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Field Trial of All-Optical 2R Regeneration in 40-Gbit/s WDM Transmission Systems with Optical Add/Drop Multiplexing

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SUMMARY Optical signal processing is one of essential technologies for improving the flexibility of all-optical network. Above all, recently there have been a lot of studies regarding all-optical 2R/3R regeneration technology. However, there are few studies about all-optical 2R/3R technologies that are carried out in field environment. In this paper, we report the successful results of field trials of an all-optical 2R regeneration system based on an electro-absorption modulator for 40-Gbit/s WDM transmission systems with optical add/drop multiplexing. It was made sure that by applying the all-optical 2R regeneration system to the optical add/drop multiplexer in the 320-km-long transmission systems the transmission characteristics of the express signal after 320-km transmission and those of the dropped signal at 160-km can be made nearly the same. It is quite important that the transmission characteristics are equal for both the dropped and express channel from a point of view of the system design, and the results in this paper suggests one possible solution for this matter.

key words: *field trial, all-optical 2R regeneration, electro-absorption modulator, optical add/drop multiplexing*

1. Introduction

In the future network, ultra high-speed and high-capacity transmission over a bit rate of 40-Gbit/s will be required since the Internet traffic increases with the progress of video transmission services, peer-to-peer communication services, and so on.

In the present network, the signal processing is performed in an electrical domain, i.e., an optical signal is changed to an electrical signal, then the signal processing is carried out in an electrical level, then the signal is converted into the optical signal again. In such a regeneration system, problems including cost, power consumption, and equipment installation space are arising. By utilizing all-optical signal processing technology, it is expected that a more flexible network will be constructed and that the above problems will be solved. Above all, all-optical 2R (re-amplification and re-shaping)/3R (re-amplification, re-shaping, and re-timing) regeneration technology are considered to be essential among all-optical signal processing technologies.

Recently, there have been a lot of studies regarding all-optical regeneration technology such as a system using the cross-phase modulation (XPM) of a semiconductor optical amplifier (SOA), the nonlinear transmission characteristics of a saturable absorber (SA), the nonlinear transmission characteristics of an electro-absorption modulator (EAM), and cross-absorption modulation (XAM) [1]–[8].

However, most of these studies are all-optical regeneration systems using the wavelength conversion by the nonlinear effect, and they need high input optical power as a probe light. In the node of the future all-optical network, the optical add/drop multiplexing (OADM) technology will be used to increase the flexibility of the network, so if the all-optical regeneration technology with wavelength conversion is applied in such a node, unnecessary wavelength conversion may cause the complexity of the optical wavelength assignment of the network. Also, it is preferable that the device for all-optical regeneration operates in relatively low power to save power consumption of the node.

Moreover, when the OADM system is introduced in a repeater node, there is a problem that the loss and noise generated by the OADM system may degrade the transmission signal quality. Especially, the signal that passes through the node without the drop experiences the accumulation of more noise than the dropped signal. Such a situation causes the signal quality degradation for the through signal at the destination. From a point of view of the system design, it is desirable that the signal qualities of the through signal and the dropped signal are equal. Therefore, it is necessary to apply a technology to compensate for the signal quality degradation of the through signal generated by the OADM system.

In this paper, we report the results of the studies about all-optical 2R regeneration system with relatively low input optical power without wavelength conversion using an EAM as an all-optical 2R regeneration device. Then, we report the results of a field trial of the 40-Gbit/s, 12-channel WDM transmission systems using 320-km-long installed fibers by applying the all-optical 2R regeneration system in an OADM system.

2. All-Optical 2R Regeneration Using Electro-Absorption Modulator

2.1 Transmission Characteristics of Electro-Absorption Modulator

The EAM has the saturable absorption characteristics that the transmission characteristics nonlinearly change by applying the electric field to the device.

This EAM used in the experiment was a generally available commercial product and was not optimized for

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all-optical 2R regeneration. The EAM region length was 100 μm and the 14-periods InGaAsP multiple-quantum-well structure with the photoluminescence peak wavelength of 1.51 μm was used. The 3-dB electrical bandwidth was more than 50 GHz that was sufficient for 40-Gbit/s modulation [9]. The extinction ratio characteristics of the EAM are shown in Fig. 1. The insertion loss without a DC bias voltage is 7.6 dB and the input optical power is 0 dBm.

Then the transmission characteristics of the EAM were measured. The transmission characteristics versus the EAM input power for a signal at a data rate of 40-Gbit/s with RZ signal format are shown in Fig. 2. Measurement wavelength was 1550.11 nm. In Fig. 2, the DC bias voltage of the EAM was used as a parameter.

