DRAGGING AND RETIMING OF ULTRAFAST PULSES USING FIBER NONLINEARITY

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INTRODUCTION

Optical pulses with picosecond-duration, high-repetition-rates and low timing jitter are in high demand in many applications such as high-speed optical communication, optical analog-to-digital conversion, and optical computing. By initiating active mode-locking of erbium-doped fiber lasers and utilizing the nonlinear effect inside the fiber, picosecond/subpicosecond pulses in the 1.55 μm wavelength-region with repetition rates from a few tens of gigahertz up to over 100 GHz and wavelength-tunability over 1530-1570 nm can be produced [1-3]. The wavelength range can be extended further by externally exploiting in optical fiber various nonlinear processes, such as supercontinuum generation [4] and soliton self-frequency shift (SSFS) [5, 6].

When coded with data and transmitted through long transmission systems, these optical pulses accumulate timing jitter as they experience repeated amplification or inter channel collisions, resulting in bit errors and significantly degradation in the performance of communication systems. A number of fiber-based schemes for eliminating the timing jitter have been demonstrated, such as synchronous amplitude modulation or phase/frequency modulation followed by propagation in dispersive fiber [7].

In this paper, we show the techniques of generating wavelength-tunable picosecond/femtosecond pulses from fiber lasers and all-optical means for retiming of such pulses at high repetition rates. In particular, we demonstrate a polarization-maintaining mode-locked erbium fiber laser using highly nonlinear photonics crystal fiber (PCF). The laser produces about 1 ps pulses at 1.55 μm wavelength range at repetition rates as high as 10-40 GHz. We further demonstrate a technique of retiming picosecond signal pulses by another train of control pulses through cross-phase modulation (XPM) in a polarization maintaining (PM) fiber. Pulse retiming of about ±2 ps at a pulse rate of 10 GHz was successfully achieved by dragging with a synchronized control pulse train.

HIGH-REPETITION-RATE PICOSECOND FIBER BASED PULSE SOURCES

The schematic diagram of a mode-locked fiber ring laser is shown in Fig. 1. The 36-m-long cavity consisted of a 20-m long Er-doped PANDA fiber, a modulator, an optical isolator, a tunable bandpass filter, an output coupler, and a 10-m-long polarization maintaining PCF (PM-PCF). The PM-PCF had a nonlinear coefficient of 39.5 $W^{-1}km^{-1}$ and a

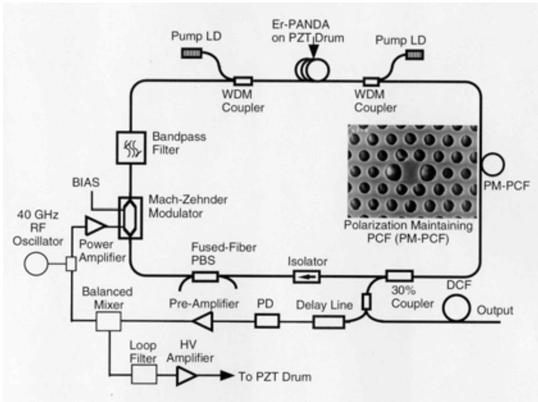

Fig. 1. Schematic diagram of a 40 GHz rate modelocked fiber laser

dispersion parameter of 104 ps/nm/km. The Er-doped fiber (dispersion: -54 ± 5 ps/nm/km), and the PM-PCF within the laser cavity mapped a dispersion-managed soliton system, with an average dispersion of 1.4 ps/nm/km. Modelocking of the laser was achieved at a repetition rate of ~40 GHz by adjusting the oscillator frequency to match a harmonic of the fundamental cavity-repetition-rate and the bias voltage of the modulator. The width of the optical spectrum (Fig. 2a) of the output pulses was 2.69 nm. The laser produced pulses with nonzero chirp that was accounted for by external chirp-compensation using a 4-m-long dispersion compensating fiber (DCF). The autocorrelation trace (Fig. 2b) of the pulse showed an FWHM pulsewidth of 1.29 ps. The average output power was 14.4 mW.

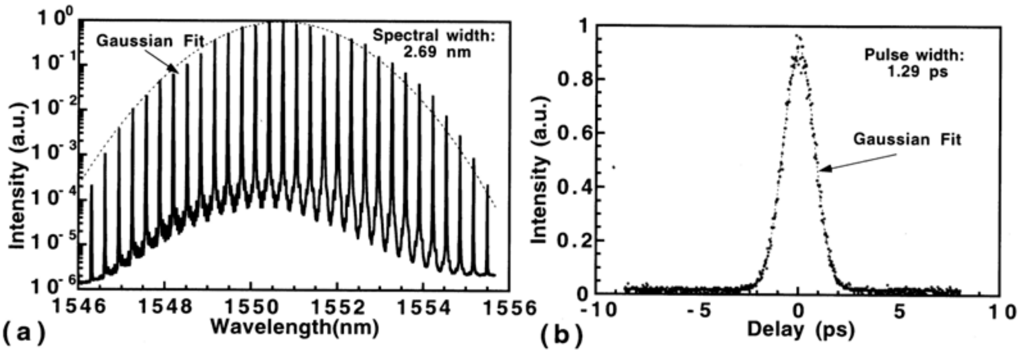

Figure 2. Output pulses. a) Optical spectrum. b) Autocorrelation trace

PULSE RETIMING AND DRAGGING BY EMPLOYING XPM IN OPTICAL FIBER

The principle of retiming is illustrated in Fig. 3, where two pulse trains (control and signal) with the same nominal repetition rates are launched into an anomalous-dispersion PM fiber with their polarizations aligned along the slow and fast axes. Depending on the temporal position of the weak pulse (signal) with respect to the strong pulse (control), the XPM-induced frequency chirp in the signal can be either positive or negative. When a signal pulse is coincident in time with a control pulse, the mean optical frequency remains unchanged. However, if the signal pulse arrives early, its frequency gets red-shifted, thus requiring a longer time for propagation in a fiber that has anomalous dispersion. On the other hand, for a pulse that arrives late, it has a shorter transit time in the fiber, as the frequency is now blue-shifted. That is, the control pulses effectively drag and retime the weak signal pulses.

