RF Amplitude and Phase-Noise Reduction of an Optical Link and an Opto-Electronic Oscillator

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***Abstract*—In this paper we examine the optical sources of noise that degrade high-performance microwave photonic links. In particular, we study the residual phase noise due to laser frequency fluctuations and the detector nonlinearity on microwave signals transmitted on an optical fiber, or generated in the opto-electronic oscillator (OEO). Based on experimental findings, we identify a significant reduction of the relative intensity noise of the laser if the received optical power saturates the photodiode. Furthermore, we suggest the use of a semiconductor optical amplifier in saturation as yet another means to reduce the phase noise induced by laser intensity fluctuations. We also identify the use of multiple photodetectors to reduce the influence of associated $1/f$ noise, which adds to the phase noise of a transmitted microwave signal, and is the ultimate limitation to the phase noise of the high-performance OEO. Reduction of noise that is due to optical interferences is also addressed.**

***Index Terms*—AM noise, optical communication, oscillators, phase noise.**

I. Introduction

FOR NEARLY two decades, microwave photonics has been regarded as a technology with the potential to significantly improve the performance of communications and radar systems. The promise of these links has been hampered by the unavailability of optical components that support the need for maintaining a high linearity in transmission of microwave signals. But in recent years, several technological challenges in the field have been successfully met, and microwave photonics has found important applications in several commercial and military systems. One of the main applications of these links is transmission of RF or microwave signals to remotely located antennas. A higher functionality is obtained when the microwave photonic link is used as a feedback loop to generate highly spectrally pure signals with the architecture known as the opto-electronic oscillator (OEO).

The advent of new schemes to realize highly linear links, in particular, promises to further expand the range of applications of the technology [1]–[4]. These schemes basically rely on high-power lasers, highly efficient modulators, and high-power photodetectors (PDs). This combination reduces the reliance on front-end amplifiers that increase the system noise temperature.

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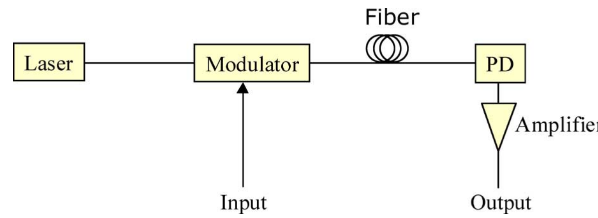

Fig. 1. Generic optical link configuration for the transmission of analog and digital information over fiber.

The increased power on the PD also reduces the shot noise, further improving the overall noise figure of the system by reducing the need for post-detection gain. The approach, however, leaves the noise induced by the laser as the outstanding source of system performance degradation. This is especially true as most high-power sources such as solid-state and fiber lasers, though having narrow linewidth, exhibit a higher level of relative intensity noise (RIN) as compared with semiconductor lasers. The higher powers also exacerbate noise produced due to residual light reflection in the photonic system.

In this paper, we discuss approaches that can be used to mitigate the residual PD and laser-induced noise in microwave photonic systems. Our study is aimed at the linear contribution of laser induced noise; nonlinear sources of noise associated with laser light including Brillouin, Raman, wave mixing, etc. will not be addressed, as they have been thoroughly discussed in the literature, and schemes for reducing them have been previously identified [5].

II. Optical Link and OEO Configurations

A basic optical link configuration is illustrated in Fig. 1. It consists of a laser, serving as the light source. The microwave signal is modulated on light as a sideband with a high-speed modulator. The detected light at the PD is then converting back to the microwave signal by mixing the carrier and sideband light fields. The detected signal also includes any amplitude and/or phase noise that is added by the link, and this could affect the performance of the system and severely distort the electronic signal at the input of the link.

Closing the loop between the input and output of such an optical link, combined with microwave amplification to compensate for losses and filtering to select the desired microwave frequency, results in the generation of stable and high spectral purity reference signals. This configuration is illustrated in Fig. 2, and is commonly known as the OEO [6]–[10]. As in the optical link, the OEO performance (mainly the phase noise is of interest) is affected by the noise of the microwave and optical

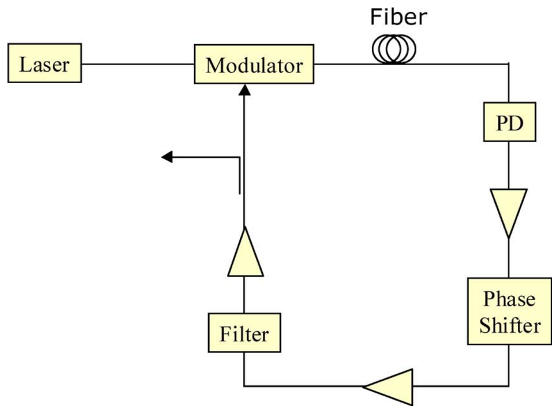

Fig. 2. OEO configuration. A closed loop with microwave amplification and filtering around an optical link.

