# Development of Ultra-Compact Highly Nonlinear Fiber Modules

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**ABSTRACT** Highly nonlinear fiber (HNLF) is a key component holding great promise in applications in the all-optical signal processing devices, broadband light sources, pulse compressors etc., which are essential to high-speed transmission systems. Improvements in HNLF functionality have been realized in recent years, but there is a need for more compact modules when these fibers are to be accommodated.

In this paper we provide a theoretical discussion of the limits of reducing cladding diameter using the finite element method (FEM), and have fabricated fiber with a cladding diameter of 51 $\mu$m. This fiber shows satisfactory characteristics in tests for mechanical strength and environment performance, and delivers ample reliability while fitting into coin-sized modules. Using prototype ultra-compact modules that we fabricated, we carried out supercontinuum (SC) light generation tests and have confirmed satisfactory characteristics.

## 1. INTRODUCTION

While nonlinear phenomenon occurring in an optical fiber is a source of signal waveform degradation in the transmission path, the optical signal processing 1) that is considered essential in the anticipated ultra-highspeed transmission systems above 160 Gbps is a technique that makes use of this phenomenon of nonlinearity. Among well-known applications are optical wavelength conversion 2) or optical pulse shaping 3), and there have also been reports, outside of signal processing, concerning broadband light sources 4), pulse compressors 5), and so on. In such applications as these, fiber that is highly nonlinear constitutes a key component.

At present there are numerous reports of HNLFs of differing materials and structures 6)~9). In order to produce nonlinearity in a fiber with high efficiency, it is necessary to have a large nonlinear coefficient ($\gamma=2\pi n_2/A_{eff}$) and low transmission loss. Compared to silica-glass HNLFs, non-silica-glass HNLFs have an extremely large value of $\gamma$, but are also characterized by extremely large values of transmission loss. For this reason, it has been reported 10) that when comparing the maximum nonlinear phase shift calculated from transmission loss and $\gamma$, silica-glass HNLF is the most efficient.

HNLF must also have, in addition to low loss and large $\gamma$, dispersion characteristics that are specific to the application. In the communications wavelength band, dispersion for silica-glass HNLF can be controlled to zero. And since a low dispersion slope can also be achieved, the region having the specified dispersion value can be maintained over a broad bandwidth. Dispersion characteristics that are stable in the lengthwise direction of the fiber also have an effect on an effective nonlinear process 11). In this respect also, silica-glass HNLF, which shows good controllability during fiber fabrication, is also advantageous.

Most of the numerous reports concerning applications using HNLF published in recent years are at the research institute level. To produce commercially viable HNLF requires more compact modules. From the standpoint of compact packaging of HNLF, non-silica-glass HNLF having a large value of $\gamma$ can be used in lengths as short as several meters 7), 9), making it advantageous in terms of achieving more compact modules. However when using HNLF in modules, which ultimately will be connected to existing optical systems, it must be spliced to ordinary single-mode fiber (SMF) or dispersion-shifted fiber (DSF), so that the large splice loss for these fibers presents problems. Since $\gamma$ is smaller for silica-glass HNLF than for non-silica-glass HNLF, the length of fiber required is greater. On the other hand, not only is the nonlinear process more efficient, dispersion more easily controlled and fabrication easier for silica-glass HNLF, but also its reliability is established and low-loss splicing (<0.2 dB) can be obtained with ordinary SMF, rendering it suitable for actual use.

In this paper we report on the down-sizing of silica-glass HNLF with a view to commercial viability. In Section 2 we discuss theoretical and mechanical design, in Section 3 the characteristics of the prototype fiber that was fabricated, and in Section 4 the characteristics of modules using the prototype fiber. In Section 5 we go on to report on SC light generation using a prototype ultra-compact module.

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## 2. DESIGNING DOWN-SIZED HNLF

The length of silica-glass HNLF when used in a nonlinear device is determined by the characteristics of the fiber and by the application, but is generally in the order of several hundred meters. If such lengths of fiber are to be accommodated in a module the fiber is generally wound on a bobbin, so that reducing bobbin size is important to achieving a more compact module. For a given length of fiber, bobbin size is dependent on the outer diameter of the fiber (coating diameter) and the inner diameter of the bobbin (the fiber spooling diameter).

