Silica-Based Highly Nonlinear Fibers and Their Applications

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Silica-based highly nonlinear fibers (HNLFs) are promising platforms for a wide range of applications utilizing fiber nonlinearities, such as broadband light sources, fiber lasers, amplification, all optical processing, sensors, metrologies, and spectroscopies. The key challenges for their practical applications are tailoring the chromatic dispersion, including higher-order dispersion, as well as high nonlinearity, low fiber attenuation, and low splice loss to standard single mode fibers. This paper outlines our silica-based HNLFs, which are designed specifically for desired applications, featuring HNLF with a longitudinally uniform zero dispersion wavelength and HNLFs with optimized fourth-order dispersion. We also demonstrate an accurate chromatic dispersion measurement and present two types of optical frequency combs that use our silica-based HNLFs as application examples.

Keywords: Highly nonlinear optical fiber, chromatic dispersion, optical frequency comb

1. Introduction

Silica-based optical fibers are widely installed around the world, and have been essential transmission media to support today's explosive growth of communication traffic. When optical signals are transmitted in an optical fiber, nonlinear phenomena including four wave mixing (FWM), self-phase modulation (SPM), and cross-phase modulation (XPM) can occur. These types of nonlinear effects can degrade the quality of optical signals, and limit the information capacity. Therefore, it is demanded to suppress the nonlinearities in optical fibers for telecommunications.[1]

On the other hand, a number of applications that positively utilize the fiber nonlinearities have attracted much attention. In order to effectively generate the fiber nonlinearities, silica-based highly nonlinear fibers (HNLFs) have been developed,[2]-[4] and used for various applications including fiber lasers, wide-band and low-noise optical amplification, supercontinuum (SC) light sources, optical signal processing, strain/temperature sensors, frequency/time/length measurement, and near-infrared spectroscopy.[5]

To apply HNLFs to these practical applications, the key challenges are tailoring chromatic dispersion,*1 as well as high nonlinearity, low fiber loss, and low splice loss. This paper introduces silica-based HNLFs we have developed so far for the applications. We also demonstrate accurate chromatic dispersion measurement, longitudinal uniformity of zero dispersion wavelength, and tailoring of chromatic dispersion including higher order dispersion. In addition, two types of optical frequency combs*2 are presented as an intriguing application of the silica-based HNLFs.

2. Silica-Based Highly Nonlinear Optical Fibers

Silica glass itself is a material with essentially low nonlinearity. However, in the case of optical fibers, nonlinear phenomena can easily appear, because optical power is tightly confined in the small core area with an effective area Aeff of several tens μm^2 or smaller, which

results in high power density, and the interaction length between the optical field and material is generally long. The nonlinear coefficient γ is often used to determine the degree of nonlinearity of an optical fiber, and is given by

$$\gamma = \frac{2\pi}{\lambda} \cdot \frac{n_2}{Aeff}$$ .... (1)

where n_2 is the nonlinear refractive index and λ is the wavelength. Table 1 compares the refractive index profiles and typical optical characteristics of an HNLF and a standard single mode fiber (SMF). The core of HNLF is doped with a high concentration of germanium dioxide (GeO_2), and its diameter is as small as approximately 4 μm. The relative refractive index difference Δn between the core and cladding is approximately 3%, which is about 10 times higher than that of SMF. In addition, n_2 of the HNLF is approximately two times larger than and Aeff is 1/8 of those of SMF. As a result, γ is 20 to 30/W/km, which is more than 16 times higher than that of SMF. Here, γ was measured for a linear polarization state using an XPM

Table 1. Refractive index profiles and optical characteristics of the HNLF and SMF