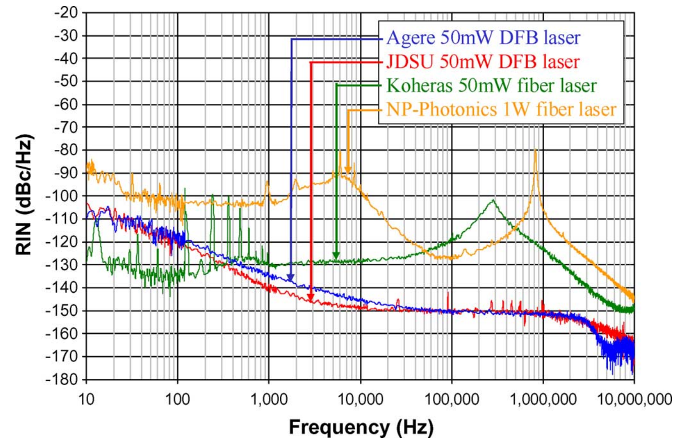

Fig. 3. Measured RIN level of 1550-nm commercial lasers.

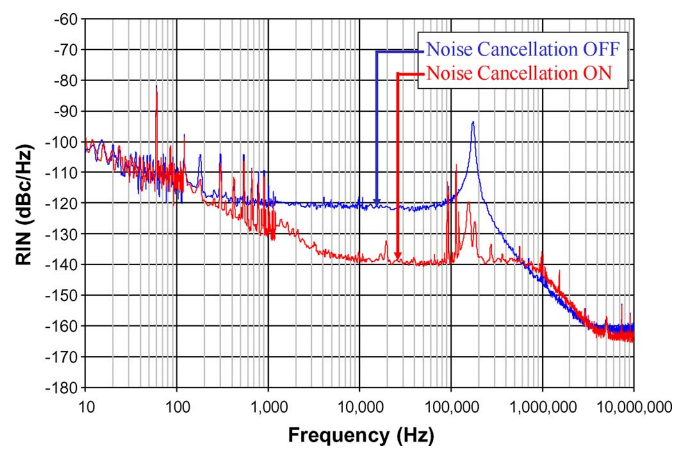

Fig. 4. Measured RIN level of 1319-nm commercial YAG laser with internal RIN cancellation circuit ON and OFF.

components in the loop. Amplitude and phase noise generated in the loop will affect the noise of the output signal. Moreover, due to nonlinearities, amplitude and phase noise could be interchanged and even up-converted from dc or baseband to higher frequencies (the input microwave frequency of the optical link or the generated signal of the OEO). It is important to select low noise components in order to improve the link or the OEO performance. It is also as important to identify the processes that convert the AM to PM noise and vise versa, and identify ways to maximize the desired performance parameters. In the following sections, we carefully examine some of the optically induced noise sources in the optical link, and identify methods to efficiently reduce them.

III. Laser RIN

Laser light intensity noise is one of the limiting factors in the transmission of analog or digital signals over fiber, and has been extensively studied in the literature. The power fluctuations corresponding to this noise increases the overall link noise and reduces the signal-to-noise ratio, thus degrading the system performance. A common parameter that describes the laser amplitude noise is the spectral density of the RIN, normalized with the total optical intensity. The RIN ($R(f)$), usually measured in units of dB/Hz, is given by [11]

$$R(f) = \frac{\Delta P_{\rm Opt}^2(f)}{P_{\rm Opt}^2} \tag{1}$$

where $P_{\rm Opt}$ is the laser average optical power and $\Delta P_{\rm Opt}(f)$ is the spectral density of the laser optical power fluctuations at frequency f.

We measured the RIN level of a few commercial lasers. In this study, the RIN was measured via a PD (Discovery DSC30) followed by a signal analyzer (Agilent 89441A). The measurement results are illustrated in Fig. 3 for various 1550-nm distributed feedback (DFB) and fiber lasers, while Fig. 4 illustrates the RIN for a 100-mW Lightwave's 1319-nm YAG laser with an internal intensity noise cancellation circuit in the ON and OFF modes. RIN at low frequencies is also sensitive to environmental effects such as thermal and acoustic fluctuations, and back reflection into the laser. At higher frequencies, RIN also includes the characteristic relaxation oscillations peaks that for fiber and YAG lasers appear below 10 MHz. Note that when the "RIN reduction" circuit is ON, the YAG laser's RIN is efficiently reduced to -140 dB/Hz above 10 kHz. DFB lasers usually have their relaxation oscillation peaks at a few gigahertz to over 10 GHz, which is outside of the range of our measurement frequency. They are also characterized by a lower RIN as compared with fiber or YAG lasers. However, they usually have a much wider linewidth compared with those lasers. A wider linewidth could also impact the link noise through light reflections or scattering, as considered below.

At high frequencies (above a few MHz), the laser's RIN level drops, and is usually limited by shot noise.

