical pulses are output only when $t = nT_R$, then the average optical power at the outputs of the PBS can be simplified into

$$\begin{cases} P_{1,\text{avg}} = P_{\text{avg}}\cos^2\left(\frac{\beta}{2}\sin\theta_e + \frac{\varphi}{2}\right) \\ P_{2,\text{avg}} = P_{\text{avg}}\sin^2\left(\frac{\beta}{2}\sin\theta_e + \frac{\varphi}{2}\right) \end{cases} \tag{3}$$

where P_{avg} represents the average optical power input to the PBS ($P_{\text{avg}} = P_{\text{pulse}}\tau_p/T_R$). As can be seen, the phase error between the optical pulses and the microwave signal θ_e causes

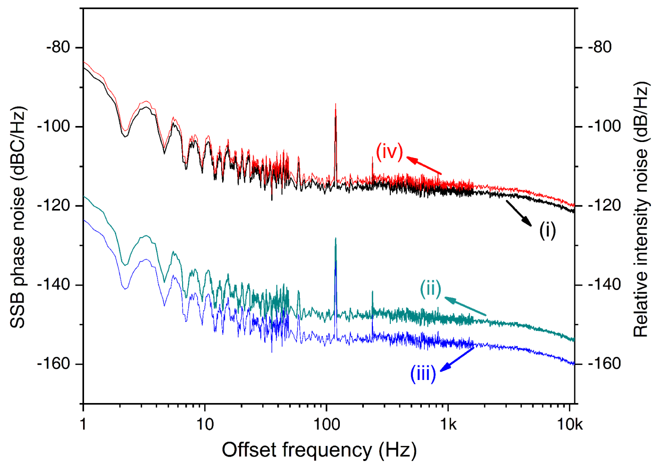

Fig. 2. Additional single-sideband (SSB) phase noise in the output of the optical-microwave phase detector originated from the relative intensity noise of the optical pulses when the optical power difference of the two inputs of the balanced photodetector are 0.1 mW [curve (ii), dark cyan], 0.05 mW [curve (iii), blue] and 0.05 mW with 20 dB feedback gain [curve (iv), red]. Curve (i) [black]: typical spectrum of a mode-locked laser's relative intensity noise.

amplitude imbalance between the optical pulse trains, which is detected by the BPD subsequently. When φ is adjusted to be $\pi/2$ by the PC, the output voltage of the BPD is

$$V_d = GRP_{\mathrm{avg}}\sin\left(\beta\, \sin\theta_e\right) \tag{4}$$

where G and R are the trans-impedance gain and responsivity of the BPD, respectively. When the optical pulses are at the zero-crossings of the microwave signal, their phase error θ_e equals to 0 and the output of the BPD $\mathrm{V}_d = 0$. Otherwise, $\theta_e \neq 0$, V_d is approximately linearly proportional to θ_e

$$V_d \approx \beta GRP_{\mathrm{avg}}\theta_e \tag{5}$$

The voltage in (5) could be fed back to control the microwave oscillator or the MLL for synchronization. The sensitivity of the proposed PolM-PD is proportional to the phase modulation index β and the incident average optical power P_{avg}. Therefore, higher incident optical and microwave power can lead to more sensitive optical-microwave phase error detection. In theory, the sensitivity is independent of the frequency of the microwave signal. However, the sensitivity generally would decrease when the frequency increases since the half-wave voltage of the modulator increases with frequency and the power of microwave sources decreases with frequency.

Note that, to achieve low noise floor of the PolM-PD, it is of great importance to keep the optical power input to the BPD balanced, because the unbalanced optical power would result in additional phase noise due to the relative intensity noise (RIN) of the optical pulses. To show the influence of the unbalanced optical power, we calculated the phase noise induced by the RIN when the optical power difference between the two inputs of the BPD is 0.1 mW, 0.05 mW, and 0.05 mW with 20 dB feedback gain (in case the error signal detected by the BPD is fed back to control a VCO or a MLL with 20 dB feedback gain). The results are depicted in Fig. 2. Curve (i) [black] represents the typical spectrum of a MLL's RIN. We suppose the trans-impedance gain and the responsivity of the BPD are 1000 V/A and 1 A/W, respectively, and the sensitivity of the optical-microwave phase detector is 3 V/rad. Then, based on curve (i), we get curve (ii) [dark cyan], curve (iii) [blue] and curve (iv) [red] that represent the projected phase noise when the optical power difference are 0.1 mW, 0.05 mW and 0.05 mW with 20 dB feedback gain, respectively. As can be seen, even very small optical power difference between the two inputs of the BPD causes non-negligible additional phase noise especially in a PLL with high feedback gain. Actually, as early as 2013, the residual phase noise of the FLOM-PD originated from the RIN of the optical pulses was suppressed by fine tuning of the optical power using two optical tunable attenuators in front of the BPD [31]. In our scheme, fine tuning of optical power could be achieved simply by rotating the PC for adjusting the polarization direction of E_{x} and E_{y}.