	HNLF	SMF
Refractive Index Profile	~30mol% GeO₂-SiO₂ / SiO₂ or F-SiO₂ / Δn: 3.0~3.5% / ~4μm	~4mol%GeO₂-SiO₂ / SiO₂ / Δn~0.4% / 10μm
Nonlinear Refractive Index n₂ [× 10⁻²⁰ m²/W] (*)	5 ~ 6	3
Aeff [μm²] (*)	8.5 ~ 11	80
Nonlinear Coefficient γ [/W/km] (*)	20 ~ 30	1.5
Fiber Loss α [dB/km] (*)	0.5 ~ 2	0.2
Zero Dispersion Wavelength λ₀ [nm]	1450 ~ 1650	1300 ~ 1320
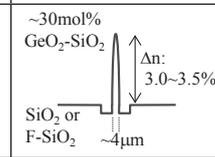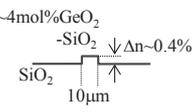
* Value at a wavelength of 1550 nm

method,[6] and the same hereinafter. A depressed cladding index profile is used to realize a single-mode operation in the target wavelengths while maintaining a high nonlinearity and flexibilities in designing of chromatic dispersion.

It is known that the efficiency of FWM generation is proportional to $(\gamma \times L_{eff} \times P_{pump})^2$, where γ is the nonlinear coefficient, L_{eff} is the effective length, and P_{pump} is the pump power. Therefore, longer L_{eff} and higher P_{pump} are required, as well as higher γ to generate FWM effectively. The effective length L_{eff} is given by Eq. (2) using the fiber length L and fiber loss α. The lower the fiber loss, the longer the effective length can be for the same fiber length.

$$L_{eff} = \frac{1 - exp(-\alpha L)}{\alpha} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (2)$$

Regarding the pump power P_{pump}, it would be required that splice losses between the HNLF and SMF are as low as possible because the pump light is usually outputted from an SMF-pigtail. We have realized an HNLF with γ of 30/W/km, which is the highest among silica-based HNLFs reported so far,[3], [7] while maintaining a low fiber loss of 0.9 dB/km. This HNLF also has a low splice loss with SMF of 0.1dB, and would be suitable for efficient FWM generation.

Non-silica glass fibers, which have two orders of magnitude greater γ than that of silica glass, have also been studied.[8] However, silica-based HNLFs have been most commonly used for various applications, because of the advantages including low fiber loss, easy tailoring of chromatic dispersion, low splice loss with SMF, high reliability, and high durability. Therefore, silica-based HNLFs should be nonlinear media suitable for practical use.

3. Tailoring of Chromatic Dispersion

3-1 Chromatic dispersion appropriate for individual applications

Another key parameter of HNLFs is chromatic dispersion. HNLFs are required to have appropriate chromatic dispersion for each desired application. Easy tailoring of chromatic dispersion is a significant feature of silica-based HNLFs. Table 2 summarizes typical optical characteristics of various silica-based HNLFs we have developed so far. Figure 1 also shows the typical chromatic dispersion spectra of four types of silica-based HNLFs. Type-I HNLF has a small positive chromatic dispersion near 1550 nm, which is in the telecommunication operation window, and can efficiently generate optical solitons. From this feature, Type-I would be applicable for generating SCs.[9] For Type-II and Type-III, on the other hand, the wavelengths where chromatic dispersion becomes zero (zero dispersion wavelengths) are in the operation window, and can efficiently generate FWM and XPM. They would be suitable for wavelength conversion,[10],[11] and parametric amplification.[12] In particular, Type-III HNLF is called as dispersion flattened HNLF because its dispersion slope is almost zero in the operation window, and can suppress relative group delay in a wide range of wavelengths.[13] Type-IV has large negative chromatic dispersion. Since it can suppress FWM and

XPM generation between signals, it is expected to be applicable to discrete Raman amplification.[14]

Table 2. Typical optical characteristics of various silica-based HNLFs

	Aeff[*1] [μm²]	γ[*1] [/W/km]	Fiber Loss α[*1] [dB/km]	Chromatic Dispersion Type (Fig. 1)	Zero Dispersion Wavelength [nm]	Dispersion Slope[*2] [ps/nm²/km]	β₄ [× 10⁻⁵⁵ s⁴/m]
HNLF-A	11	20	0.6			+0.03	-1
HNLF-B	8.5	30	0.9			+0.02	+1
HNLF-C	9.5	25	1	Type-I, II	1450 ~ 1620	+0.025	+0.2
HNLF-D	12	18	1.3			+0.05	-2
HNLF-E	9.5	25	1.3			+0.015	+2
HNLF-F	16	10	0.5	Type-III	-	< |0.005|	+4
HNLF-G	10	21	0.5	Type-IV	(*3)	+0.01	-

