The University of Kansas

Information and
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Technical Report

40Gb/s Optical Transmission System Testbed

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ABSTRACT

This technical report details the 40Gb/s optical transmission testbed established at the Lightwave Communications Laboratory. This testbed provides a foundation for future experimental research on high-speed optical transmission systems and related performance issues. It will facilitate the research on advanced optical modulation formats and the comparison of optical systems with various optical fiber types. This experimental capability on 40Gb/s optical transmission systems will enable an independent assessment of new ideas of high-speed optical transmission and validate theoretical models.

Introduction

During the past decade, tremendous advances have been made in the development of high-speed DWM optical systems and networks. To make full use of the optical bandwidth provided by the fiber, WDM channel count has been increased from 4 to 160 in a single fiber and the data rate per channel has also been increased from 622 Mb/s to 10 Gb/s in many commercial optical systems. In order to further increase the optical bandwidth efficiency, 40 Gb/s optical systems are been developed by several industrial leaders and are expected to be in the commercial market very soon.

The impact of the upcoming 40 Gb/s (OC-768) optical systems to telecommunication service providers, such as Sprint, will be tremendous. On one hand, OC-768 may greatly increase the optical bandwidth efficiency and increase the optical network capacity. But on the other hand, high-speed TDM systems like OC-768 will suffer more from fiber chromatic dispersion, PMD, and fiber nonlinearity compared to OC192 and OC48. Precise dispersion compensation, maybe in the per-channel base will be required. The system performance will be more sensitive to fiber types than ever and the optical modulation format will play a critical role in determining the spectral efficiency and system resistance to chromatic dispersion and nonlinear crosstalk.

An advanced high-speed optical system testbed will help the understanding of many practical issues related to system performance and reliability. It will also enable the validation of theoretical modeling and numerical simulations. Certainly, a good understanding in 40 Gb/s optical systems will help Sprint in the decision making process for the technical planning and integration.

In order to establish this experimental capability within our budget limitations, we have evaluated several different options, such as optical domain multiplexing, electrical domain multiplexing and fixed 40Gb/s bit-error test set. We chose electrical domain multiplexing / demultiplexing for its simplicity and flexibility. Several optical modulation formats have been tested, including non-return-to-zero (NRZ), optical duo-binary and carrier-suppressed return-to-zero (CS-RZ).

High-speed TDM Optical Systems Testbed– An overview

From a system testbed point of view, there are several different ways to generate 40Gb/s TDM bit patterns and to detect them. The simplest way is to use a 40Gb/s bit error test set (BERT) as shown in Fig.1.