One approach to reducing the outer diameter of the fiber is to reduce the thickness of the coating. Conventionally the diameter of the coating is 250 $\mu$m but this is based on the assumption that the fibers are to be made into cables and used in a variety of fields. Since HNLF is formed into coils and used inside equipment, the thickness of the coating can be reduced to the extent that stress applied to the fiber by cabling, cable laying etc. need not be considered. Another effective way to reduce coating diameter without changing coating thickness is to decrease fiber diameter (cladding diameter).

In reliability design for optical fibers, it is important that the strain on the fiber be kept low. One way to keep coil size small is to reduce the fiber spooling diameter, but the smaller the spooling diameter the greater will be the bending strain on the fiber. Since the bending strain on the fiber is inversely proportional to fiber diameter, reducing fiber diameter can limit the bending strain and at the same time allow a smaller spooling diameter.

For these reasons reducing cladding diameter is an effective way to achieve a more compact module. Previously it was possible, using 90-$\mu$m HNLF, to develop a module size of a 3.5-inch floppy disk [12], but any further reduction in module size would require even finer fiber. Since HNLF has an extremely small mode field diameter (MFD) and light confinement to the periphery of the core is strong, it is advantageous in terms of down-sizing but any major reduction in cladding diameter would require investigation of the theoretical and mechanical design.

### 2.1 Theoretical Approach to Down-Sized Design (FEM Simulation)

Transmission in optical fibers occurs generally by utilizing the difference in refractive index between the core and the cladding to confine the light in the area of the core. The intensity of this light decreases exponentially as the distance from the core becomes greater, but when the cladding diameter (cladding thickness) is insufficient, the transmission mode reaches the interface between the cladding and the coating and large leakage loss occurs. Thus in reducing cladding diameter it is necessary to clarify the cladding diameter required with respect to the design of the core.

By means of simulation using the finite element method (FEM) [13], we analyzed the relationship between cladding diameter and leakage loss. In this simulation we used the refractive index profile of the core actually adopted in silica-glass HNLF and that used in ordinary SMF. The HNLF profile was W-shaped, having a center core with high-density Ge doping and a side core with F doping, while the SMF had a single-peak profile. For each core design, simulations were carried out for leakage loss when cladding diameter was changed with no change in core diameter. Since in these simulations loss was taken as the amount of light leaking from the cladding into the coating, it did not include Rayleigh scattering or absorption, microbending loss etc.

Figure 1 shows the relationship between cladding diameter and leakage loss obtained by simulation, demonstrating that the thinner the cladding diameter the greater the leakage loss. Comparing HNLF and SMF we can see that even an HNLF with a cladding diameter of 40 $\mu$m has lower loss than 125-$\mu$m SMF.

Figure 3 shows the leakage loss under macrobending. It should be noticed that as the cladding becomes thinner and light confinement weaker, the ability to withstand

