Octave-Band Microwave Frequency Synthesizer Using Mode-Locked Laser as a Reference

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***Abstract*—An octave-band voltage-controlled oscillator is phase-locked on the envelope of the pulse train from a mode-locked laser. The locking scheme employs a balanced Mach-Zehnder modulator with two photodiodes as a phase detector. The phase.locked loop has a loop bandwidth of approximately 1 MHz and an in-band phase noise of approximately -135 dBc/Hz at all frequencies. The integrated jitter from 1 kHz to 100 MHz is 21 fs, 18.3 fs and 13.8 fs at 5.016 GHz, 7.6 GHz and 10.032 GHz carrier frequencies, respectively. To the authors' knowledge, this is the best jitter performance reported for a PLL with MZM-based phase detection and the first reported PLL of this type featuring an octave-band frequency range.**

***Index Terms*—Ultra low phase noise PLL, Low jitter PLL, Mode Locked Laser**

I. Introduction

Low phase noise signal sources are widely used in object detection, navigation systems, and ultra high speed data communication systems. The in-band phase noise of the signal sources is dominated by the reference signal phase noise [1] which is usually a Surface Acoustic Wave (SAW) or quartz oscillator. While these reference oscillators are standard for communication systems, the envelope of an optical pulse train generated by a mode-locked laser (MLL) can have a better phase noise performance up to 3 orders of magnitude [2–4]. This led to an increasing interest in opto-electronic phase-locked loops (OEPLL). [5–8] have reported generation of microwave signals from an MLL, but they all require at least two laser sources which increases the complexity of the setup. [9] has shown that using a balanced optical microwave phase detector (BOMPD) [10] significantly simplifies the locking scheme and demonstrated an OEPLL with a single laser source. However, BOMPDs employ fiber-based interferometers which are usually expensive, bulky and sensitive to vibrations. In addition, the microwave oscillator used in [9] is a dielectric resonator oscillator (DRO) which cannot provide sufficient tuning range for most RF applications. In [11] the fiber-based interferometer was replaced with a Mach-Zehnder Modulator (MZM), which is much smaller. But, the phase noise performance was poor compared to [9].

In this paper an MZM-based OEPLL with a wide RF tuning range is presented. An octave-band switched-capacitor voltage-controlled oscillator (VCO) provides a high tuning range for the OEPLL and the output frequency can be any integer multiple of the MLL repetition rate (76 MHz) in the frequency range of 5 to 10 GHz. Section II presents the block diagram and the principle of operation of the system. Section III explains the details of the measurement setup and the measurement results.

II. Theory of Operation

Fig. 1 shows the block diagram of the OEPLL. The balanced MZM acts as a sampler and undersamples the VCO signal with reference optical pulse train, as illustrated in Fig. 2. The complementary optical outputs of the MZM are then converted into current pulses with a pair of photodetectors using differential detection scheme, as illustrated in Fig. 1. The photodetector difference current is zero when the reference and the VCO signals are in quadrature. The sign of the difference current varies around this quadrature point and gives an indication of the phase difference between the reference and the VCO. These current pulses are then filtered and converted into voltage using a series RC filter. This voltage then is fed to the tuning port of the VCO to phase-lock the VCO signal onto the envelope of the reference pulse train.

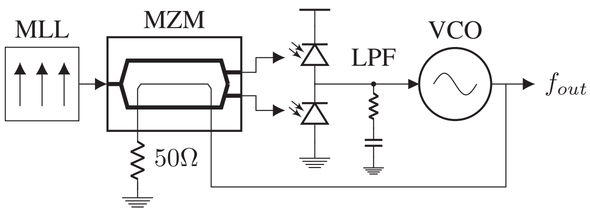

Fig. 1. Simplified block diagram of the Opto-Electronic PLL.

