A photonic frequency discriminator based laser linewidth estimation technique

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A B S T R A C T

The conventional methods on the measurement of linewidth of an individual laser or free-running beat spectrum are unable to realize both direct and accurate measurement/estimation all at once. An optical measurement or estimation technique is necessary for very high frequency optical system. The direct measurement of the optical spectrum from an RF-SA suffers from the frequency jitter, hence provides an inaccurate measurement. On the other hand methods to estimate the RF beat linewidth without directly measuring the RF spectrum are limited in terms of frequency range. We propose to use an optical discriminator to estimate the beat spectrum linewidth of a free running heterodyning system. Using a dense wavelength multiplexing (DWDM) filter as an optical discriminator, the transformation of phase modulation (PM) to intensity modulation (IM) is achieved. So, transformed laser phase noise into RIN (relative intensity noise). The proposed concept for beat spectrum linewidth estimate is shown and compared to other direct/indirect beat spectrum measurement techniques. Our proposed technique estimates the beat linewidth more accurately and by direct measurements of the beat spectrum. Moreover, the proposed technique operates in optical domain, thus not limited in frequency range. This technique is not affected by frequency jitter unlike the other methods for beat spectrum linewidth measurement.

1. Introduction

The generation of a high spectral purity RF local oscillator (LO) by means of optical heterodyning is interesting for applications like phase array antenna (PAA) (Khan et al., 2017a; 2017b), clock distribution, radar and antenna remoting (Ayotte et al., 2010; Palacio et al., 2010). The basic idea behind optical heterodyning is to generate an RF carrier by beating of two laser frequencies at the output of the photodetector (PD) (Khan et al., 2009). Narrow linewidth and highly stable lasers are critically important in this case to generate a stable and high quality RF LO (Khan et al., 2012). It is realized that the linewidth of the produced LO (i.e. the beat linewidth) will be the entirety of the linewidths of the two heterodyned laser (Khan et al., 2009).

In practice, the measurement of the RF beat linewidth of free running system is challenging due to the presence of frequency jitter (Keller et al., 2010). In this case, the linewidth of beat spectrum, measured using an RF spectrum analyzer (RF-SA), is often over estimated. This leads to an erroneous estimation of the quality of the optically generated LO. Previously, an alternative technique to determine the RF beat linewidth without directly measuring the RF spectrum has been published (Ip et al., 2005). In this scheme, an RF discriminator is used to convert the frequency fluctuations (i.e., frequency noise) into amplitude fluctuations. In this way, the effect of frequency jitter can be avoided (Ip et al., 2005). Since the RF components used in this discriminator are limited in terms of frequency range, the scheme is not suitable for measuring very high frequency (tens of GHz) LO. On the other hand, frequency to intensity noise conversion using optical discriminators has recently been demonstrated (Marpaung et al., 2010). The frequency (or phase) noise contribution in this case is observed as an additional relative intensity noise (RIN) at the photodetector output. Given a linear characteristic of the discriminator, the additional RIN is linearly proportional to the power spectral density of the

phase noise and hence, linearly proportional to the laser linewidth (Wyrwas and Wu, 2009).

In this paper, we combine the principles outlined in Marpaung et al. (2010) and Wyrwas and Wu (2009) and extend them as an alternative way to estimate the beat linewidth of the optically heterodyned LO. An optical discriminator is used to convert the phase noise from two lasers into additional RIN in the system. We verify the linearity of the discriminator used in this work and subsequently establish the relation between the additional RIN and the beat linewidth. We will demonstrate that the proposed system is not affected by the frequency jitter of the beat spectrum. The rest of the paper is organized as follows. Section 2 describes the conventional method of linewidth measurement. In Section 3 our proposed linewidth measurement technique is presented. Section 4 presents the calculation of the conversion factor. The estimation of beat spectrum linewidth is presented in Section 5. In the last section conclusions are stated.

2. Free running heterodyning scheme analysis

In practice, the measurement of the RF beat linewidth of a free running system is challenging due to the presence of large jitter in frequency (Keller et al., 2010). In that case, the linewidth of the beat spectrum, measured using an RF spectrum analyzer (RF-SA), often leads to an erroneous estimation of the optically generated LO. some conventional methods used to measure the linewidth of a free running beat spectrum produced from two independent lasers are direct beat spectrum (DBS)

measurement (Khan et al., 2011) and recirculating delayed self-heterodyning (DSH) method (Chen et al., 2006) discussed in the following sections.

2.1. Direct beat spectrum measurement

The block diagram of direct beat spectrum measurement method is presented in Fig. 1. In this method the instantaneous linewidth of a beat signal is measured by an RF spectrum analyzer (RF-SA). The two lasers used in our free running heterodyning scheme to generate a beat spectrum are a DFB laser (Avanex inc., A1905LMI) and a tunable laser (TLD, Santec TSL-210).
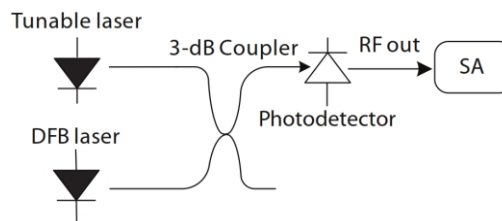

