Generation of Coherent Multi-Wavelength Lights with Hundreds GHz Frequency Spacing from an Injected Fiber Laser with an Intracavity Tunable Micro-Ring Resonator

Yen-Chu Chen, Yi-Jang Hsu,* and Yinchieh Lai
Department of Photonics and Institute of Electro-Optical Engineering, College of Electrical and Computer Engineering, National Yang Ming Chiao Tung University, Hsinchu 30010, Taiwan. R.O.C
** Corresponding Author: pasha@nycu.edu.tw*

Abstract: Coherent multi-wavelength lights with 133 and 266 GHz frequency spacing are successfully generated from a new fiber laser scheme. The phase-locking characteristics are examined through the auto-correlation contrast as well as the down-converted beating linewidth.

1. Introduction

Coherent multi-wavelength lights with hundreds GHz frequency spacing are of particular interest for many applications including optical communication [1] and optical generation of millimeter-wave (MMW) signals [2]. Recently, the utilization of integrated micro-ring resonators for optical comb generation [3] and microwave-photonic applications [4] has also become very popular. The combination of micro-ring resonators and mode-locked fiber lasers has also opened up new possibilities for coherent multi-wavelength light generation with wide frequency spacing [5-6]. In particular, the combination of the CW optical injection technique and the intra-cavity micro-ring resonator utilized in our previous work [6] has exhibited great lasing performance improvement under the frequency spacing up to hundreds GHz. We have subsequently found that if the injection light frequency is either matched to one of the resonance frequencies of the micro-ring resonator or in the exact middle between two adjacent resonance frequencies of the micro-ring resonator, excellent phase-locking characteristics can be achieved. Since the frequency alignment is critical, the micro-ring resonator needs to be continuously tunable for reaching the optimum operation point. The achieved phase-locking characteristics also need to be investigated more. There have been many recent reports on the dynamic lasing properties and noise reduction characteristics in the presence of optical injection [7-9]. The case of improved phase-locking characteristics in our fiber laser system provides another example to demonstrate the usefulness of the optical injection technique. The details of our new results will be presented in the subsequent sections.

2. Experimental setup

The experimental setup of our laser system is illustrated in Fig.1(a). The fiber laser cavity is with an intra-cavity silicon micro-ring resonator (FSR = 266GHz) and subjected to external optical injection from a narrow linewidth CW tunable laser.

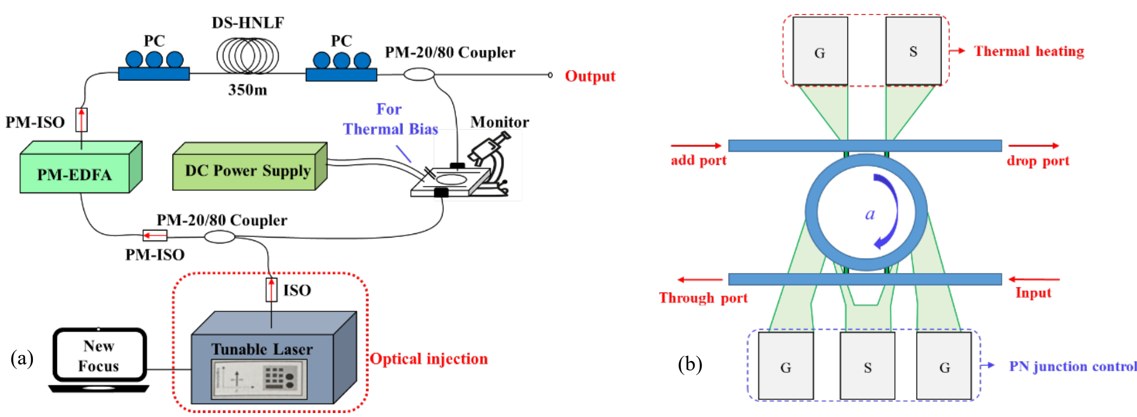

Fig 1. (a) Experimental setup of the fiber laser based on external optical injection and an intracavity silicon micro-ring resonator with tunability. (b) The picture of the silicon micro-ring resonator with the thermal and PN-junction tuning mechanisms.

