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Hamza Hallak Elwan, Ramin Khayatzadeh, Julien Poette, Beatrice Cabon. Relative intensity noise in optical heterodyning applied to millimeter-wave systems. *Microwave Photonics*, 2015, Paphos, Cyprus. hal-01958040

**HAL Id: hal-01958040**

**<https://hal.science/hal-01958040>**

Submitted on 12 Feb 2019

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# Relative Intensity Noise in Optical Heterodyning Applied to Millimeter-Wave Systems

Hamza Hallak Elwan, Ramin Khayatzadeh, Julien Poette, and Beatrice Cabon

**Abstract**—In this paper, the impact of Relative Intensity Noise (RIN) on optical heterodyne millimeter-wave (MMW) generation for Radio-over-Fiber (RoF) applications and systems is presented. The theoretical and experimental study is provided for two different techniques that generate MMW signals. The model of RIN is also presented and is in close agreement with the experiment results. The novelty and originality of this paper is the analysis of RIN in MMW frequency band, where impairments of the MMW generated carrier due to RIN are shown for the first time. The theoretical concepts and the experimental results prove that RIN appearing as side bands of MMW signal is directly generated from initial RIN at low frequency. Two significant impacts are considered: the phase noise on the beat-note carrier and the frequency response of the system, in order to extract real RIN contribution.

**Index Terms**—Distributed Feedback (DFB) Laser, Millimeter-wave (MMW), Passively Mode Locked Laser Diode (PMLLD), Phase Noise, Relative Intensity Noise (RIN), Radio-over-Fiber (RoF).

## I. INTRODUCTION

MILLIMETER-WAVE (MMW) frequency band and beyond has driven a lot of research for future wireless communication applications using Radio-over-Fiber (RoF) to distribute MMW signals [1]. MMW generation can use optical modes mixing on a photo-diode (PD) such as beating of two independent running lasers [2]. In this approach, the generated MMW signal exhibits a large phase noise because of the process of MMW generation and both laser linewidth and wavelength fluctuations [3]. Monolithic dual Distributed Feedback (DFB) lasers are developed for obtaining a narrow linewidth beat-note with reduced phase noise [4]. In another approach for optical heterodyning, Quantum Dashed Mode Locked Lasers (QD-MLL) is used to demonstrate MMW beat-note linewidth around 100 KHz. Heterodyning advantage is that mode beating avoids any external electrical oscillator [5].

In MMW frequency range, the phase noise and jitter were studied for stability problems of the generated signal and some solutions proposed to overcome this degradation whereas the Relative Intensity Noise (RIN) which is also an indicator of the laser intensity stability, has never been explored yet. Usually, RIN of laser is measured from DC to some GHz [6].

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In this paper, RIN is studied for the first time close to MMW carrier as optical heterodyne signal. Both theoretical and experimental study confirm here that the RIN phenomenon in MMW frequency band, generated from initial RIN at low frequency. Two techniques using different lasers are shown, with a very good matching between the model of RIN and the experimental results. It is worth mentioning that the results of the presented study are applicable to any kind of optical frequency generation.

Depending on the heterodyne process, RIN at MMW signal can be larger than the initial RIN at low frequency and causes spectral degradation in optical heterodyne signals. For RoF communication systems in MMW range, RIN impact on generated MMW signals can be observed by measuring Error Vector Magnitude (EVM) after suppression of phase noise effect by using an envelope detector at the receiver [7]. In this paper, due to system stabilization and applications in MMW, we have used two techniques for optical heterodyne generation. The first technique uses two independent DFB lasers and is the simplest and cheapest way. The fundamental features of this technique are the ability to generate signals on different frequencies and the capability to demonstrate several cases of RIN close to beat-note by varying the temperature and the relative optical power of the DFB lasers. Phase noise is large and previous results [8] are then used here to decorrelate RIN and phase noise impacts on MMW signal impairments. The second technique is based on Passively Mode Locked Laser Diode (PMLLD), where the Free Spectral Range (FSR) of an optical resonator at 60.64 GHz is used to generate the MMW signal. Using PMLLD, the frequency stability of MMW carrier is improved because phase noise is much smaller than previous technique. Results are compared.

