# 40 GHz Mode-Locked SOA Fiber Ring Laser with 20 nm Tuning Range

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**Summary**

High repetition rate, picosecond laser sources are key elements for WDM/OTDM transmission, switching and photonic network systems. Active mode-locking is one of the main techniques for the generation of transform limited, high repetition rate, short pulse trains. It is particularly appropriate for applications that require precise timing synchronization between the optical and electrical signals such as digital all-optical logic [1]. The majority of tunable, actively mode-locked laser sources demonstrated so far at 1.5 μm have used erbium doped fiber for gain with lithium niobate modulators to mode-lock and nonlinear compression techniques for pulse shortening [2]. These sources have demonstrated impressive performance but they are relatively complex requiring special attention to ensure stability against environmental perturbations due to their long and polarization dependent cavities. Monolithic laser diodes have also been shown to mode-lock at high repetition rates over broad tuning ranges [3] and they have been used for short pulse generation with injection mode-locking [4]. These however are research devices and they are not widely available.

Recently, we have demonstrated a new simple technique for the generation of high repetition rate pulse trains [5]. The totally fiber pigtailed laser oscillator uses a single semiconductor optical amplifier (SOA) as gain and modulation element. The source is mode-locked using an external optical pulse train provided by a gain switched semiconductor diode which periodically saturates the gain of the SOA. SOAs have been used widely as modulators [6,7] and their performance in high frequency electrical modulation has been studied [8] but in the present configuration the gain modulation in the SOA is obtained optically, raising significantly the high frequency modulation capability of the device. Key features of the source are that it can provide nearly transform limited 4.3 ps pulses over 16 nm tuning range and that it is nearly environmentally insensitive. Furthermore, by using intra-cavity repetition frequency multiplication of the optical pulse train [9], it was possible to mode-lock the source at 20 GHz, 4 times the repetition rate of the external gain switched signal used to modulate the SOA, dispensing of high frequency microwave drive circuits. Finally, the source is simple to build and may be constructed entirely from commercially available standard fiber pigtailed components.

In this communication we present an extension of our previous work, whereby by increasing the intra-cavity energy of the mode-locked pulse train it has been possible to reduce the pulsewidth to 2.5 ps and to increase the operating repetition rate of the source to 40 GHz. The increase of the intra-cavity energy of the mode-locked pulse results in deeper saturation of the SOA as well as in chirp increase due to self phase modulation and consequently in shorter pulses. In this configuration the source is shown to possess 20 nm tuning range around 1544 nm.

Figure 1 shows the experimental layout. The laser ring cavity was constructed entirely from fiber-pigtailed components. Gain was provided from a 500 μm, bulk InGaAsP/InP ridge waveguide SOA with $10^{\circ}$ angled and antireflection coated facets. The SOA had a peak small signal gain of 23 dB at 1535 nm when driven with 250 mA and a recovery time of 400 ps.

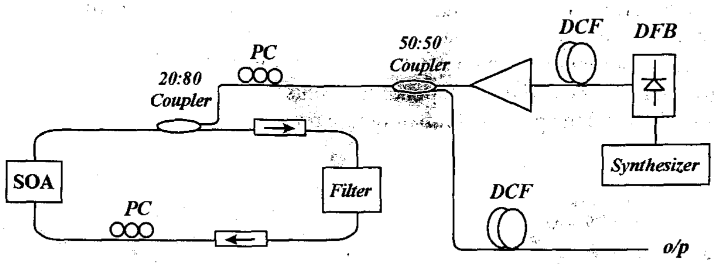
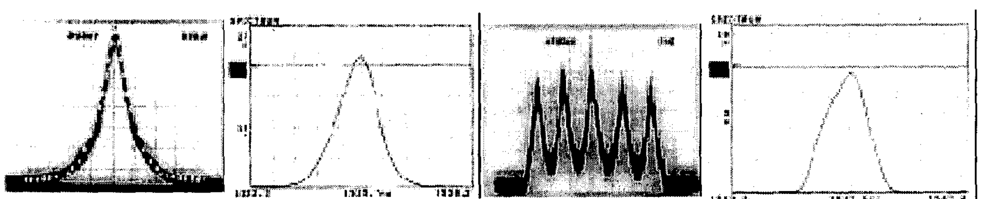



Fig. 1 Experimental setup

Faraday isolators were used in the two ports of the SOA to ensure unidirectional mode-locked oscillation, to prevent the externally introduced signal from circulating in the cavity and to stop spurious cavity reflections. Immediately after the SOA a 20:80 fused optical fiber coupler was used to insert the pulsed external signal and to tap the mode-locked pulse train. A tunable filter with 5 nm bandwidth was also used for wavelength selection. A polarization controller was placed in the input port of the SOA to adjust the polarization state of the optical signal into the SOA and to optimize the mode-locked pulses. The total length of the ring cavity was 24.25 m corresponding to a fundamental frequency of 7.98 MHz whilst the total linear loss of the cavity was 9 dB. The externally introduced pulses were generated from a 5 GHz gain switched DFB operating at 1548.5 nm. The gain switched pulses were compressed with a dispersion compensation fiber (DCF) to 7.5 ps before being amplified in an EDFA and injected into the ring cavity through the 20:80 coupler. A polarization controller was also introduced before injection of the external signal into the cavity for optimum adjustment of the polarization state of the external pulses.