IV. Conversion of Laser RIN to RF Amplitude and Phase Noise

The baseband laser RIN can be up-converted to microwave amplitude and phase noise via nonlinearities in the optical link. The main element that is responsible for the RIN-to-RF AM or PM conversion is the PD, located at the end of the optical link. Other components including the Mach–Zehnder (MZ) modulator and the optical fiber usually have much smaller nonlinearities that become significant at much higher optical power level compared with that of the PD. For low optical power levels below the PD saturation power, the number of carriers (electron hole) in the PD increases with the increase of light power. This results in a "square law" increase of the RF power at the PD input since [11]

$$P_{\mathrm{RF}} \sim P_{\mathrm{Opt}}^2 \tag{2}$$

where P_{RF} is the RF (microwave) signal power level, and P_{Opt} is the average optical power at the PD input. It also produces a change in the RF phase since the propagation speed of the RF signal (or the PD microwave refractive index) depends on the number of carriers in the semiconductor. In this range, the RF amplitude and phase sensitivities of the PD result in a significant increase of the RF amplitude and phase noise in the optical link due to the presence of baseband laser RIN.

For small laser intensity fluctuations (low RIN level), the conversion of RIN-to-RF phase noise is given by

$$S_\phi(f) = R(f) \cdot P_{\mathrm{Opt}}^2 \cdot \left(\frac{d\phi}{dP_{\mathrm{Opt}}}\right)^2 \tag{3}$$

where $S_\phi(f)$ is the phase-noise spectral density (rad^2/Hz) at offset frequency f from the RF carrier, and $d\phi/dP_{\mathrm{Opt}}$ is the RF phase-to-optical power slope. Note that the single-sideband (SSB) phase noise $L(f)$ (dBc/Hz) is given by

$$L(f) = \frac{1}{2} \cdot S_\phi(f). \tag{4}$$

The conversion of RIN-to-RF amplitude noise (at low RIN level) is approximated by

$$S_\alpha(f) = R(f) \cdot P_{\mathrm{Opt}}^2 \cdot \left(\frac{d\alpha}{dP_{\mathrm{Opt}}}\right)^2 \tag{5}$$

where $S_\alpha(f)$ is the spectral density (dBc/Hz) of the normalized RF amplitude fluctuations α given by

$$\alpha = \frac{\Delta P_{\mathrm{RF}}}{2 \cdot P_{\mathrm{RF}}} \tag{6}$$

and $d\alpha/dP_{\mathrm{Opt}}$ is the normalized RF amplitude-to-optical power slope.

In our 10-GHz OEO setup, the effect of the RIN was clearly observed with the YAG laser RIN reduction circuit. This is illustrated in Figs. 5 and 6 with the measurements of the RF spectrum (using an Agilent 8564 spectrum analyzer) and the RF phase noise (in this study, the phase noise was measured via a cross-correlation photonic delay line setup [12], [13]). By turning the circuit OFF, the laser baseband RIN is dramatically increased (see Fig. 5) with a strong peak at the relaxation oscillations frequency, which is imprinted on the OEO phase noise (Fig. 6). The thick black curves illustrate the lower noise level of each of the measurements, exhibiting similarities with the laser RIN.

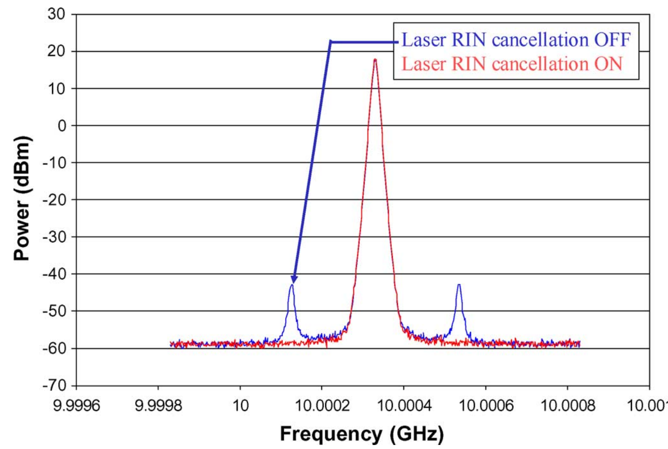

Fig. 5. OEO RF spectrum with the YAG laser RIN cancellation circuit turned ON and OFF.

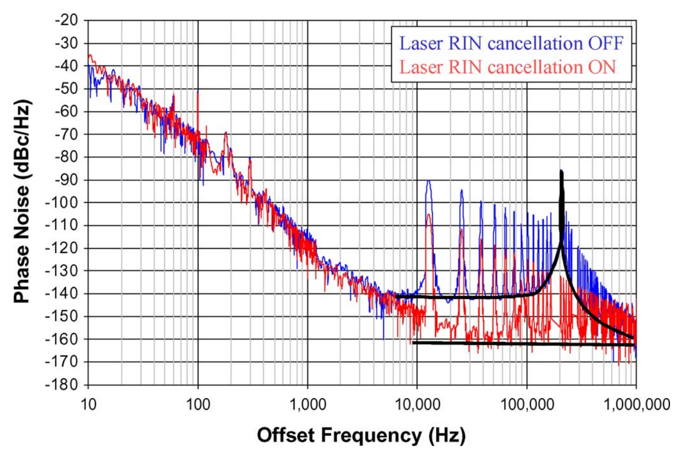

Fig. 6. OEO phase noise $L(f)$ measured with the YAG laser RIN cancellation circuit turned ON and OFF (higher noise level above 10 kHz).