III. Experimental Results and Discussion

The proposed PolM-PD is implemented according to the schematic diagram displayed in Fig. 1(a). The polarization modulator (Versawave Technologies, PL-40G-3-1550-V-FCU-FCU) supports a modulation frequency up to 40 GHz. The PC has three-paddle structure, which takes use of stress-induced birefringence produced by wrapping the single-mode fiber (SMF) around three spools to create independent wave plates. The broadband PBS cube (Thorlabs, PBS104) has a polarization extinction ratio (PER) of 30 dB for the transmitted beam, and the 150-MHz BPD (Thorlabs, PDB450C) provides a trans-impedance gain of 1000 V/A.

To measure the residual phase noise of the proposed PolM-PD, a FLOM-PD [29] is first employed to achieve synchronization of a MLL and a microwave oscillator. Then, the optical pulse train from the MLL and the microwave signal from the oscillator is led to the optical and RF input port of the PolM-PD, respectively. Ideally, the phase error output from the PolM-PD should be zero since the microwave oscillator and the MLL are phase locked, but in practice the PolM-PD would generate additional phase noise, so we still get some signal at the output of the PolM-PD, i.e., the residual phase noise.

Fig. 3 shows the setup for measuring the residual phase noise. We use a free-running MLL with a repetition rate of 250 MHz (MenloSystems GmbH, FC1500-250-ULN) as the laser source. The optical pulse train is divided into two portions. Each has around 30-mW average optical power. One is led to the PolM-PD and the other is directed to the FLOM-PD. A microwave signal from a dielectric resonator oscillator (DRO, Hittite HMC-C200) oscillating at 8 GHz is amplified to about 19 dBm, split into two paths and applied to the PolM-PD and the FLOM-PD. The phase error detected by the FLOM-PD is regulated by a proportional integral controller (PI) and a lead-compensator, and fed back to control the DRO. When the phase-locked loop is closed, the zero-crossings of the 8-GHz microwave signal is locked to the 250-MHz optical pulse train and ~2.5 mW optical power is detected at each photodiode in the BPD. The output of the proposed PolM-PD is measured by an FFT analyzer (for the offset frequency range of 1 Hz to 100 kHz) and an electrical spectrum analyzer (for the offset frequency range of 100 kHz to 10 MHz).

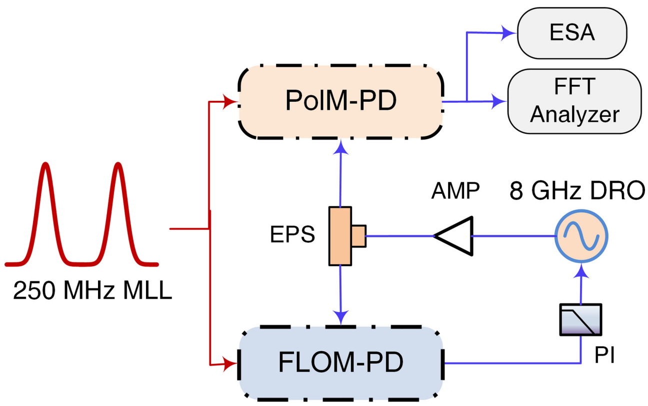

Fig. 3. Experimental setup for residual phase noise measurement of the proposed PolM-PD. ESA: electrical spectrum analyzer; MLL: mode-locked laser; DRO: dielectric resonator oscillator; EPS: electrical power splitter; AMP: electrical amplifier; PI: proportional integral controller; FLOM-PD: the fiber loop-based optical-microwave phase detector [29]; PolM-PD: the proposed optical-microwave phase detector based on polarization modulator.

