# 40 GB/S DWDM TRANSMISSION TECHNOLOGIES

# FOR FUTURE REPEATERED AND NON-REPEATERED SUBMARINE CABLE SYSTEMS


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**Abstract:** This paper describes our extensive study results toward deployment of 40Gb/s DWDM technologies in repeatered and non-repeatered submarine cable systems. For trans-Oceanic transmission of 40Gb/s WDM signal, we have optimized the system design of EDFA and medial-dispersion DMF transmission system, which supports the 40Gb/s CS-RZ WDM signal transmission over distances exceeding 6,000km. We have also confirmed by experiments that, with remote pumping scheme, over 300 km transmission of 40Gb/s WDM signal is feasible under 100GHz channel spacing.


## 1 INTRODUCTION

Over many years optical telecommunications systems have evolved from low to higher speeds, and the higher speed technology have always offered lower cost per bit. If we follow this experience, the next logical step will undoubtedly be to move to 40 Gb/s. However, in the 40Gb/s-based WDM systems, transmission quality rapidly deteriorates with increase of transmission distance due to the combined effects of fiber nonlinearity and dispersion. This is because the 40Gb/s systems require higher signal power to keep the signal-to-noise ratio with four times wider receiver bandwidth compared to 10Gb/s systems. Consequently, much effort should be paid for better system performance to deploy 40 Gb/s systems over the trans-Oceanic distance.

This paper describes our extensive study results toward deployment of 40Gb/s DWDM technologies in repeatered and non-repeatered submarine cable systems.

For trans-oceanic transmission of 40Gb/s WDM signal, optimization of transmission line design is vital. By adoption of advanced dispersion managed fiber (DMF) with reduced dispersion and optimized dispersion mapping, we have confirmed by experiments that over 6000 km transmission of 40Gb/s x 50 WDM signal with 100GHz spacing is feasible with a few dB margin by means of standard Er-doped optical amplifier repeaters[1].

Non-repeatered 40 Gb/s WDM systems are more straightforward compared with the trans-oceanic repeatered systems. The low-loss single mode fiber (SMF) cable with large dispersion is still proven the best as transmission media for long span non-repeatered 40Gb/s transmission. We have experimentally verified that, with remote pumping scheme, over 300 km transmission of 40Gb/s WDM signal is feasible under 100GHz channel spacing. The maximum span achievable is reduced only by the value of receiver sensitivity, thus almost the same reach as 10Gb/s non-repeatered systems is achievable at 40Gb/s.

For application to such 40 Gb/s systems, 40 Gb/s Line Terminal Equipment ( LTE) is being developed. Its transponder has implemented advanced FEC and DPSK-RZ modulation format to achieve higher performance. Because the optical multiplex and de-multiplex parts of LTE can be commonly used, the 40Gb/s transponders can be mixed with those of 10Gb/s.

## 2 TECHNOLOGIES FOR TRANS-OCEANIC DISTANCE 40GB/s DWDM TRANSMISSION SYSTEMS

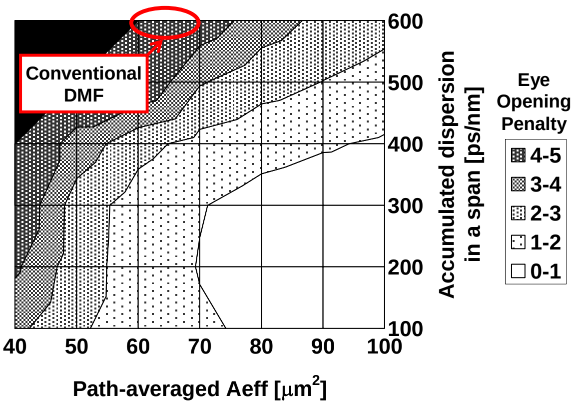
### 2.1 Fiber Design for 40Gb/s Signal Transmission

In the 40Gb/s-based WDM systems, transmission quality is inherently faded with increase of transmission distance due to the combined effects of fiber nonlinearity and dispersion. Key parameters for suppressing the dispersion-related nonlinear effect, that is, SPM-GVD are considered to be the path-averaged effective area and accumulated dispersion in one span.

