High Repetition-Rate Ultra Short-Pulse Train Generation by Short Comb-like Dispersion Profiled Fiber Using High-Nonlinearity DSF

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ABSTRACT Not only broadband DWDM transmission systems but also high bit rate transmission of over 40 Gbps per channel is investigated for the next generation of fiber optical networks. For ultra high-speed signal processing that is not available with electrical components, it is effective to use all-optical signal processing with optical fiber devices using nonlinear effects through fibers. For the purpose of developing a high speed optical pulse generator as a standard clock for all-optical signal processing, we have studied high repetition rate pulse generation by short length Comb-like Dispersion Profiled Fiber (CDPF) using high nonlinearity dispersion shifted fiber with about six times more nonlinearity than conventional DSF and 1.3 μm zero dispersion single mode fiber. To eliminate pedestal noise in the short pulse, we constructed the CDPF by incorporating a dispersion imbalanced nonlinear optical loop mirror and generated a 100 GHz 380 fs pulse train.

1. INTRODUCTION

For next-generation optical networks, it is expected that transmission capacity will be increased by making high channel density and wide band WDM systems, and increasing data bitrate per wavelength channel. The high bitrate per channel system has great potential for cost reductions in comparison with wide broaden DWDM systems of the same transmission capacity, because of a fewer number of channels and simple control of wavelength dependence. To realize a high-speed transmission system of more than 40 Gbps per channel, electrical signal processing speed at transmitters and receivers is the limiting factor. Accordingly, all-optical signal processing is necessary for signal switching and down rate conversion to use electrical signal processing. For an advanced optical transmission system using all-optical signal processing, it is desirable to have a new technique whereby the optical fiber devices use nonlinear effects through fibers.

In this report, for the purpose of developing an optical clock pulse generator that is used for the optical signal processing, we have researched short pulse generation by Comb-like Dispersion Profiled Fiber (CDPF) using a high nonlinearity fiber.

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2. HIGH REPETITION RATE PULSE SOURCE USING PULSE COMPRESSION THROUGH OPTICAL FIBER

Short optical pulse sources with high repetition rates are expected to play a key role in high capacity Optical Time Division Multiplexed (OTDM) transmissions. Since Electric Time Division Multiplexing (ETDM) methods have difficulty generating pulses at a repetition rate higher than 100 GHz, one may want to have an alternative to generate such pulse trains through other means. Pulse sources used for high bit rates of over 40 Gbps are mostly investigated using OTDM with low bit rate pulse sources [1), 2)]. Stand-alone high repetition rate ultra short pulse generation methods were suggested earlier, such as mode-locked DFB laser diode [3)], and a method using modulation instability through the fiber [4)], but it is desirable to generate high repetition pulses in a more stable and simple way for all optical signal processing. In such a case, pulse compression of beat modulation between two optical carriers is an attractive method. This technique requires only standard tunable laser sources and optical fibers, but permits us to tune the repetition rate and the center wavelength of the pulse train simply by adjusting the frequencies of the input lasers. In the process of propagating through the optical fiber, the pulse width of the beat pulse is compressed by nonlinear and dispersion effects [5)]. The techniques of beat signal conversion were previously demonstrated with Dispersion-Decreasing Fiber (DDF) [6), 7)]. An alternative approach is to profile the fiber dispersion using segments of conventional fibers with different dispersions.

Step-like dispersion profiled fiber consists of several segments of dispersion shifted fiber with different dispersion[8]. With Come-like Dispersion Profiled Fiber (CDPF) that consists of alternating segments of Dispersion Shifted Fiber (DSF) and Single Mode Fiber with 1.3 μm zero dispersion (SMF) respectively, picosecond pulse generations are observed[9), 10)]. A soliton pulse train was also generated using a CDPF comprising only of two pairs of DSF and SMF[11), 12)]. A transmission test using a pulse train generated by such a method was also carried out[13)].

A schematic of CDPF configuration is illustrated in Figure 1. A beat signal synthesized from two CW sources, which have a slightly different wavelengths, is launched into a DSF. In the DSF, Self Phase Modulation (SPM) induces a chirp in a pulse. In the following SMF, the anomalous dispersion compensates the chirp and the pulse width is compressed. After repeating this process several times, the beat signal is converted into a pulse train. Previous work on a CDPF used conventional standard DSF and SMF. In this type of fiber, the nonlinear chirp effect through the DSF plays an important role in pulse compression, and it is effective to use highly nonlinear (HNL-) DSF to shorten DSF segments[14), 15)].

