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High-Speed Optical Transmission Systems

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To meet the severe capacity demands in current fiber communication networks, an advanced integration of the high-speed time-division multiplexing (TDM) and multi-channel wavelength-division multiplexing (WDM) data transmission schemes is indispensable. This paper describes our R&D activities into high-speed TDM systems of photonic networks.
In high-speed TDM systems, fiber dispersion and non-linearity place limits on transmission speed and distance, and management of these fiber effects is the key for higher bit-rate systems. Even in 10 Gb/s systems, to achieve a satisfactory transmission distance, we had to cope with the speed limit of fiber. At the same time, we have reduced the size and cost of transmitters and receivers so they can be used as "network comodities" in small and simple network equipment. In 40 Gb/s systems, we have conducted experiments with several automatic compensation techniques for overcoming the crucial transmission speed limit of optical fibers.

1. Introduction

The explosive expansion of Internet links is challenging the capacities of data communication systems and necessitates the organic interconnection of worldwide telecommunication networks. To provide more flexible and dynamic communication structures, various optical fiber network functions such as optical add-drop multiplexers (OADMs) and optical cross-connect systems (OXCs) are being developed to integrate different photonic networks. Also, Tera b/s data transmissions per fiber are already planned for the near future.

Advanced integration of time-division multiplex (TDM) and wavelength-division multiplex (WDM) signal transmission schemes is practical; thus, the demand for more capacity can be met by denser WDM channels and faster TDM channels.

Restrictions on transmission speed and distance due to fiber effects

Optical fibers once seemed to have an almost infinite capacity, and up to 2.4 Gb/s, system speeds could keep up with the speeds of fast electronic circuits and optical devices. However, with the advent of 10 Gb/s systems, fiber dispersion and fiber non-linearity have become significant enough to cause fatal transmission waveform distortions, and the faster TDM systems suffer an abrupt degradation of transmission speed and distance (**Table 1**). The technical challenge of these limits is now unavoidable in high-speed TDM transmission systems.

Fiber self-phase modulation (SPM) limits transmitter output power. Because of the degradation of receiver sensitivity due to the noise bandwidth in high-speed systems, the power level margin is insufficient for long-distance fiber loss. The introduction of optical fiber amplifier repeaters and optical power

Table 1
Transmission distance limit by signal speed.

Fiber loss	Signal speed independent	Transmission distance depends on optical power margin between transmitter and receiver.
Noise bandwidth	$L \propto 1/B$	Signal speed increase causes S/N degradation.
SPM-GVD	$L \propto 1/DB^3$	Signal speed increase severely limits transmitter output power.
(repeated by fiber amps.)	$L \propto 1/DB$	Power management along the fiber using fiber amplifier repeaters increases the distance.
Chromatic dispersion	$L \propto 1/DB^2$	Fiber dispersion coefficient at the channel wavelength and signal spectrum spread by data modulation and transmitter chirp causes waveform distortion.
PMD	$L \propto 1/Dp^2B^2$	Conventionally installed SMFs sometimes suffer from a large PMD coefficient.

L : Transmission distance
B : Signal speed (Bit rate)
D : Fiber chromatic dispersion
Dp : Fiber polarization-mode dispersion (PMD)

management along the fibers has dramatically increased the transmission distance.

Fiber chromatic dispersion causes severe transmission waveform distortion in high-speed systems and as a result puts limits on the transmission speed and distance. The limits depend on the installed fiber constant, transmission distance, and optical wavelength. In multi-band WDM systems, each channel wavelength suffers a different fiber dispersion, so individual channel compensation may be required.

Polarization-Mode Dispersion (PMD) also restricts transmissions depending on the fiber features, optical components, and other environmental stress factors. Conventionally installed fibers, which have a large PMD constant, even degrade 10 Gb/s transmissions.

