Laser Phase Noise in Ring Resonator Assisted Direct Detection Data Transmission

Jovana Nojić, Alireza Tabatabaei-Mashayekh, Talha Rahman, Alvaro Moscoso-Mártir, Florian Merget, Xu Sun, Jeremy Witzens

Abstract—We introduce an analytical model describing the statistical and spectral properties of laser phase noise induced intensity noise in ring-resonator-based modulation. The model is validated with single sideband orthogonal frequency division multiplexing (SSB-OFDM) implemented with a silicon photonics resonantly-assisted Mach-Zehnder modulator (RA-MZM). Excellent agreement of experimental data with full link simulations, in which phase noise conversion is treated with the analytical model, confirms its validity. Moreover, we demonstrate 30 Gb/s raw data rate transmission with SSB-OFDM over 20 km of single-mode fiber with a bit error ratio below the 20% forward error correction (FEC) limit for three independently run channels of the RA-MZM, each supplied with off-the-shelf 1 MHz linewidth distributed feedback lasers.

Index Terms— Optical communications, laser noise, phase noise, integrated optics, electrooptic modulation.

I. INTRODUCTION

WAVELENGTH division multiplexed (WDM) systems based on silicon (Si) ring resonator modulators (RRM) have been widely explored in research [1]-[4] and exploited in commercial applications [5],[6]. Compact and power efficient devices, they enable seamless integration into multi-channel systems, due to their inherent wavelength selectivity. When used as phase shifters in resonantly enhanced Mach-Zehnder modulators (RA-MZM), push-pull driving enables lower chirp and higher optical modulation amplitude [7],[8]. Moreover, designs relying on the collective driving of multiple RRMs assigned to the same channel can relax wavelength and temperature sensitivities [8],[9]. Their combination with optical orthogonal frequency division multiplexing (OFDM), more specifically its single-sideband variant (SSB-OFDM) that makes use of inexpensive direct detection (DD) receivers, and offers tailored spectral loading, high spectral efficiency and increased reach due to its immunity to fiber dispersion [10-15], can substantially improve the aggregate throughput of the system. Sinusoidal modulation [16] as well as single channel data transmission [17] have both been demonstrated using RRM assisted SSB-OFDM modulators in Si photonics (SiP) technology, employing laboratory-grade, narrow linewidth optical sources.

In this work, we focus on the signal quality degradation due to noise caused by typical telecommunications-grade components present in the OFDM link, with particular emphasis on laser phase noise. In DD-OFDM links employing conventional rectilinear Mach-Zehnder modulators (MZMs), laser phase noise only plays a role during extended fiber transmission [18], penalizing the signal quality due to its interaction with dispersion. In RRM assisted modulation, however, laser phase noise is partially converted into intensity noise right at the resonator output, impacting the signal integrity even in back-to-back (BtB) configuration, as we first pointed out in [19]. The magnitude of these fluctuations can be significant when the signal variance is low, as is the case for OFDM signals, and/or when high linewidth sources, such as e.g. semiconductor mode-locked lasers (MLLs), are employed. MLLs complement RRM-based transmitter configurations elegantly, eliminating the need for multiple sources and multiplexing devices [2],[20]. However, their noise properties, including high relative intensity noise (RIN) in the order of -120 dBc/Hz for noise frequencies up to a few GHz and linewidths in the order of 5 MHz for single section lasers [21], must be carefully taken into account when estimating the performance of the proposed transmitter. For this, a thorough understanding of the role that laser phase noise plays in RRM based direct detection links is essential. After pointing out this problem in [19], we describe here, to the best of our knowledge for the first time, a detailed analytical model for the phase noise to intensity noise conversion occurring in RRM-based links and validate it with precisely modeled transmission experiments.

The paper is structured as follows. We first present a detailed analytical derivation of the statistical and spectral properties of the laser phase noise induced intensity noise in RRM based links (Section II). Next, we model a full SSB-OFDM link which also includes a semiconductor optical amplifier (SOA) used for signal amplification. Using the derived analytical model as the basis for the modeling of phase noise conversion, we verify our results through comparison with experiments. These include transmission of SSB-OFDM signals using an RA-MZM in BtB configuration, with both an off-the-shelf telecommunications

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grade distributed feedback (DFB) and a laboratory grade external cavity laser (ECL) at varying optical power levels (Section III.B). Even though we focus here on SSB-OFDM signaling, it should be noted that laser phase noise conversion occurs whenever modulation relies on RRMs, as a consequence of it acting as a light storing element and of the resonator induced dispersion. Thus, the models derived in Section II can be applied to a wide variety of optical links. Additionally, we demonstrate data transmission of SSB-OFDM signals with a single carrier raw data rate of 30 Gb/s over 20 km of fiber, for three independently operated channels of an RRM assisted modulator (Section III.C). The channels, each filling a spectral range of 11.25 GHz, have net spectral efficiencies between 2.1 b/s/Hz and 2.4 b/s/Hz, depending on the channel number, when operated with an off-the-shelf telecom grade DFB laser.

II. ANALYTICAL MODEL OF LASER PHASE NOISE TO INTENSITY NOISE CONVERSION

Conversion of phase noise into intensity noise arises from the RRM being a light storage element. During the time over which light is stored, the phase of the laser walks off due to finite phase noise, leading to a modified interference condition between ring and bus waveguide resulting in amplitude noise.