The main feature of the CDPF in this report is the use of a high nonlinearity fiber for DSF.

The transmission characteristics of the HNL-DSF are shown in Table 1. The nonlinear coefficient γ ($\gamma = n_2 / A_{eff} \cdot 2\pi/\lambda_p$, n_2 is the nonlinear refractive index, A_{eff} is the effective area, and λ_p is the wavelength) of this fiber is about six times larger than the value of the conventional DSF; therefore, we can shorten the fiber to obtain an equivalent nonlinear effect compared to a standard DSF.

It is desirable to shorten the fiber using HNL-DSF for the following reasons: (1) as fiber length decrease, the state of polarization fluctuation between two tone signals becomes smaller to produce larger Four Wave Mixing (FWM), and (2) a shorter fiber may have less dispersion fluctuations along the fiber length to better maintain the zero-dispersion condition for obtaining a large and broader bandwidth SPM.

3. PULSE GENERATION WITH 5 PAIRS OF CDPF USING HNL-DSF

We have constructed a CDPF using HNL-DSF and commercially available SMF[16)]. The fiber consisted of 5 pairs of DSF and SMF, and had a total length of 693.6 m. The composition of fibers in CDPF is shown in Table 2. The experimental setup is shown in Figure 2. A dual frequency beat signal was generated by two tunable-wavelength lasers (HP8368F). The wavelength space between two waves was set at 0.831 nm to generate a pulse train approaching a 100 GHz repetition rate. The center wavelength was tuned to coincide with the zero dispersion wavelength of the HNL-DSF to generate a nonlinear effect efficiently. Two tunable laser sources were phase modulated using the built-in modulation function to suppress Stimulated Brillouin Scattering (SBS). Two signal powers were set equally and the polarization states were aligned in parallel by adjusting polarization controllers to minimize insertion loss of the polarizer. Both waves are combined by a fiber-fused coupler. The beat signal was amplified by

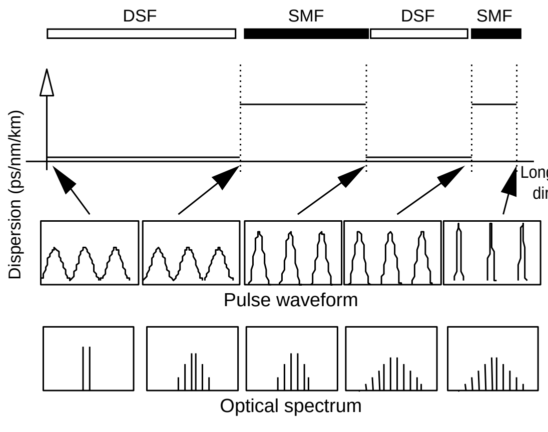

Figure 1 Pulse compression process using comb-like dispersion profiled fiber. (Example of two pairs of DSF and SMF)

Table 1 Characteristics of high nonlinearity fiber.

Parameter	Value
Attenuation coefficient	0.61 dB/km
Zero dispersion wavelength	1565.5 nm
Dispersion slope (@$\lambda = \lambda_0$)	0.029 ps/nm^2/km
Nonlinear coefficient	17.5 W^{-1} km^{-1}

Table 2 Configuration of five pairs of CDPF.

Pair of fibers	Dispersion @1565 nm	1	2	3	4	5
DSF	-0.015 ps/nm/km	160	200	100	50	30
SMF	+17 ps/nm/km	144	7	2	0.3	0.3

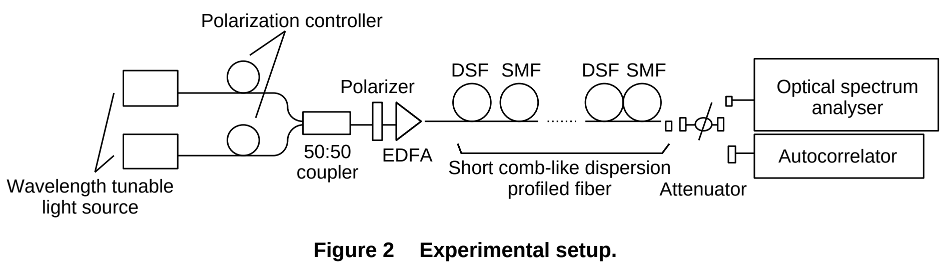

Figure 2 Experimental setup.

