Review

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Microwave Photonic Techniques in Phase-Noise Measurements of Microwave Sources: A Review

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Abstract

Microwave photonics has recently come to the forefront as a valuable approach to generating, processing, and measuring signals in high-performance domains such as communication, radar, and timing systems. Recent studies have introduced a range of photonics-based phase-noise analyzers (PNAs) that utilize a variety of architectures, including phase detection, frequency discrimination, and hybrid mechanisms that combine optical with electronic processing. This review delves into the microwave photonics methodologies developed with the specific purpose of measuring phase noise, by exploring their fundamental principles, system design frameworks, and performance indicators. Through the integration of insights garnered from recent publications, our objective is to deliver a comprehensive understanding of the strengths and limitations associated with PNAs and to pinpoint new and promising areas for advancing research in the field of oscillator metrology.

Keywords: microwave photonics; phase-noise measurement; optical fiber; delay-line method; photonic processing; sensitivity improvement

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1. Introduction

The accurate characterization of phase noise in microwave oscillators is critical to developing high-performance communication systems [1], radar systems [2,3], quantum computing [4], experiments in big physics [5], and timing systems [6,7]. Phase noise has been a major constraint on the performance of modern electronic systems [8].

The development of microwave oscillators with low phase noise has long been a fundamental challenge when creating high-performance communication, radar, navigation, and timing systems. An important milestone was achieved with the introduction of the optoelectronic oscillator (OEO) by Yao and Maleki [9], who demonstrated the potential of using optical components to generate ultra-low-phase-noise microwave signals. This led to the development and rapid expansion of a new research field: microwave photonics.

In the past three decades, the rapid advances in optical fiber communications—driven by the need for high-speed, high-capacity data transmission—has led to the development of high-performance photonic components such as modulators, detectors, and integrated optical circuits [10,11]. Concurrently, progress in integrated optics has enabled compact, stable, and broadband photonic systems, while promoting the position of microwave photonics as a powerful tool for signal generation, processing, and measurement.

Microwave photonic techniques have also been increasingly adopted in metrology. Microwave photonics measurements have been used for spectrum analysis, instantaneous frequency measurements, microwave channelization, Doppler frequency-shift measurements, angle-of-arrival detection, and phase-noise measurements [12]. These techniques stand out for their broad bandwidths and speeds, which are not achievable with conventional electronic methods [13]. Particular interest has been shown in the accurate characterization of phase noise in oscillators. As a result, several photonic-enabled phase-noise analyzers with unprecedented sensitivity and bandwidth have been realized [14].

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This review focuses on microwave photonics techniques that were specifically developed for phase-noise measurements. We examine their principles, system architectures, and performance. By synthesizing insights from our own investigations and the literature, we aim to provide an overview of microwave photonics-enabled phase-noise measurements, and to identify promising directions for future research in oscillator metrology.

2. Phase Noise and Its Characterization

Phase noise is the most important property of an oscillator and describes its short-term stability. It has been one of the main limitations of performance in the most advanced and high-end systems [8]. Therefore, it is no surprise that understanding the sources of phase noise and characterization techniques has been of great interest to researchers and industry for 60 years [15].

The signal of a non-ideal oscillator is

$$v(t) = V_0 \sin[2\pi\nu_0 t + \varphi(t)], \tag{1}$$

where V_0 is the amplitude, ν_0 is the oscillation frequency, and $\varphi(t)$ is the random phase-fluctuation process [16,17]. Note that the signal of a real oscillator also includes the amplitude noise. However, effective countermeasures are known, and amplitude noise can be filtered out of the oscillator signal, which is not the case for phase noise. Therefore, amplitude noise is often neglected when studying the noise characteristics of oscillators.

Since phase noise is a random process, it is meaningful only to report its statistical properties. It is most practical to describe the phase noise using its power spectral density (PSD). For a stationary and ergodic random process, which phase noise is, it follows that

$$S_\varphi(f) = \langle |\Phi(jf)|^2 \rangle, \tag{2}$$

where $\Phi(jf)$ is the Fourier transform of $\varphi(t)$, and the units of $S_\varphi(f)$ are rad^2/Hz.

IEEE Standard 1139 [18] defines the phase noise as

$$L(f) = \frac{S_\varphi(f)}{2} \tag{3}$$

which is reported exclusively on a logarithmic scale as $10\log_{10} L(f)$ with units of dBc/Hz. The motivation behind the choice of units and the definition in (3) is backwards compatible with the now obsolete definition of phase noise as the power ratio [16,17].

2.1. Measurement Methods

Measuring the phase noise is one of the most demanding tasks for modern electrical engineers [19]. Conventional methods for measuring the phase noise are roughly divided into the direct method, the phase-detector method, the residual or interferometric method, the frequency-discriminator or delay-line method, and the cross-correlation method [17,20,21]. Apart from the direct method, which is the simplest but also the least accurate, all the other methods are related to the phase-detector method.

