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Frequency Response of the Noise Conversion from Relative Intensity Noise to Phase Noise in the Photodetection of an Optical Pulse Train

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Abstract—The frequency response of the noise conversion from the relative intensity noise (RIN) to the phase noise in the photodetection process of an optical pulse train is characterized with pump modulation method. It is found that the conversion ratio from the RIN to the phase noise is not sensitive to the noise power or the incident optical power, but decreases approximately as $1/f$ with the increase of noise frequency. A new parameter defined as the RF power difference of the noise [spurious peaks](#) is proposed and is shown to provide an easy way to estimate the strength of the RIN-to-phase-noise conversion avoiding the need to measure the exact noise spectra of the RIN and the phase noise.

Index Terms— Phase noise, intensity noise, mode-locked laser, photodetector and pump modulation

LOW-noise mode-locked lasers are important for various applications including low-noise microwave signal synthesis [1] and high-precision clock distribution [2-3], etc. In these applications, timing precision of the signal converted from the optical domain to the RF domain is limited by the excess phase noise coupled from the intensity noise of the optical pulse train in the photodetection process, known as intensity (or power)-to-phase-noise conversion [3]. It has been known that this excess phase noise in the photodetection process originates from the power dependent pulse distortion including the power dependent pulse broadening and power dependent time delay between optical and electrical pulses [4]. A typical method to characterize this noise conversion is to apply an acousto-optic modulator (AOM) after the optical pulse train to generate a controlled intensity noise and compare with the measured phase noise [1]. Various techniques have been proposed to reduce the phase noise in the mode-locked lasers [5-9] and to measure the phase noise precisely [1, 4, 10-11]. Moreover, it has also been demonstrated that the residual timing jitter of the extracted RF signals can be as low as a few tens of femtosecond with novel designs [12-13].

In the previous work, the investigation of the noise conversion from the intensity noise to the phase noise is focused on the relation between the intensity noise power and the phase change, i.e., in the units of rad/W [1]. However, there is no study

reported on the relation between the noise conversion and the offset frequency (or Fourier frequency) in the noise spectrum. Also, the measurement setup is complicated due to the requirement of an additional AOM. In this paper we adopt pump modulation method [14] to characterize the frequency response of the relative-intensity-noise (RIN)-to-phase-noise conversion in the photodetection process. This method provides an effective way to investigate the noise conversion with respect to the offset frequency. Moreover, based on the pump modulation setup, we also propose a simple method to estimate the strength of the noise conversion avoiding the need to measure the exact noise spectra of the RIN and the phase noise.

The experimental setup is shown in Fig.1 (a). A homemade 147MHz mode-locked laser based on nonlinear polarization rotation (NPR) is used as a pulse source. Its pump diode is driven by a DC bias current and an AC modulation current. The output of the NPR mode-locked laser goes through an optical isolator to remove back reflection. An external ~ 5.8 m dispersion compensation fiber (DCF) is applied to compress the pulse. The optical spectrum and pulse autocorrelation trace after the DCF are shown in Fig.1 (b). The 3dB bandwidth is 20.4nm and the pulse width (assuming sech^2 profile) is 135fs, corresponding to a time bandwidth product (TBP) of 0.339. The output power is 3.8dBm. The signal is then fed to a 2GHz photodetector (Thorlab DET01CFC). The RF signal goes through a low pass filter (LPF) to extract the component at fundamental repetition frequency f_R and is finally measured by a signal source analyzer (SSA, Rohde & Schwarz FSUP26).

Typical noise spectra of RIN and phase noise are shown in Fig.2. The drive current of the pump diode is modulated at a frequency f_M of 5kHz (sine wave) and a modulation current I_M of 20mA. The pump DC bias current is 780mA, so that the modulation depth is 2.56%. Due to the gain modulation effect in the mode-locked laser, noise [spurious peaks](#) at harmonic frequencies of f_M can be observed in the RIN spectrum [14]. Similar noise [spurious peaks](#) can also be observed in the phase noise spectrum. [Theoretical analysis \[5\] shows that the internal RIN-to-phase-noise coupling in the laser is mainly due to the Kramers-Krönig related phase changes and Kerr nonlinearity. These two effects, however, only cause a change of phase noise](#) $\Delta S_{PH}(f) \leq 10^{-9} S_{RIN}(f)$ [with the parameter values in our](#)

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experiment, and thus very weak compared with our measurement results (shown later in Fig.3). Therefore the noise spurious peaks in the phase noise spectrum are mainly due to the noise conversion in the photodetection process. By comparing the noise power at these frequencies, the conversion ratio (CR) can be defined by

$$CR(kf_M) = S_{PH}(kf_M) / S_{RIN}(kf_M) \quad (1)$$

where $k=1,2,3\dots$ is the order of harmonic frequencies and $S_{RIN}(kf_M)$ and $S_{PH}(kf_M)$ are the power of the spurious peaks at kf_M in the RIN and the phase noise spectra, respectively. Here we use RIN rather than intensity noise to calculate the conversion ratio. When the phase noise and RIN spectra are expressed in logarithms in the units of dBc/Hz, the conversion ratio (in the units of dB) can be simply calculated by subtract the corresponding values in the phase noise and RIN spectra.

