Development of a Non-Zero Dispersion-Shifted Fiber with Ultra-low Dispersion Slope

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ABSTRACT As a next-generation medium for overland fiber-optic transmission links that offers a wider range of signal wavelengths and Raman amplification, a new type of non-zero dispersion shifted fiber (NZ-DSF) has been developed, which has a dispersion slope only about one half that of conventional NZ-DSFs with low dispersion slope.

Generally speaking a lowering of the dispersion slope is accompanied by a contraction in the effective area of the core (A_{eff}), but what is needed, on the contrary, is an expansion of A_{eff} to overcome non-linear phenomena that hamper WDM transmission. In the work reported here it has been possible, by optimizing the refractive index profile, to lower the dispersion slope to only 0.020 ps/nm^2/km, while maintaining A_{eff} at 45 μm^2--about the same as for conventional DSFs. Lowering the dispersion slope also resulted in a shift of the zero-dispersion wavelength to the shorter side, thereby not only expanding the transmission range but also enabling suppression of four wave mixing (FWM) in the pumping wavelength region when Raman amplification is applied.

It has been confirmed by a transmission simulator of the performance of the prototype NZ-DSF that 10 Gbps transmission can be achieved, and the application of a dispersion compensator for even higher rates is under consideration.

1. INTRODUCTION

With the achievement of higher bit rates and larger capacities using wavelength-division multiplexing (WDM) technology, there has come a need for a reduction in fiber non-linearity together with a flatter dispersion-wavelength characteristic, and several types of optical fibers have been proposed. In submarine and other long-haul links there have been proposals, for example, for a dispersion-management link comprising single-mode fibers (SMFs) and reverse dispersion fibers (RDFs) [1]. With such a dispersion management line, total dispersion can be suppressed over a wide range in the C-band (1530-1565 nm). On short-haul overland links, however, the adoption of dispersion management lines is difficult for reasons of installation. Attention has accordingly been turned to the non-zero dispersion-shifted fiber (NZ-DSF), which can provide an overland transmission link consisting of a single line, and R & D work is actively proceeding [2)-6)].

Work has also be done in recent years to widen the range of optical amplifiers and this has led to a need for dispersion designs covering a wide range of wavelengths--not only in the conventional C-band (1530-1565 nm)--but also including the L-band (1565-1620 nm) and S-band (1460-1530). It is also necessary to suppress or eliminate non-linear phenomena including four-wave mixing (FWM) that is inherent in WDM, self-phase modulation (SPM) and cross-phase modulation (XPM) that cause signal waveform distortion at high power input. Also, progress is being made in the practical application of Raman amplifiers, creating a need to ease the limitations on the Raman pumping region that pose a problem when using conventional NZ-DSFs as the transmission link.

An objective of the work reported here was to expand the transmission range to achieve suitability for Raman amplifiers, emphasizing the development of an NZ-DSF with lower dispersion slope. A lowering of the dispersion slope is generally accompanied by a reduction in the effective core area (A_{eff}), but what is needed, on the contrary, is an expansion of A_{eff} to suppress the non-linear phenomena. In this work the authors endeavored, by optimizing the refractive index profile, to lower the dispersion slope while maintaining A_{eff} at 45 μm^2--about the same as for conventional DSFs. This paper reports the results of the design of the fiber and the fabrication of prototypes as well as of confirming performance by means of a transmission simulator, and discusses work on the application of a dispersion compensator.

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Table 1 Characteristics of Selected types of NZ-DSF (at 1550 nm).

Fiber	Dispersion (ps/nm/km)	Dispersion slope (ps/nm^2/km)	A_{eff} (μm^2)	Attenuation (dB/km)
A	8	0.07	65	<0.21
B	5	0.09	72	<0.21
C	5	0.045	55	<0.21

2. DEVELOPMENT OF NZ-DSFs WITH LOW DISPERSION SLOPE

Table 1 shows the characteristics of selected types of NZ-DSF that have been proposed in the past. Fiber A is characterized by a comparatively large dispersion value at a wavelength of 1550 nm, and a zero-dispersion wavelength shifted to the short side; fiber B by an expanded A_{eff}, and fiber C by a dispersion slope smaller than that of the others.