The phase-detector method, in its simplest form, consists of a mixer, a low-pass filter, and an FFT analyzer, as shown in Figure 1. The signal under test (SUT) is compared to the high-performance,

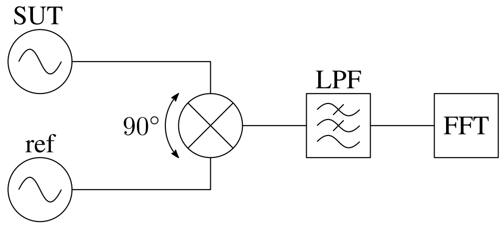

Figure 1. Phase-detector method. SUT: signal under test, LPF: low-pass filter, FFT: fast-Fourier-transform analyzer.

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low-noise reference signal. Given that the phase noise of the reference is negligible compared to the phase noise of the SUT, such that $|\varphi_{\text{ref}}(t)| \ll |\varphi_{\text{SUT}}(t)|$, and the inputs of the mixer are quadrature so that the mixer operates as a phase detector, then the output of the mixer is

$$S_v(f) = k_\phi^2 S_\varphi(f), \tag{4}$$

where $S_v(f)$ is the PSD of the voltage fluctuation at the mixer output, k_ϕ is the phase-to-voltage conversion factor of the mixer, and $S_\varphi(f)$ is the phase noise of the SUT. In practice, the requirement for quadrature on the mixer inputs dictates the use of a phased-locked loop on the reference. The need for a high-quality reference limits the usability of the method when measuring state-of-the-art low-noise sources. A solution using an optoelectronic oscillator as a high-quality reference was presented in [22].

In the delay-line method, sometimes referred to as the frequency-discriminator method, the need for a high-performance, low-noise reference is removed. Instead, the SUT is divided into two paths, one of which includes a delay τ. The two paths are multiplied on the mixer, thus a SUT is compared with its delayed self rather than with a reference signal. The delay τ introduces zeros in the transfer function

$$S_v(f) = 4k_\phi^2 \sin^2(\pi f \tau) S_\varphi(f), \tag{5}$$

which limits the useful noise bandwidth of the measurement and dictates the choice of delay. As with the phase-detector method, here too, the quadrature condition is required at the mixer inputs; therefore, in practice, some phase adjustment is required in either the delayed or non-delayed arm of the measurement setup. In practice, a delay of the order of 1 µs to 10 µs gives the best balance between sensitivity and noise bandwidth. Historically, implementing a suitable delay τ posed an obstacle that made the method unattractive. However, it has seen attempts at a commercial solution [23].

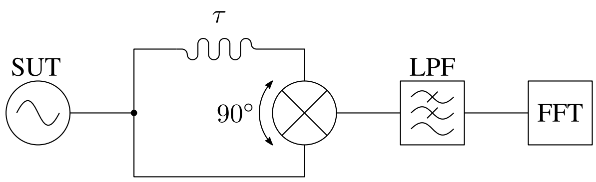

Figure 2. Delay-line or frequency-discriminator method. The SUT is split into two paths, one of which is considerably longer. The mixer operates as a phase detector. SUT: signal under test, LPF: low-pass filter, FFT: fast-Fourier-transform analyzer.

The cross-correlation method became the norm in phase-noise metrology due to its high sensitivity [24]. Therefore, it is the basis for commercial instruments such as Keysight E505xA Signal Source Analyzers and Rohde&Schwarz FSWP Phase Noise Analyzers. The sensitivity of the phase-detector method is limited by the phase noise of the reference and the additive phase noise of other components in the measurement setup. This limitation can be circumvented by taking two independent measurements simultaneously. The price is doubling the setup, including the reference. The two measurements are then cross-correlated. The measurement taken is

$$S_\varphi(f) = S_{\varphi,\text{SUT}}(f) + \frac{S_A(f) + S_B(f)}{\sqrt{m}}, \tag{6}$$

where m is the number of cross-correlations. Since the two measurement channels are independent, the contributions of each reference and the corresponding components can be arbitrarily made by simply taking more measurements. Figure 3 shows the cross-correlation method.

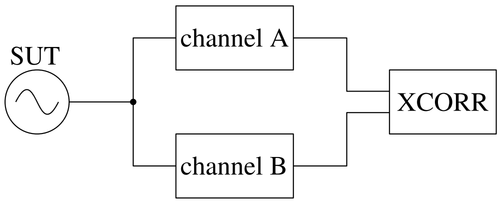

Figure 3. Cross-correlation method. SUT: signal under test, XCORR: cross-correlation.

The residual or interferometric method is used to measure the phase noise of two-port devices such as amplifiers, frequency multipliers, etc. Its topology closely resembles the delay-line method, but the delay is replaced by the device under test (DUT), as shown in Figure 4.

