Generation of high-quality sub-picosecond optical pulses using a combination of normal and anomalous dispersion fibers

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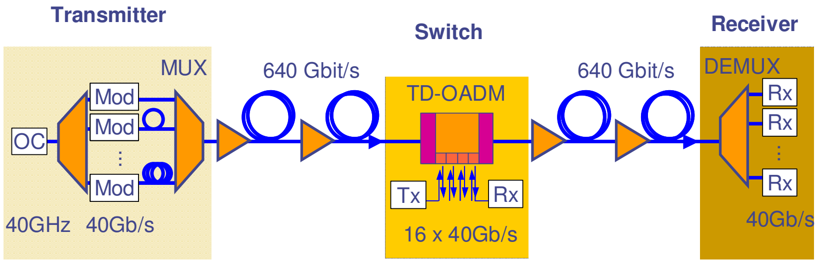
A practical method for generating high-quality optical pulses of sub-picosecond pulse widths is presented. The method uses linear chirp generation in supercontinuum pulses in a normal dispersion fiber. This linear chirp is utilized by an anomalous dispersion fiber to shorten the pulse widths down to a few hundreds of femtoseconds. This compression method results in 0.28-ps 10-GHz optical pulses. We also demonstrate that optical filtering increases the pulse contrast ratio above 30 dB but widens the pulse to 0.32 ps. This pulse performance is sufficient for 640 Gb/s transmission.

Introduction

A sub-picosecond optical pulse train at a high repetition rate in the transmission wavelength band of 1.5 μm is indispensable for future ultra high-speed optical communication systems [1-5]. For the next generation of optical transmission systems that is based on 160-Gb/s data rate, the temporal dynamics of data signal is becoming critical since the data bit period is down to a few picoseconds. For such short bit periods the light source is preferably a pulsed laser rather than a continuous wave laser. To overcome the problems related to inter-symbolic interference the light pulse at its full width at half maximum (FWHM) should be less than one third of the bit period. In addition, the pulse time jitter that is defined as short-term variation or instability in the duration of a specified time interval, as a rule of thumb, must not exceed one tenth of FWHM. This means that for 160-Gb/s application the pulse source should emit an optical pulse of less than 2 ps FWHM and the pulse should have a root-mean-squared time jitter of less than 0.2 ps. Such picosecond pulse sources are readily commercially available today and they are mainly either fiber-based or semiconductor-based mode-locked lasers. To obtain very high data rates time-multiplexing technique should be applied either in electrical domain or in optical domain. All experiments on a 160 Gb/s data rate have been performed by time-(de)multiplexing in the optical domain (OTDM) due to the absence of high-speed electronics.

640-Gb/s OTDM Transmitter

Having explored feasibilities of the 160 Gb/s technologies, several research laboratories around the world are starting to investigate 640 Gb/s and beyond, such as [1]. Technological challenges of these data rates are enormous. These sub-Tbit/s data rates require high-quality pulse generation that must preserve its high performance along the transmission line until the receiver-end. Fig. 1 depicts schematically a setup of 640 Gb/s transmission and mid-span switching. The bit period is reduced to 1.56 ps and therefore the FWHM of the pulse should be below 0.4 ps. This pulse performance may be sufficient for switching experiments in the absence of transmitting fibers. However, for transmission experiments due primarily to the destructive effects of fiber (higher-order) dispersions the spacing between the data bits should be well managed and the pulse FWHM should be below 0.3 ps without any form of pedestal in the pulse dynamics [1,2].



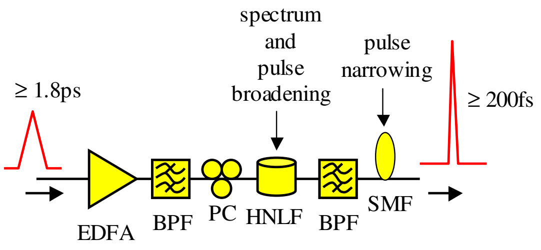
Features:
- Aggregate capacity 640 Gb/s, T=1.5625 ps
- Pulsewidth < T/3 ≈ 400 fs
- Jitter < Pulsewidth/10 ≈ 50 fs

Fig. 1: A 640-Gb/s (16×40 Gb/s) OTDM network consists of a 640-Gb/s transmitter node, a 640-Gb/s add-drop node, and a 640-Gb/s receiver node.