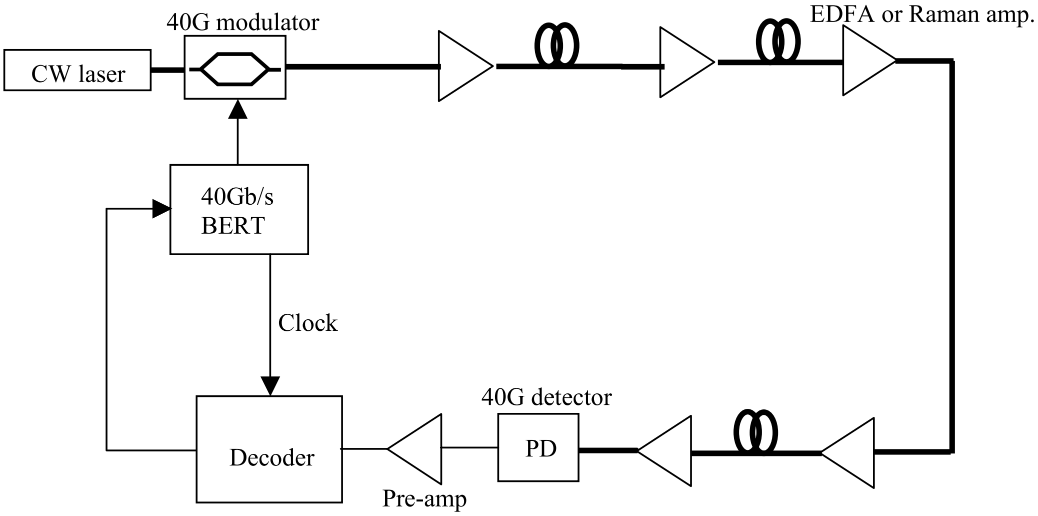


Fig.1, 40Gb/s optical testbed using a 40Gb/s BERT

In this setup, the key equipment is the 40Gb/s BERT. The advantage of this setup is its simplicity and easy to setup. However, there are several disadvantages: first of all, good quality and reliable BERT did not exist two years ago when we started this project (it is not available even now). Secondly, this setup would not be flexible to different data rate and modulation formats.

In our Lightwave Communication Laboratory, we have previously purchased an Agilent 10Gb/s BERT and it has been used for various projects. Given the budget constrain, we would like to utilize this existing equipment as much as possible. Obviously, there are two ways to multiplex the 10Gb/s bit pattern into 40Gb/s, either in optical domain or in electrical domain.

An optical domain multiplexing / demulplexing is schematically shown in Fig.2. In this setup, a mode-locked laser has to be used to produce a short optical pulse train at the repetition rate of 40GHz and the pulse width of <25ps. This periodic pulse train is on/off modulated by a 10GHz bandwidth electro-optic modulator through the electrical data stream generated by a 10Gb/s BERT. The modulated optical pulse train (at 10Gb/s) is split into 4 equal outputs by a star coupler. Then these 4 outputs are misaligned by 25ps from each other by 4 optical delay lines made by polarization maintaining (PM) fibers. After this relative delay, these 4 optical signals are combined by another star coupler to form a 40Gb/s optical data stream. At the receiver side, the 40Gb/s optical signal has to be converted into 10Gb/s optical signal in order to be detected. This data rate demultiplexing can be accomplished by an optical *AND* gate. In order to do this demultiplexing, the repetition rate of the 40 GHz optical pulse train from the mode-locked laser has to be decreased to 10GHz through an electro-optic modulator modulated by the 10GHz clock of the BERT. Although this all-optical technology is capable of handling very high-speed TDM optical signals by using narrower optical pulses from the mode-locked laser, it is generally not mature enough for practical applications.

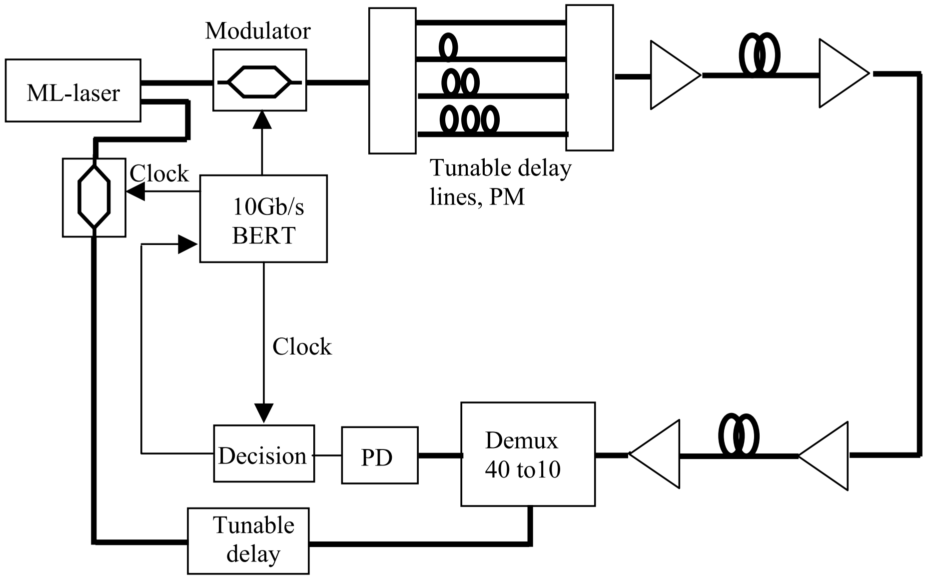


Fig.2, 40Gb/s optical system testbed using all-optical multiplexing and demultiplexing