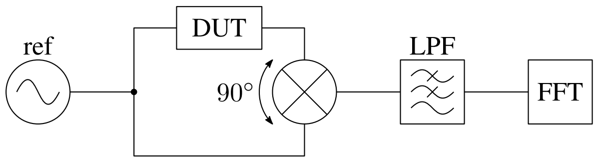

Figure 4. Residual or interferometric method. DUT: device under test, LPF: low-pass filter, FFT: fast Fourier analyzer.

If the lengths of the reference path and the path through the DUT are delay-matched, the noise from the reference oscillator is suppressed, and only the phase-noise contribution from the DUT is seen at the output of the mixer. For further details, the reader is referred to [25–28].

The development of high-speed digital electronics led to the direct digital implementation of the phase detector and cross-correlation method, which exhibits an ultra-low noise floor but is limited by the analog-to-digital conversion bandwidth [29–34]. Recently, phase-noise measurements based on the Bayesian filtering framework and machine-learning techniques have been demonstrated [35] with the phase-detector topology and [36,37] with the delay-line topology.

3. Fiber-Optic Delay-Line Method

Optical fiber, with its ultra-low loss (0.2 dB/km) and extremely wide bandwidth (tens of THz), enables unprecedented delays. It is no surprise that among the conventional methods, the delay-line method is the main subject of microwave photonics. In its simplest form, the photonic delay is implemented as an analog fiber optic link using intensity modulation and direct detection (IM/DD). This gives a delay

$$\tau = \frac{nL}{c}, \tag{7}$$

where L is the length of the optical fiber, n is the refractive index of the optical fiber, and c is the speed of light in vacuum. Tens of kilometers of fiber can be used without the need for optical amplification, making delays of hundreds of microseconds achievable. When the optoelectronic oscillator (OEO) was presented in 1996 [9], it used such a fiber-optic delay in the feedback loop of the oscillator, which spawned a whole new field of research [38–40] and as fiber-optic delay to evaluate the phase noise of the presented OEO. However, it took another 10 years for the first in-depth treatment by Rubiola et al. [41,42]. Figure 5 shows a simple implementation of the delay-line phase-noise measurement method, in which the delay is implemented as an IM/DD analog optical link with a Mach-Zehnder modulator, and quadrature is ensured with an additional variable phase shifter.

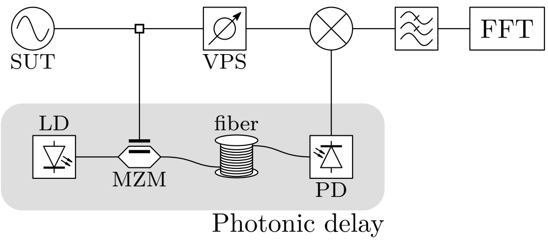

Figure 5. Photonic delay-line method with delay implemented as an analog optical link. SUT: signal under test, VPS: variable phase shifter, FFT: fast-Fourier-transform analyzer, LD: laser diode, MZM: Mach-Zehnder modulator, PD: photodiode.

Together with the Mach-Zehnder modulator, a delay realized with the electro-absorption modulator (EAM) [43] and direct modulation of the laser current [44] have been demonstrated to provide performance comparable to the MZM with reduced complexity and cost. Compared to EAM and direct modulation, the MZM solution requires the careful selection of modulation bias voltage, polarization of the incident light, and stabilization of the environment. On the other hand, a more complex MZM configuration allows a sophisticated manipulation of the optical modulated signals. Figure 6a shows the example of a dual-parallel MZM (DP-MZM), and Figure 6b shows a dual-polarization MZM (DPol-MZM), which enables the independent modulation of two orthogonal polarization planes.

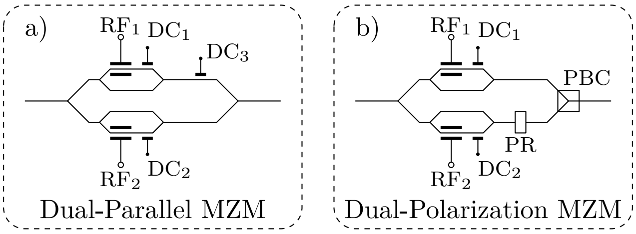

Figure 6. a) Dual-parallel Mach-Zehnder modulator, b) Dual-polarization Mach-Zehnder modulator. PR: polarization rotator, PBC: polarization beam combiner.

In [45], external low-frequency phase modulation of the SUT prior to injection into the fiber-optic delay-line phase-noise meter enables automatic calibration during measurement, making the phase-noise meter suitable for use outside laboratory environments.

The impact of the optical fiber itself on the phase noise was extensively studied in [46–48]. An in-depth investigation of the phase-noise contribution from individual elements of the IM/DD optical link was presented in [49]. The study presents the impact of fiber-related properties such as double Rayleigh scattering, chromatic dispersion, and fiber length, as well as the properties of other components such as laser relative-intensity noise, power, and linewidth.