Compactness for photonic network applications

In WDM systems and other network applications that use multiple optical wavelength channels, it is important to reduce the size and cost of all WDM channel equipment in order to minimize the system complexity and simplify the installation. We will need to be able to install 10 Gb/s systems as basic integration channel units and use them as network commodities. It will be especially helpful to reduce the size and cost of the fiber components of 10 Gb/s equipment as well as the electronic circuits.

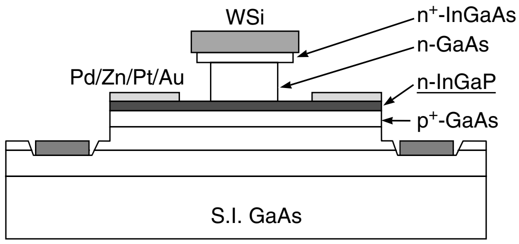
Fujitsu's R&D of 10 Gb/s TDM systems and of future 40 Gb/s TDM systems of high-capacity photonic networks are described below.

2. 10 Gb/s systems

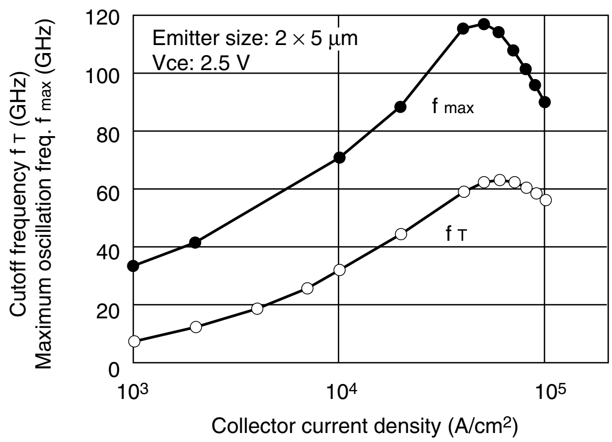
The integration of electronic circuits helps reduce the size, power, and cost of TDM transmitters and receivers. This in turn enables compact WDM channel installation and avoids the need for large and complex equipment.

The circuit speeds required for 10 Gb/s operation can be achieved using compound semiconductors with superior speed performance, and we have used InGaP/GaAs hetero-junction bipolar transistor ICs (HBT-ICs) for their speed and reliability (**Figure 1**).[1] The high-gain profile of these transistors enables high-gain and high-frequency amplifiers (preamplifiers and slice amplifiers) and high-sensitivity and high-speed decision circuits to perform stably and sufficiently (**Figure 2**).[2]

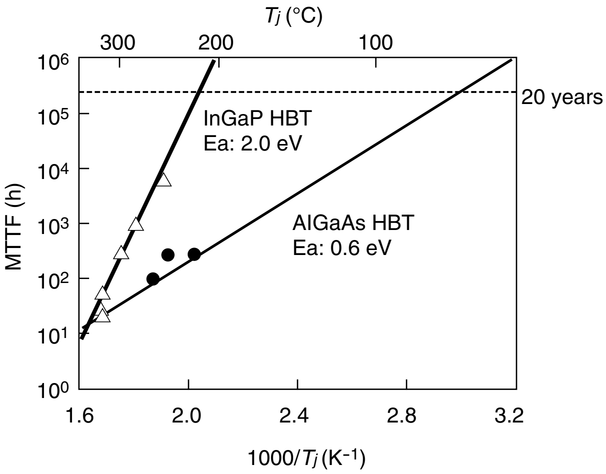
Further reductions in receiver size can be achieved through on-chip PLL timing extraction. The use of conventional resonator filter clock