Section II discusses the theory and experimental set-up. RIN results in [9 KHz – 19 GHz] band is analyzed in section III, and in [50 – 62] GHz range is given in section IV. Finally conclusion is presented in section V.

## II. THEORY AND EXPERIMENTAL SET-UP

Generating MMW signal by optical heterodyning requires at least two optical signals. The electrical field  $E_i$  of optical signal ( $i$ ) can be expressed as:

$$E_i(t) = A_i(1 + \delta_i(t))\exp(j(\omega_i t + \phi_i(t))) \quad (1)$$

where  $A_i$ ,  $\delta_i$ ,  $\omega_i$ , and  $\phi_i$  are the amplitude of electrical field  $i$ , amplitude noise, angular frequency, and phase noise, respectively.

For each laser, RIN expression was described [9], and for

a standard semiconductor laser, the generic expression of RIN that can be extracted from laser rate equation is:

$$RIN_i(\omega) = \frac{\langle |\delta_{opt}(\omega)|^2 \rangle}{\langle P_{opt} \rangle^2} = \frac{PSD(\omega)}{P_{elec}} = 4\delta_i^2(\omega) \quad (2)$$

where  $\delta_{opt}$  is the optical power variation spectrum,  $P_{opt}$  is the optical power,  $PSD$  is power spectral density of the intensity noise,  $P_{elec}$  is DC electrical power, and  $\delta_i(\omega) = \text{FFT}(\delta_i(t))$ .

#### A. RIN based on two DFB lasers:

Two independent DFB lasers, DFB<sub>1</sub> and DFB<sub>2</sub> operating in the C-band, are used to generate beat-note carrier which is adjusted and controlled by temperature and bias current of the two lasers. The polarization controller (PC) is utilized for optimizing the beating power, and (50/50) coupler is used to mix two optical signals on PD of 70 GHz bandwidth. The generic schematic diagram of experimental set-up for two separate optical sources (first technique) is shown in Fig. 1.

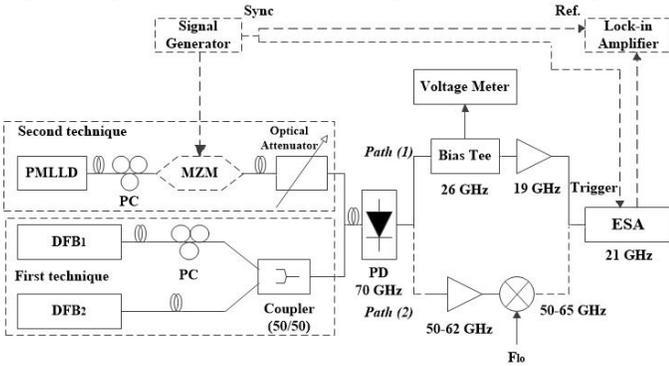


Fig. 1. Experimental set-up for optical heterodyning based on two independent lasers and PMLLD in [9 KHz-19 GHz] and [50-62] GHz.

The combined signal after coupler is transmitted through conventional single mode optical fiber of 1.5 m length to PD at the receiver end. In this case, the beating between only two modes from independent lasers is considered, and they are not phase locked, the fiber length will just impact on the received optical power. The photodetected current  $I_{PD}$  is expressed as:

$$I_{PD}(t) = (I_1 + I_2) + \left( I_1 \sqrt{RIN_1(t)} + I_2 \sqrt{RIN_2(t)} \right) + 2\sqrt{I_1 I_2} \cos((\omega_2 - \omega_1)t + (\phi_2(t) - \phi_1(t))) + \sqrt{I_1 I_2} \left( \sqrt{RIN_1(t)} + \sqrt{RIN_2(t)} \right) \cos((\omega_2 - \omega_1)t + (\phi_2(t) - \phi_1(t))) \quad (3)$$

where  $I_i$  is the DC photodetected current due to optical signal ( $i, i=1$  or  $2$ ), and  $RIN_i$  is relative intensity noise  $RIN(t) = \text{FFT}^{-1}(RIN(\omega))$ . Second order terms related to noise-to-noise beatings have been neglected.