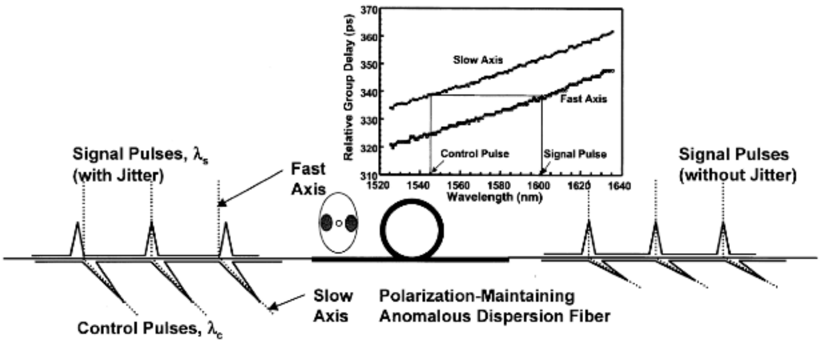

Fig. 3. Schematic diagram explaining pulse retiming by XPM from an orthogonally polarized control pulse co-propagating. in a PM fiber. Inset shows the group velocity matching achieved between control and signal wavelengths separated by ~55 nm.

In the experiment, as shown in Fig. 4, we used a 500-m-long low-birefringence PM fiber. The fiber having a chromatic dispersion and birefringence (at 1550 nm) of ~17.3 ps/nm/km, and 2.97×10^{-4}, respectively, allowed group velocity matching between orthogonally polarized pulses with wavelengths separated by 55 nm. We used a 10-GHz-repetition-rate pulsed laser operating at a wavelength of 1545 nm as a source of pulses. A fraction of the laser output was filtered and amplified, yielding a control pulse train with widths of 5.1 ps and an average power of 220 mW. The signal pulses used in the experiment had a wavelength of 1596 nm and pulsewidth of 5.3 ps and were produced by supercontinuum (SC) generation and subsequent spectral filtering. The time delay between the signal and the control pulses incident on the fiber was adjusted using a tunable delay line placed in the path of the control pulses. The signal was monitored at the filter output for various amounts of delays.

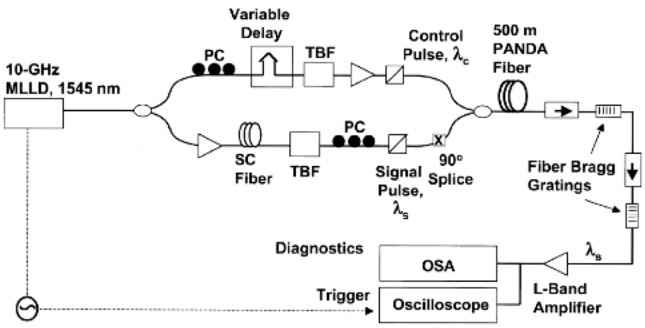

Fig. 4. Experimental setup used for retiming of the signal pulses

Figure 5 shows the optical spectrum and waveform of the output signal observed under three different cases: (a), (d) when the control pulses overlapped with the signal; (b), (e) when control pulses were advanced by 2.7 ps at the fiber input; and (c), (f) when control pulses were delayed by 2.7 ps at the fiber input. When the control pulses were advanced with respect to the signal at the fiber input, we could clearly see a blue-shift in the signal spectrum due to XPM and a corresponding shift in waveform towards the negative direction on the time axis by about 2 ps. Similarly, when the control pulses were delayed with respect to the signal, we observed a red-shift in the signal spectrum and

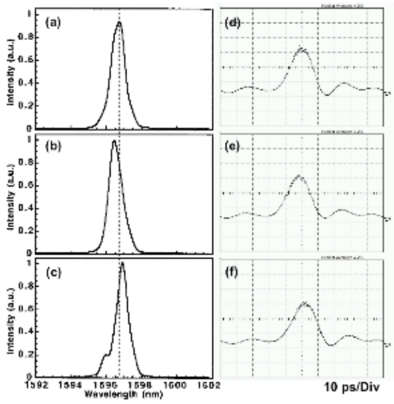

Fig. 5. Optical spectra (left) and waveforms (right) of the signal pulse detected at the PM fiber output. In (a) and (d), control pulses are coincident with the signal pulses at the fiber input; in (b) and (e), the control pulses are advanced by 2.7 ps; and in (c) and (f), the control pulses are delayed by 2.7 ps

acorresponding delay (~2 ps) of the waveform on the time axis. This clearly indicated that the strong control pulses attracted the weak signal pulses through XPM. This demonstration suggests that if the individual signal pulses in the train had random timing jitter, the control pulses would retime the signal pulses and effectively reduce the timing jitter.

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