Raman Amplifier with Integrated Dispersion-Compensating Fiber

by *Shinya Nagamatsu*[*], *Bera Pálsdóttir*[*2], *Takeshi Hirasawa*[*3],
Akira Fujisaki[*4], *Ryuji Takaoka*[*5] *and Shigeru Shikii*[*4]

ABSTRACT It has been more than 20 years since fiber-optic communication became practicable, and there has been a continuing stream of technological breakthroughs. The increased diffusion of the Internet has seen the rapid introduction of dense wavelength division multiplexing (DWDM) systems. With the burgeoning increases in communications capacity in recent years, attention has been focused on Raman amplifiers, and work goes forward on applying them to various systems. Among these may be mentioned Raman amplification technology for dispersion compensating fiber (DCF) modules. This paper reports on the results of integrating a DCF module that can be added to existing fiber-optic transmission devices with a Raman amplifier (incorporating control circuitry).

1. INTRODUCTION

It has been more than 20 years since fiber-optic communication became practicable, and there has been a continuing stream of technological breakthroughs. The increased diffusion of the Internet has seen the rapid introduction of dense wavelength division multiplexing (DWDM) systems. With the burgeoning increases in communications capacity in recent years 1), attention has been focused on Raman amplifiers 2), 3), and work goes forward on applying them to various systems. During the 1980s much work was done on the technology of Raman amplification as a prime contender for use as a fiber-optic communications amplifier, but at the practical level the development and adoption of the erbium-doped fiber amplifier meant that this never went beyond the research stage.

However as bit rates progressed from 2.5 Gbps to 10 and even 40 Gbps, it became difficult to design systems with only EDFAs, and the advantages of distributed Raman amplification, in which the transmission path itself serves as the amplification medium, were recognized. More recently, the use of Raman amplification while optimizing the dispersion characteristics of the transmission path has become an indispensable technology for upgrading transmission capacity and transmission limits. That is to say in order to upgrade transmission capacity, technologies for optimizing dispersion characteristics (dispersion management) have assumed great importance.

One of these important technologies is Raman amplification for dispersion compensating fiber (DCF) modules. This paper reports on the results of integrating a DCF module that can be added to existing fiber-optic transmission devices with a Raman amplifier (incorporating control circuitry).

2. CHARACTERISTICS OF VARIOUS OPTICAL FIBERS

Figure 1 shows the relationship between the Raman gain coefficient and fiber length for various fibers. It can be seen that in comparison to single-mode fiber, all the others--the highly nonlinear fiber (HNLF), dispersion compensating fiber (DSC), reverse dispersion compensating fiber (RDF) and dispersion-flat fiber (DFF)

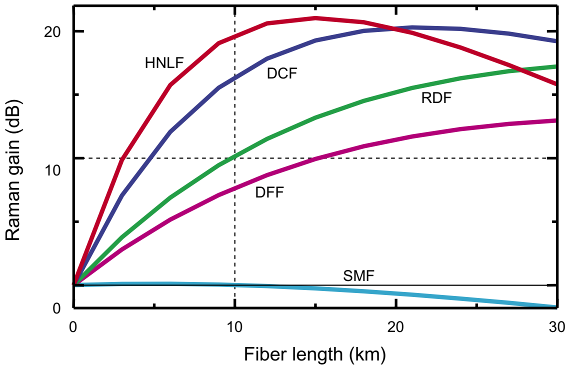

Figure 1 **Relationship between Raman gain and fiber length for various fibers.**

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[*] Metal Products Development Center, Metal Research Center
[*2] OFS FITEL Denmark I/S
[*3] Thermal Products Dept., Electronic Components Div.
[*4] Optical Components Dept., FITEL Products Div.
[*5] OptCom Div.

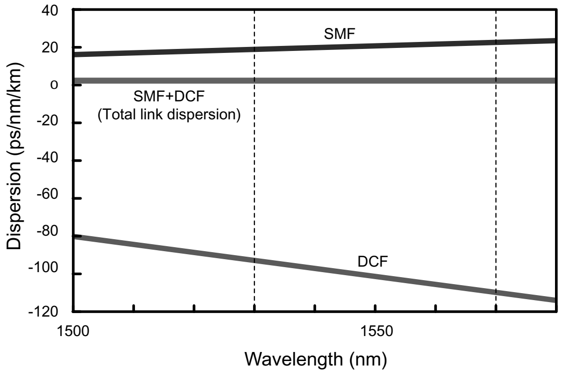

Figure 2 **Wavelength dependence of dispersion compensation using SMF + DCF link.**

Table 1 **L-band characteristics of DCF.**

Item		Value
Effective area: Aeff (μm^2)	at λc*	25.8
	at λp*	15.5
Loss coefficient: α (dB/km)	at λc	0.4
	at λp	0.4
Dispersion (ps/nm/km)	at λc	-152
Dispersion slope (ps/nm^2/km)	at λc	-0.4
PMD (ps/km$^{1/2}$)	at λc to λp	0.1
Rayleigh scattering coefficient (l/m)	at λc	0.2×10^{-5}

(* λc = 1590 nm, λp = 1470 nm)

--have higher Raman gain coefficients. Figure 2 shows an example of dispersion compensation with SMF + DSF. It will be appreciated that this is an extremely effective approach to upgrading existing SMF links while retaining their many advantages--low loss, low PMD, low cost, low nonlinearity and high localized dispersion. It also has disadvantages, however, in terms of the high loss in DCF and the space taken up when accommodated as spools in system equipment.

