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40-Gbit/s TDM Transmission Technologies Based on Ultra-High-Speed IC's

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***Abstract*— This paper presents 40-Gbit/s time division multiplexing (TDM) transmission technologies based on 0.1-μm-gate-length InP high electron mobility transistor IC's and a scheme for upgrading toward a terabit-per-second capacity system. A 40-Gbit/s, 300-km, in-line transmission experiment and a dispersion-tolerant 40-Gbit/s duobinary transmission experiment are described as 40-Gbit/s single carrier system applications on dispersion-shifted fiber. An ultra-high-speed receiver configuration using a high-output-power photodiode is introduced to realize fully electrical receiver operation beyond 40 Gbit/s. The high-sensitivity operation of the optical receiver (−27.6 dBm @ BER $= 10^{-9}$) is demonstrated at a data bit rate of 50 Gbit/s for the first time using a unitraveling carrier photodiode. A dense wavelength division multiplexing (DWDM) system operating up to terabits per second can be easily realized on a zero-dispersion flattened transmission line using ultra-high-speed TDM channels of 40 Gbit/s and beyond. An experiment demonstrates 1.04-bit/s DWDM transmission based on 40-Gbit/s TDM channels with high optical spectrum density (0.4 bit/s/Hz) without dispersion compensation.**

***Index Terms*—Broad-band photodiode, InP high electron mobility transistor (HEMT), optical fiber communication.**

I. Introduction

A trunk transmission network has to be able to handle large-capacity traffic simply, quickly, and economically, especially with the recent traffic growth of the Internet. For the past ten years, time division multiplexing (TDM) systems based on synchronous digital hierarchy have offered large-capacity networks. They have progressed in terms of transmission distance and capacity with the advent of Er-doped fiber amplifiers (EDFA's) and mature high-speed electronic large-scale integrated circuits (LSI's). A bit-rate-flexible, 10-Gbit/s trunk transmission system (FA-10G) was introduced for the first time in the world to NTT's network in 1996 [1], and a 10-Gbit/s add-drop multiplexer ring system was developed to enhance network flexibility and reduce the regional network cost [2]. Recent progress in EDFA technology has enlarged the flat-gain bandwidth up to 70 nm (1540–1610 nm) [3], [4], which allows the full utilization of the optical-fiber bandwidth (about 10 THz) in the low-loss window of the optical fiber. This has accelerated the research and development of various wavelength division multiplexing (WDM) transmission systems reaching the terabit-per-second (Tbit/s) region [5], [6]. This background naturally indicates the need for a large-capacity system that effectively utilizes optical-fiber-bandwidth resources and can be used to construct highly reliable, flexible, and cost-effective networks. The next-generation 40-Gbit/s TDM system is a promising solution to the above requirement when it is used in combination with other multiplexing schemes, such as WDM and optical TDM (OTDM) [7]. Among several device technologies for realizing IC families of 40-Gbit/s system application, InP-based heterojunction field-effect transistors and heterojunction bipolar transistors are considered to be the best candidates in term of their speed performance [8].

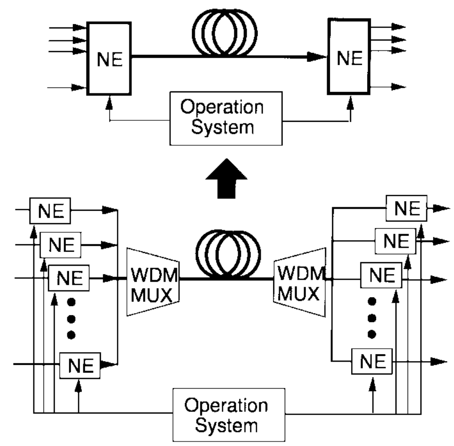

Fig. 1. Reduction of network elements by high-speed TDM.

This paper presents 40-Gbit/s TDM transmission system performance based on InP-based high electron mobility transistor (HEMT) IC's. We have confirmed stable 40-Gbit/s operations of our HEMT IC's in several transmission experiments. Using a narrow signal spectrum of the 40-Gbit/s electrical TDM channels, we demonstrated Tbit/s-class dense WDM (DWDM) transmission experiments with high signal spectrum density.

II. Impact of 40-Gbit/s TDM on Tbit/s-Capacity Network

The 40-Gbit/s TDM systems have several merits. They reduce the number of network elements (NE's) effectively, as shown in Fig. 1. This means they are capable of handling large-capacity links as a single system, which is very attractive for lightening network operation, administration, and maintenance. High signal spectrum density approaching the Nyquist

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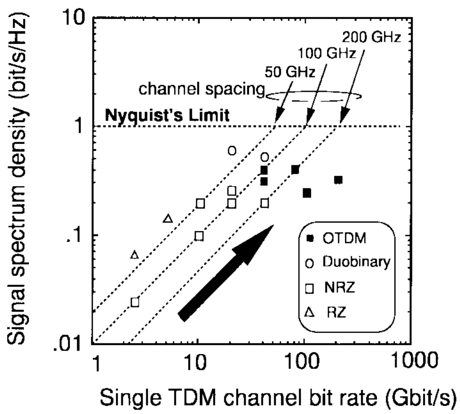


Fig. 2. Enhancement of signal spectral density in DWDM transmission experiment by high-speed TDM channels.

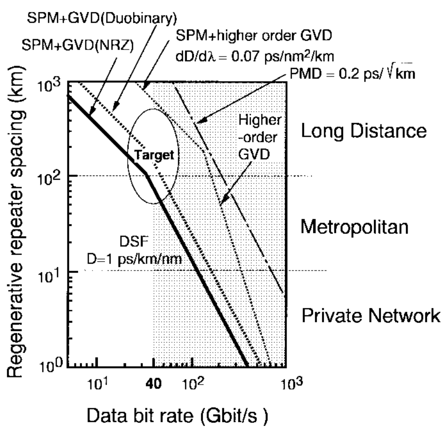


Fig. 3. Application area and limiting factor of 40-Gbit/s TDM system.

limit (1 bit/s/Hz) is easily achieved in Tbit/s-class DWDM systems considering the state of the art of optical filters, as shown in Fig. 2. In addition, a 40-Gbit/s TDM system offers large volume of bulky payload that is desirable for an IP-based data communication network.