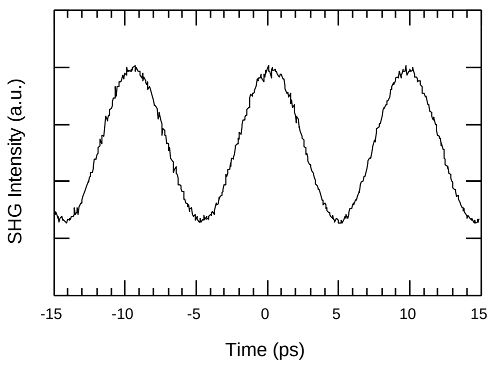

Figure 3 Autocorrelation trace of fiber input beat pulse.

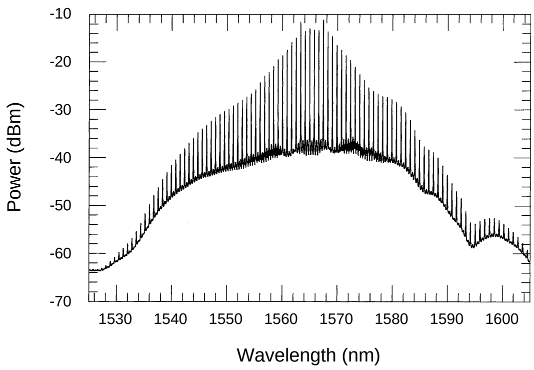

Figure 4 Optical spectrum of output pulse.

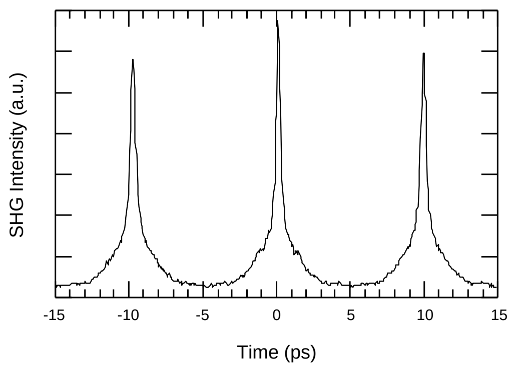

Figure 5 Autocorrelation trace of output pulse.

an Erbium Doped Fiber Amplifier (EDFA). The launched beat signal power to the first DSF of CDPF was set at +27.5 dBm, which is below the limit of SBS. Figure 3 shows the SHG autocorrelation trace of the input beat signal. The optical spectrum of the output pulse and the SHG autocorrelation trace after transmission of the 5th pair of fiber segments in CDPF are shown in Figures 4 and 5. For the pulse transmitted through the 5th pair of fiber segments, the pulse repetition rates were 104 GHz and the measured autocorrelation full-width at half-maximum (FWHM) was 505 fs, which gives a pulsewidth of 328 fs, assuming a $sech^2$ pulse-intensity profile. Also, by fitting a $sech^2$ envelope to the peaks in Figure 4, the FWHM of the spectrum was measured to be 7.59 nm. Therefore, the estimated time-bandwidth product was approximately 0.305. The duty cycle of the pulse output from the 5th pair of fiber segments in CDPF was 0.034 and the period-to-duration ratio $T/\Delta\tau$ (T is the period and $\Delta\tau$ is the FWHM of the pulse) reached 29.3.

To achieve high compression ratio in CDPF, many pairs of comb-like segments are needed and the scheme becomes complex. The nonlinear phase shift around the peak of the beat modulation is approximately parabolic and the beat modulation is compressed due to linear chirp compensation through SMF. Therefore, this implies that the foot of the pulse is not compressed and remains as pedestal noise. As shown in Figure 5, it should be noted that the pulses had pedestal noise.

4. PEDESTAL NOISE SUPPRESSED PULSE SOURCE USING DI-NOLM

DI-NOLM (Dispersion-Imbalanced Nonlinear Optical Loop Mirror) is effective to eliminate pedestal noise in the short pulse [17)~19)]. DI-NOLM is a Sagnac loop comprising fibers with different dispersions, and by propagating the input pulse split along the two directions in DI-NOLM, the split pulses experience different nonlinear phase shifts in clockwise and counterclockwise directions because they stretch differently, and the peak powers evolve differently due to the asymmetric dispersion of the loop. This feature results in the loop discriminating the transmission, depending on the derivative of electric field amplitude with respect to time. Thus, the center of the pulse can be adjusted to transmit only through the loop, while the pedestal noise is rejected.