(a) Transistor structure

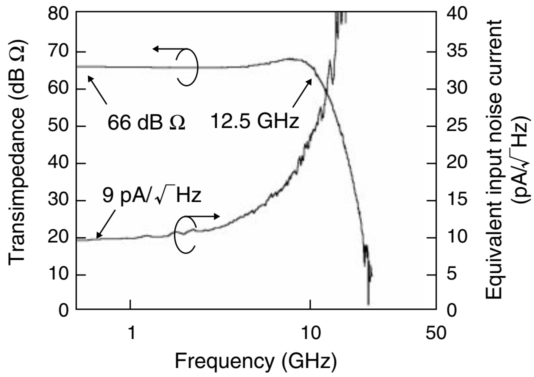


(b) Transistor frequency profile

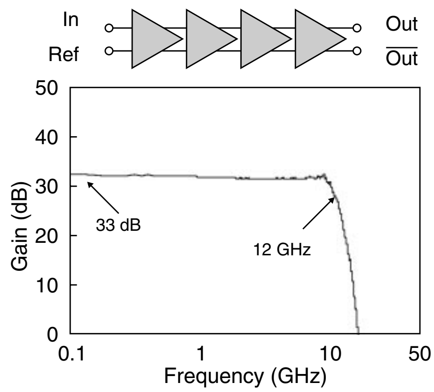


(c) Reliability of InGaP/GaAs HBT and AlGaAs/GaAs HBT

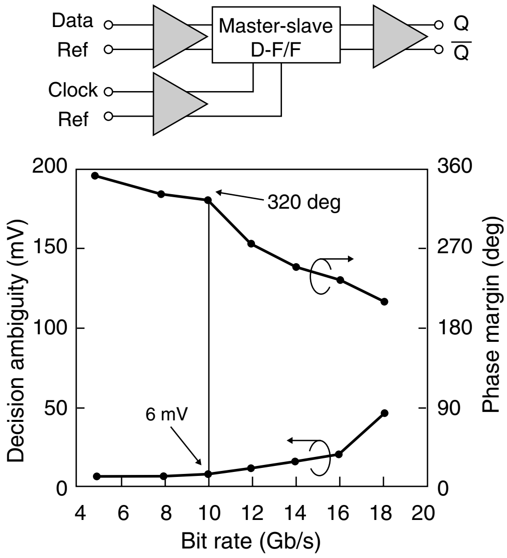
Figure 1
InGaP/GaAs HBT performance and reliability.
Fine-tuned epitaxial growth and self-aligned structure of the transistor achieved a 60 GHz cutoff frequency (f_t) and a 100 GHz maximum oscillation frequency (f_{max}), which is quite sufficient for 10 Gb/s circuit operation. InGaP emitter enables a circuit reliability exceeding 20 years even in a severe temperature environment.



(a) Preamplifier IC



(b) Slice amplifier IC



(c) Decision IC

Figure 2
HBT-IC performance.
A flat, stable, high-gain, and high-sensitivity performance is achieved which enables simple and high-performance 10 Gb/s equipment for a wide variety of transmission applications.

