Development of Highly Nonlinear Fibers for Optical Signal Processing

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ABSTRACT Nonlinear optical phenomena occurring in optical fibers result in noise and waveform distortion that are factors in signal degradation. It is therefore desirable that nonlinear phenomena in fibers used as the transmission path be reduced as much as possible. On the other hand consideration is being given to methods of optical signal processing that make use of the nonlinear phenomena occurring in the fibers. For example, by actively making use of such nonlinear phenomena as four-wave mixing (FWM) and self-phase modulation (SPM), it is possible to combine optical signals of multiple wavelengths to achieve wavelength conversion, pulse compression and the like [1)~4)]. Such techniques for utilizing nonlinear phenomena are considered promising in terms of the next generation of high-speed optical signal processing and long-haul optical transmission. A highly nonlinear optical fiber has been developed for wavelength conversion using FWM that has a dispersion slope of 0.02 ps/nm^2/km or less. This fiber relaxes the dependence of the pump wavelength in wavelength conversion using FWM, broadening the conversion bandwidth. We also report on a polarization-maintaining highly nonlinear fiber and a highly nonlinear fiber with reduced clad diameter.

1. INTRODUCTION

Nonlinear optical phenomena occurring in optical fibers result in noise and waveform distortion that are factors in signal degradation. It is therefore desirable that nonlinear phenomena in fibers used as the transmission path be reduced as much as possible. By actively making use of such nonlinear phenomena as four-wave mixing (FWM) and self-phase modulation (SPM), however, it is possible to combine optical signals of multiple wavelengths to achieve wavelength conversion, pulse compression, soliton transmission, waveform shaping, and so on. To make use of these nonlinear phenomena in optical signal processing requires that a suitable fiber be available. We have embarked on the development of a highly nonlinear dispersion-shifted fiber (HNL-DSF) for the purpose of optical signal processing using nonlinear phenomena, and as part of that process have developed a highly nonlinear fiber intended for wavelength conversion, which has a dispersion slope of 0.02 ps/nm^2/km or less and a large nonlinear coefficient. This fiber relaxes the dependence of the pump wavelength on the zero-dispersion wavelength in wavelength conversion using FWM, broadening the conversion bandwidth. We also report on a polarization-maintaining highly nonlinear fiber and a highly nonlinear fiber with reduced clad diameter.

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2. NONLINEARITY IN OPTICAL FIBERS

2.1 Nonlinear Phenomena

When a light signal of high power impinges on an optical fiber, the refractive index changes in accordance with the power of the signal. The refractive index n may be expressed as

$$n = n_0 + n_2 \cdot I \qquad (1)$$

where:
n_0 is the linear refractive index,
n_2 is the nonlinear refractive index, and
I is the power density of the signal

As a result of this, a variety of nonlinear phenomena occur in the optical fiber, including self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM), Brillouin scattering, and so on. SPM is the occurrence of an independent phase shift, while XPM is a phase shift when signals of differing wavelengths propagate simultaneously in the same direction. FWM is the phenomenon whereby, when signals of two or more wavelengths impinge, a new signal is produced of a wavelength determined by a certain rule. Pulse compression using SPM and soliton transmission become possible. Wavelength conversion using FWM is also possible.

We may consider nonlinear phase shift as an index of the effect of nonlinear optical phenomena. We may represent the nonlinear phase shift Φ_{NL} during SPM by the equation

$$\Phi_{NL} = (2\pi/\lambda)\cdot(n_2/A_{eff})\cdot I\cdot L_{eff} \quad (2)$$

where:
λ is the wavelength,
A_{eff} is the effective area of the core, and
L_{eff} is the effective length of the fiber.

2.2 Wavelength Conversion by FWM

Following is a simplified explanation of the process of wavelength conversion using four-wave mixing (FWM). FWM is a nonlinear phenomenon whereby, as can be seen in Figure 1, a converted signal (idler signal) is produced by the input of pump light and signal (probe) light of differing wavelengths, such as to satisfy the frequency conditions set forth in the equation

$$f_{conv} = 2\cdot f_{pump} - f_{signal} \quad (3)$$

where:
f_{pump} is the pump frequency,
f_{signal} is the signal frequency, and
f_{conv} is the converted signal frequency.