V. Reduction of Laser RIN via Amplitude Limiting Devices

The laser RIN could be reduced by various methods. One method is with a feedback loop, as used in the YAG laser. In this scheme, the laser power is detected and the electrical control signal is fed back to the laser bias current or to an external power control such as an optical modulator. Another method, which we explored in this study, is to transmit the laser light through a power limiter. An optical amplitude or power limiter is characterized by an output power that is not sensitive to changes in the input power, thus variations of the laser intensity will be reduced dramatically at the limiter output. Passive devices working on this principle are available and are mostly based on material nonlinearities, but active devices, such as optical amplifiers, could also serve as optical limiters if operated in saturation. When the input signal to the optical amplifier and the gain are sufficiently large to saturate the amplifier, then the output power will have a significantly reduced sensitivity to any fluctuations at the input. To verify this, we performed RIN measurements of the laser followed by a semiconductor optical amplifier (SOA), and observed a RIN reduction of approximately 10 dB, as illustrated in Figs. 7 and 8.

The optical amplifier also provides amplification of the signal before coupling to the PD, which could result in a stronger RF signal, as well as in saturating the PD (see Section VI). On the

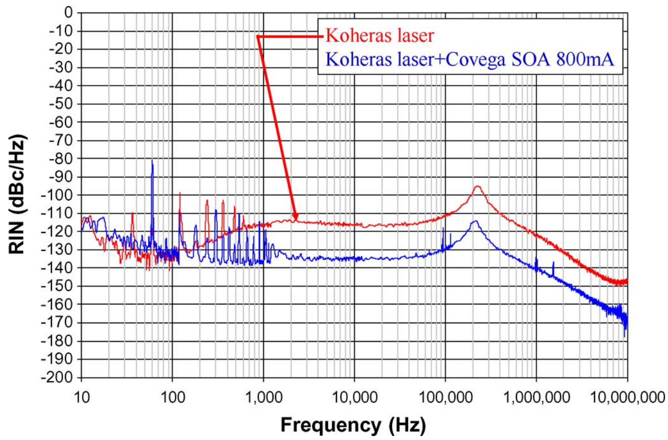

Fig. 7. Reduction of Koheras laser RIN with an SOA serving as optical amplitude limiter.

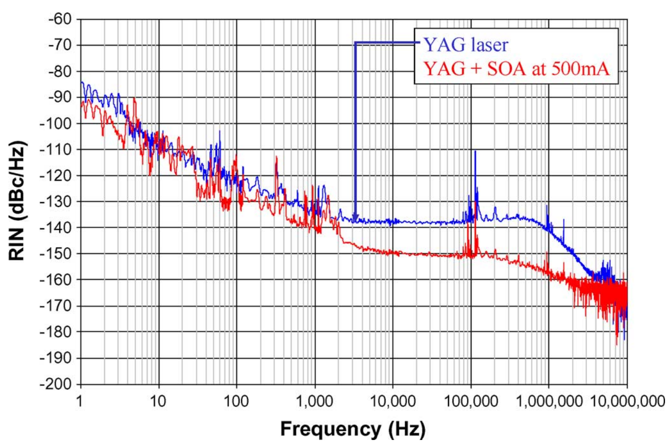

Fig. 8. Reduction of YAG laser RIN with an SOA.

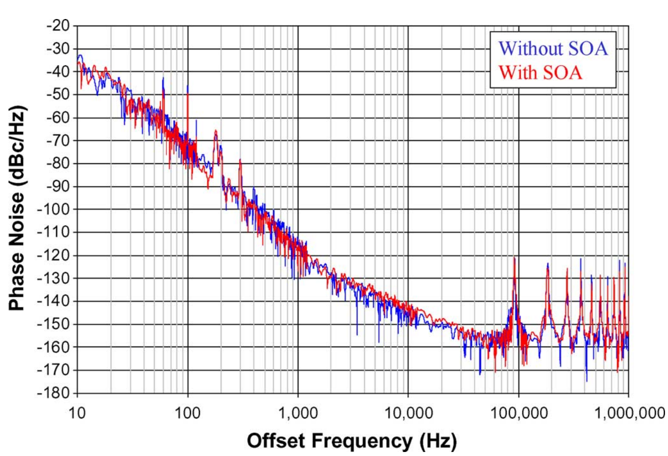

Fig. 9. OEO phase noise with and without an SOA. The setup consists of 1319-nm YAG laser.

other hand, since the SOA is an active device, it could increase the noise figure in the link. We have verified that, in our OEO setup, adding the SOA at the end of the fiber link (just before the PD) did not result in an increase of the RF phase noise. This measurement is illustrated in Fig. 9.

