A Comb-Like Profiled Fiber (CPF) Compressor and an Ultra-short Pulse Light Source

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ABSTRACT Ultra-short (picosecond and femtosecond range) pulse light sources using optical fibers are attracting attention, not only in the field of telecommunications, but also in such fields as optical metrology, materials processing, bio-photonics, and physics. As the optical fiber compressor for generating ultra-short pulses, we have proposed a comb-like profiled fiber (CPF) which is an alternate concatenation of highly nonlinear fiber (HNLF) and single-mode fiber (SMF). In the present work we examined whether or not uniform output pulse characteristics could be obtained from a CPF compressor even if the wavelength or repetition rate of the input pulse is changed. As a result we were able to confirm that output pulse characteristics were uniform over wavelengths from 1530 to 1560 nm, and over repetition rates from 5 to 500 MHz.

1. INTRODUCTION

Ultra-short pulse light sources using optical fibers are attracting attention from the standpoint of compactness, low cost and stable performance, in the fields of ultra-high-speed optical communication and optical metrology, as well as materials processing, bio-photonics, physics, etc.

As the optical fiber compressor for generating ultra-short pulses, we have reported on a comb-like profiled fiber (CPF) which is an alternate concatenation of highly nonlinear fiber (HNLF) and single-mode fiber (SMF) [1)~3)]. A CPF compressor can be flexibly designed with respect to its dispersion profile, making it very advantageous in terms of ease of manufacture. In the present work, in an effort to confirm the further utility of the CPF compressor, we examined whether or not uniform output pulse characteristics could be obtained even if the wavelength or repetition rate of the input pulse changes. And we report that we have been able to confirm that output pulse characteristics were uniform over wavelengths from 1530 to 1560 nm [4)], and over repetition rates from 5 MHz to 500 MHz [5)].

1.1 Importance of Wavelength-Tunable Ultra-short Pulse Light Source

To increase the capacity of optical transmission systems, research has been carried forward on wavelength-division multiplexing (WDM) systems, in which signals are multiplexed on the wavelength axis, and on time-division multiplexing (TDM) systems, in which signals are multiplexed on the time axis. Because TDM systems suffered from problems such as limits on the speed of electronic circuitry, it is WDM systems that have been more actively brought into practical use. Attention is, however, being paid to optical TDM (OTDM) systems, which have a smaller number of transmitter/receiver units and easier batch control than WDM, and in this sort of ultra-high-speed optical communications applications, it has become important to develop all-optical signal processing, which eliminates optical-electric conversion. The key device in realizing all-optical signal processing is an ultra-short pulse light source, which works as a stable clock pulse train. And for wavelength-division multiplexing of OTDM systems there must be clock pulse trains at various wavelengths, that is to say, an ultra-short pulse light source.

1.2 Expectations for a Repetition Rate-Tunable Ultra-short Pulse Light Source

In the fields of optical metrology, materials processing, bio-photonics, physics, etc., attention is being given from the standpoint of compactness, low cost and stable operation, to the development of an ultra-short pulse light source using optical fiber. Further improvement in its utility can be anticipated if it can be made tunable by repetition rate, wavelength, pulse width, pulse energy and so on. For the mode-locked fiber lasers that have been in general use as ultra-short pulse light sources, however, cavity length is fixed, so that it was difficult to change the repetition rate to any great degree. In contrast light sources that use an optical pulse compressor can vary the repetition rate of the seed pulse, holding promise that repetition rate tunable response can be achieved. If the repeti-

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tion rate can be controlled, average power can be controlled while maintaining the various pulse characteristics, thereby increasing the utility of the light source.

2. OPTICAL PULSE COMPRESSION TECHNOLOGIES

2.1 Adiabatic Soliton Compression

Adiabatic soliton compression is a term for techniques whereby optical pulses are compressed, imparting to the basic soliton a gentle perturbation inside the fiber. They are advantageous in that there is so little degradation in time waveforms or spectral profiles.