Figure 1 shows a single signal but in wavelength conversion using FWM it is possible, as shown in Figure 2, to perform batch conversion of signals of several wavelengths using a single pump. This type of wavelength conversion has the further advantage that it proceeds at the same speed as the propagation of light in the fiber.

3. PERFORMANCE REQUIREMENTS FOR HIGHLY NONLINEAR FIBERS

As can be seen from Equation (2), increasing the nonlinear phase shift can be accomplished in terms of optical fiber characteristics by raising the value of n^2/A_{eff} --that is increasing n^2 and/or decreasing A_{eff}. The value of n^2 is determined by the material used. In optical fibers based on silica glass, the core is doped with germanium, which increases the refractive index, and by increasing the amount of germanium dopant n^2 can be increased. Increasing the difference between the refractive indexes of the core and clad improves the efficiency of light confinement, making it possible to narrow the region of light transmission--that is to say, to decrease effective area A_{eff}.

Further, in wavelength conversion using FWM, it is necessary, in satisfying the conditions for phase matching, that the pump wavelength match the zero-dispersion wavelength of the fiber. Thus if, for example, the pump wavelength is set at 1550 nm, the absolute value of the fiber's wavelength dispersion at 1550 nm should be as small as possible. Whether or not wavelength conversion makes use of FWM, it is required, even for pulse compression using SPM or some other nonlinear phenomenon, soliton transmission, or wave shaping, that the highly nonlinear fiber used should have a value of wavelength dispersion that corresponds to its nonlinearity.

If the wavelength dispersion slope of the highly nonlinear fiber used is low, the bandwidth within the desired wavelength dispersion of that fiber will be wider, rendering it more useful. Figure 3 shows the wavelength dispersion characteristics of a conventional fiber with a higher dispersion slope and a fiber with a low dispersion slope. It can be seen that the same wavelength dispersion spread covers a wider bandwidth when the dispersion slope is low than when it is high.

In terms of the characteristics of a highly nonlinear fiber, low A_{eff}. and low dispersion slope must be combined with a short cut-off wavelength with respect to the wavelengths used.

Based on the foregoing discussion, we proceeded, using nonlinear phenomena, to develop a highly nonlinear fiber which not only has a large coefficient of nonlinearity, but also offers the desired wavelength dispersion and a low wavelength dispersion slope.

4. FIBER DESIGN

A study was made on simultaneously decreasing the coefficient of nonlinearity and lowering the dispersion slope. Figure 4 shows representative refractive index profiles for optical fibers. Simulations were run, and the results

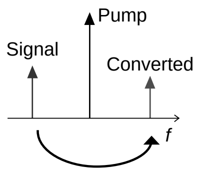

Figure 1 Conversion of a single wavelength by FWM.

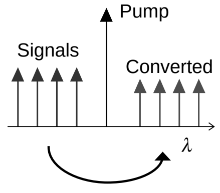

Figure 2 Conversion of multiple wavelengths by FWM.

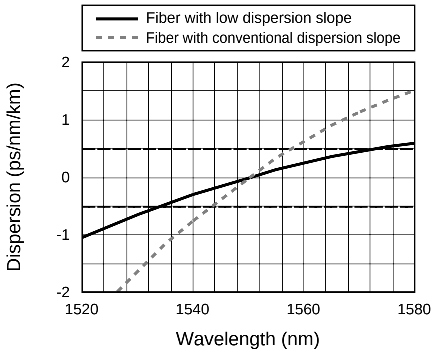

Figure 3 Wider bandwidth achieved by lower dispersion slope.

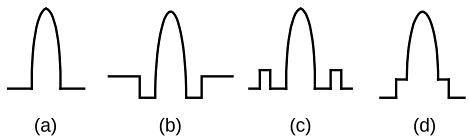

Figure 4 Representative refractive index profiles.

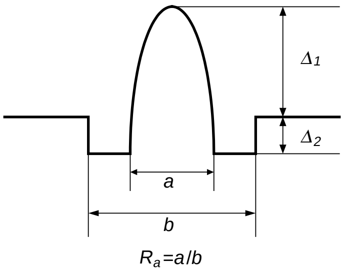

Figure 5 W-shaped refractive index profile detail.

