A Highly Nonlinear Fiber Module and its Application to the Generation of Ultra-High Repetition-Rate Sub-Picosecond Optical Pulse Trains

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ABSTRACT Work is going forward on examining the efficacy of highly nonlinear fiber (HNLF) with respect to various types of highly nonlinear optical devices, and on developing modules. Studies on the adaptation of HNLF to the generation of ultra-high repetition-rate sub-picosecond optical pulse trains, one of its applications, have demonstrated the efficacy of HNLF with respect to generating 160-GHz 0.8 ps ultra-high purity soliton trains using comb-like dispersion-profiled fiber (CDPF). An HNLF module having a conveniently usable configuration has also been developed. Studies have also been carried out on applying this module in subsystems, and its efficacy with respect to optical delay circuitry and all-optical regeneration has also been demonstrated.

1. INTRODUCTION

The technology of nonlinear optical signal processing is indispensable in optical fiber transmission systems having single-channel bit rates in excess of 100 Gbit/s. Various semiconductors and dielectrics have been considered for use as the nonlinear material, and devices using them have been fabricated. Of them all it is optical fiber that has been found to be superior in terms of the high speed, low noise and low loss of its nonlinear response. In fact there have been a large number of proposals for methods of using four-wave mixing [1] and nonlinear polarization rotation [2] in optical fibers, and for techniques for using nonlinear fiber loop mirrors [3], and examples exhibiting superior broad-band properties and ultra high-speed characteristics have been reported.

One of the most important issues in improving the performance of these nonlinear optical fiber devices is increasing the nonlinearity of the fiber. Despite the fact that the third-order nonlinear coefficient of silica glass is not inherently large, its nonlinearity can be increased by such means as adding material with a high refractive index to the fiber core, or reducing the core diameter. Indeed highly nonlinear fibers (HNLFs) have been reported that have nonlinear coefficients some ten times greater than that of conventional fiber [4, 5], and discussions are progressing on their application in subsystems [4, 6~8].

Against this background the authors are investigating the efficacy of HNLF with respect to a variety of nonlinear optical signal processing devices and subsystems. At the same time studies are also being carried out on the development of modules. When HNLF is to be used in a subsystem, it is indispensable that its configuration be of outstanding stability and reliability, and be easy to use, and development of HNLF modules is the most important issue. This paper will present an HNLF module that advances the development of ultra-high repetition-rate sub-picosecond soliton train generation [8], as an application of HNLF.

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2. GENERATION OF ULTRA-HIGH REPETITION-RATE HIGH PURITY SUB-PICOSECOND SOLITON TRAINS

Optical transmission systems exceeding 100 Gbit/s per channel require a clock pulse generator with a repetition frequency corresponding to the bit rate. Since it is difficult, based on methods using conventional electronic circuit technologies, to operate in the range above 100 GHz, the normal way of achieving the desired ultra-high repetition rate is by the dividing, delaying and combining of a 10- or 40-GHz pulse train to achieve time-division multiplexing. It is not, however, a simple matter to control and stabilize the delay, and another problem is presented by coherence degradation of the pulse train.

It was at this point that the authors identified a method of converting a dual-mode optical beat signal into an optical soliton train by a process of adiabatic soliton compression in the optical fiber [9]. Since it is possible, by combining two continuous waves (CW) having a wavelength difference corresponding to the desired repetition frequency, to produce a beat signal optically, this method does not require a high-speed electrical circuit. It is also possible that, since the conversion from beat signal to a soliton train uses the process of adiabatic soliton compression, it would be possible to generate a soliton train of extremely high purity. We may also say that by stabilizing and controlling the continuous wave wavelength using an electronic circuit of comparatively low frequency (MHz order) it is possible to achieve synchronism with an external reference signal.

The crucial point in this technique for generating an ultra-high repetition-rate soliton train lies in adiabatic soliton compression. As means of achieving this there are reports of methods using Raman amplification fiber[9], dispersion-decreasing fiber[10], and fibers with step-like[11] and comb-like[12] dispersion profiles. Of these the authors focused on comb-like dispersion profiled fiber (CDPF) consisting of two types of fiber having significantly different dispersion values. From the standpoint of ease of manufacture there is nothing remotely approaching a CDPF in which adiabatic soliton compression is realized by two types of fiber. The CDPF is also advantageous in terms of suppression of the phenomenon of stimulated Brillouin scattering, which limits compression. This is because, generally speaking, fibers with significantly differing dispersion values have different Brillouin gain bands[12].

Figure 1 is a schematic showing the principle of the CDPF. Ideally the CDPF provides a transmission path in which a nonlinear medium and a dispersion medium repeat alternately. Generally a zero dispersion-shifted fiber (DSF) is used for the nonlinear medium and a single-mode fiber (SMF) is used for the dispersion medium, spliced together to form the CDPF. Here, the use of HNLF for the nonlinear medium not only enables the realization of an ideal nonlinear medium, but also enables the possibility of a high degree of shortening of the fibers. Recognizing this, the authors fabricated a CDPF using HNLF, and while clarifying the compression performance for a 160-GHz beat signal, investigated the effect of the HNLF.