The first term of (3) represents the total average current, the second term represents the noise current of two optical signals from DC to some GHz. The third term is the beat-note current created during their simultaneous detection, where the beat frequency is equal to difference between frequencies of the two optical modes ( $f_2 - f_1$ ). The last term represents noise current of the two optical signals close to beat-note. The angular frequency ( $\omega_2 - \omega_1$ ) exhibits phase noise ( $\phi_2 - \phi_1$ ) that varies due to how the two optical modes are produced, which depends on the correlation between these modes. In the last

term from (3), it can be noticed that there is interdependence between the two laser amplitudes in opposition to the second term. This non-linear process could lead to an increase of intensity noise during heterodyne process comparing to the initial intensity noise. This increase is noticeable especially when the optical powers of the two lasers are different.

After substituting (3) in (2), and as there is no correlation between modes when considering two independent DFB lasers, the initial relative intensity noise ( $RIN_{ini}$ ) at low frequency and relative intensity noise close to beat-note ( $RIN_{mmw}$ ) are then obtained as follows:

$$RIN_{ini}(f) = \frac{I_1^2 RIN_1(f) + I_2^2 RIN_2(f)}{(I_1 + I_2)^2} \quad (4)$$

$$RIN_{mmw}(f) = \frac{I_1 I_2 (RIN_1(f) + RIN_2(f))}{(I_1 + I_2)^2} \quad (5)$$

As can be seen, they are correlated. In the last term of (3), the product in time domain of mode intensity noises with the carrier leads to the frequency conversion of the noise spectrum directly to the beat frequency. In case the optical signals have the same amplitudes ( $I_1 = I_2$ ), then  $RIN_{ini} = RIN_{mmw}$ . While a power difference exists, for example ( $I_2 > I_1$ ), the  $RIN_i$  of less powerful mode ( $RIN_1$ ) in (5) is increased by a factor  $I_2/I_1$  as compared to  $RIN_i$  in (4) thus  $RIN_{mmw}$  is larger than  $RIN_{ini}$  by a factor  $I_2/I_1$ . This phenomenon has not been published yet to the best of our knowledge and is evidenced in section III with both experimental and model results.

The paper investigates RIN at MMW, for two purposes: more accurate recognition between  $RIN_{ini}$  and  $RIN_{mmw}$  and better amplification of the received signal, we present results in [9 KHz-19 GHz] frequency band. After PD in Fig. 1 (path 1), the bias tee is added to suppress the DC component and to extract the photodetected RIN value. Low Noise Amplifier (LNA) whose center frequency is 9.5 GHz and gain is 40 dB is used. In path 2, MMW signal is amplified using 35 dB LNA of 50-62 GHz bandwidth, then the amplified signal is down-converted by a mixer 50-65 GHz of 6 dB losses and a local oscillator (LO). Finally, a spectrum analyzer (ESA) of 20 GHz bandwidth is monitored to extract spectral power density of measured RIN.

#### B. RIN based on PMLLD:

The electrical field  $E_{PMLLD}$  of any multi-mode laser such PMLLD for ( $M$ ) modes can be defined as:

$$E_{PMLLD}(t) = \sum_i A_i (1 + \delta_i(t)) \exp((\omega_0 + i\omega_{RF})t + \phi_i(t)) \quad (6)$$

where  $i$  is the mode number, and  $A_i$ ,  $\delta_i$ , and  $\phi_i$  are the amplitude, amplitude noise, and phase noise of mode  $i$ , respectively.  $\omega_0$  and  $\omega_{RF}$  are the angular frequency of the first mode and the angular frequency of beat-note correspond to FSR. In Fig. 1, the generic schematic diagram of experimental set-up based on multi-mode laser is shown (second technique) for two frequency bands. In some cases, by increasing the bias current of optical source, PSD of thermal noise is close to PSD of intensity noise, then the sensitivity of the system must be improved by using a lock-in amplifier. A digital signal

generator drives one electrode of a Mach-Zehnder modulator (MZM) and some synchronization is necessary between ESA and lock-in amplifier via signal generator.

