Hybrid-type passively and actively modelocked fiber laser with a DI-NOLM

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Received October 28, 2002

We present a 10-GHz hybrid actively and passively mode-locked fiber ring laser with a dispersion imbalanced nonlinear loop mirror (DI-NOLM), whose nonlinear switching characteristic can make the laser operate at additive pulse modelocking (APM) mode or additive pulse limiting (APL) mode. When the laser operated at APM, 5.45 ps of transform-limited pulse series were obtained. When the laser was biased at APL region, supermode noise was suppressed and the laser output was more stable.

OCIS codes: 140.4050, 140.3510, 060.4370, 320.5540.

Ultrashort pulse generation from modelocked erbium-doped fiber ring lasers is attractive optical sources for high bit rates optical time-division-multiplexing (OTDM) communication transmission. Actively modelocked fiber ring lasers are able to generate high repetition rates synchronous pulse train, but the pulse widths are much longer. A passively modelocked fiber laser (MFL) can generate short pulses of a few hundred femtoseconds[1-4], but it has the disadvantages of low repetition rates and poor synchronization. Thus, hybrid-type passively and actively MFL can share the merits of each scheme. S. Li *et al.* obtained 11.08-GHz, 7.1-ps transform-limited pulses from an '8' geometry fiber laser[5]. In another experiment, by adopting a Nonlinear amplification loop mirror (NALM) passively and actively MFL was achieved[6].

In this paper, we present a 10-GHz actively mode-locked fiber ring laser with a dispersion imbalanced nonlinear loop mirror (DI-NOLM). By tuning the modulation frequency, the average power in the cavity and the polarization of the pulse in the DI-NOLM, the laser can operate simultaneously in passive modelocking and active modelocking. When the hybrid type MFL was biased at additive pulse limiting (APL) region, supermode noise was suppressed and the laser output was more stable against amplitude fluctuations. When the laser was biased at additive pulse modelocking (APM), 5.45 ps of transform-limited pulse series were obtained.

The DI-NOLM acts as a nonlinear switching element in the MFL cavity and it is constructed by two segments of fiber, one with high anomalous dispersion, D_1, and another segment with much lower amount of dispersion, $D_2 \approx 0$, as depicted in Fig. 1(a). When an initial pulse enters the DI-NOLM, it is split into two equal counterpropagating fields. In the clockwise (CW) propagating direction inside the loop, the incident pulse disperses quickly due to the large D_1 of standard mode fiber (SMF) and then remains broad in the dispersion shift fiber (DSF) segment. The pulse peak power decreases along this process and little nonlinear phase shift $\Delta\varphi_{\mathrm{CW}}$ is induced, as depicted in Fig. 1(b). While the counterclockwise (CCW) pulse remains short in the DSF, where the fiber is almost dispersionless, and hence acquires relatively larger nonlinear phase shift $\Delta\varphi_{\mathrm{CCW}}$. When the CW and CCW pulses arrive at the

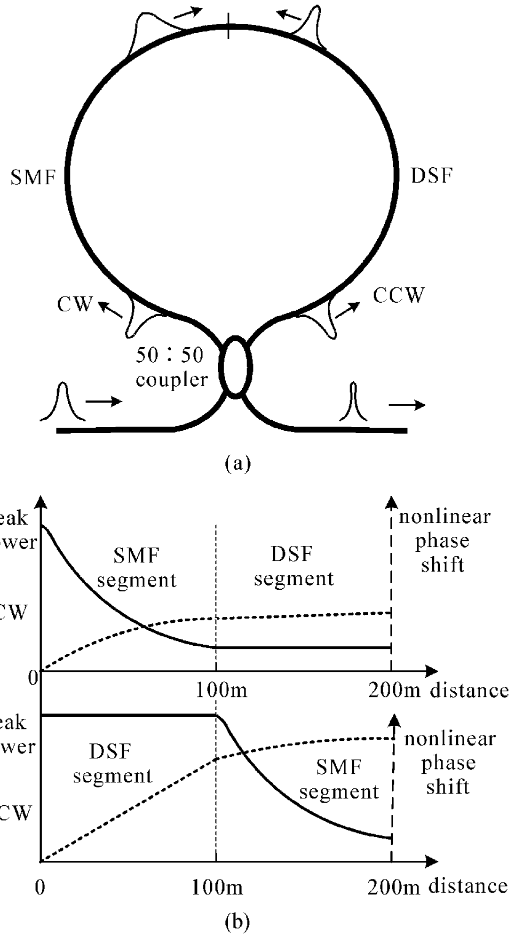

Fig. 1. (a) Conception operation of a DI-NOLM. (b) Peak power changes (dashed lines) and nonlinear phase shift accumulated (solid lines) of two reversely propagating pulses along distance.