There are four main techniques for adiabatic soliton compression, namely: 1) a method using dispersion-decreasing fiber (DDF) [6]; 2) a method using step-like dispersion profiled fiber (SDPF), in which a plurality of optical fibers having different dispersions are used, changing the dispersion profile in the longitudinal direction of the fiber [7]; 3) a method using comb-like dispersion profiled fiber (CDPF), in which two optical fibers having different dispersions are used, changing the dispersion profile in the longitudinal direction of the fiber [8]; and 4) a method using Raman compression, in which gain is gently imparted in the longitudinal direction of the fiber [9].

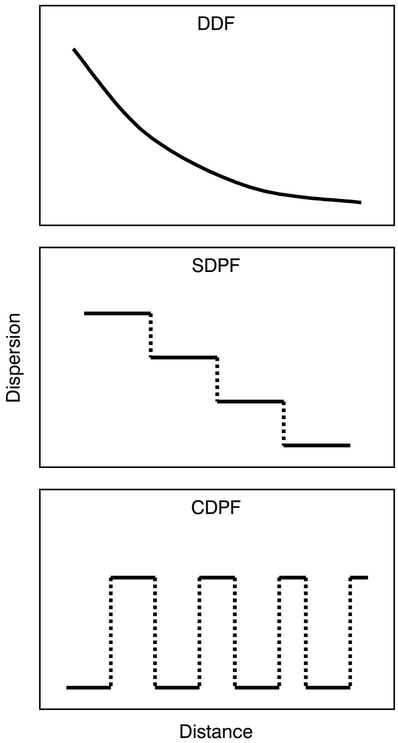


Figure 1 Schematic profiles of DDF, SDPF and CDPF fibers.

Table 1 Comparison among methods of adiabatic soliton compression.

Method	Advantages	Disadvantages
DDF	Ideal adiabatic compression is possible	Fiber is difficult to make
SDPF	Fiber is relatively easy to make	Multiple types of fiber are required Number of connection points is large
CDPF	Can be designed with two types of fiber Suppressive effect of stimulated Brillouin scattering	Number of connection points is large
Raman	Compression ratio can be controlled using gain compression	Longitudinal distribution of gain is difficult to control

Figure 1 shows schematic profiles of DDF, SDPF and CDPF fibers. Table 1 compares the four methods of adiabatic soliton compression.

As Figure 1 shows, in the DDF method it is possible to gently decrease the dispersion constituting the perturbation, so that an ideal adiabatic soliton compression can be achieved. It is difficult, however, to manufacture an optical fiber in which dispersion parameters decrease in an ideal manner along the length of the optical fiber. Accordingly the SDPF and CDPF methods have been proposed, using a combination of a plurality of optical fibers of differing dispersions, to achieve a DDF profile by approximation. Whereas SDPF requires several types of optical fiber, CDPF can be manufactured with two types, and is thus preferable from the practical point of view. What is more in CDPF, fibers of greatly differing dispersion are connected in multiple steps, making it superior from the standpoint of stimulated Brillouin scattering, as well.

2.2 Optical Pulse Compression Using Comb-like Profiled Fiber

The ideal CDPF comprises a nonlinear medium and a dispersion medium in a multistep connection configuration. Generally zero dispersion-shifted fiber (DSF) is used for the nonlinear medium and single-mode fiber (SMF) is used for the dispersion medium, and they are connected by fusion splicing.

We are proposing a novel comb-like profiled fiber (CPF) in which a pair of HNLF and SMF is multistep connected. Since HNLF is used instead of DSF, it has, as shown in

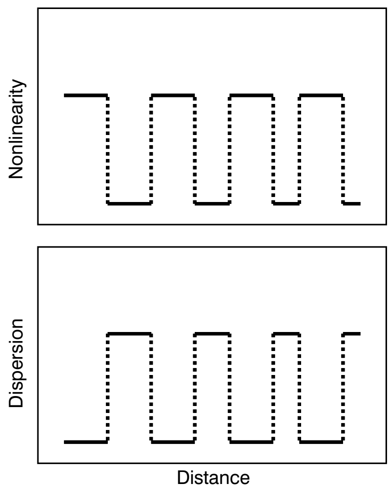


Figure 2 Schematic of nonlinearity coefficient and dispersion profile of CPF.