The fiber cavity is mainly connected by the polarization maintaining fiber (PM fiber) except the dispersion-shifted high nonlinearity fiber (DS-HNLF) section and the corresponding polarization controllers. The length of this fiber section is 350 m in order to provide enough four wave mixing nonlinearity for spectral broadening. A high-power PM-type EDFA is used in the cavity to boost the inside optical power to the order of hundreds mW before entering the high nonlinearity fiber. The external injected light is coupled into the cavity right before the EDFA through a 80/20 PM-type fiber coupler. After passing through the high nonlinearity fiber, another PM-type 80/20 coupler is added, of which 20% is used for measurement and 80% is used for coupling into the micro-ring resonator. The isolator in the structure ensures that the laser light is transmitted in the single direction and also avoid unwanted impacts caused by reflection. Due to its discrete tuning resolution limit, the narrow linewidth CW tunable laser is only used for coarse alignment of the injection light frequency with the resonance frequency of the micro-ring resonator. Fig.1(b) shows the schematic structure of the silicon micro-ring resonator we use. The FSR of the ring resonator is 266GHz, corresponding to 2.16nm in terms of the wavelength. Both thermal and PN-junction tuning mechanisms are implemented for the fabricated device. In this work we mainly use the thermal tuning mechanism to continuously fine-tune the resonance frequency of the silicon micro-ring resonator to optimally match the injection frequency. The typical output power from the laser is around several tens mW.

3. Experiment results

The studied fiber laser can be passively mode-locked without the optical injection. However for this case the auto-correlation contrast is poor, indicating that the phase-locking characteristics are not good enough by merely resorting to the nonlinear four wave mixing effects in the laser cavity. When we turn on the external optical injection laser and carefully match the injection light frequency and the resonance frequency of the micro-ring resonator by thermally tuning the micro-ring resonator, the lasing performance is greatly improved. From the measured optical spectrum as in Fig. 2(a) and (d), we can determine the magnitudes of each lasing frequency components. By ideally assuming their phases are the same, we can calculate the ideal autocorrelation traces as in Fig. 2(c) and (f), which can be compared with the experimental autocorrelation traces as in Fig. 2(b) and (e). Here one important quality factor is the auto-correlation contrast, which is defined as in Eq.(1):

$$Autocorrelation\ contrast = \frac{peak-deep}{peak} \times 100\% \qquad (1)$$

The ideal fitting curve based on the measured optical spectrum should give the highest auto-correlation contrast. The phase-locking noises as well as phase chirps in the frequency domain will broaden the auto-correlation trace and thus reduce the contrast. Therefore one can regard the auto-correlation contrast as a quality factor for the phase-locking characteristics. In our experiments, we first tune the injection light frequency to match one of the resonance frequencies of the micro-ring resonator (i.e., the one next to the main peak of free lasing) and stable coherent multi-wavelength lights with 266 GHz (1 FSR) are successfully generated. We then tune the injection light frequency to be in the exact middle between the two adjacent peaks of the micro-ring resonator and stable coherent multi-wavelength lights with 133 GHz (0.5 FSR) are successfully generated. The results for both cases are shown in Fig. 2. One can see that the auto-correlation contrasts are close to the ideal theoretical fitting curves based on the optical spectra.

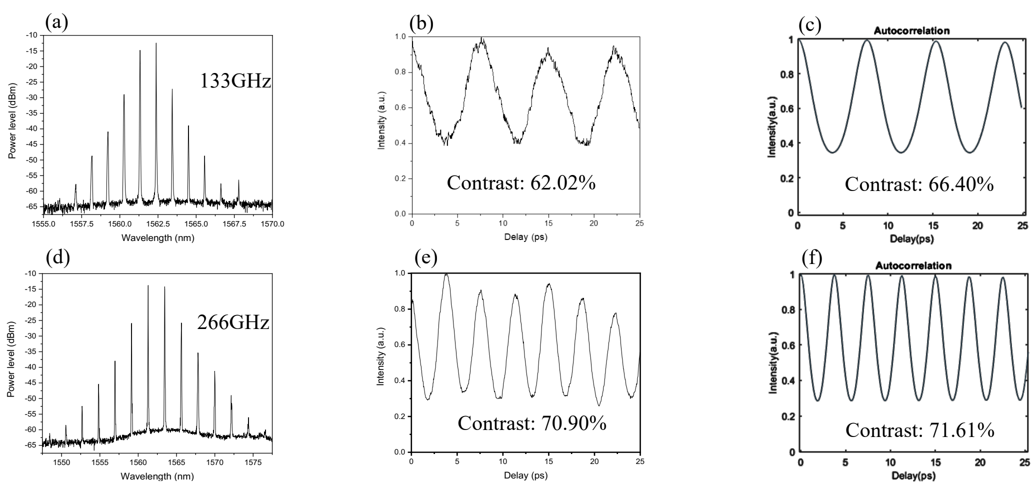

Fig 2. (a) The experimental optical spectrum and the corresponding autocorrelation traces from (b) experimental and (c) fitting results from optical spectrum for the 133GHz (0.5*FSR) case. (d)(e)(f) Results for the 266 GHz (1*FSR) case.