We have comprehensively performed theoretical anlyses to find a window for the best 40Gb/s transmission. Figure 1 shows an example of the numerical study of transmission fiber for 40 Gb/s CS-RZ signals. The contour map shows the criteria for lower power penalty transmission in terms of the path-averaged effective area and accumulated dispersion, where white area corresponds to the area for penalties of less than 1 dB.

As shown in this figure, it is important to have the best design by considering both the path-averaged effective area and accumulated dispersion in one span.

The case of conventional DMF, which is designed for trans-Pacific 10Gb/s WDM systems[2], is also plotted in Fig.1. Accumulated dispersion of conventional DMF is considered to be too large for long-distance transmission of 40Gb/s signals.




*Simulation parameters*

| | |
|---|---|
| ***Bit rate*** | ***42.8Gb/s*** |
| ***Channel spacing*** | ***100GHz*** |
| ***Signal format*** | ***CS-RZ*** |
| ***Span length*** | ***45km*** |
| ***Repeater*** | ***EDFA*** |
| ***Power*** | ***-2dBm/ch*** |
| ***Distance*** | ***5,000km*** |

Fig. 1. Numerical Simulation of 40Gb/s Transmission

For fitting to lower penalty area, the reduction of local dispersion in each DMF span is predicted to be preferable, while the DMF is required to keep lower nonlinearity and dispersion flatness over wide wavelength band as well. As one of possible transmission lines to meet this requirement, we have studied the DMF transmission line using medial-dispersion-fiber, what we call MD-DMF [3]. Table 1 shows the properties of the positive dispersion fiber (P-MDF) and the negative dispersion fiber (N-MDF) which are included in our MD-DMF developed. The ensemble accumulated dispersion and path-averaged Aeff are 270 ps/nm and 60μm$^2$, respectively.

Table 1. MD-DMF Characteristics

| | Dispersion [ps/nm/km] | Disp. Slope [ps/nm$^2$/km] | Aeff [ m$^2$] |
|---|---|---|---|
| P-MDF | +13 | +0.07 | 93 |
| N-MDF | -13 | -0.07 | 33 |

The dispersion map shown in Fig. 2 was optimized by numerical simulations, in order to maximize the transmission distance of the 40Gb/s CS-RZ signals. Average dispersion in each span was set to -1 ps/nm/km and accumulated dispersion was compensated with a DCF span inserted at every five DMF spans. The typical variance of the residual dispersion after 6,000 km was 200 ps/nm over 40nm signal band.

The dispersion map of the conventional DMF is also depicted in Fig.2. Eventually, both the dispersion deviation and average dispersion for the MD-DMF system can be reduced to almost half of the conventional MF for 10Gb/s DWDM systems.

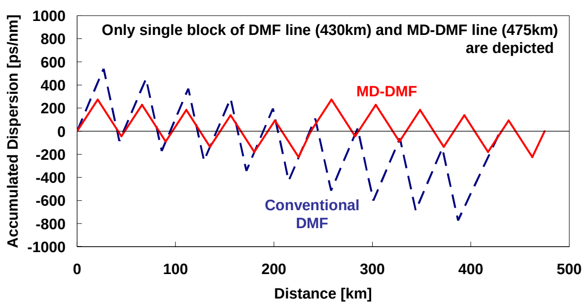



Fig. 2. Dispersion Map

## 2.2 40Gb/s x 50WDM 6,175km Transmission

Figure 3 shows an experimental setup for 100 GHz-spaced 50 x 42.8Gb/s CS-RZ signals transmission. The transmitter was comprised of 50 DFB-LDs equally spaced at 100 GHz intervals ranging from 1529.6 nm to 1568.8 nm. Even and odd channels were separately modulated into 42.8Gb/s CS-RZ signals by 42.8Gb/s CS-RZ transponder with A-FEC. Four 9.95Gb/s $2^{23}$-1 PRBS signals, delayed from each other by quarter word-length, are used for tributary inputs. The even and odd channels were pre-filtered and orthogonally multiplexed by a polarization-maintained 100/200 GHz interleaver. The transmission line was composed of ten spans of 45 km-long MD-DMF, two DCF spans and 13 EDFA repeaters. The repeater output powers were set at +12 dBm. In the receiver end, each channel selected by an AWG was detected by a 42.8-Gb/s ETDM receiver at the transponder. Four 9.95-Gb/s output signals from the transponder are transmitted to the error detector. The bit-error-rate (BER) of each channel was measured twice with the FEC decoder set to ”off” and ”on” conditions, respectively.