Since it is very difficult to generate such ultra-short pulses directly from a laser, a pulse compression concept is required. The optical fiber technology based on Kerr-nonlinearities is the most viable technology for shortening the durations of pulses generated by commercial pulse sources due to the ultrafast nonlinear process [3]. This paper presents an experimental study on practical realization of a pulse compressor for 320 and 640 Gb/s applications.

Pulse Compression based on SPM in normal dispersion fibers

In contrast to adiabatic soliton compressors [2] where an optical pulse becomes narrower as it propagates along a dispersion decreasing fiber, a self-phase modulation (SPM)-based pulse compressor [4] consists primarily of two parts, see Fig. 2.



EDFA: high-power Er-doped fiber amplifier
BPF: bandpass filter
PC: polarization controller
HNLF: high nonlinear fiber with normal dispersion
SMF: standard single-mode fiber with anomalous dispersion

Fig. 2: SPM-based pulse compressor.

One part causes spectral broadening due to interaction between SPM and normal group velocity dispersion (GVD) in a high-nonlinear fiber (HNLF). This interaction amounts in linear chirp across the entire pulse width, which is then used in a second part to decrease the pulse width down to several hundreds of femtoseconds by a proper amount of anomalous GVD. Requirements for the input pulse are more relaxed compared to adiabatic soliton compressors. The pulse shape is by spectral broadening adapted to accommodate the build-up of the linear chirp. As a result, pulse sources having substantial chirp in their spectrum such as semiconductor lasers can function as the input of this compressor.

Simulation

Simulation results of the amplitude, spectrum, and chirp of a high-intensity optical pulse propagating in a HNLF of length L are presented in Fig. 3.

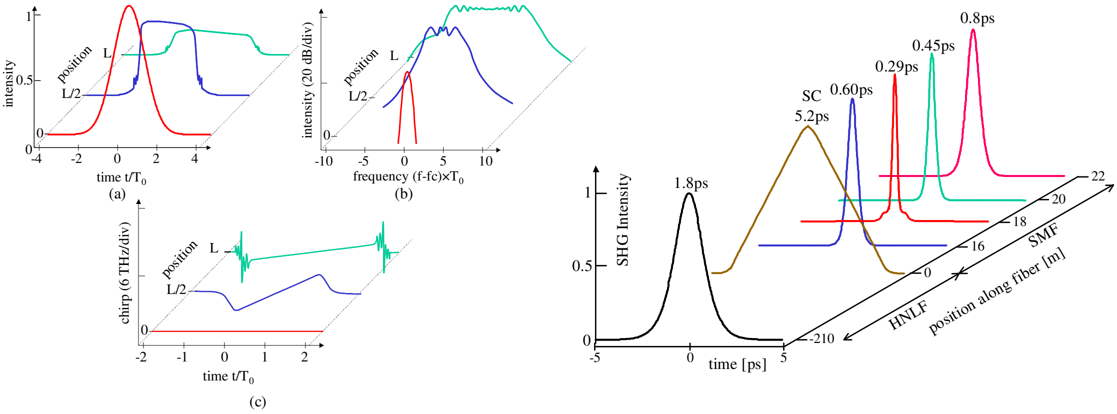


Fig. 3: Simulation of pulse performance. The left panel shows (a) temporal, (b) spectral, and (c) chirp response of a sech2-shape optical pulse at three points along a HNL fiber. The right panel shows simulation of auto-correlated shape of a pulse in HNLF and a SMF patch cord.