Another way to construct a 40Gb/s optical TDM system testbed is to use electrical domain multiplexing and demultiplexing. This setup is flexible, practical and relatively cost effective. Therefore, we decided to build up out 40Gb/s testbed for this project based on electrical domain multiplexing and demultiplexing configuration.

Description of the 40Gb/s Experimental Testbed

Our 40Gb/s optical transmission testbed is based on electrical domain multiplexing and demultiplexing. The block diagram is shown in Fig.3.

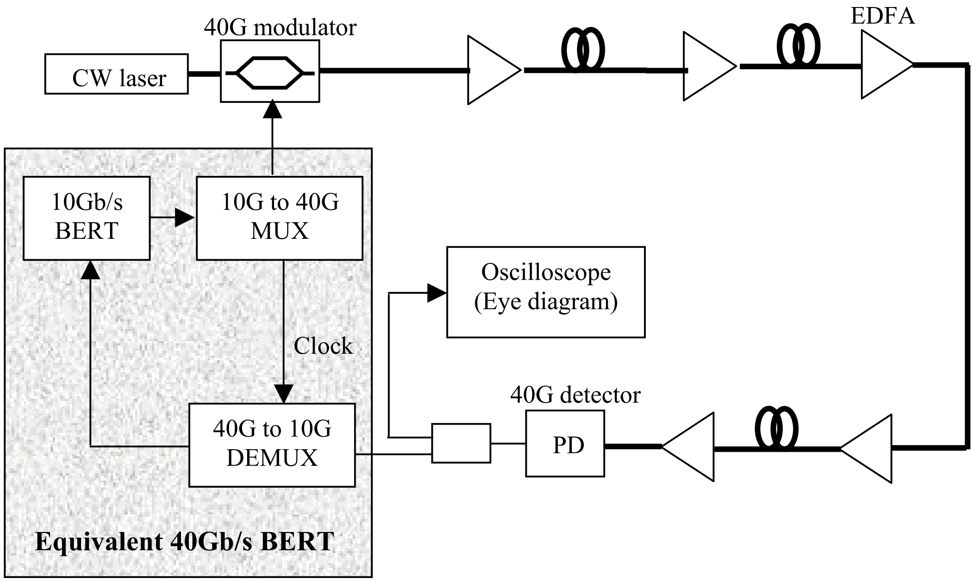
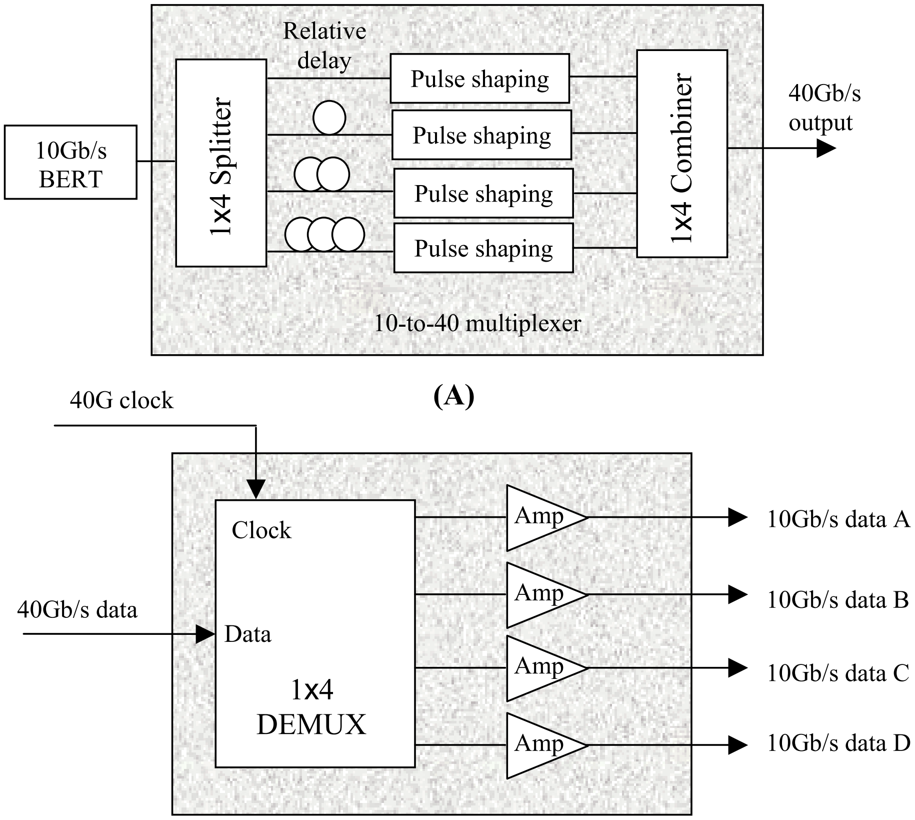