Fig. 1: Direct beat spectrum measurement

The linewidth of the RF beat spectrum will be the sum of two linewidths of the individual lasers, as depicted in Fig. 2. The optical power of the TLD is set in a value where the linewidth is 1.8 MHz. The increase of injection current of the DFB laser increases the optical power. The injection current is set to 200 mA with an output optical power of 30 mW. At 200 mA injection current the linewidth of the DFB laser is 1.5 MHz. In this case the RF beat linewidth should be 3.3 MHz.
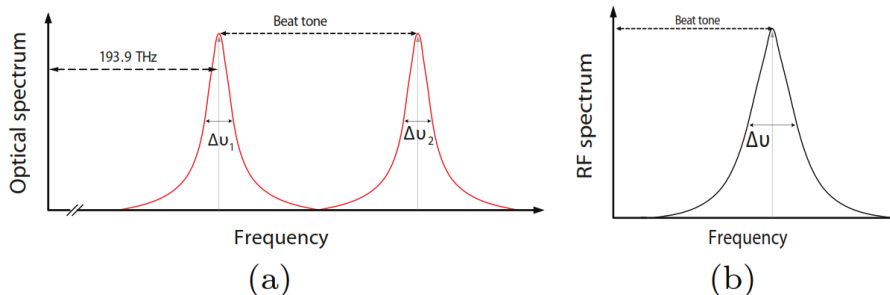

Fig. 2: Linewidth of (a) optical spectrum (b) RF beat spectrum

In a free running heterodyning system the frequency jitter from the individual lasers directly transfers to the RF beat spectrum. In order to predict the RF instability due to large jitter in frequency in the beat spectrum we took two individual readings on the RF-SA shown in Fig. 3. Here, a single snapshot measurement is depicted together with a measurement taken in a duration of one minute where the Maxhold function of the RF-SA is used. The long term measurement shows a much larger linewidth of 200 MHz compared to 3.3 MHz obtained from the snapshot, highlighting the deleterious effect of the jitter on free running heterodyning. This large jitter will lead to an erroneous measurement of the instantaneous linewidth by the RF-SA. Several

instantaneous measurements are taken and the results are shown in Fig. 4. From Schawlow-Townes theorem (Paschotta, 2008) it is known that the laser linewidth decrease with increase of optical power. This implies that the beat linewidth should decrease with increase of optical power of DFB laser. This phenomenon is not reflected on direct beat spectrum measurements, thus this method is not trust worthy.

2.2. Recirculating delayed self-heterodyning method

The delayed self-heterodyne method (DSH) (Okoshi et al., 1980) is an optical heterodyning technique used to measure the linewidth of a single-

frequency laser, shown in Fig. 5a. In a DSH method, first the laser light is divided in to two paths. Light from one path of the laser beam is sent through a long optical fiber in order to introduce some time delay. This delay ought to be longer than the laser coherence time. Light from the other path of the laser beam is passed through an acousto-optic modulator (AOM), used to shift the optical frequency.
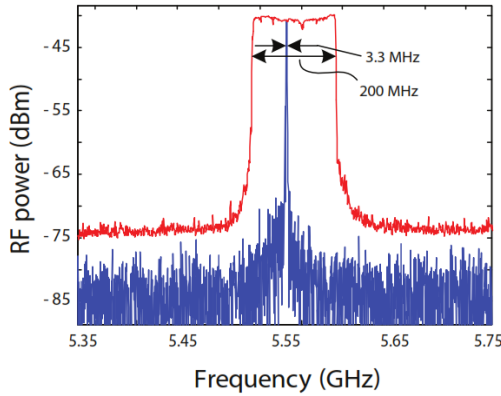

Fig. 3: Free running beat spectrum measurement. Single snap and one minute measurement with the Maxhold function of RF-SA
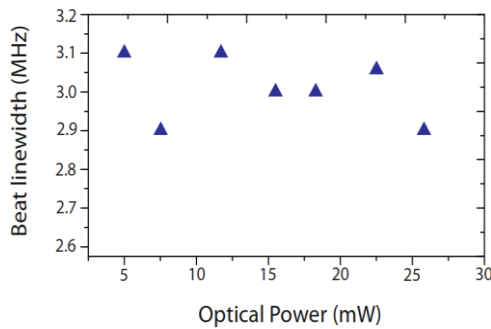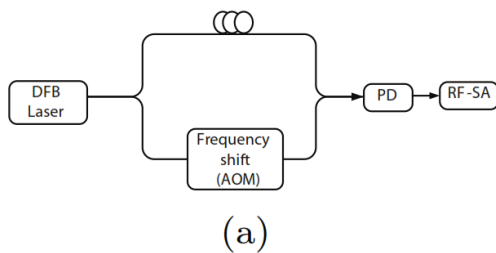

Fig. 4: Direct beat spectrum measurement

Finally, light from the both paths are combined in an optical combiner and inserted into a photo detector. The resulting beat note will be centered at the AOM frequency. The linewidth of the laser can

then be determined. However, the requirement that the delay time, τ_d, should exceed the coherence time of the laser, τ_c, limits the usefulness of this technique to lasers with relatively low linewidths. The relation between the coherence time, τ_c, and the linewidth of the laser, Δv, is expressed as

$$\tau_c = \frac{1}{\pi \Delta v}. \tag{1}$$

Tsuchida (1990) reported on an improvement to the delayed self-heterodyning (DSH) method which uses a recirculating delay, allowing the same fiber delay to be used multiple times. By including an acousto-optic modulator as a frequency shifter in the delay arm of the recirculating DSH (RDSH), multiple delays could be determined by counting the frequency shifts. However, due to large losses, Tsuchida (1990) was only able to measure up to three passes through the fiber delay. We include in the delay arm an erbium-doped fiber amplifier (EDFA). By partially compensating the large loss of the delay arm with gain from the fiber amplifier we easily recognize beat notes from light that has passed through the delay line. The validity and the resolution Δv_{res}, of the DSH is thus often cited as (Horak and Loh, 2006)

