

Dispersion-Managed Transmission Lines with Reverse-Dispersion Fiber

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ABSTRACT As a new-generation means to enable large-capacity wavelength division multiplexed transmission over long distances, Furukawa Electric has proposed links consisting of a combination of conventional single-mode fibers (SMF) and reverse-dispersion fibers (RDF). By optimizing the refractive index profile, it has been possible to produce RDFs that give substantially flat dispersion over a wide range of wavelengths, while maintaining low nonlinearity, low loss and low polarization mode dispersion (PMD). It has also been possible to fabricate a submarine unit of the currently-used tight-buffering type, and to confirm its satisfactory performance.

1. INTRODUCTION

Recent years have seen the full implementation of wavelength division multiplexing (WDM) technology in long-haul submarine telecommunications, and dispersion-shifted fiber (DSF) of various profiles has been used as the transmission medium. Even with such DSF, however, it has not been possible to realize the improvements in terms of dispersion flatness over a wide range of wavelengths and the increases in A_{eff} required for suppression of nonlinearity that will be needed to meet expected demand for long-haul, high bit-rate transmission.

A few years ago, in a program to upgrade existing 1300-nm SMF lines, 1550-nm WDM transmission was begun using dispersion-compensating fiber (DCF) modules. These modules feature a dispersion slope compensation technology that almost completely cancels dispersion over a wide range of wavelengths. Because of the strong demand for compact design (the modules are installed inside the repeater stations) they were designed to provide maximum dispersion in a short length: i.e., by the use of fibers with an extremely high relative refractive index difference (delta value) to achieve large negative dispersion. On the other hand they were heavily germanium-doped, so that transmission loss and nonlinearity were high and polarization mode dispersion (PMD) deterioration readily occurred.

Thus if DCF is used without modification for dispersion-managed links, it can easily be connected with SMF to provide flat dispersion, but transmission losses in the link as a whole will be much higher than with conventional DSF. There are also a number of problems that arise

when DCF is used in high-capacity WDM transmission, including limitations on optical power input due to nonlinearity, and signal distortion due to high PMD.

In an effort to overcome these problems, the authors investigated refractive index profiles and have developed a link using RDF optimized for transmission lines. These offer low loss, low nonlinearity and low PMD, yet keep the dispersion characteristic almost entirely flat.¹⁻²⁾ This paper describes the profile design and transmission characteristics of the RDF, WDM transmission experiments, and the characteristics of prototype RDF units.

2. RDF DESIGN

In large-capacity WDM transmission, it is necessary to minimize wavelength dispersion in the link over a wide range of wavelengths. To realize a dispersion managed link in which RDF and SMF are connected, the overall dispersion characteristic and dispersion slope of the link taken as a whole are of greater importance than those of the RDF alone. To evaluate the flatness of dispersion in the link as a whole, a dispersion compensating rate R is in general use, defined by the equation

$$R (\%) = \frac{S_{\text{RDF}}/D_{\text{RDF}}}{S_{\text{SMF}}/D_{\text{SMF}}} \times 100 = \frac{\text{DPS}_{\text{RDF}}}{\text{DPS}_{\text{SMF}}} \times 100 \quad (1)$$

where:

S is slope,

D is dispersion, and

DPS is dispersion divided by slope.

The closer the dispersion compensating rate is to 100% the easier it is to realize a transmission link with zero dispersion over a wide range of wavelengths. Since the dispersion compensating rate is 100% only if the DPS of the

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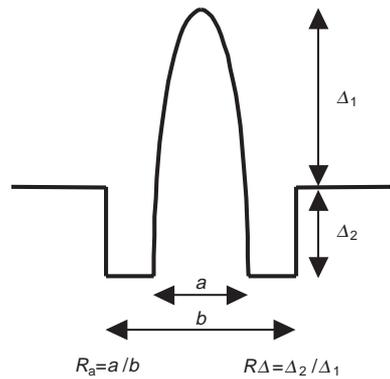


