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Noise conversion from pump to the passively mode-locked fiber lasers at 1.5 μm

Kan Wu,¹ Perry Ping Shum,^{1,2,*} Sheel Aditya,¹ Chunmei Ouyang,¹ Jia Haur Wong,¹
Huy Quoc Lam,³ and Kenneth Eng Kian Lee³

¹School of Electrical and Electronic Engineering, Nanyang Technological University, 50 Nanyang Drive, Singapore 637553

²CINTRA CNRS/NTU/THALES, UMI 3288, Research Techno Plaza, 50 Nanyang Drive, Level 6, Singapore 637553

³Temasek Laboratories, Nanyang Technological University, Singapore 637553

*Corresponding author: EPSum@ntu.edu.sg

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We characterize the noise conversion from the pump relative intensity noise (RIN) to the RIN and phase noise of passively mode-locked lasers at 1.5 μm . Two mode locking mechanisms, nonlinear polarization rotation (NPR) and semiconductor saturable absorber mirror (SESAM), are compared for noise conversion for the first time. It is found that the RIN and the phase noise of both types of lasers are dominated by the noise converted from the pump RIN and thus, can be predicted with the measured pump RIN and noise conversion ratios. The SESAM laser is found to show an excess noise conversion from the laser RIN to the laser phase noise due to the slow saturable absorber effect. © 2012 Optical Society of America

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Low-noise mode-locked lasers (MLLs) are of importance in many research areas such as frequency metrology [1] and microwave signal synthesis [2]. Various studies have been done on the quantum noise limits [3–4], pulse dynamics [5], noise reduction [6–8], and noise measurement, [9] etc. It has been known that the relative intensity noise (RIN) of the pump converts to the RIN and phase noise of the MLL through various mechanisms [4,10,11]. The phase noise in this paper refers to the timing jitter of the MLLs. The noise conversion from the pump RIN to the RIN and phase noise in Ti:Sapphire lasers has been experimentally measured [11,12]. We have also investigated the nonlinear noise conversion from the pump RIN to the laser RIN [10]. However, there is no reported work yet investigating in detail the noise conversion from the pump RIN to the laser RIN and laser phase noise for the MLLs at 1.5 μm , and no work on the comparison of the noise conversions for different mode locking mechanisms, e.g., nonlinear polarization rotation (NPR) and semiconductor saturable absorber mirror (SESAM).

In this paper, we characterize the noise conversion from the pump RIN to the RIN and phase noise of the passively MLLs at 1.5 μm , and compare, for the first time, the noise conversion for two different mode locking mechanisms, NPR and SESAM. Pump modulation technique is applied. Both lasers (NPR laser and SESAM laser) are mode locked in the soliton region. It is found that both the RIN and phase noise of the two lasers are dominated by the noise converted from the pump RIN, i.e., the RIN and phase noise power spectral densities (PSDs) can be predicted with the measured pump RIN PSD and noise conversion ratios. Moreover, compared with the NPR laser, SESAM laser is found to have an excess noise conversion from the laser RIN to the laser phase noise due to the slow saturable absorber effect.

The experimental setup is shown in Fig. 1(a) and the detailed setups of the two lasers are shown in Figs. 1(b) and 1(c).

The lasers are pumped by a 976 nm diode and the drive current of the pump diode is modulated to generate a controlled RIN of the pump. This pump RIN then transfers to the RIN and the phase noise of the MLLs through various mechanisms, such as gain modulation effect [10]. After an isolator, the output of the lasers is fed into an acousto-optic modulator (AOM) and then into a 2 GHz photodetector (PD). The AOM is used to evaluate the RIN-to-phase-noise conversion in the photodetector [13–14] to guarantee that this excess noise conversion induced by the photodetector is below the original noise in the laser and that it will not affect the measurement results in the experiment. A low pass filter (LPF) and a low-noise amplifier (LNA) are used to extract the electrical signal at fundamental repetition rate of the lasers for noise measurement by a signal source analyzer (SSA, R&S FSUP26). The NPR laser has a repetition rate of 66.1 MHz, a center wavelength of 1560 nm, a 3 dB bandwidth of 15.1 nm, an intracavity power of 17 mW, and a net dispersion of -0.06 ps^2 . The SESAM laser has a repetition rate of 163.4 MHz, a center wavelength of 1581 nm, a 3 dB bandwidth of 10.4 nm, an intracavity power of 14 mW, and a net dispersion of -0.013 ps^2 . The inset