3. IMPROVING DCF CHARACTERISTICS

Removing the two disadvantages referred to above would make the approach described a highly effective solution. The first area we focused on was improving the characteristics of the DCF itself. Table 1 shows the improved characteristics. It can be seen that DCF loss has been held to around 0.4 dB for both the amplification band (1470 nm) and the signal band (1590 nm).

When considering Raman amplification, the important factors are: 1) the pumping band loss because it is directly related to Raman amplification efficiency, and 2) the Rayleigh scattering coefficient, which should be as low as possible since it gives rise to problems such as double Rayleigh back-scattering noise (multipath interference noise, or MPI).

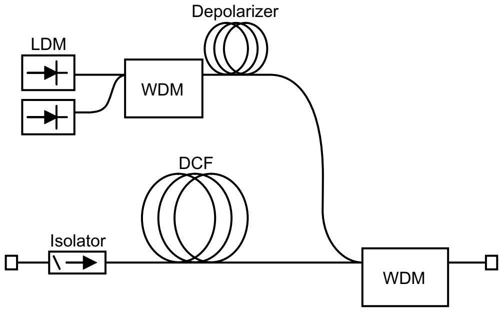

Figure 3 **Optical configuration.**

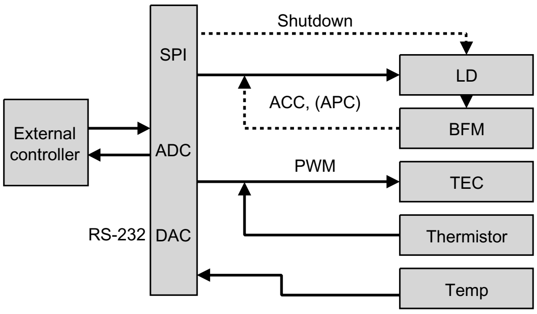

Figure 4 **Block diagram of control system.**

It can be seen that the Rayleigh scattering coefficient, at 0.2×10^{-5} l/m, has been improved to a level approaching the SMF value of 0.1×10^{-5} l/m .

4. DESIGN OF RAMAN PUMPING LASER

Based on the improvements to DCF characteristics described above, we proceeded to design the simplest possible Raman pumping laser. Figure 3 shows the optical configuration that was used.

The pumping laser used in this case was of a 2-wavelength structure, with one laser diode module for each of the two wavelengths. And the Raman module used was entirely contained within the DCF spool, in a structure in which no further space was required to add the Raman module.

Considering that use could be made of the space accommodating the DCF, a control function was therefore provided to enable independent control of the Raman module. Figure 4 is a block diagram of the control system.

As can be seen the control circuitry is accommodated within the Raman module, and pulse width modulation (PWM) control is utilized to reduce the power consumption of the amplifier.

Both a serial peripheral interface (SPI) and a RS232 port are provided as communications control interfaces. This was done to facilitate control from a personal computer over the RS232, and to support the SPI buses used for communications control when built into existing transmission devices.

Figure 5 shows an outside view of the Raman pumping laser module and Figure 6 shows the inside.

The Raman pumping laser module is circular in outline, from which emerges the communications control interfaces. Two types of control are supported: automatic current control (ACC) and automatic power control (APC). There is also a shutdown function for use when a fault is detected. Figure 7 shows the final configuration of a Raman amplifier module with integrated DCF. As can be seen this Raman pumping laser is entirely enclosed within the DCF module, making it possible to add the laser without increasing the space allotted for the DCF module inside conventional transmitting devices.

Figure 5 Outside view of Raman pumping laser module.

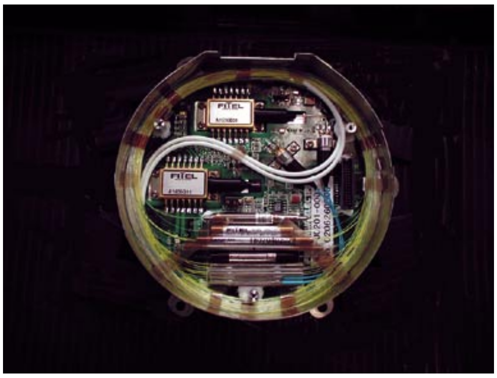

Figure 6 Inside view of Raman pumping laser module.