Figure 2, a comb-like profile not only for dispersion but also for the nonlinearity coefficient.

For the nonlinear medium we have used an optical fiber with a small dispersion and high nonlinearity, so that it is possible both to obtain an ideal nonlinear medium and to achieve a compressor of shorter length. Also, as in the SDPF, since we have multistep connection of optical fibers with greatly differing dispersion values, it is superior in suppressing stimulated Brillouin scattering. Note however that stimulated Brillouin scattering is not suppressed completely, so that isolators must be inserted as needed.

2.3 Development of Highly Nonlinear Fiber

We have also developed a highly nonlinear fiber (HNLF) with a large nonlinearity coefficient and a small dispersion value, suited for use in the CPF [10]. Table 2 gives a comparison of typical characteristics for SMF and DSF, which have been used in conventional pulse compressors, and for the HNLF that we have developed. The nonlinearity coefficient of HNLF is more than ten times greater than that of SMF, and about ten times that of DSF.

3. FEMTOSECOND COMPRESSION OF OPTICAL PULSES USING CPF COMPRESSORS

We evaluated the wavelength tunability and repetition rate tunability of femtosecond compression using CPF, and report the results below. Specifically, we evaluated the uniformity of characteristics from the optical spectra and autocorrelation traces while varying the wavelength of the input pulses to the CPF in order to obtain optimum operation. In the same way we evaluated the uniformity of characteristics while varying the repetition rate of the input pulses to the CPF in order to obtain optimum operation.

Table 2 Comparison of characteristics among selected fibers.

Parameter (@ 1550 nm)	SMF	DSF	NLF
Attenuation coefficient (dB/km)	0.20	0.21	1.16
Zero-dispersion wavelength (nm)	1310	1550	1500~1600
Dispersion slope (ps/nm²/km)	0.09	0.07	0.013
Effective area (μm²)	80	50	9.7
Nonlinearity (1/W/km)	1.3	2.7	25.1

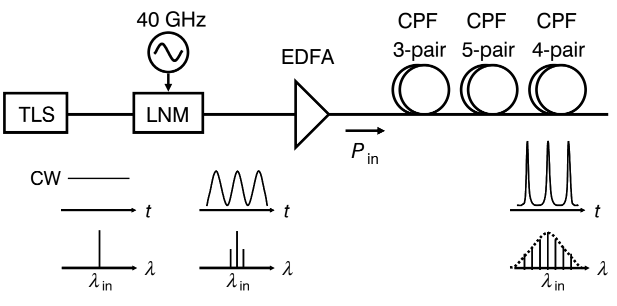


Figure 3 Schematic diagram of wavelength-tunable ultra-short pulse light source.

3.1 Wavelength-Tunable Femtosecond Compression Using CPF Compressors

Figure 3 is a schematic showing the experimental set-up for CPF compression of a 40-GHz pulse train. The 40-GHz pulse train was generated by external modulation of a continuous wave (CW) light beam of wavelength λ_{in} from a wavelength-tunable laser by means of a $LiNbO_3$ modulator (LNM). This was then amplified by an erbium-doped fiber amplifier (EDFA) and adjusted to the optimal input power P_{in} for CPF compression. The CPF comprises 12 HNLF-SMF pairs, totaling 1.4 km. Figure 4 shows the profiles of dispersion and nonlinearity coefficient for the 12-pair CPF. For the HNLF dispersion is 1 ps/nm/km or less and the dispersion slope is 0.02 ps/nm²/km. To suppress stimulated Brillouin scattering, two isolators were inserted along the CPF.