Figure 4 shows the optical spectrum and Q-values converted from the averaged BER of four 9.95-Gb/s tributaries with the FEC decoder off at 6,175 km. For all 50 channels, the average and worst Q values were 10.6 dB and 9.7 dB, respectively. When the FEC decoder was on, all 50 channels were recorded error-free over several minutes. If we consider system margins during 25 years operation, deployment of 40-Gb/s DWDM submarine system is technically sound for systems up to around 3000 km to 4000 km.

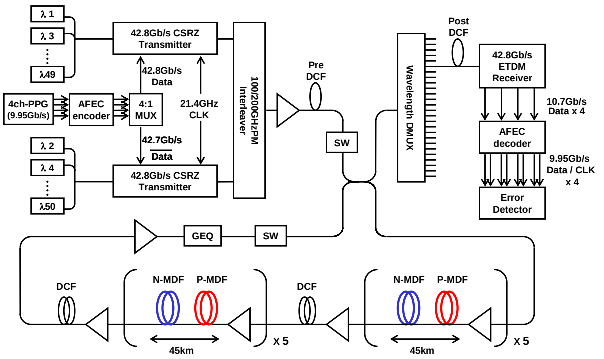



Fig. 3. Experimental Setup

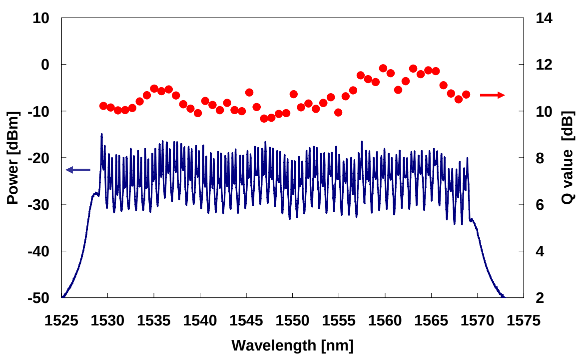



Fig. 4. Optical Spectrum and Q values at 6,175 km

## 3 40GB/S TRANSMISSION PERFORMANCE IN SUBMARINE NON-REPEATERED WDM SYSTEMS

### 3.1 Modulation Format

To stretch the maximum transmission distance for 40 Gb/s DWDM non-repeated systems, the increase of fiber input power and improvement of receiver sensitivity are essential. For this purpose, Return-to-Zero Differential-Phase-Shift-Keying (RZ-DPSK) signal format is the promising candidate because of its improved receiving sensitivity and superior tolerance for nonlinear effect [4].

Figure 5 shows the calculated eye opening penalties against fiber input power for NRZ, RZ and RZ-DPSK in 40Gb/s non-repeatered WDM transmission. RZ-DPSK indicates the superior non-linear tolerance compared to other two modulation formats.

Furthermore, RZ-DPSK can offer excellent suppression of stimulated Brillouin scattering (SBS) in optical fiber , which is one of the dominant limiting factor for high power signal transmission. This is because there is no large peak component at carrier frequency in the RZ-DPSK signal spectrum. So, larger optical power transmission is possible without suffering the SBS penalty. In our evaluation, no SBS effect was observed with fiber input power of more than +24 dBm/ch for 40Gb/s RZ-DPSK signal.