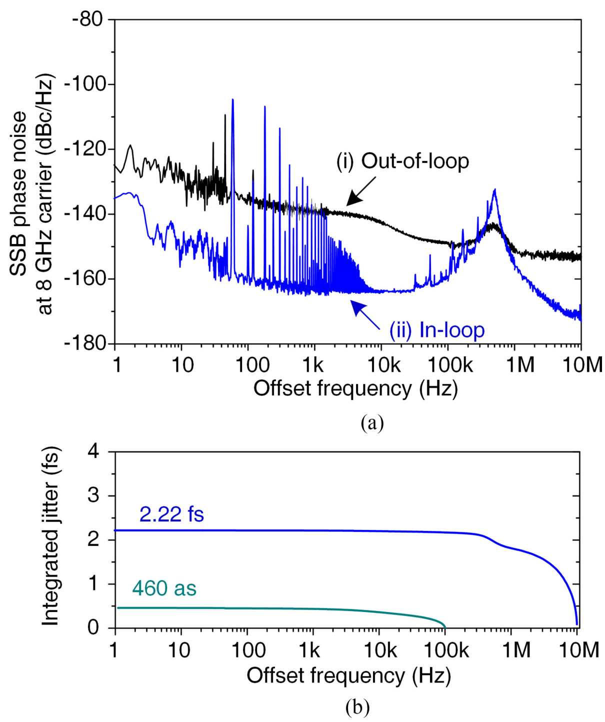

Fig. 4. (a) Measured single-sideband (SSB) phase noise at 8 GHz: (i) the residual out-of-loop phase noise of the PolM-PD when the 8-GHz DRO is locked to the 250-MHz MLL by the FLOM-PD; (ii) the in-loop phase noise of the PolM-PD when its output is used to control the 8-GHz DRO. (b) Timing jitter integrated from 100 kHz (10 MHz) down to 1 Hz using the measured residual out-of-loop phase noise.

Fig. 4(a) shows the measured single-sideband (SSB) phase noise at 8 GHz. Curve (i) shows the out-of-loop residual phase noise of the PolM-PD when the 8-GHz DRO is synchronized to the 250-MHz MLL, which is −120 dBc/Hz (−150 dBc/Hz) at 1 Hz (100 kHz) offset frequency. According to [29], the FLOM-PD has a much lower residual phase noise, so it will not introduce significant errors to the residual phase noise measurement of the PolM-PD. The residual timing jitter of the PolM-PD can be obtained from curve (i), which is 460 attoseconds (2.22 femtoseconds) when integrated from 100 kHz (10 MHz) down to 1 Hz as shown in Fig. 3(b). Note that the resonance peak around 600 kHz takes up a majority of the integrated timing jitter. Carefully tuning the parameters of the PI and the lead compensator might further reduce the resonance peak and the integrated timing jitter.

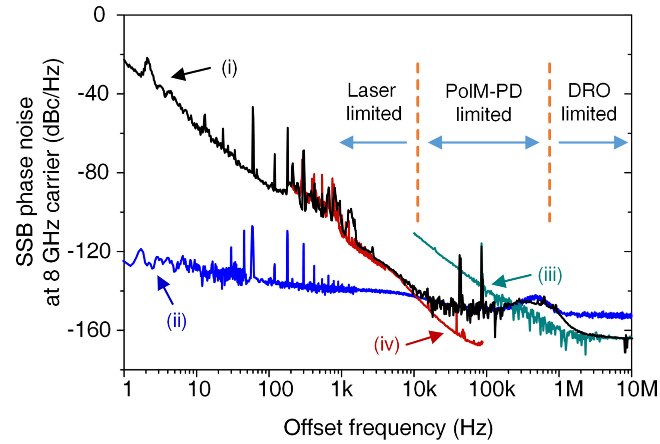

Fig. 5. Single-sideband (SSB) phase noise of the 8-GHz carrier. Curve (i): absolute phase noise of the 8-GHz DRO measured by a signal source analyzer when locked to the 250-MHz MLL. Curve (ii) is residual phase noise of the proposed PolM-PD. Curve (iii) is the absolute phase noise of free-running 8-GHz DRO. Curve (iv) is phase noise of the MLL's repetition rate measured by the fiber interferometer-based repetition-rate stabilization technique (FIRST) [39] and projected to 8 GHz.