A. Optical Sampler As Phase Detector

A balanced Mach-Zehnder modulator can sample the VCO signal with the sample rate of the reference frequency. When the VCO is locked to the reference, the intensity-modulated output signals of the MZM contain sufficient information about the phase difference between the envelope of the optical signal and the VCO signal to keep the loop locked. Fig. 3 shows the operating principle of the modulator. The optical input x_{opt} is first divided into two paths. The upper path adds a phase shift ϕ to the optical signal and the lower path adds

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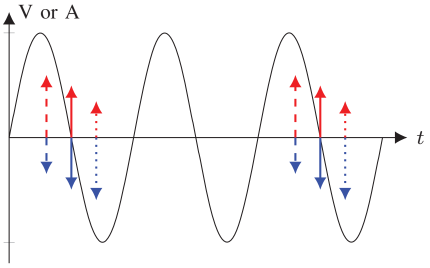

Fig. 2. (black) Excitation voltage of MZM, currents pulses generated at the upper (red) and lower (blue) photodiodes, when the reference and the VCO signals are in quadrature (solid), when reference has a phase lag (dashed) and when reference has a phase lead (dotted). This is a qualitative figure and the y-axis has units of Volts for the voltage waveform and Amperes for the current pulses.

the reverse amount of the same phase shift, $-\phi$, to the signal. The magnitude of these phase shifts are proportional to the excitation voltage v_{RF}. The phase-shifted optical signals are then combined with a 90° coupler.

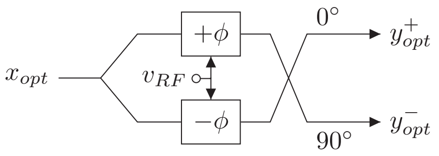

Fig. 3. Simplified architecture of the balanced MZM.

Using this figure, the intensities of the optical outputs, y_{opt}^{+} and y_{opt}^{-}, can be derived as

$$P_y^{\pm} = 0.5 P_x [1 \pm \sin(2\phi)] \tag{1}$$

where P_y^+ and P_y^- correspond to the intensity of y_{opt}^+ and y_{opt}^-, respectively, and $\phi = \pi . v_{RF}/2V_\pi$. Fig. 4 shows these intensities vs. the excitation voltage. These intensities are clearly complementary and by employing a differential photodetection scheme, the photodetector difference current will be

$$i_{PD} = R_\lambda P_x \sin\left(\frac{\pi . v_{RF}}{V_\pi}\right) \approx R_\lambda P_x \frac{\pi . v_{RF}}{V_\pi}, \tag{2}$$

where R_λ is the responsivity of the photodetector and the approximation holds for small excitation voltages. (2) shows that the instantaneous difference current i_{PD} is approximately linearly scaled with the instantaneous value of the RF signal which means that the RF signal is effectively sampled by the narrow optical pulses of the MLL pulse train. Therefore, a balanced MZM can act as a phase detector.

B. *Effect of the Loop Filter on the Phase Noise*

In order to analyze the phase noise of the OEPLL, a linear model of the PLL in the phase domain has been used. Fig. 5 shows this model including the noise sources.

The effect of the reference, phase detector and VCO phase noise on the overall phase noise has been studied very well in

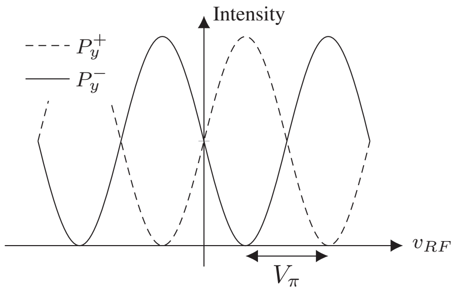

Fig. 4. The intensities of the outputs of the balanced MZM as a function of the excitation voltage.

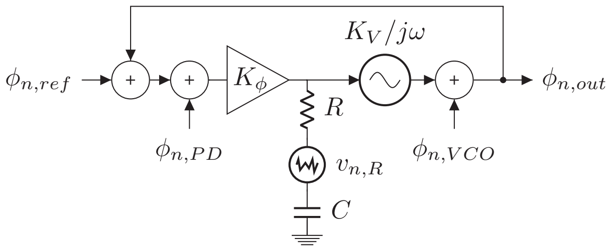

Fig. 5. Linear model of the OEPLL with the noise sources.