Increasing the optical input power to the EAM, we can confirm the saturable absorption phenomena at DC bias voltages between −1.5 V and −2.5 V. On the other hand, we can confirm that the other nonlinear effect in which the transmission loss increases in the bias conditions of 0 V to −1.0 V and −3.0 V to −4.0 V.

The above nonlinear effects can be explained by three reasons in the following. At first, we consider the effect of quantum-confined Stark effect (QCSE) in multi-quantum-well electro-absorption modulator (MQW-EAM) [13]–[15]. This effect can be described as the absorption-edge wavelength shifts to longer wavelength side since the wave function and quantum energy levels of electrons and holes confined to a quantum well structure is changed by applying the external vertical electric field to the well layer.

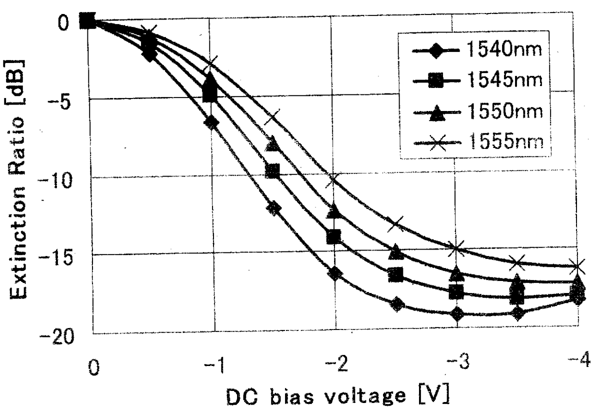


Fig. 1 Extinction ratio characteristics of EAM.

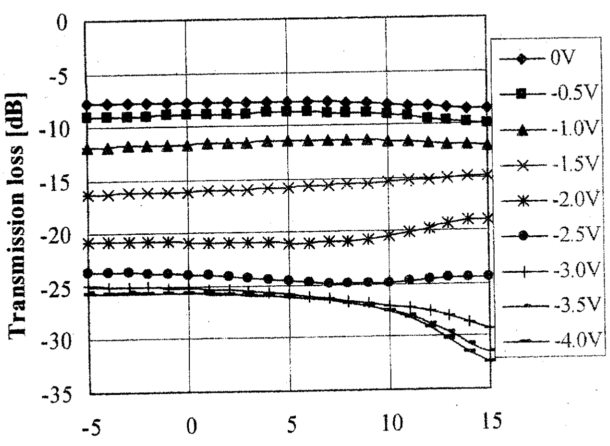


Fig. 2 Transmission characteristics of EAM (40-Gbit/s, RZ signal).

As the second reason, we can consider the effect of absorption saturation [16]. In the MQW-EAM, the electron-hole pair is generated by the absorption of the light in the absorption layer. When optical input power to the EAM is small, carriers are extracted efficiently by applying electric field to the MQW-EAM. However, when the optical input power of EAM is increased, the carrier pile-up effect in the absorption layer occurs in the MQW-EAM because the carriers cannot be extracted efficiently. By increasing the carrier density, the energy level is gradually filled from the lower energy side. As a result, band-filling effect in which the absorption edge wavelength shifts to the shorter wavelength occurs. By the absorption edge wavelength shift to the shorter wavelength side, the absorption coefficient becomes smaller by increasing optical input power.

For the third reason, we can consider the fact that the degree of Stark shift (absorption edge wavelength shift value generated by QCSE) differs for TE (transverse electric) polarization and TM (transverse magnetic) polarization. The waveguide type MQW-EAM with a traditional lattice matching rectangular quantum well showed polarization dependence. The reason for this is as follows. The heavy hole (HH) and light hole (LH) degenerating in bulk semiconductor were dissolved that degeneracy in the quantum well, and it forms each different quantum level for HH and LH at valence band in the direction of quantum confinement. Optical absorption in quantum well was occurred by the process that an incident photon created an electron at conduction band and a hole at valance band, respectively. In this time, TE polarization (the light has horizontal electric field vector for quantum well surface) and TM polarization (the light has vertical electric field vector for quantum well surface) have anisotropy for the condition of optical absorption. Strong transition of electron to heavy hole (E-HH) occurs for TE polarization. On the other hand, it doesn't occur for TM polarization. As a result, absorption edge for TE polarization is located at a longer wavelength side than that for TM polarization. Stark shift value ΔE is shown as follows:

$$\Delta E = -C \cdot \frac{me^2 L^4}{\hbar} F^2 \tag{1}$$

where C: constant, m: effective mass of carrier, e: electric charge, L: well width, and F: electric field [11].