The output current of PD can be described as:

$$I_{PD}(t) = \sum_i I_i + \sum_i I_i \sqrt{RIN_i(t)} + 2 \sum_{i,j:i \neq j} \sqrt{I_i I_j} \cos((\omega_j - \omega_i)t + (\phi_j(t) - \phi_i(t))) + \sum_{i,j:i \neq j} \sqrt{I_i I_j} (\sqrt{RIN_i(t)} + \sqrt{RIN_j(t)}) \cos((\omega_j - \omega_i)t + (\phi_j(t) - \phi_i(t))) \quad (7)$$

The initial relative intensity noise ( $RIN_{ini}$ ) and relative intensity noise at beat-note ( $RIN_{mmw}$ ) can be expressed as:

$$RIN_{ini}(f) = \left( \sum_i I_i \sqrt{RIN_i(f)} \right)^2 \times \left( \sum_i I_i \right)^{-2} \quad (8)$$

$$RIN_{mmw}(f) = \left( \sum_{i,j:i \neq j} \sqrt{I_i I_j} (\sqrt{RIN_i(f)} + \sqrt{RIN_j(f)}) \right)^2 \times \left( \sum_i I_i \right)^{-2} \quad (9)$$

Terms in (7) for M modes have same expressions as in (3) for two modes. RIN expressions of (8) and (9) are also the same as (4) and (5) respectively, but the extremely important difference between the two cases is the correlation of modes for the case of PMLLD.

### III. RIN IN [9 KHZ – 19 GHZ] FREQUENCY BAND

The essential features of a two different DFB laser-technique (see Fig. 1 path 1) are ability to distribute beat signals on various frequencies and demonstration different cases of RIN at beat-note by changing the temperature and the relative optical power of lasers. Due to the relaxation frequency of the lasers of 4.1 GHz and the 19 GHz bandwidth limitation of the amplifier, a beat signal around 14 GHz has been chosen to highlight the impact of RIN in optical heterodyne process as shown on Fig. 2.

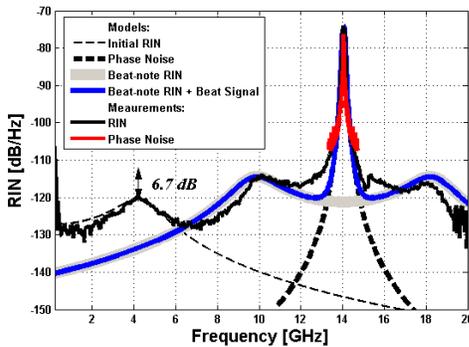


Fig. 2: RIN and phase noise of a heterodyne signal around 14 GHz for two independent DFB lasers.

For verifying (4) and (5), the bias current of the first laser DFB<sub>1</sub> is set to 15 mA ( $P_{opt} = -2.1$  dBm) while the bias current of the second laser DFB<sub>2</sub> is 90 mA ( $P_{opt} = +3.5$  dBm), thus  $RIN_1$  and  $RIN_2$  levels are very different for the first and second laser respectively. The experimental and theoretical results of initial  $RIN_{ini}$  and beat-note  $RIN_{mmw}$  are given in Fig. 2. On RIN in results, the thermal noise impact is removed when lasers are turned off, the shot noise has been measured and then removed, and the frequency response of the global

system has been removed as well after global S parameters are measured with a Vector Network Analyzer (VNA).