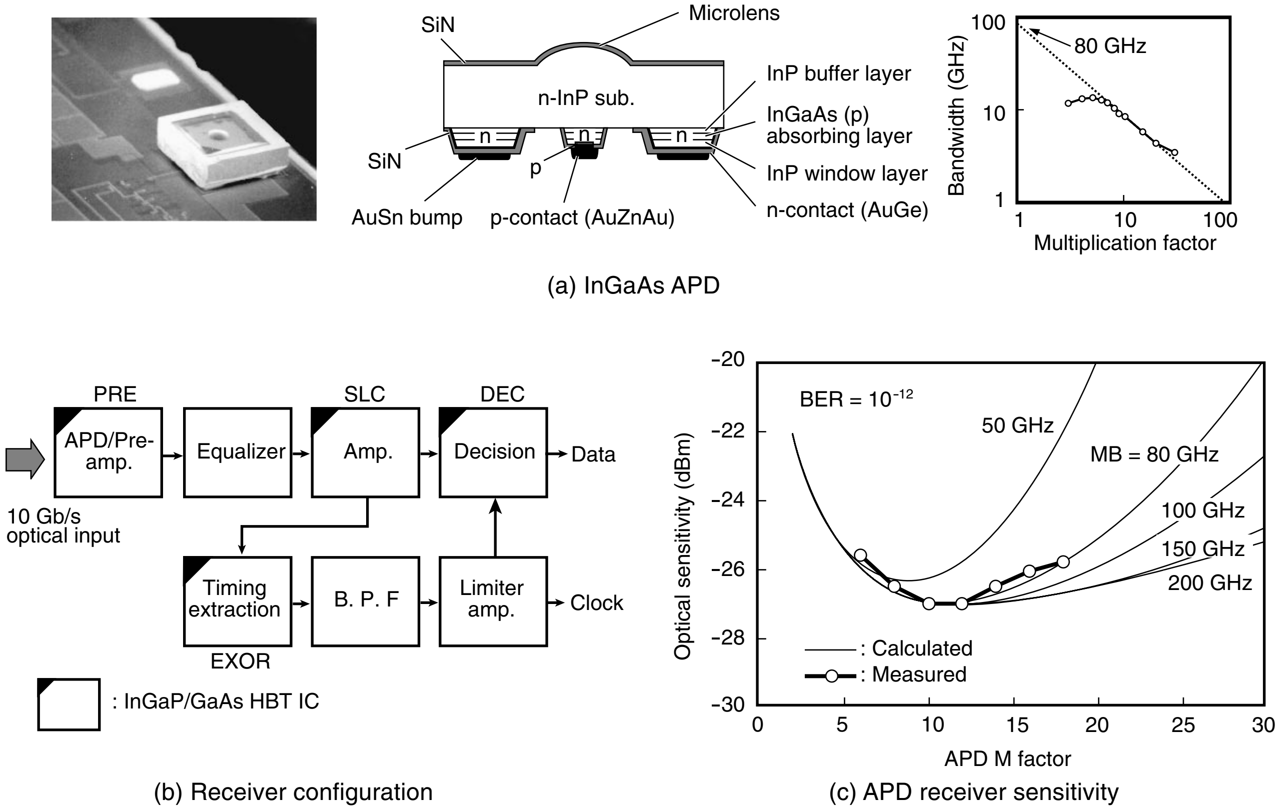


Figure 3
10 Gb/s receiver using InGaAs avalanche photodiode (APD).
Flipchip mount structure and monolithic lens focusing of the APD achieve an 80 GHz gain-bandwidth product. Maximum receiver sensitivity is -27 dBm, which is achieved at a multiplication factor (M) of 10.

extraction is not practical in 10 Gb/s receivers because of the frequency limit of surface acoustic wave (SAW) filters and the large size of the dielectric resonator filter (DRF).

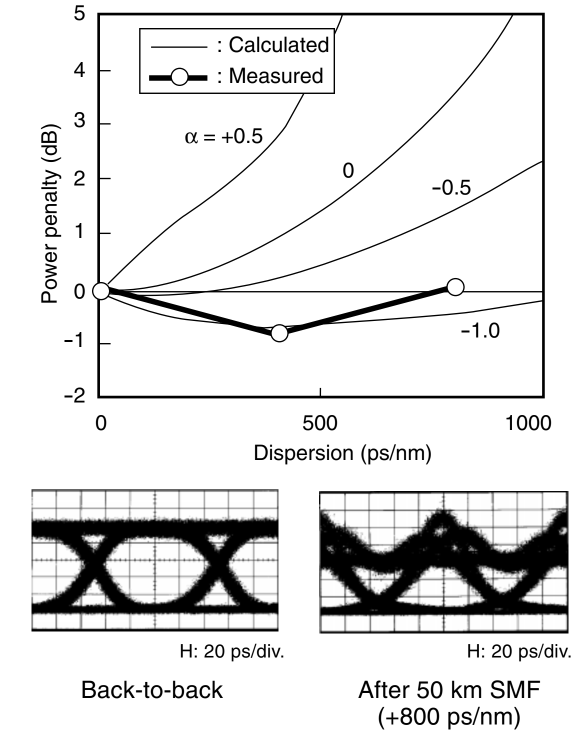
Fiber amplifiers and dispersion compensating fibers (DCFs) are widely used, even in 10 Gb/s systems, to overcome the transmission speed limit of the fibers. However, the long fibers needed in these components make them too big for network equipment. Therefore, in network commodity installations, fiber components must be eliminated to achieve compactness with no degradation of speed or distance.