$$\tau_c \ll \tau_d \tag{2}$$
$$\tau_c = \frac{1}{\pi \Delta v} \tag{3}$$

where c=3×10^8 m/s is the velocity of light in vacuum, *n* is the refractive index of the fiber, *m* is the number of circulation, *L* is the length of the fiber. The validity of the above relations has been analyzed in (Richter et al., 1986). A 10 km fiber delay line with *n*=1.5 yields a resolution limit of 6.3 kHz with a standard DSH. Our loss-compensated RDSH yielded a resolution limit of 579 Hz for the same fiber length. The block diagram of the experimental setup is shown in Fig. 5b.
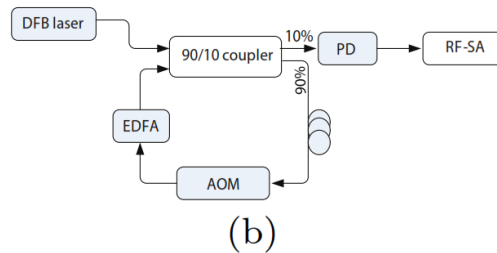

Fig. 5: (a) Delayed self-heterodyning (DSH) method. (b) Recirculating delayed self-heterodyning (RDSH) method

Components include an acousto-optic modulator (AOM) (Opto-electronics inc., model MT80), which provides a frequency shift of 80 MHz; a delay line consisting of an 10 km length of optical fiber having a net loss of 0.2 dB/km in the wavelength range of interest; an optical coupler with a 90/10 coupling ratio; an EDFA (Firmstein Technology Inc., Model PR25R). 90/10 optical coupler is used in the setup so that maximum optical power can be circulate in the

loop to compensate power loss. All these components are shown in Fig. 6a.

90 % of the light per pass was returned to the loop and 10% was sent to the photo detector. We estimate that the total loss per go through the recirculator was roughly 18 dB without an EDFA. Light was detected with a photo detector (Discovery semiconductor DSC30S) having a frequency response up to 20 GHz. The measures spectrum

shows that the beat frequencies are at 80 MHz and
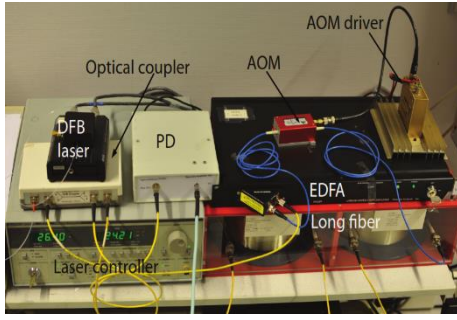
its multiple orders, as shown in Fig. 6b.

a
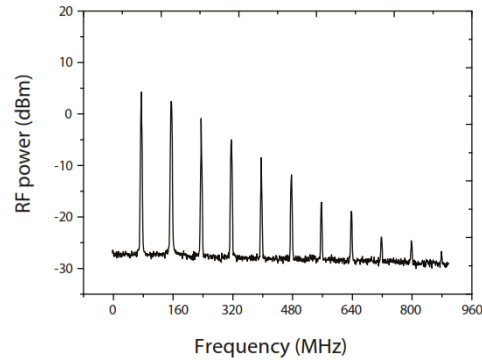
b

Fig. 6: (a) The components used measurement setup for RDSH method. (b) Linewidth measurement using RDSH method

The linewidth of this RF beat signal will be half of the optical linewidth. From this beat signal, the laser linewidth can then be extracted. In Fig. 7, the results of a linewidth measurement using the RDSH method on a DFB laser are shown. In this case, the difference of the measured 3-dB linewidths of 1.8 MHz obtained from a snapshot and one minute measurement of 3 MHz with the Maxhold function turned on is relatively small. From these measurements, we can conclude that the RDSH method is very little affected by frequency jitter. For this reason, we use the RDSH technique to determine the linewidth of the DFB laser for various optical powers, as shown in Fig. 8. As expected from Schawlow-Townes theorem (Paschotta, 2008) the laser linewidth decreases with the increase of the optical power.

3. Proposed technique to estimate beat-linewidth

The conventional methods on the measurement of linewidth of a free-running beat spectrum, are unable to realize both direct and accurate measurement/estimation all at once. The DBS measurement method uses direct measure of the spectrum from an RF-SA and suffers from the frequency jitter, hence provides an inaccurate measurement. On the other hand the recirculating delayed self-heterodyning method measures the linewidth of the individual lasers quite accurately and thereafter calculate the linewidth of a beat spectrum. Hence makes this method as an indirect way to extract the free running beat linewidth.

Beside these conventional methods, a technique called "frequency noise spectrum (FNS) method" to estimate the RF beat linewidth without directly measuring the RF spectrum has been published (Ip et al., 2005). In the FNS method, an RF discriminator is used to convert the RF phase fluctuations (i.e. frequency noise) into amplitude fluctuations. Giving a linear characteristic of the discriminator, the effect of frequency jitter can be avoided (Ip et al., 2005). Since the RF components used in this discriminator are limited in terms of frequency range, the scheme is not suitable for measuring very high frequencies (tens of GHz).
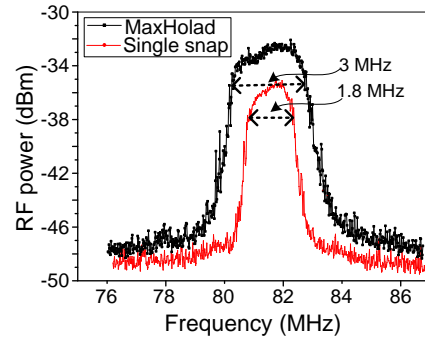