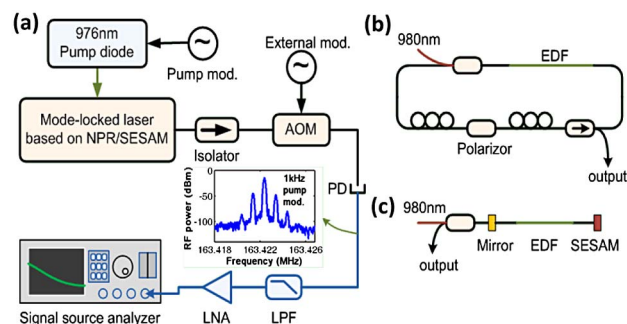


Fig. 1. (Color online) (a) Setup for characterization of the noise conversion from the pump to the mode-locked fiber lasers; Inset: RF spectrum of the SESAM laser with 1 kHz pump modulation after photodetection; (b) NPR laser setup; and (c) SESAM laser setup.

in Fig. 1(a) shows the RF spectrum measured at the repetition frequency of the SESAM laser with 1 kHz pump modulation. The sidebands induced by the pump modulation can be clearly observed.

The noise conversion ratios are obtained with the following method. A modulation frequency f_M is applied to the drive current of the pump diode and generates a controlled pump RIN. The pump RIN $S_{\text{Pump-RIN}}$ at f_M (a spurious peak, with the units of dBc) is measured by feeding the pump output to the PD with proper attenuation and then characterized by a baseband spectrum analyzer. The laser RIN S_{RIN} and phase noise S_{PN} at f_M (with the units of dBc) are characterized by the signal source analyzer. Then the noise conversion ratios from the pump RIN to the laser RIN, r_{RIN} , and to the laser phase noise, r_{PN} , are given by

$$r_{\text{RIN}}(f_M) = S_{\text{RIN}}(f_M)/S_{\text{Pump-RIN}}(f_M), \quad (1)$$

$$r_{\text{PN}}(f_M) = S_{\text{PN}}(f_M)/S_{\text{Pump-RIN}}(f_M). \quad (2)$$

Meanwhile, the power of the sidebands in the laser RF spectrum induced by pump modulation is equal to the sum of the RIN and phase noise of the lasers [3]. So if we define the conversion ratio from the pump RIN to the relative RF power of the sidebands, r_{RF} , as follows

$$r_{\text{RF}}(f_M) = P(f_R \pm f_M)/P(f_R)/S_{\text{Pump-RIN}}(f_M), \quad (3)$$

where $P(f_R \pm f_M)/P(f_R)$ represents the relative RF power of the sidebands, we have $r_{\text{RF}} = r_{\text{RIN}} + r_{\text{PN}}$ for all modulation frequencies. The left hand side, r_{RF} , is measured by the RF spectrum analyzer and the right hand side, r_{RIN} and r_{PN} , are measured by the demodulation method in the signal source analyzer. Therefore, this relation between the RF sidebands and RIN and phase noise can be used to verify the correctness of the measurement results of the RIN and phase noise conversion ratios. Fig. 2(a) shows the three conversion ratios r_{RIN} , r_{PN} , and r_{RF} measured for the NPR laser. The $1/f^2$ line is drawn for reference. Very good agreement with this equation can be found. This confirms the correctness of the measurement results. With the knowledge of noise conversion ratios r_{RIN} and r_{PN} , and pump RIN PSD, we can predict the RIN and phase noise PSDs of the lasers according to Eqs. 1 and 2. As shown in Fig. 2(b), the noise PSDs predicted this way agree well with the measured noise PSDs, also indicating that the laser RIN and phase noise are dominated by the noise converted from the pump RIN. The disagreement for the offset frequencies greater than 20 kHz is due to the noise floor of the measurement system.