In Fig. 2, the initial  $RIN_{ini}$  from 9 KHz to 7 GHz and two side-bands  $RIN_{mmw}$  on each side of the heterodyne signal are well observed. Since the stability of this technique is poor, the phase noise (red curve) is provided to prove that impairments are not due to phase noise, but come from laser intensity noise, **the beat linewidth is 150 MHz**. The values of initial  $RIN_{ini}$  and the beat-note  $RIN_{mmw}$  using (4) and (5) are calculated:  $RIN_{ini} = -119.3$  dB/Hz and  $RIN_{mmw} = -112.7$  dB/Hz; which well agree with the experimental results. From Fig. 2 and computations, it can also be observed that the beat-note  $RIN_{mmw}$  is higher than the initial  $RIN_{ini}$  by a factor  $I_2/I_1 = 6.7$  dB because the optical power of DFB<sub>2</sub> is larger, the RIN of less powerful mode ( $RIN_1$ ) in (5) is then increased by a factor  $I_2/I_1$  compared to  $RIN_1$  in (4) as expected.

The initial  $RIN_{ini}$  has also been modeled (thin dashed curve) from RIN expression of laser [9]. The phase noise of beat signal corresponds to the convolution of the two optical individual spectrums. The noise shape can be modeled by lorentzian distribution, while other random variations of the wavelength difference are considered as Gaussian fluctuations, resulting in a Voigt profile (thick dashed curve). The model of beat-note  $RIN_{mmw}$  (light thick curve) in Fig. 2 refers to the last term in (3), representing the phase noise of the beating signal multiplied in time domain by the sum of the individual laser intensity noises. Then, the model results of beat signal phase noise and  $RIN_{mmw}$  are summed and presented in the blue curve. Based on the aforementioned, experimental results are well confirmed by model results and give evidence of RIN phenomenon at MMW, as presented in (3), (4), and (5).

In Fig. 3, **we intend to show that  $RIN_{mmw}$  and not phase noise impacts mainly the MMW impairments**. Since the relative intensity noise ( $RIN_1$ ) of DFB<sub>1</sub> has the main impact on the initial  $RIN_{ini}$ , two different bias currents are set for DFB<sub>1</sub>: 13 mA ( $P_{opt} = -4.1$  dBm) and 17 mA ( $P_{opt} = -0.6$  dBm) corresponding to relaxation frequencies of 3.3 GHz and 4.6 GHz respectively, while DFB<sub>2</sub> is still biased at 90 mA ( $P_{opt} = +3.5$  dBm). The temperature of both lasers is set to keep the beat-note around 14 GHz, results are shown in Fig. 3.

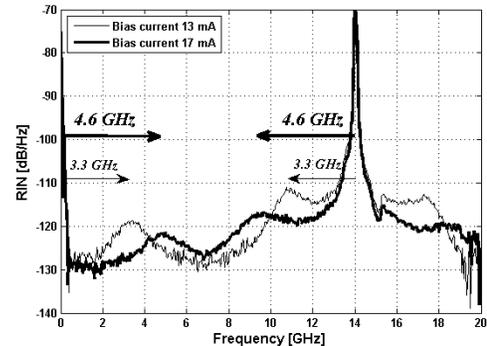


Fig. 3: RIN of a beat-note signal around 14 GHz for two different bias current of the first laser DFB<sub>1</sub>.

From this figure, it is inferred that  $RIN_{mmw}$  close to beat signal is directly generated from initial  $RIN_{ini}$  and have the same profiles. The difference between initial  $RIN_{ini}$  and  $RIN_{mmw}$  at beat-note for the above two cases is also observed

because the lowest powered mode will be increased through the heterodyne process by  $I_2/I_1$ . Fig. 3 depicts that **despite** the phase noise of beat-note for both cases are approximately identical,  $RIN_{mmw}$  keeps the same profiles as initial  $RIN_{ini}$ , so this further confirms that RIN phenomenon at generated MMW signal is distinct from phase noise of heterodyne signal.

#### IV. RIN IN [50 – 62] GHz FREQUENCY BAND

In MMW measurements and using PMLLD to generate the MMW signal at 60.64 GHz due to FSR of an optical resonator, the schematic diagram of experimental set-up is described in path 2 of Fig. 1 (second technique). A mixer and an LO whose frequency is fixed at 52.2 GHz is used for down-conversion to adjust the ESA bandwidth. The mixing process does not influence on the quality of the involved signals because the LO phase noise is very low (-140 dBc/Hz for frequency offset more than 10 MHz) [10]. PMLLD is biased at 53 mA ( $P_{opt} = +1.8$  dBm), and the temperature is set to 25°C. Fig. 4 represents the beat-note in [50-62] GHz before down-conversion, but **PSD** has been measured after mixer, thus in Fig. 4 using MATLAB the shifted spectrum is presented.