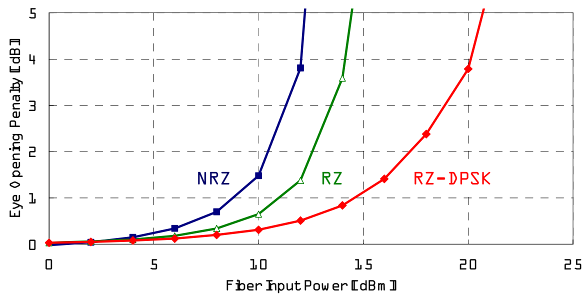



Fig. 5. Comparison of Non-linear Tolerance

### 3.2 40Gb/s-16WDM-320km Transmission

Figure 6 shows an experimental setup for 16 x 42.8 Gb/s 320 km non-repeatered transmission. The transmitter was comprised of 16 DFB-LDs equally spaced at 100 GHz intervals ranging from 1546.9 nm to 1559.0 nm. Even and odd channels were separately modulated into 42.8Gb/s RZ-DPSK signals. The even and odd channels were multiplexed by a 100/200 GHz interleaver and amplified by the booster amplifier. The transmission line was composed of low-loss pure silica core fiber (PSCF) with 320 km large dispersion. In the transmission line, a remotely pumped EDF, which is pumped by a 1480nm LD source at the receiver end, is inserted at the 80km from receiver end. In the receiver, after dispersion compensation, each channel selected by an AWG was detected by a 42.8Gb/s DPSK receiver.

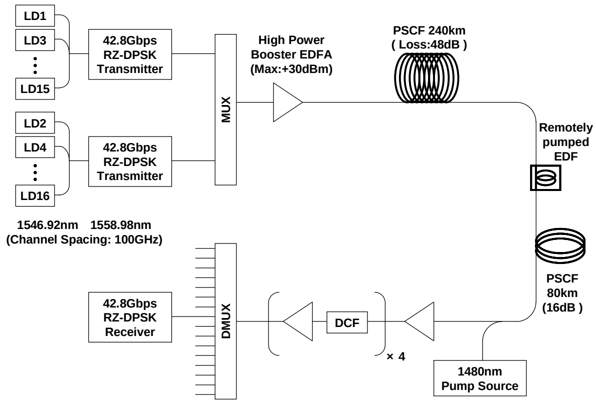



Fig. 6. Experimental Setup

Figure 7 shows experimental Q value at 1552.5 nm against the fiber input power for various settings of 1480nm LD pumping source (PSR). According to the increase of fiber input power, Q values are improved and fiber input power of +16 to +17 dBm/ch seems to be the optimum level. However, further increase of fiber input power beyond +18dBm/ch causes excess non-linearity penalty, resulting Q value degradation by contraries. On the other hand, Q values are almost the same with 1480nm LD pumping power setting of more than 430 mW because of the gain saturation of remotely pumped EDF.

Figure 8 shows the wavelength dependence of Q value with fiber input power of +17 dBm/ch and 1480 nm LD pumping power of 700 mW. The Q values are 14.5 dB on average and 13.9dB at minimum for eight channels measured, which are 5dB higher than our FEC detection limit. This result shows that 320km non-repeatered transmission of 16 x 40Gb/s DWDM signals can be achieved with sufficient system margin.

According to our evaluation, the maximum fiber input power of 100GHz-spaced 40Gb/s dense-WDM signals with RZ-DPSK modulation format can be increased up to almost the same level as the 10Gb/s case. Although increase of bit-rates from 10Gb/s to 40Gb/s degrades the receiver sensitivity by 6dB, introduction of RZ-DPSK modulation format, which improve the receiver sensitivity of around 6dB compared to NRZ, allows the equivalent receiver sensitivity as 10Gb/s NRZ signal. Thus, the 40Gb/s system with RZ-DPSK signal provides four times as much system capacity as 10Gb/s system designed with NRZ signal without sacrificing the transmission distance.