Figure 1 W-shaped profile

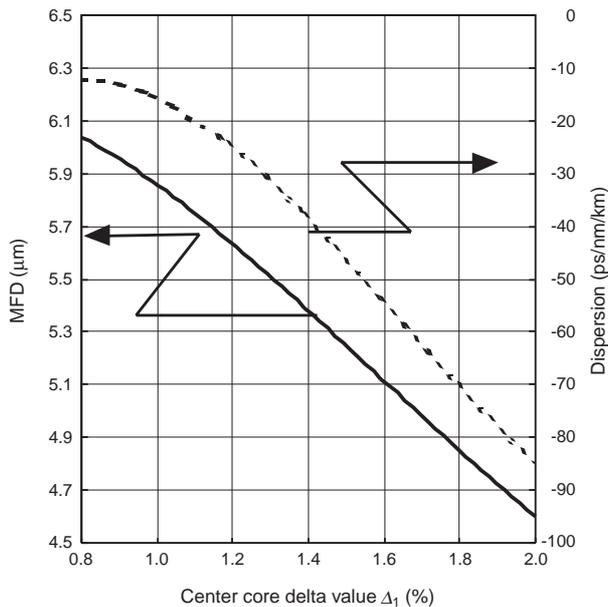


Figure 2 Relationship of dispersion and MFD to center core relative refractive index difference

RDF and SMF are equal, DPS is widely used as an index showing the dispersion compensation capacity of the fiber alone.

Since a dispersion-managed link is characterized by its broadband dispersion compensation characteristics, the most important objective of RDF design is to have the dispersion compensating rate when connected with SMF equal 100%, or in other words for its DPS to be equal to that of the SMF. The W-shaped profile shown in Figure 1 has been most investigated in DCF design for several reasons: its structure is comparatively simple, it is easy to fabricate, and it achieves a dispersion compensating rate of close to 100%.³⁾⁻⁵⁾ The W-shaped profile was therefore adopted for the RDF as well, and optimization was carried out.

By optimizing W-profile parameters it is fully possible to achieve high dispersion compensation, but for high bit-rate, large-capacity transmission an equally important point is the suppression of signal distortion due to the nonlinear phenomena. One of these nonlinear phenomena--

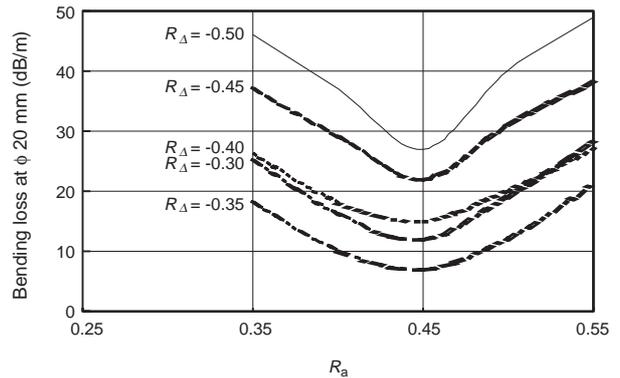


Figure 3 Relationship of bending loss to R_a for selected values of R_Δ

four-wave mixing (FWM)--is conspicuous where local dispersion is small, and exerts a particularly strong influence in the vicinity of zero dispersion. Fibers like SMF and DCF, however, have large local dispersion, and are therefore advantageous with respect to the suppression of FWM.

Conventional DCF, on the other hand, inherently has a small MFD and large center core delta value, so that it is highly subject to waveform distortion due to self-phase modulation (SPM) and cross-phase modulation (XPM). This is a major difficulty when it comes to use in transmission lines. Waveform distortion caused by SPM and XPM (ϕ_{NL}) may be expressed by

$$\phi_{NL} = (n_2/A_{eff}) \times L_{eff} \times (P_1 + P_2 + P_3 + \dots + P_n) \quad (2)$$

where:

- n_2 is the nonlinear refractive index,
- A_{eff} is the effective core area,
- n_2/A_{eff} is the nonlinearity constant,
- L_{eff} is the effective length and
- P is input optical power.

From Equation (2) it can be seen that the most effective means of suppressing wavelength distortion is either to increase A_{eff} (which is proportional to the square of MFD), or to reduce n_2 (which basically increases with the center core delta value).

RDF is designed, through optimization of its refractive index profile, to reduce nonlinearity. The center core delta value (Δ_1) has an especially strong effect on nonlinearity, and this relationship is shown in Figure 2.