Based on the simple implementation shown in Figure 5, the research went in two directions: setting and maintaining the quadrature condition for correct operation, and improving the sensitivity. Both directions have in common the graduated move of functionalities from the microwave to the optical domain.

3.1. Photonic Processing

Microwave photonics has emerged as a field in which photonics are exploited for processing microwave signals. For the correct operation of the down-converting phase noise to the baseband, a quadrature condition needs to be satisfied on the down-converting component. This requires some method of signal phase manipulation in the measurement setup. While simple solutions [41,43,44] use a mechanical microwave phase shifter that requires manual adjustment, Zhu et al. [50] used a photonic processor based on a microwave photonic phase shifter implemented with a single-sided polarization modulator and polarizer, as shown in Figure 7.

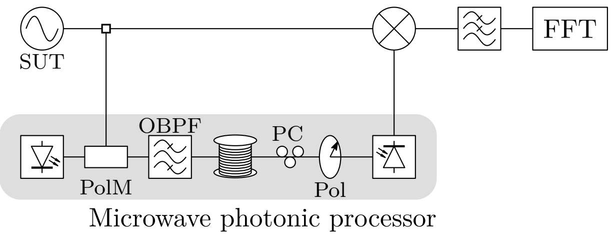

Figure 7. Phase-noise measurement with a microwave photonic processor presented in [50], which utilizes both delay and phase tuning. SUT: signal-under-test, FFT: fast-Fourier-transform analyzer, PolM: polarization modulator, OBPF: optical band-pass filter, PC: polarization controller, Pol: polarizer.

By carefully selecting the bias voltage of the polarization modulator, the phase between the signals in the two main polarization planes can be carefully selected. The polarization controller (PC) together with the polarizer acts as a selective detector. The microwave photonics subsystem now provides both the required delay and phase shift. However, the use of polarization modulation makes the system very sensitive to environmental disturbances. This is addressed by the use of a dual-parallel MZM and optical band-pass filter (OBPF) in [51]. By carefully selecting the three bias voltages of the dual-parallel MZM, the phase between the modulation sidebands and the optical carrier can be continuously selected. The setup is shown in Figure 8.

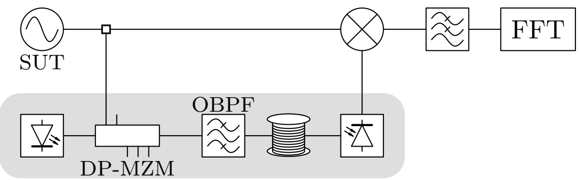

Figure 8. Photonic-assisted phase shifter and delay utilized by dual-parallel MZM [51]. SUT: signal-under-test, FFT: fast-Fourier-transform analyzer, DP-MZM: dual-parallel Mach-Zehnder modulator, OBPF: optical band-pass filter.

The OBPF ensures single-sideband detection at the photodiode. Another way of achieving the required phase shift was presented in [52]. This approach uses photonic-assisted frequency up- and down-conversion. The proposed solution requires a local oscillator that provides frequency up-conversion together with a dual-drive MZM and OBPF.

The required quadrature condition at the mixer inputs can also be achieved via precise delay tuning. The authors presented a solution that exploits the otherwise undesirable effect of chromatic dispersion to fine tune the delay of the modulated signal. Chromatic dispersion is the result of frequency dependence of the refractive index of the optical fiber. The propagation delay of the signal can be written as

$$\tau = \tau_p + \Delta\tau_g, \tag{8}$$

where τ_p is the non-dispersive delay and $\Delta\tau_g$ is the group delay caused by the chromatic dispersion. For small changes in the wavelength $\Delta\lambda$, the change in group delay can be approximated as

$$\Delta\tau_g \approx LD\Delta\lambda, \tag{9}$$

where L is the fiber length and D is the average chromatic dispersion coefficient over $\Delta\lambda$. It follows from equations (8) and (9) that by changing the laser's wavelength, the delay can be accurately tuned. The tuning of the delay for $\Delta\tau_g$ according to equation (9) translates into the available phase change of the signal

$$\Delta\theta = 2\pi\nu_0\Delta\tau_g = 2\pi\nu_0 LD\Delta\lambda. \tag{10}$$

This can be easily achieved with standard telecom components using the temperature control of the laser diode for wavelength tuning [53]. Such a realization is robust and economical because its reuse of mass-produced telecom components and slow electronics for temperature control. Standard G.652

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fiber has a relatively low chromatic dispersion coefficient, typically +17 ps/(km nm) in the C-band wavelengths, which limits delay tunability to approximately 140 ps. With equation (10) in mind, a full 360° phase shift is available for SUT in the X-band and above. Techniques to increase delay tunability were further investigated.