Curve (ii) indicates the in-loop phase noise of the PolM-PD measured when the PolM-PD is used to achieve synchronization of the 8-GHz DRO and the 250-MHz MLL with a locking bandwidth of ∼600 kHz. In contrast to curve (i), curve (ii) is much lower in the PLL's locking range because the PolM-PD is in the PLL and its residual phase noise will be compensated by the PLL.

The absolute phase noise of the 8-GHz DRO is also measured by a signal source analyzer (Keysight, E5052B) when the PolM-PD is employed to synchronize the 8-GHz DRO to the 250-MHz MLL. The measured results are shown in Fig. 5. As can be seen from curve (i), the absolute phase noise of the 8-GHz DRO at 1 kHz, 10 kHz and 10 MHz offset frequency is −108 dBc/Hz, −138 dBc/Hz and −165 dBc/Hz, respectively. Curve (ii) represents the residual phase noise of the PolM-PD (the same as curve (i) in Fig. 4), curve (iii) denotes the absolute phase noise of the free-running DRO measured by the signal source analyzer, and curve (iv) shows the phase noise of the free-running MLL, which is obtained by using a fiber interferometer-based repetition-rate stabilization technique (FIRST) [39] to measure the frequency noise of the MLL's repetition rate (i.e., 250 MHz) and scaling the result to that of 8 GHz. As can be seen, the absolute phase noise of the locked 8-GHz DRO beyond the locking bandwidth is determined by the DRO, indicating that a high quality DRO with low phase noise at high offset frequency is necessary for low-phase-noise microwave signal extraction from MLLs. The close-to-carrier phase noise (<10 kHz) is determined by the frequency noise of the free-running MLL. By utilizing an MLL with stabilized repetition rate, much lower phase noise at low offset frequencies can be achieved [12]. At offset frequencies between 10 kHz and 1 MHz, the absolute

TABLE I
POLARIZATION EXTINCTION RATIOS OF THE PBSs

Type	Port 1	Port 2
Fiber-based PBS1	25 dB	21 dB
Fiber-based PBS2	24 dB	23 dB
free-space PBS1	30 dB	13-20 dB
free-space PBS2	30 dB	43-50 dB

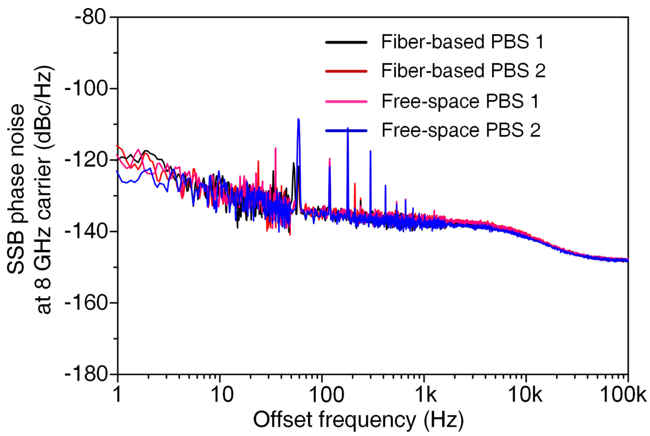

Fig. 6. Residual phase noise of the proposed PolM-PD using four polarization beam splitters with different polarization extinction ratios shown in Table I.

phase noise of the locked 8-GHz DRO is restricted by the residual phase noise of the PolM-PD.

Next, the influence of the degree of polarization (DOP) of the optical pulse train is investigated. Typically, the output of a passive MLL is not fully polarized, for instance, the DOP of the 250-MHz MLL used in the experiment is ∼95%, measured by a polarization analyzer (General Photonics, PSY-201), and the PolM has a PER of 23.2 dB for $\pm\pi/2$ modulation. To study whether the DOP of the optical pulse train affects the phase noise floor of the PolM-PD, the residual out-of-loop phase noise of the PolM-PD is measured by using four PBSs with different PERs, including two fiber-based PBSs and two free-space PBSs. Among them, one of the free-space PBS is made of two PBS cubes in a way that one PBS cube's transmission port cascades with the reflection port of the other PBS cube. Because the PBS cubes are designed to fit with the transmission beam, they have a PER of 30 dB for the transmission beam and 13–20 dB for the reflection beam. The exact PERs for the four PBSs used in the experiment are listed in Table I. The residual phase noise of the PolM-PD with different PBSs is measured by the setup in Fig. 3. As can be seen from Fig. 6, the measured results show no obvious difference. Therefore, the DOP of optical pulse train is not the factor that limits the phase noise floor of the proposed phase detector.