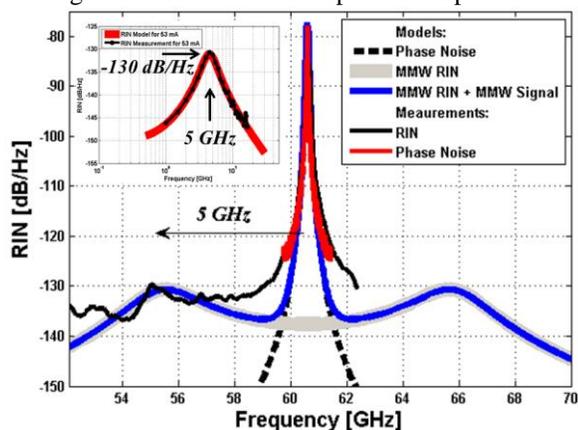


Fig. 4: RIN and phase noise of a heterodyne signal around 55 GHz for two independent DFB lasers.

Fig. 4 depicts one side-band  $RIN_{mmw}$  of MMW signal because the insertion loss of system (PD, amplifier, mixer, and ESA) is -22 dB with frequency cutoff at 62 GHz. The initial  $RIN_{ini}$  (black curve in a small frame) and phase noise (red curve) are presented, and the linewidth of MMW carrier is 90 MHz. The models of  $RIN_{ini}$  (red curve in a small frame),  $RIN_{mmw}$  (light curve), and phase noise (thick dashed curve) are in good agreement with the experimental results. According to equilibrium of optical power between M modes, it is very important to observe that the beat-note  $RIN_{mmw}$  is not increased or decreased as compared to the initial  $RIN_{ini}$  because of the factor  $I_j/I_i=1$  as in (8) and (9), the value of  $RIN_{ini}$  and  $RIN_{mmw}$  is -130 dB/Hz. From this figure, the relaxation frequency of  $RIN_{ini}$  and  $RIN_{mmw}$  is approximately 5 GHz, so  $RIN_{mmw}$  is generated from initial  $RIN_{ini}$ . As comparison between these two techniques using two different lasers and from the experimental results presented in Fig. 2 and Fig. 4, we can conclude that the physical phenomenon of RIN is the same: generation of  $RIN_{mmw}$  close to beat signal for any kind of optical heterodyne generation. For two DFB lasers

at MMW frequency band, we measured  $RIN_{mmw}$ , and we obtained on the two side-bands of  $RIN_{mmw}$  for beat carrier generated around 55 GHz due to controlling the temperature of both DFB lasers. **We also measured  $RIN_{mmw}$  when increasing the bias current of PMLLD using lock-in amplifier for improving the system sensitivity**, but we can not present these results due to the limited size of the paper.

#### V. CONCLUSION

In this paper, we have analyzed relative intensity noise of optical heterodyne signals in MMW frequency band for RoF applications and systems, and we have verified the phenomenon of RIN close to beat-note based on two different techniques, two independent DFB lasers and PMLLD. In order to show a real  $RIN_{mmw}$ , the phase noise result is provided, and the frequency response of system has been removed.

The experimental results confirm that  $RIN_{mmw}$  at MMW carrier is directly generated from initial  $RIN_{ini}$  at low frequency and is distinct from phase noise of beat signal. Due to the heterodyne process the  $RIN_{mmw}$  level can be higher than the  $RIN_{ini}$ , and this increasing depends on a factor  $I_j/I_i$  between the modes power. These results are independent from how the two optical modes are generated, so they can be directly transposed to any kind of optical generation of beat frequencies. The models of  $RIN_{ini}$  and  $RIN_{mmw}$  are presented and are in very good matching with the experimental results.

#### ACKNOWLEDGMENT

We would like to express our gratitude to III-V labs for proving the PMLLD chip.

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