3 Physical Layer Technologies / Optical Signal Processing

3-1 Optical Signal Processing using Fiber Nonlinearity

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We demonstrate compact high-repetition rate picosecond/femtosecond pulse sources, wavelength converters using nonlinear pulse shaping and ultrafast pulse retimers that are based on nonlinear effect in optical fibers. We generated picosecond pulses at a 40-GHz repetition rate from a laser that employs photonic crystal fiber for reducing the cavity length. Furthermore, we produce 10-GHz femtosecond solitons, tunable over a 90-nm range, by means of soliton self-frequency shift of the mode-locked laser pulses in a 12.6-m-long PCF. Finally, retiming of signal pulses by orthogonally polarized control pulses co-propagating using a polarization-maintaining fiber is also demonstrated.

Keywords
Optical nonlinearity, Photonic crystal fiber, Soliton, Fiber laser,
All-optical signal processing

1 Introduction

When intense light is propagated through optical fibers, the refractive index of the fiber is changed almost instantaneously. This effect, know as Kerr nonlinearity has been used extensively in many applications in the area of optical communications. The refractive index in the fiber changes according to the relation, $n = n_o + n_2 .I(t, x, y)$, where n_2 is the nonlinear-index coefficient and I is the optical intensity (Power/Area). This results in a change in the phase of light that is given by $\phi_{NL} = \gamma P\ L_{eff}$, where L_{eff} is the effective length of the fiber that includes the effect of absorption loss, P is the optical power, and γ is the nonlinear coefficient as defined by, $\gamma = 2\pi n_2/(\lambda A_{eff})$. In order to acquire large nonlinear phase change from a shorter length, it is thus necessary to utilize fibers that have large nonlinear parameter. This is generally achieved by utilizing fibers with large nonlinear coefficient n_2 and using fibers specially designed to have a small core size. Table 1 shows summarizes various optical fibers made of silica as well as non-silica glass designed to have nonlinear coefficients more than two order of magnitude larger than the standard silica fiber. Fibers tailored with such a large nonlinearity and with suitable dispersion can lead to a many applications in the areas of ultrafast communications.

In this paper, we show some application of nonlinearity of optical fiber in the generation of wavelength-tunable picosecond/femtosecond pulses from fiber lasers, the conversion of wavelength over a broad range, and the retiming of such pulses at high repetition rates using the nonlinear effects in optical fiber. In

Table 1 *Various optical fibers with large nonlinear coefficients*

Material	n_2 m^2/W	Fiber structure	A_{eff} (μm^2)	γ ($km^{-1}W^{-1}$)
SiO_2	4.9×10^{-20}	HNL-DSF	10	20
SiO_2	2.7×10^{-20}	Holey Fiber	1.5	70
Bi_2O_3	1.1×10^{-18}	Step Index	3.3	1360
As_2Se_3	9.2×10^{-18}	Step Index	39	162
SF57	4.1×10^{-19}	Holey Fiber	3	956

particular, we demonstrate a polarization-maintaining mode-locked erbium fiber laser using highly nonlinear photonic crystal fiber (PCF). The laser produces stable pulses about 1 ps width at repetition rates as high as 10–40 GHz at 1.55 μm wavelength range. The wavelength of the modelocked pulses at 10 GHz repetition rate were shifted to over 100 nm range using nonlinear soliton self-frequency shift (SSFS) in a highly nonlinear photonic crystal fiber. We further demonstrate ultrafast pulse retiming of picosecond signal 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.

2 High repetition rate picosecond fiber laser

Optical pulses with picosecond-duration, high-repetition-rates and low timing jitter are in high demand in 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]. At high repetition rates (10–40 GHz), picosecond pulses can be generated by soliton-effect compression in a few hundred meter-long anomalous-dispersion fiber placed inside the cavity.

The chromatic dispersion parameters β_2 of the optical fibers used for intracavity nonlinear pulse compression so far were rather small. Since the soliton period equals $\pi\tau_0^2/2\beta_2$ (where τ_0 is the 1/e pulse width)[8], a fiber length of 100 m or longer is required to achieve any pulse compression. Therefore, it is expected that the length of the fiber required for nonlinear pulse compression could be significantly reduced using highly nonlinear optical fiber with large anomalous dispersion.

The schematic diagram of a mode-locked fiber ring laser is shown in Fig. 1. The 36-m-long cavity consisted of Er-doped PANDA fiber, a modulator, an optical isolator, a tunable bandpass filter, an output coupler, and polarization maintaining PCF (PM-PCF). The PM-PCF had a nonlinear coefficient of 39.5 $W^{-1}km^{-1}$ and a dispersion parameter of 104 ps/nm/km

Modelocking of the laser was achieved at a repetition rate of ~40 GHz by proper adjustment of the oscillator frequency. 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 pulse-width of 1.29 ps. The average output power was 14.4 mW.