Looking at fiber C, an NZ-DSF with low dispersion slope, it attains an A_{eff} of 55 μm^2 while the lowering of dispersion slope is limited to 0.045 ps/nm^2/km. And since the zero-dispersion wavelength is in the Raman pumping region, we may say that fibers B and C are specifically unsuited for transmission links using a distributed Raman amplifier (see Figure 1).

In this work the objective was to lower the dispersion slope to 0,020 ps/nm^2/km, i.e., less than half the value for fiber C in Table 1, while maintaining A_{eff} at 45 μm^2, about the same as that of the conventional DSF. And in order to make it a fiber that is also applicable in transmission links using distributed Raman amplifiers, it was an objective that the zero-dispersion wavelength be shorter than 1430 nm [7)~10)]. This paper not only describes the design and fabrication of prototype NZ-DSFs, but also considers a system model applying a distributed Raman amplifier and reports on the results of a simulation of the characteristics of the prototype NZ-DSF as a transmission link.

3. DESIGN OF AN NZ-DSF WITH ULTRA-LOW DISPERSION SLOPE

In considering the refractive index profile of an NZ-DSF with low dispersion slope, the authors first undertook a review of the dual-shaped refractive index profile of a 2-layered structure (see Figure 2-a) Such a profile is easy to fabricate, and in the past has frequently been considered for transmission link fibers. The electrical field distribution is substantially Gaussian, making for easy connection to other fibers. As a result of simulations in which each parameter of the dual-shaped profile was minutely altered, it was found that with this profile the dispersion slope could not be lowered further than 0.06 ps/nm^2/km making it virtually impossible to obtain the target value. Next an analogous investigation was made into the W-shaped profile (see Figure 2-b) which, like the dual-shaped profile, is in wide use, but it was found that lowering its dispersion slope would also be difficult.

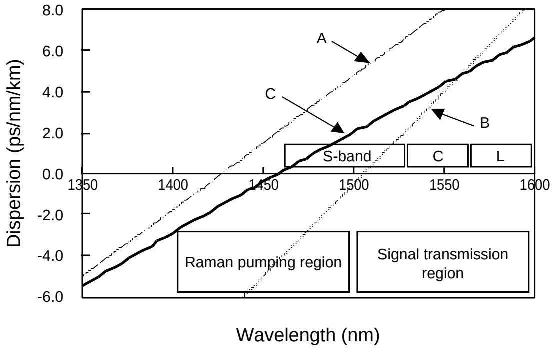

Figure 1 Chromatic dispersion of selected NZ-DSFs.

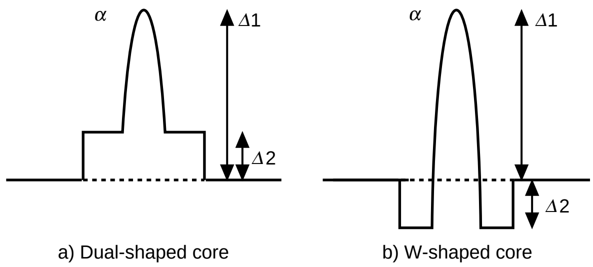

Figure 2 Refractive index profile of a 2-layered structure.

Since the foregoing investigations demonstrated the difficulty of achieving our target with the 2-layered structure we proceeded to study a more complex 3-layered structure profile, and determined that its use would make it possible to lower the dispersion slope to the target value of 0.020 ps/nm^2/km. It was also discovered, however that if the dispersion slope was low there would be a strong tendency toward degradation of other characteristics such as a contraction of A_{eff} and a shift to a longer cutoff wavelength. We accordingly revised the design, reviewing in detail the relative refractive index difference Δ, the Δ's structural parameter α, the diameter ratio, and the like, following an optimization process that achieved, in a balanced manner, the target values for the various characteristics--dispersion, dispersion slope, A_{eff}, cutoff wavelength, bending loss, and so on.

4. TRANSMISSION CHARACTERISTICS

Prototypes were then fabricated in accordance with the design described above. Within a range of refractive index profiles indicated by the results of the simulation, the synthesizing conditions and drawing conditions were optimized resulting in completion of an NZ-DSF with ultra-low dispersion slope capable of being used in a link with low loss and low polarization-mode dispersion (PMD).