Fig.3, 40Gb/s optical testbed using electrical MUX/DEMUX

In this setup, a 10Gb/s BERT is used to generate the pseudo-random bit pattern. As illustrated in Fig.4(A), this 10Gb/s PSBR bit stream is multiplexed into 40Gb/s datarate through a 10-to-40 multiplexer. The basic operation of this multiplexer is to split the 10Gb/s PRBS into 4 channels, introduce a relative delay between each of them, reshape the 100ps electrical pulses width into 25ps and then recombine these 4 channels into one 40Gb/s digital output. Although this is essentially a self-multiplexed data pattern and is not a traditional 40Gb/s PRBS, it does serve as a good approximation to a PRBS.



(A)

(B)

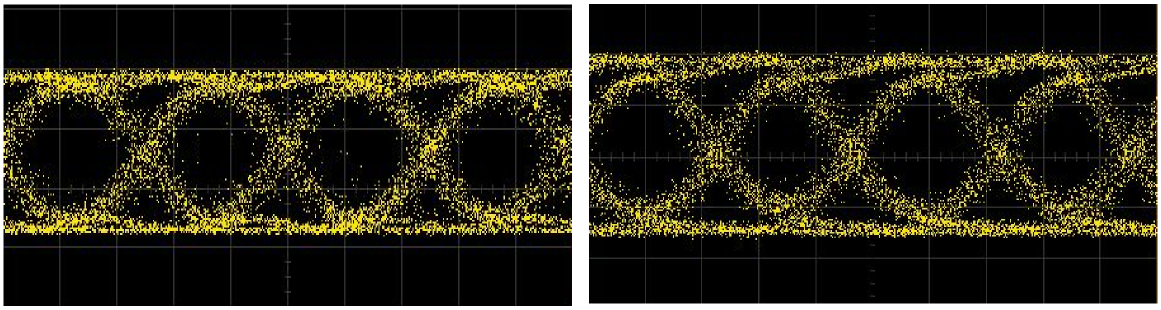
Fig.4, Schematics of Electrical domain MUX (A) and DEMUX (B)

In the receiver side, the 40Gb/s optical signal is detected by a 40Gb/s optical receiver and then electrically demultiplexed into 4 parallel channels of 10Gb/s data streams. The BER performance can be detected by the10Gb/s BERT. The combination of the10Gb/s BERT, the 10-to-40 MUX and the 1x4 DEMUX makes an equivalent 40Gb/s BERT. The MUX and DEMUX in our experimental setup were bought from SHF Communications AG.

Based on this 40Gb/s BERT, we have evaluated a number of optical systems with various optical modulation formats.

