A 40 GHZ POLARIZATION MAINTAINING PICOSECOND MODELOCKED FIBER LASER EMPLOYING PHOTONIC CRYSTAL FIBER

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Abstract: We demonstrate a harmonically mode-locked dispersion-managed polarization-maintaining erbium fiber laser that uses photonic crystal fiber for nonlinear pulse compression. The high nonlinearity and large anomalous dispersion of the PCF resulted in significant reduction in the cavity length and increased the long-term stability. The laser cavity, only 36-m-long, yielded stable 1.3 ps pulses at a 40-GHz repetition-rate, with supermode noise suppression of over 60 dB.

1. INTRODUCTION

Compact tunable sources providing picosecond pulses with tens of GHz repetition rates and low timing jitter have high demands in many application such as, high speed optical communication systems, optical analog-to-digital conversion and so on. Harmonically active modelocking of fiber lasers is a very useful technique for generating picosecond pulses from fiber lasers with repetition rates of tens to even over a hundred GHz [1-7]. Mode-locked fiber lasers using the erbium-doped fibers (EDF) as the gain medium have been studied most extensively as they produce pulses in the 1.55 μm communication window where the silica fibers exhibit the lowest loss. Technically, short pulse generation at GHz-repetition-rate in erbium doped fiber laser is conveniently realized by taking

advantage of the high saturation power and the availability of optical fibers with both normal and anomalous dispersion characteristic. One can appropriately manage the cavity-dispersion to favor intracavity nonlinear processes, such as the formation of optical solitons. Operation of the laser in the soliton regime not only yields pulses shorter than the Kuizenga-Siegman limit [8], but also ensures pulse-dropout which is particularly important for application in error-free optical communication.

In the high-repetition-rate (10 GHz or above), picosecond pulses can be generated by soliton-effect compression in a long segment of suitable anomalous dispersion fiber placed inside the cavity. Using dispersion shifted fiber (DSF) of 190 m long inside a laser cavity, solitons with widths of 2.7 ps at 10 GHz-rate [2] and 0.9 ps at 40-GHz rate were generated [6]. Recently, highly nonlinear DSF fibers were also deployed with an aim to reduce the length of nonlinear fiber, and indeed 1.2 ps pulses at 40 GHz-rate were obtained from an actively mode-locked fiber laser that used 100 m of highly nonlinear DSF fiber [4].

Alternatively, picosecond pulses can also be produced from a dispersion managed (DM) laser cavity, which has fiber segments with large local dispersion, but a small anomalous path-averaged dispersion. In a DM laser a pulse spends much of its time in a stretched state and experiences a lower effective nonlinearity than a fundamental soliton pulse in a comparable uniform dispersion cavity [9]. This allows pulses to circulate with higher energy in the cavity, yielding higher output power. Pulses with a width of 1.3 ps, timing jitters of only 10 fs, and pulse dropout ratio smaller than 10^{-14} were generated at 10 GHz rate from a DM sigma fiber laser [3, 10].

We have recently demonstrated a mode-locked erbium fiber laser which uses a polarization maintaining PCF (PM-PCF) with high nonlinearity and anomalous dispersion for nonlinear pulse compression [11]. The high nonlinearity and large anomalous dispersion of the PCF made nonlinear pulse compression achievable in fiber only 10-m long. Highly-stable pulses with 1-ps-width and 10-GHz repetition-rate were obtained over a range of 1535-1560 nm. In this paper, we demonstrate successful operation of PCF-based compact fiber laser at 40-GHz-repetition-rate. We have produced ~1.3 ps pulses at 40-GHz repetition rate with supermode noise suppression better than 60 dB and output power of over 14 mw.