To derive an analytical expression characterizing the generated intensity noise, we consider the conventional resonator configuration shown in Fig. 1(a). We start from the differential equation describing the time evolution of the field amplitude, $a$, stored inside the resonator

$$\frac{da}{dt} = i\omega_0 a - a/\tau_a + i\mu E_{in},$$  

(1)

where $\omega_0$ is the angular resonance frequency, $\tau_a$ the E-field amplitude lifetime related to the loaded resonator quality factor $Q$ by $\tau_a = 2Q/\omega_0$, $\mu$ the time domain field coupling coefficient between the ring and the bus waveguide, and $E_{in}$ the input field from the bus waveguide given by $E_{0} \exp(i\omega t)$ in the absence of noise [22]. $\mu$ is related to $\tau_f$, the field transmission coefficient of the directional coupler, by $\mu^2 = -\ln(t_f^2)v_g/L$, with $v_g$ the group velocity of the light and $L$ the circumference of the ring. A small laser phase increment $\delta\varphi$ in the input field creates a step perturbation $i\delta\varphi E_{0} \exp(i\omega t)$ after linearization, leading to a response $\delta a$ inside the resonator satisfying the differential equation

$$\frac{d(\delta a)}{dt} = i\omega_0 \delta a - \delta a/\tau_a - i\mu\delta\varphi E_{0}\exp(i\omega t),$$  

(2)

whose solution can be written as

$$\delta a = Ke^{i\omega t}\left[1 - e^{-t/\tau_a - i(\omega - \omega_0)t}\right].$$  

(3)

where

$$K = -\frac{\mu\delta\varphi E_{0}}{1/\tau_a + i(\omega - \omega_0)}.$$  

(4)

The response of the ring stabilizes at its asymptotic value $K\exp(i\omega t)$ with a time-constant $\tau_a$, after which the phase increment inside the bus waveguide is fully tracked by the modified phase of the field inside the ring (that is also incremented by $\delta\varphi$, as obtained from comparing $\delta a$ to the unperturbed amplitude $a$), compensating any transiently induced intensity noise at the output of the RRM. The transient deviation of the field inside the resonator from its stabilized response to the phase perturbation is therefore

$$\delta a - Ke^{i\omega t} = -Ke^{-t/\tau_a + i\omega_0 t},$$  

(5)

which oscillates at the resonance frequency of the ring.

This leads in turn to a transient deviation in the field coupled back from the ring to the bus waveguide expressed as

$$\frac{i\mu^2\delta\varphi E_{0}}{1/\tau_a + i(\omega - \omega_0)} \exp(-t/\tau_a + i\omega_0 t) = -i\delta\varphi E_{cb}\exp(-t/\tau_a - i(\omega - \omega_0)t),$$

(6)

where $E_{cb} = -\mu^2 E_0 \exp(i\omega t)/(1/\tau_a + i(\omega - \omega_0))$ is the field coupled back from the ring in the absence of noise. This field deviation is decomposed into components that are in phase and out of phase with $E_{cb}$ according to the nomenclature given above, where $\delta\eta$ corresponds to the relative amplitude noise observed in the coupled back field and $\delta\theta$ to its phase error.

Assuming the laser phase noise to follow a Wiener process, i.e., the laser to have a Lorentzian linewidth, the variance of the incremental phase noise is given by $2\pi\Delta\nu dt$, where $\Delta\nu$ marks the linewidth of the optical source and $dt$ the time increment. All the previous phase jumps are independent from each other and add as a sum of variances, after weighing by the ring’s step response $-i \exp(-t/\tau_a - i(\omega - \omega_0)t)$, resulting in the total variances

$$\sigma_{\delta\theta}^2 = \int_0^\infty \left[\text{Re}\left\{e^{-t/\tau_a - i(\omega - \omega_0)t}\right\}\right]^2 2\pi\Delta\nu dt = 2\pi\Delta\nu \frac{\omega_0}{4} \left(1 + \frac{1}{1 + 2\eta^2(\omega - \omega_0)^2}\right),$$

(7)

and

$$\sigma_{\delta\eta}^2 = \int_0^\infty \left[\text{Im}\left\{e^{-t/\tau_a - i(\omega - \omega_0)t}\right\}\right]^2 2\pi\Delta\nu dt = 2\pi\Delta\nu \frac{\omega_0}{4} \left(1 - \frac{1}{1 + 2\eta^2(\omega - \omega_0)^2}\right).$$

(8)

Additionally, the covariance of the amplitude and phase error of the coupled-back field can be non-zero, and is given by

$$\sigma_{\delta\theta\delta\eta} = \int_0^\infty \text{Re}\left\{e^{-t/\tau_a - i(\omega - \omega_0)t}\right\} \text{Im}\left\{e^{-t/\tau_a - i(\omega - \omega_0)t}\right\} 2\pi\Delta\nu dt = 2\pi\Delta\nu \frac{\omega_0}{4} \frac{\omega_0}{1 + 2\eta^2(\omega - \omega_0)^2}.$$  

(9)
The overall optical power $P_{out}$ at the output of the resonator can then be calculated as

$$P_{out} / P_{in} = |E_{in} + E_{cb}(1 + \delta \eta)e^{i\delta \theta}|^2 / P_{in}$$

$$\approx |TE_{in} + E_{cb} \delta \eta + iE_{cb} \delta \theta|^2 / P_{in}$$

$$\approx |T|^2 - 2Im(T)\delta \theta + 2(Re(T)Re(T-1) + Im(T)^2)\delta \eta$$

$$= |T|^2 + \delta I,$$

(10)

where $P_{in}$ is the power at the input of the RRM and $T = 1 + E_{cb}/E_{in}$ the overall field transmission coefficient of the RRM at the carrier frequency (cf. Fig. 1). $\delta I$ is the intensity noise at the output of the RRM. In this derivation, we used $2Re(T \cdot (iE_{cb}/E_{in}^*)^\dagger) = 2Im(T \cdot (T-1)^*) = -2Im(T)$.

