Journal of the Optical Society of Korea, Vol. 6, No. 1, March 2002, pp. 13-17

1.28-Tb/s (64 × 20 Gb/s) WDM Transmission Over 320 km of Single-Mode Fiber with 0.4 -(bit/s)/Hz Spectral Efficiency

Hwan Seok Chung, Sang Bae Jun, and Yun Chur Chung*

Dept. of Electrical Engineering and Computer Science,
Korea Advanced Institute of Science and Technology, Daejeon 305-701, KOREA

Duk Hwa Hyun

KEPRI, Daejon 305-380, KOREA

(Received December 6, 2001)

We demonstrated 1.28-Tb/s (64 ch × 20 Gb/s) WDM transmission with 50-GHz channel spacing over 320 km of conventional single mode fibers. The spectral efficiency was 0.4 (bit/s)/Hz. Thus, we could accommodate all the sixty-four WDM channels within the C-band of EDFA. The average Q-factor was measured to be better than 17.8 dB after transmission over 320 km.

OCIS codes : 060.2330, 060.4370, 060.4510.

I. INTRODUCTION

To accommodate explosive growth of data traffic in recent years, it is desirable to increase the transmission capacity of optical fiber trunk lines. Wavelength division multiplexed (WDM) systems are very attractive for this purpose as they can increase transmission capacity by adding new channels and/or increasing bit-rate per channel. Recently, there have been many efforts to increase the transmission capacity of optical fiber [1,2]. For example, a 10 Tb/s WDM transmission experiment has been already reported by using all the C- (conventional), L- (long wavelength), and S- (short wavelength) band of optical fiber [1]. In Korea, there have also been substantial efforts to increse transmission capacity of optical fiber [3,4]. However, capacities of these experiments have still remained below 1 Tb/s. In order to maximize the transmission capacity of WDM systems, it is necessary to increase the bit rate of each channel and reduce the channel spacing(i.e. increase spectral efficiency). In this paper, we report 1.28-Tb/s (64 ch × 20 Gb/s) WDM transmission with 50-GHz channel spacing over 320 km of conventional single mode fiber (SMF) for the first time in Korea. The spectral efficiency is 0.4 (bit/s)/Hz. Thus, we can accommodate all the 64 WDM channels within the C-band (1534.65 nm ~ 1559.79 nm).

II. EXPERIMENTAL SETUP

Fig. 1 shows the experimental setup for 1.28-Tb/s (64 × 20 Gb/s) WDM transmission over 320 km of conventional SMF. The output of 64 DFB lasers, operating from 1534.65 to 1559.79 nm (channel spacing: 50 GHz), were multiplexed into a single fiber using arrayed waveguide grating (AWG) and couplers. The multiplexed channels were modulated at 20 Gb/s using a $LiNbO_3$ modulator (extinction ratio: 12.5 dB). The 20-Gb/s NRZ signal was generated by electronically multiplexing two copies of 10-Gb/s data signals. The 64 × 20 Gb/s WDM signals were de-correlated and pre-compensated by using a small section of a dispersion compensation fiber, and then traveled through four erbium-doped fiber amplifier (EDFA) modules followed by 80-km-long SMF's (span loss: 18 dB). The EDFA module, composed of a two-stage EDFA, a dispersion-compensation fiber (DCF) and a gain-flattening filter (GFF), had gain and noise figures of 18 and 6 dB, respectively. The output power of the first and second stages of the EDFA modules were set to be - 5dBm/channel and 0 dBm/channel, respectively. After 320-km transmission, each channel was demultiplexed using an AWG (bandwidth: 40 GHz, crosstalk: 24 dB) and sent to the 20-Gb/s receiver. The recovered data and clock were electronically demultiplexed to 10-Gb/s signal for Q-factor measurement.

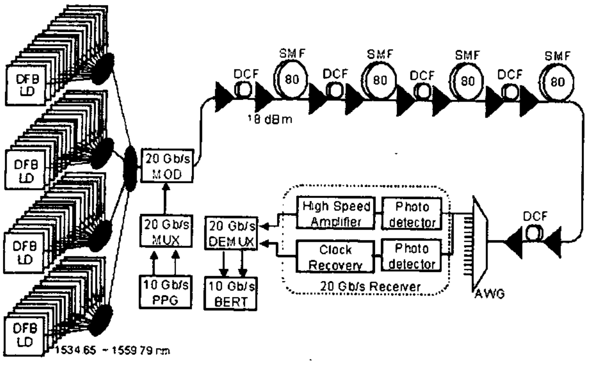


FIG. 1. Experimental setup for 1.28 Tb/s (64 × 20 Gb/s) WDM transmission over 320 km of conventional SMFs. (MOD: modulator, SMF: single mode fiber, DCF: dispersion compensating fiber, AWG: arrayed waveguide grating, PPG: pulse pattern generator, BERT: bit error rate tester).