*1: Value at a wavelength of 1550 nm
*2: Value at the zero dispersion wavelength
*3: Chromatic dispersion around -15 ps/nm/km at 1550 nm
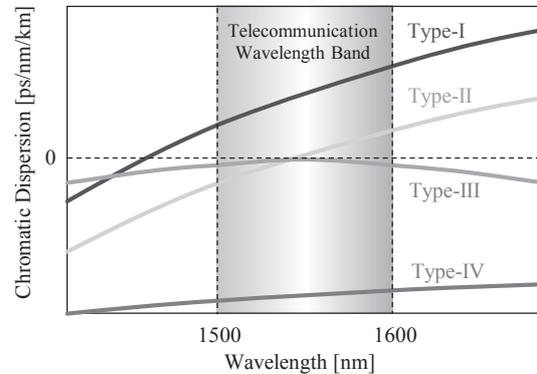
Fig. 1. Typical chromatic dispersion spectra of various silica-based HNLFs

3-2 Accurate measurement of chromatic dispersion

To apply HNLFs with appropriate chromatic dispersion for specific applications, it is also important to accurately measure the chromatic dispersion. However, it is quite difficult to accurately measure the chromatic dispersion of HNLFs using the conventional method (phase method), because short length of HNLFs are generally used for the applications and the absolute values of chromatic dispersion are usually small in the operation window. Therefore, we have proposed a new measurement method based on a fact that wavelengths where the FWM generation efficiency becomes local maxima and minima appear periodically.[15] Figure 2 is the examples of chromatic dispersion of HNLFs with the lengths of 1000 m and 50 m measured by the proposed method (FWM method) and conventional phase method. From Fig. 2, both methods give almost the same chromatic dispersion spectra for a 1000 m HNLF. However, the phase method shows large measurement errors for an HNLF with a shorter length of 50 m. In contrast, the measured spectra of a 50 m HNLF with the FWM method agrees well with that of a 1000 m HNLF. From this result, the FWM method can measure

chromatic dispersion with high precision. It is also noted that we have demonstrated the γ measurements of HNLFs using this method.[16]
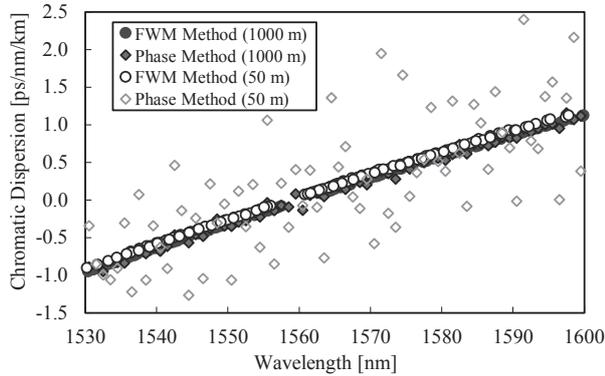
Fig. 2. Measured chromatic dispersion spectra of HNLFs with lengths of 1000 m and 50 m using FWM and phase methods

3-3 Longitudinal uniformity of chromatic dispersion

FWM is a nonlinear phenomenon in which when a probe light (signal) and high power pump lights are launched into an optical fiber, a new light (idler) is generated at a frequency f_{idler}. $f_{idler} = f_{p1} + f_{p2} - f_{probe}$, where f_{p1} and f_{p2} are pump frequencies, and f_{probe} is a probe frequency. FWM is used for various applications including wavelength conversion. The FWM conversion efficiency can be maximized when the phase matching condition is satisfied among the probe, pump, and idler lights, because the idler light is always added with the same phase. If the pump wavelength is identical to the zero dispersion wavelength of the HNLF, the phase matching condition satisfies over a wide range of probe wavelengths, and FWM conversion bandwidth (wavelength range of the probe light where FWM conversion efficiency is 1/2 or higher) can be generally enlarged. Usually, the structure of optical fiber can be assumed to be uniform in the longitudinal direction. However, in actuality, there are microscopic structural fluctuations. Due to the structural fluctuation, the zero dispersion wavelength may vary along the fiber length, and the FWM conversion bandwidth can be degraded. Therefore, it is strongly required to minimize the fluctuations of zero dispersion wavelength in the whole length of HNLFs. To resolve this issue, we have succeeded in suppressing structural fluctuations of an HNLF by applying our matured technology for manufacturing transmission optical fibers. Figure 3 shows the measured zero dispersion wavelength fluctuation along the length of a 3 km-long HNLF. The fluctuation of zero dispersion wavelength is as small as ±1 nm or smaller along the whole length of 3 km.[3] This corresponds to the relative core diameter fluctuation of ±0.03% or smaller. Since typical core diameter of HNLFs is about 4 μm, the core diameter fluctuation would be only ±1.2 nm or smaller. This small fluctuation of the core diameter would be comparable to the molecular network structure of silica glass. Figure 4 is a schematic molecular network

