Cost-Effective Transition to 40 Gb/s Line Rate Using the Existing 10 Gb/s-Based DWDM Infrastructure

Sang Soo Lee, Hyunwoo Cho, Sang-Kyu Lim, Dong-Soo Lee, Kyeong-Mo Yoon,
Yong-Gi Lee, Kwangjoon Kim, and Jesoo Ko

In this paper, we propose and demonstrate a cost-effective technique to upgrade the capacity of dense wavelength division multiplexing (DWDM) networks to a 40 Gb/s line rate using the existing 10 Gb/s-based infrastructure. To accommodate 40 Gb/s over the link optimized for 10 Gb/s, we propose applying a combination of super-FEC, carrier-suppressed return-to-zero, and pre-emphasis to the 40 Gb/s transponder. The transmission of 40 Gb/s DWDM channels over existing 10 Gb/s line-rate long-haul DWDM links, including 40×40 Gb/s transmission over KT's standard single-mode fiber optimized for 10 Gb/s achieves successful results. The proposed upgrading technique allows the Q-value margin for a 40 Gb/s line rate to be compatible with that of 10 Gb/s.

Keywords: Optical communications, 40 Gb/s, optical link, Q-value, modulation format, forward error correction, optical signal-to-noise ratio.

I. Introduction

The recent tremendous increase in data traffic induces carriers to upgrade their backbone and metro networks to 40 Gb/s per-channel line rate. Since the first demonstration of the 40 Gb/s transmission in 1997 [1], much progress in capacity and transmission distance expansion has been reported as a result of new modulation formats [2]-[4], new type of fibers [5], [6], and fiber Raman amplifiers. In spite of technical advances in the 40 Gb/s line rate, its proliferation has been slow because the deployment of new transmission equipment requires huge expenditure.

To provide a cost-effective transition to a 40 Gb/s line rate, it is essential for 40 Gb/s channels to be accommodated within the existing 10 Gb/s dense wavelength division multiplexing (DWDM) networks infrastructure, which consists of conventional erbium-doped fiber amplifiers and standard single-mode fiber [7]-[9]. To date, studies on 40 Gb/s over 10 Gb/s infrastructure have focused on nonlinear behavior [7], dispersion effects [8], and the add-drop issue [9]. However, smooth transition from 10 Gb/s to 40 Gb/s is important, and 40 Gb/s channels should be introduced on a line card basis in active 10 Gb/s-based DWDM links, gradually replacing 10 Gb/s channels as the traffic grows. There are already plenty of legacy WDM transmission networks optimized for a 10 Gb/s line rate, the chromatic dispersion, polarization effects, and optical signal-to-noise ratio (OSNR). In the upgrading scenario, it is desirable to keep the network infrastructure, namely, the transmission fiber and optical amplifiers, as they are.

In this paper, we propose the configuration of a 40 Gb/s transponder, which provides a cost-effective capacity upgrade

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Sang Soo Lee (phone: + 82 42 860 6186, email: soolee@etri.re.kr), Kwangjoon Kim (email: kjk@etri.re.kr), and Jesoo Ko (email: jsko@etri.re.kr) are with the Optical Communications Research Center, ETRI, Daejeon, Rep. of Korea.

Hyunwoo Cho (email: tenace@etri.re.kr) is with the Broadcasting & Telecommunications Convergence Research Laboratory, ETRI, Daejeon, Rep. of Korea.

Sang-Kyu Lim (email: sklim@etri.re.kr) is with the IT Convergence Technology Research Laboratory, ETRI, Daejeon, Rep. of Korea.

Dong-Soo Lee (email: d-soolee@etri.re.kr) is with the Optical Communications Research Center, ETRI, Gwangju, Rep. of Korea.

Kyoeng-Mo Yoon (email: kmyoon@kt.co.kr) is with the Technology Engineering BU Network Planning Department, KT, Seongnam, Rep. of Korea.

