Tuning power spectrum of semiconductor and intracavity-etalon based modelocked laser via detuning

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A report is presented on the tuning of the frequency envelope of a broadband comb source generated from a semiconductor-based modelocked ring laser with an intracavity high finesse Fabry-Perot etalon (FPE). By deliberately adjusting the matching condition between FPE transmission peaks and lasing optical comb frequencies, ~ 7 nm tuning of more than 200 optical frequency comb lines spaced by 10 GHz is achieved.

Introduction: Wideband, flat optical frequency combs at relatively high repetition rates are very attractive for many applications, such as high capacity WDM communications [1], arbitrary waveform generation [2], optical code division multiple access [3], microwave photonic filters [4] etc. It is known that a semiconductor-based modelocked ring laser (SB-MLL) with an intracavity Fabry-Perot etalon (FPE) can produce such combs [5]. For stable modelocked operation, the SB-MLL with a FPE should satisfy the following conditions [5]: (i) the modelocked pulse repetition rate equals an integer multiple of the laser cavity resonance frequency spacing, (ii) the free spectral range (FSR) of the FPE exactly equals the pulse repetition rate, and (iii) all the optical comb frequencies match with the FPE transmission peaks. Significant efforts have been focused on locking optical comb frequencies to the FPE transmission (TX) peaks (in a sense, conditions (i) and (ii)) based on a subset of condition (iii). Techniques for precise FPE-FSR measurement [5] and very fine cavity length control [5] have been developed. With perfect frequency matching, the gains of individual modes are not affected by the FPE-TX curve and depend only on the cavity length of the semiconductor optical amplifier (SOA) used as a gain medium [5]. Therefore, the SB-MLL operates at the gain peak of the SOA. In practice, perfect matching may not be possible, and/or tuning of the laser away from the SOA gain peak may be desired.

Experiments: Our experimental setup is shown in Fig. 1. The cavity length of the SB-MLL, including 0.8 m-long dispersion compensating fibre, is 7.6 m, corresponding to a 26 MHz cavity resonance frequency (fr). The FPE has 15 mm air-spaced concave (50 cm radius) – flat mirrors with 0.01 ppm/K temperature dependence. The free spectral range (FSR: FFSR) and finesse of the FPE are 9.99575 and 270 GHz, respectively, so that the neighbouring cavity resonance modes experience > 4 dB excess loss compared to modes aligned with the FPE transmission peaks. The mode field matching of the FPE is implemented using a pair of commercially available, fibre pigtailed focusers. The overall fibre-to-fibre loss is 1.5 dB. For active modelocking of the laser, the intensity modulator (IM) is driven by a low-noise oscillator (Agilent E8257D) around the FSR of the FPE. To obtain stable and broadband comb lines, we deliberately match the lasing optical comb frequencies and FPE-TX peaks using a piezoelectric translator (PZT) to finely translate the FPE focusing lens. This tunes the cavity length over a wavelength scale. To maintain the matching condition, we use a feedback loop similar to that applied in other works [5]. Part of the output is phase modulated at 377 MHz, and re-injected to the FPE through the polarising beam splitter (PBS). The reflected probe beam from the FPE is separated by the PBS, and detected by a photodetector to be mixed with a portion of the phase modulator (PM) drive signal. The output characteristics are measured by a 50 GHz sampling scope and an RF spectrum analyser coupled with a fast photodetector and by an optical spectrum analyser.

Fig. 1 Experimental setup (abbreviations can be found in text)