In the absence of the external pulse train, the fiber ring laser runs CW providing approximately 100 μW output power for 110 mA SOA drive current and tunes between 1523 nm and 1576 nm. With the DFB gain switched at around 5 GHz on a cavity harmonic and the EDFA adjusted to provide up to 1.7 mW average power in the ring cavity, the laser mode-locks at the same repetition frequency. By increasing the frequency of the signal generator away from this value by $\delta f_{ext}=f_{ring}/n$, it is possible to obtain multiplication by a factor of n in the repetition frequency of the output pulse train from the fiber ring laser. In this relation n is an integer, $\delta f_{ext}$ is the change in the drive frequency of the external pulse train and $f_{ring}$ is the fundamental frequency of the ring oscillator. In the present experiment it was possible to multiply the repetition frequency of the external signal by up to a factor of 8 and obtain up to 40 GHz from the fiber ring source.



(a) (b) (c) (d)

Fig. 2 (a) Second harmonic autocorrelation trace obtained at 20 GHz. The time base corresponds to 4.15 ps and (b) the optical spectrum. (c) Second harmonic autocorrelation trace obtained at 40 GHz. The time base corresponds to 16.6 ps and (d) the optical spectrum.

With this cavity arrangement it was possible to obtain 6 ps pulses directly from the laser oscillator which, however, were not transform limited due to the frequency chirp from the saturation of the SOA. In order to compensate for this, a DCF with total dispersion of −11.4 ps/nm was placed at its output. Figs. 2(a) and

(b) show the second harmonic autocorrelation trace after compression and the optical spectrum of the output pulse train at 20 GHz. The trace has been fitted with the autocorrelation of a squared hyperbolic secant profile of 2.5 ps pulsewidth (white dots) and shows a good fit. The pulsewidth-bandwidth product is 0.34. Figs. 2(c) and (d) show the corresponding results for the 40 GHz pulse train. In that case the pulsewidth is also 2.5 ps and the pulsewidth-bandwidth product is 0.35.

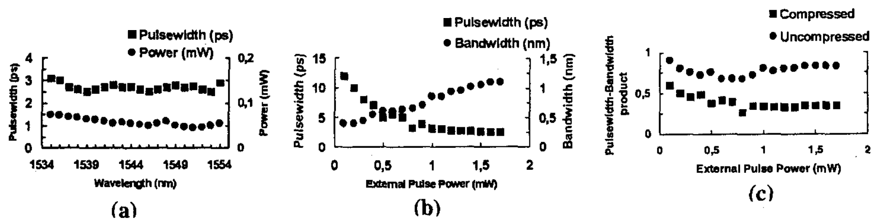



Fig. 3 (a) Tuning curve for pulsewidth and average power of mode-locked pulses at 40 GHz, (b) Variation of the pulsewidth and bandwidth of the mode-locked pulses against the external pulse power, (c) Pulsewidth-bandwidth product of the uncompressed and the compressed mode-locked pulses at 40 GHz.

Fig. 3(a) shows the change of the pulsewidth and the average optical power of the mode-locked pulses versus wavelength when the source is operated at 40 GHz and indicates nearly constant pulse duration across a 20 nm tuning range. It was observed that by increasing the pulse energy of the external pulses and increasing the current of the SOA, it is possible to obtain shorter pulses from the cavity. This is a consequence of the stronger gain saturation imposed on the SOA by the external pulses and at the same time the reduction of the recovery time of the SOA due to the increase in the drive current. This results in a sharper gain modulating function which correspondingly results in shorter pulses. Fig. 3(b) shows the variation of the pulsewidth after compression with a DCF and the bandwidth of the mode-locked pulses as the average power from the external signal is increased for 40 GHz operation. The extra frequency chirp results primarily from the saturation of the SOA as the power of the external pulses increases. Fig 3(c) shows the corresponding pulsewidth-bandwidth product before and after compression from the DCF. The figure indicates that the output pulses are approximately transform limited for an average power of the external pulses between 1.2 and 1.7 mW and that they are nearly transform limited.

In conclusion we have shown a simple, tunable, high repetition rate, short pulse fiber ring laser, mode-locked with the saturation of its SOA with a 5 GHz DFB laser. It can provide 2.5 ps pulse trains at up to 40 GHz over 20 nm tuning range across which its output is approximately constant. The source may be constructed from commercially available components and may form a platform to build a mode-locked multi-wavelength source or optical clock recovery circuit.

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