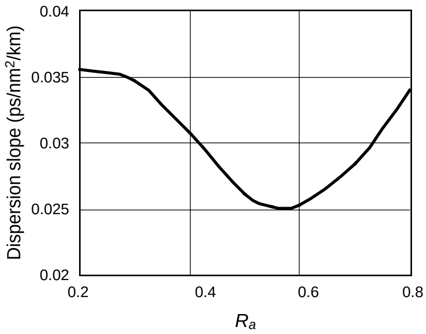

Figure 6 R_a-dependence of dispersion slope.

showed that the W-shaped profile in Figure 4(b), with depressed layers of low refractive index around the center core, gave the optimum balance between the two characteristics mentioned.

We then examined in detail the parameters of the W-shaped profile. In Figure 5 let the outer diameter of the center core be a, the outer diameter of the depressed layers be b, and the ratio of a to b be $R_a = a/b$. Changes in R_a produce the variations in fiber optical characteristics shown in Figures 6 through 8, in which wavelength dispersion at 1550 nm is zero.

It can be seen from Figures 6 through 8 that there is an optimum parameter satisfying the characteristics of lower A_{eff}, lower dispersion slope and shorter cut-off wavelength.

Based on the results of simulations, we selected fibers A and B having a good balance of characteristics, as shown in Table 1, as candidates for prototype manufacture. The characteristics shown in Table 1 are when dispersion at 1550 nm is 0 ps/nm/km.

5. CHARACTERISTICS OF PROTOTYPES

Table 2 shows the characteristics of highly nonlinear fiber prototypes manufactured according to the new design (A and B), together with an older prototype manufactured previously (C) for purposes of comparison. Figure 9 shows the dispersion characteristic of the three fibers.

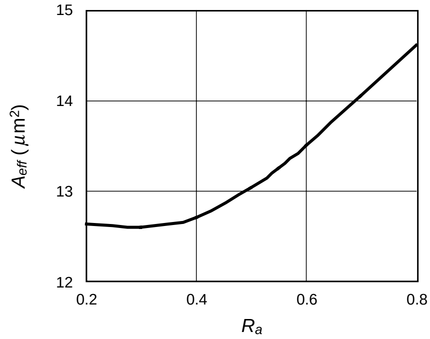

Figure 7 R_a-dependence of effective area A_{eff}.

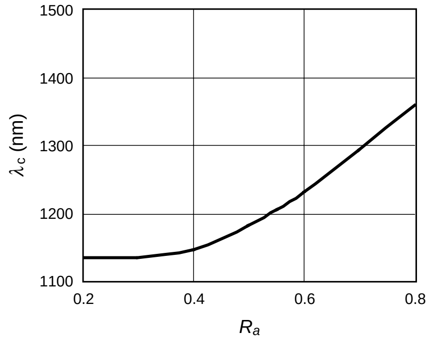

Figure 8 R_a-dependence of cutoff wavelength λ_c.

Table 1 Characteristics of highly nonlinear fibers by simulation when dispersion at 1550 nm is 0 ps/nm/km.

Fiber	A	B
Dispersion slope (ps/nm^2/km)@1550 nm	0.024	0.021
λ_c (nm)	1217	1342
A_{eff} (μm^2)@1550 nm	13.5	9.0

Table 2 Characteristics of Prototype Highly Nonlinear Fibers.

Fiber	A	B	C
Dispersion slope (ps/nm^2/km)@1550 nm	0.016	0.013	0.031
Dispersion (ps/nm/km)@1550 nm	0.11	-0.08	0.12
λ_c (nm)	1222	1354	1427
A_{eff} (μm^2)@1550 nm	14.7	9.7	12.6
n^2/A_{eff} ($\times 10^{-10}$/W)@1550 nm	31.0	61.9	43.2
Loss (dB/km)@1550 nm	0.48	1.16	0.83
γ (W^{-1}km^{-1})@1550 nm	12.6	25.1	17.5
PMD (ps/km$^{1/2}$)@1550 nm	0.04	0.12	0.04
Splicing loss* (dB)@1550 nm	<0.1	<0.1	<0.1

* to single-mode fiber

The dispersion slopes of the prototypes manufactured to the new design were 0.016 ps/nm^2/km for A and 0.013 ps/nm^2/km for B, successfully achieving values less that