The graphs are obtained by numerically solving the nonlinear Schrodinger equation [5]. Initial pulse parameters are T_0=1.8ps (FWHM sech^2), λ_C=1.545μm, $\Delta\lambda_{FWHM}$=1.9nm, and P_C=9W. The HNL fiber has the following parameters. γ=21W^{-1}km^{-1}, L=210m, λ_{ZD}=1.602μm, α=0.5dB/km, β_2=2.71ps^2/km, and β_3=0.084ps^3/km. In a normal HNL-dispersion shifted fiber (DSF), dispersion slope causes an asymmetric spectrum. The spectrum becomes more stretched to longer than to shorter wavelengths. As the pulse propagates, it broadens and develops a nearly rectangular profile with a sharp leading and trailing edge. New frequencies are generated mainly near the edges. Across its entire width the pulse accumulates linear frequency chirp. Ripples in the center of the pulse spectrum are due basically to SPM. The ripples can be made smoother by increasing dispersion values. Residual nonlinear chirp occurs as an oscillatory structure out of the pulse center, responsible for pedestals. This chirp is generated mainly at the both side of the spectrum and its power can therefore be suppressed by suitably filtering the spectrum. Fig. 3 (right panel) shows the pulse shape (auto-correlated intensity) from the launching into the HNLF until the end of a standard single-mode fiber (SMF). It should be noted here that an intensity auto-correlator always produces a symmetric shape. For L=18m, the pulse width becomes the smallest, i.e. 0.29 ps. However, the pulse has pedestals around its edges.

Experiment

In corporation with the Fujitsu Research Lab we conducted experiments to substantiate the theoretical results. SPM-based pulse compressor was constructed using standard commercial pigtailed components. The setup and main results are summarized in Fig. 4. The initial pulse width coupled into the HNLF is 1.8ps. After the HNLF the pulse width becomes more than 5ps. Introducing anomalous dispersion in 18-m SMF the pulse is narrowed to 0.28ps with visible pedestals. Filtering with 9nm makes the pulse nearly pedestal-free (>30 dB from the pulse peak) but at the cost of slightly wider pulse, i.e. 0.32ps.

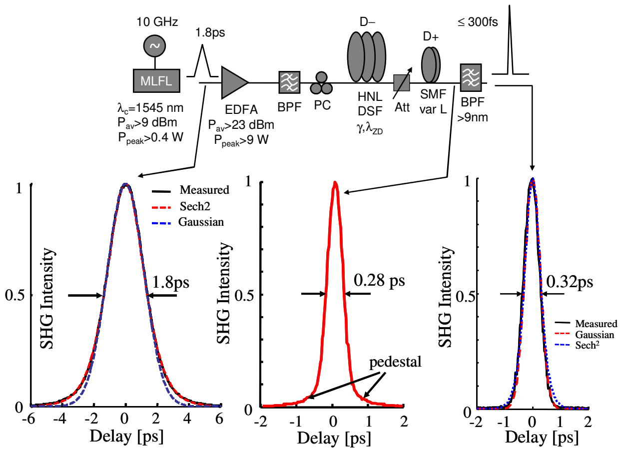


Fig. 4: Realization of a SPM-based pulse compressor: setup and results.

Conclusion

We have demonstrated a simple and a ready-to-deploy optical pulse compressor from standard commercial optical components. The compressor is based on self-phase modulation in a normal dispersion fiber followed by an anomalous dispersion fiber. This concept has been successfully tested to generate 10-GHz, 0.28ps optical pulses. An optical filter can be employed to remove considerably pulse pedestals, increasing the pulse contrast ratio to >30 dB. A nearly pedestal-free pulse train of 0.32ps is feasible with this concept.

Acknowledgment

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References

[1] M. Nakazawa, T. Yamamoto, and K. Tamura, "1.28 Tbit/s 70 km OTDM transmission using third- and fourth-order simultaneous dispersion compensation with a phase modulator," in Proceedings of European Conference on Optical Communication (ECOC), 2000, postdeadline 2.6.

[2] M. Nakazawa, E. Yoshida, K. Kubota, and Y. Kimura, "Generation of 170fs, 10GHz transform-limited pulse train at 1.55 µm using a dispersion-decreasing, erbium-doped active soliton compressor," Electron. Lett., vol. 30, no, 24, pp. 2038-2040, 1994.

[3] S. Watanabe and F. Futami, "All-optical signal processing using highly nonlinear optical fibers," IEICE Trans. Commun., vol. E84-B, no. 5, pp. 1179-1189, 2001.

[4] C.V. Shank, R.L. Fork, R. Yen, R.H. Stolen, and W.I. Tomlinson, "Compression of femtosecond optical pulses," Appl. Phys. Lett., vol. 40, no. 9, pp. 761-763, 1992.

[5] G.P. Agrawal, Nonlinear fiber optics, 3rd edition, San Diego, CA: Academic Press, 2001.