Characteristics of the prototype NZ-DSFs are shown in Table 2, where dispersion, dispersion slope, mode field diameter (MFD), effective core area (A_{eff}) and attenuation are the values at 1550 nm; λ_c is the cutoff wavelength, with a length of 2 m; λ_0 is the zero-dispersion wavelength; bending loss is the value of loss with respect to 1550 nm

Table 2 Typical transmission characteristics of prototype NZ-DSFs (at 1550 nm).

Prototype number	1	2	3	Target
Dispersion (ps/nm/km)	4.2	4.9	5.7	4~8
Dispersion slope (ps/nm^2/km)	0.016	0.020	0.029	<0.020
MFD (m)	7.5	7.6	8.0	
A_{eff} (μm^2)	43	45	48	>45
λ_c (nm)	1156	1273	1446	<1460
λ_0 (nm)	1396	1387	1393	<1430
Attenuation (dB/km)	0.216	0.218	0.207	
Bending loss ϕ20 mm (dB/m)	4.0	1.0	0.5	<1
PMD (ps/km$^{1/2}$)	0.026	0.027	0.048	

when bent to a 20-mm diameter; and PMD is the value for polarization mode dispersion. In Table 2 prototype #1 has a dispersion slope of 0.016 ps/nm^2/km, meeting the target, but A_{eff} is somewhat low--45μm^2. Prototype #3, on the other hand, with an A_{eff} of 48μm^2, meets the target but has a dispersion slope that is somewhat too large--0.029 ps/nm^2/km. Prototype #2 has a dispersion slope of 0.020 and A_{eff} of 45μm^2, thereby meeting both targets. In all three the lower dispersion slope resulted in a short-side shift in zero-dispersion wavelength λ_0 to below 1430 nm. The values for the other characteristics--cuttoff wavelength, λ_c, bending loss, PMD, etc.--were also satisfactory.

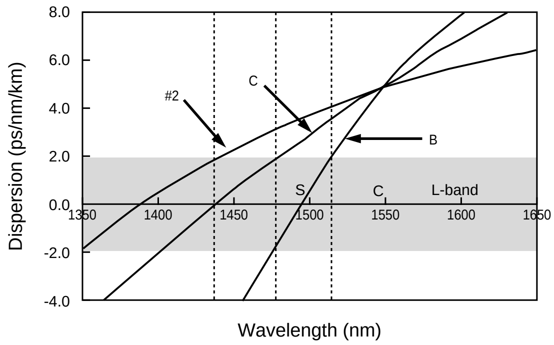

Figure 3 Comparison of dispersion curves of selected NZ-DSFs.

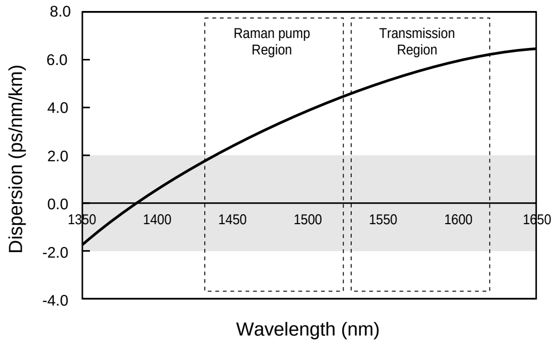

Figure 4 Chromatic dispersion of prototype #2 in transmission and Raman pumping regions.

5. CHROMATIC DISPERSION CHARACTERISTICS AND RAMAN GAIN EFFICIENCY

To investigate the effect of lower dispersion slope, a comparison was made among the three types of NZ-DSFs described in the foregoing section, which all have a dispersion at 1550 nm of 5 ps/nm/km but different dispersion slopes. As a result of prototype fabrication, fiber #2, which has a dispersion slope of 0.020 ps/nm^2/km while maintaining an A_{eff} of 45μm^2, was selected. As a comparison, Figure 3 shows the dispersion curves for fiber B with expanded A_{eff} in Table 1 (dispersion slope of 0.090 ps/nm^2/km and A_{eff} of 72μm^2), and fiber C with low dispersion slope in Table 1 (dispersion slope of 0.045 ps/nm^2/km and A_{eff} of 55μm^2). In the C-band the three NZ-DSFs show similar dispersion characteristics, whereas in the L-band, prototype #2, which achieved an ultra-low dispersion slope, had the greatest suppression of accumulated dispersion.