Yong-Gi Lee (email: leeyg@kt.co.kr) is with the Network Engineering Department, Platform Laboratory, KT, Daejeon, Rep. of Korea.

to a 40 Gb/s line rate as discussed in section II. After the transmission of 20×10 Gb/s non-return-to-zero (NRZ) and 20×40 Gb/s carrier-suppressed return-to-zero (CS-RZ) hybrid signals over 640 km of 10 Gb/s-based standard single-mode fiber (SSMF), we measure the Q-value for each channel and compare the Q-value margins of 40 Gb/s and 10 Gb/s channels in section III. Finally, we transmit 40 channels of 42.8 Gb/s CS-RZ signals over 511 km of KT's SSMF link with conventional EDFAs and measure the Q-value for each channel and Q-value fluctuation for a selected channel in section IV.

II. Configuration of 40 Gb/s Transponder

To realize the 40 Gb/s and 10 Gb/s hybrid transmission approach, we propose a 40 Gb/s transponder which consists of a CS-RZ transceiver, a super-FEC coder/decoder and a tunable dispersion compensator. The configuration of the proposed transponder is shown in Fig. 1.

For the 40 Gb/s application, the modulation format must provide higher receiver sensitivity with a compact modulation spectrum, higher nonlinear effects tolerance, and a simple configuration.

The return-to-zero (RZ) modulation format performs better than NRZ due to its higher receiver sensitivity at a low OSNR, high polarization mode dispersion (PMD), and high nonlinear effect environment. On the other hand, RZ shows insufficient filter and chromatic dispersion margins due to its wide spectrum characteristics. To maximize the advantages and minimize the disadvantages, a CS-RZ modulation format was proposed in [2].

The conventional forward error correction (FEC) scheme based on Reed-Solomon (RS) [255, 239] code provides a 6 dB coding gain and is widely used for existing 10 Gb/s-based terrestrial systems. To provide higher correction ability, the super-FEC schemes were recommended in ITU-T G.975.1 [10]. The super-FEC schemes consist of a combination of conventional coders, such as [RS+RS], [BCH (Bose-Chaudhuri-Hocquenghem)+BCH], and [RS+BCH]. Since the super-FECs provide a coding gain of 9 dB with 7% redundancy, OSNR sensitivity can be improved by 3 dB for a 40 Gb/s line rate. Therefore, effective improvement in OSNR sensitivity for 40 Gb/s can be achieved in cooperation with super-FEC and a CS-RZ modulation format.

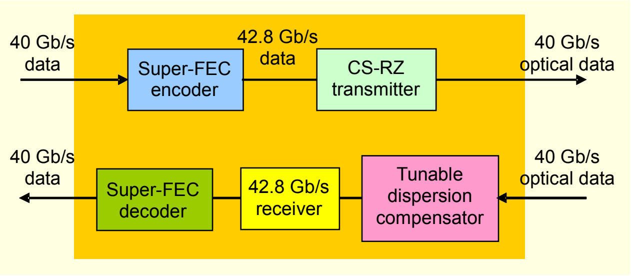

Fig. 1. Configuration of proposed 40 Gb/s transponder.

To ensure precise dispersion compensation, an optical tuneable dispersion compensator (TDC) is needed at the front-end of the receiver. The TDC consists of a chirped fiber Bragg grating and carries out dynamic dispersion compensation with thermal gradient.

III. 20×10 Gb/s and 20×42.8 Gb/s Transmission over 640 km SSMF

Figure 2 depicts the configuration of an optical link for 20×10 Gb/s and 20×42.8 Gb/s signals. Twenty laser diodes from 1530.33 nm to 1545.32 nm were modulated to a 10 Gb/s NRZ format, and twenty laser diodes from 1546.12 nm to 1561.42 nm were modulated to a 42.8 Gb/s CS-RZ format. In general, when a higher rate signal co-propagates with an intensity-modulated lower rate signal, waveform distortion can occur due to the cross-phase modulation (XPM) effect. To avoid nonlinear impairments, consecutive channel allocation was selected instead of interleaved or random channel allocation methods.