III. Application Area of 40-Gbit/s TDM System

Fig. 3 shows the application area and factors limiting regenerative repeater spacing. In the case of dispersion shifted fiber with average dispersion of 1 ps/nm/km, 60-km transmission is possible for nonreturn-to-zero (NRZ) format without any dispersion control, as shown by the solid line. Within this range, low-cost implementation to a regional or metropolitan area is expected. For long-distance application over 100 km, self-phase modulation (SPM) and group velocity dispersion (GVD) severely limit the repeater spacing. Therefore, in addition to high-speed LSI's, dispersion-compensation technologies and dispersion-tolerant transmission code are important. Higher order dispersion effect and polarization mode dispersion (PMD) of 0.2 ps/$\sqrt{\text{km}}$ do not limit the spacing at a distance up to several hundreds of kilometers.

IV. Performance of 40-Gbit/s IC's

The TDM system is very attractive because of the simple and compact integration of multiplexing, demultiplexing, retiming, reshaping, and regenerating functions into LSI's. It is important to realize a 40-Gbit/s IC family. Stable 40-Gbit/s operation is required for digital IC's, and flat and broad-band response and broad-band, high-optical/electrical conversion efficiency are required for analog IC's and optical devices, respectively.

TABLE I
Typical Operation of InP HEMT Digital IC's

Circuit	Maximum Bit Rate	Output	Wafer / Package	Power
2:1 MUX	52 Gbit/s 80 Gbit/s	1.0 Vpp	Package on Wafer	2.7 W
1:2 DEMUX	1 - 40 Gbit/s	1.1 Vpp	Package	3.9 W
Decision	20 - 46 Gbit/s	0.9 Vpp	Package	1.7 W
Freq. divider	8 - 47 GHz 5 - 60 GHz	0.8 Vpp	Package on Wafer	1.1 W
EX-OR	40-GHz timing ext.	0.9 Vpp	Package	1.7 W

TABLE II
Typical Operation of InP HEMT Analog IC's

Circuit	Bandwidth	Output	Gain	Power
Baseband amplifier	DC - 47 GHz DC - 90 GHz	1.2 Vpp 1.2 Vpp	16 dB 10 dB	1.1 W 0.86 W
Signal distributor	DC - 100 GHz	0.5 Vpp	-2.5 dB	1.1 W
Limiting amplifier	34 - 40 GHz	10 dBm	17 dB	70 mW

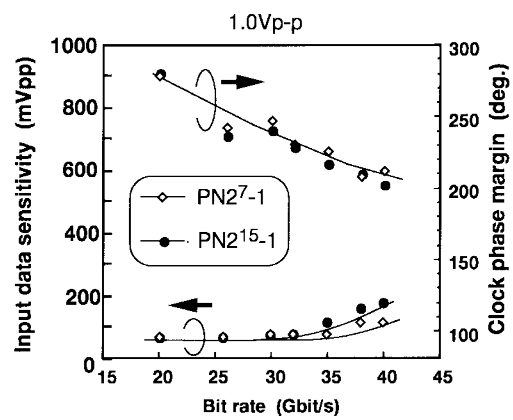


Fig. 4. Decision ambiguity width and phase margin of a 40-Gbit/s InP HEMT superdynamic D-FF IC.

A. InP HEMT Digital and Analog IC's

As a 40-Gbit/s IC process, a 0.1-μm gate InP HEMT with InP recess etch stopper was adopted [9]. Tables I and II show the typical operation of InP HEMT IC's [10]. Forty-Gbit/s operations after packaging were confirmed with a wide margin. Among these IC's, the D-type flip-flop (D-FF) is one of the most important digital IC's for the TDM transmission system. To realize stable 40-GHz clock operation of D-FF, a new circuit configuration called superdynamic D-FF (SD-FF) was introduced [10]. Fig. 4 shows the decision ambiguity width and phase margin of a typical D-FF. The decision ambiguity

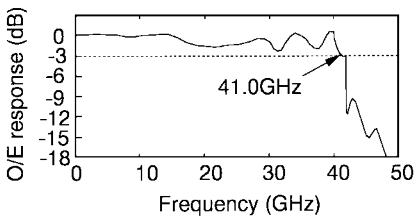


Fig. 5. Frequency response of a 40-Gbit/s receiver module.

width of less than 104 mV was obtained with the pattern length of $2^7 - 1$, and 166 mV for $2^{15} - 1$. This result shows that 40-Gbit/s stable regeneration is feasible.

B. Optical Receiver Module

Fig. 5 shows the frequency response of an optical front-end module [11]. A waveguide pin photodiode (WGPD) was used for high conversion efficiency and broad bandwidth (50 GHz) [12]. The WGPD was directly mounted on the distributed amplifier IC chip by microsolder bumps [13] with low parasitics. Bandwidth of 41 GHz and high responsivity of 0.84 A/W were obtained.

C. $LiNbO_3$ Optical Intensity Modulator

A ridged-type structure was introduced in a Mach–Zehnder (MZ)-type $LiNbO_3$ intensity modulator for broad-band and low-driving-voltage operation [14]. This structure enhances the electrical field strength of the optical waveguide and reduces driving voltage. Low driving voltage (2.9 V) and over 30 GHz bandwidth were achieved. This low driving voltage relaxes the severe design constraints of the modulator driver.

