Design and applications of Highly nonlinear fibers

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Abstract: Highly nonlinear fibers which can be utilized in all-optical signal processing is introduced. Characteristics of highly nonlinear fiber and requirements from various applications are summarized.

1. Introduction

Nonlinearity in optical fibers is known as the limiting factor for high-capacity and long-haul transmission systems. Higher optical signal power into transmission fibers to improve the OSNR makes signal deterioration if noise caused by nonlinear phase shift generated by excessive signal power. Since ITU-T G.652 [1] Fiber is installed as a general transmission line, many transmission systems are designed to utilize these fibers. In these days, higher capacity is required to operate hyper-scale data center and video streaming. To meet the demand, ITU-T G.654 [2] fibers whose non-linearity is reduced by enlargement of mode field diameter (MFD).

On the other hand, all-optical signal processing using nonlinearity such as wavelength conversion[3] and reshaping signal wave form [4] using nonlinear phase shift in fibers is required to reduce power consumption and improve flexibilities. Since standard fibers utilized in the fiber cables require very high power to conduct the nonlinear phase shift, special fibers are needed for these schemes.

Furthermore, amplification technology using nonlinearity is discussed, recently. C-band systems which is suitable for ultra-high-capacity transmission utilizing EDFA have been established and still been improving. L-band which is used for further expansion can also be operated utilizing EDFA. New amplifiers are required for new band such as E-band, S-band and U-band. As amplifiers for new bands, optical parametric amplifiers (OPA)[5] and Raman amplification [6] is proposed. Both of them can be used as discrete amplifiers to replace EDFA in C-band and L-band. But their low power conversion efficiency, utilizing EDFA is better solutions for standard systems. Raman effect is utilized as distribute amplification using installed fiber cables.

In this report, we describe the features of highly nonlinear fibers (HNLF) suitable for utilizing nonlinearity for all-optical signal processing. Design and characteristics of optical fibers, fiber packaging technology is summarized. Furthermore, some applications are introduced.

2. Nonlinearity in optical fibers

The nonlinearity of optical fibers is expressed by Equation (1)[7]

$$\gamma = 2\pi\cdot n_2/A_{eff} \qquad (1)$$

n2 and A_{eff} indicates the indicates the nonlinear refractive index and effective cross-sectional area of the optical fiber, respectively. Aeff is determined by the design of the optical fiber. In order to achieve a smaller A_{eff}, it can be achieved by reducing the core diameter and increasing the refractive index of the core. The refractive index of quartz glass has a nonlinear term and is expressed by equation (2)[8] n2 increases as the concentration of dopants in the core of the optical fiber increases.

$$n=n_0+n_2\cdot I \qquad (2)$$

The nonlinearity of optical fibers varies by their host glass. Fibers with other host glass with greater nonlinearity than quartz glass is also introduced [9)-10]. Holly fiber is also attractive because of its high refractive index difference between core and cladding which consists with glass and air holes even if its host glass is composed of quartz glass. Nonlinearity of holey fibers can be enhanced by very small core diameter and higher refractive index difference. [11] HNLF by special host glass and holey fibers have tend to have higher γ comparing with quartz glass-based solid fibers whose maximum γ of about 25. [12] However, it is important that how large optical power can be inputted into HNLF. Splice loss between standard single-mode fibers (SMF) which is used as pigtails of light sources is important. Reduction of splice loss for special types of fibers less than 1dB/point is difficult. That means higher power is lost at splice point. The lost power would be causing thermal problems. For economical, safety and efficiency reasons, quartz based HNLF which can be fusion splice to SMF with less than 0.1dB is the good solution for practical applications.

3. Design and characteristics of HNLF

In this section, design of HNLF whose host glass is quartz fibers are described. To obtain higher refractive index difference, core with high concentrate GeO_2 and fluorine doped cladding is used. If the refractive index difference of the optical fiber is increased, cut-off wavelength shifts to longer wavelength even if core diameter is set to smaller. For control cut-off wavelength shorter than 1530nm, utilizing W-shaped profile is effective. By applying W-shaped index profile, keeping smaller Aeff and shifting cut-off wavelength shorter, simultaneously.