To reduce the size and cost of the optical fiber preamplifier, we used an InP/InGaAs avalanche photodiode (APD) which multiplies optical signal current even at 10 Gb/s. The APD was flipchip mounted to the HBT preamplifier IC and provided sufficient receiver sensitivity (**Figure 3**).[2)]

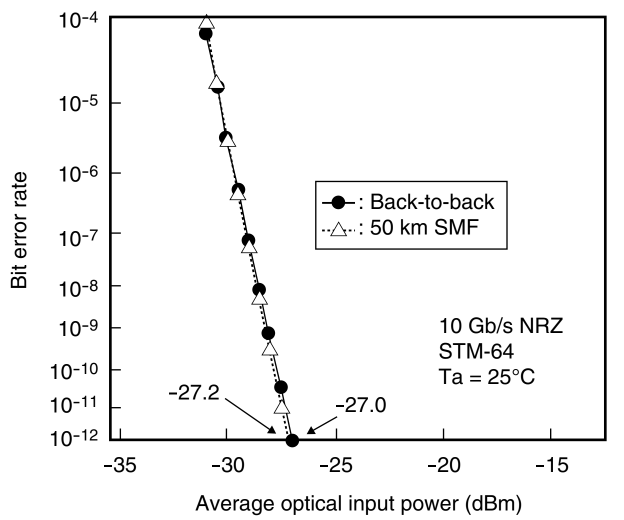
We perform pre-chirping using a Ti: $LiNbO_3$ external modulator to maintain transmission distance through large-dispersion SMFs and to eliminate DCFs (**Figure 4**).[3)] The well-defined and stable receiver bandwidth needed to cope with the wide variety of transmission waveforms encountered with different fiber dispersions is achieved through HBT-IC amplifiers with highly stable frequency characteristics.

3. 40 Gb/s system

To achieve Tera b/s capacities, the capacity of each WDM channel can be increased to 40 Gb/s because of the practical restriction on wavelength channel density. However, the transmission speed



(a) Dispersion penalty improvement by transmitter pre-chirping parameter α of −1.0



(b) SMF 50 km transmission with no sensitivity degradation

Figure 4
SMF 50 km transmission using Ti: $LiNbO_3$ external modulator transmitter and APD receiver.
SMF 50 km transmission (800 ps/nm dispersion) is achieved without fiber amplifier. APD receiver sensitivity and pulse compression technique by using transmitter pre-chirping enable non-penalty transmission through high-dispersion fiber without fiber preamplifiers or DCFs.

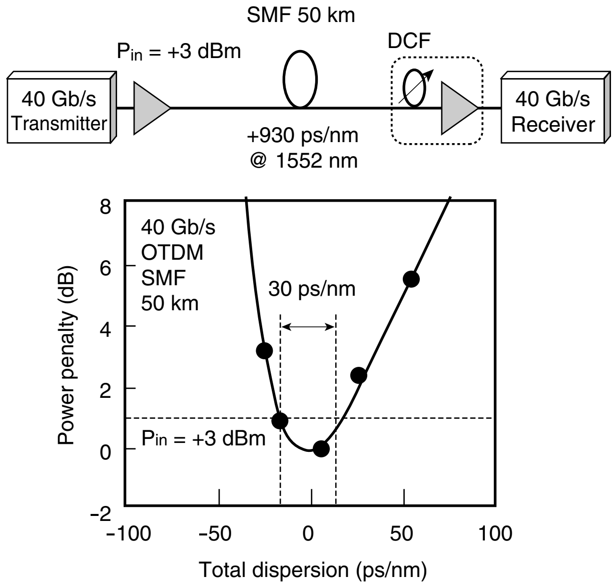


Figure 5
40 Gb/s dispersion tolerance.
In a demonstration of 40 Gb/s optical TDM (OTDM) transmission, the maximum allowable dispersion for acceptable transmission quality was 30 ps/nm.