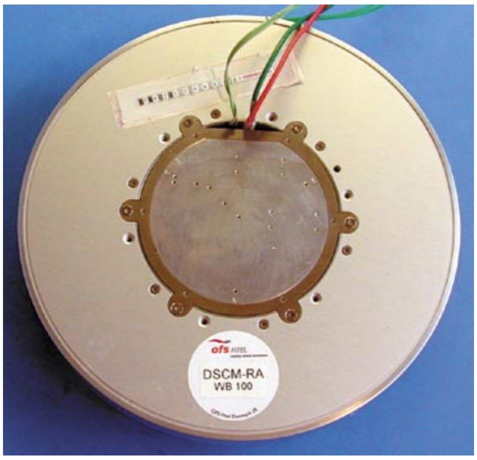

Figure 7 Raman amplifier module with integrated DCF.

5. EVALUATION OF CHARACTERISTICS

The characteristics of the Raman amplifier described above were then evaluated. The evaluation was carried out with respect to a dispersion and slope compensating fiber using pumping lasers of two wavelengths--1430 and 1455 nm.

Figure 8 shows the results of measurements of the noise figure (NF) and multipath interference noise (MPI) with respect to gain for NZ-DSF (TrueWave®) and SMF fibers with a compensating distance of 125 km and an input power of 5 dBm. In the case of NZ-DSF compensation the gain was at the 0 dB level and MPI was -50 dB, and for SMF compensation the gain was at the -1 dB level and MPI was -45 dB.

Specifically it was found that for NZ-DSF 125-km compensation, a completely loss-free condition (gain = 0 dB or above) was obtained at MPI of -50 dB.

Figure 9 shows the results of measurements of relative intensity noise (RIN). Based on measurements using four laser diode modules, results were stable for frequencies

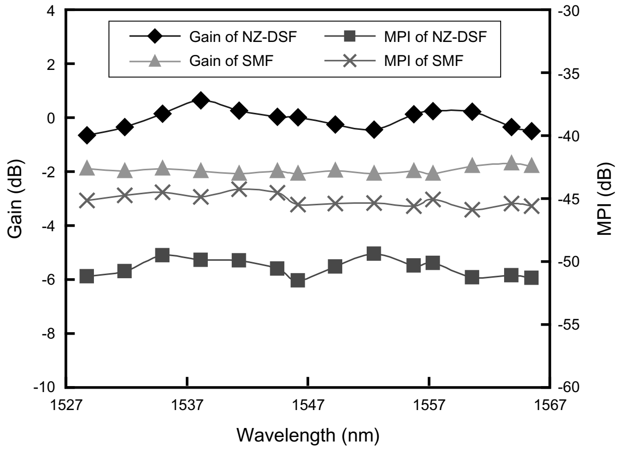

Figure 8 Measured characteristics of Raman amplifier.

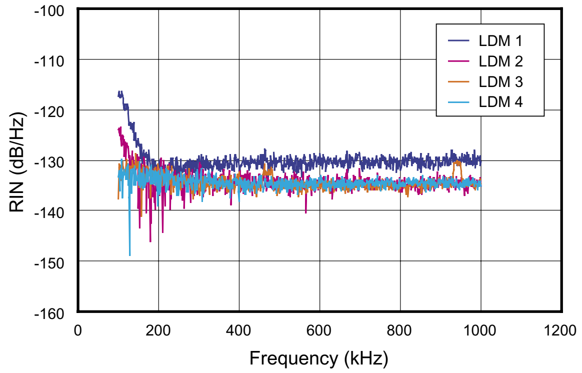

Figure 9 Frequency dependence of relative intensity noise (RIN).

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† TrueWave® is a registered trademark of OFS Fitel.

Table 2 Measured power consumption of Raman amplifier.

Case No.	LDM No.	Operating current (mA)	Power consumption (W)
1	1	416	9.27
	2	404	
2	3	435	9.93
	4	422	

of 200 kHz and above, at -130 dB/Hz or better, confirming that no problem exists with respect to control circuit noise.

Table 2 shows the results of measuring power consumption under the conditions described above: NZ-DSF 125-km compensation at a gain of 0 dB.

Since this module is installed in a location where the use of a Raman pumping laser was not envisaged, there was a strong requirement that the heat emitted by the pumping laser be as small as possible. For this reason a pulse width modulation (PWM) drive system was used for the Peltier module of the LDM, which has the greatest power consumption. As Table 2 shows, consumption was held to below 10 W.

6. SUMMARY

A significant improvement has been effected in the loss of dispersion compensation fiber, with a transmission loss of 0.4 dB/km. Success was also achieved in integrating a DCF module with a Raman amplifier (incorporating control circuitry).

As a result it was confirmed that for a compensation distance of 125 km it was possible to use both NZ-DSF and SMF in actual applications.

Specially noteworthy is that for NZ-DSF 125-km compensation a loss-free (gain = 0 dB) condition was achieved at an MPI of -50 dB or below. This technology has the advantage of facilitating the upgrading of existing transmission devices, and at the same time enabling transmission devices to be designed without considering DCF insertion loss.

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