Similarly, Fig. 3 shows the measured noise conversion ratios and PSDs for the SESAM laser. Again, good agreement can be observed among r_{RIN} , r_{PN} , and r_{RF} . It is noticed that, both for the NPR and SESAM lasers, the RIN noise conversion ratio r_{RIN} exhibits a plateau in the low-offset frequency range and then a rapid decay in the high-offset frequency range. This behavior represents a pump induced fluctuation of the intracavity pulse energy [12]. For the NPR laser, the decay at high-offset frequency

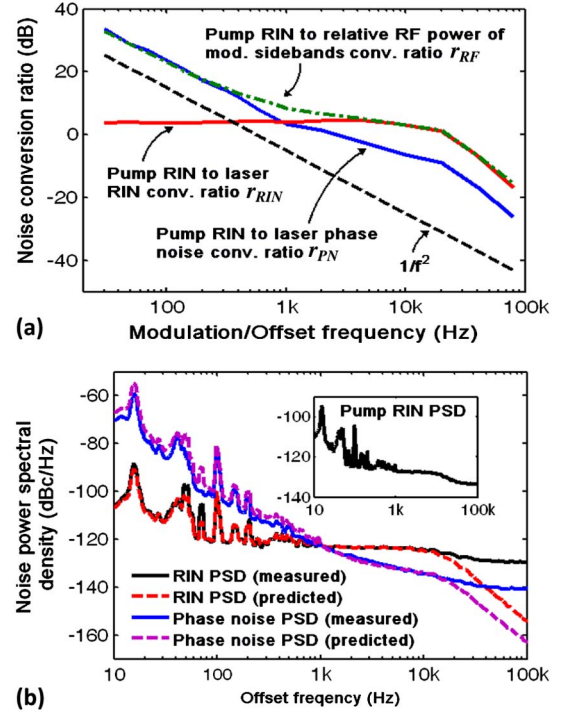


Fig. 2. (Color online) (a) Noise conversion ratios r_{RIN} , r_{PN} , and r_{RF} measured for the NPR laser and (b) measured and predicted PSDs of RIN and phase noise of the NPR laser. Inset: PSD of the pump RIN.

range is -40 dB/dec. For the SESAM laser, due to the lower pump power, the photons decay faster in the cavity; thus, a -20 dB/dec the range of 10 kHz–100 kHz

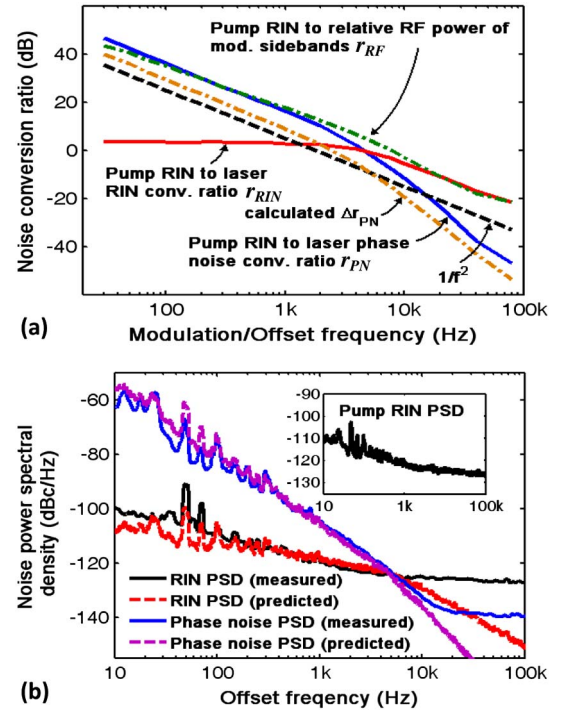


Fig. 3. (Color online) (a) Noise conversion ratios r_{RIN} , r_{PN} , and r_{RF} measured for the SESAM laser and the calculated excess phase noise Δr_{PN} based on Eq. (4) and (b) measured and predicted PSDs of RIN and phase noise of the SESAM laser. Inset: PSD of the pump RIN.