limit of optical fibers prevents the simple installation of a 40 Gb/s system into a photonic network.

Especially, at 40 Gb/s, fiber chromatic dispersion and PMD worsen the tradeoff between speed and distance by a factor of 16 compared to that at 10 Gb/s. The dispersion tolerance margin is critical in 40 Gb/s systems (**Figure 5**) and can be easily exceeded due to differences in fiber distance, dispersion, and temperature.[4] Adoptive dispersion compensation will be the key technique to overcome the fiber dispersion limit. We have demonstrated automatic dispersion compensation using a tunable laser diode (LD) (**Figure 6**).[5] Computer-processed feedback about the received data spectrum is used to tune the LD to the best transmitter optical wavelength for minimum waveform distortion.

The PMD coefficient is also an important factor in several old types of fibers. We have demonstrated automatic PMD compensation using a polarization controller and a polarization-maintaining fiber (**Figure 7**).[6]

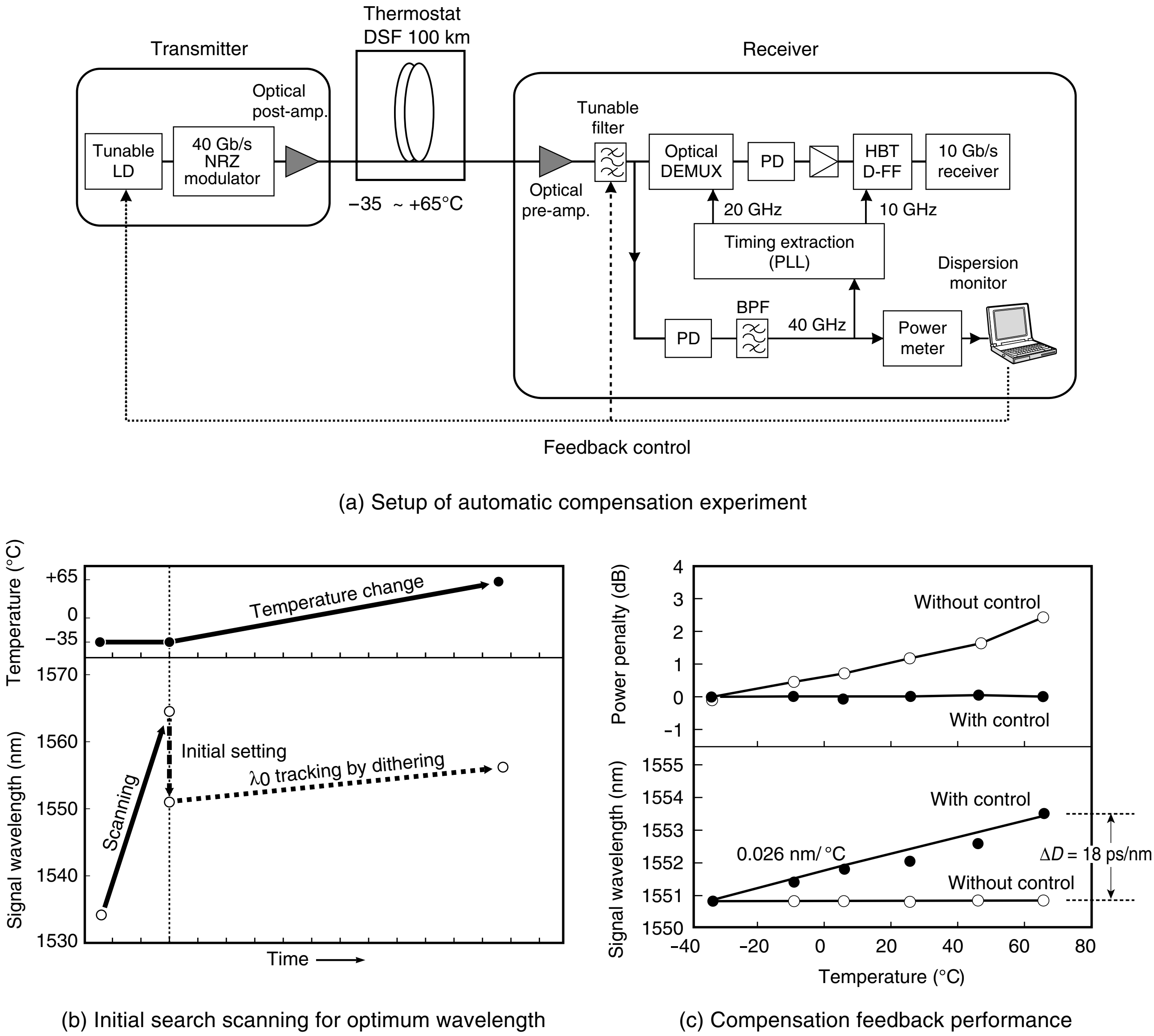
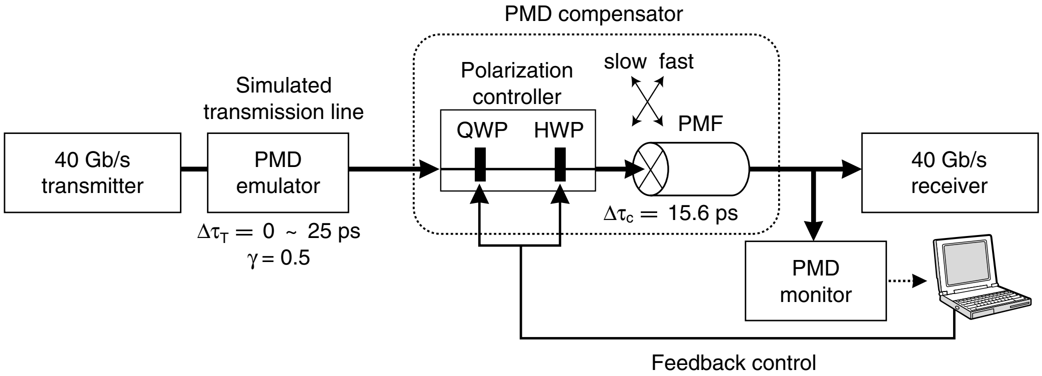