Fig. 2 shows the schematic diagram of a 20-Gb/s receiver. At first, the incident optical signal was pre-amplified and converted to an electrical signal by the optical receiver front end, which was composed of an optical pre-amplifier and photo-detector. A uni-travelling carrier photo-detector (UTC-PD) was used to accommodate high power and wide band optical signals. The converted electrical signal was amplified about 1 V_{pp} using a wide band RF amplifier to maintain input voltage requirement of a 20-Gb/s electrical demultiplexer. In the clock recovery circuit, the converted 20-Gb/s electrical NRZ signal was amplified and then sent to a mixer after dividing into two signal paths. The delay between two paths was adjusted to be one half of the bit period (25 ps) because there was no 20-GHz frequency component in the at 20-Gb/s NRZ signal. The output signal of the mixer was then passed through a narrow band dielectric resonator (DR) to extract 20-GHz clock frequency. These 20-Gb/s NRZ data and 20-GHz clock components

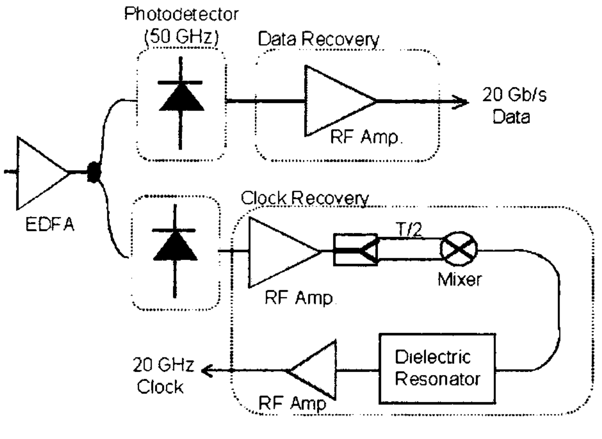
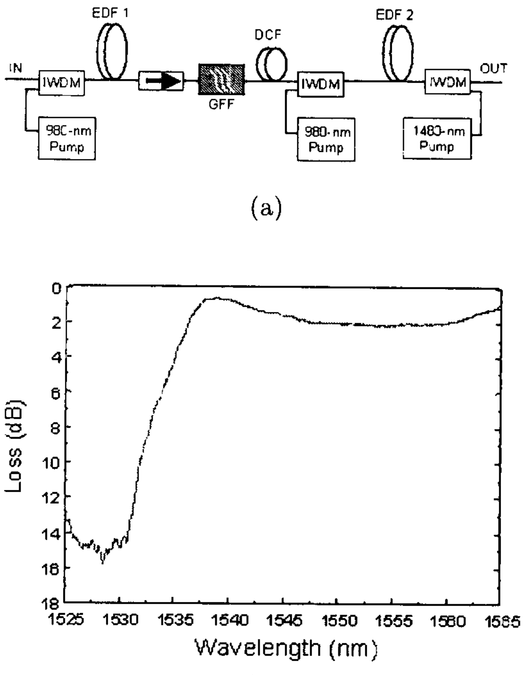


FIG. 2. The schematic diagram of a 20 Gb/s receiver.



(a)

(b)

FIG. 3. Two-stage EDFA for amplification of sixty four 20-Gb/s signals. (a) Schematic diagram, (b) Transmission characteristic of a gain flattening filter. (IWDM: Isolator + wavelength division multiplexer, EDF: erbium-doped fiber, GFF: gain flattening filter).

were sent to the 20-Gb/s electrical demultiplexer to reconstruct two 10-Gb/s NRZ signals. The measured receiver sensitivity was -31.4 dBm at the BER of 10^{-9} (pattern length: 2^{31} - 1).