Fig. 7: The RDSH method. Single snap and one minute measurement with the Maxhold function of RF-SA
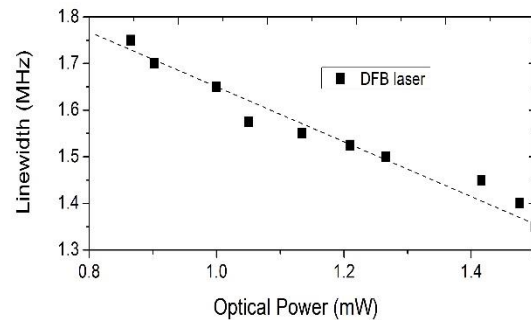

Fig. 8: Linewidth of the DFB laser for various optical powers using the RDSH method

Moreover, measurement of linewidth of individual laser using an optical spectrum analyzer (OSA) is not suitable as the resolution of the commercially available OSA is in range of 0.02 nm (or 2.5 GHz) not good enough to measure a linewidth in the range of few MHz or narrower. However, frequency to intensity conversion using optical discriminators has recently been demonstrated (Marpaung et al., 2010). The frequency (or phase) noise contribution in this case is observed as an additional relative intensity noise (RIN) at the photo detector output. Given a linear characteristic of the discriminator, the additional RIN is proportional to the power spectral density of the phase noise and hence, proportional to the laser linewidth (Wyrwas and Wu, 2009). In this section, we combine the principles outlined in Marpaung et al. (2010) and Wyrwas and Wu (2009) and extend them as an alternative way to estimate the beat linewidth of the

optically heterodyning LO. An optical discriminator is used to convert the phase noise from two lasers into additional RIN in the system. We verify the linearity of the discriminator used in this work and subsequently establish the relation between the additional RIN and the beat linewidth.

3.1. Discriminator aided PM-IM conversion principle

An optical discriminator follows the principle of an optical Mach-Zehnder interferometer (MZI). The block diagram of the MZI is shown in Fig. 9a where the light from a laser is divided into two parts and then combined in a photo detector, after one part is being delayed by an optical delay element (i.e., optical ring resonator). An MZI works by modifying the phase and amplitude relationships such that the amplitude of the envelope of the resultant signal at the output of a photo detector fluctuates in the same manner as did the instantaneous frequency (or phase) of the original light signal. The discriminator can be considered a function with an instant frequency (or phase) depending amplitude. The slope of the function converts variations in the optical phase into variations in the amplitude. Let the field from a laser given is:

$$E(t) = E(t)\exp(j[2\pi f_0 t + \phi_1(t)]) \qquad (4)$$

the photo-current at the output of the photodetector is given by

$$I(t) \approx |E(t) + E(t - \tau)|^2 + 2Re\{E(t)E(t - \tau)^* \exp(j[2\pi f_0 t + \Delta\phi(t)])\} \qquad (5)$$

where we have assumed 3-dB directional couplers, matched output polarization states and a differential time delay τ for the recombining beams. Substituting Equation (4) into Equation (5), the photo-current can be expressed as

$$I(t) \approx |E(t)|^2 + |E(t - \tau)|^2 + 2Re\{E(t)E(t - \tau)^* \exp(j[2\pi f_0 t + \Delta\phi(t)])\} \qquad (6)$$

where the differential phase $\Delta\phi(t)$ due to the differential delay τ through the interferometer is defined as

$$\Delta\phi(t) \triangleq \phi(t) - \phi(t - \tau). \qquad (7)$$

Equation (7) shows that photo-current varies as a function of differential phase, hence gives phase modulation (PM) to intensity modulation (IM) conversion. Fig. 9b shows how the photo-current varies as a function of this differential phase shift.
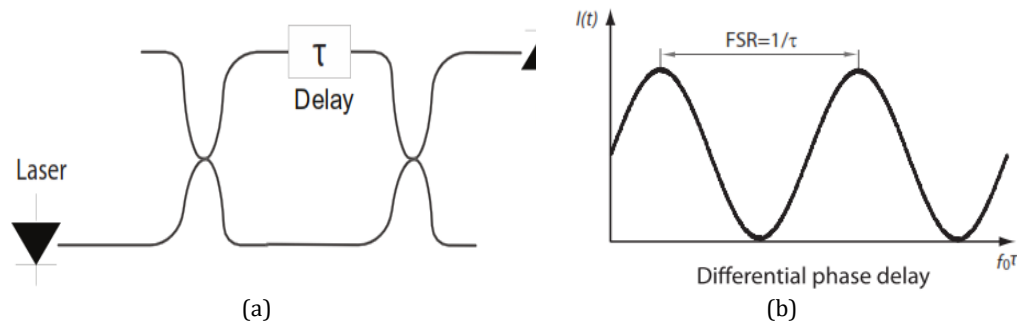

Fig. 9: (a) Optical discriminator. (b) Variation of photo-current at output of discriminator as a function of interferometer differential time delay (τ) or input optical frequency (f_0)

3.2. Characterization of the laser

One of the lasers used in the beat spectrum linewidth experiments is a DFB laser (A1905LMI) from Avanex inc. The laser is packaged in a 14-pin butterfly package and pigtailed with a single mode (SM) fiber. The emission wavelength of the laser is 1561.42 nm. The characterization of the laser starts with the determination of light-output versus current (L-I) curve. The measurement setup for this characterization is shown in Fig. 10.

The laser injection current is varied from 50 mA to 250 mA with a step of 10 mA. An optical attenuator (Agilent 8156A) was used to limit the optical power going to the optical power meter (HP 8153A) to avoid the saturation of this power meter. The resulting L-I curve is shown in Fig. 11a. At the injection current of 250 mA the laser emits an optical power of 35 mW. Next, wavelength of the laser as a function of its injection current for different temperature is investigated and shown in Fig. 11b.