The range shown shaded in gray was the region in which the absolute value of dispersion was less than ±2 and the efficiency with which FWM occurred was higher. If the wavelength at which the dispersion curve enters this "gray zone" is shown by a broken line, it can be seen that, the broken lines for B, C and #2, which have a large dispersion slope, shift toward shorter wavelength (to the left) in that order, and FWM interference in the S-band is avoided for prototype #2.

As described above it was possible, by lowering the dispersion slope, to achieve a flat dispersion characteristics and avoid accumulated dispersion on the long-wavelength side, and also to widen the range in which the occurrence of FWM can be avoided toward the short-wavelength side, thereby expanding the range supporting transmission to include the full range of the S-, C- and L-bands.

Next to be discussed is the suitability of NZ-DSF for Raman amplifiers. There are two types of Raman amplifier: the discrete type and the distributed type, and both play important roles in the technology of optical communications. Great attention has been paid to the efficacy of Raman amplification, and a particularly large number of experiments in high-capacity transmission using distributed-type Raman amplification have been reported. Reports are also beginning to appear, on the other hand, that some NZ-DSFs are unsuited for use in transmission links that use distributed-type Raman amplification due to the effects of the zero-dispersion wavelength (λ_0). For this reason most recent reports of experiments using Raman amplification involve the use of SMFs as the transmission link [11), 12)].

As is generally known, in amplifying the signal transmission band of 1530-1620 nm (C- and L-bands), it is necessary to input a pumping light of 1430-1520 nm. In the case of prototype #2, Figure 4 shows that, in both the signal transmission region and the pumping region for Raman amplification, the dispersion curve does not enter the gray zone so that interference by FWM with the pumping light is avoided.

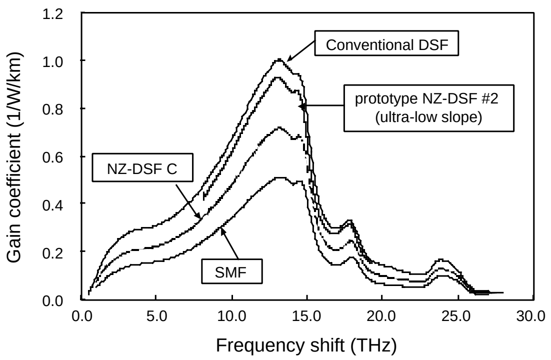

Figure 5 Raman gain coefficients at a pumping wavelength of 1420 nm for selected fibers.

Figure 5 shows the results of measured Raman gain coefficients at a pumping wavelength of 1420 nm for selected fibers. The Raman gain coefficient is normally inversely proportional to A_{eff}, and is therefore smaller for an SMF with a large A_{eff} (80 μm^2) than for a conventional DSF with a small A_{eff} (45 μm^2). For NZ-DSFs, prototype #2 (A_{eff} = 45 μm^2) has a considerably larger Raman gain coefficient than NZ-DSF C in Table 1 (A_{eff} = 55 μm^2), giving promise of Raman amplification characteristics that are equivalent to those of conventional DSFs.

6. SIMULATING TRANSMISSION PERFORMANCE BY DISTRIBUTED-TYPE RAMAN AMPLIFICATION

The present work consisted not only of comparing a prototype NZ-DSF fabricated to achieve an ultra-low dispersion slope (#2 in Table 2) with an NZ-DSF with low dispersion slope (C in Table 1) in terms of fiber characteristics, but also of investigating the way in which the transmission performance differed for systems in which these NZ-DSFs were actually used.