Our next goal is to achieve more efficient pulse compression than with the above-mentioned 5 pairs-CDPF and simultaneous pedestal suppression using a simple configuration. We have constructed a short 3 pair CDPF with HNL-DSF, and SMF and incorporated them into this CDPF DI-NOLM, which does both beat pulse compression and pedestal noise suppression at the same time [20)].

5. EXPERIMENTAL SETUP AND RESULTS

The experimental setup is shown in Figure 6. We constructed the CDPF and fiber loop mirror using the HNL-DSF and commercially available SMF. The CDPF consists of 2 segments of DSF and one segment SMF and the loop mirror consists of 2 segments of SMF and one segment of DSF. The characteristics of fibers in CDPF and DI-NOLM are shown in Table 3. The zero dispersion wavelength of HNL-DSF approaches 1557 nm and the other characteristics of the HNL-DSF are the same as those shown in Table 1. A dual frequency beat signal was generated by two tunable-wavelength lasers. Two wavelengths were respectively set at 1557.04 nm and 1557.84 nm, because the wavelength space between two waves was set at 0.8 nm to generate a pulse train at a near 100 GHz repetition rate. Two signal powers were set to be equal and the polarization states were aligned to be parallel by adjusting

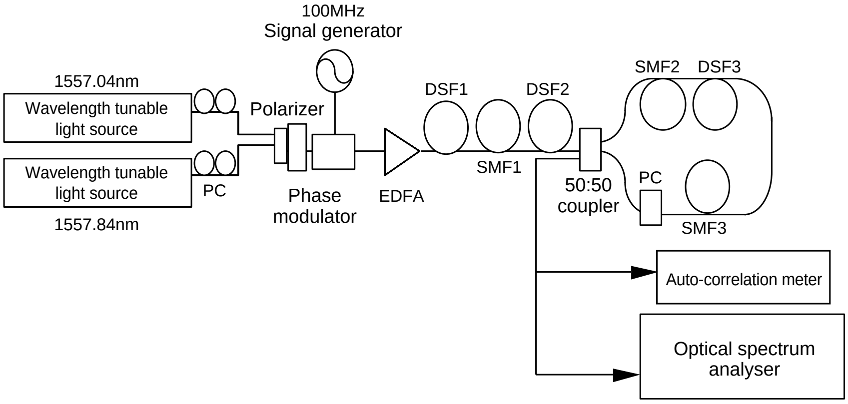

Figure 6 Experimental setup. P.C.: polarization controller

Table 3 Comb-like dispersion profiled fiber length.

Segments	1	2	3
DSF	200	100	62
SMF	91	7.5	0.3

polarization controllers to minimize insertion loss of the polarizer placed at the input port of the phase modulator. Both waves were combined by a fiber-fused coupler. Two tunable laser sources were jointly phase-modulated using a phase modulator driven by a 100 MHz frequency signal to suppress SBS. The beat signal was amplified by an EDFA. The launched beat signal power to the first DSF of CDPF was set at +27.7 dBm. In the DI-NOLM, the compression ratio of the counterclockwise propagating pulse is designed to be smaller than that of the clockwise propagating pulse. Therefore, there is a difference in the nonlinear phase shift between the two pulses propagating in the opposite directions. The length of SMF3 was optimized to best suppress pedestal noise. The polarization states of clockwise and counterclockwise propagating pulses were adjusted by a lossless polarization controller set in the loop. Because the DI-NOLM is composed by a part of CDPF, the output pulse from the fiber loop mirror is compressed and its pedestal noise is suppressed simultaneously.