Large detuning between the optical frequencies and FPE-TX peaks induces destabilisation of the modelocking due to high loss [5]. However, we have found that introducing a small detuning enables controllable translation of the frequency envelope of the modelocked laser output. Fig. 2 shows the basic concept of the lasing comb line selection based on detuning. Here, we assume that the gain spectrum of the SOA is sufficiently broad. Let the optical comb frequency spacing, determined by the IM modulation frequency, differ (here, be smaller) slightly (say by a few tens of kHz) from the FSR of the FPE, as schematically shown by the solid arrows in Fig. 2. Then, the alignments (with respect to the FPE transmission peaks) of various cavity resonances selected by the FPE differ, which introduces frequency dependent loss. If we assume that the optical frequencies belonging to a certain supermode are matched well with the FPE-TX peaks, then modes belonging to that supermode are selected for lasing around the minimum of the frequency dependent loss. The lines lasing are designated ‘mode group 1’ in Fig. 2. Now, we can shift the individual optical frequencies by changing the cavity length slightly; δν = νfΔL/λ, where δν is the optical frequency shift, ΔL the cavity length change and λ the optical wavelength. The negative sign shows the blue shift when the cavity length decreases. Here, we assume a blue shift, as shown by the dotted arrows in Fig. 2. This shift in the frequencies of the individual lines interacts with the frequency-dependent loss mechanism mentioned above to yield a much larger shift in the net gain spectrum. As a result, the envelope of the generated comb shifts in frequency by an amount that may be large compared with the comb spacing. The new set of laser modes is designated ‘mode group 2’ in Fig. 2.

Fig. 2 Lasing comb line selection by optical frequency shift from FPE-TX peaks

Small amount of frequency shift induces a much larger shift of effective net gain peak as determined by overlap between laser lines and FPE-TX curve

By increasing the proportional and integration (PI) controller offset voltage for the PZT control in Fig. 1, we can increase the laser cavity length. This induces a red shift of the optical frequencies, resulting in a much larger shift in the centre of the comb gain spectrum, as discussed. Fig. 3 shows the wavelength tuning results obtained by the PI controller offset voltage increase. We achieved ~ 7 nm tuning by changing the cavity length by less than 1/10th of the wavelength. In any case, we obtain a smooth and flat comb spectrum over a 10 dB bandwidth of 16 nm, covering more than 200 optical frequency comb lines with 10 GHz spacing. From the wavelength tuning (Δλ) data, we can predict the difference (δν) between the modelocking frequency and the FPE-FSR, δν = νfΔL/λ, where λ represents the frequency tuning corresponding to Δλ. The predicted value of δν ~ 20 kHz agrees roughly with the initially set value.
Fig. 3 Wavelength tuning by cavity length control, showing ~7 nm tuning of more than 200 comb lines spaced 10 GHz.

Fig. 4 shows a typical RF spectrum around 10 GHz of the optoelectronic converted signal of a modelocked output. The RF spectrum shows that the supermode beating noise near 26 MHz is completely suppressed below -120 dBc/Hz (resolution bandwidth = 1 kHz). Note that the output noise level (blue line) approaches that of the oscillator for IM modulation which is depicted by the red line. Thus, as shown in the inset of Fig. 3, the low-frequency noise of the oscillator appears to be transferred onto the modelocked output. Measured typical phase noise over the 10 Hz to 1 MHz interval was ~6 × 10^{-3} rad, corresponding to an ~95 fs timing jitter. Non-averaged sampling scope (bandwidth: 50 GHz) traces, shown in Fig. 5, also confirm very stable pulse train generation.

Fig. 4 Typical RF spectrum of optoelectronic converted modelocked output (blue line)

For comparison, corresponding RF spectrum of 10 GHz oscillator is shown by red line. Inset: Detailed spectra around low-frequency region

Fig. 5 Non-averaged sampling scope (bandwidth: 50 GHz) traces of typical modelocked output showing very stable pulse train generation

Conclusion: We have discussed tuning of the frequency comb from a SB-MLL with an intracavity FPE as a result of the interaction between small, cavity length induced changes in the individual frequencies and small repetition rate detuning. A small shift in the frequency of individual comb lines induces a much larger shift in the centre frequency of the comb envelope. By deliberately adjusting the laser cavity length (i.e. optical frequencies), we achieve ~7 nm tuning of more than 200 optical frequency comb lines spaced by 10 GHz. The RF spectra, sampling scope traces and phase noises confirm very stable modelocked outputs at variously tuned conditions. The relationship between tuning of the comb envelope and slight detuning of the repetition rate and cavity length may also provide a new principle applicable to measuring the FSR of an FPE.

References

Note: Any opinion, findings or conclusions or recommendations expressed in this Letter are those of the authors and do not necessarily reflect the views of the sponsors.

Acknowledgments: This work was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2012-0008390) and by the Naval Postgraduate School under grant N00244-09-1-0068 under the National Security Science and Engineering Faculty Fellowship program. The authors thank P.J. Delfyett and his group members at CREOL for helpful discussions.

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