The overall amplitude transfer function of the ring at the carrier frequency can be expressed as $T = 1 - \mu^2 \tau_a / (1 + i(\omega - \omega_0)\tau_a)$. In this expression, $(\omega - \omega_0)\tau_a = 2Q(\omega - \omega_0)/\omega_0$ and $\mu \sqrt{\tau_a}$ are the normalized frequency detuning and normalized coupling strength, with $\mu \sqrt{\tau_a} = 1$ at critical coupling and $\mu \sqrt{\tau_a} > 1$ for our over-coupled ring. From the previous expression, the variance of $\delta I$ can be derived as

$$\sigma_{\delta I}^2 = 4 \left[ \frac{|Im(T)|^2 \sigma_{\delta \eta}^2 + |Re(T)Re(T-1) + Im(T)^2| \sigma_{\delta \eta}^2}{1 - 2m(T)\{Re(T)Re(T-1) + Im(T)^2\} \sigma_{\delta \eta}} \right]$$

(11)

The first two terms in this expression arise from the phase and amplitude noise of $E_{cb}$ and add up. The third term arises from their cross-correlation and has the opposite sign when the RRM is over-coupled (as for the devices utilized here), reducing again the overall induced RIN.

After some algebraic manipulations, we convert this equation into

$$\sigma_{\delta I}^2 = 2\pi \Delta v \tau_a \cdot (\omega - \omega_0)^2 \tau_a^2 \cdot \mu^2 \tau_a^2 \cdot$$

$$\left[ \frac{1}{(1 + (\omega - \omega_0)^2 \tau_a^2)} + \frac{(2 - \mu^2 \tau_a)^2}{(1 + (\omega - \omega_0)^2 \tau_a^2)^3} \right]$$

(12)

Eq. (12) gives a closed form expression of the intensity noise at the output of the RRM, parameterized by the laser linewidth ($\Delta v$), the photon lifetime ($\tau_a$), the carrier to resonance frequency detuning $(\omega - \omega_0)$, and ring to bus waveguide coupling strength $(\mu)$. It is interesting to note that the induced intensity noise is proportional to $2\pi \Delta v \tau_a$, the walk-off of the phase accumulated by the laser during the storage time of the RRM, as expected.

To verify these expressions, we implement a stochastic numerical model and compare its outputs to the analytical predictions. In addition to the overall RIN generated from phase to amplitude noise conversion, we also extract the portions arising individually from amplitude and phase noise of the coupled back field $E_{cb}$, so that the three terms of Eq. (11) can be independently verified, for additional confidence in the results. The laser phase noise is modeled as a Wiener process, and the propagation through the resonator is simulated by directly solving the dynamic resonator equation (Eq. (1)). To isolate the influence of the laser phase noise, all other noise sources otherwise present in the system, including laser RIN, are turned off here. Numerical values are obtained assuming a laser linewidth of 1 MHz and optical power levels adjusted to mimic the scenario of one of the experiments described in the following, in which the laser output power is set to 6 dBm. The conversion to voltage units is performed with the 150 V/W conversion gain of the utilized receiver. The laser phase noise induced intensity noise, as calculated by our stochastic model, follows a Gaussian statistic, with zero mean and a wavelength dependent standard deviation closely matching the derived analytical expressions as shown in Fig. 2 (in which the same parameters as in the modeling of the full link are assumed, see Table I). The loaded Q-factor is 11000, the intrinsic Q-factor 52500, the coupling strength is given by $\mu^2 = 82.5$ ns$^{-1}$ and the photon storage time by $\tau_a = 18$ ps.

Interestingly, the induced RIN is zeroed if the carrier is chosen to be on-resonance $(\omega - \omega_0 = 0)$. This results from the transient deviation of the coupled back field $E_{cb}(\delta \eta + i\delta \theta)$ being in quadrature with the baseline field transmitted through the RRM in the noiseless case $(T \cdot E_{in})$, so that interference between these two terms does not result in amplitude noise at resonance [19]. While biasing an RRM at resonance would also
result in zeroing of its electro-optic (EO) S_{21} when used as a standalone amplitude modulator, in an RA-MZM it is used as a resonantly enhanced phase shifter with a phase shifting efficiency that is maximized at resonance [8],[9]. Thus, we can exploit this property to minimize this noise term here. While at resonance the field coupled back from the resonator is in phase with the field propagating in the other branch of the RA-MZM operated as an IQ modulator and one could thus assume phase noise conversion to occur at the output coupler, this is actually not the case. After transiting through the RRMs, the carriers in the two branches of the MZM have the same intensity and phase noise and are only shifted by 90 degrees relative to one another, so that additional interference does not occur. In other words, the field coupled back from an RRM of the upper branch does interfere with the field of the lower branch, resulting in phase to amplitude noise conversion. However, the exact opposite amplitude noise is generated by interference of the corresponding RRM of the lower branch with the field in the upper branch, so that the two cancel out.

As a complementary derivation to the one followed above, focusing on the RRM as a light storage element, one can also observe that the phase noise to intensity noise conversion seen here arises from the dispersion inherent to the resonator transfer function, similarly to phase to amplitude noise conversion during propagation over long segments of dispersive fiber [23]. This dispersion is zeroed on resonance due to the symmetricity of the transfer function, similarly to the zeroing of the linewidth broadening factor in lasers (also corresponding to phase noise to intensity noise conversion) when using ideal atomic like gain media with a symmetric gain spectrum [24].