V. 40-Gbit/s System Experiments

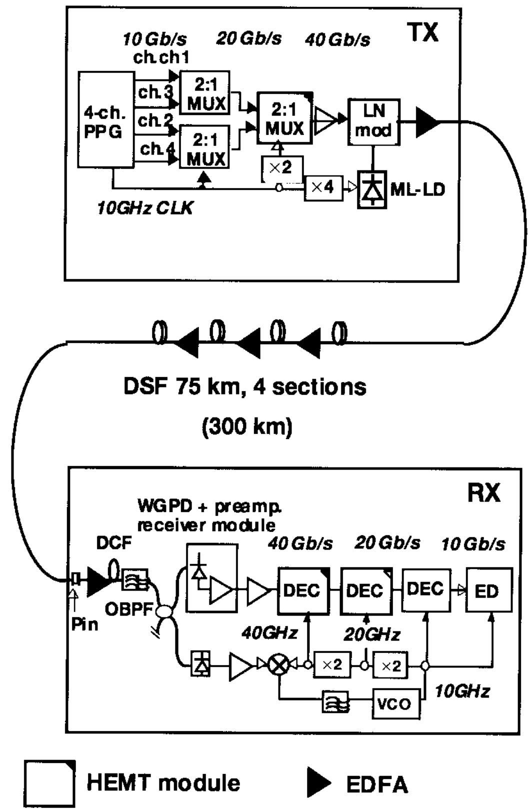
We tested the 40-Gbit/s system operation of the key components in a transmission experiment and confirmed the stable, error-free operation. We also applied these 40-Gbit/s electronics and optical devices to optical duobinary signal transmission and verified the enlargement of dispersion tolerance.

A. 40-Gbit/s Electrically Multiplexed TDM Signal Transmission on 300-km-Long Link

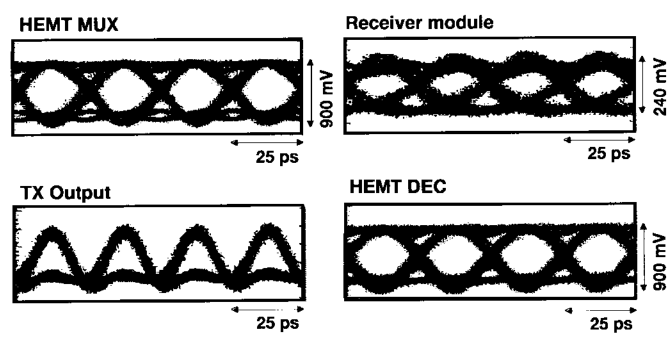
Fig. 6(a) shows the experimental setup of the first demonstration of fully implemented 40-Gbit/s electrical TDM transmission [15]. The transmission link consists of four pieces of 75-km dispersion shifted fiber and three in-line optical amplifier repeaters. Each span's dispersion was compensated in an in-line amplifier. As shown in Fig. 6(b), clear 40-Gbit/s eye opening was confirmed at each interface: the InP HEMT multiplexer IC output, transmitter optical output, receiver module output, and InP HEMT decision IC output. There is little degradation after 300-km transmission (Fig. 7). These results show that an electrical 40-Gbit/s TDM system with stable regeneration function is feasible.

B. 40-Gbit/s Optical Duobinary Signal Transmission

Optical duobinary code is very attractive in that the dispersion tolerance can be enlarged by a factor of two, as shown



(a)



(b)

Fig. 6. A 40-Gbit/s, 300-km transmission experiment. (a) Experimental setup. (b) Eye diagrams at 40 Gbit/s.

in Fig. 2, since the optical signal bandwidth can be effectively reduced by electrical baseband digital and analog processing. Fig. 8(a) shows the basic configuration of the optical duobinary transmission system. The electrical duobinary code is well known as a three-level signal, shown as the solid line in part C of Fig. 8(b) (dotted line is an equivalent digital signal). If the electrical duobinary code was simply converted into a three-level optical signal, the receiver sensitivity would be degraded due to the shot noise of two optical "on" levels, and a conventional binary optical receiver could not be used. In the optical duobinary transmission using the folding characteristic of an optical Mach–Zehnder modulator, the three-level electrical duobinary signal is converted into a binary optical signal [16]. This feature ensures high receiver sensitivity while keeping high dispersion tolerance. The optical duobinary transmitter consists of three key components: a precoder, low-

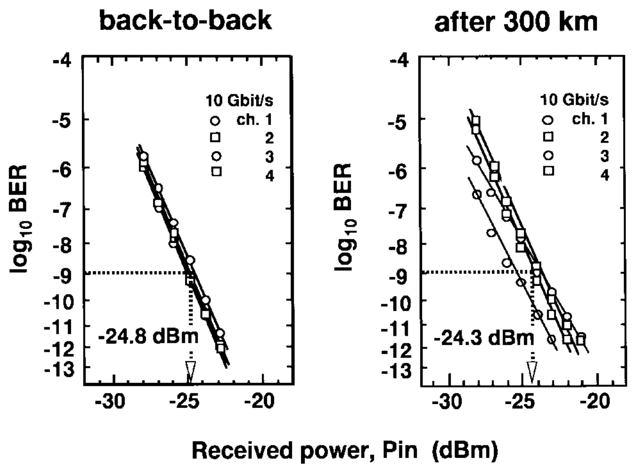


Fig. 7. The 40-Gbit/s bit-error-rate performance.