As can be seen from Figure 2, setting Δ_1 at the low side--say 1.0 to 1.2%--increases MFD and reduces the nonlinear refractive index, thereby achieving low nonlinearity. Generally, however, reducing Δ_1 results in an increase in bending loss so that center core shape, R_a and R_Δ were optimized, thereby preventing an increase in bending loss while maintaining a high compensating rate. Figure 3 shows fluctuations in the bending loss characteristic at a dispersion compensating rate of 100% and varying values of R_a and R_Δ .

Table 1 Characteristics of prototype reverse-dispersion fiber

Item	Typical value
Cladding diameter (μm)	125.0 \pm 1.0
Cladding non-circularity (%)	0.1
Core concentricity error (μm)	0.1
Transmission loss (dB/km) @ 1550 nm	0.24
Dispersion (ps/nm/km) @ 1550 nm	-20 \pm 5.0
DPS (nm) @ 1550 nm	350
Dispersion compensating rate (%) @ 1550 nm	94
λ_c (nm)	820
MFD (μm) @ 1550 nm	5.6
A_{eff} (μm^2) @ 1550 nm	24
Nonlinearity constant (1/W)	12.4 \times 10 ⁻¹⁰
20-mm bend (dB/m) @ 1550 nm	10
Polarization mode dispersion (PMD) (ps/ $\sqrt{\text{km}}$)	0.07
Screening level	>1.0%

Table 2 Characteristics of positive-dispersion fibers

Type of fiber	Dispersion (ps/nm/km)	DPS (nm)	Loss (dB/km)	A_{eff} (μm^2)
SMF	16.6	286	0.195	75
CSF	18.5	308	0.189	83
FF	18.5	330	0.172	73

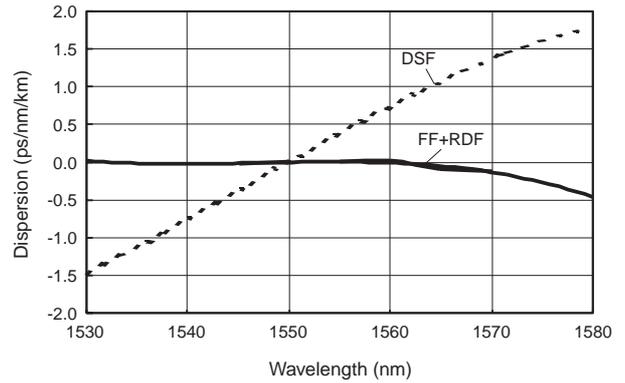
 $\lambda=1550$ nm**Table 3 Characteristics of transmission lines as a whole**

	Average loss (dB/km)	Dispersion slope (ps/nm ² /km)
SMF+RDF	0.213	0.005
CSF+RDF	0.210	0.003
FF+RDF	0.201	0.001
DSF	0.215	0.070
Low-slope DSF	0.220	0.035

 $\lambda=1550$ nm

3. FIBER CHARACTERISTICS

The fabrication of prototypes was then begun based on the design described above. RDF was fabricated with a refractive index profile indicated by simulation results, by establishing the optimum fabrication and drawing conditions. Table 1 shows the characteristics, demonstrating that low loss and low PDM were achieved while maintaining an extremely high dispersion compensating rate. With respect to the crucial characteristic of nonlinearity, a value of approximately 12.4 \times 10⁻¹⁰ I/W was achieved--only about 60% of the value for conventional DCF.

**Figure 4 Wavelength dispersion characteristic of conventional DSF and FF+RDF**

4. CHARACTERISTICS OF A TRANSMISSION LINK USING RDF

The primary feature of RDF is that it can be used, in combination with positive-dispersion fiber, to configure links having a flat dispersion characteristic. Thus RDF performance is determined by its overall characteristics in the transmission link incorporating SMF. Accordingly evaluations of overall transmission line characteristics were carried out using Furukawa Electric's conventional SMF, germanium-doped cut-off shifted fiber (CSF), and fully fluorine-doped fiber (FF).

Table 2 shows the characteristics of positive-dispersion fibers used as paired with RDF.

Table 3 shows the total loss and dispersion slope when the various fibers and RDF were connected at optimum length. It can be seen that for each link, a flat dispersion characteristic was obtained at extremely low loss.

