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Characterization of the RIN-to-Phase-Noise Conversion in the Mode-Locked Fiber Lasers

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Abstract: A method to characterize the noise conversion from the relative intensity noise to the phase noise in the mode-locked fiber lasers is proposed. The method is based on pump modulation and external modulation techniques.

OCIS codes: (140.4050) Mode-locked lasers; (270.2500) Fluctuations, relaxations, and noise;

Mode-locked lasers (MLLs) with low relative intensity noise (RIN) and timing phase noise attract intense interest for various applications including photonics analog-to-digital conversion (ADC) [1] and high-precision clock distribution [2-3], etc. In these applications, the phase noise (all the phase noises mentioned in this paper refer to the phase noise of the repetition frequency of the mode-locked lasers) of the mode-locked lasers is a key parameter to achieve high ENOB in photonic ADC or low-jitter time dissemination. On the other hand, it has been known that the RIN of pump leads to the RIN in the mode-locked lasers [4], and further couples to the phase noise in the lasers due to various mechanisms [5]. In this paper, we propose a method to characterize the RIN-to-phase-noise conversion of mode-locked lasers by applying pump modulation and external modulation simultaneously. Two fiber lasers at 1.5 μm mode locked by nonlinear polarization rotation (NPR) and semiconductor saturable absorber mirror (SESAM) are tested, respectively. It is found that, due to the effect of slow saturable absorber, the laser mode locked by SESAM has a stronger RIN-to-phase-noise conversion than the laser mode locked by NPR.

The experimental setup is shown in Fig.1 (a). The mode-locked laser is 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 of the mode-locked lasers through gain modulation effect [4]. After an isolator, the output of the mode-locked laser is fed into an acousto-optic modulator (AOM) for external modulation. The signal then goes to a 2 GHz photodetector (PD), a low pass filter (LPF) and a low-noise amplifier (LNA) to extract the fundamental repetition frequency for RIN and phase noise measurement by a signal source analyzer (SSA, R&S FSUP26). The purpose of using an external AOM is to evaluate the RIN-to-phase-noise conversion induced by the electrical detection system (PD and the LNA). When the pump modulation is applied and external modulation is off, the total RIN-to-phase-noise conversion (i.e., the noise conversion occurs both in the laser and in the electrical detection system) can be characterized. When the pump modulation is off and external modulation is on, the RIN-to-phase-noise conversion induced by the detection system is characterized. By comparing these two noise conversion ratios, the noise conversion in the mode-locked lasers can be obtained. Two lasers are tested. One is a SESAM based mode-locked fiber laser with an output power of -7 dBm, a center wavelength of 1567 nm and a 3-dB bandwidth of ~8 nm. The other one is a NPR based mode-locked fiber laser with an output power of 1.5 dBm, a center wavelength of 1559 nm and a 3-dB bandwidth of ~10 nm.

Fig.1 (a) Setup for characterization of RIN-to-phase-noise conversion in the mode-locked lasers; (b) Noise power spectral density of the relative intensity noise and phase noise for a SESAM mode-locked laser with 20 kHz external modulation by AOM

Fig.1 (b) shows the typical RIN and phase noise spectra when 20 kHz external modulation is applied for a SESAM based mode-locked laser. By comparing the spurious peaks at modulation frequency, the RIN-to-phase noise conversion ratio r can be obtained as follows:

$$r = S_{PH}(f_M) / S_{RIN}(f_M) \quad (1)$$

where $S_{PH}(f_M)$ and $S_{RIN}(f_M)$ are the values of phase noise spectrum and RIN spectrum at modulation frequency f_M . The RF spectra of the laser output are also shown in Fig.2 (a) when different modulation frequencies are applied on AOM. Very clear sidebands induced by the RIN can be seen. Three modulation frequencies 10 kHz, 20 kHz and 40 kHz are tested both for pump modulation and external modulation. The measured RIN-to-phase-noise conversion ratios are shown in Fig.2 (b) tested from two lasers mode-locked by NPR and SESAM, respectively. In our previous publication [6], we have shown that the RIN-to-phase-noise conversion ratio of the detection system (mainly from PD) is dependent on the input optical power. Therefore if the RIN-to-phase-noise conversion in the detection system is too strong, the original RIN-to-phase-noise conversion in the mode-locked lasers cannot be observed. This happens for our NPR based mode-locked laser when the signal after AOM (-1.5 dBm) is directly fed into the photodetection. By attenuating the output power of the NPR based mode-locked laser, the difference of RIN-to-phase-noise conversion ratios obtained by pump modulation and external modulation can be observed. Then the RIN-to-phase-noise conversion in the mode-locked laser can be obtained as follows:

$$r_{MLL} = r_{PUMP} - r_{AOM} \quad (2)$$

where r_{MLL} is the RIN-to-phase-noise conversion ratios of the mode-locked lasers and r_{PUMP} and r_{AOM} are the noise conversion ratios obtained by pump modulation and external modulation, respectively. The results are shown in Fig.2 (c). It can be seen that the noise conversion ratio is ~ 23 dB for SESAM based laser and ~ 30 dB for NPR based laser. The reason of higher noise conversion ratio in SESAM based mode-locked laser is probably due to the slow saturable absorption of SESAM which causes additional RIN-to-phase-noise conversion [5].

Fig.2 (a) RF spectra of the SESAM based laser output when different modulation frequencies are applied on AOM; (b) RIN-to-phase-noise conversion ratios obtained by comparing the RIN and phase noise spectra from the modulated NPR and SESAM mode-locked lasers; (c) RIN-to-phase-noise conversion ratio in the SESAM and NPR based mode-locked lasers

In conclusion, we have proposed a method to experimentally characterize the RIN-to-phase-noise conversion in the mode-locked lasers. Two fiber lasers mode locked by nonlinear polarization rotation and SESAM are tested, respectively. It is found that the noise conversion ratio of the SESAM based laser is 7 dB higher than that of the NPR based laser due to its property as a slow saturable absorber.

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