The intensity noise power spectral density (PSD) (Fig. 3, dashed lines, right axis) takes the shape of the carrier wavelength dependent RRM small-signal frequency response (Fig. 3, solid lines, left axis), as calculated with the equations derived in [25], when voltage dependent free carrier absorption is disregarded (in reality, the EO S_{21} depends not only on refractive index modulation, but to a lesser degree also on the variation of absorption losses, which is ignored here in the plotted S_{21} to make this comparison for the reasons explained below). The EO S_{21} is normalized here such that it corresponds to the variance of the output signal divided by the average power squared at the output of the modulator, when driven by a 2 V_{pp} signal typical for the experiments reported in the following. The S_{21} is thus modified in this graph by being normalized relative to the average output power rather than the average input power, again in order to highlight the identical spectral distribution with the converted phase noise (that is normalized relative to the average power at the output, where the noise is recorded, as per the conventional definition of RIN). Incidentally, if the RRM were used as a standalone amplitude modulator with a laser following an ideal Wiener process, the signal to noise ratio (SNR) as limited by this noise type would be independent on the carrier wavelength and signal frequency offset. However, we are using the RRM in an RA-MZM configuration here, so that the coincidence of the noise spectrum with the standalone RRM S_{21} is only used as a tool to predict the spectral shape of the noise.

Following the previous derivation, this behavior can be explained as follows. The phase noise increment $\delta \varphi$, occurring in the field of the bus waveguide, is subjected to filtering by the resonator, with a step response proportional to $\exp(-t/\tau_a - i(\omega - \omega_0)t)$. Let us assume a phase noise component at the offset frequency $\omega_{off}$, oscillating as $\exp(i\omega_{off}t)$. The phase increments are proportional to its derivative $i\omega_{off}\exp(i\omega_{off}t)$, so that the resulting filtered response is proportional to

$$
\int e^{-t/\tau_a - i(\omega - \omega_0)t} e^{i\omega_{off}t} i\omega_{off} dt
$$

$$
\cong -\frac{i\omega_{off}}{1 + i\tau_a(\omega - \omega_0 - \omega_{off})}
$$

(13)

Since, for a Wiener process, the phase noise PSD scales as $1/\omega_{off}^2$ [26], the overall single-sided PSD of the induced intensity noise, taking into account phase noise at both $+\omega_{off}$ and $-\omega_{off}$, scales as

$$
\frac{1}{1 + \tau_a^2(\omega - \omega_0 - \omega_{off})^2} + \frac{1}{1 + \tau_a^2(\omega - \omega_0 + \omega_{off})^2}
$$

(14)

featuring the expected enhancement at noise frequencies coinciding with the detuning between the resonance and carrier frequencies, as for the EO S_{21} of the modulator [25].

An even quicker way of reaching this result starts from the observation that a Wiener process features a white frequency noise spectrum (expressed in Hz^2/Hz) [26]. At the output of the RRM, prior to any further optical filtering or dispersion, the optical power is the same independently on whether the carrier frequency or the resonance frequency of the RRM are being dithered [as can be derived for example by dithering the frequency of $E_{in}$ in Eq. (1)]. Since carrier phase noise can be modeled by the former and amplitude modulation by regular operation of the RRM by the latter, one directly obtains the coincidence between the frequency dependence of the S_{21} and the PSD of the induced intensity noise. This also provides a means of predicting the PSD of the induced intensity noise when the laser does not follow a Wiener process, as in this case it will be shaped by both the S_{21} of the modulator and the frequency noise spectrum of the laser. We confirmed the validity of this interpretation by verifying that the simulated noise, in dB/Hz, is below the calculated S_{21} in Fig. (3) by an amount

$$
10\log_{10} \left( \frac{h_0 \lambda_0^2}{\lambda_0^2 \Delta f} \right)
$$

(15)

where $h_0$ is the frequency noise PSD given by $\Delta f/\pi$ for a Wiener process [26], $\lambda_0$ and $f_0$ are the carrier wavelength and frequency, $\Delta f$ is the high-speed wavelength tuning efficiency of the RRM (in pm/V), and $V_{rms} = V_{pp}/\sqrt{2}$ is the drive voltage expressed as a root mean square voltage.

III. EXPERIMENTAL RESULTS

To verify this model, we performed SSB-OFDM transmission experiments using an integrated SiP RA-MZM modulator. In this section, we first describe the modulator structure and the
measurement setup. Then we show the experimental results and their comparison to the modeling of the full link, in which the inherent laser phase noise is included through the previously presented analytical expressions, thus confirming the validity of our model. Finally, we demonstrate the transmission in full capacity for three channels of the RRM assisted SSB-OFDM system in BiB and 20 km fiber transmission, in a link including a DFB laser and an SOA.

A. Measurement Setup

A schematic of a single channel RRM assisted SSB modulator is shown in the inset of Fig. 4(a). It consists of two identical RRMs coupled to the two arms of an MZM. The RRMs are over-coupled depletion-based devices with a 10.1 µm radius and 430 nm wide rib waveguides, both in the ring and in the bus section. Each modulator acts as a phase shifter, with a quality (Q) factor ~11000, an average wavelength tuning efficiency of 12 pm/V between 0 and 2 V, and an extinction at resonance of 6.3 dB.

The 90-degree phase shift between the arms, ensuring the quadrature condition, is introduced passively through a 2-by-2 multi-mode interferometer (MMI) used as power splitter at the input of the MZM. Additionally, on-chip titanium nitride (TiN) thermal tuners [27] are implemented in the MZM arms to correct for any fabrication induced residual phase offset from the quadrature point, as well as in the rings in order to tune their resonance relative to the targeted wavelength. The phase shifters used to bias the MZMs are 2 µm wide, 200 µm long TiN resistors located above the waveguides. The phase shifters used to tune the ring resonances are also 2 µm wide and cover 95% of the rings’ circumference. The electrical power consumption required to achieve a 2π phase shift is respectively 25 mW and 110 mW for these two tuner types, wherein the increased power consumption of the RRM tuners is caused by the metal lines used for RF connectivity also conducting heat away and making it more difficult to heat up the device.