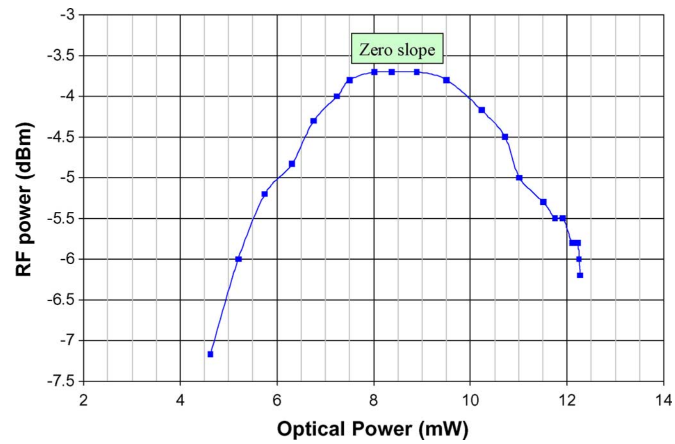

Fig. 10. Discovery PD RF output power versus input optical power.

VI. Reduction of RF Amplitude and RF Phase Noise Due to PD Nonlinearity

In this study, we also studied the effect of PD saturation on the conversion of laser baseband RIN into amplitude and phase noise. Previously, a study was made to measure the RIN-to-RF phase conversion in the case of short optical pulses at the PD input [14]. It was found that the variation of the RF phase with optical power exhibited only positive slopes of "non-monotonic with deep minima" with a strong dependence on the harmonics number of the pulse repetition rate. It was also found [14] that the optical power level where the "deep minima" were observed for the RF phase slope did not coincide with the maximum RF power at the PD output. The maximum achievable RF power level is an important parameter for the reduction of thermal and shot noise. Here we show that for a 10-GHz sinusoidal modulation of the 1319-nm light, the PD slope for both the RF amplitude and phase is a linear monotonic decreasing function with zero slopes at certain optical power. Moreover, at the zero slope point, the RIN-to-RF phase and amplitude noise conversions could approximately vanish for both amplitude and phase noise since both conditions occur for similar input optical power at the PD. Similar measurements were performed for an electroabsorption modulator (reverse biased to operate as a PD at 1550 nm) with results that are discussed below.

Our investigations began with the measurements of the power and the relative phase of an RF signal at the output of the PD as a function of the RF modulated optical power at the input of the PD. In the first measurement, our optical link consisted of a DSC30 Discovery PD, and a 1319-nm Lightwave YAG laser modulated at 10 GHz with the help of a high-speed MZ modulator. The measured RF power at the PD output is illustrated in Fig. 10. At low input optical power (<5.6 mW), the square law behavior (1) is approximately obeyed, and the RF power is approximately four times higher when the optical input power is doubled. As the input optical power approaches the PD saturation power, the slope of the RF power versus input optical power decreases and reaches zero at optical power of 8–9 mW. This is due to the fact that at saturation, the generated electron–hole carriers screen the external electric field of the reversed dc bias at the PD junction [15] so that an increase in the optical power does not result in generation of additional dc and RF currents.

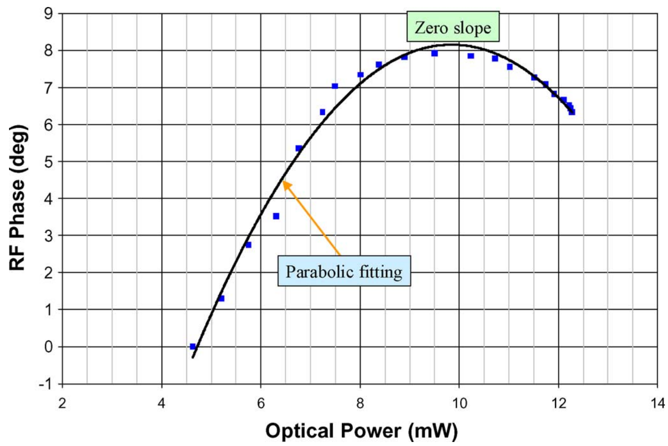

Fig. 11. Measured input to output relative phase of the PD. The measured data is fitted with a parabola.

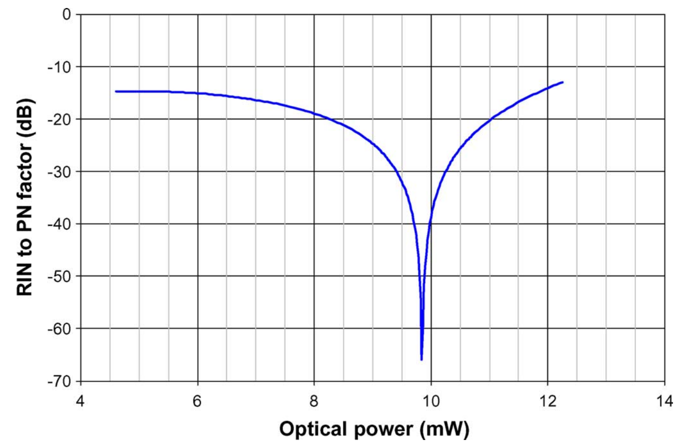

Fig. 12. Optical link (open-loop OEO) RIN-to-SSB phase-noise conversion factor $F(P_{\mathrm{Opt}})$ versus optical power of the discovery PD parabolic behavior (Fig. 11).