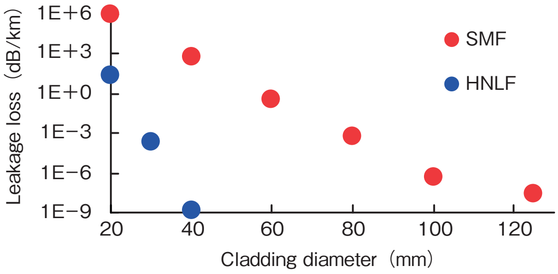

**Figure 1** Relationship between cladding diameter and leakage loss.

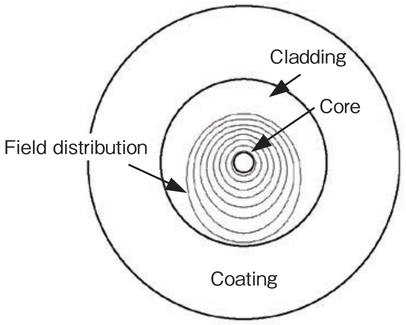

**Figure 2** Field distribution under macrobending (SMF with 80-µm cladding, r = 20 mm).

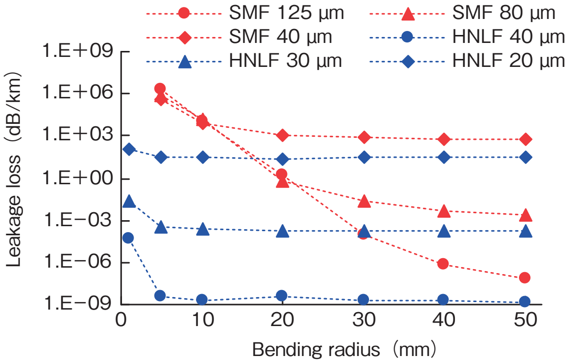

**Figure 3** Leakage loss under macrobending.

bending changes. However it can be seen that an HNLF having a core designed for extremely strong light confinement will be only slightly susceptible to the effects of bending, and even when the cladding is thinner the ability to withstand bending will not change to any degree.

Thus from the results of a theoretical study based on these simulations, we may conclude that for HNLF, as long as the cladding diameter is 40 μm or more, leakage loss characteristics will be as good as or better than SMF with a cladding diameter of 125 μm.

### 2.2 Investigation of Mechanical Strength

In fabricating fibers of greatly reduced cladding diameter, it is necessary to consider mechanical strength in addition to optical characteristics. Generally speaking, when handling optical fiber, a tensile strength of the order of 10 N is required. The tensile strength of optical fiber with a cladding diameter of 125 μm is approximately 50~60 N, and this tensile strength is substantially proportional to the cross-sectional area of the cladding. Figure 4 shows the dependence of tensile strength on cladding diameter, and from it we see that to obtain adequate tensile strength of at least 10 N we need a cladding diameter of about 50-55 μm.

## 3. CHARACTERISTICS OF DOWN-SIZED HNLF

Table 1 shows the characteristics of prototype down-sized HNLFs designed and fabricated based on our study of down-sizing. Fibers A and B are of differing core design but both have a cladding diameter greater than 55 μm, and a tensile strength in excess of 10 N. Both A and B were given a 2-layer coating with a view to achieving ample reliability. Compared to fiber A, fiber B has a lower dispersion slope, and loss is also less. The basic optical characteristics shown in Table 1 are similar to those for an HNLF with a cladding diameter of 125 μm having the same core design.

We also evaluated the mechanical characteristics of the prototype fibers. Figure 5 is a Weibull distribution plot. The Weibull distribution coefficients $m_1$ (high strength) and $m_2$ (low strength) were 44.7 and 1.2, respectively. Figure 6 shows the result of dynamic fatigue tests. The dynamic fatigue coefficient $n$ for the prototype down-sized fibers was 27.6 (by the IEC and TIA/EIA methods).

From these results it was confirmed that the prototype down-sized HNLFs had satisfactory mechanical strength characteristics comparable to ordinary-sized fibers.

## 4. DESIGN OF ULTRA-COMPACT MODULES

### 4.1 Mechanical Strength Reliability Test

Making a smaller bobbin for spooling the fiber is an effective means of enclosing it more compactly. It would thus be desirable if the spooling diameter (inner diameter of the bobbin) were as small as possible but if the spooling diameter is too small, we also must consider the effect of the bending strain applied to the fiber on its failure life. From the theory of optical fiber failure life [14], the probabili-