3 Wavelength conversion using soliton self-frequency shift

Besides small width, low jitter, and low dropout ratio, another desirable feature of pulses is wavelength tunability. Wavelength tunability can be extended beyond the gain bandwidth of erbium by exploiting externally in optical fiber various nonlinear processes such as supercontinuum generation[4] and soliton self-frequency shift (SSFS)[5][6]. SSFS is initiated by soliton propagation in an anomalous dispersion fiber. The frequency

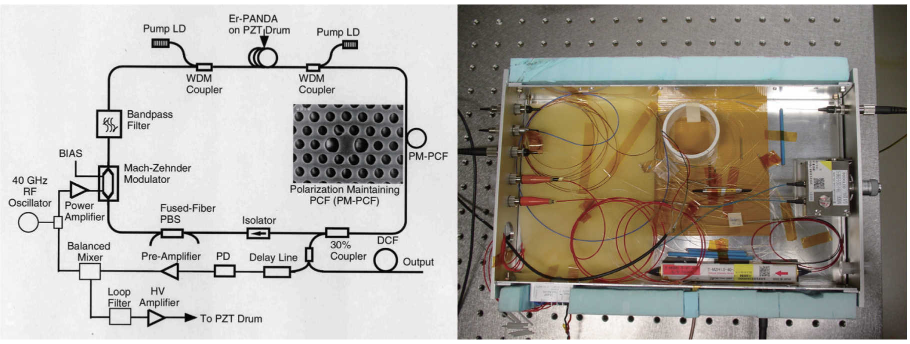

Fig.1 *Schematic diagram of a 40 GHz rate modelocked fiber laser*

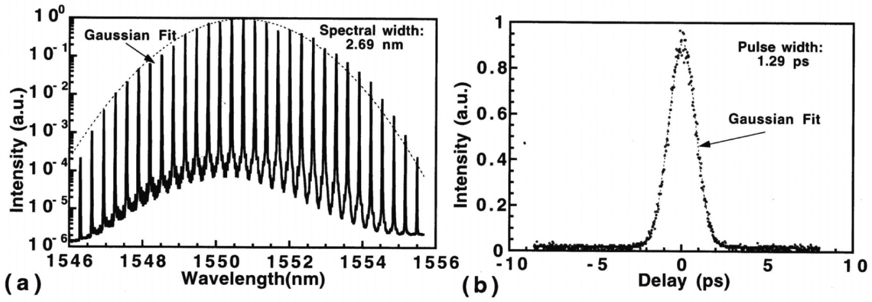

Fig.2 *Output pulses. (a) Optical spectrum, (b) Autocorrelation trace*

shift occurs due to the intrapulse stimulated Raman scattering (SRS), which transfers energy from the higher-frequency components of the soliton to its lower-frequency ones.

Figure 3 shows the change in the optical spectrum seen at the output of a 12.6-m PCF when the launched power applied to the PCF was gradually increased to about 1.1 W. Solitons with wavelength tunability over the range 1550–1630 nm were obtained at the output of PCF. Figure 4(a) shows an optical spectrum observed for solitons with a center wavelength of 1610 nm. The corresponding autocorrelation trace, shown in Fig. 4(b), yielded a pulse width of 176 fs.

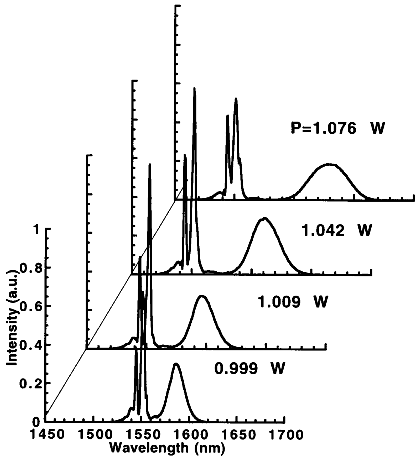

Fig.3 *Typical optical spectra of Raman solitons observed at the PCF output for increasing launched powers. The PCF was 12.6 m long.*

4 Pulse retiming by using fiber nonlinearity

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[8].

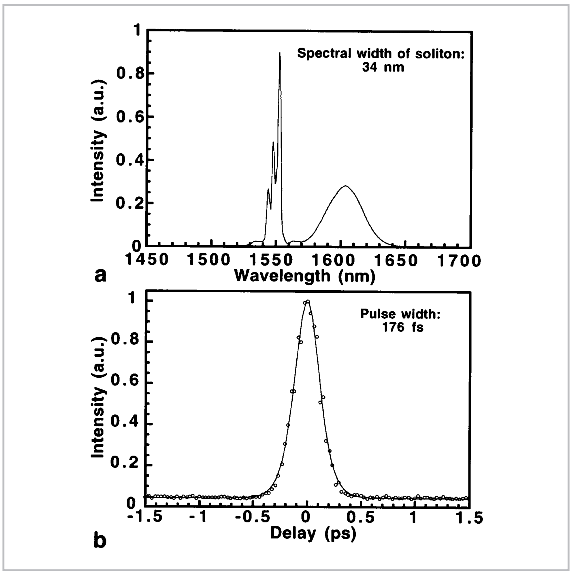

Fig.4 *Characteristics of the output pulses at the exit of the PCF*

(a) Optical spectrum showing solitons with a peak wavelength of 1610 nm and (b) autocorrelation trace of the Raman soliton.