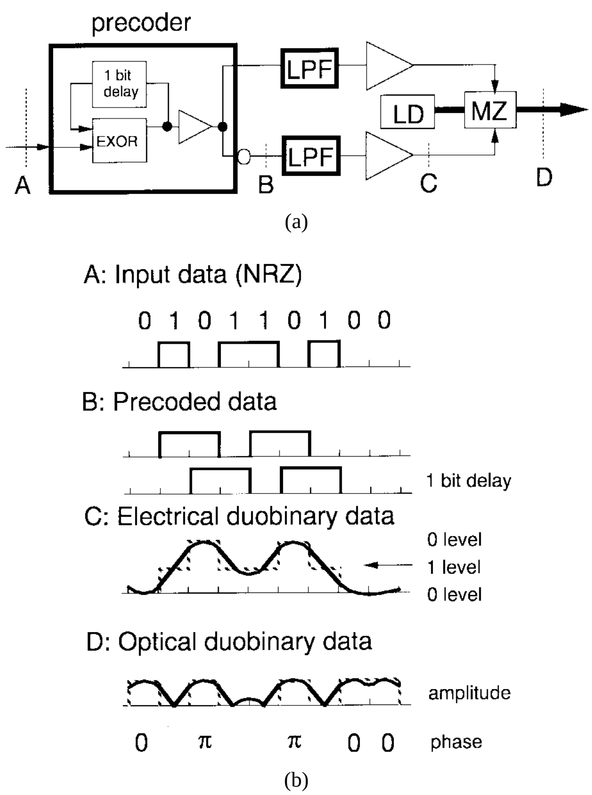


Fig. 8. Optical duobinary transmission scheme. (a) Configuration of an optical duobinary transmitter. LPF: low-pass filter know as duobinary filter. The 3-dB-down bandwidth is $B/4$, where B is transmission bit rate; LD: laser diode with continuous-wave operation; and MZ: dual-drive Mach–Zehnder modulator. (b) Generation of optical duobinary signal.

pass filters known as duobinary filters, and a dual-drive MZ modulator. Among them, the precoder circuit is operation-speed critical. The logic function of the precoder is a simple binary digital circuit consisting of an exclusive OR (EXOR) and 1-bit delay feedback. In the conventional configuration, this 1-bit delay-feedback operation prevents speeds above 10 Gbit/s. To solve this problem, parallel processing is introduced into the precoder configuration, and the speed-critical operation is done at a prescaled clock rate of the transmission bit rate, as shown in Fig. 9. Fig. 10 shows the 40-Gbit/s precoder circuit

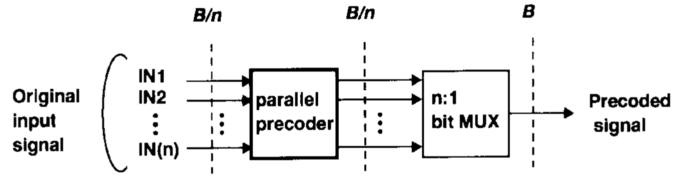


Fig. 9. Design concept of precoder circuit for over 40-Gbit/s operation. B is transmission bit rate and B/n is digital processing clock rate.

with four parallel channels [17]. A commercial 0.2-μm GaAs MESFET process was used for the precise design of gate delay management of the four parallel channels. In this precoder, the 1-bit delay-feedback operation is done at 10 GHz, and a 40-Gbit/s precoded signal can be generated in combination with an InP HEMT-based 4 : 1 bit interleave multiplexer.

Using an InP-HEMT-based multiplexer, a 40-Gbit/s duobinary transmitter was constructed. Bessel–Tomson filters of 12 GHz bandwidth were used as duobinary filters to generate electrical duobinary signals. A dual-drive LN-MZ modulator with half-wavelength voltage of 3.9 V was driven by 5.0 $V_{p\text{-}p}$ electrical duobinary signals complementarily. The narrow spectrum of the 40-Gbit/s optical duobinary signal is shown in Fig. 11(a). Fig. 11(b) shows the 40-Gbit/s dispersion tolerance of the duobinary signal and conventional NRZ signal. A pseudorandom binary sequence (PRBS) signal was used as the test signal. Owing to the unique property of the PRBS test signal, a precoder circuit, which is indispensable for a live data transmission, was not used in this experiment. We have experimentally confirmed the enlargement of dispersion tolerance by a factor of two compared with the conventional NRZ format [18]. This enhancement is effective in realizing a 40-Gbit/s link of 100 km long using conventional dispersion shifted fiber without any dispersion control.

VI. Future Prospects for Tbit/s Transmission

A. Impact of High-Power Photodiode-Based Receiver

We proposed a new receiver configuration [19], which has the potential to realize over 40-Gbit/s optical receiver interface on the InP platform, as shown in Fig. 12. If a high-output-power photodiode can directly drive a digital IC including a demultiplexer, there is no high-speed, baseband, analog electrical interface, and all electrical signals are digital, parallel, and demultiplexed signals. Since this configuration eliminates the waveform distortion caused by the interconnection of high-speed baseband analog equalization circuits, a high-sensitivity receiver can be easily constructed. In addition, the low-speed, digital electrical output interface eases module packaging of the high-speed IC chip shown in Fig. 12. We first demonstrate a 50-Gbit/s high-sensitivity optical receiver with this configuration. A unitraveling-carrier photodiode (UTC-PD) [20] was packaged and directly connected to a high-speed InP HEMT decision IC operating as a 1 : 2 demultiplexer. An input optical signal was amplified up to +14.5 dBm by using the cascaded low-noise and high-power EDFA's. The EDFA output was directly fed to the UTC-PD. Since the output peak current of the UTC-PD does not saturate over 60 mA, the