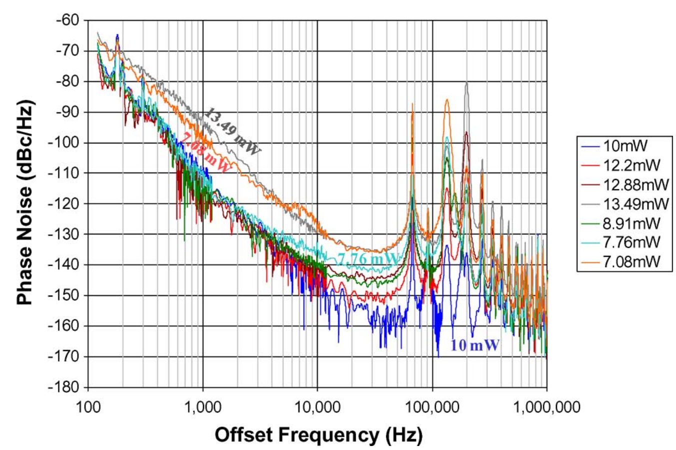

Fig. 13. Phase noise of an OEO $L(f)$ at different optical power levels at the PD input. The lowest phase noise is measured when the PD is at saturation ($\sim$10 mW).

Above saturation, due to the increase of carrier transit time and recombination of electron and holes, the RF power is actually reduced with additional increase of the optical signal level [15].

The relative RF phase between that of the signal carried by the light at the input to the PD and that of the converted RF signal at the PD output was measured as well (via a mixed signal of the RF reference and the PD output). Fig. 11 illustrates the measured phase as a function of the input optical power $\phi(P_{\mathrm{Opt}})$ (blue squares in online version). As expected, at low input power, the RF phase increases with the optical power. However, due to the screening effect, this phase slope is zero at the PD saturation power, and the RF phase to optical power has a negative slope above saturation. A good fit to the measurement data was obtained with a parabola (black curve). The slope of this curve $d\phi/dP_{\mathrm{Opt}}$ is a monotonic decreasing function with zero slope around $P_{\mathrm{Opt}} \sim 9$ to 10 mW.

The fact that both the RF amplitude and RF relative phase of the PD have zero slopes at similar PD input optical power levels is very important for the laser RIN-to-RF amplitude and phase-noise conversion of a link. As can be seen from (3)–(6), a zero slope implies that the contribution of RIN-to-RF amplitude and phase noise is small or zero at the PD. More explicitly, (3) together with the derivative of the parabolic fit of the phase behavior of the Discovery PD (Fig. 11) were used to predict the optical link RIN-to-phase-noise conversion level (open-loop RIN-to-phase-noise conversion of the OEO). This factor $F(P_{\mathrm{Opt}})$ is given by

$$F(P_{\mathrm{Opt}}) = \frac{P_{\mathrm{Opt}}^2}{2} \cdot \left(\frac{d\phi}{dP_{\mathrm{Opt}}}\right)^2. \tag{7}$$

The result of the calculation of (7) is illustrated in Fig. 12 (for optical power in the range of the measurement). It is evident that a reduction by 30–40 dB (or higher) of RIN to phase-noise conversion is achievable when the PD is in high saturation. In other words, a laser RIN level of -140 dB/Hz will be converted to phase noise that is below -170 dBc/Hz. This level of phase noise is usually below the shot and thermal noise in most applications. Note that the units of (7) were calculated in decibels in order to illustrate the conversion of RIN (units of dB/Hz) to RF SSB phase noise $L(f)$ (units of dBc/Hz).

In order to confirm the generality of our observations and predictions, a measurement of the phase noise of a low-noise OEO was performed with different optical power levels P_{Opt} at the PD. The 10-GHz OEO consists of the Lightwave YAG laser and the Discovery DSC30 PD, together with low-noise amplifiers. The phase-noise measurements are illustrated in Fig. 13. Indeed, we obtained the lowest phase-noise level (approaching -160 dBc/Hz at a few kilohertzs of offset frequency from the 10-GHz carrier) at the PD saturation power, and this value was most probably limited by shot noise. While at higher or lower power levels from the saturation power, the noise increased dramatically. For example, at ± 3 mW away from 10 mW ($\sim$7 and $\sim$13 mW), the phase noise increased by 25–30 dB or more at high offset frequencies.

It should be noted that similar measurements of RF phase and amplitude dependence on optical power were performed at 1550 nm with the same PD. In this case, the zero slopes of RF power and RF phase did not appear at the same optical power level (though, the RF phase did have the characteristic of zero slope). These results will be published elsewhere.