(this means γ_{sp} in Eq. (4) in [12] is very large and dominates the equation in the range of 10 kHz–100 kHz). However, the phase noise conversion ratio r_{PN} shows a very different behavior for the two lasers under test. For NPR laser, r_{PN} is very similar to the one measured in a Ti:Sapphire laser [11], which shows a -20 dB/dec decay in the low-offset frequency range (<1 kHz) due to the thermo-optic effect and a rapid decay at high-offset frequency range (>10 kHz) due to the Kerr nonlinearity with self-steepening [12]. However, for the SESAM laser, r_{PN} is much greater in the low-offset frequency range and then quickly decays in the high-offset frequency range. Kerr nonlinearity and the difference of the intracavity pulse energy in the two lasers is not likely to be the reason because the higher pulse energy in the NPR laser (~ 257 pJ) than in the SESAM laser (~ 86 pJ) would indicate that RIN to phase noise conversion via Kerr nonlinearity in the cavity should be higher in the NPR laser [4]. It is noted that the SESAM is a slow saturable absorber and causes an excess noise conversion effect from the laser RIN to the laser phase noise [4]. The saturation parameter s for the SESAM laser, defined as the ratio of intracavity pulse energy and saturation energy of SESAM, is ~ 2 . Then, the excess RIN to phase noise conversion due to the slow saturable absorber effect is given by Eq. (4) in logarithmic scale with the units of dBc/Hz. See Eq. (29) in [4] for more details. The pulse shift induced by the slow saturable absorber, $\partial\Delta t/\partial s$, is estimated as ~ 30 fs.)

$$\Delta S_{PN}(f) \approx 65 - 20 \cdot \lg f + S_{RIN}(f) \quad (\text{dBc/Hz}). \quad (4)$$

Note that r_{RIN} and r_{PN} are related to S_{RIN} and S_{PN} by Eqs. (1) and (2). Equation (4) can also be applied to r_{RIN} and r_{PN} where we use Δr_{PN} to represent the excess phase noise conversion ratio from the laser RIN. The calculated Δr_{PN} based on Eq. (4) is shown in Fig. 3(a). It can be seen that Δr_{PN} is almost the same as r_{PN} except a ~ 5 dB difference which may be due to an error in the estimation of saturation parameter s and the intracavity pulse energy. Therefore, it can be concluded that in the SESAM laser under test, the phase noise is mainly caused by the noise conversion from the laser RIN due to the slow saturable absorber effect. It is also the first time, to our knowledge, this effect is experimentally reported. NPR mode-locking based on Kerr nonlinearity is a fast saturable absorber with nearly instant response time and thus, does not have this excess noise conversion effect. Also, for both lasers, no relaxation oscillation peak is observed in the RF spectrum since the lasers are adjusted in the optimum operation condition which leads to the strongest damping of relaxation oscillation. Weak relaxation oscillation peaks appear in the RF spectrum (a few kHz to a few hundred kHz) when the lasers are

detuned from the optimum operation condition by adjusting the intracavity polarization controller, but they have negligible effect on the noise conversion ratios.

In conclusion, we have experimentally characterized the noise conversion from the pump RIN to the RIN and phase noise of two passively mode-locked fiber lasers at $1.5 \mu\text{m}$. Two mode locking mechanisms, NPR and SESAM, are compared. It is found that the RIN and phase noise in both lasers (NPR laser and SESAM laser) are dominated by the noise converted from the pump RIN and thus, can be predicted with the measured noise conversion ratios and pump RIN. Both lasers show similar noise conversion ratios from the pump RIN to the laser RIN with a plateau in the low-offset frequency range and a rapid decay in the high-offset frequency range. For the noise conversion ratio from the pump RIN to the laser phase noise, the SESAM laser shows a much higher phase noise conversion ratio than the NPR laser due to the slow saturable absorber effect of the SESAM.

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