Figure 5 shows autocorrelation traces and optical spectra of the input pulse and the 3- 8- and 12-pair output pulses of the CPF, where λ_{in} is 1550 nm and P_{in} is 23.6 dB. It can be seen that for both the autocorrelation traces

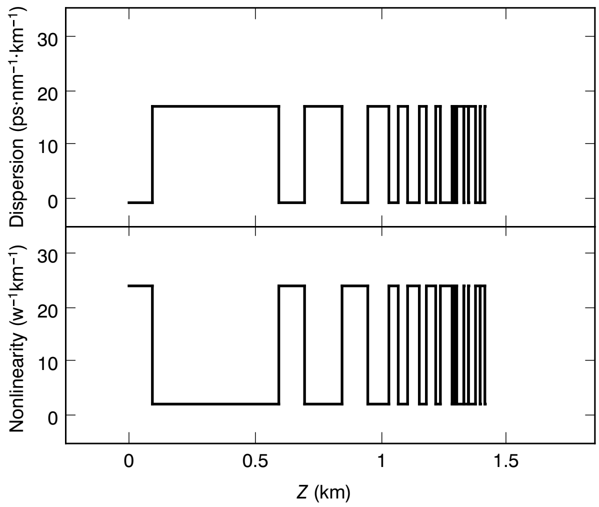
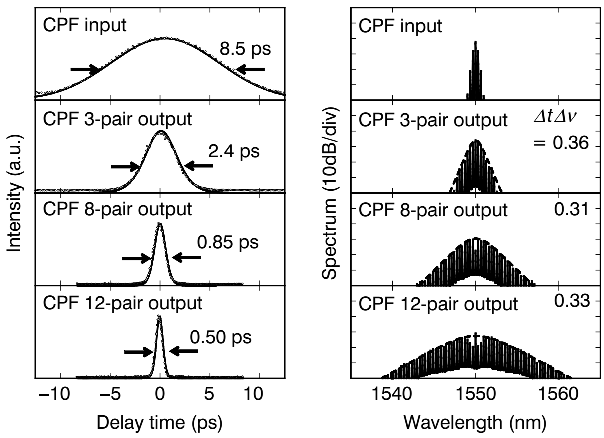


Figure 4 Profiles of dispersion and nonlinearity coefficient for 12-pair CPF.



a) Autocorrelation traces **b) Optical spectra**

Figure 5 Characteristics of input and various output pulses of CPF.

and the optical spectra shown in Figure 5, there was good agreement between the experimental values (solid lines) and the fitting with $sech^2$ (broken lines). It will also be seen that as the optical pulses were compressed as they propagated in the CPF, to the extent that at the 12-pair output they were compressed to a pulse width of 500 fs. The time-bandwidth product $\Delta t\Delta v$ at the 12-pair output was 0.33, and the peak-to-pedestal ratio R_{pp} was 15 dB.

Figure 6 shows the dependence of pulse width Δt, time-bandwidth product $\Delta t\Delta v$, CPF input power P_{in} and peak-to-pedestal ratio R_{pp} on the input wavelength of the tunable light source λ_{in}, when λ_{in} was varied in the range of 1530~1560 nm and P_{in} was fine-tuned so that the CPF 12-pair output pulse width was 500 fs. From Figure 6 it can be seen that by optimizing P_{in}, it is possible to keep Δt to 550 fs or less and $\Delta t\Delta v$ to 0.36 or less. It was also confirmed that R_{pp} was 14 dB or less.

Next we examined the wavelength tunability of the CPF. Wavelength tunability is significantly affected by wavelength dependence of the 2nd-order dispersion β_2 of the dispersion medium. That is to say it is significantly affected by β_3. Thus the larger the ratio $|\beta_2/\beta_3|$, the more advantageous in terms of wavelength tunability. Figure 7 is a schematic diagram showing the 2nd-order dispersion for CPF and DDF. Since 2nd-order dispersion β_2 is greater for CPF than for DDF, the influence of 3rd-order dispersion β_3 is less apparent, and wavelength tunability is more easily achieved.