The transmission simulations were carried in out in systems using a distributed-type Raman amplifier with the gain characteristics shown in Figure 6. The system model featured 10-Gbps 8-channel NRZ signals at 50-GHz spacing, three 80-km spans of fiber, no dispersion compensation, and all transmission loss compensated by distributed-type Raman amplification. The worst-channel BER (minimum value) was compared for C-band transmission and L-band transmission when using the NZ-DSF with ultra-low dispersion slope (prototype #2 in Table 2) and the NZ-DSF with low dispersion slope (C in Table 1).

In the simulations, first of all, with an NRZ signal of constant power input to the fibers, the conditions of Raman pumping light sufficient to compensate completely for NZ-DSF loss were compared for prototype #2 (Table 2) and fiber C (Table 1). For a signal wavelength of 1550 nm (C-band) it was found that in a system using prototype #2, 64 % of the power required by a system using fiber C was sufficient. Similarly at a wavelength of 1600 nm (L-band) the power required by prototype #2 was 65 % of that for

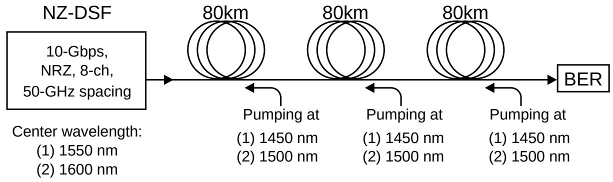

Figure 6 Configuration of system model for transmission simulation.

Table 3 Minimum bit error rate on worst channel.

	C-band (1550 nm)	L-band (1600 nm)
NZ-DSF C (low slope, see Table 1)	10^{-18}	10^{-5}
Prototype NZ-DSF #2 (ultra-low slope, see Table 2)	10^{-17}	10^{-9}

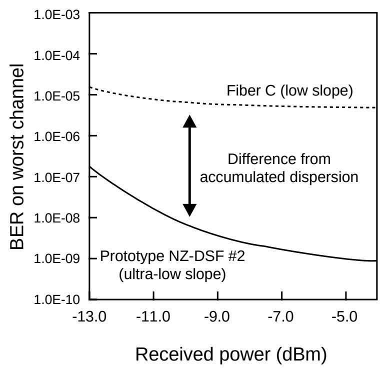

Figure 7 Relationship between bit error rate on the worst channel in L-band and received power.

fiber C. It was thus confirmed that the pumping power needed to compensate completely for transmission loss in distributed-type Raman amplification was lower in the prototype NZ-DSF with large Raman gain.

Table 3 shows the minimum BER on the worst channel for C-band (1550 nm) and L-band (1600 nm) transmission. In C-band transmission the BER was satisfactory for both prototype #2 and fiber C, but it was found that in the L-band, the BER was better for prototype #2.

Figure 7 shows the relationship between the BER on the worst channel in the L-band and received power. For prototype NZ-DSF #2, accumulated dispersion in the L-band was suppressed, giving better L-band transmission characteristics than low-slope NZ-DSF C, and achieving a BER of 10^{-9}.

It is therefore considered that the prototype NZ-DSF #2 is capable of 10-Gbps C-band and L-band transmission with distributed-type Raman amplification even without dispersion compensation.

Table 4 Dispersion compensation for selected transmission fibers.

	Rate of compensation with DCF at 1550 nm	Compensation (design of DSCF)
SMF	100 %	easy
Prototype NZ-DSF #2 (ultra-low slope, see Table 2)	82 %	
NZ-DSF C (low slope, see Table 1)	35 %	
NZ-DSF B (large A_{eff}, see Table 1)	20 %	difficult

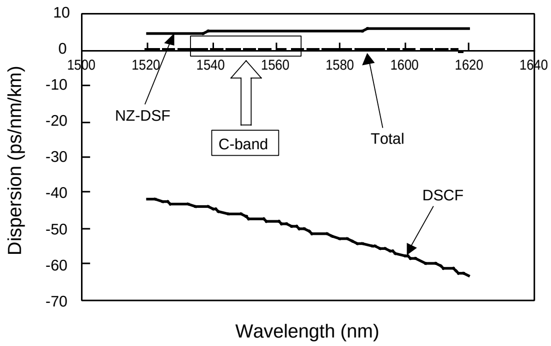

Figure 8 Compensating for NZ-DSF dispersion by means of DSCF.