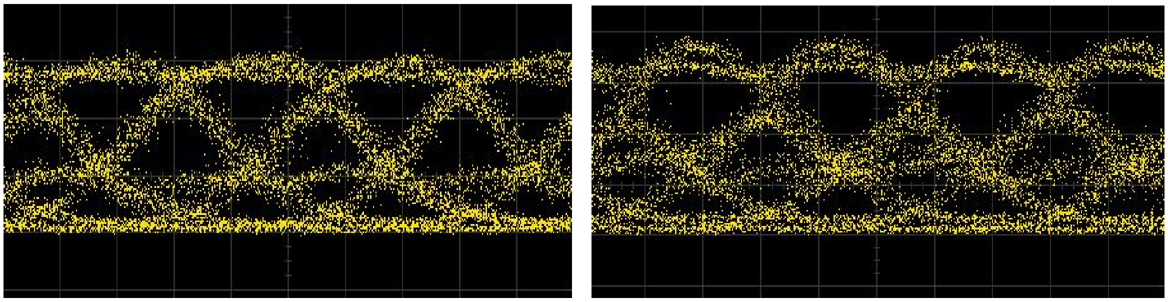
40Gb/s optical system with NRZ modulation format

In this system, a 1550nm tunable laser is used to provide the optical signal and a 38GHz bandwidth LiNbO3 electro-optical intensity modulator was directly modulated by the 40Gb/s electrical data pattern. Examples of 40Gb/s eye-diagram are shown in Fig.5 for different length of transmission fibers.



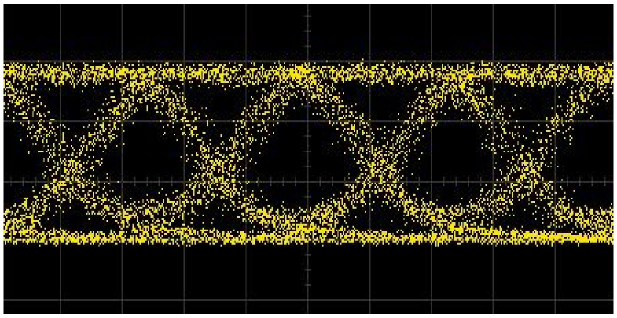
(A) Back-to-back

(B) After 2km SMF



(C) After 5km SMF

(D) After 8km SMF



(E) After 10km SMF and a 100% dispersion compensation

Fig.5, Eye diagrams measured at back-to-back (A), 2km (B), 5km (C) and 8km (D) without dispersion compensation and 10km with dispersion compensation (E)

In general, the dispersion tolerance of a 40Gb/s optical system is 16 time less that that for a 10Gb/s optical system. If we assume the dispersion tolerance for a 10Gb/s system is 1360 ps/nm/km (which is equivalent to 80km of standard single mode fiber), the dispersion tolerance for a 40Gb/s system will be approximately 85 ps/nm/km. This is equivalent to about 5km of standard single mode fiber transmission. Fig.5 clearly shows a severe waveform distortion at fiber length of longer than 5km. When a dispersion compensating fiber is added at the end of the system, the integrity of the waveform is restored and the eye is reopened. And this is shown in Fig.5(E).

Because of this low tolerance to chromatic dispersion and the stringent requirement on the precision of dispersion compensation, NRZ modulated 40Gb/s optical system is very delicate and vulnerable to uncertainties in the system parameters. In order to improve the performance of optical systems, other modulation formats have been proposed. Another modulation format we have experimented is CS-RZ.

40Gb/s optical system with CS-RZ modulation format

CS-RZ modulation format was proposed in recent years, it has been demonstrated to have better tolerance to chromatic dispersion and signal waveform degradation due to Kerr effect nonlinearities. CS-RZ optical signal has no carrier component and therefore in multi-wavelength WDM systems, it is less sensitive to four wave-mixing (FWM) than NRZ.