Cross sectional area of HNLF is the important because more than 100m HNLF is mainly used to get required nonlinear effect. Reduction of fiber outer diameter can be done by reduction of coating thickness and/or cladding diameter. Since micro-bending loss of HNLF is very small, coating thickness can be reduced. For HNLF, coating thickness for both primary and secondly coating can be reduced to 10μm. Smaller Aeff is effective to reduce cladding diameter. For HNLF with Aeff of less than 10μm^2, cladding diameter can be reduced to 60 μm.[13)]

Examples of various HNLF are shown in table 1. Dispersion coefficient is set to be close to zero to enhance four wave mixing (FWM) for HNLF #A-#E. #F can be useful for Raman amplification. Making polarization maintaining fiber (PMF) with similar characteristics of all HNLF described in table 1. Polarization crosstalk of 30dB/100m can be realized.

Table1 Examples of Highly nonlinear fibers

Items	Unit	wavelength	#A	#B	#C	#D	#E	#F
γ	W^{-1} km^{-1}	1550nm	12.6	25.1	20.5	12.9	17.5	18.0
Aeff	μm^2	1550nm	14.7	9.7	9.7	14.7	12.6	10.5
Attenuation loss	dB/km	1550nm	0.48	1.16	1.13	0.37	0.83	0.33
Dispersion Slope	$ps/nm^2/km$	1550nm	0.016	0.013	0.0013	0.022	0.031	-0.002
Dispersion	ps/nm/km	1550nm	0.11	-0.08	0.005	-0.31	0.12	-50
λc	nm	-	1222	1354	1254	1161	1427	1065

4. Packaging and splicing

For practical use in several applications, packaging technique is important. Since HNLF have smaller macro-bend loss characteristics, no loss increases even if bent to a small diameter. Also, reduction of cladding diameter is effective to reduce winding inner diameter. [14)] It is known that PMF causes crosstalk deterioration when stored in a small coil. It has also been shown that this can be avoided by improved winding condition.[15)]

Fusion splicing between HNLF and SMF is important to enhance nonlinear phenomena in HNLF. Mode field conversion technique is used to avoid splice loss between SMF with larger MFD and HNLF with smaller MFD. Fusion splicing technique between SMF and HNLF with smaller cladding diameter is also established. Splice loss between SMF and HNLF with reduced cladding is achieved to be less than 0.2dB. Also, crosstalk degradation is avoided in fusion splice between PM-SMF and PM-HNLF

5. Applications utilizing HNLF

HNLF is utilized in various applications. In this section, some applications using HNLF is introduced.

5.1 Pulse compression

It is known that pulse compression can be performed by alternating highly nonlinear fibers and SMFs.[16)] By using nonlinear fibers as a simple nonlinear medium with zero dispersion and SMF as a simple dispersion medium because it is low nonlinear, we can simplify the configuration and optimize the length of each fs Grade pulses can be generated.

5.2 Wavelength conversion and OPA

FWM is famous nonlinear effect in optical fibers. Using this phenomenon, when high-intensity pump light is input with the signal light, converted signals can be obtained according to the frequency difference between the pump light and the signal light. The most important feature of fiber-type wavelength conversion is the wide conversion bandwidth. All WDM signals in the entire C-band can be converted to other bands. Furthermore, by strengthening the excitation light, it is possible to amplify the signal light itself. This phenomenon is OPA. It is attractive that it can be amplified at any wavelength with low noise figure (NF).

5.3 Raman amplification

Raman amplification is a phenomenon in which a signal is gained by placing pump light at a short wavelength of about 100 nm of signal light. The Raman gain coefficient increases as A_{eff} decreases. Therefore, it exhibits the same trend as γ. In discrete Raman amplification, it is not necessary to reduce the dispersion to zero, so signal degradation due to FWM is reduced.