Dispersion slope is about 0.07 ps/nm²/km for conventional DSF and that, even for much-studied DSF with reduced dispersion slope, reaches only 0.03-0.04 ps/nm²/km. It is therefore noteworthy that for links combining positive dispersion fiber and RDF, values an order of magnitude lower were obtained.

Figure 4 compares the wavelength-dispersion characteristic for an FF+RDF link and conventional DSF. The remarkable flatness of the characteristic demonstrates conclusively the suitability of such links for broadband WDM transmission. Although at longer wavelengths a small negative slope can be discerned, this does not present a problem in actual use. It is also possible, for example, by using a fiber with a positive dispersion slope as a dispersion compensator, to obtain perfect dispersion flatness even at longer wavelengths, making possible WDM transmission using both the C and L bands.⁶⁾

Just as important as dispersion flatness across wavelength, however, is the flatness of the wavelength-loss characteristic (attenuation spectrum). Figure 5 shows the attenuation spectrum of FF+RDF, and it can be seen that it is also flat.

Next let us examine nonlinearity. Although RDF offers about 60% lower nonlinearity than conventional DCF used

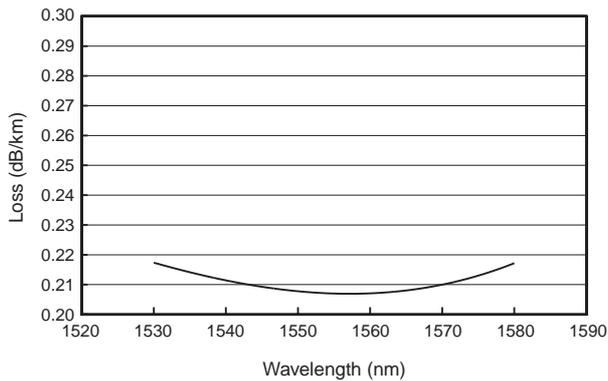


Figure 5 Attenuation spectrum of FF+RDF

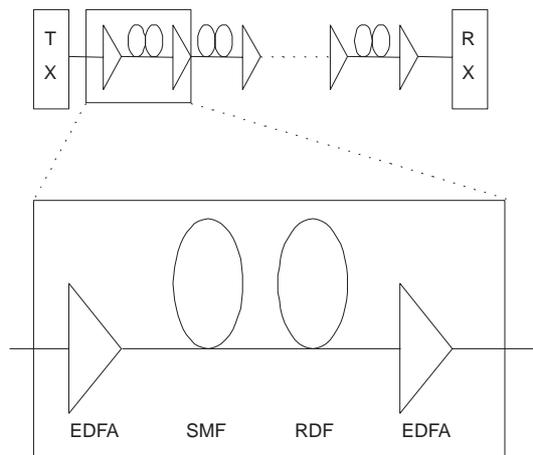


Figure 6 Typical WDM transmission link consisting of SMF and RDF

for short lengths, the nonlinearity constant is still about an order of magnitude greater than that of conventional SMF. This is because the W-shaped profile used to obtain the negative dispersion slope makes it much more difficult to increase MFD than the conventional profile used for SMF.

Figure 6 shows a typical WDM transmission link consisting of a combination of SMF and RDF. SMF has extremely low nonlinearity, and to make effective use of this, it is desirable to provide a pre-stage immediately after erbium-doped fiber (EDF) amplification as shown in Figure 6, for the injection of high power. As described above in Section 2 "RDF Design", signal distortion due to nonlinearity occurs easily when input optical power is high. Optical signal strength is obviously greatest immediately after the optical amplifier, after which it decreases exponentially due to transmission loss in the pre-stage fiber (SMF in this system). Thus when the attenuated signal is then input to the post-stage fiber, there is less tendency for signal distortion due to nonlinearity to occur, even in RDF having highly nonlinear characteristics.