Similar measurements were performed with a CyOptics electroabsorption modulator. The electroabsorption modulator was

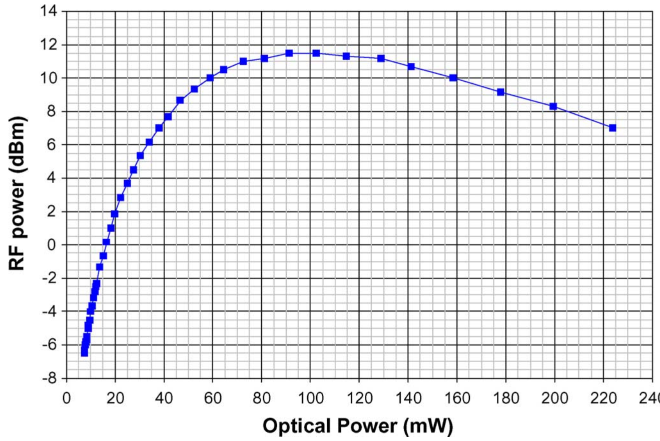

Fig. 14. CyOptics electroabsorption modulator as PD RF output power versus input optical power.

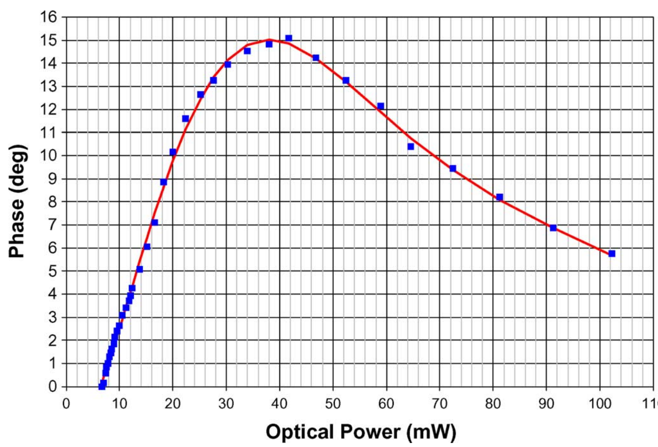

Fig. 15. Measured input to output relative phase of the EAM as PD (blue squares in online version). The measured data is fitted with a seven-order polynomial (red curve in online version).

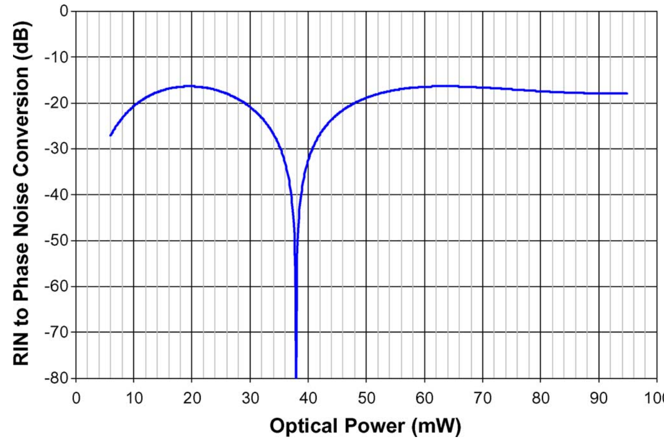

Fig. 16. Optical link (open loop OEO) RIN-to-SSB phase-noise conversion factor $F(P_{\rm Opt})$ (7) versus optical power of the EAM as PD seventh-order polynomial behavior (Fig. 15).

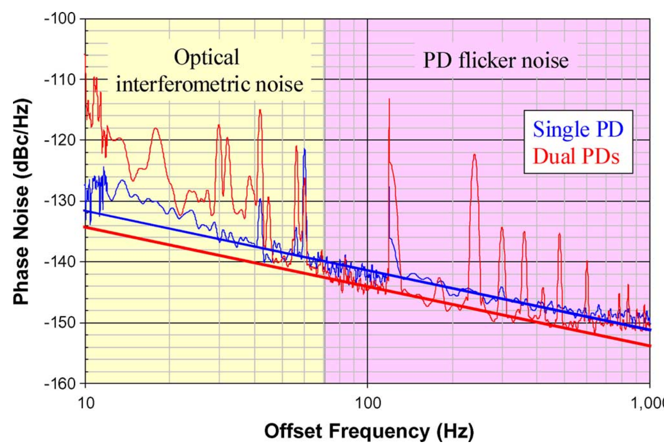

Fig. 17. Close-in phase-noise measurements of single DSC30 discovery PD and that of a dual PD configuration.

reversed biased at relatively higher voltage, serving as a high-power PD. The setup consisted of a Koheras laser followed by an Erbium-doped fiber amplifier before the electroabsorption modulator. Fig. 14 illustrates the measured RF signal as a function of the optical power at the input to the electroabsorption modulator, while Fig. 15 illustrates the relative RF phase.

Note that in the case of the electroabsorption modulator as PD, the zero slopes of the RF power and RF relative phase do not coincide at the same optical power. The former appears at approximately 100 mW of optical power at the electroabsorption modulator, while the later appears at only 38 mW. Again, (7) and the seventh-order polynomial fitting were used to calculate the RIN to SSB phase-noise conversion for the electroabsorption modulator as PD. This is illustrated in Fig. 16. As before, strong reduction (30–40 dB or higher) of the RIN to phase-noise conversion is achievable.