50 : 50 coupler, they interfere according to the amount of nonlinear phase shift difference $\Delta\varphi(=|\Delta\varphi_{\mathrm{CW}}-\Delta\varphi_{\mathrm{CCW}}|)$. So the nonlinear phase shift difference $\Delta\varphi$ determines if the pulse is transmitted or reflected back from the DI-NOLM. It is important to note that such a nonreciprocal phase shift only exists for pulsed input but not for continuous wave.

When the $\Delta\varphi$ of the peak nonlinear phase shift between the CW and CCW pulses becomes π, the peak of the pulse is completely transmitted through the DI-NOLM, while the low intensity part of the pulse is reflected back. So, under this condition, the pulse center experiences little loss while the pulse wings undergo great loss, and the DI-NOLM acts as a fast saturable absorber. If the hybrid MFL was modelocked at this state, APM shorter pulse output can be obtained. But in this case, a more stable environment is required to maintain this state.

By tuning the polarization and peak power of the input pulse, which changes the $\Delta\varphi$, we can make the pulse center experience great loss while the pulse wings undergo little loss. Essentially, in the laser cavity, only the pulses that experience least loss can oscillate. So when the hybrid MFL operates at this state, higher intensity pulses experience larger loss, hence, the laser will minimize its pulse intensity fluctuations.

Figure 2 depicts the configuration of a hybrid MFL with a DI-NOLM. The gain of the laser loop was provided by an EDFA, which included 2 polarization independent isolators to ensure unidirectional oscillation of the ring cavity. A $\mathrm{LiNbO_3}$ amplitude modulator (MOD) was the key modelocking element, which was biased at halfwave voltage and driven by a 10-GHz sinusoidal RF signal. To achieve optimal modulation, a polarization controller (PC3) was placed before the modulator. A tunable optical filter (BPF) with a 3-dB bandwidth of 3 nm was used to obtain wideband wavelength tuning. A 50 : 50 fused fiber coupler, 100 m of DSF and 100 m of SMF composed the DI-NOLM. The dispersion values of DSF and SMF are −0.771 and 16.452 ps/(km·nm) at 1550 nm, respectively. In order to adjust the bias phase shift, two polarization controllers PC1 and PC2 were positioned at the input of DI-NOLM and in the loop, respectively. Note that the DI-NOLM was placed just after the EDFA output port to obtain sufficient nonlinear phase shift. The laser pulse output from a 10% coupler was simultaneously monitored by Agilent 86100B Digital Commutation Analyzer, Ando AQ6315A Optical Spectra Analyzer and SHG Autocorrelator.

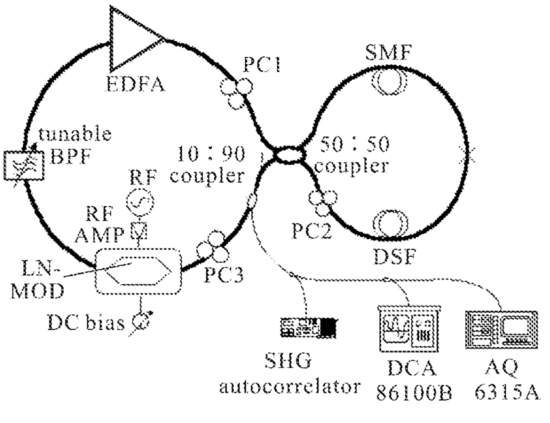

Fig. 2. Experimental setup.

Under the same modulation depth, the hybrid MFL can oscillate under the APM or APL by precisely adjusting the pump level and tuning PC1 and PC2. Figures 3 and 4 show the waveforms, spectra and SHG autocorrelation traces of the modelocked pulse, respectively. The APM modelocked pulse had a pulse duration (FWHM) of 5.45 ps (assuming that the pulse had a hyperbolic secant envelope), 3-dB spectrum envelope width of 0.461 nm and the corresponding time-bandwidth-product (TBP) of about 0.314, which was nearly transform-limited. The pulse duration of APL modelocked pulse was 15.2 ps (assuming the pulse envelope were Guassian), and the spectrum envelope width was 0.236 nm, which made a TBP of about 0.448 and also transform-limited Guassian pulse. For comparison, the output pulse characteristic of MFL without the DI-NOLM is shown in Fig. 5. The pulse duration, spectrum envelope width and TBP were 12.8 ps, 0.316 nm and 0.505, respectively. Because the net dispersion of the ring cavity was in the anomalous region, the output pulse had a small amount of negative chirp, which can be compressed by a segment of DCF outside the cavity.