Figure 2 shows the experimental setup. Using a CDPF made up of six HNLF-SMF pairs, the apparatus achieves the adiabatic soliton compression of a 160-GHz beat signal obtained by combining the output CWs from two laser diodes having an optical frequency difference of 160 GHz. The HNLF used here has a dispersion of −0.8 ps/nm/km and a nonlinear coefficient of 24 1/W/km. The profiles for dispersion D of the CDPF and average dispersion for each pair D_{ave} are depicted in the upper panel of Figure 3, the point to note being that D_{ave} increases in the three pairs of the first stage and decreases in the three pairs of the last stage.

The design is such that the beat signal is efficiently converted into a soliton train by the increased-dispersion CDPF of the first stage, and the soliton compression is then performed by the decreased-dispersion CDPF. The profile of nonlinear coefficient γ is shown in the middle panel of Figure 3. It can be seen that through the use of HNLF in the CDPF, both the fiber dispersion and the nonlinear coefficient assume a comb-like profile, realizing an ideal CDPF transmission path. It is also to be noted that noise amplification through modulation instability gain has been suppressed by using a normal dispersion HNLF.

The autocorrelation traces and optical spectra of the CDPF compression system are shown for the input and output pulse trains in Figure 4 (a) and 4 (b) respectively. The broken line shows the results of fitting the pulse waveform to the sech² waveform. Since the CDPF output pulse waveform and the broken line are in good agreement, not only on the autocorrelation trace but also in the optical spectra, this shows that a high-purity soliton train is generated. In addition, with respect to the

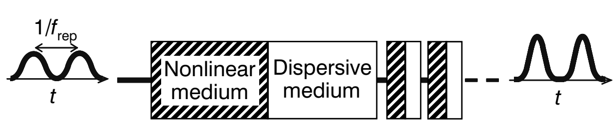


Figure 1 Schematic showing principle of CDPF, where f_{rep} is the repetition rate.

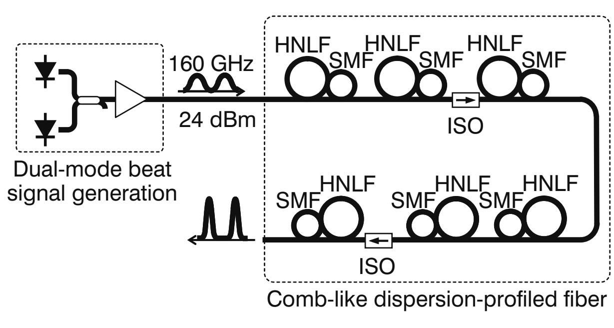


Figure 2 Experimental setup for 160-GHz soliton train generation using CDPF.

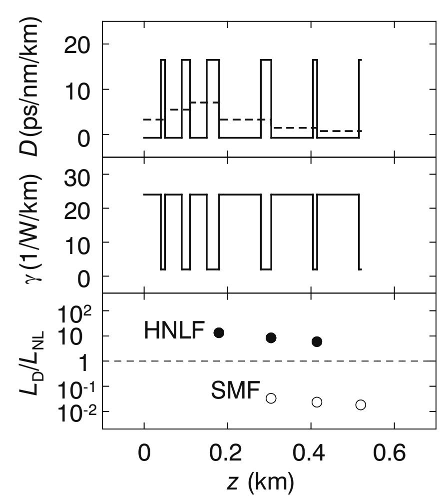
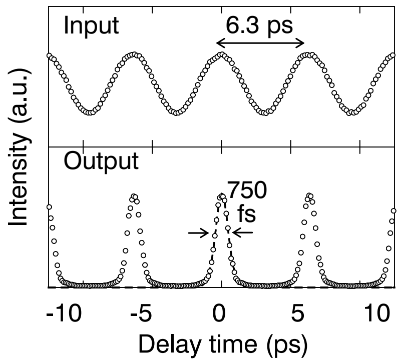
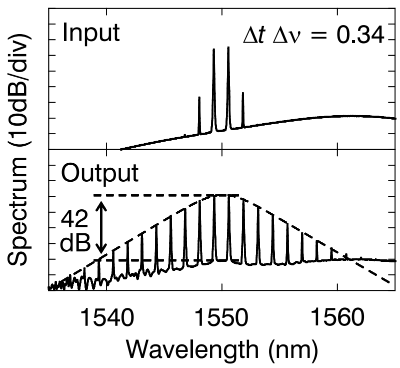


Figure 3 Profiles of dispersion (D) and nonlinearity γ, and the ratio of dispersion length (L_D) to nonlinear length (L_{NL}). Broken line shows the averaged dispersion for each pair (D_{ave}).