The 42.8 Gb/s transmitter consists of a 42.8 Gb/s CS-RZ modulator, a drive amplifier, and a 4:1 electrical multiplexer. A 4×0.7 Gb/s pseudo-random-bit sequence (PRBS) pattern of 2^{31}–1 stage from a pulse pattern generator (PPG) makes the bit-rate of 42.8 Gb/s, which reflects the 7% redundancy for the super-FEC coding rate. To enhance the OSNR of the 42.8 Gb/s channels, 2 dB pre-emphasis was applied, and the per-channel output powers of the 10 Gb/s and 42.8 Gb/s channels were –18 dBm and –16 dBm, respectively.

The optical amplifier consists of two amplification gain blocks separated by a mid-stage functional block including a voltage controlled attenuator, a gain flattening filter, and a dispersion compensation module, for gain clamping, gain equalization and dispersion compensation, respectively. The nominal output power and the noise figure of the amplifier were 20 dBm and 6 dB, respectively. The slope compensated dispersion compensation modules (DCMs) were inserted at the mid-stage of the amplifiers. The transmission distance was 640 km, and each span was 80 km. The average loss and dispersion coefficient of the fiber were 0.275 dB/km and 17 ps/nm/km, respectively, at 1550 nm. Figure 3 represents the dispersion map of an optical link. Pre-compensation was applied to reduce the detrimental behavior induced by nonlinear effects. After 640 km transmission, the residual dispersion value ranged from –14.2 to 0.4 ps/nm. The dispersion mismatch between the 40 Gb/s and 10 Gb/s signals is an important issue with this kind of upgrade

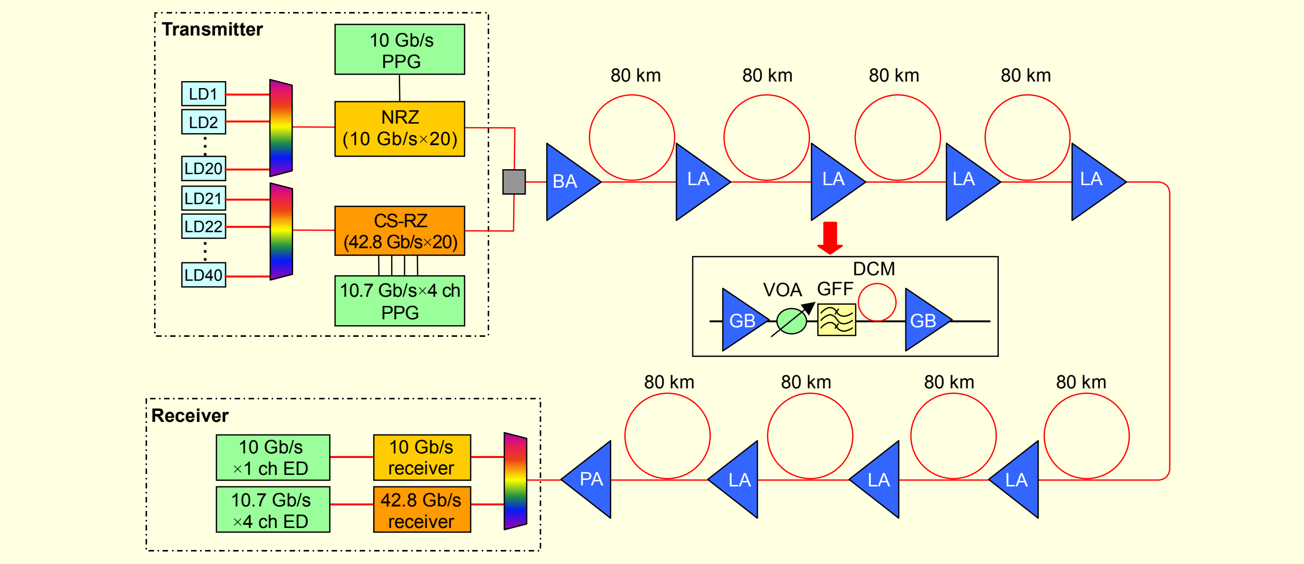

Fig. 2. Experimental set-up for 20×10 Gb/s and 20×42.8 Gb/s signals over 640 km SSMF. PPG: pulse pattern generator, LD: laser diode, BA: booster amplifier, LA: line amplifier, PA: preamplifier, GB: gain block, VOA: variable optical attenuator, GFF: gain flattening filter, DCM: dispersion compensation module, ED: error detector.