The wavelength increases with increase of injection current of the laser. As the laser power is proportional to the laser current, this shows that the wavelength of the laser increases with increase of the laser power.

3.2.1. Laser noise measurements

In this section the noise of the laser is investigated. The noise measurement setup is shown in Fig. 12.

The injection current of the laser is varied from 100 mA to 250 mA with a step of 10 mA and for each step the total noise power spectral density (PSD) is measured with the RF-SA using the noise marker. The marker is positioned at the frequency of 3.8 GHz [The RF-SA (Agilent MXA N9020A)] used in this setup gives the lowest noise floor at this frequency and the noise was measured in a 10 kHz noise bandwidth.
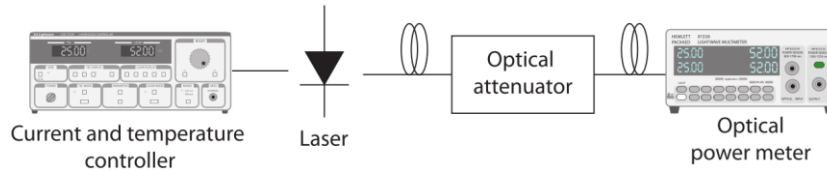
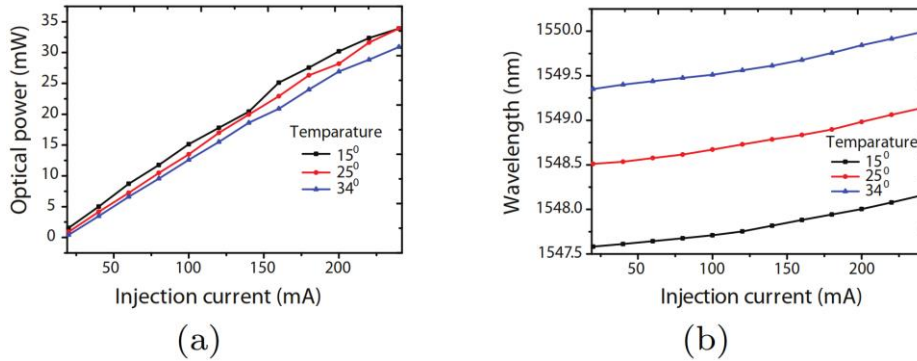**Fig. 10:** The measurement setup for L-I curve characterization

Fig. 11: The laser characteristic (a) measured L-I curve (b) wavelength, as a functions of the injection current. The connecting lines are only guides for the eye
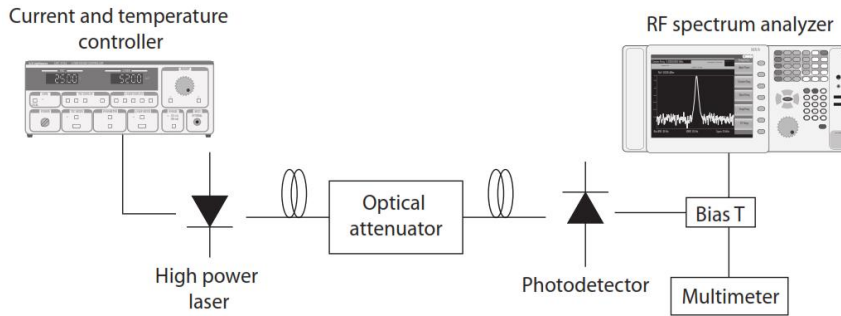

Fig. 12: The measurement setup for laser RIN characterization

The marker gives the measured noise power normalized to 1 Hz bandwidth, i.e., in dBm/Hz. Suppose that the average photocurrent during the noise measurement is I_{av} and the load resistance in the detector is R_L, we can write the noise PSD in W/Hz. Assuming that impedance matching has been imposed at the detector, the total noise PSD can be written as (Khan et al., 2011):

$$p_N = p_{th} + p_{shot} + p_{RIN} = p_{th,mL} + \frac{1}{4}\left(2qI_{av} + 10^{\frac{RIN}{10}}I_{av}^2\right)R_L \tag{8}$$

where $p_{th,mL}$, p_{shot} and p_{RIN} are the thermal noise, shot noise and RIN PSDs in W/Hz. The detected photocurrent was measured with a multimeter from the d.c. output of the bias-T. Thus, substituting p_N in Equation (8), we can determine the RIN values of the laser for different optical powers.

3.3. Laser linewidth estimation using optical frequency discriminator

The proposed technique employs optical PM-IM conversion where demultiplexer filter is used as an optical discriminator. Thus, additional intensity noise is produced. This additional noise is then converted as the linewidth of the optical spectrum. In the first step of the estimation procedure, the PM-IM conversion will be conducted using the DFB laser only. This is used to establish the relation of the linewidth of the DFB laser (obtained by RDSH measurement) and the additional RIN. In this way the proportionality factor that relates these parameters can be determined. Next, the PM-IM process will be repeated for the beat spectrum of two lasers. Thus, the estimation of the linewidth of the beat spectrum will be obtained using the additional RIN of the two lasers and the conversion factor determined from single laser measurement. The proportionality factor of the PM-IM conversion is directly related to the slope of the frequency discriminator. This is illustrated in Fig. 13 where the RIN is measured at two different positions in the filter response.