(a) Autocorrelation traces



(b) Optical spectra, where $\Delta t \, \Delta v$ is the time-bandwidth product

Figure 4 Input and output pulse trains of CDPF.

peak ratio of the optical signal component and the noise component on the optical spectra, not only were values of 40 dB or above obtained, but since there was no major change in the input/output spectral linewidth of the CDPF, it would seem that noise amplification in the compression process was adequately suppressed. From the sech² fitting with respect to the autocorrelation trace, the time width is calculated as 830 fs. Furthermore $\Delta t \Delta v$ was 0.34, indicating that a substantially Fourier transform limited pulse was obtained.

For the purposes of a quantitative discussion of the effectiveness of using HNLF for the CDPF, the ratio between nonlinear length and dispersion length (L_D/L_{NL}) has been plotted in the lower panel of Figure 3 using black circles for HNLF input and white circles for SMF output. The point to note here is for the HNLF the values are greater than 1, and for the SMF less than 1. This shows that in the HNLF the nonlinear effect is dominant, whereas it is the dispersion effect that is dominant for the SMF. From this discussion it may be concluded that using HNLF in the CDPF has realized an ideal CDPF transmission path, and as a result solitons of ultra-high quality were generated.

3. DEVELOPMENT OF HNLF MODULES

Investigations have been carried out not only into the generation of ultra-high repetition-rate pulse trains referred to in the foregoing, but also into the effectiveness of HNLF in wavelength conversion and spectrum broadening, and discussion is on-going with regard to subsystem applications for them. Generally speaking, however, fiber devices, being subject to external disturbance, can hardly be described as easy to use. In addition specialized fibers like HNLF, having core diameters that differ significantly from those of ordinary fibers, cannot readily be joined to conventional fibers by means of connectors.

From this it can be seen that the development of HNLF modules is a problem that must be addressed. Accordingly the authors are working to develop a compact HNLF module to enable connection with ordinary fibers. Generally the dimensions of fiber devices are determined by the diameter of the coils into which they can be rolled. Since HNLF provides strong optical confinement it can be rolled into smaller coils, allowing modules to be more compact. And enclosing the coiled HNLF in a casing makes it possible to realize a device that offers good resistance to external disturbance. In addition, joining short lengths of SMF with connectors attached by low-loss splicing to the two ends of the HNLF facilitates connections to ordinary fibers. In the following the techniques adopted in developing HNLF modules will be discussed in detail.

3.1 Coil Rolling

The first step toward realizing a module in this work was the use of a medium-sized coil 16 mm in diameter. Characteristics before and after rolling are shown in Table 1. Not only has bend-induced loss been suppressed, but it is also to be noted that changes in the wavelength at zero dispersion (λ_0) and the dispersion slope, which are crucial to the performance of the device, have also been suppressed. And although there was a certain amount of increase in polarization mode dispersion, it would not seem to be of a degree that would seriously affect device performance.

3.2 Fiber Ends

Although it is difficult to join HNLF and SMF using connectors, it is easy to achieve low-loss splicing between the two. In fact splicing loss can be reduced to 0.1 dB or better by optimizing splicing conditions. Thus by splicing SMF with connectors attached to the ends of the HNLF, as shown in Figure 5, it is possible for these modules to be joined to ordinary fibers by low-loss connectors, as in the case of conventional devices.

Table 1 Characteristics of HNLF before and after rolling.

	Before	After
λ_0 (nm)	1494	1497
Dispersion slope (nm)	0.02	0.02
Loss (dB)	0.47	0.48
PMD (ps/$\sqrt{\text{km}}$)	0.03	0.13

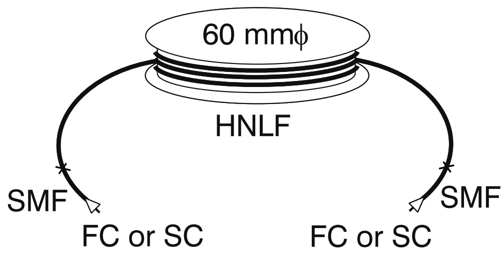


Figure 5 Splicing of SMF to the ends of the HNLF, and the input and output connectors.

Figure 6 HNLF module measuring 180(L)×150(W)×40(D) mm.

3.3 Module Configuration and its Performance

Figure 6 shows the HNLF module, in which coils of HNLF are enclosed in a casing. Lengths of SMF with connectors attached are spliced to the input and output ends, and splicing loss is 0.2 dB or better. We may say that such modules, resistant to external disturbance and easy to use, are of a configuration that is advantageous in applications to subsystems. In fact studies have been conducted on the application of these modules to optical delay circuits [13] and optical regeneration in 40-Gbit/s transmission [14], demonstrating their efficacy.

4. CONCLUSION

As the result of investigation of ultra-high repetition-rate pulse train generation as an application of HNLF, generation of a 160-GHz 0.8-ps ultra-high purity soliton train has been demonstrated by means of CDPF using HNLF. HNLF is indispensable to the generation of such high-purity solitons. Investigations are also being made into the development of HNLF modules. Since modules constitute a configuration that is easy to use and highly stable, it is important to subsystem applications. The efficacy of these modules in optical delay circuits and all-optical regeneration has been demonstrated.

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