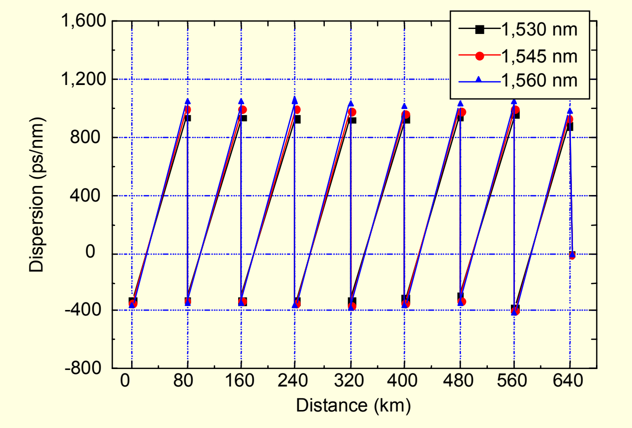

Fig. 3. Dispersion map of an optical link.

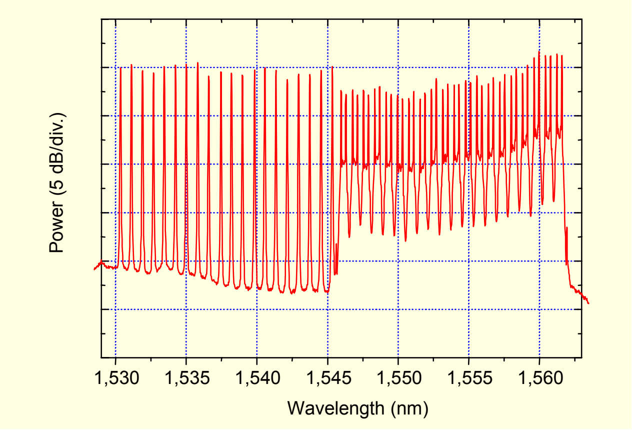

Fig. 4. Optical spectrum after 640 km transmission.

scenario. Our simulation results show that the required dispersion margin for the 40 Gb/s CS-RZ is 40 ps/nm. Compared with that of the 10 Gb/s NRZ signal, the value was reduced by 1/25. However, the residual dispersion characteristics satisfy the minimum requirement for 40 Gb/s CS-RZ transmission. Although we are proposing a transponder configuration that includes a tunable dispersion compensator, it was not adopted in the experiment because the residual dispersion was sufficiently small for 40 Gb/s transmission.

The variation of chromatic dispersion in relation to temperature change is a critical issue in higher bit-rate transmission. However, the effect is more dominant in aerial fiber than in buried fiber.

After the transmission, the signals were demultiplexed using an arrayed waveguide grating (AWG) demultipexer. The

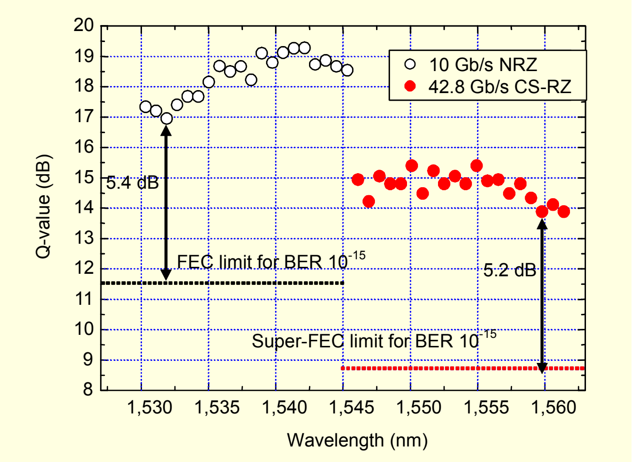

Fig. 5. Q-value performance for 42.8 Gb/s and 10 Gb/s channels.