To consider the effect on conversion ratio of the modulation depth (current), the modulation frequency and the incident optical power, the conditions listed in TABLE I are tested and the corresponding conversion ratio is shown in Fig.3.

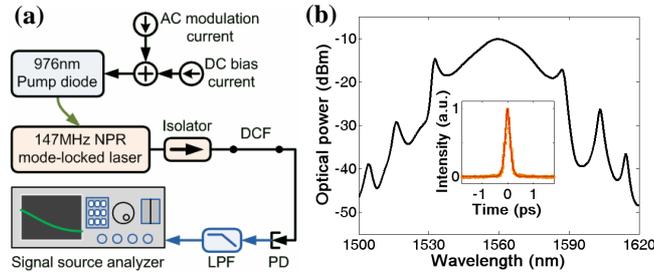


Fig.1. (a) Setup for characterization of the RIN-to-phase-noise conversion in the photodetection process by pump modulation of a mode-locked laser; (b) the optical spectrum. Inset: the pulse autocorrelation trace after the external DCF

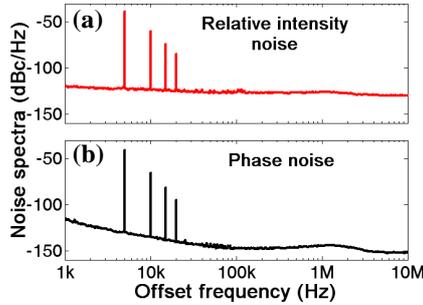


Fig.2. The noise spectra of (a) relative intensity noise, and (b) phase noise.

TABLE I
TEST CONDITIONS FOR THE RIN-TO-PHASE-NOISE CONVERSION

Purpose	Variable condition	Fixed condition
The effect of modulation depth (current)	Modulation current 1mA, 3mA, 10mA, 20mA, 30mA	Modulation frequency 5kHz RF power at f_R -4dBm
The effect of modulation frequency	Modulation frequency 5kHz, 10kHz, 20kHz, 40kHz, 80kHz	Modulation current 20mA RF power at f_R -4dBm
The effect of incident optical power ^a	RF power at f_R -4dBm, -5dBm, -10dBm	Modulation frequency 5kHz Modulation current 20mA

^a The incident optical power is represented equivalently by the RF power at fundamental repetition frequency f_R because the photodetector is operating in

the linear region. The optical power is changed by inserting a variable attenuator before the pulse train entering the photodetector.

It can be seen in Fig.3 that the change of the modulation current and the incident optical power do not change the conversion ratio. However, the conversion ratio decreases quickly with the increase of the modulation frequency (or offset frequency in the noise spectrum). A 1/f curve is drawn in Fig.3 for comparison. It can be seen that most dots in the figure are near this 1/f curve. The origin of this 1/f decrease is unclear. A possible explanation is that the space-charge buildup in the depletion region of the photodetector takes time to affect the velocity of photo-generated charge carriers and therefore the high-frequency intensity noise (large f_M) is attenuated more during the conversion to the time delay or phase noise of the output electrical pulses [15].

It is also worth noting that in the previously reported measurement of the noise conversion ratio, $\Delta\phi / \Delta I$ decreases with the increase of incident optical intensity I_{opt} [1]. A simple calculation shows that this result does not conflict with our results. The excess phase noise introduced by photodetection can be estimated by $\Delta\phi \approx \sqrt{S_{PH}(f_M)}$ because the noise spurious peaks contribute the majority of the excess phase noise. Similarly, the RIN can be estimated by $\Delta I / I_{opt} \doteq \sqrt{S_{RIN}(f_M)}$. Therefore the ratio $\Delta\phi / \Delta I \doteq S_{PH}^{1/2}(f_M) S_{RIN}^{-1/2}(f_M) I_{opt}^{-1}$ will decrease with the increase of incident optical power.

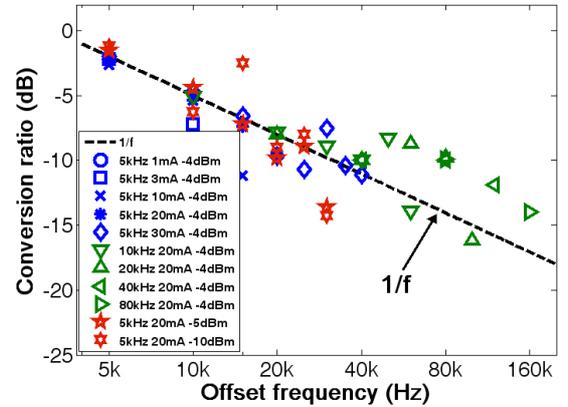


Fig.3. The conversion ratio from the RIN to the phase noise by comparing the power at noise spurious peaks induced by pump modulation. A 1/f curve is also given in dashed line. The values shown in the legend correspond to the modulation frequency, modulation current and RF power at fundamental repetition frequency, respectively.