the literature [1]. The transfer function of these noise sources are

$$H_{n,PD}(\omega) = H_{n,ref}(\omega) = \frac{H_L(\omega)}{1 + H_L(\omega)} \tag{3}$$

and

$$H_{n,VCO}(\omega) = \frac{1}{1 + H_L(\omega)}, \tag{4}$$

where $H_{n,PD}$, $H_{n,ref}$ and $H_{n,VCO}$ are the noise transfer function of the the phase detector, the reference and the VCO to the output. H_L is the open loop transfer function

$$H_L(\omega) = K_\phi (R + \frac{1}{j\omega C}) \frac{K_V}{j\omega}, \tag{5}$$

where K_ϕ and K_V are the phase detector gain and the VCO tuning sensitivity, respectively. (5) can be used to design the loop filter for a given unity gain frequency (UGF) and phase margin (PM). For a phase margin of 45°, the loop filter components are

$$C = \frac{\sqrt{2} K_\phi K_V}{\omega_u^2} \quad \text{and} \quad R = \frac{\omega_u}{\sqrt{2} K_\phi K_V}, \tag{6}$$

where ω_u is the unity gain angular frequency.

One can manipulate the low pass and high pass characteristic of the transfer functions in (3) and (4) to optimize the overall phase noise using unity gain frequency as a degree of freedom. However, the noise injected by the loop filter plays a significant role in ultra low phase noise PLLs. The transfer characteristic of the resistor voltage noise to the output is

$$H_{n,R}(\omega) = \frac{K_V}{j\omega [1 + H_L(\omega)]}. \tag{7}$$

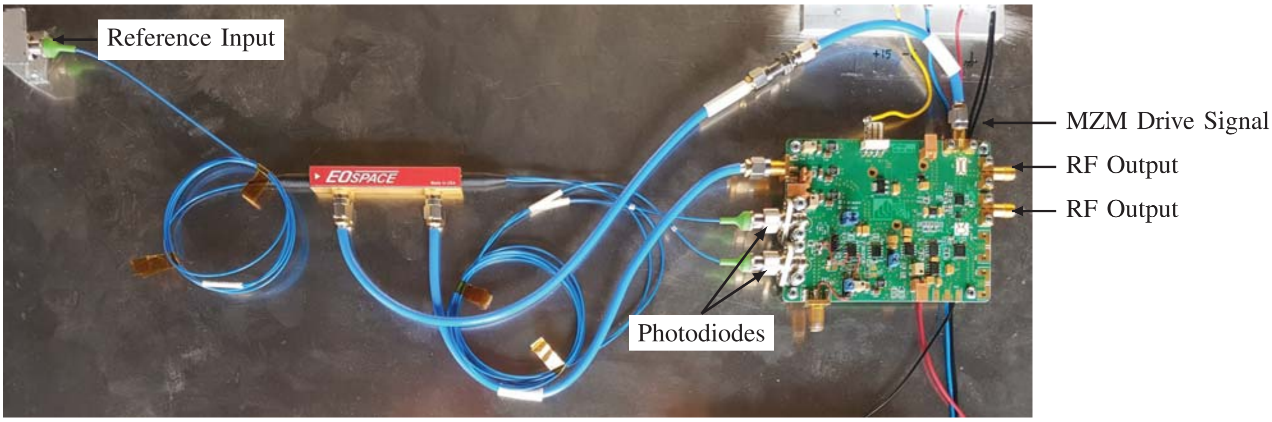

Fig. 6. Photograph of the developed unit.

Therefore, the resistor contribution to the overall phase noise single-sided power spectral density, $S_{\phi_R}(\omega)$, is

$$S_{\phi_R}(\omega) = \frac{2kTR}{\pi}\left|\frac{K_V}{j\omega[1+H_L(\omega)]}\right|^2, \tag{8}$$

where k is the Boltzmann constant and T is the absolute temperature. (8) shows the resistor noise transferred to the output is proportional to K_V, since R is proportional to K_V^{-1}. Therefore, increasing the VCO tuning sensitivity leads to more noise from the loop filter resistor, for a given UGF and PM.

III. Experimental Setup and Measurement Results

An ORIGAMI MLL was selected as a reference oscillator due to its low phase noise. The wavelength of the laser is at 1550 nm and the repetition rate of the optical pulses is 76 MHz.

For a high output frequency range we decided to use an octave-band VCO. Unfortunately such VCOs usually have a high tuning sensitivity and this leads to the increase of the resistor noise contribution to the overall phase noise, as discussed in Section II-B. In order to avoid such problems, a multi-core octave-band switched capacitor VCO is used to keep the tuning sensitivity below 100 MHz/V. Another advantage of this design choice is that it limits the bandwidth of each VCO core to approximately 100MHz and the PLL can lock at maximum two of the reference harmonics, since the reference repetition rate is 76 MHz. Therefore, the designer has a better control over the harmonic number which the VCO locks into.