The optical signal is coupled in and out of the chip through surface emitting grating couplers (GC). The 3-channel system, whose layout is shown in Fig. 4(c), is simply formed by adding two more sets of RRMs along each arm of the MZM, each tuned to a different wavelength, corresponding to two more WDM channels. In order for the RA-MZM to operate as an IQ modulator for all channels, the MZM needs to remain biased at its quadrature point across all the carrier frequencies. The wavelength dependent phase shift variation introduced by the conventional 2 by 2 MMI at the input of the MZM remains within less than ±1° of the targeted 90° over the entire C-band (if sized around the lowest sensitivity point) and can be made even less wavelength sensitive with subwavelength structures [28]. While the MZM is designed to be nominally balanced, another source of wavelength dependent phase error arises from fabrication errors. While the MZM phase tuner can correct the phase error at the center wavelength, across the C-band the phase shift induced by the phase tuner varies by ±1% of its nominal value. Similarly, the fabrication induced phase shift varies by ±2% of its value at the center wavelength, stacking up with the phase tuner sensitivity to a total ±3%. Given the 70° phase error that had to be corrected in the experimentally realized modulator and the phase error induced by the MMI, this results in a total ±3° phased error across the C-band that remains modest and does not significantly degrade the performance of the modulator across channels, other than a small reduction in sideband suppression ratio (SSB) as discussed further in Section III.C.
The wavelength dependent modulation efficiency of a standalone RRM nominally identical to the ones used in the RA-MZM and operated as an amplitude modulator, described in terms of the optical modulation amplitude (OMA) normalized relative to the input power in the bus waveguide and of the extinction ratio (ER), as well as its 3-dB EO cutoff frequency, are shown in Fig. 5. Although the OMA of the RRM operated as a standalone amplitude modulator is not directly relevant for the RA-MZM modulation scheme used in this work, it serves for benchmarking the device employed here (with performance constrained by the standard doping levels of the utilized process) against RRMs typically used in conventional amplitude modulation. The EO cutoff frequency on the other hand is directly relevant for the experiments performed in the following.

The chips were fabricated at the Institute of Microelectronics, IME, Singapore, in a standard multi-project wafer (MPW) run with predefined doping levels.

The block diagram of the measurement setup is shown in Fig. 4(a). To ease the application of the modulating signals, the chip is mounted on and wire-bonded to a high-speed fan-out printed circuit board (PCB) [Fig. 4(b)]. The chips are not thermally stabilized during the measurements. The OFDM signals are generated using a 512 elements fast Fourier transform (FFT), in which one half of the sub-carriers is loaded with zeroes to create a single-sideband signal. An additional gap of 20 sub-carriers is introduced next to the optical carrier, keeping the signal out of the region most affected by sub-carrier interference [29]. In a link scenario including semiconductor MLLs, for example, this gap would prove doubly beneficial, since it also offsets the signal spectrum away from the low frequency region where laser RIN dominates [30] and SOA induced signal distortion is the worst [31]. The guard band is followed by 100 sub-carriers, each loaded with randomly generated quadrature phase shift keyed (QPSK) symbols. Based on the bandwidth limitation of the RRMs, we allocated the frequency band up to 16 GHz for the transmission of up to 256 subcarriers spaced by 62.5 MHz, so that, consequently, the signal covers the frequency span from 1.25 to 7.5 GHz for the 100 loaded subcarriers investigated in this section. A block of 128 OFDM symbols, each appended with a 3% cyclic prefix (CP), is then transmitted. It should be mentioned that in these experiments the overall throughput was not maximized, since their main purpose was to examine the properties of the noise present in the system. We push the performance to higher limits in the full capacity experiments reported in Section III.C. The modulating signals are upsampled, converted by a 2-channel DAC, and amplified by fixed gain high-speed amplifiers. To adjust the amplifier gain, a 6-dB attenuator (ATT) is added at the amplifier output in both signal paths. A -1.5 V DC bias is added to the AC signals using bias-tees, resulting in a slightly higher 3-dB RRM EO cutoff frequency due to a reduced junction capacitance, before finally routing them to the PCB. Ultimately, with the loss of the PCB traces included, -2 V peak-to-peak ($V_{pp}$) signals reach the RRMs.

The real part of the OFDM signal is routed to the RRM in one RA-MZM arm, while the imaginary part is routed to the RRM in the other arm, thus creating an SSB signal in the optical domain. The optical signal from the chip output is further routed to a single polarization SOA, with isolators (ISOLs) inserted both at the input and output of the amplifier to suppress back-reflections. The out-of-band amplified spontaneous emission (ASE) is removed by means of an optical bandpass filter (OBPF) placed after the SOA (40 GHz -3dB optical passband). The signal is converted back to the electrical domain using a commercial high-speed photodetector (PD) and captured by a real-time sampling oscilloscope. The optical power levels are monitored by in-line power meters (PWMs) at the output of the chip, SOA output, filter output, as well as after propagation through standard single mode fiber (SMF) in long distance transmission experiments. The monitor at the SOA output is also used as an attenuator, reducing the amplified signal by 11.6 dB, to keep the power reaching the PD within its operating bounds (-10 to 3 dBm). The relevant component parameters are summarized in Table I.