At point "A" where the slope is essentially zero, the measured RIN is the RIN of the laser. On the other hand, at point "B" where the slope is large, it is clear that the measured RIN is higher compared to the RIN of the laser. These phenomena are illustrated in Fig. 14. The proposed optical linewidth measurement method using an optical discriminator is shown in Fig. 14. In order to determine the additional RIN, first the optical power at the output of the laser is divided by a 3-dB coupler. One output of the coupler goes directly to the one port of a balanced photo detector (BPD) (Discovery

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semiconductor DSC710) while the other output goes to the other port of the BPD through the demultiplexer filter. The detected photocurrent is measured using a multi-meter connected to the DC output of the bias-T. The optical power at both branches is equalized using variable optical attenuators (VOAs).

In Fig. 14 "X" and "Y" branches are inserted in the BPD separately. The laser RIN, (RIN_{laser}) is measured by using the branch without filter (branch "X") while branch "Y" is inactive by applying very high attenuation in VOA2. In the branch with demultiplexer filter (branch "Y"), due to PM-IM conversion the phase noise of the laser is converted into RIN. Hence, using the branch with filter (branch "Y") while branch "X" is inactive by applying very high attenuation in VOA1, the total RIN of the system, (RINsys), is the combination of the RIN of the

laser and the RIN due to PM-IM conversion, $RIN_{PM\text{-}IM}$, following the relation:

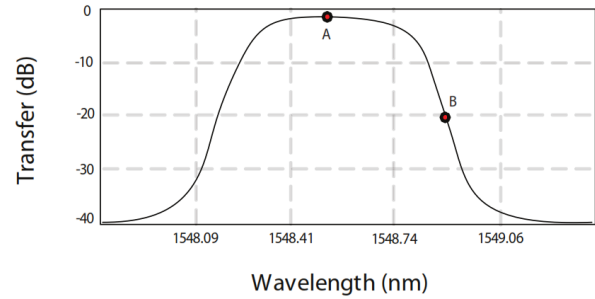$$RIN_{sys} = RIN_{laser} + RIN_{PM-IM}. \tag{9}$$

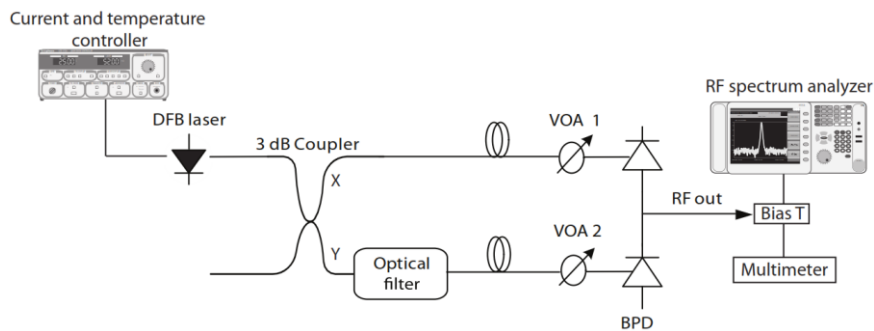**Fig. 13:** Response of the filter normalized to its maximum value

Fig. 14: Proposed laser linewidth estimation method using optical discriminator used for a single laser. VOA=variable optical attenuator, BPD=Balanced photodetector

The relation of the RIN to the noise power spectral density (PSD):

$$S_{RIN} = RIN_{sys}I_{av}^2R_L \tag{10}$$

where I_{av} and R_L are the average photo-current and load impedance at the output of the photo detector. The measured system noise at the balanced photo detector (BPD) output comprises of thermal noise, shot noise and RIN.

Following the procedure explained in Khan et al. (2011), the RIN is calculated.

3.4. Calibration of the measurement setup

In the previous section the technique to measure the additional RIN due to PM-IM conversion is presented. This will lead to establish a relation between this additional RIN and the linewidth of the laser. Measuring the total noise for the cases with and without filter and using Equation (8), one can derive the RIN values. As mentioned earlier, in case of optical filtering the system RIN comprises the contribution of the laser RIN and the additional RIN from PM-IM conversion in the filter. Thus, the extraction of the RIN contribution due to the laser phase noise, (RIN_{PM-IM}), is straightforward using Equation (9). It is useful to observe the PM-IM conversion at various laser linewidths. As shown in Fig. 8, the linewidth of the DFB laser is inversely proportional to the laser power. In practice, laser

power increases with increase of bias current which ultimately changes the central wavelength of the laser. The change of laser power and wavelength with change of laser injection current is shown in Fig. 11.

From Fig. 11b the change in wavelength of the DFB laser is measured to be 0.0026 nm/mA. For our DFB laser, to achieve a change of linewidth of 0.35 MHz as shown in Fig. 8, the optical power should change by 19 mW. From Fig. 11a, this change of power implies that the bias-current has to change by 140 mA. This will lead to a shift in a central wavelength of 0.364 nm. From Fig. 13 it is clear that the wavelength will deviate from the position "B" where the PM-IM conversion slope is optimum. Thus it is desired to keep the central wavelength at point "B" (at 1548.95 nm) while changing the laser linewidth. Since the demultiplexer filter used in our experiment is not tunable, as an alternative the wavelength of the DFB laser is tuned. In our experiment the shift of central wavelength due to the change in injection current is compensated by changing the laser temperature by 0.08 nm/^{0}C to shift back the wavelength to 1548.95 nm, as shown in Fig. 15.