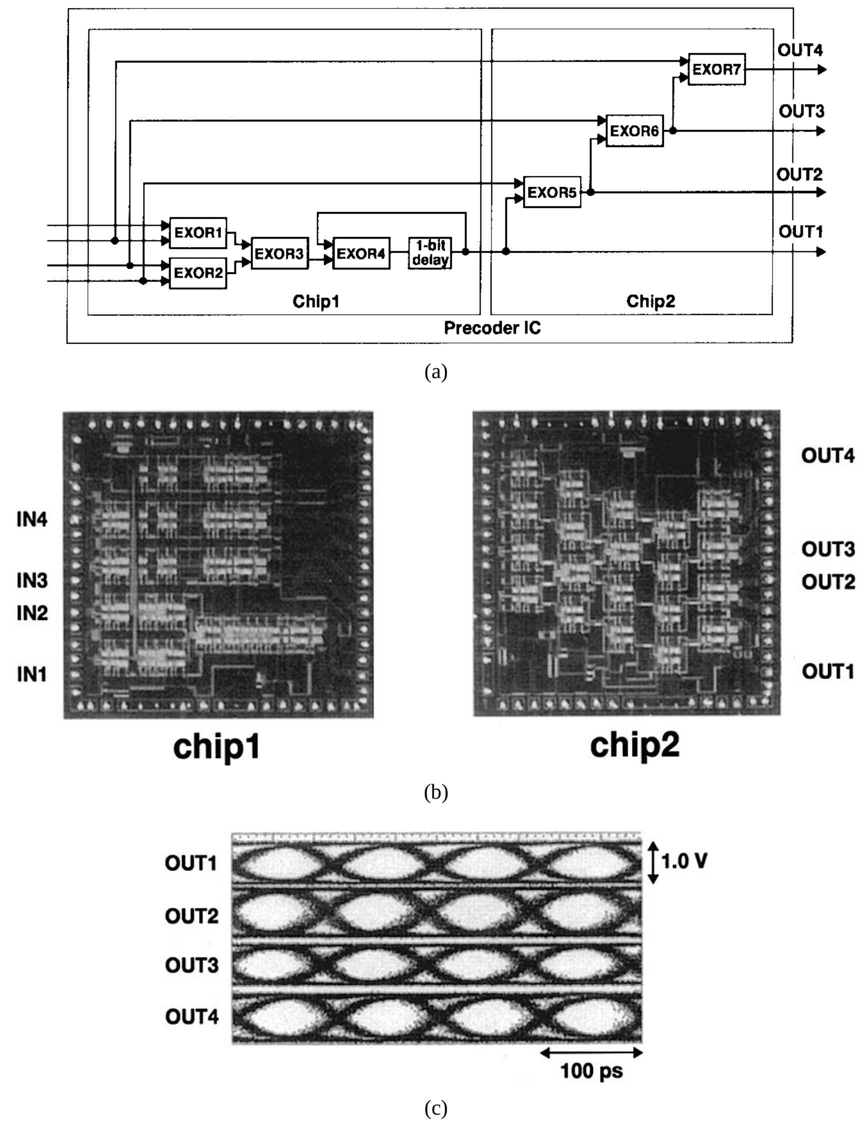


Fig. 10. A 40-Gbit/s precoder circuit using a four parallel channel configuration based on multichip GaAs MESFET IC's. (a) Circuit diagram. (b) Chip micrographs. (c) Output waveform of four-parallel 10-Gbit/s precoded signal.

1.0-$V_{\text{p-p}}$ electrical signal (0/$-$1 V) was easily obtained from the photodiode module [21], as shown in Fig. 13(a). Therefore, the decision circuit could be directly driven by the photodiode. The 25-Gbit/s demultiplexed signals from the HEMT decision circuit were further demultiplexed into 12.5-Gbit/s signals to check the bit error rate. The bit error rate of all four 12.5-Gbit/s channels was measured. The 50-Gbit/s high-receiver sensitivity (best channel: $-$28.6 dBm; worst channel: $-$27.6 dBm) was obtained as shown in Fig. 13(b). The best receiver sensitivity ($-$30.0 dBm) was also obtained at 40 Gbit/s with very small (0.4 dB) pattern-length dependency between the pattern length of 2^7-1 and that of $2^{15}-1$ of the PRBS signals [Fig. 13(c)].

B. 40-Gbit/s TDM Channel-Based DWDM System on ZDF Transmission Line

The next-generation fiber should simply support DWDM systems using high-speed TDM channels. A zero-dispersion-flattened (ZDF) transmission line has a great potential to relax the GVD and higher order GVD limitation in Fig. 3 of the high-speed TDM-based DWDM system [22]. A ZDF transmission line consists of standard single-mode fiber and reverse dispersion fiber whose dispersion and dispersion slope have opposite polarity and almost the same absolute value. This configuration realizes large local dispersion, which suppresses four-wave-mixing crosstalk impairment in a DWDM system and average zero dispersion over wide-wavelength range (1540–1580 nm), which is desirable for high-speed TDM systems.

Using four concatenated 176.4-km ZDF lines, we conducted ten-channel, 40-Gbit/s, NRZ transmission. The signal wavelengths were in the 15-nm range with 200-GHz spacing. A 40-Gbit/s electrically multiplexed signal was generated by an InP-HEMT multiplexer IC. The ten optical carriers were simultaneously modulated into the 40-Gbit/s NRZ signals, as shown in Fig. 14 [23]. All channels could be transmitted with error-free operation without individual terminal dispersion compensation (Fig. 15). By combining these 40-Gbit/s TDM technologies

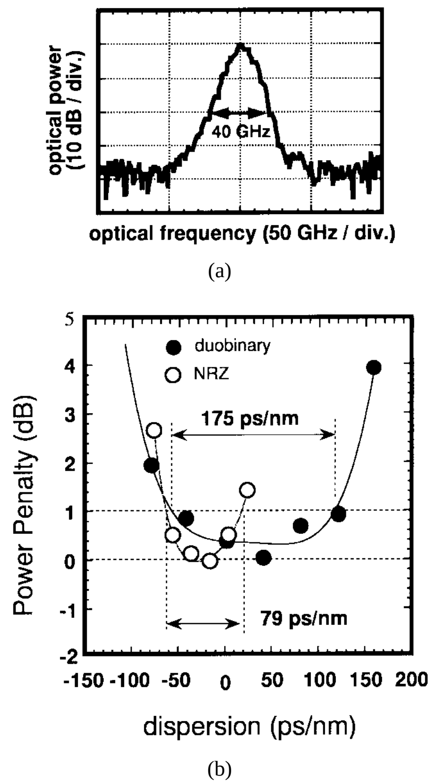


Fig. 11. Enlargement of dispersion tolerance by optical duobinary code at 40 Gbit/s. (a) Optical spectrum of 40-Gbit/s optical duobinary signal. (b) Dispersion tolerance characteristics of conventional NRZ signal and duobinary signal.