The block diagram of our 40Gb/s CS-RZ experimental system is shown in Fig.6. Two dual-electrode Mach-Zehnder (MZ) modulators were used. The first MZ modulator has a bandwidth of 38GHz. It was used to encode the 40Gb/s NRZ data directly coming from the 40Gb/s BERT. On the other hand, the second MZ modulator has a bandwidth of 20GHz. It is driven by a 20GHz clock signal. This second modulator is biased at the minimum transmission point as shown in Fig.7, so that it works as a frequency doubler and generates a 40GHz optical clock. It is important to notice that there is a "π" phase difference between adjacent pulses. The cascading of these two modulators provides a mean to generate 40Gb/s RZ modulation with carrier suppression.

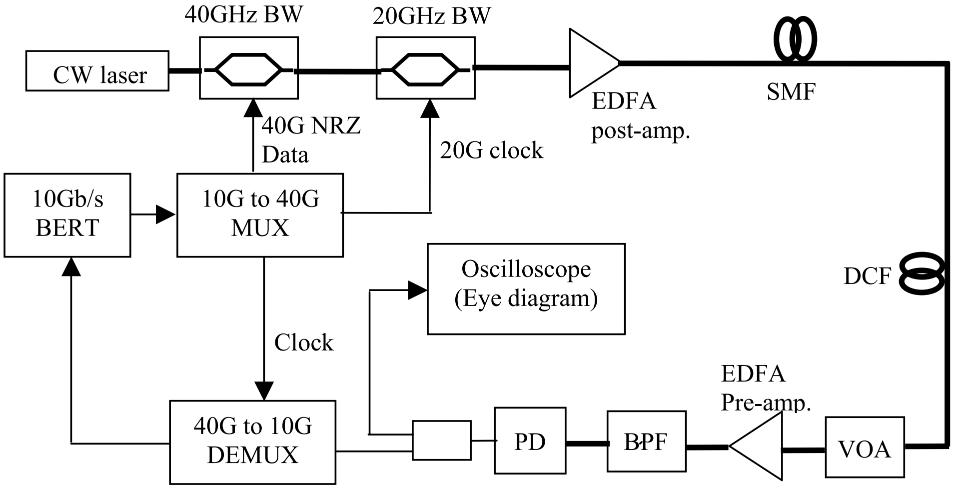


Fig.6, 40Gb/s optical system with CS-RZ modulation

Fig.7 illustrates the principle of CS-RZ optical signal generation. The second MZ modulator is biased at the minimum power transmission point, at which the field transfer function changes the sign. A 20GHz electrical clock will produce a 40GHz optical power train. Since the optical field changes the polarity for every other pulse, the average optical field is zero. Therefore, there is no carrier component for the optical field spectrum and the two characteristic frequency components will be at $\pm 20GHz$. This is commonly referred to carrier suppression. Use this carrier-suppressed optical pulse train to sample the NRZ modulated optical signal generated by the first MZ modulator will create a CS-RZ optical signal as illustrated in Fig.7.