As is known from Eq. (1), Stark shift is increased in proportion to effective mass of carrier. The mass of TE polarization is larger than that of TM polarization. The mass of HH is larger than that of LH, so the Stark shift value of TE polarization becomes larger than that of TM polarization.

If we consider the above-mentioned optical transition principle, Stark shift for TE polarization with the absorption edge at a longer wavelength side is large. On the other hand, Stark shift for TM polarization having the absorption edge at a shorter wavelength side is relatively small. So the Stark shift value of TE polarization becomes larger than that of TM polarization.

Recent studies have proposed the method to avoid the above-mentioned polarization dependence in which the tensile-strained quantum well and potential-tailored quantum well structures are used [10], [12]. The tensile-strained quantum well structure can realize the same absorption edge wavelength for TE and TM polarization [10], [11]. The structure using the potential-tailored quantum well can achieve the same Stark shift value for the TE and TM polarization. The MQW-EAM used in the experiments show some degree of polarization dependence since the above-mentioned structure is not applied.

From the above reasons, we can consider that the transmission characteristics of the MQW-EAM are complicated since those are considered to be changed by the combination of the above-mentioned effects. The effect in which the transmission loss increases as we increase the device input power in the bias conditions 0 V to −1.0 V and −3.0 V to −4.0 V is considered to be due to the combination of the above-mentioned effects. In the experiments, we have chosen to use the above effects in a relatively low input power regime for all-optical 2R regeneration.

By using the above effects, we can expect to realize the noise suppression in the mark state ("1" level) of the signal. We can expect that the saturable absorption effect can be realized by increasing the optical input power to the EAM. However, high input power is not preferable since it may damage the device. For this reason, we chose the relatively low input optical power regime.

2.2 Measurement of Bit-Error Rate Characteristics with All-Optical 2R Regeneration System

Figure 3 shows the experimental set up of the bit-error rate (BER) characteristics measurement with all-optical 2R regeneration system.

All-optical 2R regeneration system consists of an optical amplifier (AMP3), an optical band-pass filter (OBPF), a variable optical attenuator (ATT2), and an EAM as shown in the part surrounded by the broken line in Fig. 3. ATT2 is used for adjusting the optical input power into the EAM.

In the BER measurement, 40-Gbit/s data signal is demultiplexed into 10-Gbit/s signals by optical time domain demultiplexing with two-stage EAMs. Therefore, the BER is measured at 10-Gbit/s for the demultiplexed signal. Moreover, in the measurement in order to degrade the quality of a signal intentionally, the amplified spontaneous emission (ASE) noise is added to the 40-Gbit/s signal from AMP2. A polarization controller (PC) is inserted at the input of the all-optical 2R regeneration system to compensate for the polarization dependency of the EAM.

The transmission characteristics were measured for the two cases, i.e., without the EAM (without all-optical 2R regeneration) and with the EAM (with all-optical 2R regeneration). The EAM input optical power and EAM DC bias voltage were +11 dBm and −3.5 V, respectively.

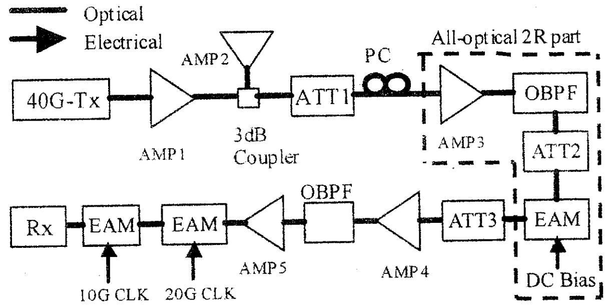


Fig. 3 BER measurement setup of all-optical 2R regeneration system.

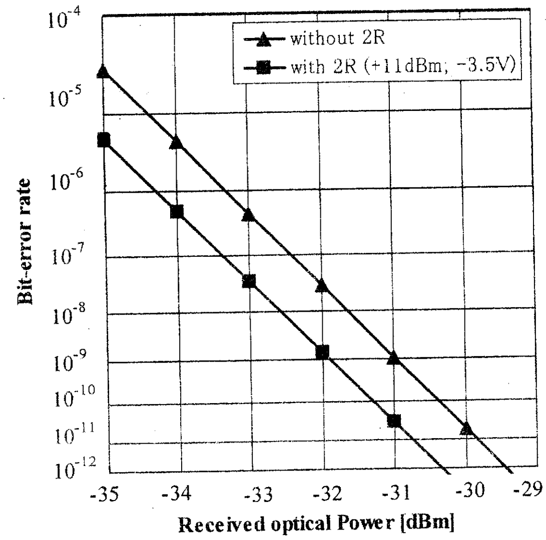


Fig. 4 Measurement result of BER characteristics.

