Low-timing-jitter Mode-locked Fiber Laser Based on Graphene Oxide PVA Thin Film as Saturable Absorber

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Abstract: We demonstrate a mode-locked fiber laser based on graphene oxide saturable absorber at 1550nm. The laser has a timing jitter of 53fs (100Hz to 100kHz). The contribution from the slow saturable absorber is also investigated.
OCIS codes: (160.4330) Nonlinear optical materials; (140.4050) Mode-locked lasers; (270.2500) Fluctuations, relaxations, and noise.

1. Introduction

Novel materials have attracted intense interest in recent years for their flexible functions as saturable absorbers (SAs) for mode-locked lasers. Different SA properties can be obtained by modifying the synthesis process. These materials include carbon nanotubes (CNTs), graphene, graphene oxide (GO), topological insulators and chalcogenides MoS_2 [1]. With these SAs, mode-locked lasers with different center wavelength, repetition rate, pulse energy have been demonstrated. Besides mode locking Q switched operation are reported, which indicates the versatile function of these novel material as SAs in the laser applications. Meanwhile, semiconductor saturable absorber mirror (SESAM), as another well-known SA, also exhibits excellent engineering flexibility for different SA parameters and has been proved a significant success in the mode locking operations.

In the applications such as frequency metrology, optical sampling and optical sensing, timing jitter is a key specification to achieve high precision. The timing jitter properties of mode-locked lasers have been developed and experimental investigated. However, it is still unclear how the SAs affect the laser timing jitter in the mode locking operation. In this paper, from the view of timing jitter of the mode-locked lasers, we investigate the noise properties of the fiber lasers operating at 1.5 μm mode locked by GO and compare it with a reference laser mode locked by SESAM (denoted as GO laser and SESAM laser, respectively). Both GO and SESAM share exactly the same linear laser cavity so that the influence of the laser cavity difference can be excluded in the comparison. It is found that timing phase noises of three lasers are all dominated by the noise coupled from the laser relative intensity noise (RIN) due to the slow saturable absorber (SSA) effect. Moreover, compared with the SESAM laser, the GO laser shows lower timing phase noise and timing jitter due to the smaller SA decay time and weaker SSA effect. 7-dB improvement in the timing phase noise spectrum and 45% timing jitter reduction is observed in the GO laser. This result indicates that SAs with smaller decay time have the potential to achieve low-noise mode locking operation.

2. Preparation of graphene oxide PVA thin film

For the ease of incorporation, GO is embedded in PVA thin films for the experiments. GO sheets are fabricated by ultrasonic agitation after chemical oxidation of graphite and then dispersed in water. PVA is then added to the GO solutions, heated to 90 degrees and further mixed with GO by ultrasonic process. The prepared solutions are then poured into polystyrene cells. Part of the solution is adhered to the polystyrene cell wall due to the high viscosity to the cell wall. After evaporation process, GO-PVA thin films are formed and attached to the cell wall, which can be easily stripped off by tweezers. These SA thin films are then cut into small pieces and placed on the fiber end for experimental use. The thickness of GO-PVA thin films is between 35 ~ 50 μm characterized by the scanning electron microscope (SEM). The whole process is summarized in Fig. 1.

The saturable absorption of the GO-PVA thin film is characterized by a homemade mode-locked laser operating at 1560 nm. GO-PVA thin film has a modulation depth of ~2% and a saturable fluence of 9.6 $\mu J/cm^2$. There is also ~20% non-saturable loss which is probably due to the PVA absorption and scattering loss. As a reference, the saturable absorption of the SESAM (BATOP SAM-1550-9-2ps) is also measured. It has a modulation depth of ~6% and a saturable fluence of 40.2 $\mu J/cm^2$.