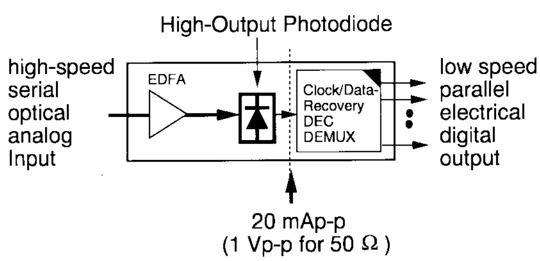


Fig. 12. Ultra-high-speed receiver configuration.

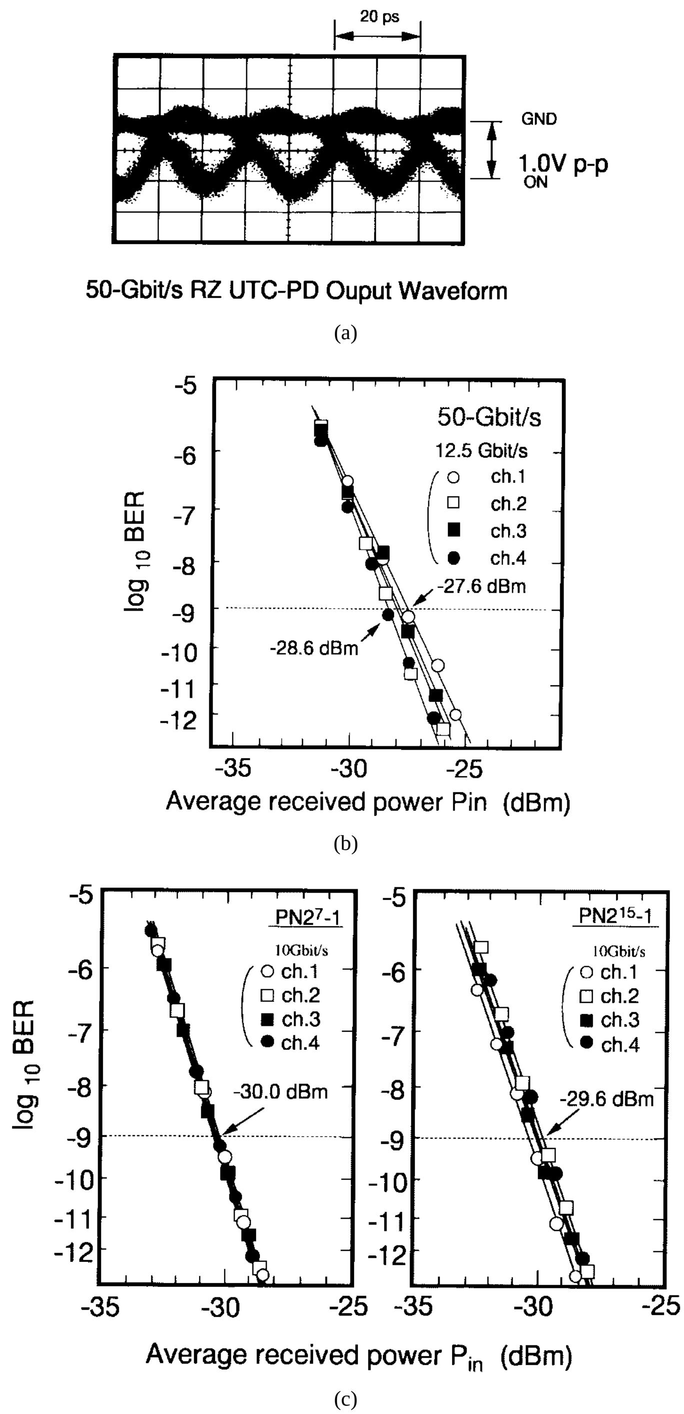


Fig. 13. Back-to-back receiver performances beyond 40 Gbit/s. (a) A 50-Gbit/s eye diagram from the UTC-PD module. (b) The 50-Gbit/s bit-error-rate performance. (c) PRBS pattern-length dependency of 40-Gbit/s receiver sensitivity.

with an alternate-polarization optical TDM (OTDM) scheme, the single-channel bit rate can be easily doubled while maintaining a narrow optical signal bandwidth. Thirteen-channel, 80-Gbit/s OTDM signal (aggregate data bit rate: 1.04 Tbit/s) transmission was also conducted successfully over an 89-km ZDF in-line repeated link based on 40-Gbit/s TDM channels with high signal spectrum efficiency of 0.4 bit/s/Hz (Fig. 16) [24]. These results show that capacity upgrade toward the Tbit/s range is feasible with high signal spectrum efficiency based on 40-Gbit/s electrical TDM technologies and the ZDF transmission line.