These figures were obtained by tuning the modulation frequency and PC controllers until the optical pulses are the most stable and minimum temporal width. If there is a pulse amplitude fluctuation, the sampled points of waveforms will be scattered and form a broad trace. From the waveforms and spectra of the pulses in Figs. 3, 4 and 5, it is obvious that the pulses had more even and stable amplitude and supermode noise was suppressed to some extent when the laser was APL modelocked. However the pulse duration was more larger. When biased at the APM region, although the laser cavity generated

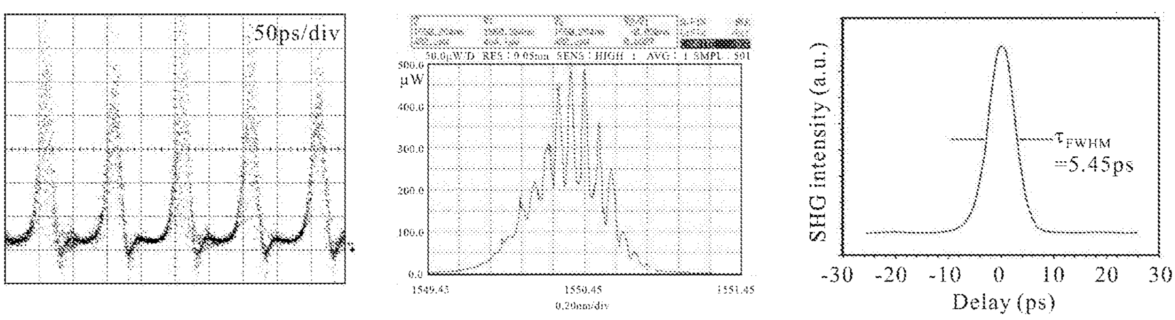

Fig. 3. Waveform, spectrum and autocorrelation trace of APM output pulses.

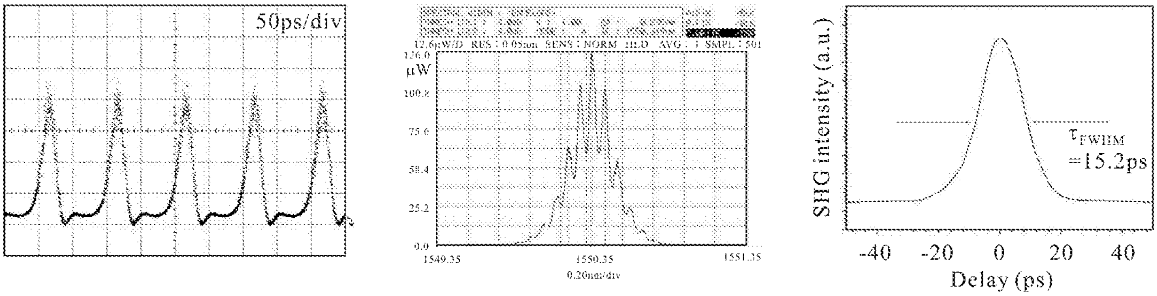

Fig. 4. Waveform, spectrum and autocorrelation trace of APL output pulses.

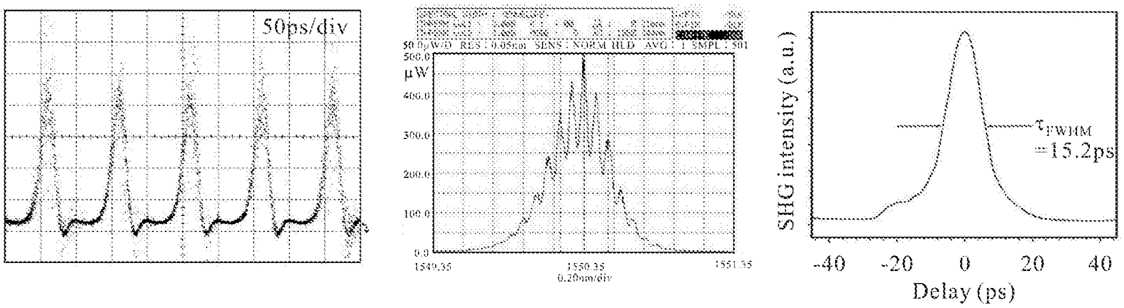

Fig. 5. Waveform, spectrum and autocorrelation trace of MFL output pulses without DI-NOLM.

narrower pulses, it was more subjected to the environmental disturbance and exhibited large time jitter and amplitude fluctuation. For all cases, due to the large cavity length, the modelocking cannot last for long.

We also experimented HMFL with DI-NOLM constructed by various lengths of SMF and DSF pairs, obvious phenomena were observed only with DI-NOLM of 100-m SMF and 100-m DSF, because of not adopting any means of cavity length stabilizing and synchronization between the DI-NOLM and the main loop. So further work should be done to understand the operation of an HMFL with a DI-NOLM.

In this paper, we achieved the operation of a hybrid-type actively and passively modelocked fiber ring laser with a DI-NOLM. The experimental results agree well with the theoretical analysis. When the laser was biased at APL region, supermode noise was suppressed and the laser output was more stable against amplitude fluctuations. And when biased at APM, 5.45 ps of transform-limited pulses were obtained.

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