The schematic diagram of the two-stage EDFA module used in the experiment was shown in Fig. 3. We inserted a DCF module between the first and second stages of EDFAs for dispersion compensation and a GFF for gain equalization. We used a forward pumping scheme with a 980-nm laser diode in the first stage to reduce the noise figure while a bi-directional pumping scheme with 980-nm and 1480-nm laser diodes was used in the second stage to increase output power. The gain and noise figure of the EDFA were 18 and 6 dB, respectively. In this experiment, we could not increase the output power of the EDFA over 18 dBm because of insufficient output power of the pump laser diode. Fig. 3(b) shows the transmission characteristic of the GFF. We designed a GFF having a loss of 15 dB in the 1530-nm band to remove the amplified spontaneous emission (ASE) noise.

In a high-speed transmission system over 20 Gb/s, the dispersion compensation is a crucial problem. For

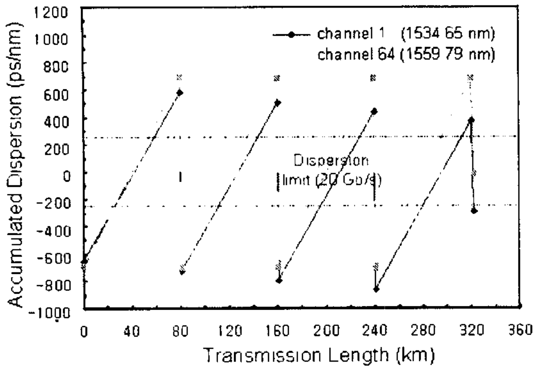


FIG. 4. Dispersion map of a transmission line.

instance, when a conventional SMF was used without dispersion compensation, the maximum transmission distance would be limited to mere 15 km [5]. Thus, we compensated the accumulated dispersion of the fiber using a 'negative-slope DCF' module at each EDFA. This was mainly because it was essential to compensate the slope of dispersion as well as dispersion in high speed/capacity systems. The dispersion map of the transmission line used in this experiment was shown in Fig. 4. The dispersion and dispersion slope of the SMF at 1550 nm were 16.6 ps/nm/km and 0.08 ps/nm^2/km, respectively. The DCF had a dispersion value of - 97 ps/nm/km at 1550 nm. At this wavelength, the dispersion slope was - 0.3 ps/nm^2/km. The accumulated dispersion of 320-km transmission was varied from - 285.9 ps/nm (channel 1) to - 16.3 ps/nm (channel 64). We operated the LiNbO$_3$ modulator with negative chirp since the accumulated dispersion of short-wavelength channels exceeded the dispersion tolerance of ± 250 ps/nm (required for the transmission of 20-Gb/s signals).

III. RESULTS AND DISCUSSIONS

Fig. 5 shows the measured optical spectra of 64 WDM channels. The power differences between channels were less than 0.5 dB after 80-km transmission. However, the output powers of long-wavelength channels were increased significantly (compare to the powers of short-wavelength channels) as transmission distance was increased. In fact, the accumulated ASE noise changed the gain spectrum of the EDFA. We preformed that the same experiment after replacing the optical fiber with optical attenuator and confirmed that the effect of stimulated Raman scattering (SRS) was negligible. The maximum power differences between channels were less than 5 dB after 320-km transmission. The optical signal-to-noise ratio (OSNR) at