Due to chromatic dispersion, the carrier and sidebands accumulate different phases along the fiber, resulting in pulse spreading and power fading [54]. To combat this effect in optical communication networks, special dispersion-compensating fiber (DCF) is used [55–57]. DCF has a high chromatic dispersion coefficient with the opposite sign to standard telecom fiber. Using DCF greatly increases the delay tunability for the same fiber length and wavelength tuning of the laser. A phase-noise measurement using DCF was presented in [58]. These solutions maintain simplicity by changing only the type of fiber, while improving the operating bandwidth of the setup. However, DCFs are available in modules optimized to compensate for a specific length of standard optical fiber, which limits the flexibility of their use in other applications. To overcome this limitation, a dual-fiber solution is proposed in [59] and shown in Figure 9.

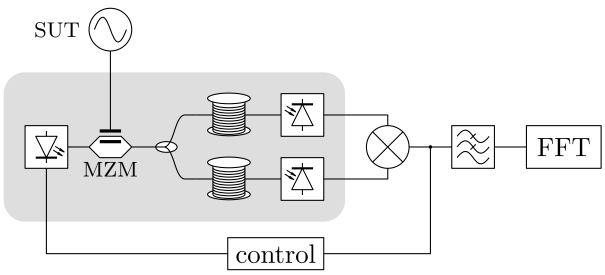

Figure 9. Dual-fiber wavelength-tuned phase-noise measurement exploiting the chromatic dispersion of the fiber. SUT: signal under test, MZM: Mach-Zehnder modulator, FFT: fast-Fourier-transform analyzer.

What distinguishes this solution from the setup in [41] is that the fibers used in each branch have different chromatic dispersion coefficients. In this way, the delay tuning is given by

$$\Delta\tau_g = (L_1 D_1 - L_2 D_2)\Delta\lambda, \tag{11}$$

where D_i and L_i are the chromatic dispersion coefficients and fiber lengths, respectively. The available tuning range can be extended by using longer fibers, as long as the difference between the two paths satisfies the required delay given by equation (7).

The above solutions used photonics techniques to ensure the quadrature condition for the correct operating regime of the microwave mixer. Another solution, shown in Figure 10 and presented in [60], uses a photodiode in place of the mixer, thus implementing a photonic down-converter.

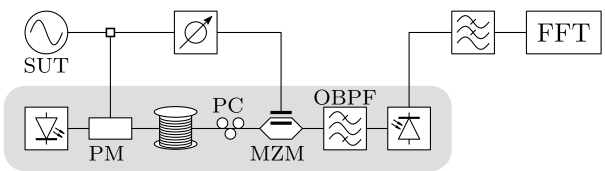

Figure 10. Photonic downconverter presented in [60]. The photodiode functions as a phase detector, so the phase noise is downconverted directly from the optical domain to the baseband. SUT: signal under test, FFT: fast-Fourier-transform analyzer, PM: phase modulator, PC: polarization controller, MZM: Mach-Zehnder modulator, OBPF: optical bandpass filter.

This is realized by using two electro-optic modulators and an OBPF to filter out only one pair of sidebands. On the photodiode, the pair of sidebands is converted directly to the baseband of the noise. The phase shifter sets the correct phase between the sidebands. The use of a photonic phase shifter and a photonic delay was merged, as shown in Figure 11 and was first presented in [61].

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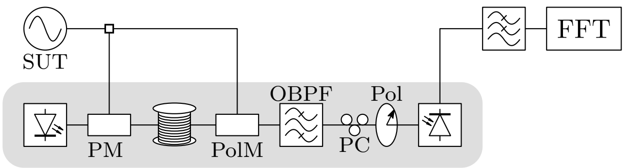

Figure 11. Photonic-assisted phase-noise measurement presented in [61]. The delay, phase manipulation, and downconversion are all performed in the optical domain. SUT: signal under test, FFT: fast-Fourier-transform analyzer, PM: phase modulator, PolM: polarization modulator, OBPF: optical bandpass filter, PC: polarization controller, Pol: polarizer.

The second modulator is replaced by the polarization modulator, and an additional polarizer is inserted in front of the photodiode. This was further improved in [62], where the polarization modulator is replaced by a dual polarization MZM, thus reducing the cost and improving the bandwidth of the measurement setup.

The need for phase manipulation in either branch of the delay-line measurement can be avoided by using the quadrature mixer with digital phase demodulation, as presented in [63]. The implementation with photonic delay, described in [64] and shown in Figure 12, follows this approach.

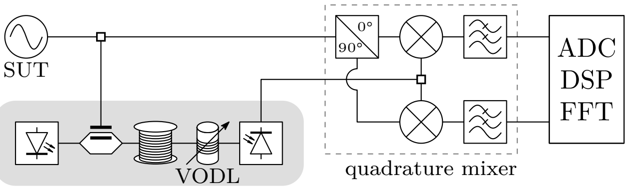

Figure 12. Digitally demodulated phase-noise measurement with photonic delay and microwave IQ mixer, as presented in [64]. SUT: signal under test, VODL: variable optical delay line, ADC: analog-to-digital converter, DSP: digital signal processing, FFT: fast Fourier transform.