It is known that the correlation between the RIN and the phase noise will lead to the asymmetry of the sidebands in the RF spectrum [16]. This asymmetry can be adopted as a parameter to describe the strength of the RIN-to-phase-noise conversion discussed above. Two RF spectra generated by 5kHz and 20kHz pump modulation, respectively, are given in Fig.4(a) for comparison. It can be clearly observed that the power difference between the spurious peaks at $f_R - 5kHz$ and $f_R + 5kHz$ in the 5kHz-modulated spectrum is much larger than the difference between the peaks at $f_R - 20kHz$ and

$f_R + 20\text{kHz}$ in the 20kHz-modulated spectrum. We define this power difference ΔP to describe the strength of the noise conversion as

$$\Delta P = P_{RF}(f_R - f_M) - P_{RF}(f_R + f_M) \quad (2)$$

As before, the conditions listed in TABLE I are tested to investigate the roles of modulation current, incident optical power and modulation frequency. The results are summarized in Fig.4(b)-(d). The upper plots are for the RF power at $f_R - f_M$ and the lower plots are for ΔP . Very similar to the conversion ratio plotted in Fig.3, ΔP is not sensitive to the modulation current (Fig.4(b)) and the incident optical power (Fig.4(c)) but significantly decreases from 10.5dB to 0.7dB when the modulation frequency increases from 5kHz to 80kHz (Fig.4(d)). Therefore, ΔP has the same trend as that of the conversion ratio in Fig.3 obtained by comparing the exact RIN and phase noise spectra but only requires an RF spectrum analyzer with no need of a complicated setup for noise measurement or signal source analyzer.

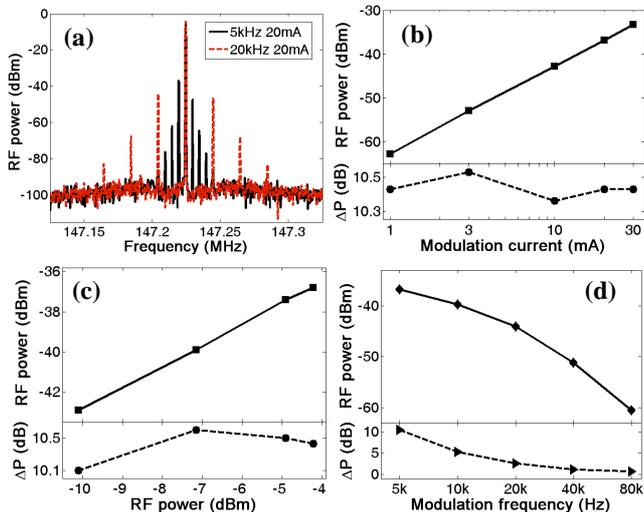


Fig.4. (a) RF spectra at fundamental repetition frequency $\sim 147.225\text{MHz}$ with 20mA pump modulation current and modulation frequency of 5kHz (solid line) and 20kHz (dashed line), respectively. Harmonics of the modulation frequency due to the gain modulation effect in the laser can also be seen; (b)-(d) The RF power at $f_R - f_M$ (solid line in the upper plots) and RF power difference ΔP defined as $P_{RF}(f_R - f_M) - P_{RF}(f_R + f_M)$ (dashed line in the lower plots) under the following conditions: (b) modulation frequency $f_M = 5\text{kHz}$ and modulation current I_M is varied from 1mA to 30mA; (c) $f_M = 5\text{kHz}$ and $I_M = 20\text{mA}$ and the incident optical power is varied by optical attenuator. The horizontal axis is the RF power at f_R ; (d) $I_M = 20\text{mA}$ and f_M is varied from 5kHz to 80kHz.

It is also noted that when the modulation current is varied, the change of RF power at $f_R - f_M$ (upper plot in Fig.4(b)) satisfies the square law induced by the photodetection process, i.e., the RF power increases by 100 times or 20dB when the modulation current increases by 10 times, which again confirms that the photodetector is operating in the linear region.

In conclusion, we have characterized the frequency response of the noise conversion from the relative intensity noise to the phase noise in the photodetection process of an optical pulse train by adopting pump modulation method. It is found that the

RIN-to-phase-noise conversion ratio is not sensitive to the noise power or the incident optical power, but decreases approximately as $1/f$ with the increase of the noise frequency. Moreover, a new parameter ΔP , defined as $\Delta P = P_{RF}(f_R - f_M) - P_{RF}(f_R + f_M)$, is proposed and is shown to have the same trend as the noise conversion ratio. This parameter provides an easy way to estimate the strength of the RIN-to-phase-noise conversion avoiding the need to measure the exact noise spectra of the RIN and the phase noise.

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