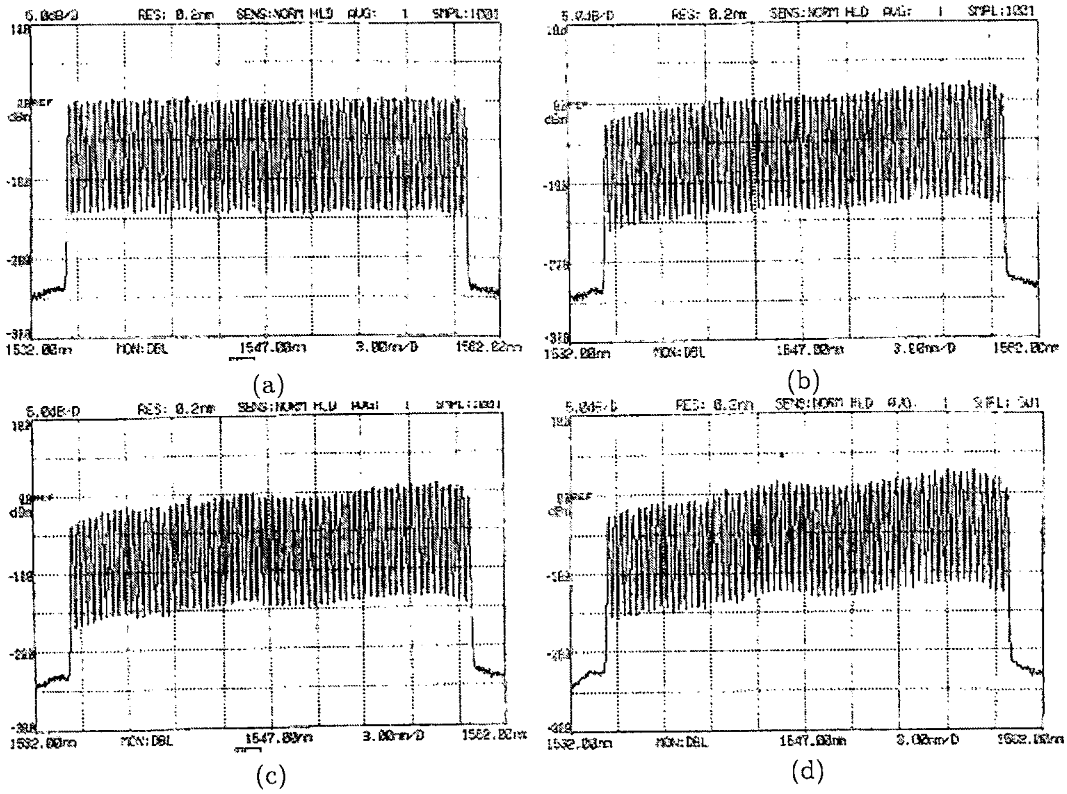
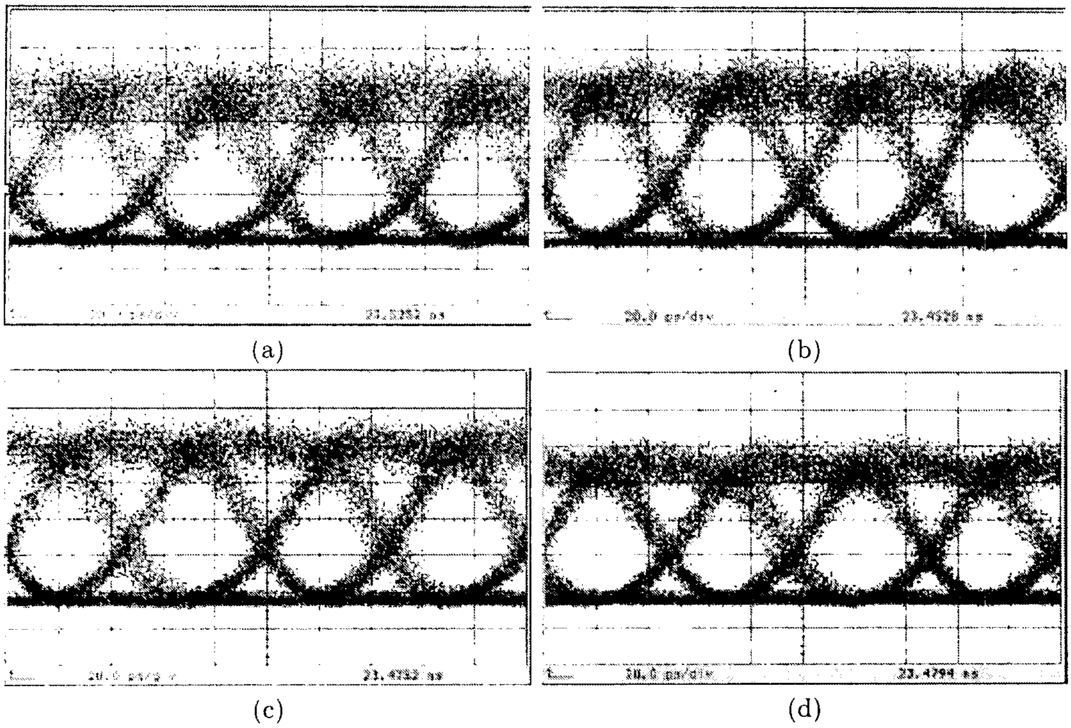


FIG. 5. Measured spectra after transmission. (a) 80km, (b) 160km, (c) 240km, (d) 320km.