The mixer that serves as the phase detector is replaced by a quadrature mixer realized with discrete, off-the-shelf connectorized modules. The baseband now requires two analog-to-digital converters (ADCs) to sample both the in-phase (I) and quadrature (Q) components of the down-converted signal. The phase noise is then extracted with digital post-processing

$$\varphi(t) = \arctan\left(\frac{v_Q(t)}{v_I(t)}\right) \tag{12}$$

Additionally, the setup in [64] introduces a fiber piezo-stretcher, which allows slow delay modulation by stretching the fiber length. The small but known fluctuation in time delay is converted to the known phase fluctuation of a down-converted signal, enabling automatic calibration of the measurement setup and compensation of the quadrature mixer's imperfections.

Following the trend of shifting functionalities to the optical domain, a solution with photonic-assisted I/Q mixing was presented in [65], where a photonic I/Q mixer is used instead of a microwave mixer. The photonic I/Q mixer is implemented by driving a dual-polarization MZM from a 90° hybrid. Each modulation sideband consists of an in-phase and quadrature component, which are now polarization-coded. Using an OBPF, only one sideband is selected, and then one sideband is split via a polarization beam splitter (PBS), thus separating the components to two individual photodiodes. The output of the photodiodes includes the corresponding in-phase or quadrature signal and a DC offset, which needs to be measured in advance and corrected during post-processing. Figure 13 shows the described measurement setup based on a photonic-assisted I/Q mixer.

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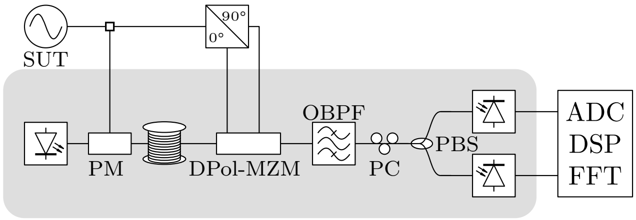

Figure 13. Phase-noise measurement based on a photonic-assisted I/Q mixer presented in [65]. SUT: signal under test, PM: phase modulator, DPol-MZM: dual-polarization Mach-Zehnder modulator, OBPF: optical band-pass filter, PC: polarization controller, PBS: polarization beam splitter, ADC: analog-to-digital converter, DSP: digital signal processing, FFT: fast Fourier transform.

The use of an electrical 90° hybrid limits the microwave bandwidth of the proposed setup. This limitation was successfully addressed in [66], where the dual-polarization MZM is replaced by a polarization modulator, as in [50]. In the same manner as in [64], the variable optical delay line enables the automatic calibration and correction of the quadrature relation between the two polarizations by changing the PolM bias voltage. Figure 14 shows an all-optical I/Q mixer measurement. The use of a PolM relaxes the microwave bandwidth constraints but is sensitive to environmental changes.

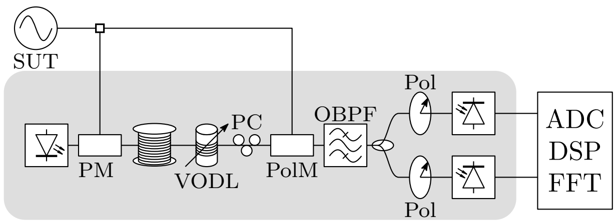

Figure 14. Phase-noise measurement using an all-optical microwave I/Q mixer as presented in [66]. SUT: signal under test, PM: phase modulator, VODL: variable optical delay line, PC: polarization controller, PolM: polarization modulator, OBPF: optical band-pass filter, Pol: polarizer, ADC: analog-to-digital converter, DSP: digital signal processing, FFT: fast Fourier transform.

3.2. Sensitivity Improvements

Another challenge addressed in the literature is the sensitivity of the phase-noise measurement setup. Assuming the system is operating correctly, the question is how low the measured phase noise can be while still being distinguishable from the noise of the measuring device. Hong and Yin showed in [67] that the careful selection of components can greatly improve the sensitivity of a simple, single delay-line measurement setup.

The industry and research standard with conventional phase-noise measurements is the use of cross-correlation. This can be easily implemented by duplicating the setup and performing a cross-correlation over simultaneous measurements. The successful adoption of the cross-correlation technique with the photonic delay method was presented in [68–73] and is shown in Figure 15. The same fiber was reused in both channels using wavelength division multiplexing in [74]. Two variable optical delay lines are used for each channel to ensure a quadrature condition on the corresponding mixers.