7. DISPERSION COMPENSATOR TO ACHIEVE EVEN HIGHER BIT-RATES

In the foregoing section we have talked about transmission using the NZ-DSF by itself, on the assumption that there is no need for a dispersion compensator. When we come to higher bit rates--say 40 Gbps--the dispersion tolerance in the transmission link has to be controlled to the order of 60 ps/nm, and it becomes impossible, from the viewpoint of FWM suppression, to have a long-haul link made of a single fiber. It thus becomes necessary to have a dispersion compensator that compensates for NZ-DSF dispersion [13), 14)].

Table 4 shows the dispersion compensation rates for selected NZ-DSFs with a DCF, used for compensation of SMFs. Of all the NZ-DSFs examined, the DCF compensation rate was largest for prototype #2 (see Table 2) and compensator design is easy.

By fabricating a dispersion slope compensating fiber (DSCF), designed to compensate optimally for the dispersion slope of prototype #2, the compensating rate was 100 % at 1550 nm.

Figure 8 shows the average dispersion for prototype NZ-DSF #2 fabricated in this work, for the DSCF that optimally compensated for that NZ-DSF, and for the transmission link as a whole following compensation (marked "total"). It can be seen that over the whole of the C-band it was virtually zero. Figure 9 shows this portion of the vertical axis on an expanded scale, and it can be seen that the average dispersion in the C-band after compensation was contained between -0.05 and 0 ps/nm/km. This indicates

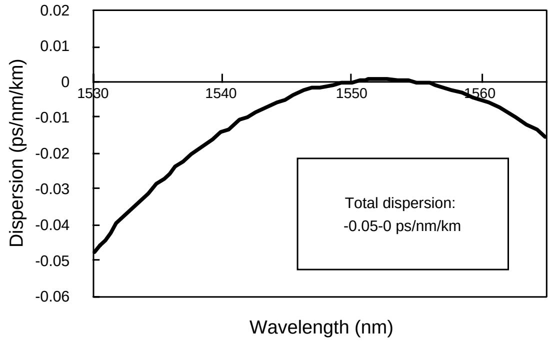

Figure 9 Total dispersion after compensation in C-band.

that 40-Gbps in the C-band can be achieved using a transmission link consisting of prototype NZ-DSF #2 and the optimally designed DSCF.

8. CONCLUSION

In the work the authors addressed the development of an NZ-DSF having an ultra-low dispersion slope for the next generation of overland fiber-optic transmission links. Because of the priority attaching to lowering the dispersion slope, we adopted the objective of achieving a value of 0.020 ps/nm^2/km, even better than the 0.045 ps/nm^2/km of currently available NZ-DSFs. A number of profiles were considered and simulation was used for parameter optimization, and a prototype was fabricated which maintained an A_{eff} of 45 μm^2 and reached the dispersion slope target of 0.020 ps/nm^2/km. By lowering the dispersion slope, accumulated dispersion in the long-wavelength region was suppressed and the short-side shift in the zero-dispersion wavelength made it possible to widen the range of wavelengths in which the occurrence of FWM could be avoided, making transmission possible over a wider range of wavelengths.

Next the suitability for Raman amplifiers was considered. The short-side shift of the zero-dispersion wavelength made it possible to avoid the interference from FWM due to the Raman pumping light, which has constituted a problem in the past. It was also confirmed that an A_{eff} of 45 μm^2 holds the promise of high-efficiency Raman amplification.

A comparative study was also undertaken by means of simulation using a system model applying a distributed-type Raman amplifier and using as the transmission link the new prototype NZ-DSF with ultra-low dispersion slope and the existing NZ-DSF having a low dispersion slope. It was discovered that while the existing NZ-DSF with low dispersion slope suffered a deterioration of the bit error rate (BER), particularly in the L-band, the prototype, with ultra-low dispersion slope, was capable of 10 Gbps transmission in the C-band and L-band, even without dispersion compensation.

The application of dispersion compensators geared to even higher transmission bit rates was also considered. Even a DCF designed as a compensator for single-mode fibers delivers a compensation of 82 %, and it has been confirmed that it is a simple matter to design specialized compensators to deliver 100 % compensation.

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