2. EXPERIMENTAL SETUP

The experimental setup of the mode-locked fiber ring laser is shown in Fig. 1. The cavity consisted of a 20-m long Er-doped PANDA fiber, a Mach-Zehnder modulator, an optical isolator, a tunable bandpass filter (3-dB-bandwidth: 8 nm), a 30% output coupler, and a 10-m-long polarization maintaining PCF (PM-PCF)

section. The Er-fiber had an un-pumped absorption coefficient of 3.28 dB/m and dispersion of -54 ± 5 ps/nm/km at 1550 nm. The PM-PCF, manufactured by Mitsubishi Cable Industries, had a Ge-doped core that was surrounded by a hexagonal array of holes. The cross section of the PM-PCF is shown in the inset of Fig 1. The fiber had a zero-dispersion wavelength at 876 nm, and exhibited a dispersion parameter of 104 and 126 ps/nm/km, for the slow and fast axes respectively. The PM-PCF had a nonlinear coefficient of 39.5 $W^{-1}km^{-1}$ and a loss coefficient of 16 dB/km (at 1550 nm). To facilitate optical coupling, both ends of the PM-PCF were fusion-spliced to standard PANDA fiber through a mode-field converter, which yielded a loss/splice of only 1.6 dB. The cavity also employed a fused fiber polarization beam splitter (PBS) that restricted oscillation to slow axes in the cavity. The doped fiber and PM-PCF within the laser cavity mapped a dispersion-managed (DM) periodic system with large dispersion variation. The dispersion map of the cavity, which mostly consisted of the erbium fiber and the PCF is shown in Fig. 2. The average value of dispersion in the 36-m-long cavity was 1.4 ps/nm/km, and the fundamental cavity repetition rate was 5.6 MHz.

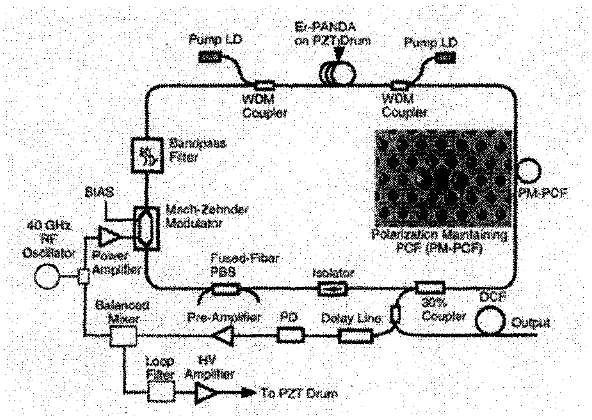

Figure 1. Experimental setup

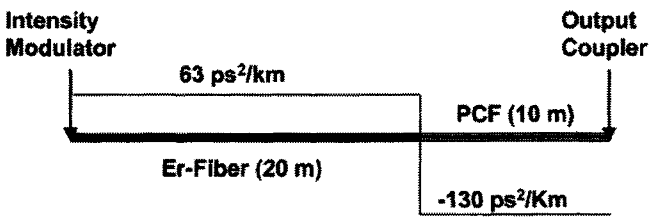

Figure 2. Dispersion map of the laser.

For modelocking at a 40-GHz-repetition-rate, we directly drove the modulator using an RF oscillator and a narrow band RF power amplifier. We also stabilized the cavity by controlling the length of the Er-PANDA fiber that was wound around a cylindrical piezoelectric transducer (PZT). The error signal necessary for active feedback was obtained from the phase of the output pulses relative to the clock signal available at the IF output port of the double balanced mixer. The error signal was processed with proportional and integration control circuitry, amplified and applied to the PZT [12].

3. RESULTS

Modelocking of the laser was achieved at a repetition rate of ~40 GHz by carefully adjusting the oscillator frequency to match a harmonic of the fundamental cavity-repetition-rate and the bias voltage of the modulator. The optical spectrum of the mode-locked pulses is shown in Fig. 3(a), which shows the optical comb of frequencies separated by a frequency equal to pulse repetition rate. The ASE noise-floor was over 10^{-4} times lower than the peak of spectrum. The envelope of the optical spectrum could be fitted by a Gaussian-like envelope with an FWHM bandwidth of 2.69 nm. In soliton systems that has largely differing dispersions [3, 10], optical spectrum with the Gaussian rather than sech-profile are commonly seen. In our experiment, we obtained output pulses with nonzero chirp that was accounted for by external chirp-compensation using dispersion compensating fiber (DCF) of about a 4-m-long. The autocorrelation trace of the shortest pulse thus obtained is shown in Fig. 3(b), which yielded an FWHM pulsewidth of 1.29 ps.