Except for the DOP of the pulse train, the state of polarization (SOP) of the polarized light in a single-mode fiber would fluctuate even when the length is shorter than 1 m [40]. The fluctuation of the SOP would lead to amplitude fluctuation at the PBS's outputs, which results in unbalanced optical power and excess phase noise. Since the PolM has a SMF pigtail with a length of ∼1 m, the SOP fluctuation originated from the SMF pigtail may account for the limited residual phase noise. If the single-mode fiber can be removed by, for example, photonic integration technologies, lower residual phase noise and more robust implementation would be possible.

IV. CONCLUSION

We have proposed and experimentally demonstrated a compact optical-microwave phase detector based on a polarization modulator, of which the out-of-loop residual phase noise is −120 dBc/Hz (−150 dBc/Hz) at 1 Hz (100 kHz) offset frequency when an 8-GHz DRO is synchronized to a 250-MHz MLL. A PLL is successfully established based on the proposed PolM-PD to extract an 8-GHz microwave signal from the 250-MHz MLL. The absolute SSB phase noise is −138 dBc/Hz (−165 dBc/Hz) at an offset frequency of 10 kHz (10 MHz). The proposed PolM-PD has very few optical and electrical components, which could significantly simplify the schemes for optical-microwave synchronization as well as microwave signal generation from MLLs.

REFERENCES

[1] T. Ideguchi, A. Poisson, G. Guelachvili, N. Picque, and T. W. Hansch, "Adaptive real-time dual-comb spectroscopy," *Nature Commun.*, vol. 5, Feb. 2014, Paper 3375.

[2] I. Coddington, W. C. Swann, and N. R. Newbury, "Coherent dual-comb spectroscopy at high signal-to-noise ratio," *Phys. Rev. A*, vol. 82, no. 4, Oct. 2010, Paper 043817.

[3] A. M. Zolot, F. R. Giorgetta, E. Baumann, J. W. Nicholson, W. C. Swann, I. Coddington, and N. R. Newbury, "Direct-comb molecular spectroscopy with accurate, resolved comb teeth over 43 THz," *Opt. Lett.*, vol. 37, no. 4, pp. 638–640, Feb. 2012.

[4] S. T. Cundiff and A. M. Weiner, "Optical arbitrary waveform generation," *Nature Photon.*, vol. 4, no. 11, pp. 760–766, Nov. 2010.

[5] A. Khilo, S. J. Spector, M. E. Grein, A. H. Nejadmalayeri, C. W. Holzwarth, M. Y. Sander, M. S. Dahlem, M. Y. Peng, M. W. Geis, N. A. DiLello, J. U. Yoon, A. Motamedi, J. S. Orcutt, J. P. Wang, C. M. Sorace-Agaskar, M. A. Popovic, J. Sun, G.-R. Zhou, H. Byun, J. Chen, J. L. Hoyt, H. I. Smith, R. J. Ram, M. Perrott, T. M. Lyszczarz, E. P. Ippen, and F. X. Kaertner, "Photonic ADC: Overcoming the bottleneck of electronic jitter," *Opt. Express*, vol. 20, no. 4, pp. 4454–4469, Feb. 2012.

[6] G. C. Valley, "Photonic analog-to-digital converters," *Opt. Express*, vol. 15, no. 5, pp. 1955–1982, Mar. 2007.

[7] S. A. Diddams, D. J. Jones, J. Ye, S. T. Cundiff, J. L. Hall, J. K. Ranka, R. S. Windeler, R. Holzwarth, T. Udem, and T. W. Hansch, "Direct link between microwave and optical frequencies with a 300 THz femtosecond laser comb," *Phys. Rev. Lett.*, vol. 84, no. 22, pp. 5102–5105, May 2000.

[8] T. Udem, R. Holzwarth, and T. W. Hansch, "Optical frequency metrology," *Nature*, vol. 416, no. 6877, pp. 233–237, Mar. 2002.