Further, when we consider a system consisting of different types of fibers, as described above, another point that must be taken into account is splice characteristics. The greatest advantage of RDF is that its Δ_1 is small while MFD is larger than in conventional DCF, although only about half the value of ordinary SMF. This means that

Table 4 Fusion splice loss between RDF and selected positive-dispersion fibers

	Before improvement (dB)	After improvement (dB)
SMF	0.70	0.20
CSF	0.73	0.23
FF	0.65	0.17

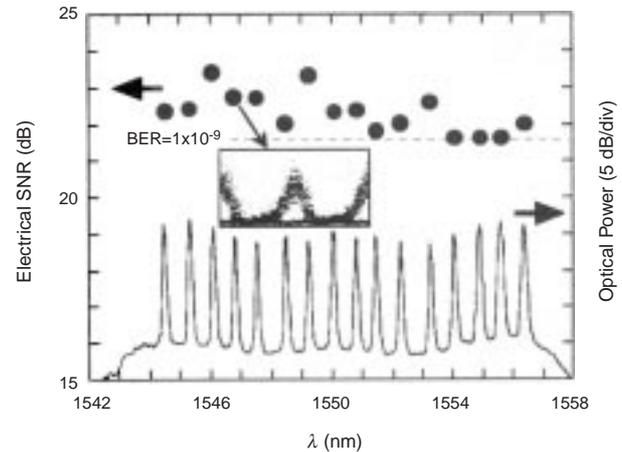


Figure 7 Optical spectrum of a 10-Gbps x 16-ch x 9412-km WDM transmission system using SMF and RDF⁹⁾

connecting SMF and RDF poses a major problem. If ordinary fusion splicing is used, splice loss will reach 0.8-1.0 dB.

Accordingly the question of optimizing fusion conditions so as to minimize splice loss was investigated, and this was accomplished by a state-of-the-art technique involving the use of thermal diffusion of the germanium layer. Table 4 compares the fusion splice loss between RDF and selected positive-dispersion fibers before and after improvement. It was thus confirmed that this improvement made possible fusion splicing with loss levels of 0.30 dB or less for all RDF-positive dispersion fiber combinations.

A variety of transmission experiments have been carried out using links connecting one of the above positive-dispersion fibers and RDF. Outstanding transmission characteristics have been reported, and these links have showed excellent promise for the achievement of higher bit-rates and larger capacities for both WDM and TDM.⁷⁾⁻⁹⁾

Figure 7 shows the optical spectrum of one of the experiments for WDM transmission, demonstrating its feasibility for high bit-rate, large capacity transmission over long distances.

5. UNIT CHARACTERISTICS

As has been pointed out above, RDF is a cable-type dispersion compensating fiber, so that its characteristics after cabling must be equivalent to conventional submarine cable. Accordingly a prototype of the tight-buffering unit used in Japan was fabricated and its characteristics evaluated.

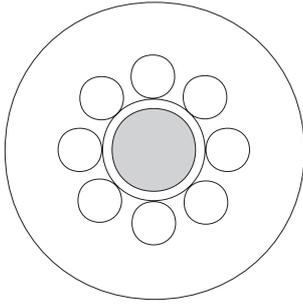


Figure 8 Cross-section of prototype RDF unit

Table 5 Results of environmental tests on RDF units

Test	Test conditions	Loss fluctuation
Temperature cycling	-20~+50°C	<±0.004 dB
Lateral force	0~50 N/cm	<±0.002 dB
Water pressure	0~10 MPa/cm ²	<±0.01 dB

The fiber used in the evaluation had a coating diameter of 400 μm --as is currently used for submarine cables--and the prototype unit consisted of 8 cores with an outer diameter of 2.5 mm (cross-section shown in Figure 8).

The RDF for this prototype had typical characteristics as shown in Table 1.

There was no difference between before and after unit fabrication in any of the fibers with respect to any of the test items--transmission loss, dispersion characteristics, PMD, etc. As an environmental test for the RDF unit to check for fluctuation in characteristics under ambient changes, the temperature-loss characteristic was evaluated, and lateral force and water pressure tests were also carried out.¹⁰⁾ Table 5 shows the tests performed and the results obtained. In all characteristics evaluated, performance was equivalent to ordinary submarine units. Figure 9 shows the temperature-loss characteristic. Loss decreased at low temperatures and increased at elevated temperature, in the same way as for ordinary submarine units, and the degree of change was equivalent to that of conventional products. This demonstrates that RDF is fully practicable for use in submarine cables.