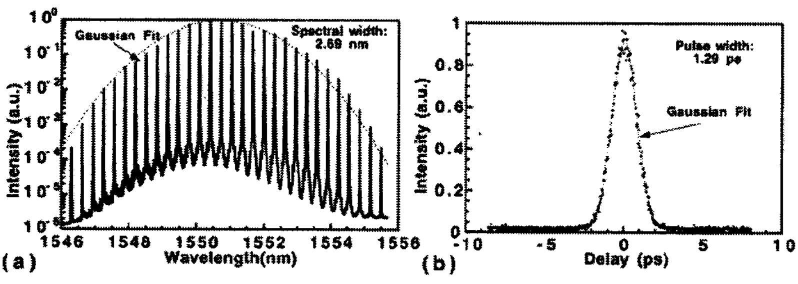

Figure 3. Output pulses. a) Optical spectrum. b) Autocorrelation trace.

Figure 4(a) represents the autocorrelation trace measured over a longer time scale, which shows periodic pulse trains separated by about ~25 ps, in consistent with the RF modulation frequency. The RF spectrum of the output pulses showed a frequency component equal to pulse repetition-rate of 39.463 GHz. The supermode

noise was suppressed by more than 60 dB. The average output power was 14.4 mW, which was limited by the power of the pump LDs. The wavelength of the output could be changed through the use of the tunable bandpass filter.

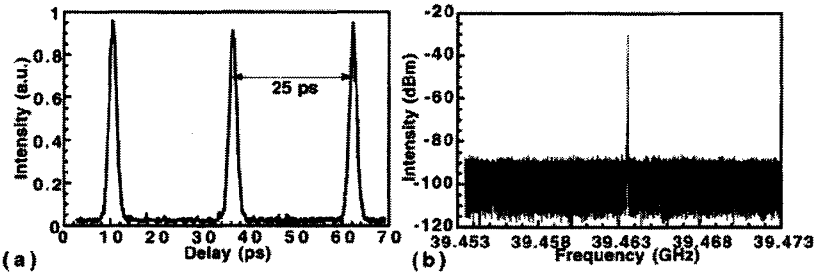

Figure 4. Output pulses. a) Auto/cross correlation trace, b) RF spectrum.

It is known that in a fiber system with dispersion maps that have large deviations of the local dispersion from the average-dispersion, the pulses have enhanced energy relative to solitons in a system with uniform dispersion that is equal to the path-averaged dispersion of the map [13]. The dispersion map strength factor $\gamma_S = 2 \ {}_n\left|(\beta_{2n} - \beta_{2avg})l_n\right| / \tau_{FWHM}{}^2$ of the DM soliton laser, where β_{2n} and l_n is the group velocity dispersion and length of the nth fiber segment forming the cavity, τ_{FWHM} is the shortest FWHM pulse duration, β_{2avg} is the average dispersion, can be determined using a value of 1.29 ps for τ_{FWHM} and the parameters of the PCF and Er-PANDA. We obtain a value for γ_S of ~3.0 for the 36-m-long dispersion map, while it was 4.5 for the same laser used for producing 1.07 ps pulse at 10 GHz, repetition rate [11]. Higher value of γ and, correspondingly shorter pulses with larger output power are expected by using pump LDs with higher power and further optimization of the dispersion map of the cavity.

4. CONCLUSIONS

In this paper we have demonstrated the application of highly nonlinear and anomalously dispersive PCF in compact pulse sources that generate tunable picosecond pulse at high repetition rate suitable for optical communication. The use of PCF has helped reduction in the cavity length by an order of magnitude. We successfully produced 1.3 ps pulses at a 40 GHz repletion rate, and the supermode noise was suppressed by more than 60 dB.

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