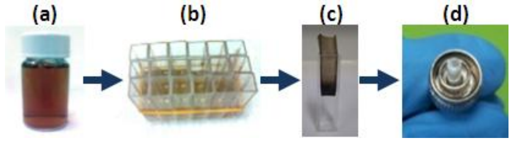

Fig. 1. Preparation of GO-PVA and CNT-PVA thin film SAs (a) GO and CNT dispersed solution; (b) polystyrene cells filled with solutions; (c) thin film stripped off the cell wall after heating and evaporation process; (d) small piece of thin film SA on a fiber end

3. Experiment and results

In order to compare the mode locking operation and the timing phase noise properties of different SAs, a fiber laser with linear cavity is designed as shown in Fig.2(a). The cavity consists of 25-cm Erbium-doped fiber with normal dispersion of -8 ps/km nm and ~135 cm standard single mode fiber with anomalous dispersion of 17 ps/km nm. The SAs are placed at the right side of the cavity. For GO-PVA thin film, it is embedded between a fiber end and a total reflection mirror coating (on another fiber end), shown in Fig.2(b). For SESAM, it is directly butt coupled to the fiber end. 976-nm pump is injected into the cavity through a 980/1550 wavelength division multiplexer (WDM) outside the cavity. Different SAs share the same laser cavity to exclude the influence of laser cavity difference and thus the laser output can actually reflect the role of these SAs on the mode locking operation and laser timing phase noise. The output of the laser is fed into the measurement equipment including optical spectrum analyzer (OSA), autocorrelator and signal source analyzer (R&S FSUP26) for the characterization of its optical and noise properties.

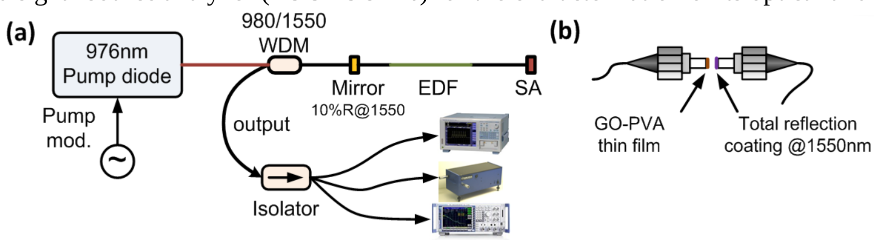

Fig. 2. (a) Laser design with linear cavity; (b) Placement of GO-PVA and CNT-PVA thin film saturable absorbers.

The GO laser has an output power of 820 μW, a center wavelength of 1561.8 nm, a 3-dB bandwidth of 4.7 nm, a pulse width of 735 fs and a repetition rate of 62.2 MHz. For comparison, the SESAM laser has an output power of 1.3 mW, a center wavelength of 1563.2 nm, a 3-dB bandwidth of 6.2 nm, a pulse width of 709 fs and a repetition rate of 62.2 MHz. Due to the higher saturation intensity and lower non-saturable loss, the SESAM laser has wider bandwidth and higher output power.

Then we compare the timing phase noise properties of two lasers. Pump modulation technique is applied in the measurement of noise conversion from the pump RIN to the laser noise [2]. The laser RIN and phase noise spectra are measured directly by the signal source analyzer. The results are shown in Fig.3 for the GO laser and Fig.4 for the SESAM laser.

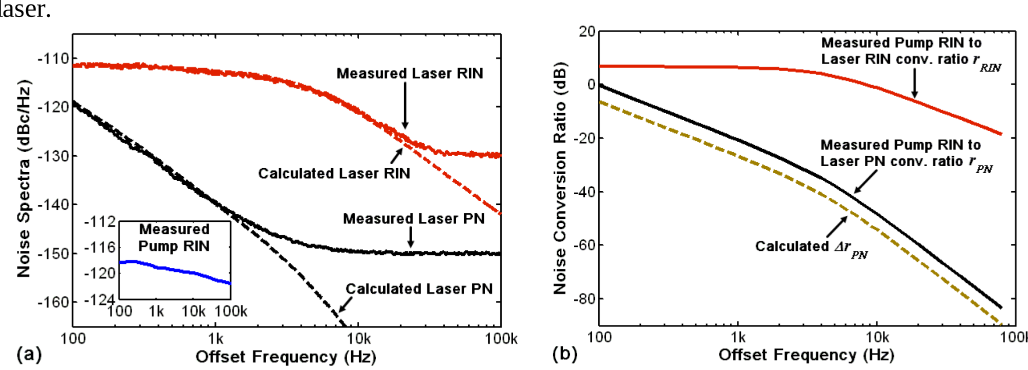

Fig.3. (a) Noise spectra of the GO laser. Inset: Pump RIN spectrum; (b) Measured noise conversion ratios and calculated excess phase noise conversion Δr_{PN} due to the slow saturable absorber effect.