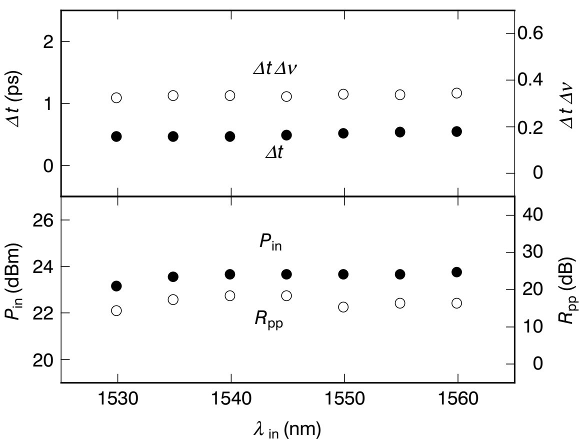


Figure 6 Dependence of pulse width Δt, time-bandwidth product $\Delta t\Delta v$, CPF input power P_{in} and peak-to-pedestal ratio R_{pp} on wavelength λ_{in}.

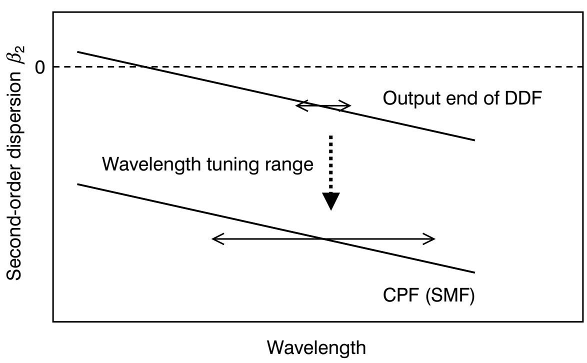


Figure 7 Schematic diagram of 2nd-order dispersion for CPF and DDF.

3.2 Repetition Rate Tunable Femtosecond Compression Using CPF Compressors

Figure 8 is a schematic diagram showing a repetition rate tunable ultra-short pulse light source. A distributed feedback laser diode (DFB-LD) is gain switched by a 400-ps electrical pulse from a pulse pattern generator (PPG), and a seed pulse is generated by chirp compensation using a dispersion compensating fiber (DCF). This seed pulse is first amplified by the 1st-stage EDFA to the pulse energy that is optimum for CPF compression, after which it is input to the CPF. It is then amplified to a pulse energy of 50 pJ by the normal-dispersion EDFA (ND-EDFA). The CPF consists of 13 HNLF-SMF pairs, with a total fiber length of 2.5 km. In the ND-EDFA we make use of two stages of EDFA comprising 20 m of EDF with a dispersion of −4 ps/nm/km. Then 2 m of SMF is connected after the ND-EDFA. The repetition rate of the seed pulse can be controlled by the repetition rate of the electrical pulse used to gain switch the DFB-LD.

Figures 9 through 11 show the autocorrelation traces and optical spectra for the seed pulse output, CPF output and ND-EDFA output respectively, and correspond to the points in Figure 8 indicated by A, B and C respectively.

From the results in Figure 9 for the autocorrelation traces for the seed pulse output, it can be seen that the input pulses to the CPF showed a certain amount of deviation, in the order of 12 to 17 ps. This is attributed to such factors as the band of the electrical amplifier and the adjustment method.

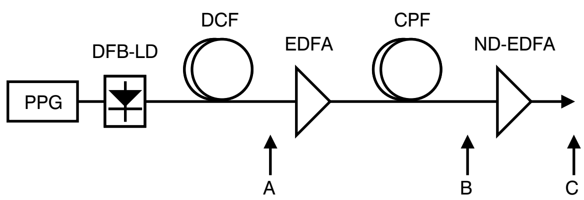


Figure 8 Schematic diagram of repetition rate tunable ultra-short pulse light source