[9] S. L. Pan and J. P. Yao, "Photonics-based broadband microwave measurement," *J. Lightw. Technol.*, vol. 35, no. 16, pp. 3498–3513, Aug. 2017.

[10] X. Xie, R. Bouchand, D. Nicolodi, M. Giunta, W. Haensel, M. Lezius, A. Joshi, S. Datta, C. Alexandre, M. Lours, P.-A. Tremblin, G. Santarelli, R. Holzwarth, and Y. Le Coq, "Photonic microwave signals with zeptosecond-level absolute timing noise," *Nature Photon.*, vol. 11, no. 1, pp. 44–47, Jan. 2017.

[11] J. Millo, R. Boudot, M. Lours, P. Y. Bourgeois, A. N. Luiten, Y. Le Coq, Y. Kersale, and G. Santarelli, "Ultra-low-noise microwave extraction from fiber-based optical frequency comb," *Opt. Lett.*, vol. 34, no. 23, pp. 3707–3709, Dec. 2009.

[12] J. Wei, D. Kwon, S. Zhang, S. Pan, and J. Kim, "All-fiber-photonics-based ultralow-noise agile frequency synthesizer for X-band radars," *Photon. Res.*, vol. 6, no. 1, pp. 12–17, Jan. 2018.

[13] T. M. Fortier, A. Rolland, F. Quinlan, F. N. Baynes, A. J. Metcalf, A. Hati, A. D. Ludlow, N. Hinkley, M. Shimizu, T. Ishibashi, J. C. Campbell, and S. A. Diddams, "Optically referenced broadband electronic synthesizer with 15 digits of resolution," *Laser Photon. Rev.*, vol. 10, no. 5, pp. 780–790, Sep. 2016.

[14] P. Ghelfi, F. Laghezza, F. Scotti, G. Serafino, A. Capria, S. Pinna, D. Onori, C. Porzi, M. Scaffardi, A. Malacarne, V. Vercesi, E. Lazzeri, F. Berizzi, and A. Bogoni, “A fully photonics-based coherent radar system,” *Nature*, vol. 507, no. 7492, pp. 341–345, Mar. 2014.

[15] S. L. Pan, D. Zhu, S. F. Liu, K. Xu, Y. T. Dai, T. L. Wang, J. G. Liu, N. H. Zhu, Y. Xue and N. J. Liu, “Satellite payloads pay off,” *IEEE Microw. Mag.*, vol. 16, no. 8, pp. 61–73, Sep. 2015.

[16] E. N. Ivanov, S. A. Diddams, and L. Hollberg, “Analysis of noise mechanisms limiting the frequency stability of microwave signals generated with a femtosecond laser,” *IEEE J. Sel. Topics Quantum Electron.*, vol. 9, no. 4, pp. 1059–1065, Jul./Aug. 2003.

[17] A. Haboucha, W. Zhang, T. Li, M. Lours, A. N. Luiten, Y. Le Coq, and G. Santarelli, “Optical-fiber pulse rate multiplier for ultralow phase-noise signal generation,” *Opt. Lett.*, vol. 36, no. 18, pp. 3654–3656, Sep. 2011.

[18] 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 Photon. J.*, vol. 3, no. 1, pp. 140–151, Feb. 2011.

[19] K. Wu, C. M. Ouyang, J. H. Wong, S. Aditya, and P. Shum, “Frequency response of the noise conversion from relative intensity noise to phase noise in the photodetection of an optical pulse train,” *IEEE Photon. Technol. Lett.*, vol. 23, no. 8, pp. 468–470, Apr. 2011.

[20] 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,” *Appl. Phys. B, Lasers Opt.*, vol. 106, no. 2, pp. 301–308, Feb. 2012.

[21] 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,” *Opt. Express*, vol. 17, no. 5, pp. 3331–3340, Mar. 2009.

[22] R. Bouchand, D. Nicolodi, X. P. Xie, C. Alexandre, and Y. Le Coq, “Accurate control of optoelectronic amplitude to phase noise conversion in photodetection of ultra-fast optical pulses,” *Opt. Express*, vol. 25, no. 11, pp. 12268–12281, May 2017.

[23] F. N. Baynes, F. Quinlan, T. M. Fortier, Q. Zhou, A. Beling, J. C. Campbell, and S. A. Diddams, “Attosecond timing in optical-to-electrical conversion,” *Optica*, vol. 2, no. 2, pp. 141–146, Feb. 2015.