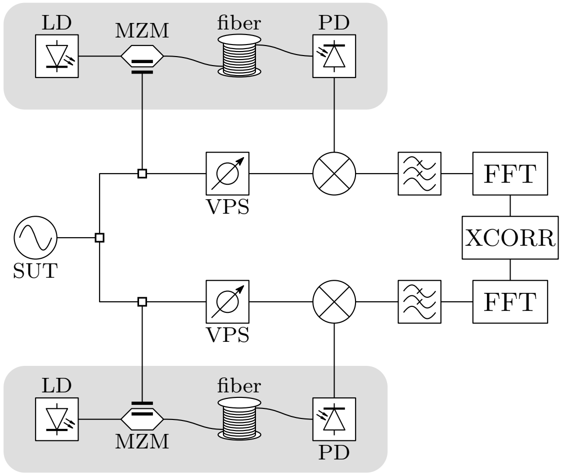

Figure 15. Dual photonic-delay cross-correlation method presented in [69]. SUT: signal under test, VPS: variable phase shifter, FFT: fast-Fourier-transform analyzer, LD: laser diode, MZM: Mach-Zehnder modulator, PD: photodiode, XCORR: cross-correlation.

The uncertainty of the photonic-delay cross-correlation method has been rigorously examined [75,76].

Another technique to increase sensitivity was adopted in [77], where an electro-optic frequency comb is used to amplify the measured phase noise. The DUT drives an electro-optical frequency comb, where the phase noise of the DUT is transferred to the higher-order modes of the comb

$$\varphi_n(t) = \varphi_{cw}(t) + n\varphi_{\mathrm{DUT}}(t) \tag{13}$$

where $\pm n$ is the order of the comb mode. The phase-noise contribution from the DUT rises linearly with the order of the comb mode, while the contribution of the measurement setup, mainly the laser noise, is constant. Since selecting the higher-order modes of the comb is effectively a frequency multiplication, n-times-faster electronics are implied. However, [77] proposes the self-heterodyne method, also used for characterizing mode-locked lasers [78,79]. The comb on the non-delayed path is frequency shifted by f_{AOM} with the acusto-optic modulator (AOM). After the delay and frequency shift, two OBPF selects a pair of $\pm n$ modes. The required bandwidth of the photodiodes and electronics is then determined by f_{AOM}, which is in the range of 100 MHz. The proposed solution is shown in Figure 16.

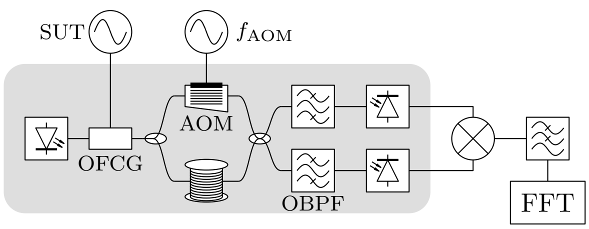

Figure 16. Optical frequency comb-based self-heterodyne phase-noise measurement method presented in [77]. SUT: signal under test, OFCG: optical frequency comb generator, AOM: acusto-optic modulator, OBPF: optical bandpass filter, FFT: fast Fourier transform.

The technique was further developed in [80], where heterodyning with an AOM was replaced by an I/Q detector based on optical hybrids. In addition to two optical 90° hybrids, four balanced photodiodes (BPDs) are used, which are free of DC voltage on detection. Apart from the DC absence on the detection, BPDs also suppress the DUT amplitude noise and the contribution of the laser noise, which also contributes to an enhanced measurement sensitivity. The complete setup is shown in Figure 17. Although such a complete system exhibits impressive bandwidth and sensitivity, it requires

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application-specific components such as optical 90° hybrids and reconfigurable optical bandpass filters, making the system costly and inaccessible outside specialized laboratory environments.

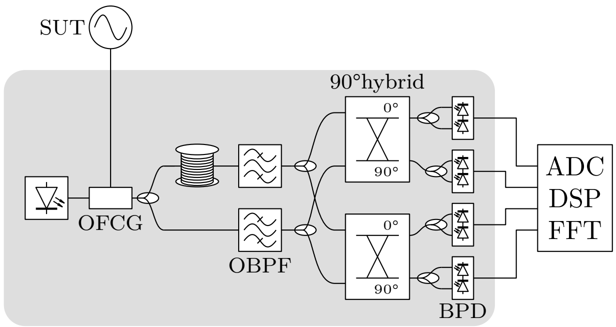

Figure 17. Optical frequency comb-based self-calibrating and high-sensitivity phase noise measurement with optical I/Q detector, as presented in [80]. SUT: signal under test, OFCG: optical frequency comb generator, OBPF: optical bandpass filter, BPD: balanced photodiode, ADC: analog-to-digital converter, DSP: digital signal processing, FFT: fast Fourier transform.

The laser and the amplifiers are the main contributors to the noise floor of the measurement setup. The delay-line method inherently uses the topology of an interferometer, so it is no surprise that advanced techniques of the interferometric or residual method to measure the phase noise [26] have also been adopted for the delay-line method. Rubiola et al. presented in [81] a detection scheme in which the carrier is suppressed in one arm of the setup. The scheme, shown in Figure 18, takes advantage of the fact that there is no up-conversion of the 1/f noise in the absence of a strong carrier signal [27].