The RIN measurements with and without the optical discriminator are shown in Fig. 16. With the help of Equation (9) the additional RIN is calculated and also plotted in Fig. 16 and observed that the RIN is inversely proportional to the laser power. We

investigate the relation between the linewidth of the laser and the additional RIN.
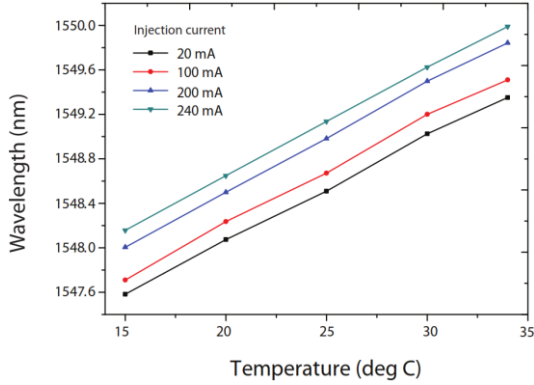

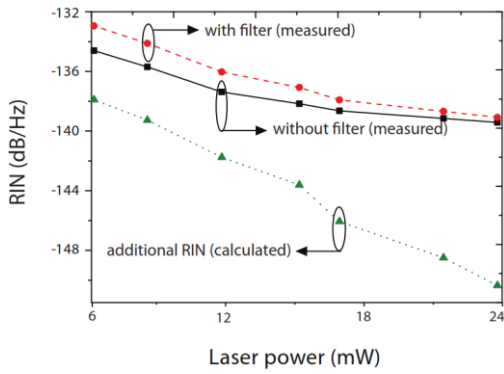**Fig. 15**: Laser wavelength change as a function of temperature

Fig. 16: RIN measurement for DFB laser (with and without filter)

With help of Fig. 8 and Fig. 16 the additional RIN (RIN_{PM-IM}) is plotted as a function of the laser linewidth in Fig. 17.
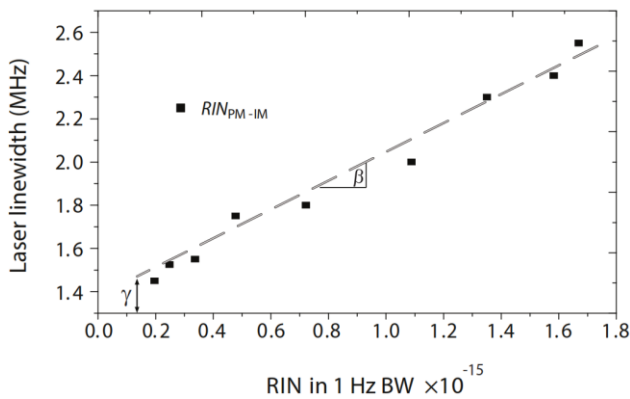

Fig. 17: Additional RIN and laser linewidth relation

Assuming that the laser-frequency fluctuations (i.e., noise) exhibit a white Gaussian distribution, the single-sided power spectral density (PSD) of the phase noise is proportional to the laser's -3 dB linewidth, Δv_{laser}, (Tarighat et al., 2006) such that:

$$S_\phi(f) \propto \frac{\Delta v_{laser}}{\pi f^2}. \tag{11}$$

The phase fluctuation is converted to intensity fluctuations using the slope of an optical filter (Wyrwas and Wu, 2009). Hence, the phase noise

power spectral density (PSD), $S(f)$, of the laser is again proportional to the additional RIN (RIN_{PM-IM}) (Marpaung et al., 2010)

$$S_\phi(f) \propto RIN_{PM-IM} \tag{12}$$

Using Equation (11) and Equation (12), we can conclude that the linewidth of the laser is proportional to the additional RIN. To establish a relationship, we can write:

$$\Delta v_{laser} = \beta RIN_{PM-IM} + \gamma \tag{13}$$

where β is the PM-IM conversion factor and γ is the correction factor due to linear curve fit. In Fig. 17, β gives the slope of the conversion and γ gives the position on the graph. The DFB laser linewidth, Δv_{laser}, is estimated using the conversion factor γ =8.95×10^{19} Hz and additional RIN. To fit this estimation with the curve of DFB laser in Fig. 8, the correction factor in Equation (13) is chosen to be γ =1×10^6 Hz.

3.5. Estimation of beat spectrum linewidth

We repeat the PM-IM conversion using two free running lasers to estimate the linewidth of the beat spectrum, the setup is shown in Fig. 18 (the two branch of the BPD is used separately to obtain two different RIN measurement). The RIN measured in the beat spectrum (RIN_{beat}) without filter are the total RIN contribution from the individual lasers. Rewriting Equation (9) for the beat spectrum,

$$RIN_{Total,sys} = RIN_{beat} + RIN_{Total,PM-IM} \tag{14}$$

where $RIN_{Total,PM-IM}$ is the total additional RIN due to PM-IM conversion of the beat spectrum. Hence, using the conversion factor, determined previously, it is possible to estimate the beat linewidth as:

$$\Delta v_{LO} = \beta RIN_{Total,PM-IM} + \gamma \tag{15}$$

Following the procedure for a single laser, the RIN measurement of the free running beat spectrum with and without filter at various optical power is performed. The experimental setup is shown in Fig. 19. The measured additional RIN is presented in Fig. 20. The total additional RIN ($RIN_{Total,PM-IM}$) is also plotted. While changing the power of the DFB laser the tunable laser power is kept constant to keep its RIN constant at -155 dB/Hz.