[24] T. M. Fortier, F. Quinlan, A. Hati, C. Nelson, J. A. Taylor, Y. Fu, J. Campbell, and S. A. Diddams, “Photonic microwave generation with high-power photodiodes,” *Opt. Lett.*, vol. 38, no. 10, pp. 1712–1714, May 2013.

[25] S. Schulz, I. Grguras, C. Behrens, H. Bromberger, J. T. Costello, M. K. Czwalinna, M. Felber, M. C. Hoffmann, M. Ilchen, H. Y. Liu, T. Mazza, M. Meyer, S. Pfeiffer, P. Predki, S. Schefer, C. Schmidt, U. Wegner, H. Schlarb, and A. L. Cavalieri, “Femtosecond all-optical synchronization of an X-ray free-electron laser,” *Nature Commun.*, vol. 6, Jan. 2015, Paper 5938.

[26] M. Ferianis, A. Bucconi, G. Gaio, G. Mian, M. Predonzani, and F. Rossi, “The copper free FERMI timing system: Implementation and results,” in *Proc. Beam Instrum. Workshop*, 2010, pp. 398–402.

[27] B. Lorbeer, F. Ludwig, H. Schlarb, and A. Winter, “Noise and drift characterization of direct laser to RF conversion scheme for the laser based synchronization system for FLASH at DESY,” in *Proc. 2007 IEEE Part. Accel. Conf.*, 2007, pp. 182–184.

[28] J. Kim, F. X. Kartner, and M. H. Perrott, “Femtosecond synchronization of radio frequency signals with optical pulse trains,” *Opt. Lett.*, vol. 29, no. 17, pp. 2076–2078, Sep. 2004.

[29] K. Jung and J. Kim, “Subfemtosecond synchronization of microwave oscillators with mode-locked Er-fiber lasers,” *Opt. Lett.*, vol. 37, no. 14, pp. 2958–2960, Jul. 2012.

[30] K. Jung, J. Shin, and J. Kim, “Ultralow phase noise microwave generation from mode-locked Er-Fiber lasers with subfemtosecond integrated timing jitter,” *IEEE Photon. J.*, vol. 5, no. 3, Jun. 2013, Paper 5500906.

[31] M. Lessing, H. S. Margolis, C. T. A. Brown, P. Gill, and G. Marra, “Suppression of amplitude-to-phase noise conversion in balanced optical-microwave phase detectors,” *Opt. Express*, vol. 21, no. 22, pp. 27057–27062, Nov. 2013.

[32] J. Kim, F. X. Kartner, and F. Ludwig, “Balanced optical-microwave phase detectors for optoelectronic phase-locked loops,” *Opt. Lett.*, vol. 31, no. 24, pp. 3659–3661, Dec. 2006.

[33] J. Kim and F. X. Kartner, “Attosecond-precision ultrafast photonics,” *Laser Photon. Rev.*, vol. 4, no. 3, pp. 432–456, May 2010.

[34] M. Y. Peng, A. Kalaydzhyan, and F. X. Kartner, “Balanced optical-microwave phase detector for sub-femtosecond optical-RF synchronization,” *Opt. Express*, vol. 22, no. 22, pp. 27102–27111, Nov. 2014.

[35] T. Lamb, M. K. Bock, M. Bousonville, M. Felber, P. Gessler, E. Janas, F. Ludwig, S. Ruzin, H. Schlarb, B. Schmidt, and S. Schulz, “Femtosecond stable laser-to-RF phase detection using optical modulators,” in *Proc. 2011 Free Electron Laser Conf.*, 2011, pp. 551–554.

[36] M. Titberidze, F. Grüner, A. R. Maier, B. Zeitler, H. Schlarb, M. Felber, T. Lamb, C. Sydlo. K. Flöttmann, U. Mavric, J. Müller, S. Epp, and E. Janas, “Present and future optical-to-microwave synchronization systems at REGAE facility for electron diffraction and plasma acceleration experiments,” in *Proc. 2015 Int. Part Accel. Conf.*, 2015, pp. 833–836.

[37] J. Wei, S. Zhang, S. Pan, and J. Kim, “A compact optical-microwave phase detector based on a polarization modulator,” in *Proc. 2017 IEEE Int. Topic Meeting Microw. Photon.*, 2017, pp. 1–3.