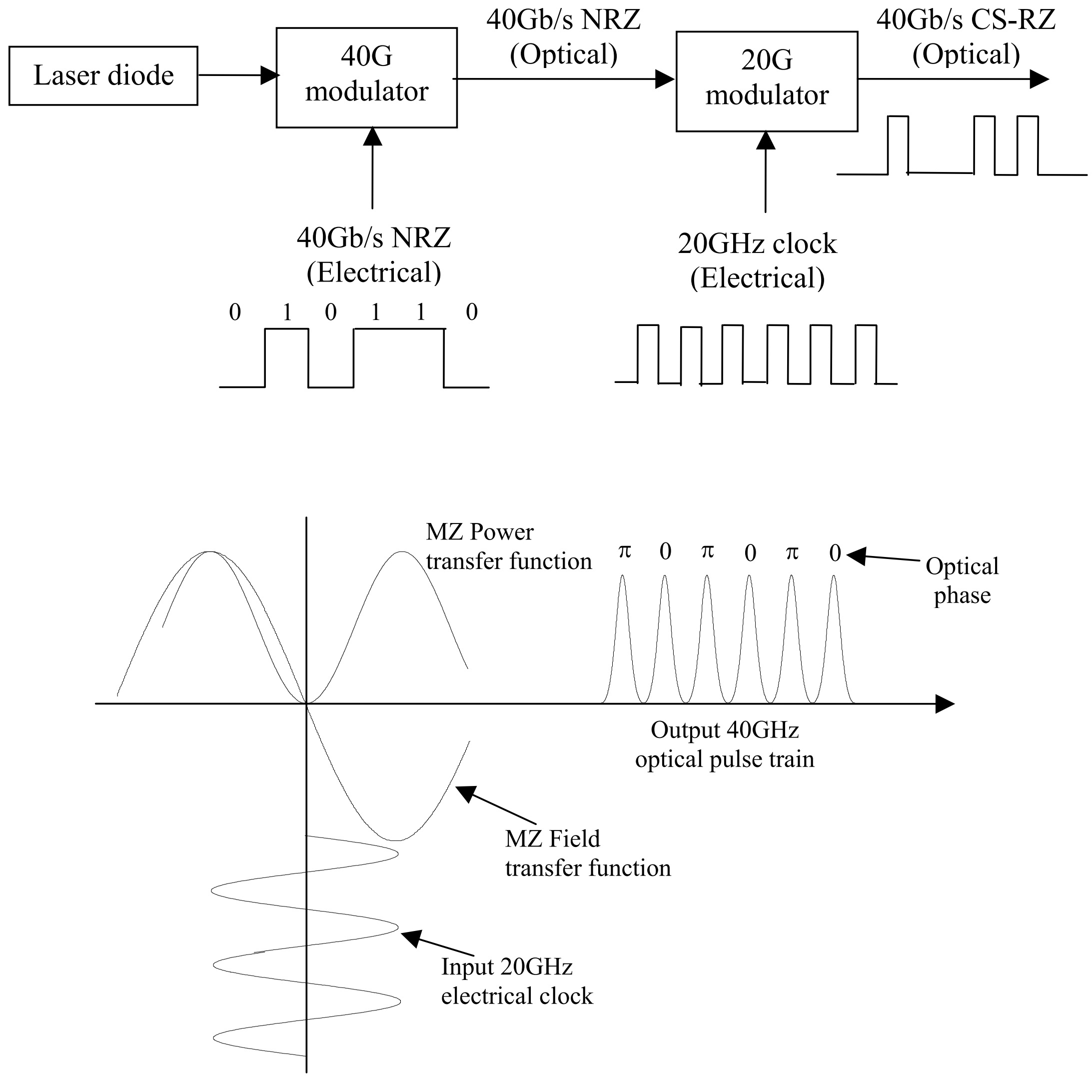
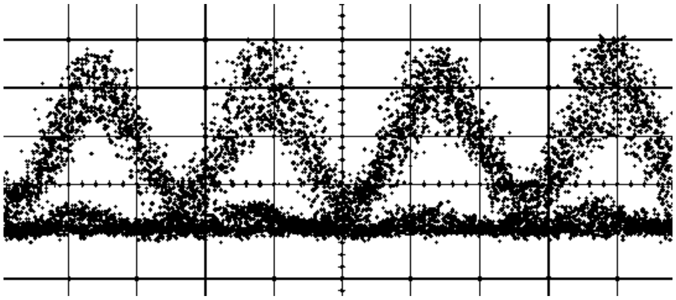


Fig.7, Illustration of how the CS-RZ optical signal is generated

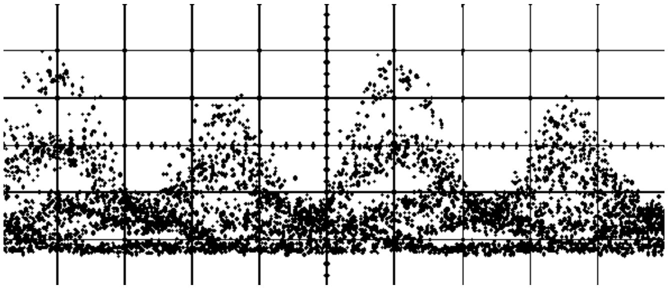
In the experiment, Corning SMF28™ fiber was used with the attenuation of approximately 0.30dB/km. The dispersion-compensation fiber (DCF) is Lucent DCF with dispersion of –164 ps/nm. The laser is tuned at 1532nm with output power of –2dBm.