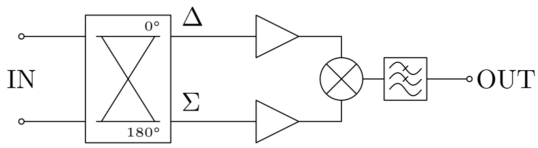

Figure 18. Carrier-suppression scheme for low-level signal detection presented in [81]. The absence of a carrier at amplifier A_Δ allows high gain without signal degradation.

This allows a gain of 40 dB without polluting the signal with the amplifier's own noise [25]. The described carrier-suppression technique has been successfully applied to the photonic-delay method in [82] where the carrier-suppression scheme of Figure 18 follows the photodiodes. Using this technique, the laser-noise contribution was suppressed by approximately 60 dB, and the noise floor was improved compared to commercial instruments.

An attempt to improve the sensitivity of the coaxial-cable-based delay-line method was presented in [83], where a SUT is converted down to the intermediate frequency, resulting in lower attenuation for the coaxial cable delay. This idea was further developed in [84], where the delay is implemented using photonics. With optical fiber, the delay loss is no longer an issue. Translating the frequency to the intermediate frequency also benefits the requirements for photodiodes and microwave electronics. The proposed solution is shown in Figure 19.

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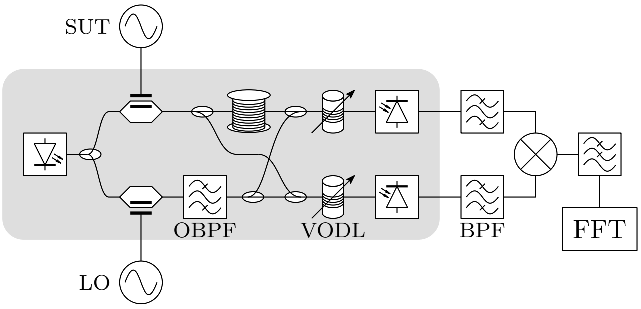

Figure 19. Photonic delay-line method with delay-matched frequency translation presented in [84]. The two paths of the LO signal are delay-matched, which results in noise suppression when down-converting to the intermediate frequency. SUT: signal under test, LO: local oscillator, OBPF: optical bandpass filter, VODL: variable optical delay line, BPF: bandpass filter, FFT: fast Fourier transform analyzer.

The optical carrier is divided into two paths. One is modulated by the SUT, and the other is modulated by a local oscillator (LO) for frequency translation. In the LO path, a single modulation sideband is passed through the OBPF to the two photodiodes, while the SUT is further split into delayed and non-delayed paths. in addition to the optical-electrical conversion, the role of photodiodes is also frequency translation to the intermediate frequency

$$f_{\mathrm{IF}} = |f_{\mathrm{SUT}} - f_{\mathrm{LO}}|. \tag{14}$$

While the SUT path follows the delay-line or frequency-discriminator method in which a longer mismatch between two arms translates to better sensitivity, the LO path follows the residual or interferometric method in which the two arms have to be equal to suppress the noise of the reference oscillator, in this case the LO. To achieve this, two variable optical delay lines are inserted before the photodiodes. The requirements in terms of LO quality are loosened due to the noise suppression.

4. Conclusion

This review provides an organized overview of microwave photonic techniques for phase-noise measurements in microwave signal sources. We examined the development and progress in phase-noise measurements using microwave photonic techniques. The primary focus of the field is the delay-line method, which became attractive because optical fiber allows adequate photonic delays. The fiber-optic delay-line method forms the foundation of most approaches, benefiting from the exceptionally low loss and wide bandwidth of optical fiber. The earliest microwave photonic implementations of phase-noise measurements simply replaced the delay element with an analog optical link. More advanced and complex microwave photonic techniques have transferred processing functionalities to the optical domain, enabling all-optical phase-noise meters that outperform commercially available instruments. Regardless of the success, the photonic delay-line phase-noise measurement method continues to be an attractive research topic. It has been used successfully for the emulation and characterization of phase-noise impact on frequency-modulated continuous wave radar [85]. The photonic delay has also been used to reduce the phase noise of noisy voltage-controlled oscillators [86].

Looking ahead, integrating photonic delay, modulation, and mixing functions on chip-scale platforms is expected to greatly reduce the cost, footprint, and environmental sensitivity.

In summary, microwave photonic phase-noise measurements have matured into a versatile and powerful framework that now surpasses many state-of-the-art electronic solutions in sensitivity and bandwidth. Continued development toward compact, stable, and self-calibrating photonic architectures will be the key to enabling next-generation high-performance communication, radar, and time-frequency systems.

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