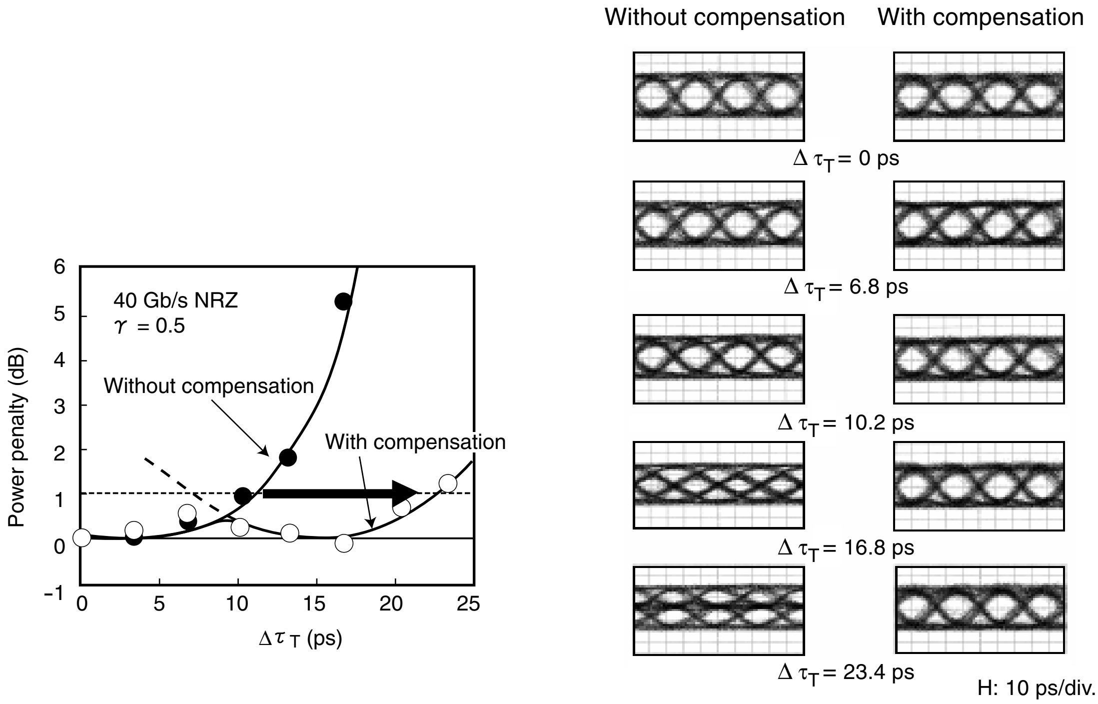
Figure 6
40 Gb/s automatic dispersion equalization experiment.
Adoptive dispersion compensation is performed by automatic optical wavelength control using a tunable laser. A computer controls the initial search scanning and feedback operation from receiver to transmitter by monitoring the 40 GHz component of the received signal. 18 ps/nm dispersion tracking was demonstrated in the experiment.

A compensation scheme with strict dispersion management seems indispensable for 40 Gb/s system installation.

A different approach would be to introduce another modulation scheme. Instead of the SONET/SDH fiber transmission standard, forward-error correction (FEC) coding by adding an extra FEC frame to the data stream is a promising way to improve transmission distance while maintaining the transmission quality. Special optical modulation schemes such as optical duobinary modulation are also attractive. The narrow transmission data spectrum of duobinary modulation avoids dispersion effects and enables WDM channels to be brought closer together without reducing their capacities. These techniques



(a) Setup of automatic PMD compensation experiment



(b) Compensation feedback performance

Figure 7
40 Gb/s automatic PMD compensation experiment.
Adoptive PMD compensation was performed by polarization control of an optical signal input to a polarization maintaining fiber (PMF). Computer feedback control improved the PMD tolerance from 11 ps to 23 ps, which corresponds to a transmission distance improvement from 50 km to 230 km.

can also be used in 10 Gb/s systems for further increases in transmission distance and better system configurations.

The tradeoff between fiber transmission speed and distance may first recommend the use of 40 Gb/s systems in short-haul network applications such as heavy-traffic, intra-office systems and metropolitan systems and the introduction of regenerative repeaters to meet even higher speed and distance requirements.

4. Conclusion

This paper discussed the technology of high-speed TDM systems in photonic networks as an integration unit for achieving a wide variety of network functions and transmission capacities that exceed the Tera b/s range.

It described the use of high-sensitivity APDs, pre-chirping of Ti: $LiNbO_3$ modulators, and GaAs HBT-ICs in 10 Gb/s transmitters and receivers in order to eliminate fiber components in simple photonic networks while maintaining a high transmission quality. This paper also looked at automatic dispersion and PMD compensation trials for 40 Gb/s systems and proposed several ways to overcome the speed limit of transmission fiber.

In step with WDM systems, TDM systems must continue to evolve to satisfy the ever growing need for more network functions and higher capacities.

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