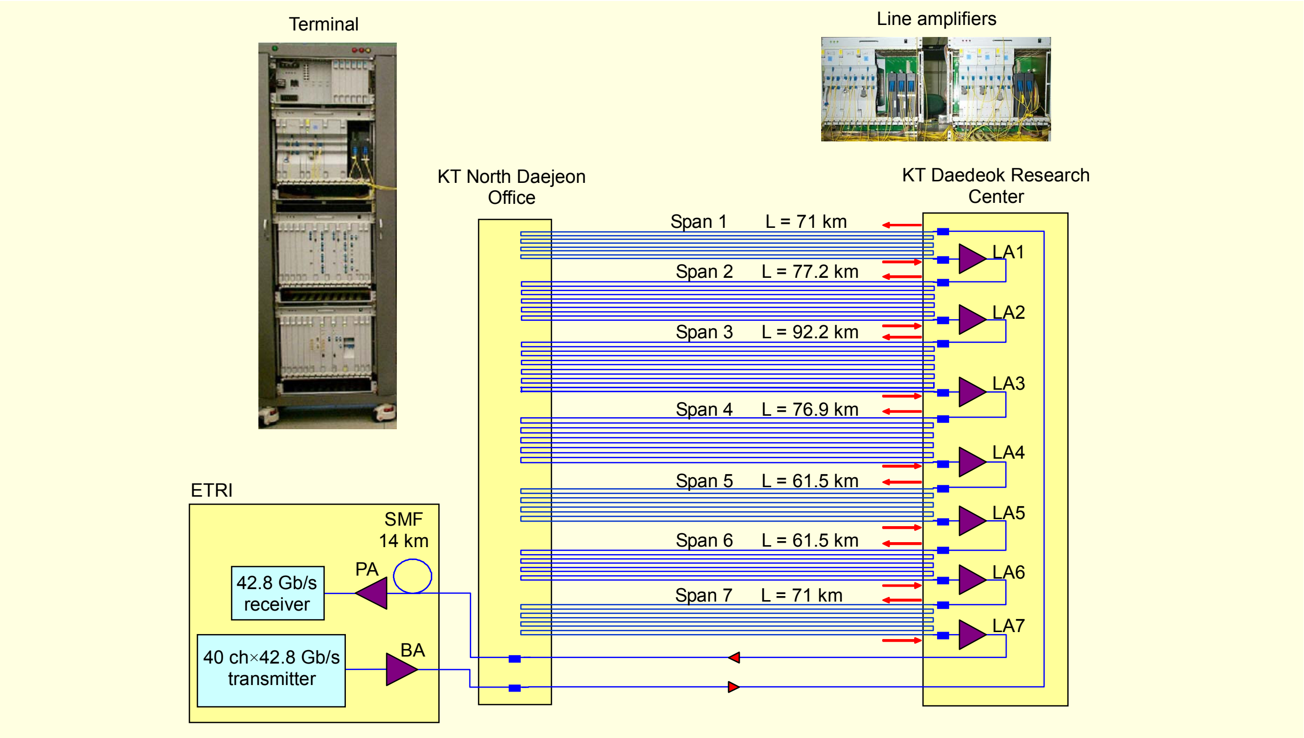

Fig. 6. Configuration of field installed optical link for transmission of 40×42.8 Gb/s signals over 511 km.

demultiplexer had a flat-top profile with the bandwidth of 0.4 nm at –1 dB.

The optical receiver consisted of a 40 Gb/s positive intrinsic negative-transimpedance amplifier (PIN-TIA) front-end [11], clock recovery circuitry, and a 1:4 electrical demultiplexer. Using the optical receiver, a 42.8 GHz clock and 42.8 Gb/s of regenerated data were obtained. The regenerated data was de-multiplexed into four tributaries, and the Q-values for each channel were measured using an error detector (ED).

Figure 4 represents the optical spectrum measured at optical bandwidth of 0.1 nm after 640 km transmission. Since we adopted pre-emphasis on the 42.8 Gb/s channels, the measured power difference between the maximum and minimum channels became 4 dB.