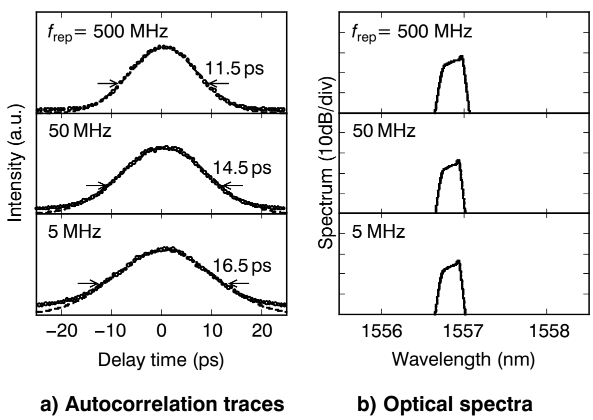
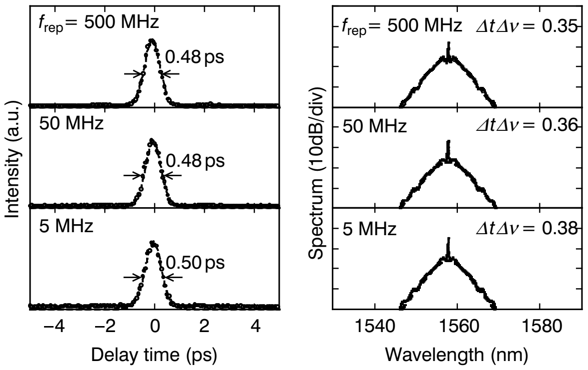
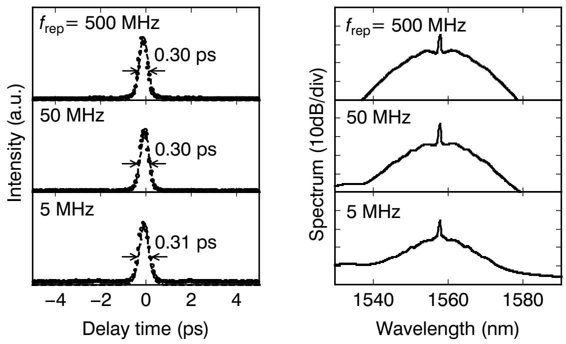


Figure 9 Seed pulse output characteristics.



a) Autocorrelation traces **b) Optical spectra**

Figure 10 CPF output characteristics.



a) Autocorrelation traces **b) Optical spectra**

Figure 11 ND-EDFA output characteristics.

The broken line plot in Figure 10 shows the fitting of sech² to the experimental results. It can be seen that there is a good fit to the experimental results for the autocorrelation traces and the optical spectra. When pulse width and peak-to-pedestal ratio at CPF output were estimated from the autocorrelation traces, we obtained values of <500 fs and >10 dB respectively. From this it can be seen that the CPF is responsive to a wide range of repetition rate tuning. Further, it can be seen from Figure 9 that even when the width of the pulse input to the CPF changes by several picoseconds, an output of constant pulse width can be obtained.

From the results in Figure 11 for the autocorrelation traces for the ND-EDFA output, it can be seen that the output pulse width is constant at approximately 300 fs, irrespective of the repetition rate. It can also be seen that the 500-fs CPF output pulse is being further compressed to 300 fs by the nonlinearity effect within the ND-EDFA, and by dispersion compensation by the SMF.

Figure 12 summarizes the results of Figures 9 through 11, showing the dependence of pulse width and pulse energy on the repetition rate. Values at seed pulse output are indicated by A, at CPF output by B and at ND-EDFA output by C, corresponding to the points indicated by A, B and C in Figure 8. It can be seen that over a range of repetition rates from 5 MHz to 500 MHz, a uniform train of 300-fs, 50-pJ pulses is obtained.

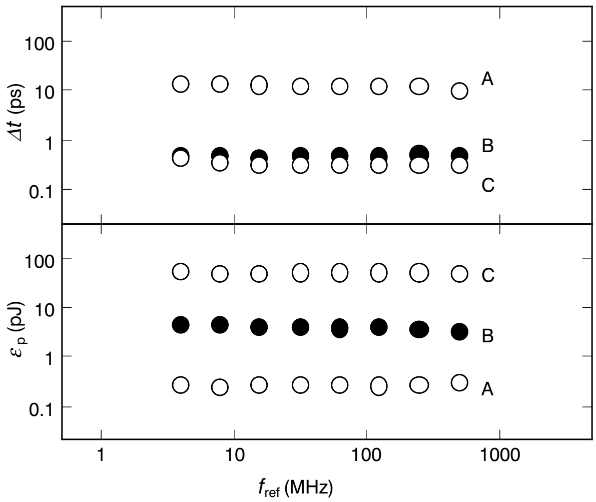


Figure 12 Dependence of pulse width Δt and pulse energy ε_p on repetition rate f_{rep} at outputs from seed pulse (A), CPF (B), and ND-EDFA (C).