(a) (b)

(c) (d)

FIG. 6. Measured eye diagram after 320-km transmission. (a) channel 1, (b) channel 21, (c) channel 42, (d) channel 64.

the receiver was measured to be 23 dB for short-wavelength channels and 26 dB for long-wavelength-channels at 0.1-nm resolution bandwidth.

Measured eye diagrams of channel 1, 21, 42, and 64 after 320-km transmission were shown in Fig. 6. Fiber chromatic dispersion compensation was clearly evident, allowing successful transmission of 64 × 20 Gb/s WDM channels over 320 km of conventional SMFs. It should be noted that negative-slope DCF modules compensated the accumulated dispersion of the entire C-band of the EDFA without using channel-by-channel dispersion compensation. The reduced OSNR at channel 1 slightly increased noise in the mark level as shown in Fig. 6(a).

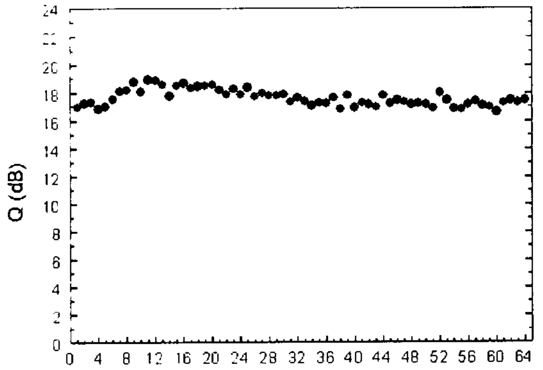


FIG. 7. Measured Q-factor for 1.28 Tb/s (64 × 20 Gb/s) WDM signal after 320-km transmission.

Fig. 7 shows the measured Q-factors for 64 WDM channels. We measured Q-factors by changing decision threshold of a receiver [6]. The average Q-factor was measured to be better than 17.8 dB (BER: $\sim 10^{-15}$) after transmission over 320 km. The inferior performance of short-wavelength channels was mainly due to the deterioration of the OSNR.

IV. SUMMARY

We demonstrated 1.28-Tb/s (64 ch × 20 Gb/s) WDM transmission over 320 km of conventional SMF. In this paper, we accommodated all the 64 WDM channels within the C-band (1534.65 ~ 1559.79 nm) by utilizing 50-GHz channel spacing. Thus, the spectral efficiency was 0.4 (bit/s)/Hz. We used conventional SMFs to suppress fiber nonlinearities and a negative-slope DCF module to obtain wide-band dispersion slope compensation. In addition, we used specially designed gain-fattening filters for gain equalization. The average Q-factor was measured to be better than 17.8 dB (BER: $\sim 10^{-15}$) after transmission over 320 km.

*Corresponding author : ychung@ee.kaist.ac.kr.

REFERENCES

[1] K. Fukuchi, T. Kasamatsu, M. Morie, R. Ohhira, T. Ito, K. Sekiya, D. Ogasahara, and T. Ono, in Optical Fiber Communication Conference 2001, (Optical Society of America, Anaheim, USA, 2001), PDP 24.

[2] S. Bigo, Y. Frignac, G. Charlet, S. Borne, P. Tran, C. Simonneau, D. Bayart, A. Jourdan, J. P. Hamaide, W. Idler, R. Dischler, G. Veithet, H. Gross, and W. Poehlmann, in Optical Fiber Communication Conference 2001, (Optical Society of America, Anaheim, USA, 2001), PDP 25.

[3] H. S. Chung, H. Kim, S. E. Jin, E. S. Son, D. W. Kim, K. M. Lee, H. Y. Park, and Y. C. Chung, IEEE Photon. Technol. Lett. **12**, 1397 (2000).

[4] H. S. Chung, S. K. Shin, D. W. Lee, D. W. Kim, and Y. C. Chung, IEE Electron. Lett. **37**, 618 (2001).

[5] A. Elrefaie, R. E. Wanger, D. A. Atlas, and D. G. Daut, IEEE J. Lightwave Technol. **6**, 704 (1988).

[6] N. Begano, F. W. Kerfoot, and C. R. Davidson, IEEE Photon. Technol. Lett. **5**, 304 (1993).