6. Summary

The types and characteristics of HNLF, and their application are summarized. The use of nonlinear optical fibers is essential for all-optical signal processing and wideband transmission. HNLF with enhanced nonlinearity is expected to be the key to high-capacity transmission in the future.

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9. References

[1] ITU-T Recommendation G.652
[2] ITU-T Recommendation G.654
[3] M. Takahashi, S. Takasaka, R. Sugizaki and T. Yagi, "Arbitrary wavelength conversion in entire CL-band based on pump-wavelength-tunable FWM in a HNLF," 2010 Conference on Optical Fiber Communication (OFC/NFOEC), collocated National Fiber Optic Engineers Conference, 2010, pp. 1-3, doi: 10.1364/OFC.2010.OWP4.
[4] P. V. Mamyshev, "All-optical data regeneration based on self-phase modulation effect," 24th European Conference on Optical Communication. ECOC '98 (IEEE Cat. No.98TH8398), 1998, pp. 475-476 vol.1, doi: 10.1109/ECOC.1998.732666.
[5] S. Takasaka, "Highly Nonlinear Fiber for Optical Parametric Amplifier," 2019 Optical Fiber Communications Conference and Exhibition (OFC), 2019, pp. 1-3.
[6] Y. Akasaka, I. Morita, M. E. Marhic, M. . -C. Ho and L. G. Kazovsky, "Cross phase modulation in discrete Raman amplifiers and its reduction," Optical Fiber Communication Conference. Technical Digest Postconference Edition. Trends in Optics and Photonics Vol.37 (IEEE Cat. No. 00CH37079), 2000, pp. 197-199 vol.3, doi: 10.1109/OFC.2000.868563.
[7] G. P. Agrawal, Nonlinear Fiber Optics, San Diego:Academic Press, 2001.
[8] ITU-T Recommendation G. Sup47
[9] N. Sugimoto, T. Nagashima, T. Hasegawa and S. Ohara, "Bismuth-based optical fiber with nonlinear coefficient of 1360 W/sup -1/ km/sup -1/," Optical Fiber Communication Conference, 2004. OFC 2004, 2004, pp. 3 pp. vol.2-.
[10] D. Méchin et al., "Recent advances in very highly nonlinear chalcogenide photonic crystal fibers and their applications," IEEE Photonics Society Summer Topicals 2010, 2010, pp. 117-118, doi: 10.1109/PHOSST.2010.5553651.
[11] L. Tartara, L. Cristiani and V. Degiorgio, "Blue light and infrared continuum generation in a highly nonlinear holey fiber," Summaries of Papers Presented at the Lasers and Electro-Optics. CLEO '02. Technical Diges, 2002, pp. 283-284 vol.1, doi: 10.1109/CLEO.2002.1033977.
[12]J. Hiroishi et al., "Dispersion slope controlled HNL-DSF with high γ of 25 W-1km-1and band conversion experiment using this fiber," 2002 28TH European Conference on Optical Communication, 2002, pp. 1-2.
[13] M. Takahashi, Y. Mimura, J. Hiroishi, R. Sugizaki, M. Sakano and T. Yagi, "Study of down-sized silica highly non-linear fiber," 2005 31st European Conference on Optical Communication, ECOC 2005, 2005, pp. 465-466 vol.3, doi: 10.1049/cp:20050563.
[14] M. Takahashi et al., "Investigation of a Downsized Silica Highly Nonlinear Fiber," in Journal of Lightwave Technology, vol. 25, no. 8, pp. 2103-2107, Aug. 2007, doi: 10.1109/JLT.2007.899797.
[15] M. Takahashi, T. Gonda, S. Takasaka and R. Sugizaki, "φ25 mm coin-sized polarization-maintaining highly nonlinear fiber module with practical polarization crosstalk," 2011 Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference, 2011, pp. 1-3.
[16] Y. Ozeki et al., "Terahertz repetition rate optical pulse train generation based on comb-like profiled fiber," Digest of the LEOS Summer Topical Meetings, 2005., 2005, pp. 115-116, doi: 10.1109/LEOSST.2005.1528020.