4. CONCLUSION

We have described a CPF compressor in which the nonlinearity coefficient and dispersion value have a comb-like distribution along the length of the optical fiber due to multistep connection of HNLF-SMF pairs. It has been confirmed that, at wavelengths ranging from 1530 to 1560 nm, that the CPF compressor can achieve uniform compression of approximately 500 fs. It has further been confirmed that in the 5-MHz to 500-MHz range uniform output pulses can be obtained. Since the CPF compressor is outstandingly easy to manufacture and responds flexibly to both wavelength tuning and repetition rate tuning, it is expected to find applications in the fields of optical communication and optical metrology, as well as bio-photonics, materials processing, physics, etc.

REFERENCES

1) K. Igarashi, R. Miyabe, J. Hiroishi, S. Takasaka, H. Tobioka, S. Matsushita, T. Yagi, S. Namiki, "Ultra-highly pure 160 GHz subpicosecond soliton train generation with average dispersion-managed comb-like dispersion profiled fiber using highly-nonlinear fiber", CLEO2003 (2003), CMH7.
2) K. Igarashi, H. Tobioka, S. Takasaka, S. Matsushita, S. Namiki, "Duration-tunable 100-GHz sub-picosecond soliton train generation through adiabatic Raman amplification in conjunction with soliton reshaping", OFC2003 (2003), ThB6.
3) K. Igarashi, S. Takasaka, R. Miyabe, J. Hiroishi, R. Sugizaki, T. Yagi, S. Namiki, "Wideband-tunable highly pure 40 GHz picosecond soliton train generation by short comb-like profiled fiber", CLEO2004 (2004), CFC2.
4) K. Igarashi, H. Tobioka, M. Takahashi, J. Hiroishi, t. Yagi, M. Sakano and S. Namiki, "Widely tunable sub-picosecond compression of 40 GHz externally-modulated pulse train using 1.4 km long comb-like profiled fiber", OFC2005, (2005), JWA6.
5) K. Igarashi, H. Tobioka, A. Oguri, T. Akutsu, S. Namiki, M. Sakano, R. Kawahara, K. Okamura, Y. Aoyagi and N. Kagi, "5 - 500 MHz repetition-programmable low pedestal femtosecond pulse source using comb-like profiled fiber", CLEO2005 (2005), CTuCC4.

6) K.R. Tamura and M. Nakazawa, "54-fs, 10-GHz soliton generation from a polarization-maintaining dispersion-flattened dispersion-decreasing fiber pulse compressor", Opt. Lett., 26, (2001), 762.
7) S.V. Chernikov, J.R.Taylor, R. Kashyap, "Experimental demonstration of step-like dispersion profiling in optical fibre for soliton pulse generation and compression", Electron. Lett., 30, (1994), 433.
8) S.V. Chernikov, J.R. Taylor, R. Kashyap, "Comblike dispersion-profiled fiber for soliton pulse train generation", Opt. Lett., 19, (1994), 539.
9) P.C. Reeves-Hall, J.R. Taylor, "Wavelength and duration tunable subpicosecond source using adiabatic Raman compression", Electron. Lett., 37, (2001), 417.
10) J. Hiroish, N. Kumano, K. Mukasa, R. Sugizaki, R. Miyabe, S. Matsushita, H. Tobioka, S. Namiki, T. Yagi, "Dispersion slope controlled HNL-DSF with high g of 25 W-1km-1 and band conversion experiment using this fiber", ECOC2004, (2004), PD1.5.