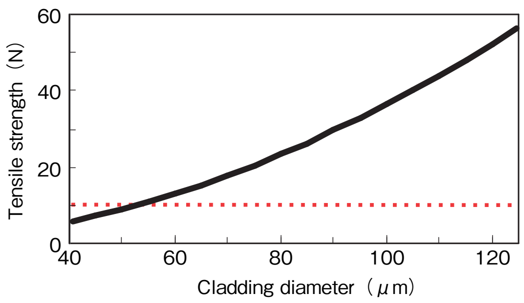

**Figure 4** Dependence of tensile strength on cladding diameter.

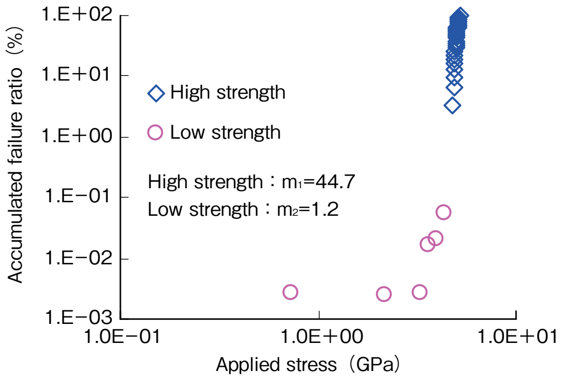

**Figure 5** Weibull distribution in prototype HNLFs.

**Table 1** Characteristics of prototype HNLF (@ 1550 nm).

| Item | Unit | A | B |
|---|---|---|---|
| Cladding diameter | (μm) | 56 | 58 |
| Coating diameter | (μm) | 130 | 124 |
| Dispersion slope | (ps/nm$^2$/km) | 0.026 | 0.013 |
| Dispersion | (ps/nm/km) | −0.29 | 0.63 |
| $\lambda_0$ | (nm) | 1539 | 1617 |
| γ (XPM) | (W$^{-1}$km$^{-1}$) | 13.3 | 12.1 |
| Attenuation loss | (dB/km) | 0.64 | 0.50 |
| Bending loss (15 mm dia.) | (dB/m) | <0.1 | <0.1 |
| PMD | (ps/nm$^{1/2}$) | 0.06 | 0.13 |

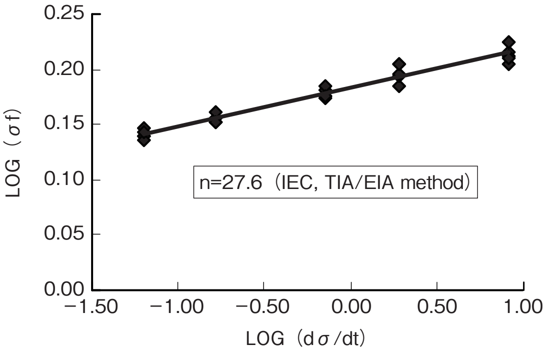

**Figure 6** Result of dynamic fatigue tests.

ty of fiber failure may be stated as

$$\lambda = aN_{\mathrm{P}} \frac{B_{\mathrm{P}}/E^2}{(B/E^2)^{\beta}} \frac{(\bar{\varepsilon}^{\mathrm{n}} t_{\mathrm{s}})^{\beta}}{\varepsilon_{\mathrm{P}}^{n_{\mathrm{p}}} t_{\mathrm{P}}} \qquad (1)$$

| Symbol | Significance |
|---|---|
| $a$ | $m/n_p^{-2}$ |
| $N_{\mathrm{P}}$ | Frequency of fiber failure |
| $\frac{B_{\mathrm{P}}/E^2}{(B/E^2)^{\beta}}$ | Environmental parameter |
| $\bar{\varepsilon}$ | Equivalent applied strain |
| $\varepsilon_{\mathrm{P}}$ | Applied strain |
| $n_{\mathrm{P}}$ | Fatigue parameter |
| $N$ | Fatigue parameter |
| $t_{\mathrm{P}}$ | Time of $\varepsilon_{\mathrm{P}}$ applied |
| $t_{\mathrm{S}}$ | Time of $\bar{\varepsilon}$ applied |

Based on Equation (1) we calculated the failure ratio for the down-sized HNLFs from parameters obtained from this prototype and its evaluation. Figure 7 shows the relationship between spooling diameter and failure ratio. When a 125-$\mu$m fiber is spooled to a 60-mm diameter, the 20-year failure ratio is about 0.25 %. The prototype down-sized fiber fabricated here can be spooled to a diameter of 20 mm with the same failure ratio. By setting the proof test level at the time of fabrication at 2 %, the down-sized fiber can be spooled to a diameter of 12 mm.