VII. Conclusion

This paper has presented a 40-Gbit/s single-channel TDM transmission system performance based on InP HEMT IC's and a scheme for upgrading toward Tbit/s capacity. We have realized stable 40-GHz clock digital regeneration with 0.1-μm InP HEMT D-FF IC, as well as broad and flat baseband response of a front-end circuit used in combination with a waveguide photodiode and low-driving-voltage $LiNbO_3$ modulator. Based on these components, we successfully construct a basic 40-Gbit/s optical regenerative repeater system in a 40-Gbit/s, 300-km, in-line repeated system. We applied these components to construct a 40-Gbit/s optical duobinary transmission system as a dispersion-tolerant system. In the duobinary modulation circuit, we first demonstrated 40-Gbit/s operation of GaAs MESFET-based precoding IC's

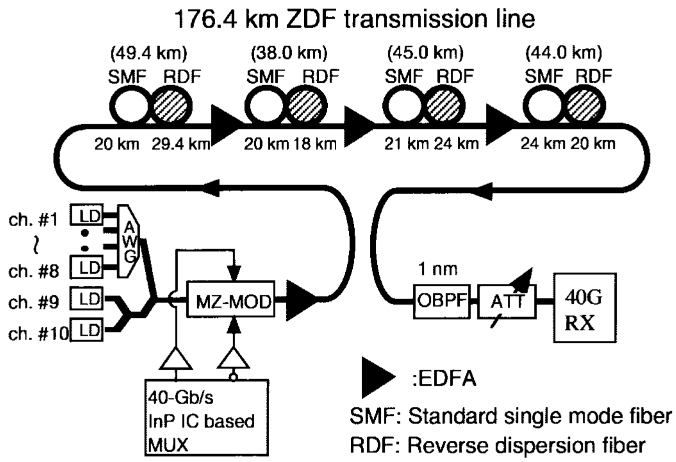


Fig. 14. DWDM transmission experiment with zero-dispersion-flattened transmission based on 40-Gbit/s TDM channels.

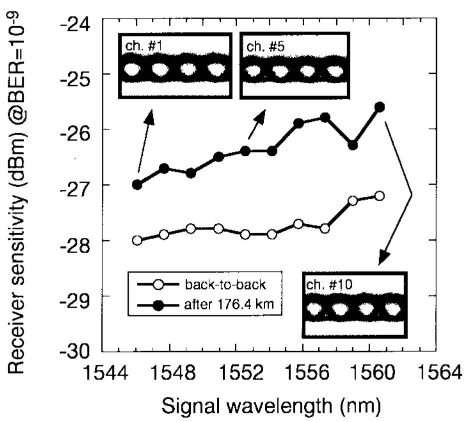


Fig. 15. Ten-channel, 40-Gbit/s WDM transmission experiment.

by introducing parallel processing circuit configuration. We have demonstrated two aspects in which to upgrade Tbit/s capacity to base on ultra-high-speed electrical TDM channels. One is to make the single-channel TDM capacity over 40 Gbit/s. Using a new receiver configuration with a high-output-power photodiode, a 50-Gbit/s high-sensitivity receiver can be achieved, which shows the possibility of increasing the fully electrical TDM channel bit rate beyond 40 Gbit/s. The other aspect is to combine these ultra-high-speed TDM channel technologies with both WDM and OTDM schemes on a dispersion-managed line called a zero-dispersion-flattened transmission line. High signal spectrum efficiency of 0.4 bit/s was achieved in a 1.04-Tbit/s experimental DWDM transmission system using alternate-polarization OTDM based on 40-Gbit/s TDM channels. These results shows that 40-Gbit/s TDM system technology is the key to realizing next-generation Tbit/s trunk systems that effectively utilize the limited EDFA gain band resources.

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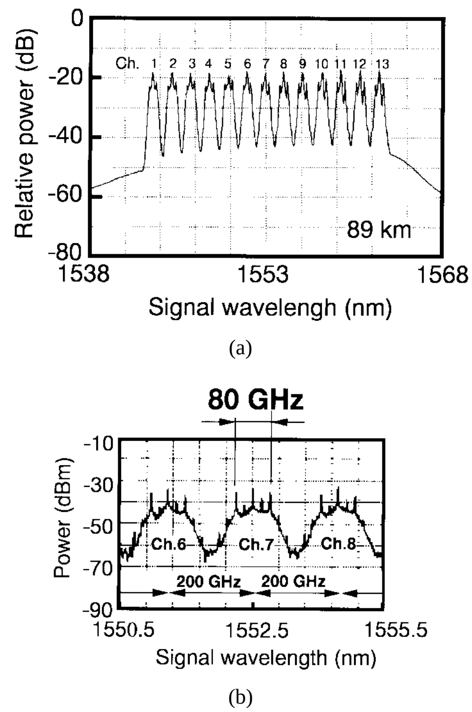

Fig. 16. A 1.04-Tbit/s DWDM transmission based on alternate-polarization 80-Gbit/s OTDM signals generated from 40-Gbit/s TDM channels with the optical signal spectrum efficiency of 0.4 bit/s/Hz. (a) 1.04-Tbit/s DWDM signal spectra. (b) Detailed DWDM spectra during channel 7.

REFERENCES

[1] K. Hagimoto, "Dynamic evolution of advanced optical network in Japan," in *Tech. Dig. OECC'96*, 1996, paper 17A1-9, pp. 96–97.

[2] S. Matsuoka and Y. Tetsuya, "Very-high-speed ring network in transmission networks: ADM 10G ring system," *NTT R&D*, vol. 48, pp. 27–32, Jan. 1998 (in Japanese).

[3] H. Masuda, M. Kawai, K. Suzuki, and K. Aida, "Wideband gain-flattened amplifiers with 3dB bandwidth of >50 nm," *Electron. Lett.*, vol. 33, pp. 1070–1072, 1997.

[4] A. Mori, Y. Ohishi, M. Yamada, H. Ono, Y. Hishida, K. Oikawa, and S. Sudo, "1.5 mm broadband amplification by Tellurite-based EDFA's," in *Tech. Dig. OFC'97*, 1997, postdeadline paper PD1-1.

