Repetition rate continuously tunable 10-GHz picosecond mode-locked fiber ring laser

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A couple of simple-structure phase modulators were used in active mode-locked fiber laser to implement repetition rate continuous tuning. The laser produces pulse as short as 5.7 ps whose repetition rate tuning can cover the spacing of the adjoining order mode-locking frequencies.

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Stable optical short pulse sources with a high repletion rate are very important for wavelength division multiplexing/optical time domain multiplexing (WDM/OTDM) transmission and optical networks systems. Active mode-locking is one of the main techniques, which shows many potential advantages over other techniques such as passive mode-locking. Several impressed results for picosecond-class pulse width, high repetition rate, and long-term stability have been reported for actively mode-locked erbium fiber lasers using lithium niobate modulators[1,2]. However, these techniques are relatively complex for paying special attention to the environmental perturbations due to their long and polarization dependent cavities. Considerable researches have shown that a sinusoidally driven electroabsorption modulator (EAM) incorporating with semiconductor optical amplifier (SOA) is an ideal source for systems applications due to its simplicity and low-cost[3,4]. In order to apply this technique to the synchronous digital hierarchy (SDH) systems, the repetition rate and the wavelength should be precisely tunable. Impressively, very high quality pulse whose wavelength is tunable over a wide band, while its repetition rate is fixed has been generated[5,6]. However, to meet the requirement of the foward-error-correcting (FEC) in the OC-192 systems, the wide range continuous tuning of the repetition rate is also important and necessary. In order to realize the wide range repetition rate tuning, the phase modulators should have a very wide tuning range of the fiber length.

In this paper, we demonstrate a simple and robust 1.5-μm 10-GHz mode-locked fiber laser using a monolithic device incorporating both EAM and SOA. Two simple-structure phase modulators connected in the fiber ring promise a wide tunability of both the wavelength and the repetition rate that can cover the spacing of the adjoining orders mode-locking frequencies.

The schematic of mode-locked laser is depicted in Fig. 1(a). It was composed entirely from fiber-pigtailed devices. A major fraction of the light is exported by a 20/80 coupler and the output chirped pulses that originate from self-phase modulation (SPM) due to the SOA gain saturation were compressed by a 160-m-long conventional 1.31-μm zero-dispersion fiber[7]. A 30-nm tunable band-pass filter with a full width at half-maximum (FWHM) of 2.9 nm was included to control the lasing wavelength conveniently. The phase modulator (PM) consists of a metal ring with a small cleft and a micrometer as shown in Fig. 1(b). Each phase modulator's metal ring is wound by about 40 turns of fibers. The micrometer is used to adjust the width of the cleft slightly in order to change the length of the fiber ring precisely. The mechanism of the repetition rate tuning can be summarized as follows: the repetition rate $f_{\text{repetition}} = N\frac{c}{nL}$, where N represents the mode-locking order, n is the refractive index, and L is the length of the cavity. The repetition rate can be adjusted precisely by changing L through adjusting the cleft of the phase modulators. For proper L and modulator design, the tunable range can cover the adjoining positive integer N, i.e., the repetition rate can reach hundreds of MHz. The diameter of the metal ring is about 69.5 mm. The structures of two phase modulators in tandem

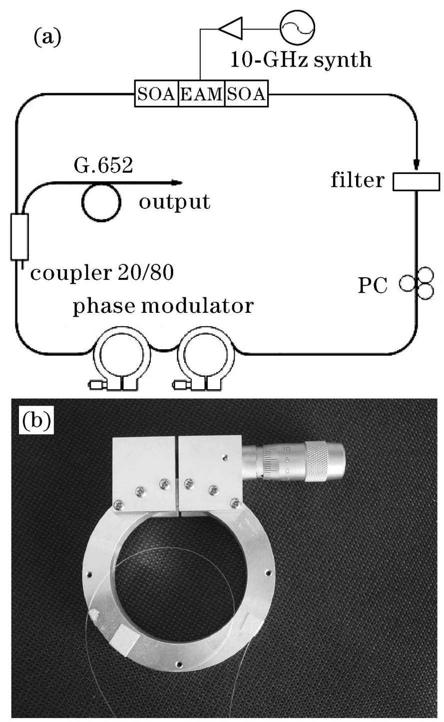

Fig. 1. Laser cavity schematic figure (a) and phase modulator (b). PC: polarization controller.

guarantee a wide range and a high resolution tuning of the fiber length. Most of the laser cavities are made up of standard non-PM components and fibers except for the input pigtail of the monolithic device.

The cavity was measured to have a fundamental mode frequency of 6.063 MHz, corresponding to an overall length of $\sim$ 33.7 m. All measurements were taken with the monolithic device's thermoelectric cooler set to about 20 °C.