Thus by reducing cladding diameter to reduce spooling diameter and decreasing fiber diameter (coating diameter) (i.e., reducing the space factor of the fiber), it is possible to accommodate the down-sized fiber in a smaller bobbin. Figure 8 shows small bobbins for down-sized HNLFs. Using these bobbins 200 m of fiber can be accommodated in the size of a coin (photo shows a 500-yen coin).

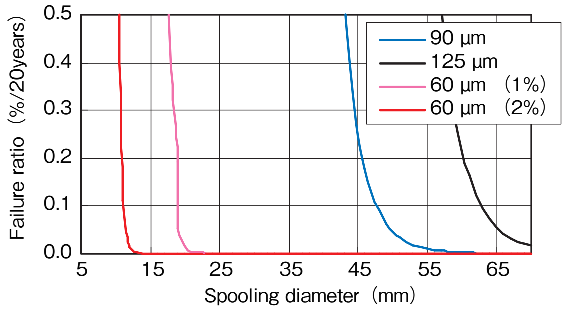

**Figure 7** **Relationship between spooling diameter and failure ratio.**

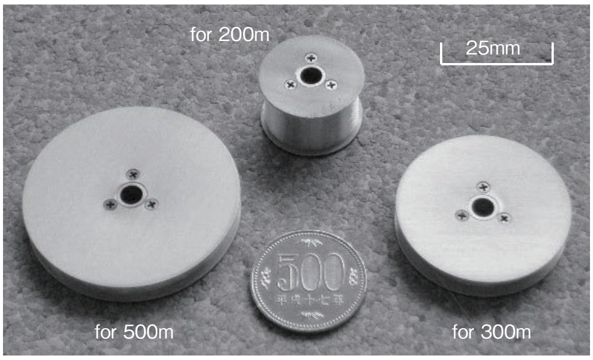

**Figure 8** **Small bobbins for down-sized HNLFs.**

## 4.2 Splicing Characteristics

An important parameter with respect to HNLF is splice loss. It is assumed that this type of fiber will mainly be used as a component inside devices that make up equipment, but it will ultimately have to be connected to the SMF of existing optical systems. With HNLF, increasing the nonlinearity of the fiber improves the efficiency of the nonlinear process, promising a reduction in the power required, but if splice loss is too great, the input power to the HNLF will decrease so that this advantage will not be fully realized.

Using commercially available splicing tools and varying splicing conditions, the prototype down-sized HNLF can be fusion spliced directly to ordinary SMF. Splice loss can be kept to 0.2 dB or less.

## 4.3 Environment Resistance

Using the prototype ultra-compact module, environment tests in conformity with Telcordia GR-63-CORE were carried out. The temperature pattern used is shown in Figure 10, the results of the environment tests in Table 2, and the result of measurements of operating temperature in Figure 11.

As can be seen from Table 2, in all environment tests the change in loss was less than 0.1 dB and the change in polarization mode dispersion (PMD) was less than 0.1 ps. Further, in the operating temperature tests the variation in power for all values of temperature and humidity was less than 0.02 dB. It was thus confirmed on the basis of these results that the prototype ultra-compact module fabricated possesses satisfactory environment character-

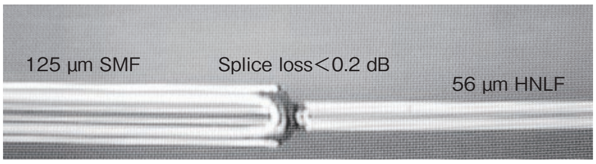

**Figure 9** **Fusion splice between prototype HNLF and SMF.**

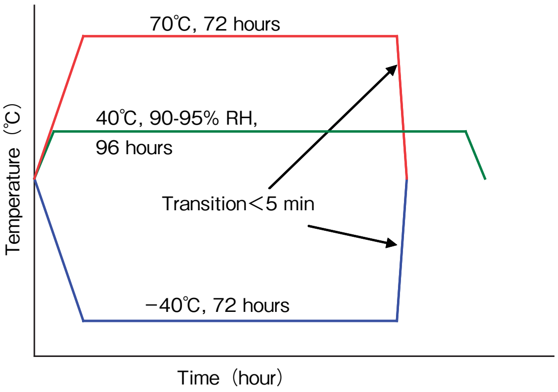

**Figure 10** **Temperature and humidity patterns under GR-63-CORE.**

istics.