### B. Noise characterization experiments

To test the validity of our analytical model, we run experiments with two optical sources that mainly differ in their noise characteristics, in an otherwise identical link configuration to the one described in the previous section. The first source is a laboratory-grade tunable external cavity laser (Keysight Technologies 81642A), denoted as ECL in the following, that exhibits RIN in the order of -150 dBc/Hz for all the investigated power levels and a linewidth in the order of 100 kHz. The second is a DFB laser module (Thorlabs PRO 8000) intended for WDM applications, which features a higher, pump current dependent RIN, as well as a higher linewidth in the order of 1 MHz. The RIN measurements for both sources are shown in

| Parameter | Value |
|-----------|-------|
| RRM       | Radius: 10.1 μm |
|           | Tuning Efficiency: 12 pm/V |
|           | Quality Factor: -11000 |
|           | Resonance ER: 6.3 dB |
| DFB Laser | Linewidth: 1 MHz |
| Tunable Laser | Linewidth: 100 kHz |
| SOA       | Gain: 30.5 dB |
|           | Noise Figure: 7 dB |
|           | Output Saturation Power: 14.4 dBm |
|           | Carrier Lifetime: 0.17 ps |
| Optical Filter | IL: 1.9 dB |
|           | 1 dB Optical Bandwidth: 24 GHz |
|           | 3 dB Optical Bandwidth: 40 GHz |
| Photodetector | 3 dB Bandwidth: 40 GHz |
|           | Conversion Gain: 150 V/W |
|           | Input Referred Noise: 30 ps/Hz²/2 |
|           | Input Power Range: -30 to 3 dBm |
|           | Sampling Rate: 96 Gsample/s |
| RF Amplifier | Gain: 24 dB |
|           | Output Voltage Swing: ~0.3 Vpp |
| PCB & Connector | IL @ 10 GHz: 3.28 dB |
| GC         | IL @ max. transmission: 4.1 dB |
| Fiber      | Dispersion: 17 ps/nm/km |
|           | Loss @ 10 km: 3.3 dB |
|           | Loss @ 20 km: 5.2 dB |
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Results of the experiments are shown together with the model predictions in Fig. 7. In subpanels (a)-(e), the experimental data for the ECL and DFB are respectively shown by star shaped and circular markers, while solid lines correspond to modeling results. Matching of the chip output power [Fig. 7(a)] in experiments and model confirms that the metrics of interest are compared at the same carrier to RRM resonance frequency detuning points. Similarly, the overlay of the receiver power levels [Fig. 7(b)] confirms that the SOA gain and overall insertion losses of the link are modeled appropriately, as well as the std. dev. of the signal with (d) ECL and (e) DFB as the optical source. (f) Overlay of modeled noise std. dev. with ECL (dotted line) and DFB (solid line) as optical sources. (g) Partitioning of modeled noise std. dev. at the end of the link, with DFB as optical source and 6 dBm laser power; (h) std. dev. of intensity noise at the end of the link arising from laser RIN (dashed thick green line), RIN correlated phase noise (dashed thin purple line), and their joint contribution (solid line) with an asymmetric shape resulting from their correlation. Cumulative EVM for (i) LSB and (j) USB loaded SSB-OFDM transmission with ECL (star shaped markers) and DFB (circles). PNtRIN refers to intensity noise resulting from conversion of the “baseline” laser phase noise by the RRM and is uncorrelated to laser RIN, RINcPNtRIN refers to the conversion of the RIN correlated laser phase noise into intensity noise and is correlated to the laser RIN.
as that link conditions have remained unchanged in the two experiments. Overlay of the standard deviation of the signal [Fig. 7(c)], measuring the signal strength, further confirms proper modeling of the RRM, and gives confidence that modulator properties, such as modulation efficiency and bandwidth, are correctly taken into account in our numerical model. The depicted signal strength is extracted from the measured data by averaging 11 nominally identical oscilloscope traces for noise reduction. At the lowest measured laser output power, -3 dBm, the bulk of the noise comes from the SOA ASE and photoreceiver noise, allowing us to correctly include these noise sources into our model. It remains then to verify laser and RRM induced noise modeling.

As can be seen in Fig. 7(d) and 7(e), the modeled wavelength dependent noise standard deviation for the whole link is in good agreement with experimental data for both the ECL and DFB, thus confirming the effectiveness of our analytical model.

Contrary to the standard deviation of the phase noise induced intensity noise shown in Fig. 2, which is symmetric relative to the ring resonance, the standard deviation extracted from experiments for the DFB laser, as depicted in Fig. 7(e), shows asymmetric features. This asymmetry is caused by the correlation of part of the laser phase noise with the laser RIN already mentioned above. The intensity noise resulting from conversion of this correlated phase noise by the RRM remains correlated to the laser RIN, with the sign of the correlation changing from negative to positive as we sweep the carrier wavelength from shorter to longer than the ring resonance wavelength. This is due to the dispersion induced by the RRM also changing sign. Moreover, as we increase the output laser power from 3 dBm [yellow data in Fig. 7(e)] to 6 dBm [purple data in Fig. 7(e)], this asymmetry reduces due to the reduction of the overall laser RIN (Fig. 6).

From Fig. 7(f), which compares the modeled noise standard deviation of the links that include an ECL (dotted line) and a DFB (solid line), better noise performance with the lower linewidth optical source is evident, more notably so for the wavelengths longer than the resonance at which positive correlation with the laser RIN further worsens the overall noise level.

Next, to examine contributions of individual noise sources, we show the partitioning of the overall noise at the end of the link in Fig. 7(g) for the simulation assuming a DFB source with 6 dBm output power. This is practically implemented by turning on a single noise source at a time in the simulation and iterating through all noise sources present in the system. Photodetector input referred noise (thin orange dot-dash line) does not depend on the received power, i.e., on the optical carrier biasing, as expected. The intensity noise caused by the baseline laser linewidth (purple dotted line) features the expected detuning dependent std. dev. The same wavelength dependency is observed for the std. dev. of noise induced by conversion of the phase noise that is correlated to the laser RIN (thin purple dashed line). The wavelength dependency of the std. dev. of noise caused by laser RIN (thick green dashed line) deviates from the simple shape expected from filtering by the resonator (monotonous increase with increasing filtered carrier power as the carrier detuning from resonance is increased). This is caused in part by RIN to phase noise conversion mediated by the dispersion of the RRM, leading to a reduction of RIN off-resonance (as for the converse phase noise to intensity noise conversion, it disappears at resonance). It is also caused in part by the RIN reduction resulting from partial SOA saturation, that is more pronounced at higher carrier to resonance detunings as a consequence of the higher SOA input power levels [35]. When examined individually, none of the std. dev. vs. wavelength curves feature the asymmetry relative to RRM resonance which is present in the overall noise. For this, the laser RIN and its correlated phase noise must be turned on simultaneously in the model. In Fig. 7(h), it can be observed that the asymmetry then appears (thick solid line), confirming that it indeed stems from the correlation of these two noise types.