structure of silica glass. Silica glass has a structure composed of six-membered rings of silicon and oxygen (Si-O), and the size of the six-membered ring is approximately 0.6 nm. Therefore, the fluctuations of the core diameter in a 3 km-long fiber would be equivalent to only two six-membered rings, which indicates extremely high uniformity.
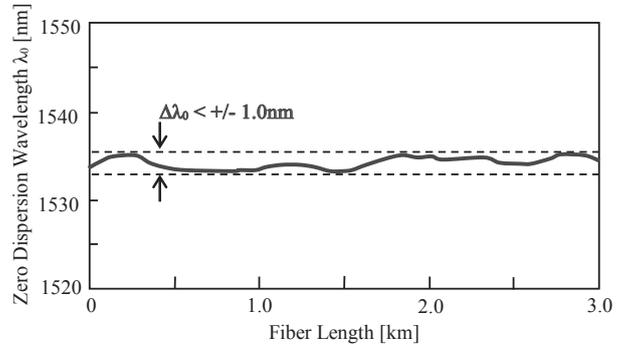
Fig. 3. Measured zero dispersion wavelength fluctuation in a 3 km-HNLF
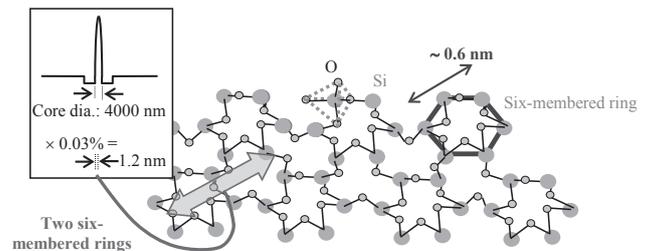
Fig. 4. Schematic molecular network structure of silica glass

3-4 Tailoring higher order dispersion

To further enlarge the FWM conversion bandwidth, it is essential to tailor the higher order dispersion, as well as chromatic dispersion. Deriving phase matching conditions for up to 4th dispersion terms, the deviation from the phase matching condition (phase mismatching parameter) Δβ can be written as

$$\Delta\beta = -\beta_2 \cdot 4\pi^2 c^2 \cdot \left(\frac{1}{\lambda_{pump}} - \frac{1}{\lambda_{probe}} \right)^2$$
$$-\beta_4 \cdot \frac{4}{3} \pi^4 c^4 \cdot \left(\frac{1}{\lambda_{pump}} - \frac{1}{\lambda_{probe}} \right)^4 \quad \cdots\cdots\cdots\cdots (3)$$

where λ_{pump} and λ_{probe} are the wavelength of pump and probe, respectively. β_2 and β_4 are the second- and fourth-order dispersion at λ_{pump}, and c is the light speed in vacuum. From Eq. (3), even if the pump wavelength is identical to the zero dispersion wavelength ($\beta_2 = 0$), the higher-order dispersion β_4 may not be zero, and Δβ cannot be zero. Therefore, by reducing β_4, $\Delta\beta \approx 0$ can be realized in a wider range of probe wavelengths, and FWM conversion bandwidth can be expanded.[12] We have developed an