## 5. SC LIGHT GENERATION BY DOWN-SIZED HNLF

We conducted supercontinuum (SC) light generation tests using the ultra-compact module achieved by means of down-sized HNLF. SC light generated in the normal dispersion domain of HNLF is low in noise, and since it has a good signal-to-noise ratio (SNR), it is promising for applications in optical signal processing or as a broadband light source [4]. For these applications to be actually used in the field, it is anticipated that the fiber will be accommodated within the device as one of the components making up the device, so that achieving a more compact module is considered essential. The ultra-compact module developed in this work will, it is suggested, prove extremely useful in such applications.

### 5.1 A Fiber Design Suited to SC Light Generation

To improve the efficiency of SC light generation requires that the nonlinear phenomenon be generated at high efficiency, and this necessitates a large value of $\gamma$ and low transmission loss. A lower value of fiber dispersion at the wavelength of pumping light incidence is also preferable. However to generate emission of broadband low-noise SC light, it is necessary to obtain a normal dispersion domain over a broad band. For this reason a fiber having a low dispersion slope is desirable. And by increasing fiber length it can be anticipated that efficiency will be higher [15]. Lengthening of the fiber is, however, counterproductive in terms of module down-sizing.

Taking these conditions into account, we carried out optimization by means of numerical calculation. The main parameters used in this calculation were: pumping wavelength 1560 nm, repetition rate 10 GHz, pulse width 2 ps, average pump power 100 mW, and $\gamma$ 14 $km^{-1}W^{-1}$. As a result we designed and fabricated a prototype HNLF with a fiber length of 1 km having a dispersion value of −0.8 ps/km/nm at 1560 nm.

**Table 2 Results of environment tests.**

| Item | Loss | PMD |
|---|---|---|
| | (dB) | (ps) |
| Low-temperature and thermal shock | <0.1 | <0.1 |
| High-temperature and thermal shock | <0.1 | <0.1 |
| High relative humidity exposure | <0.1 | <0.1 |
| Operating temperature and humidity | <0.02 | — |

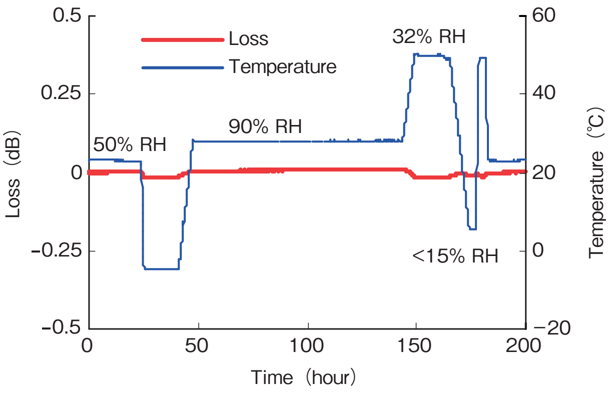

**Figure 11 Result of measurements of operating temperature.**

### 5.2 Characteristics of Prototype Fiber

Table 3 shows the characteristics of the prototype fiber that we fabricated. It was possible to obtain an HNLF having substantially the same value of dispersion and low dispersion slope as the design. The $\gamma$ of this fiber was 13.8 $km^{-1}W^{-1}$ by the CW-SPM method. Furthermore cladding diameter was reduced to 51 μm, and by optimizing coating structure it was possible to reduce the coating diameter (outer diameter of the fiber) to 85 μm. In this way the space factor was reduced to about half that of the HNLF shown in Table 1, and it was possible to accommodate about twice the fiber length on the bobbins shown in Figure 8.