To qualitatively compare the performance of the two light sources, we examine the cumulative error vector magnitude (EVM) of all sub-carriers, extracted for all the recorded signal traces after OFDM demodulation and 1-tap equalization, with the sources’ output power set to 6 dBm. We do this for two scenarios: when the data is loaded onto the lower frequency sideband (LSB) [Fig. 7(i)] in the first case, which was also the case for the data and modeling shown in Figs. 7(a)-7(h), as well as the upper frequency sideband (USB) [Fig. 7(j)] in the second case.

The data shows, as expected, that the performance of the DFB based link is penalized at carrier wavelengths longer than the resonance, where the noise magnitude reaches its maximum. It is also worth noting that slightly better performance is obtained with the ECL when the USB is used for transmission and the optical carrier biased at wavelengths longer than the resonance, reducing the EVM from 15.8% to 13% for the best operating point when compared to the LSB loaded transmission. Improvement for above resonance carrier wavelengths is seen for the ECL due to the interplay between dynamic losses and dynamic phase shifts inside the RRM, leading to an asymmetric modulation efficiency [25], see also Fig. 5(a). Moreover, better performance is generally obtained when the loaded sideband is towards the resonance relative to the carrier, as the RRM peaking effect than enhances the $S_{21}$ [25]. In short, for the DFB the laser noise determines the optimum RRM bias point, while for the ECL it is the modulation efficiency that dominates. As a consequence, when the USB is loaded with data, the difference in EVM between the optimal point for the ECL and the optimal point for the DFB amounts to ~7%.

The full capacity experiments reported in the next section were thus done with LSB loading due to the utilized light source being a DFB (for which LSB loading shows the better performance for the aforementioned reasons) and due to the difficulty of biasing the carrier above the resonance wavelength at high optical power levels (9 dBm DFB power) due to nonlinear effects inside the ring. These are primarily thermally induced and too slow to impact the high speed dynamics of the RRM once an effective bias point has been determined [25], so that no refinement of the models described above is necessary,
however it leads to instabilities when the ring is tuned into the carrier starting from a resonance wavelength below that of the fixed carrier.

C. Full capacity transmission experiments

Using the identical measurement setup as in the previous experiments, we optimize the data transmission at full capacity for all the three channels of the RRM assisted SSB-OFDM modulator used with DFB lasers at wavelengths 1547.05 nm (CH1), 1547.75 nm (CH2), and 1548.45 nm (CH3). The subchannels are loaded such that the overall bit error ratio (BER) of the worst performing channel remains below the 20% hard decision forward error correction (HD-FEC) limit ($1.5 \times 10^{-5}$) [36] for a 20 km link. Here, we opt for transmission experiments using DFBs, since they better reflect a practical scenario in DD-links, in which they are more commonly employed than more expensive, lower linewidth sources, which are typical for coherent links. The laser power is set to 9 dBm for all measurements. Sub-carriers 2-121 are loaded with 8QAM symbols, while carriers 122-181 are loaded with QPSK symbols due to their lower SNR resulting from the modulator roll-off. Consequently, the signal is occupying the frequency band from 62.5 MHz to 11.31 GHz. Once again, a block of 128 symbols is sent through the link. Due to the number of symbols remaining insufficient for reliable extraction of sub-carrier specific statistics, cumulative BERs are calculated for the entire transmitted sequence. The number of transmitted bits, namely 61440, is, nevertheless, large enough for accurate predictions of BERs on the order of $10^{-3}$. A raw data rate of 30 Gb/s is achieved for all three channels, when operated individually, for transmission distances up to 20 km, with a very modest degradation in performance at longer fiber lengths mostly due to the lower power reaching the receiver [Fig. 8(a)]. This is evidenced by the absence of spectral distortions in the received spectra for the longer reach experiments, as exemplified by the electrical spectrum of channel 1 (CH1) for 20 km transmission as shown in Fig. 8(d). Exemplary constellation diagrams for 8QAM and QPSK, for 20 km CH1 transmission, are shown in Figs. 8(b) and 8(c), respectively. The achieved net spectral efficiency for CH1 is ~2.4 b/s/Hz, taking into account both 3% CP and 7% HD-FEC overheads. For CH2 and CH3, the net spectral efficiency is reduced to ~2.1 b/s/Hz, due to the higher HD-FEC overhead of 20% necessary for achieving error-free transmission with these worse performing channels. The difference in performance correlates with the Q-factor of the RRM, that was highest for CH1, so that it appears the modulation efficiency, that goes up with Q-factor, was the dominant driver for system performance in this specific configuration.