Knowing the conversion factor β from the previous section, estimation of the beat spectrum linewidth, Δv_{LO}, is straightforward using Equation (15). The estimated beat spectrum linewidth is plotted in Fig. 21. Here we compare the estimated beat spectrum linewidth with calculated value by summing the individual linewidths of the lasers obtained from the recirculating delayed self-heterodyning (RDSH) method (Fig. 8) as well as

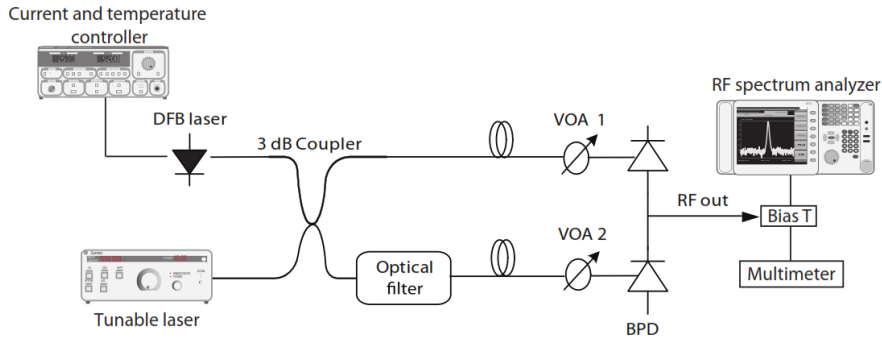measured values using directly beat spectrum

measurement (Fig. 4).

Fig. 18: Proposed beat spectrum linewidth estimation method using optical discriminator. VOA=variable optical attenuator, BPD=Balanced photodetector
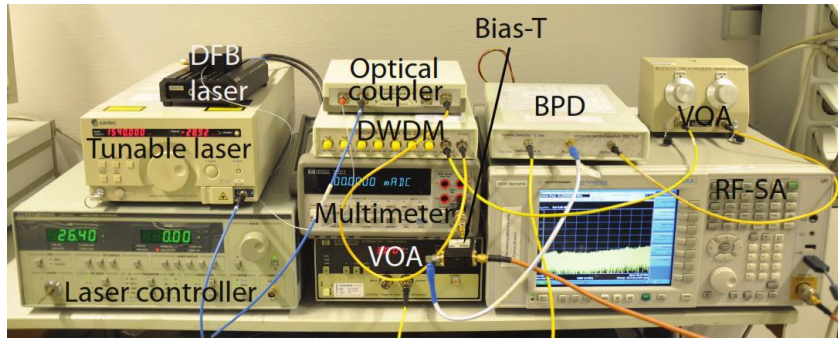

Fig. 19: The measurement setup for PM-IM conversion

Than we have compared this calculated value with the value estimated by proposed PM-IM method. We express the percentage of error of the estimated values from the calculated values. The relative error (the estimated value minus the calculated value divided by calculated value times 100) is calculated as 4%. The error might be attributed to the imperfection in the measurement where the temperature tuning of the laser makes slight change in laser linewidth as well as laser RIN.
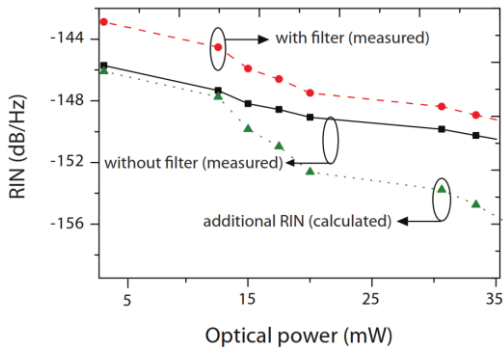

Fig. 20: RIN measurement for free running beat spectrum (with and without filter)

4. Comparison

The comparison of different methods for free-running linewidth measurement is compared with the proposed technique as shown in Table 1.

As shown in Table 1, our proposed technique estimates the beat linewidth more accurately and by direct measurements of the beat spectrum. Moreover, the proposed technique operates in optical domain, thus not limited in frequency range.

This technique is not affected by frequency jitter unlike the others methods for beat spectrum linewidth measurement.
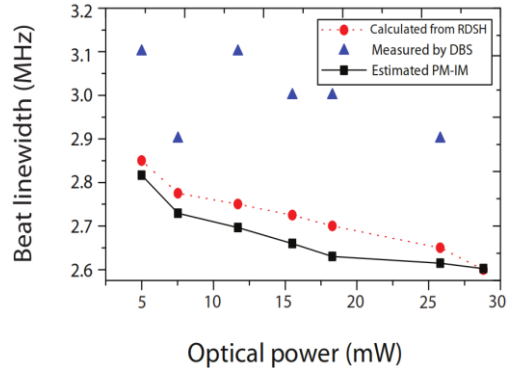

Fig. 21: Beat spectrum linewidth comparison for estimated, measured and calculated values

5. Conclusion

We have demonstrated a novel technique to measure the beat spectrum linewidth of free running heterodyning scheme in presence of high frequency jitter. An optical discriminator based PM IM conversion technique is used. A relationship between the linewidth of laser and additional RIN is established.

The estimation can be improved in terms of accuracy and conversion factor by using a tunable optical discriminator. The proposed scheme is not affected to frequency jitter and well suited for very wide frequency range of operation. The scheme is also promising for measurement of very narrow linewidth lasers such as the one reported in

([Bernhardi et al., 2010](#)). In that case the additional RIN will be very small and can be compensated by the large conversion factor. A tunable optical discriminator having very high slope will serve this purpose. So, the characterization of the tunable optical filter makes a scope to improve our proposed scheme.

Table 1: Comparison of conventional methods for free running linewidth measurement with proposed technique

Method	Measurement Accuracy	Action	Performance		
			Frequency domain	Jitter affect	Limited by
DBS [12]	inaccurate	direct	RF	yes	RF-SA
DSH [15]	accurate	indirect	RF	no	fiber length
RDSH [13]	accurate	indirect	RF	yes	fiber length
FNS [9]	limited	estimated	RF	no	RF discriminator
OSA	limited	direct	optical	yes	resolution
Proposed PM-IM	high	estimated	optical	no	Optical discriminator

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Compliance with ethical standards

Conflict of interest

The authors declare that they have no conflict of interest.

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