Table 4 shows the characteristics of the module made using this fiber. A 1-km length of the prototype HNLF was spooled on a bobbin 50 mm in diameter and 5 mm thick (labeled for 500 m in Figure 8). It was possible to connect this fiber to SMF using a commercially available fusion splicer as described in Section 4.2, and splice loss was kept down to 0.2 dB or less.

### 5.3 SC Light Generation Experiments

SC light generation experiments were carried out using the prototype HNLF module. Figure 12 shows the experimental set-up, which was extremely simple, consisting of a mode-lock laser (MLL), EDFA, compact HNLF module, and optical spectrum analyzer (OSA). In all the experiments the repetition rate of the light source was 10 GHz, the pulse width (FWHM) was 2.1 ps, the pulse configuration Sech² was $\Delta t \times \Delta\nu$ 0.35, and the wavelength was 1560 nm.

Figure 13 shows the SC spectrum at an input power of

**Table 3 Characteristics of prototype HNLF for SC module.**

| Item | | |
|---|---|---|
| Cladding diameter | (μm) | 51 |
| Coating diameter | (μm) | 85 |
| Dispersion slope | ($ps/nm^2/km$) | 0.017 |
| Dispersion | (ps/nm/km) | 0.82 |
| Attenuation loss | (dB/km) | 1.14 |
| $\gamma$ (SPM) | ($W^{-1}km^{-1}$) | 13.8 |
| PMD | ($ps/nm^{1/2}$) | 0.05 |

**Table 4 Characteristics of SC module.**

| Item | | |
|---|---|---|
| Fiber length | (m) | 1000 |
| Insertion loss | (dB) | <1.5 |
| PMD | ($ps/nm^{1/2}$) | 0.05 |
| Bobbin size | (mm) | $\phi$50 |

100 mW. OSA resolution was set at 0.01 nm. Ripple around the pumping light input wavelength was sufficiently small at about 3 dB, and by using the normal dispersion domain of the HNLF the spectrum was observed to have excellent flatness. The spectrum spread (bandwidth) at the points where power decreased 10 dB and 20 dB from peak power was 28.1 nm and 32.1 nm respectively. It is thought that by increasing input power it will be possible to further increase the bandwidth.

## 6. CONCLUSION

By means of simulations using the finite element method we have clarified the theoretical limits of down-sizing for silica-glass HNLF. As a result of this theoretical investigation and of mechanical strength design, we designed and fabricated a prototype HNLF with a cladding diameter of 51 $\mu$m and a coating diameter of 85 $\mu$m, and by using this fiber were able to realize coin-size HNLF modules. In various reliability tests the prototype down-sized HNLF and ultra-compact modules exhibited characteristics that were satisfactory compared to those of conventional fibers. SC light generation experiments were also carried out using the prototype ultra-compact modules, and satisfactory characteristics were confirmed.

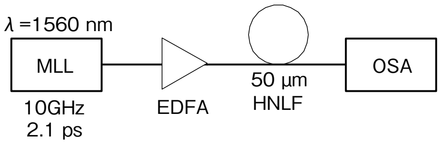

**Figure 12 Experimental set-up.**

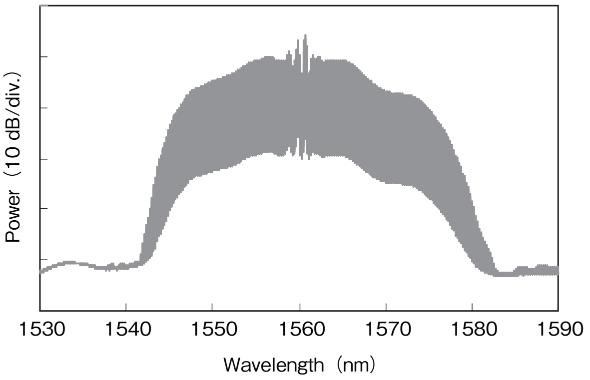

**Figure 13 SC spectrum at input power of 100 mW.**

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