VII. Reduction of the PD Flicker Phase Noise With an Array

The phase noise of the optical link is characterized by flicker or $1/f$ type of noise at close-in offset frequencies, which is converted to flicker of frequency for a closed-loop OEO [6]. In the OEO, the major sources of flicker phase noise have been the RF/microwave amplifiers. The amplifier flicker noise level could vary over a wide range, depending on the material and type of transistor used, but much research has been performed with amplifier flicker noise over the years, and improvements have been applied recently so that this noise has been dramatically reduced. Thus, other components could now be the limiting elements at close-in frequencies due to their flicker noise [16].

We studied the notion of a PD array for the reduction of PD flicker noise based on the model that an array of N PDs in parallel will reduce the flicker noise by $10\cdot\log(N)$ (dB) relative to the carrier level. To test this idea, the phase noise of a single PD was measured and was compared with that of a dual PD array configuration. In these measurements, we used the DSC30 Discovery PDs. Fig. 17 illustrates the single (blue curve in online version) and dual PDs (red curve in online version) phase noise (the measurement setup is similar to those in [16] and [17]). At offset frequencies above 70 Hz (pink shaded area in online version), the measured phase noise is limited by the PD's flicker. In this range, the flicker noise is improved by 3 dB with the array, as expected. At offset frequencies below 70 Hz (yellow

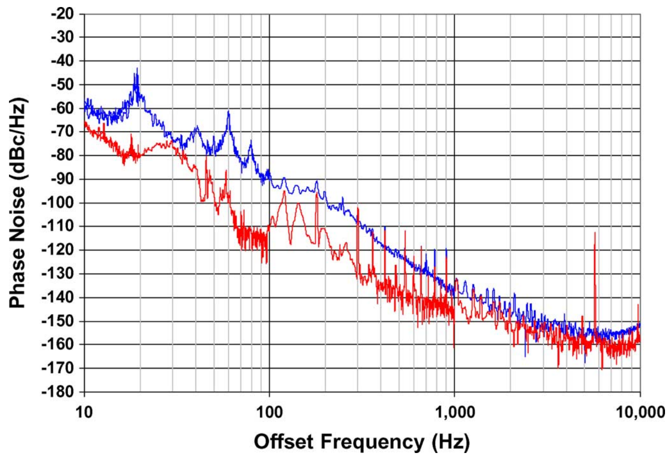

Fig. 18. SSB phase-noise $L(f)$ measured for a low-noise OEO with (red bottom curve in online version) and without (blue top curve in online version) light frequency modulation. The modulation frequency is 5.7 kHz.

shaded area in online version), the noise is limited by the optical interference due to light reflections (see Section VIII). Indeed, this noise is higher for the dual PD configuration since a larger number of optical connectors were used. Note, however, that this noise could be significantly reduced with special attention to reducing reflections, and via optical isolation.

Another important improvement that the PD array configuration could bring is a potential solution for the limited RF power generation due to PD saturation. In many cases, a high-power laser and optical amplifiers are used, resulting in excess available optical power over the needed saturation power of a single PD. In these systems, the laser power could be divided between several saturated PDs. Since the signals are coherent and in-phase in the array, they would potentially add up and the generated RF power would be N times that of a single PD (or $10 \cdot \log(N)$ in decibel units).

VIII. Reduction of Noise Due to Light Scattering and Reflection

Another source of noise that might affect performance is the light scattering due to double Rayleigh scattering from imperfections in the optical fiber or due to reflection at optical connectors or fiber splices. The scattered light is converted to RF amplitude or phase noise due to light interference between the scattered and nonscattered light at the PD [17]. The interference exhibit themselves as RF noise at offset frequencies that are within the laser linewidth. An efficient method to reduce this type of noise is via frequency modulation of the laser light [18]. The light modulation results in the spreading of the RF noise over a wide range of frequencies around harmonics of the modulation frequency, moving the noise away from the RF carrier frequency. We have applied this method with our 10-GHz OEO consisting of low phase-noise components. The OEO SSB phase noise (with and without the light frequency modulation) is illustrated in Fig. 18. The modulation frequency in this case is 5.7 kHz. It is clear that efficient reduction of noise due to light interference is achievable with the laser modulation. Over 25 dB of noise reduction was observed at offsets between 70–100 Hz from the carrier. Overall, the RF phase noise is not limited by optical interference anymore. The noise above 80 Hz becomes RF amplifier limited, and we believe that below 80 Hz, it is limited by environmental noise.

IX. Summary

We have reported on a number of studies aimed at identification and reduction of noise generated by optical components in a microwave photonics link. Our experiments confirm that, in high-performance links, such as those targeted for use in radar systems and other antenna remoting applications, the laser RIN noise and noise associated with the PD could produce a significant degradation in the amplitude and the phase noise of the system. We have demonstrated that several schemes could be devised to reduce the noise, including the use of an SOA as a limiter for the laser RIN, the operation of the PD in the saturation limit, and the use of a PD array to reduce the flicker noise. It was also shown that noise due to reflection in optical connectors or splices, and due to double Rayleigh scattering in fiber, could be efficiently reduced by laser frequency modulation. These approaches will allow demonstration of high-performance photonic links and ultra-low-noise OEOs at X- and Ka-band.

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