Figure 5 shows the measured Q-value characteristics after 640 km transmission. The Q-value for the 10 Gb/s channels ranged from 17 to 19.2 dB. The results demonstrated a minimum 5.4 dB Q-value margin to the conventional FEC limit. On the other hand, for the 42.8 Gb/s channels, the Q-values ranged from 13.8 to 15.2 dB and gave a 5.2 dB margin to the super-FEC limit. The results demonstrate that adopting the super-FEC, CS-RZ, precise dispersion compensation, and pre-emphasis techniques together for 40 Gb/s channels, the Q-value margin can reach the value achievable by the conventional FEC in 10 Gb/s channels.

Table 1. Fiber characteristics of each span.

No.	L (km)	D (ps/nm/km)	S (ps/nm^2/km)	α (dB)	PMD (ps/(km)$^{1/2}$)
1	71	16.9	0.06	20.0	0.13
2	77.2	16.9	0.06	18.2	0.10
3	92.2	16.9	0.06	22.8	0.13
4	77	17.1	0.06	19.0	0.05
5	61.5	17.0	0.06	18.3	0.07
6	61.5	17.0	0.06	18.4	0.08
7	71	16.9	0.06	23.3	0.09

L: length, D: dispersion coefficient, S: dispersion slope, α: attenuation, PMD: polarization mode dispersion.

IV. 40×42.8 Gb/s Transmission over 511 km SSMF

A field trial of 42.8 Gb/s CS-RZ signal transmission over 511 km of KT's SSMF with conventional EDFAs was performed, with all the channels upgraded to 40 Gb/s.

Figure 6 depicts the configuration of the field-installed optical link. The transmission line was located between KT's North Daejeon office, which is adjacent to ETRI, and Daedeok Research Center. Since the distance between them was not long enough, we made each span with multiple round trips (4 to 5 times) via patches in a fiber distributed frame (FDF). The

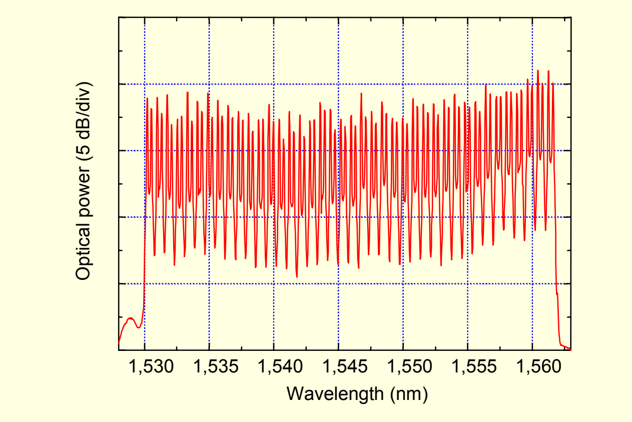

Fig. 7. Optical spectrum of 40×42.8 Gb/s CS-RZ after 511 km transmission.

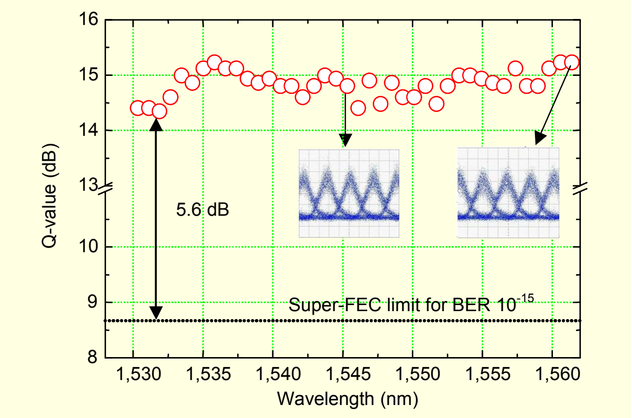

Fig. 8. Measured Q-value performance for 40×42.8 Gb/s CS-RZ after 511 km transmission.

optical fiber link consisted of 7 line amplifier spans, which ranged from 61.5 to 92.3 km. The major characteristics of the optical fiber are summarized in Table 1.