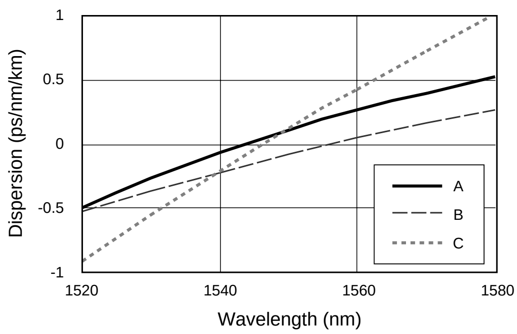

Figure 9 Dispersion characteristic of prototype fibers.

half that shown by the previous design (C). Prototype B in particular combined a low dispersion slope with a large n^2/A_{eff} value of 61.9×10^{-10}W^{-1}. Both A and B prototype fibers had a cut-off wavelength well under 1400 nm.

6. WAVELENGTH CONVERSION EXPERIMENT

To verify the superiority of the highly nonlinear fibers with low dispersion slope, a wavelength conversion experiment using FWM was carried out. Figure 10 shows the experimental set-up. The pump and signal light beams were introduced together into the highly nonlinear fiber, and the power at the converted wavelength was measured by optical spectrum analyser (OSA). The length of the fiber used was 200 m. Keeping the difference between the wavelengths of the pump light and signal (probe) light at 20 nm, the wavelengths of both the pump and signal light were varied in the vicinity of the zero-dispersion wavelength of the highly nonlinear fiber (HNL-DSF), and the power of the converted wavelength was measured.

Figure 11 shows the results obtained. The conversion efficiency was highest when the pump wavelength was set to the zero-dispersion wavelength of the fiber, and decreased progressively as the pump wavelength departed from the zero-dispersion wavelength, but it was found that when fiber A was used, the drop in conversion efficiency when departing from the zero-dispersion wavelength was less than in the case of fiber C. In this it can be seen that by using a highly nonlinear fiber of low dispersion slope, the dependence of the pump wavelength during conversion was relaxed.

7. POLARIZATION MAINTAINING HIGHLY NONLINEAR FIBER

Optical signal processing by means of nonlinear phenomena is also influenced, in addition to the wavelength dispersion of the fiber, by its polarization state. For this reason there are numerous subsystems in which polarization maintenance is required for nonlinear fibers. Here we report on a polarization maintaining nonlinear fiber made of a stressed material.

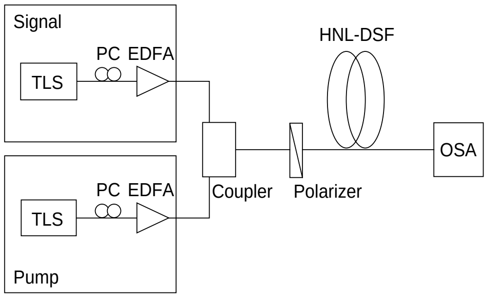

Figure 10 Set-up for wavelength conversion experiment.

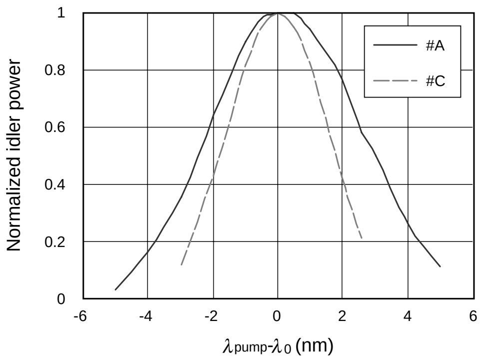

Figure 11 Pump wavelength tolerance.

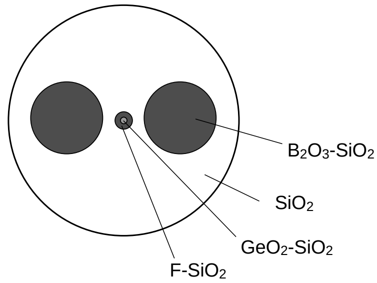

Figure 12 Structure of PANDA highly nonlinear fiber.