[5] K. Srivastava, Y. Sun, J. W. Sulhoff, C. Wolf, M. Zirngibl, R. Monnard, A. R. Chraplyvy, A. A. Abaramov, R. O. Espindola, T. A. Strassser, J. R. Pedrazzani, A. M. Vengsarkar, J. L. Xyskind, J. Zhou, D. Ferrand, P. F. Wysocki, J. B. Judkins, and Y. P. Li, "1 Tb/s transmission of 100 WDM 10 Gbit/s channels over 400 km of truewave fiber," in *Tech. Dig. OFC'98*, 1998, postdeadline paper PD10.

[6] S. Aisawa, T. Sakamoto, M. Fukui, J. Kani, M. Jinno, and K. Oguchi," Ultra-wide band, long distance WDM transmission demonstration; 1 Tb/s (50 × 20 Gb/s), 600 km transmission using 1550 and 1580 nm wavelength bands," in *Tech. Dig. OFC'98*, post deadline paper PD11, 1998.

[7] K. Hagimoto, Y. Miyamoto, and Y. Yamagbayashi, "40-Gbit/s transmission systems" in *Tech. Dig. OFC'98*, 1998, paper WC3, pp. 114–115.

[8] Y. Ishii, "Fabrication technologies of InP-based digital IC's and MMIC's," in *Tech. Dig. 8th Int. Conf. InP and Related Materials*, 1996, paper WC3, pp. 53–56.

[9] T. Enoki, H. Itoh, K. Ikuta, and Y. Ishii. "0.1 μm InAlAs/InGaAs HEMT's with an InP-recess-etch stopper grown by MOCVD," in *Tech. Dig. IPRM'97*, 1995, paper WB2.4.

[10] T. Otsuji, E. Sano, Y. Imai, and T. Enoki. "40-Gbit/s IC's for future lightwave communication systems," in *GaAs IC Symp. '96 Tech. Dig.*, 1996, pp. 14–17.

[11] Y. Miyamoto, M. Yoneyama, Y. Imai, K. Kato, and H. Tsunetsugu, "40 Gbit/s optical receiver module using a flip-chip bonding technique for device interconnection," *Electron. Lett.*, vol. 34, pp. 493–494, Mar. 1998.
[12] K. Kato, S. Hata, K. Kawano, J. Yoshida, and A. Kozen, "A high-efficiency 50-GHz InGaAs multimode waveguide photodetector," *IEEE J. Quantum Electron.*, vol. 28, pp. 2728–2735, Dec. 1992.
[13] H. Tsunetsugu, T. Hayashi, M. Hosoya, and K. Katsura, "New flip-chip bonding technique using transferred microsolder bumps," in *Proc. IEMT/IMC Symp. '98*, 1997, pp. 56–61.
[14] K. Noguchi, O. Mitomi, and H. Miyazawa, "Low-voltage and broadband $Ti:LiNbO_3$ modulators operating in the millimeter wavelength region," in *Tech. Dig. OFC'96*, 1996, paper ThB2, pp. 205–206.
[15] M. Yoneyama, A. Sano, K. Hagimoto, T. Otsuji, K. Murata, Y. Imai, S. Yamaguchi, T. Enoki, and E. Sano, "40 Gbit/s optical repeater circuits using InAlAs/InGaAs HEMT digital IC chip set," in *Tech. Dig. MTT-S'97*, May 1997, paper WE1D-2, pp. 461–464.
[16] K. Yonenaga, S. Kuwano, S. Norimatsu, and N. Shibata, "Optical duobinary transmission system with no receiver sensitivity degradation," *Electron. Lett.*, vol. 31, pp. 302–304, Feb. 1995.
[17] M. Yoneyama, K. Yonenaga, Y. Kisaka, and Y. Miyamoto, "Differential precoder IC modules for over-20 Gbit/s optical duobinary transmission systems," in *Proc. MTT-S'99*, 1999, vol. 1, paper MO3A-1, pp. 189–192.
[18] K. Yonenaga, A. Hirano, M. Yoneyama, Y. Miyamoto, K. Hagimoto, and K. Noguchi, "Expansion of tolerable dispersion range in a 40-Gbit/s optical transmission system by using an optical duobinary signal," *Electron. Lett.*, vol. 34, pp. 385–386, 1998.
[19] K. Hagimoto, Y. Miyamoto, T. Kataoka, H. Ichino, and O. Nakajima, "Twenty-Gbit/s signal transmission using a simple high-sensitivity optical receiver," in *Tech. Dig. OFC'92*, 1992, paper TuI3, p. 48.
[20] T. Ishibashi, N. Shimizu, H. Ito, T Nagatsuma, and T. Furuta, "Uni-traveling-carrier photodiode," in *Tech. Dig. UEO'97*, 1997, paper UWA2-1, pp. 166–168.
[21] Y. Miyamoto, M. Yoneyama, K. Hagimoto, T. Ishibashi, and N. Shimizu," 40-Gbit/s high sensitivity receiver with uni-travelling-carrier photodiode acting as a decision IC driver," *Electron. Lett.*, vol. 34, pp. 214–215, Jan. 1998.
[22] 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," in *Tech. Dig. ECOC'97*, vol. 1, 1997, pp. 127–130.
[23] K. Yonenaga, A. Matsuura, S. Kuwahara, M. Yoneyama, Y. Miyamoto, Y. Yamabayashi, K. Hagimoto, K. Noguchi, and H. Miyazawa, in *Tech. Dig. OECC'98*, July 1998, postdeadline paper PD1-3.
[24] Y. Miyamoto, K. Yonenaga, A. Hirano, N. Shimizu, M. Yoneyama, H. Takara, K. Noguchi, and K. Tsuzuki, "1.04-Tbit/s DWDM transmission experiment based on alternate-polarization 80-Gbit/s OTDM signals," in *Tech. Dig. ECOC'98*, Sept. 1998, postdeadline paper, pp. 55–56.

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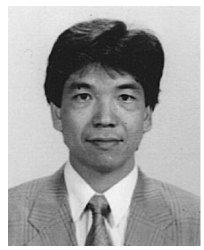

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