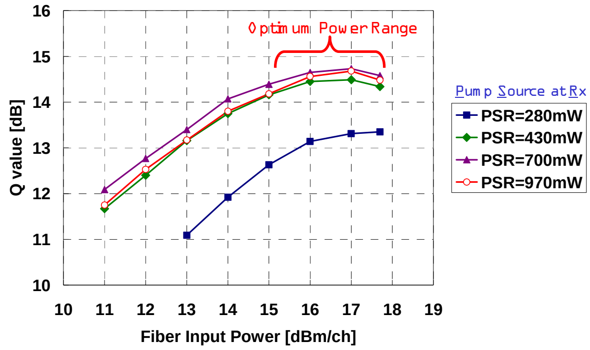



Fig. 7. Optimization of Fiber Input Power

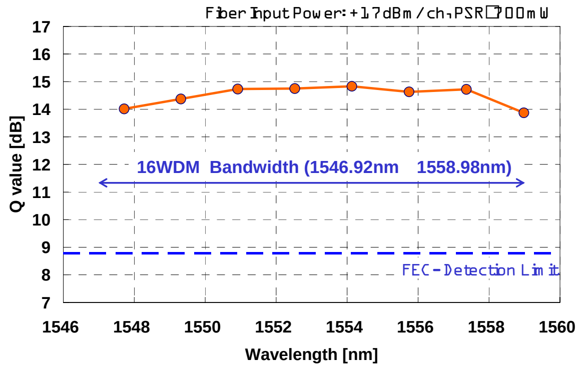



Fig. 8. Q values after 320-km Transmission

## 4 40GB/S LINE TERMINAL EQUIPMENT DEVELOPMENT

In order to suppress the fiber non-linear effect during transmission, we have studied the improvement of DMF property, dispersion map optimization and advanced RZ-DPSK modulation format, and experimentally confirmed the effectiveness of these technologies. The remaining and significant issue for 40Gb/s trans-oceanic submarine cable systems is the waveform degradation induced by polarization mode dispersion (PMD).

To cope with the PMD induced degradation, we have developed the electrical equalizer (EE) [5] and introduced the EE to the 43Gb/s transponder, which is compliant with ITU-T G.709 OTU3, along with the advanced FEC and RZ-DPSK modulation format. Figure 9 shows the front view of a 43Gb/s transponder. Because the optical multiplex and de-multiplex parts of LTE can be commonly used, the 40G transponders can be mixed with those of 10G.

Figure 10 shows the principal block diagram of the 43Gb/s RZ-DPSK transponder. An RZ-DPSK modulator consisting of two cascaded MZ-modulator generates 43Gb/s RZ-DPSK signal with duty cycle of 33%. An EE was inserted between the dual O/E converter and CDR-DMUX in the receiver part. This EE consists of four gain stages in a four- tap transversal filter topology and gain-limiting block, having the advantage of controllability for frequency response and gain as well as wide range compensation for various distortions at a fixed top-weight setting.

In case of “high sensitivity” setting of EE, superior performance can be expected under the condition that PMD effect of transmission line is sufficiently small and transmission performance is mainly limited with optical SNR or fiber nonlinearity. While there are a strong correlation between PMD and BER fluctuation and PMD-induced performance fluctuation is increased according to PMD. On the other hand, in case of “high PMD” setting, the EE contributes to suppress the BER fluctuation due to PMD, and BER becomes insensitive to the PMD. With this “high PMD” setting, superior performance is obtained than “high sensitivity” setting of EE under relatively high PMD conditions. As explained above, our 43Gb/s transponder can flexibly be applied to various transmission line conditions by simply adjusting the setting of EE.

Fig. 9. Front View of 43Gb/s Transponder

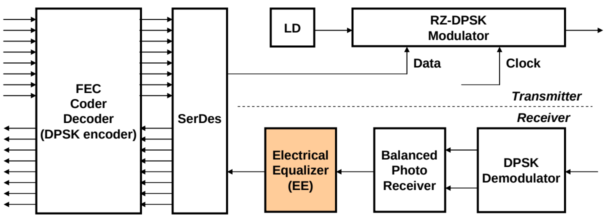



Fig. 10. Principal Block Diagram of 43Gb/s Transponder with EE

## 5 CONCLUSION

This paper has described the study results of 40Gb/s DWDM transmission technologies as well as introduction of 40Gb/s equipment for both repeatered and non-repeatered submarine cable systems. Our Prototype 43Gb/s RZ-DPSK transponder is flexibly applied to various transmission lines by adjusting its built-in Electrical Equalizer.

## 6 REFERENCES

[1] Y. Inada et al., ECOC2004, Th3.5.4, 2004.
[2] R. Kurebayashi et al., ECOC2002. 9.1.2, 2002.
[3] K. Mukasa et al., ECOC2000, 2.4.2, 2000.
[4] A. Gnauck et al., OFC2004, Tu-F5(Tutorial), 2004.
[5] S. Wada et al., OFC2006, paper OWE2, 2006.