To achieve best multi-channel spectral efficiency resulting from a tight stacking of WDM channels, high extinction of the unused sideband is required. Sideband extinction is limited by several factors, as verified with modeling of the link at the same
bias points as in the full capacity measurements (but with the bit loading used in section III.B). Simulations without noise at the output of the RA-MZM show a sideband suppression ratio (SSR) of more than 25 dB relative to the signal strength [curve (2) in Fig. 9], in line with what is reported in the literature for tightly packed WDM configurations [37]. It is limited by the nonlinearity of the RRM’s EO transfer function, as evidenced by its dependency on signal strength, and is significantly above the level modeled with an ideal linear modulator [curve (1)] as limited by the sourced electrical signal [10]. It can be further worsened by deviations of the MZM from the quadrature condition, as discussed in Section III.A, by about 1 dB per degree of phase error. In the same noiseless model, the SSR is significantly degraded at the output of the partially saturated SOA, due to four wave mixing (FWM) creating a mirror image of the modulated sideband [38] (since waveguide dispersion is not considered in our SOA model, FWM might be overestimated even at the small pump-signal frequency spacings considered here). This is only seen in simulations with high laser power as the 9 dBm assumed here, in which case it reduces the SSR to the 10 dB to 20 dB range. Figure 9(b) shows simulation results with all the noise sources turned back on. Curve (4) shows the spectrum when the modulation is turned off, in order to visualize the noise floor. It can be seen that noise is higher at frequencies close to the optical carrier, at which laser RIN and converted phase noise play a dominant role (at larger offset frequencies, the optical noise floor reduces to the level determined by ASE). Curve (5) shows the optical spectrum obtained from the full model with modulation turned back on.

Replacing the SOA with an erbium doped fiber amplifier (EDFA) would largely solve the issue associated with FWM or the laser power could be reduced to 4 dBm to recover an SOA limited SSR of 20 dB, even though this would lead to a reduction in SNR. Laser noise remains a limitation, but a guard band of 5 GHz above the carrier frequency would be sufficient to recover a 20 dB suppression of the noise floor relative to the adjacent channel’s signal strength, as laser induced noise sufficiently decays beyond that point. This guard band would however result in a reduction of the spectral efficiency to ~1.7 bit/s/Hz.

Since the reduction in performance at increased fiber length in the experiments reported above is mostly due to the additional 5.2 dB propagation losses, better performance could have been achieved by reducing the attenuation at the output of the transmitter accordingly. One should note that for highly accurate modeling over long propagation distances, the conversion between phase and amplitude noise due to fiber dispersion, as well as excess phase noise generated by the SOA due to amplitude to phase noise coupling via the linewidth broadening factor of the gain medium, should also be taken into account.

IV. CONCLUSIONS

In the presented work, we derived a detailed analytical model for the conversion of phase into intensity noise in RRM based modulation schemes. It describes the statistical and spectral properties of the induced intensity noise as dependent on the optical carrier to ring resonance detuning. We implement our phase noise model as a part of the full link analysis of an RRM assisted SSB-OFDM link, including other noise sources such as SOA ASE and input referred receiver noise, as well as laser RIN partially correlated with the phase noise. With the correction for the laser phase noise to RIN correlation implemented numerically, the predicted noise behavior based on our analytical model matches closely the experimental results. They clearly show improved noise performance with narrow linewidth lasers and, when a DFB laser is utilized, for optical carriers biased at wavelengths shorter than the ring resonance (for the case of the over-coupled RRM used here). We also demonstrate a raw data rate of 30 Gb/s over 20 km for three individually operated channels with net spectral efficiencies between 2.1 and 2.4 b/s/Hz. In future design iterations, the RRM can be further optimized by increasing doping levels to achieve simultaneously higher bandwidth and modulation efficiency, while maintaining a 2 Vpp drive voltage, which was not possible in the MPW run used here.

REFERENCES

[1] R. Ding et al., “A Compact Low-Power 320-Gb/s WDM Transmitter Based on Silicon Microrings,” IEEE Photon. J., vol. 6, no. 3, pp. 1–8, Jun. 2014, doi: 10.1109/JPHOT.2014.2326656.

[2] A. Moscoso-Mártir et al., “8-channel WDM silicon photonics transceiver with SOA and semiconductor mode-locked laser,” Opt. Expr., vol. 26, no. 19, pp. 25446–25459, Sep. 2018, doi: 10.1364/OE.26.025446.

[3] M. Moralis-Pegios et al., “4-channel 200 Gb/s WDM O-band silicon photonic transceiver sub-assembly,” Opt. Expr., vol. 28, no. 4, pp. 5706–5714, Feb. 2020, doi: 10.1364/OE.373454.

[4] J. Nojic et al., “Fabrication tolerant high-speed SiP ring modulators and optical add-drop multiplexers for WDM applications,” in Proc. SPIE, vol. 11285, Silicon Photonics XV, Art. ID 112850A, Feb. 2020, doi: 10.1117/12.2543324.

[5] J. Sun, R. Kumar, M. Sakib, J. B. Driscoll, H. Jayatilleka, H. Rong, “A 128 Gb/s PAM4 Silicon Microring Modulator with Integrated Thermo-OpticResonance Tuning,” J. Lightwave Technol., vol. 37, no. 1, pp. 110–115, Jun. 2019, doi: 10.1109/JLT.2018.2878327.

[6] D. J. S. Beckett, R. Hickey, D. F. Logan, A. P. Knights, R. Chen, B. Cao, J. F. Wheelock, “Application of quantum-dot multi-wavelength lasers and silicon photonic ring resonators to data-center optical interconnects,” in Proc. SPIE, vol. 10537, Silicon Photonics XIII, Art. ID 105370K, Feb. 2018, doi: 10.1117/12.2287915.

[7] R. Li, D. Patel, E. El-Fiky, A. Samani, Z. Xing, M. Morsy-Osman, D. V. Plant, “High-speed low-chip PAM-4 transmission based on push-pull silicon photonic microring modulators,” Opt. Expr., vol. 25, no. 12, pp. 13222–13229, Jun. 2017, doi: 10.1364/OE.25.013222.

[8] J. Witzens, “High-Speed Silicon Photonics Modulators,” Proc. SPIE, vol. 106, no. 12, pp. 2158–2182, Dec. 2018, doi: 10.1117/12.2287763.

[9] S. Romero-García et al., “High-speed resonantly enhanced silicon photonics modulator with a large operating temperature range,” Opt. Lett., vol. 42, no. 1, pp. 81–84, Jan. 2017, doi: 10.1364/OL.42.000081.

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