HNLF-C in Table 2 with β_4 of 0.2×10^{-55} [s^4/m], which is one order of magnitude smaller than that of a standard HNLF (HNLF-A). Figure 5 shows the measured FWM conversion efficiency spectra of HNLF-C and HNLF-A with a length of 100 m. From Fig. 5, a broad FWM conversion bandwidth of 220 nm is demonstrated with HNLF-C, while that of HNLF-A is around 100 nm.[3],[10] This result indicates that HNLF-C can be applicable to a broadband wavelength conversions.
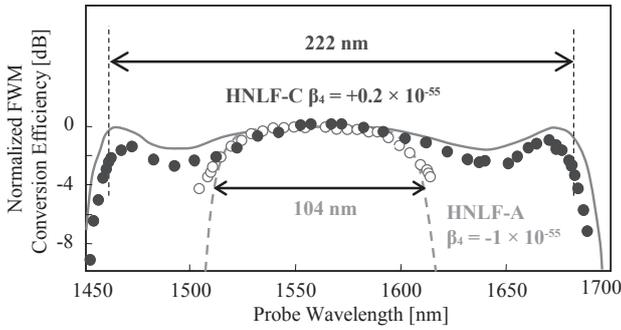
Fig. 5. FWM conversion efficiency spectra of HNLF-C and HNLF-A (● and ○: Measured, Solid and dashed line: Calculated)

On the other hand, it is also found from Eq. (3) that if β_2 is positive, and β_4 is negative and large, $\Delta\beta \approx 0$ satisfies at a certain λ_{probe}. Therefore, selective wavelength conversion of probe light at a specific wavelength may be possible. To realize the selective wavelength conversion, HNLF-D in Table 2 has been developed, whose β_4 is negative and twice as large as that of HNLF-A. Figure 6 shows the measured FWM conversion efficiency using HNLF-D with a length of 100 m.[11],[17] Here, the zero dispersion wavelength of HNLF-D is 1528 nm. From Fig. 6, when λ_{pump} is 1527.2 nm, wavelength conversion can be performed only at wavelengths near 1600 nm. In addition, if λ_{pump} is changed to 1527.0 nm and 1526.8 nm, the probe wavelength at which wavelength conversion is performed is shifted to 1610 nm
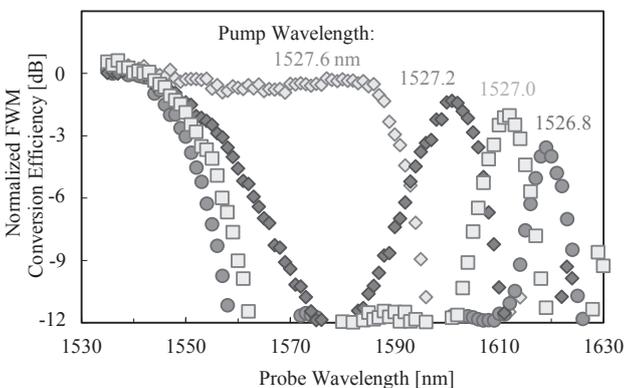
and 1620 nm, respectively. Therefore, by changing the pump wavelength only by 0.2 nm, the probe wavelength at which wavelength conversion is performed is shifted by 10 nm. It is expected that the HNLF-D is applied to selective wavelength switches.

4. Applications of Silica-Based Highly Nonlinear Optical Fibers

This chapter introduces two types of optical frequency combs as applications using silica-based HNLFs, which are receiving increased attentions. Although optical frequency combs are not a new research area, applications to multi-wavelength signal sources for high-capacity wavelength division multiplexing (WDM) optical communication systems and applications to the exoplanet surveys in astronomy have been actively studied in recent years.

For a multi-wavelength signal source for WDM systems, an optical frequency comb using a dispersion-flattened HNLF (Type-III in Fig. 1) has been proposed and developed.[18] It uses a continuous wave (CW) laser as the seed light, and can change the frequency spacing by setting the modulation frequency of the phase modulator. Figure 7 shows an example of output spectra with a frequency spacing of 100 GHz. Using a dispersion flattened HNLF, more than 100 channels of multi-wavelength lights with flat spectra over a broad bandwidth of 100 nm or wider has been obtained. This optical frequency comb source also has equivalent or better performances compared with commercial light sources for digital coherent communication systems, including the narrow linewidth (10 kHz), low noise (relative intensity noise of -140 dB/Hz or lower), and high frequency stability (fluctuations of 10 MHz). Utilizing this optical frequency comb source, a transmission experiment with a record high capacity per single fiber of 2.15 Pbit/s was demonstrated in 2015.[19] In this experiment, 399 channels of WDM signals were generated from the comb source, and transmitted over a 31 km of 22-core single-mode multi-core fiber we developed. From this result, the optical frequency comb source using dispersion flattened HNLF is expected to be applied to ultra-high capacity optical transmission in near future.