The output pulses were stable when the SOAs were driven with currents of 86 and 85 mA respectively and the EAM biased at a direct current (DC) voltage of -3.0 V with a radio-frequency (RF) signal of $\sim$ 5 V peak-to-peak (into 50 Ω). When the filter was tuned to 1563 nm and the two phase modulators were both relax, the mode-locked laser's autocorrelation (Femtochrome Research Inc.FR-103PD Two Photon Conductivity Autocorrelator) and optical spectrum were obtained as shown in Fig. 2. The asymmetric structure of the autocorrelation trace may be brought by the second harmonic generation (SHG) autocorrelator. Assuming a Gaussian pulse shape, the output pulses were found to be $\sim$ 6.2-ps-long with a 0.6-nm FWHM width, corresponding to a time-bandwidth (TBW) product of 0.46 which indicated that the pulses were closely transform-limited. After encapsulating the whole system into a constant temperature box, the laser mode-locking instability was not observed for 8 hours without cavity-length feedback control. The long-term stability is mainly due to stabilization of the state of polarization resulting from the SOA input PM pigtail, the polarization controller, and the short cavity length. Furthermore, the sharp nonlinear pulse carving of the electroabsorption and the fast gain dynamics of the SOA have important contributions to the long-term stability[5].

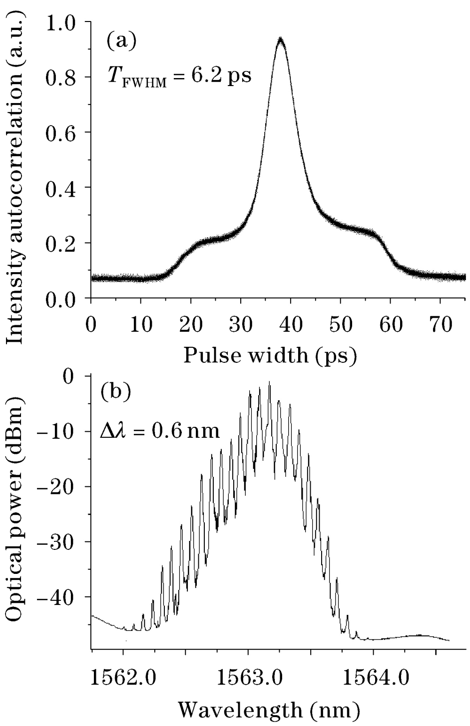

Fig. 2. Measured autocorrelation trace (a) and optical spectrum of mode-locked laser (b).

When we fixed the wavelength centered at 1558 nm, similar high quality pulses were found while the repetition rate covering the spacing of the adjoining orders mode-locking frequencies which predicts that the tuning range can be up to hundreds of MHz (because the laser can be mode-locked at different orders). In Fig. 3(a), the head and the rear frequency points are the adjoining natural mode-locking frequencies and the stable pulses can be generated at different repetition rates between the two frequency points. The pulse width (the minimum pulse width is $\sim$ 5.7 ps) and the TBW products are shown in Fig. 3(a). The TBW products of about 0.6 indicated that the pulses were not transform-limited (the chirp pulses resulted from the SOA amplifier and the short cavity length cannot compensate them). The transform-limited pulses could be obtained by external nonlinear fiber compression. The wavelengths nearly remained invariable through the entire repetition rate adjustment process (Fig. 3(b)).

The frequencies in Fig. 3(a) have an interval of 500 kHz which means the resolution of the two phase modulators in tandem can be at least 100 kHz, responding to a $\sim$ 0.01-mm micrometer tuning. This fiber ring laser would be competent for the OC-192 system if further improvement was introduced such as constructing the cavity with polarization-maintaining fiber and replacing the micrometers with micro electro mechanical (MEM) devices.

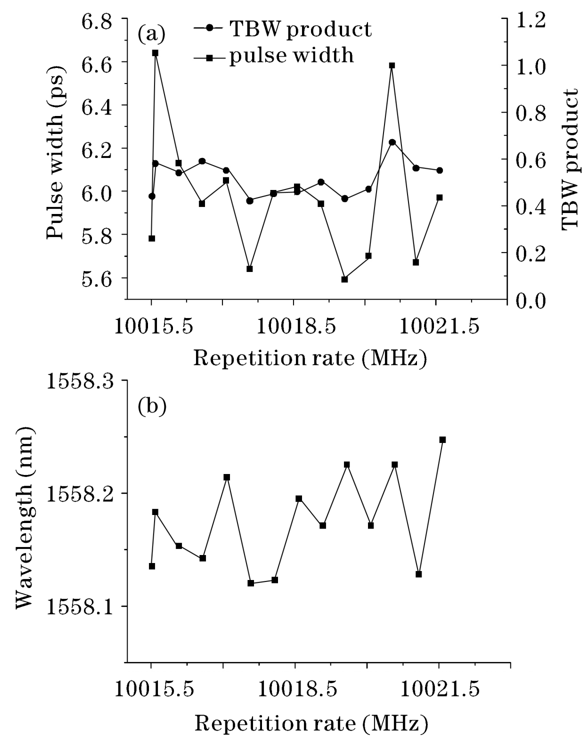

Fig. 3. (a) The pulsewidth and the TBW product of the laser pulse while the repetition rate covering the spacing of the adjoining natural mode-locking frequencies. The first and the last frequency points are the 1652- and 1653-order mode-locking frequency respectively when the modulators are both relax. (b) The center wavelength nearly keeps unchangeable while the repetition rate tuning.

In conclusion, we succeeded in obtaining a stable pulse train with a wide rang repetition rate and wavelength tunable actively mode-locked fiber laser by introducing two simple-structure phase modulators. The pulse width was as short as 5.7 ps at 1558 nm, which would be competent as the transmitter in OC-192 system after time domain multiplexing (TDM).

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