The SHG autocorrelation traces of input and output pulses of the DI-NOLM are shown in Figure 7 and Figure 8 shows the optical spectrum after DI-NOLM transmission. The repetition rate of the output pulse from DI-NOLM was 98.9 GHz and the measured Full-Width at Half-Maximum (FWHM) of autocorrelation was 587 fs, which gives a pulsewidth of 380 fs, assuming a $sech^2$ pulse-intensity profile. Also, by fitting a $sech^2$ envelope to the peaks in Figure 8, the FWHM of the spectrum was measured to be 1229 GHz. Therefore, the estimated time-bandwidth product was approximately 0.467. In Figure 7, comparing the input and output pulses, the input 1.369 ps pulse is compressed by a factor of 3.6 down to 380 fs. In Figure 9, the autocorrelation traces of the pulses after clockwise transmission from SMF3 and from loop mirror output are compared. The pulse after transmission from SMF3 is equivalent to the output pulse from a straight-line CDPF configuration. By constructing the loop mirror incorporated in CDPF, the pedestal component in the output pulse from the loop mirror is suppressed more than that from the 'straight-line' CDPF, and the pulse profile is reshaped to near the soliton function. The period-to-duration ratio $T/\Delta\tau$ reached 26.6.

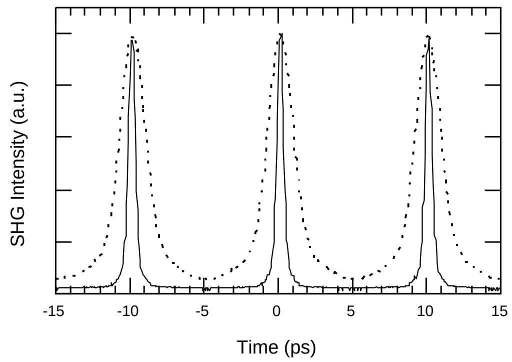

Figure 7 Autocorrelation traces of DI-NOLM input (dashed line) and output (solid line) pulses.

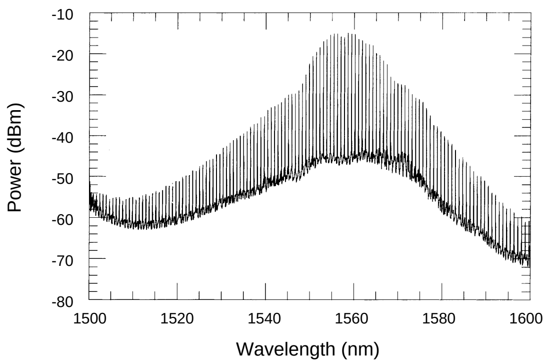

Figure 8 Optical spectrum of DI-NOLM output pulse.

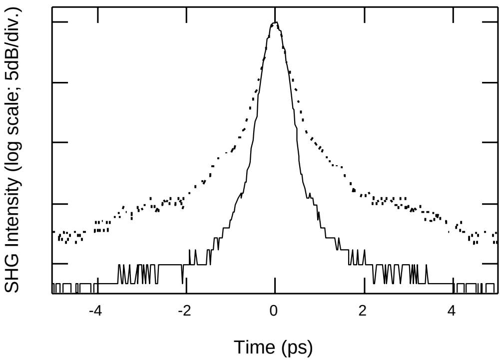

Figure 9 Autocorrelation trace of DI-NOLM output pulse, showing loop mirror output (solid line) and SMF3 output clockwise propagation in the DI-NOLM (dashed line).

6. CONCLUSION

We aimed to develop a high repetition rate ultra short pulse source using fiber nonlinearity for all-optical signal processing in high bit rate transmission over 40 Gbps. We constructed a 693.6 m long Comb-like Dispersion Profiled Fiber using a HNL-DSF with a nonlinear coefficient that is about six times larger than that of a conventional DSF. Using this short CDPF, we generated a 104 GHz soliton pulse train with a 328 fs pulsewidth and achieved a period-to-duration ratio $T/\Delta\tau$ of 29.3. Furthermore, to simplify the fiber configuration and eliminate pedestal noise while keeping a high pulse compression ratio, we constructed a short 3-pair CDPF with HNL-DSF and SMF, and incorporated into this CDPF DI-NOLM. We generated a 100 GHz, 380 fs pulse train through this CDPF-DI-NOLM. In the output pulse, pedestal noise is suppressed more than in a 5-pair straight line CDPF output. This type of high repetition beat pulse source has potential for optical clocks using all-optical signal processing, and future problems are to reduce timing jitter and noise, to shorten pulsewidth, and to make it more compact.

ACKNOWLEDGEMENT

We would like to thank Mr. Yagi, Mr. Hiroishi, Ms. Kumano, and Mr. Sugisaki in the WF team for making the HNL-DSF.

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