To adapt the residual dispersion and dispersion slope of the whole link, a 14 km standard single-mode fiber was inserted in front of the optical preamplifier. After transmission over 511 km of SSMF, the total dispersion values of the whole bandwidth were set to range from –6.4 to +17.4 ps/nm. These values reveal that it is not necessary to use channel-by-channel dispersion compensation.

The measured PMD values ranged from 0.05 to 0.13 ps/(km)$^{1/2}$ and were low enough to transmit 40 Gb/s signals.

The wavelength of each channel was allocated between 1530.33 nm and 1561.41 nm with 0.8 nm (100 GHz) channel spacing. The fiber launching powers of each span were varied from 16.5 to 20.5 dBm according to the span loss variation.

After transmission, the signals were demultiplexed using an AWG demultipexer. Figure 7 represents the measured optical spectrum with 0.1 nm resolution.

Figure 8 shows the measured Q-values of the 10.7 Gb/s tributaries after transmission over 511 km of SMF. The measured Q-values ranged from 14.3 to 15.3 dB. The worst channel showed 5.9 dB margin to the super-FEC limt of 10^{-15} BER. The inset shows the measured eye diagrams for selected channels.

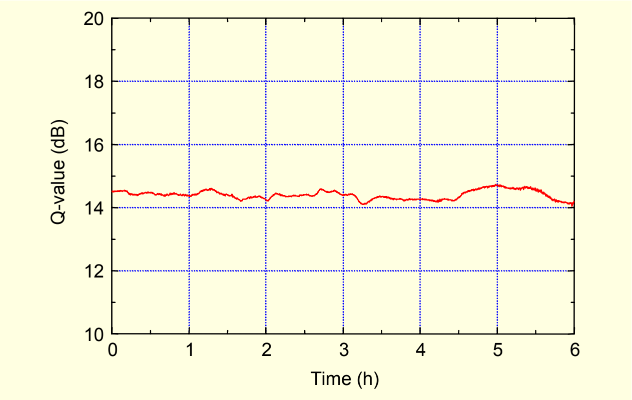

Fig. 9. Fluctuation of Q-value for the worst channel after 511 km transmission.

In practice, the minimum Q-value is more important than the average Q-value, since the Q-value fluctuates due to polarization effects [12]. To confirm the long-term stability and minimum Q-value of the transmitted signal, the fluctuation of the Q-value for the worst channel (λ=1531.90 nm) was monitored for 6 hours, and the result is shown in Fig. 9. The mean Q-value was 14.30 dB, and its fluctuation was found to be very small. The standard deviation was 0.14 dB, which is stable enough for actual system operation.

V. Conclusion

In this paper, we proposed a cost-effective method to upgrade the capacity of DWDM networks to a 40 Gb/s line rate using the existing 10 Gb/s-based infrastructure. To overcome the obstacles to capacity upgrading, we have proposed a 40 Gb/s transponder, which consists of a CS-RZ transceiver, a super-FEC coder/decoder, and a tunable dispersion compensator.

We transmitted 20×10 Gb/s NRZ and 20×42.8 Gb/s CS-RZ mixed channels over 640 km SSMF with conventional EDFAs. The minimum Q-value margins for the 10 Gb/s and 40 Gb/s channels were 5.4 and 5.2 dB, respectively. The results revealed that when the super-FEC, CS-RZ, and pre-emphasis were applied for 40 Gb/s channels, the achieved operation margin was comparable to that of 10 Gb/s channels with the conventional FEC.

The field trial of 40×42.8 Gb/s CS-RZ transmission over KT's 511 km of KT's SSMF gave measured Q-values ranging from 14.3 to 15.3 dB. The worst channel showed a 5.9 dB margin to the super-FEC BER limit of 10^{-15}. The long-term measurement of Q-value for the worst channel showed a mean value of 14.30 dB and a standard deviation of 0.14 dB. Therefore, the signal is stable enough for actual system operation.

We believe that all the obtained experimental results demonstrate the possibility of a cost-effective capacity upgrade to a 40 Gb/s line rate using the existing 10 Gb/s optimized DWDM network infrastructures.