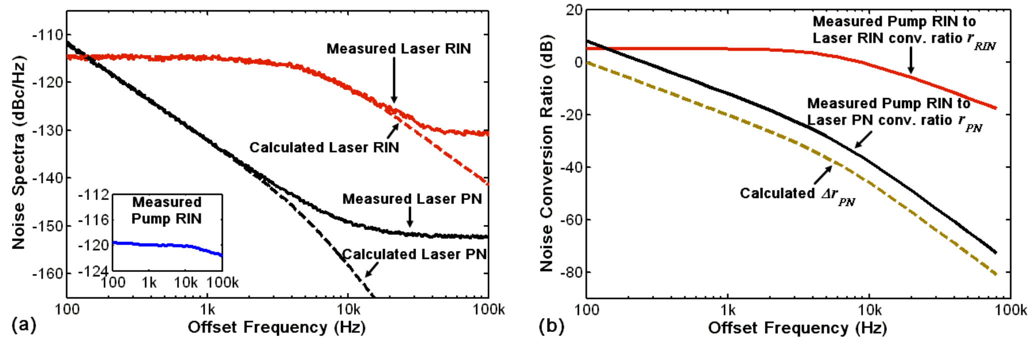

Fig.4. (a) Noise spectra of the SESAM laser. Inset: Pump RIN spectrum; (b) Measured noise conversion ratios and calculated excess phase noise conversion Δr_{PN} due to the slow saturable absorber effect

Very good agreement can be observed between the measured laser RIN/phase noise spectra and the calculated laser RIN/phase noise spectra for both GO and SESAM lasers, which confirms the validity of the noise conversion measurement. We have previously shown that SSA effect is the dominant effect causing laser RIN to laser phase noise coupling in a linear cavity [3]. Therefore we can use the theoretical model of SSA to estimate the excess phase noise conversion (Δr_{PN}) from the laser RIN (r_{RIN}), given by [4]

$$\Delta r_{PN}(f) = \left(\frac{f_R^2}{f} \frac{\partial \Delta t}{\partial s} s \right)^2 r_{RIN}(f)$$

where f_R is the repetition rate, f is the offset frequency, s is the saturation parameter defined as the ratio between input pulse energy and the SA saturation energy, Δt is the pulse temporal shift due to the SSA effect. The calculated is also shown in Fig.3(b) and Fig.4(b). Nearly identical trend can be found which indicates the SSA effect is indeed the dominant factor causing the laser timing phase noise in a linear-cavity laser. Due to the much faster decay time in the GO compared with the SESAM, the GO laser exhibits much lower timing phase noise and timing jitter. Compared with the SESAM laser, the GO laser has a phase noise conversion 8.6 dB lower at 1 kHz, a phase noise 7 dB lower at 1 kHz and a timing jitter 45% reduced integrated from 100 Hz to 100 kHz (See table I).

Table I Noise properties of the three lasers

	GO laser	SESAM laser
Phase noise conversion at 1kHz	-20.6 dB	-12.0 dB
Phase noise at 1kHz	-139 dBc/Hz	-132 dBc/Hz
Timing jitter (100Hz-100kHz)	52.9 fs	95.8 fs

4. Conclusions

In conclusion, the timing phase noise properties of mode-locked lasers are characterized and compared between GO and SESAM saturable absorbers. It is found that due to the smaller saturable absorber decay time and thus weaker excess phase noise conversion induced by the slow saturable absorber effect, the GO laser exhibits better timing phase noise and timing jitter compared with the SESAM laser. A timing phase noise reduction of 7 dB and a timing jitter reduction of 45% are achieved in the GO laser. Our finding suggests that saturable absorbers with fast decay time may have the potential for low-timing-phase-noise mode locking operation.

Acknowledgements

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