Here we show an all-optical method of retiming of optical pulses using the fiber nonlinearity. The principle of retiming is illustrated in Fig. 5, 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[9]. 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. The matching of the group velocities between two orthogonally polarized pulses with different wavelengths that is required for implementing the scheme is shown in Fig. 6.

In the experiment, as shown in Fig. 7, 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.

Figure 8 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)

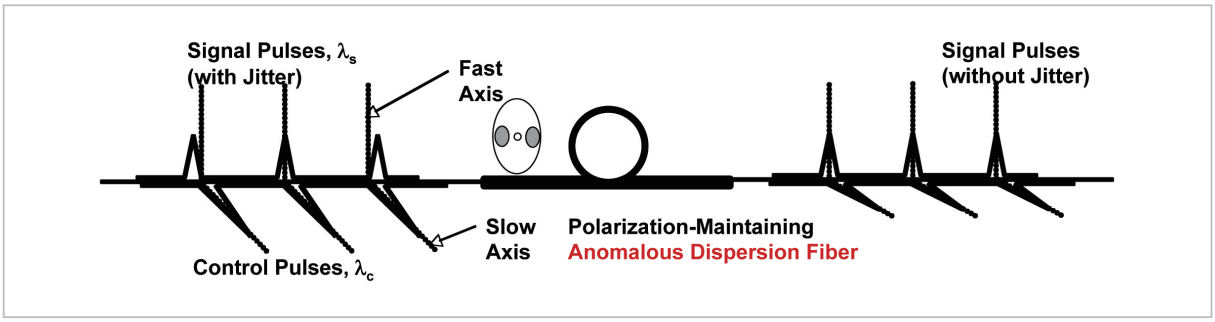

Fig.5 *Schematic diagram explaining pulse retiming by XPM from an orthogonally polarized control pulse co-propagating in a PM fiber*

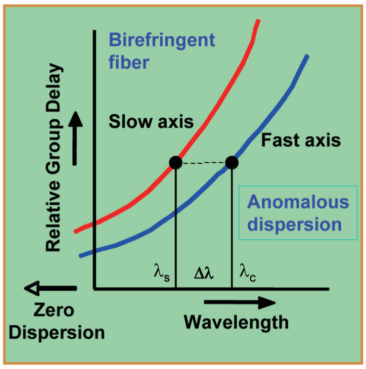

Fig.6 *Group velocity matching between orthogonal polarized pulses.*

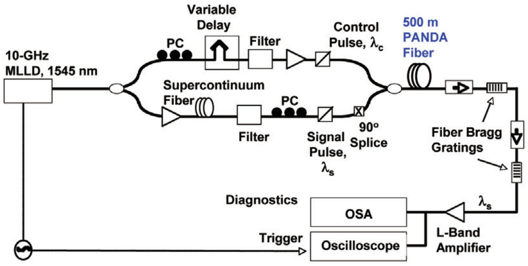

Fig.7 *Experimental setup used for retiming of the signal pulses*

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 a corresponding 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.

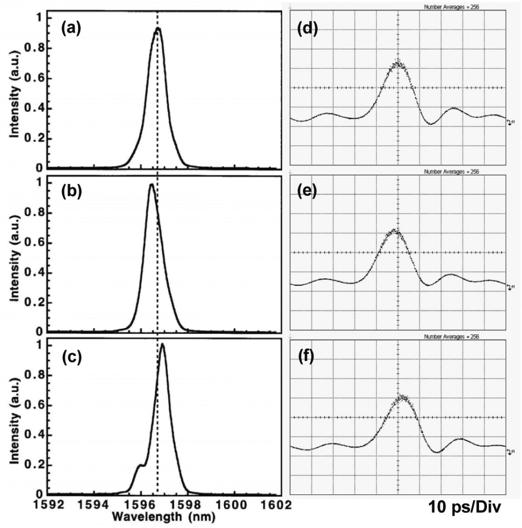

Fig.8 *Optical spectra (left) and waveforms (right) of the signal pulse detected at the PM fiber output*

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

5 Conclusions

In this paper we have demonstrated the application of highly nonlinear and anomalously dispersive PCF in compact pulse sources that generate tunable picosecond and femtosecond pulse at a high repetition rate suitable for optical communication. The use of PCF has helped to significantly reduce the device length. We demonstrate the generation of 1.3-ps pulses at a 40-GHz repetition rate using a PCF based fiber laser We have reported retiming of pulses achieved through walk-off-free XPM by orthogonally polarized control pulses co-propagating in an anomalous-dispersion polarization-maintaining fiber. Pulse retiming by about ±2 ps at a pulse rate of 10 GHz was successfully achieved.

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