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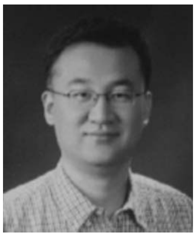
Sang Soo Lee received the BS and MS degrees in Applied Physics from Inha University, Korea in 1988 and 1990, respectively. He received the PhD degree in DWDM transmission technology from the same university in 2001. In 1990, he joined the Optical Communication Department of ETRI. His research activities include 2.5, 10 Gb/s and 40 Gb/s based DWDM optical transmission and ROADM system. His current research interests are all-optical networking, optical packet switching, high-speed optical transmission, and quantum communications. He is currently a principal member of engineering staff of the Optical Communications Research Center of ETRI.

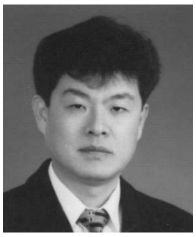
Hyunwoo Cho received the BS and MS degrees in electrical engineering from Seoul National University in 1999 and 2001, respectively. In 2001, he joined ETRI, Daejeon, Korea. From 2001 to 2006, he worked on the 40 Gb/s optical transmission system, especially focusing on 40 Gb/s optical transceiver modules. Since 2007, he has been researching the framer or mapper chips for optical transport networks (OTNs).

Sang-Kyu Lim received the BS degree in physics in 1995 and the MS and PhD degrees in electronics engineering in 1997 and 2001, respectively, from Sogang University, Seoul, Rep. of Korea. In 2001, he joined ETRI, Daejeon, Rep. of Korea, where he has worked on passive and active microwave circuits for 40 Gb/s optical transmission technologies. His research interests include the design and fabrication of microwave and millimeter-wave circuits for high-speed optical transmission systems. He is currently a senior member of the engineering staff of the Optical Communications Research Center of ETRI.

Dong-Soo Lee received the BS in physics from Sogang University in 1993, and received the MS and PhD in engineering from the Information and Communications University in 2000 and 2004, respectively. His research interests are next generation optical access networks, high-speed optical transmission systems, and optical wireless communications. In 2005, he joined the Optical Communications Research Center of ETRI, Gwangju, Korea, where he is engaged in research and development on 10 G EPON/GPON technology for the next generation optical access network.



Kyeong-Mo Yoon received the BS and MS degrees in electronic engineering from Kangwon National University in 1994 and 1996, respectively. He joined KT in 1996 and has been involved in the Technology Engineering BU Network Planning Department. His main research areas are ultra long-haul transmission, 40 Gbit/s ETDM/WDM transmission, all-optical networking, and optical switching.



Yong-Gi Lee received his BS and MS degrees in electronic engineering from Kyungpook National University, Korea in 1981 and 1985, respectively, and the PhD degree in electronic engineering from Tohoku University, Japan in 1996. He joined the KT R&D Group in 1985, where he works as a research director with the Platform Laboratory. His research interests are WDM devices and their applications, ultra-long-haul transmission, optical internet and optical test-bed construction, and network design and management systems.

Kwangjoon Kim received the BS and MS degrees in physics from Seoul National University, Seoul, Korea, and the PhD degree in physics from Ohio State University, Columbus, Ohio, USA, in 1981, 1983, and 1993, respectively. He joined ETRI in 1984 and worked on HF communications, until he enrolled in the PhD program with Ohio State University, where he worked on linear and nonlinear optical behavior of conducting polymers. He rejoined ETRI and has worked on optical semiconductor devices with quantum wells. His current research interests focus on WDM optical communication systems and high-speed optical transmission.

Jesoo Ko received the BS degree in electrical engineering from Ulsan University in 1981 and the MS degree in electronic engineering from Korea University in 1983. In 1983, he joined ETRI, Daejeon, Korea, where he has engaged in research and development of 40 Gb/s optical transmission technologies. His main research interests include high-speed optical transport systems, optical modules, and related devices. He is currently a principal member of the engineering staff of the Optical Communications Research Center of ETRI.