From the experiment, we have discovered that when the wavelength of the external optical injection is matched with the resonance wavelength, good autocorrelation results can be obtained. However, in order to more directly justify the phase-locking characteristics, we measure the down-converted beating spectrum of the two adjacent lasing peaks by using a Fabry-Perot EO modulator operated at 25 GHz to generate the down-converted side-bands. Fig 3(a) shows the

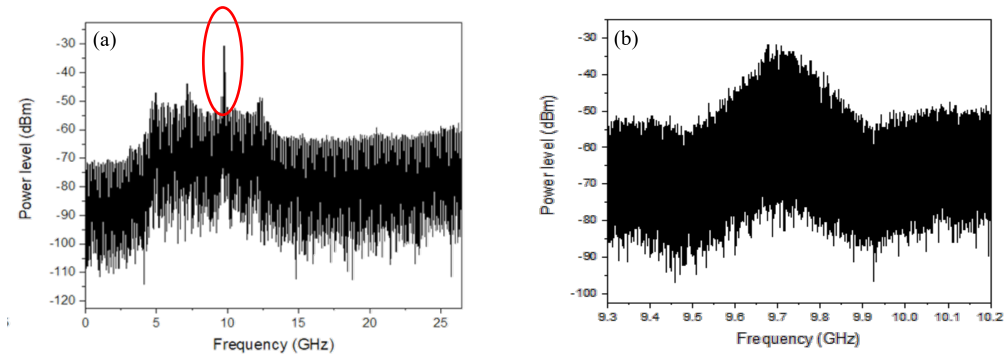

Fig 3. (a) Down-converted RF beating spectrum of the adjacent lasing peaks for the 266 GHz (1 FSR) case. (b) The zoom-in spectrum to show that the beating linewidth is around 16.6MHz.

results of the down-converted RF beating spectrum when the tunable laser is injected at the resonance peak. There is a very sharp peak around 9.7GHz, and the beating linewidth shown in the Fig 3(b) is around 16.6MHz, indicating that the laser has good phase-locking characteristics. It should also be noted that, in Fig 3(a), the side peaks with 2.5GHz spacing are not from the fiber laser, but due to the Fabry-Perot EO modulator for down conversion measurement, which has a FSR of 2.5GHz. To have the best performance, the micro-ring resonator should also be carefully fine-tuned to match with the injection light frequency.

4. Conclusion

We have successfully demonstrated that coherent multi-wavelength lights with 133 and 266 GHz frequency spacing can be generated from an optically-injected fiber laser with an intra-cavity silicon micro-ring resonator (FSR=266GHz). The phase-locking characteristics have been carefully examined through the auto-correlation contrast as well as the down-converted beating linewidth. The auto-correlation contrast is close to the ideal theoretical fitting curve based on the measured optical spectrum and the down-converted beating linewidth is in the order of 16.6 MHz, both indicating excellent phase-locking characteristics have been achieved. Most interestingly, the results for the 133 GHz case indicate that optical injection at a fractional frequency with respect to the resonance frequencies of the micro-ring resonator may still be able to produce excellent phase-locking results, which can provide more frequency spacing switchability from the same laser. The achieved beating linewidth should also be able to get improved by using a micro-ring resonator with higher Q values. Thus the scheme should be of excellent application potentials for optical communication and microwave photonics.

5. References

[1] K. Zeb, *et al.*, "A quantum-dash dual-wavelength DFB laser for optical millimeter-wave radio-over-fiber systems," Optical Fiber Communication Conference (OFC), 2021 OSA Technical Digest (Optical Society of America, 2021), paper W1J.5.

[2] L. Fan, *et al.*, "High-purity 60GHz band millimeter-wave generation based on optically injected semiconductor laser under subharmonic microwave modulation," Opt. Express **24**, 18252–18265 (2016).

[3] M. Zhang, *et al.*, "Broadband electro-optic frequency comb generation in a lithium niobate microring resonator," Nature 5**68**, 373–377 (2019).

[4] P. T. Do, *et al.*, "Wideband tunable microwave signal generation in a silicon-micro-ring-based optoelectronic oscillator," Sci. Rep. **10**, 6982 (2020).

[5] S. S. Jyu, *et al*, "250-GHz passive harmonic mode-locked Er-doped fiber laser by dissipative four-wave mixing with silicon-based micro-ring," IEEE Photonics Journal **5**, 1502107 (2013).

[6] P. H. Yen, *et al*, "Tunable optical frequency comb generation based on a micro-ring assisted fiber laser with optical injection-locking," Frontiers in Optics - Proceedings Frontiers in Optics + Laser Science APS/DLS (Optical Society of America, 2019), paper FTh3B.4.

[7] V. Billault *et al.*, "Experimental investigation on dynamic properties and noise reduction in actively mode-locked lasers by external CW optical injection," J. Light. Technol., **39**, 2924-2930 (2021)

[8] T. T. Yu, *et al.*, "High-precision passive stabilization of repetition rate for a mode-locked fiber laser based on optical pulse injection," Optics Express, **29**, 20930-20940(2021).

[9] A. S. Voloshin *et al.*, "Dynamics of soliton self-injection locking in optical microresonators," Nat. Commun. **12**, 235 (2021)