[38] S. L. Pan, P. Zhou, Z. Z. Tang, Y. M. Zhang, F. Z. Zhang, and D. Zhu, “Optoelectronic oscillator based on polarization modulation,” *Fiber Integr. Opt.*, vol. 34, no. 4, pp. 211–229, Jul. 2015.

[39] D. Kwon, C. G. Jeon, J. Shin, M. S. Heo, S. E. Park, Y. Song, and J. Kim, “Reference-free, high-resolution measurement method of timing jitter spectra of optical frequency combs,” *Sci. Rep.*, vol. 7, Jan. 2017, Paper 40917.

[40] G. Garlichs, “Polarization behavior fluctuations of a single-mode fiber,” *Electron. Lett.*, vol. 17, no. 23, pp. 894–896, Nov. 1981.

Juan Wei received the B.S. degree in electronic information science and technology from the Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 2012, where she is currently working toward the Ph.D. degree in communication and information system. Her research interest includes stable RF transmission over optical fiber and ultra-stable microwave signal generation.

Shuangyou Zhang received the B.S. degree from Jilin University, and the Ph.D. degree from Peking University in 2016, both in electronics. After completing Ph.D. degree, he was with the Korea Advanced Institute of Science and Technology, South Korea, for one year. He is currently a Higher Research Scientist with the UK's National Physical Laboratory. His research interest includes optical frequency combs and their applications, microresonator-based Kerr frequency comb, chip-scale atomic clock and integrated photonics.

Jungwon Kim (S'98–M'08–SM'12) received the B.S. degree in electrical engineering from Seoul National University, Seoul, South Korea, in 1999, and the S.M. and Ph.D. degrees in electrical engineering and computer science from the Massachusetts Institute of Technology (MIT), Cambridge, MA, USA, in 2004 and 2007, respectively. From 1999 to 2002, he was a Development Engineer with FiberPro, Inc. From 2007 to 2009, he was a Postdoctoral Associate with the Research Laboratory of Electronics, MIT. In 2009, he joined the faculty of the Korea Advanced Institute of Science and Technology, Daejeon, South Korea, where he is currently an Associate Professor of mechanical and aerospace engineering. He has 50 journal publications, more than 100 conference proceeding papers, 24 issued/pending patents, and has given more than 80 invited talks. His research interests include ultralow-noise, integrated femtosecond lasers and their applications in photonic signal processing, ultrafast X-ray and electron sources, long-distance transfer and communication, industrial metrology, and remote sensing.

Dr. Kim is currently an Editorial Board Member of Scientific Reports. He is a Senior Member of OSA.

Shilong Pan (S'06–M'09–SM'13) received the B.S. and Ph.D. degrees in electronics engineering from Tsinghua University, Beijing, China, in 2004 and 2008, respectively.

From 2008 to 2010, he was a “Vision 2010” Postdoctoral Research Fellow with the Microwave Photonics Research Laboratory, University of Ottawa, Ottawa, ON, Canada. In 2010, he joined the College of Electronic and Information Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, China, where he is currently a Full Professor and an Executive Director of the Key Laboratory of Radar Imaging and Microwave Photonics, the Ministry of Education. He has authored or coauthored more than 350 research papers, including more than 180 papers in peer-reviewed journals and 170 papers in conference proceedings. His research has focused on microwave photonics, which includes optical generation and processing of microwave signals, analog photonic links, photonic microwave measurement, and integrated microwave photonics.

Dr. Pan is currently a Topical Editor for the *Chinese Optics Letters*. He is a Chair of numerous international conferences and workshops, including the TPC Chair of the International Conference on Optical Communications and Networks in 2015, the TPC Co-Chair for the IEEE International Topical Meeting on Microwave Photonics in 2017, the TPC Chair of the high-speed and broadband wireless technologies subcommittee of the IEEE Radio Wireless Symposium in 2013, 2014, and 2016, the TPC Chair of the Optical fiber sensors and microwave photonics subcommittee of the OptoElectronics and Communication Conference in 2015, and a Chair of the microwave photonics for broadband measurement workshop of International Microwave Symposium in 2015. He was the recipient of an OSA Outstanding Reviewer Award in 2015 and a Top Reviewer for the *Journal of Lightwave Technology* in 2016.