Figure 12 shows the structure of a polarization maintaining highly nonlinear fiber. In this fiber the core is sandwiched between stressed material made of B_2O_3-SiO_2, which has a large coefficient of linear expansion than the pure silica of which the clad is made. For this reason, during the period of cooling during the fiber drawing process, a drawing strain is imparted to the stressed portion by means of which polarization maintenance is achieved.

Table 3 shows the characteristics obtained with the polarization maintaining highly nonlinear fiber which is shown in Figure 12 and has the same profile as fiber A in Table 1. As can be seen the fiber in Table 3 has outstanding performance, with a low dispersion slope. It can also be seen that satisfactory values were obtained for crosstalk and beat length.

Table 3 Characteristics of PANDA highly nonlinear fiber.

Item	Characteristic
Dispersion slope (ps/nm^2/km)@1550 nm	0.018
Dispersion (ps/nm/km)@1550 nm	0.04
λ_c (nm)	1205
MFD (μm)@1550 nm	4.3
Loss (dB/km)@1550 nm	0.89
Crosstalk (dB/100 m)@1550 nm	-32.9
Beat length (mm)	4.5

8. HIGHLY NONLINEAR FIBER WITH SMALL CLAD DIAMETER

Generally speaking the highly nonlinear fibers used in optical signal processing are accommodated in subsystems in a modular configuration. This means that minimizing the space occupied by the fibers affects the compactness of the system. Single-mode fibers (SMFs) and dispersion-shifted fibers (DSFs) normally used have a clad diameter of 125 μm, but for this work we have examined the possibility of a highly nonlinear fiber with a clad and resin coating of smaller diameter.

Table 4 shows the characteristics obtained with a highly nonlinear fiber with a clad diameter of 90 μm, which has the same profile as fiber A in Table 1, and, for purposes of comparison, the characteristics of a highly nonlinear fiber of the same refractive index profile and a clad diameter of 125 μm.

As Table 4 shows it was possible, with a 90-μm clad diameter, to achieve a coating diameter of only 145 μm. This is only 58 % of the coating diameter and 34 % of the cross-sectional area of a conventional fiber with a 125-μm clad and 250-μm coating, enabling module size to be reduced by 35 % and more compact subsystems to be realized.

It was also confirmed that the fiber with the 90-μm clad was in no way inferior to the 125-μm clad fiber in terms of performance characteristics.

9. CONCLUSION

We have developed a highly nonlinear optical fiber with a low dispersion slope. In wavelength conversion experiments by FWM using this fiber it was confirmed that pump wavelength tolerance was increased. Prototypes were also built of a panda-type highly nonlinear fiber, and a highly nonlinear fiber with reduced clad diameter to realize more compact systems.

Optical signal processing using highly nonlinear fibers can be used for high-speed optical-to-optical processing, as well as multiple wavelength batch conversion, pulse compression, soliton transmission and wave shaping, and accordingly offers great promise of playing an important role in the high-speed signal processing and long-haul transmission applications of the future.

Table 4 Characteristics of highly nonlinear fibers with small and conventional clad diameters.

Item	Small diameter fiber	Conventional diameter fiber
Clad diameter (μm)	90	125
Coating diameter (μm)	145	250
Dispersion slope (ps/nm^2/km)@1550 nm	0.017	0.016
Dispersion (ps/nm/km)@1550 nm	-0.64	0.11
λ_c (nm)	1213	1222
MFD (μm)@1550 nm	4.3	4.3
n_2/A_{eff} ($\times 10^{-10}$/W)@1550 nm	31.5	31.0
Loss (dB/km)@1550 nm	0.41	0.48
Bending loss (dB/m)@1550 nm	<0.5	<0.5
PMD (ps/km$^{1/2}$)@1550 nm	0.049	0.042
Splicing loss* (dB)@1550 nm	<0.1	<0.1

* to single-mode fiber

ACKNOWLEDGMENT

We would like to take this opportunity of expressing our thanks to the following persons for their participation in the development work here described: Messrs. Kamiya, Tamura, Onuma, Oyama and Shimotakahara of the Chiba Fiber Fabrication Dept.; Messrs. Koaizawa, Nakamura, Uchikoshi and Inoue of the Production Technology Development Center; Messrs. Sakano and Namiki of the Optical Subsystems Development Dept., Fitel Photonics Laboratory; and Messrs. Kokura, Yagi and Kumano of the WF Team.

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