The balanced Mach Zehnder modulator is an X-cut Lithium Niobate Dual-Output Modulator with 18 GHz electrical bandwidth at 1550 nm from EOSPACE. The photodetectors are InGaAs PIN photodiodes with an active area diameter of 120 μm.

A Printed Circuit Board (PCB) containing the loop filter, octave-band VCO, the InGaAs photodiodes and auxiliary circuitry such as voltage references and driver amplifiers was developed. Fig. 6 shows the PCB connected to the MZM.

Fig. 7 shows the measured phase noise of the OE-PLL, characterized with an Anapico phase noise analyzer (APPH20G), at the carrier frequencies of 5.016 GHz, 7.6 GHz and 10.032 GHz which correspond to the 66th, 100th and 132th reference harmonics, respectively. The sum of the reference and the phase detector noises is approximately -135 dBc/Hz at frequency offsets above 10 kHz in the in-band frequency range. The UGF was chosen as 1 MHz. The VCO phase noise at 1 MHz offset is higher than the in-band phase noise by approximately 10 dB. Although this leads to an increase of the phase noise at around 1 MHz frequency offset, the overall jitter performance is better due to further suppression of the reference and phase detector noises at higher frequency offsets. The jitter was measured as 21 fs at 5.016 GHz, 18.3 fs at 7.6 GHz and 13.8 fs at 10.032 GHz, integrated from 1 kHz to

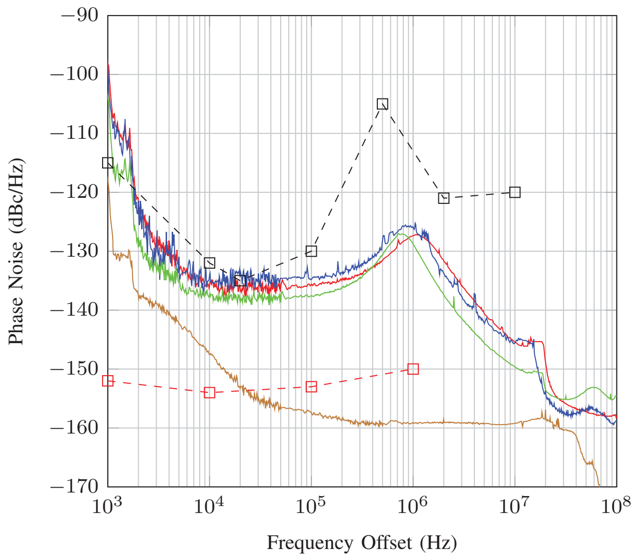

Fig. 7. Phase noise comparison: (brown) measured phase noise of 12th harmonic of the optical reference at 912 MHz, (red) measured phase noise of OEPLL at 10.032 GHz, (blue) measured phase noise at 7.6 GHz, (green) measured phase noise at 5.016 GHz, (dashed red) phase noise of [9] normalized to 10 GHz, (dashed black) phase noise of [11] at 10.17 GHz

100 MHz.

The measurement results show an improved performance of the phase noise both inside and outside of the loop bandwidth compared to [11]. But, [9] still has a better phase noise. The main reason for this difference is the MLL source. By comparing the reference phase noise of this work at 912 MHz with the phase noise of [9] at 10 GHz in Fig. 7, it can be seen that [9] has a MLL source with better jitter performance by 10-15 dB. Another reason for this difference is that this works uses a switched capacitor VCO (instead of DRO in [9]) which has a higher phase noise by approximately 25 dB at 1 MHz frequency offset, however allowing for higher RF bandwidth.

IV. Conclusions

This paper presented a wideband OEPLL locked to an optical reference, using a balanced MZM and a balanced photodetection scheme as a phase detector. The OEPLL has an in-band phase noise of -135 dBc/Hz and a jitter of 13.8 fs at 10.032 GHz carrier frequency, integrated from 1 kHz to 100 MHz. To the authors' knowledge, our OEPLL provides both lower phase noise and larger output frequency range than any other MZM-based OEPLL.

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