Fig. 6. FWM conversion efficiency spectra of HNLF-D
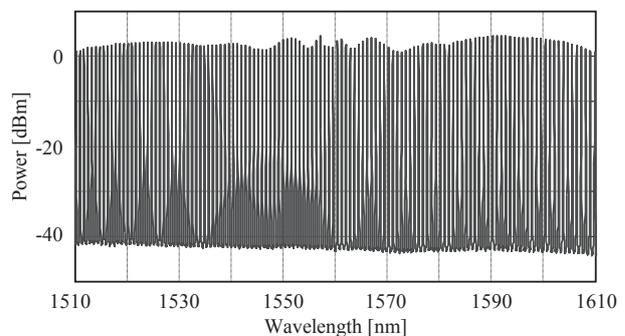
Fig. 7. Example of output spectrum of optical frequency comb (Courtesy of Prof. Radic of the University of California, San Diego)

Another application of the optical frequency comb using HNLFs would be earth-like extrasolar planet (exoplanet) surveys, which is one of the hot topics in astronomy. Since it is difficult to directly observe the dark exoplanets, the star lights are collected with a very large telescope and its spectral absorption lines are detected by a spectrometer. An optical frequency comb has been utilized to calibrate the spectrometer and ensure the accurate spectrum measurement.

The optical frequency comb for exoplanet surveys requires extremely high performance. First, it requires a broadband generation covering the atmospheric windows, Y-, J-, and H-bands (970 to 1750 nm) where the atmospheric transmittance is relatively high. In addition, wide frequency spacing of 10 GHz or more is required because the spacing needs to be a few times wider than the resolution of the spectrometer. However, it is challenging to generate such a broadband frequency comb with the wide frequency spacing because the peak power of the seed light becomes lower with wider frequency spacing. To obtain the broadband optical frequency comb, we have developed a new HNLF with a zero dispersion wavelength of as short as 1325 nm. By concatenating the new HNLF with another HNLF having a zero dispersion wavelength of 1430 nm, we have expanded the comb generation bandwidth to the shorter wavelength side, and successfully demonstrated a broadband optical frequency comb ranging from 1040 to 1750 nm with the frequency spacing of 12.5 GHz.[20] It is expected that this broadband optical frequency comb will contribute to developing new research fields of astronomy.

5. Conclusion

This paper introduced silica-based HNLFs we have developed. The silica-based HNLFs have big advantages including easy tailoring of chromatic dispersion characteristics, high order dispersion, longitudinal structural uniformity, low fiber loss, and low splice loss. Silica-based HNLFs are promising media using fiber nonlinearities, and expected to be utilized to a number of practical applications.

6. Acknowledgements

Technical Terms

*1 Chromatic dispersion: A characteristic of optical fibers indicating the difference in propagation delays between lights with different wavelengths. In general, it is defined as "a time delay [ps] between lights with wavelengths different by 1 nm being propagated in an optical fiber over 1 km." The chromatic dispersion D is related to the second order dispersion β_2 as D = $-(2\pi c/\lambda^2) \times \beta_2$ (c: Light speed in vacuum; λ: Wavelength). The slope of chromatic dispersion against the wavelength is a dispersion slope, and the wavelength dependency of the dispersion slope is the fourth order dispersion.

*2 Optical frequency comb: Multi-wavelength light having a comb-shaped spectrum consisting of discrete and equally spaced frequency components. Taking advantage of the ultra-high frequency accuracy, applications to time/frequency/length measurement and spectroscopy have been studied for a long time. Optical frequency combs can be generated by launching seed light with a single wavelength or a small number of wavelengths into a nonlinear medium.

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