Fig.8 shows the measured eye diagrams for back-to-back, over 10km without dispersion compensation and over 10km with dispersion compensation. In back-to-back operation, the receiver sensitivity was -27.9dBm to achieve a 10^{-9} bit-error-rate. This was measured by adjusting the variable optical attenuator (VOA) inserted before the EDFA preamplifier as shown in Fig.6. For 10km transmission with 100% dispersion compensation, the receiver sensitivity is approximately identical to the back-to-back operation.

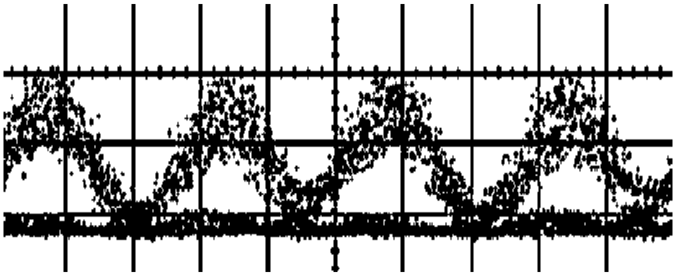
Fig.9 shows the measured optical spectrum of CS-RZ signal. In the ideal case, the spectrum of a CS-RZ signal has two half-clock-rate frequency components at 20GHz and the carrier is suppressed. Here in our measurement, however, there is a small residual carrier component in the optical spectrum. We believe it was caused by the non-optimum biasing of the two MZ modulators in the experiment. In practical systems, automatic bias control is required.



(A) Back-to-back



(B) After 10km without DCF



(C) After 10km with DCF

Fig.8, CS-RZ eye diagram measured at back-to-back (A), after 10km SMP without DCF (B) and after 10km with DCF (C).

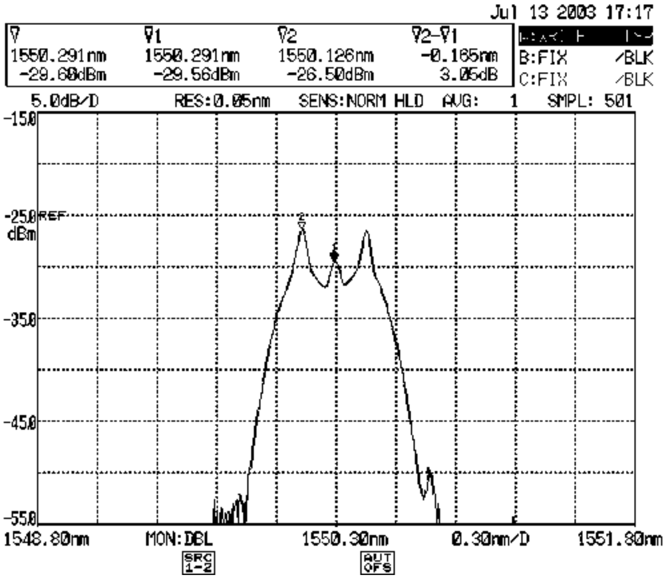


Fig.9, Measured optical spectrum of CS-RZ signal.

Conclusion

In conclusion, we have established a 40Gb/s optical transmission system testbed at the Lightwave Communications Laboratory. Experiments of 40Gb/s transmission with different optical modulation formats have been performed. This testbed provides a foundation for future experimental research on high-speed optical transmission systems and related performance issues. This experimental capability on 40Gb/s optical transmission systems will enable independent assessments of new ideas of high-speed optical transmission and validate theoretical models.