While it is not possible to go into detail here, prototypes were also fabricated for tape-slotted and loose-tube cables, and were confirmed to have satisfactory characteristics.¹¹⁾

6. CONCLUSIONS

By optimizing the W-shaped profile, RDF with low nonlinearity, low loss and low PMD was developed for use in combination with SMF. It was also confirmed that by combining RDF with SMF or other positive-dispersion fibers it was possible to configure transmission links having extremely flat dispersion and low loss. Large numbers of experiments involving long-haul, large-capacity transmission in systems using such links have been reported, and transmission characteristics have proved to be very good

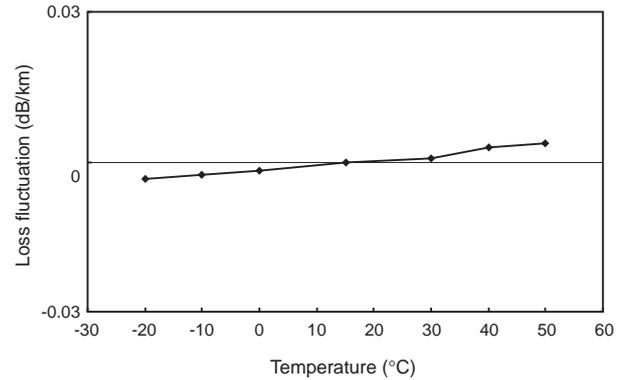


Figure 9 Temperature-loss characteristic of RDF unit

indeed.

RDF unit characteristics were confirmed assuming use as submarine cables, and excellent results obtained.

REFERENCES

- 1) K. Mukasa, Y. Akasaka, Y. Suzuki and T. Kamiya: Novel network fiber to manage dispersion at 1.55 μm with combination of 1.3 μm zero dispersion single mode fiber, Proceeding of ECOC'97, (1997), MO3C-127
- 2) K. Mukasa, Y. Akasaka, and Y. Suzuki: Development of line type low nonlinearity DFCF, Society Conference of IEICE, (1997) C-3-76 (in Japanese)
- 3) Y. Akasaka, R. Sugizaki, A. Umeda, I. Oshima and K. Kokura: Dispersion-compensating fiber with W-shaped index profile, OFC'95 Technical Digest, (1995) ThH3
- 4) R. Sugizaki, Y. Akasaka, S. Arai, K. Furukawa, Y. Suzuki, T. Kamiya and H. Hondo: High-reliability dispersion compensator using negative slope DCF, IWCS'96, (1996) pp.888-891
- 5) Y. Akasaka, R. Sugizaki and T. Kamiya: Dispersion compensating technique of 1300nm zero-dispersion SM fiber to get flat dispersion at 1550 nm range, Proceeding of ECOC'95, (1995) We.B.2.4
- 6) K. Fukuchi, M. Kakui, A. Sasaki, T. Ito, Y. Inada, T. Tsuzaki, T. Shitomi, K. Fujii, S. Shikii, H. Sugahara, A. Hasegawa: 1.1-Tb/s (55 x 20-Gb/s) dense WDM soliton transmission over 3,020-km widely-dispersion-managed transmission line employing 1.55/1.58- μm hybrid repeaters, Proceeding of ECOC'99 (1999) PD2-10
- 7) K. Yonenaga, A. Matsuura, S. Kuwahara, M. Yoneyama, Y. Miyamoto and K. Hagimoto: Dispersion-compensation-free 40 Gbit/s x 4-channel WDM transmission experiment using zero-dispersion-flattened transmission line, OFC'98 Technical Digest (1998), PD20
- 8) Murakami, Maeda and Imai: 16 x 10 Gb/s wavelength-multiplexed long distance transmission based on higher-order fiber dispersion management, Society Conference of IEICE, (1998) B-10-167 (in Japanese)
- 9) T. Yamamoto, E. Yoshida, K.R. Tamura and M. Nakazawa: Single-channel 640 Gbit/s TDM transmission over 100 km, Proceeding of ECOC'99 (1999) We C1.4
- 10) Edited by Oyama and Kuwabara: Optical submarine cables communication, KEC (1991), 81 (in Japanese)
- 11) M. Morimoto, I. Kobayashi, H. Hiramatsu, K. Mukasa, R. Sugizaki, Y. Suzuki, Y. Kamikura: Development of Dispersion Compensation Cable Using Reverse Dispersion Fiber, Proceedings of APCC/OECC'99 (1999) C6.8 pp.1590-1593

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