Figure 4 shows the results of BER measurement for the both cases. From Fig. 4, we can see that by applying the all-optical 2R regeneration system, the receiver sensitivity can be improved by about 1 dB at a BER of 10^{-12}.

3. Field Trial of All-Optical 2R Regeneration in 40-Gbit/s WDM Transmission Systems

3.1 Outline of Field Trial

In this section, we report the results of the field trial for all-optical 2R regeneration system in 40-Gbit/s 12-channnels WDM transmission systems. In this field trial, we performed the two tests.

- Field trial with and without all-optical 2R regeneration systems in a 320-km-long transmission system.
- Field trial with and without all-optical 2R regeneration system for a system with the OADM.

In this field trial, we used all-optical 2R regeneration system in Sect. 2. Figure 5 shows the cable route of the field trial. All the network equipment is installed at National Institute of Informatics (NII) Building.

The signal from the NII Building is transmitted over a 4.5-km-long installed cable, and reaches the Tokyo station.

Then the signal passes through the Tokyo Station and is transmitted over an 11.7-km-long installed cable nearby the railroad to Shinjuku Station. Between Tokyo Station and Shinjuku Station, several fibers are interconnected to form an appropriate path length. Finally, the signal goes back to NII Building. The total span length described above is about 80-km. Four fiber spans with a length of 80-km were prepared as shown in Fig. 5. All fibers used in the field trial were single-mode fiber (SMF). Table 1 shows the characteristics of the fibers at each span.

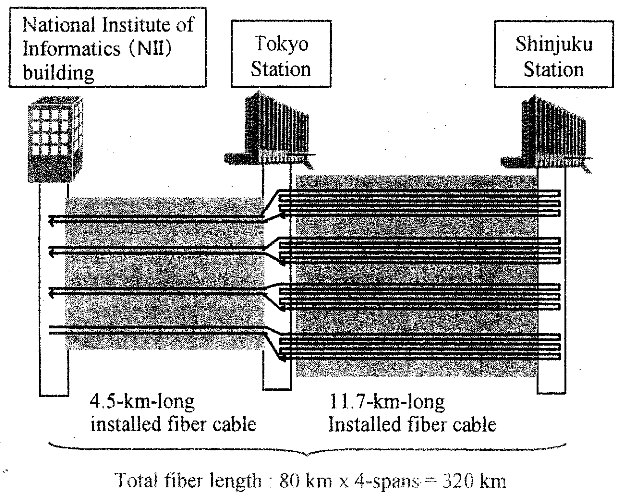


Fig. 5 Cable location.

Table 1 Installed fiber parameter characteristics at each span.

		Span1	Span2	Span3	Span4
Transmission loss	[dB]	26.6	24.5	25.0	27.9
Chromatic dipersion	[ps/nm/km]	16.869	16.887	16.609	16.642
Poralization mode dispersion	[ps/√km]	0.17	0.09	0.07	0.08

3.2 Experimental Setup

Figure 6 shows a field trial setup. Transmitters are 12 lasers whose wavelengths range from 1548 nm to 1559 nm with a channel spacing of 100 GHz in the ITU Grid.

The modulation data format is RZ with $2^{15}-1$ pseudo-random binary sequences at a data rate of 40-Gbit/s. The transmission line consists of four spans with a span length of 80-km. At a receiver, the BER measurement is performed. Between each span, an optical amplifier repeater is installed and in each repeater the chromatic dispersion (CD) and CD slope is almost compensated with a slope-compensating dispersion compensation fiber (SC-DCF).

The OADM system is located in the repeater between the second and third spans. The system has two arrayed waveguide gratings (AWGs) for wavelength-demultiplexing and multiplexing the signals. The all-optical 2R regeneration system is the same as that described in Sect. 2.

3.3 Experimental Results of All-Optical 2R Regeneration in 40-Gbit/s WDM Transmission Systems

In this section, we report the transmission characteristics of the 320-km-long straight-line systems without/with the all-optical 2R regeneration system.

In all the experiments, only the characteristics of the channel 2 at a wavelength of 1550.11 nm were measured due to the limited availability of the CD compensation system. The PC was adjusted to be the optimum polarization conditions. In order to compare the characteristics for various

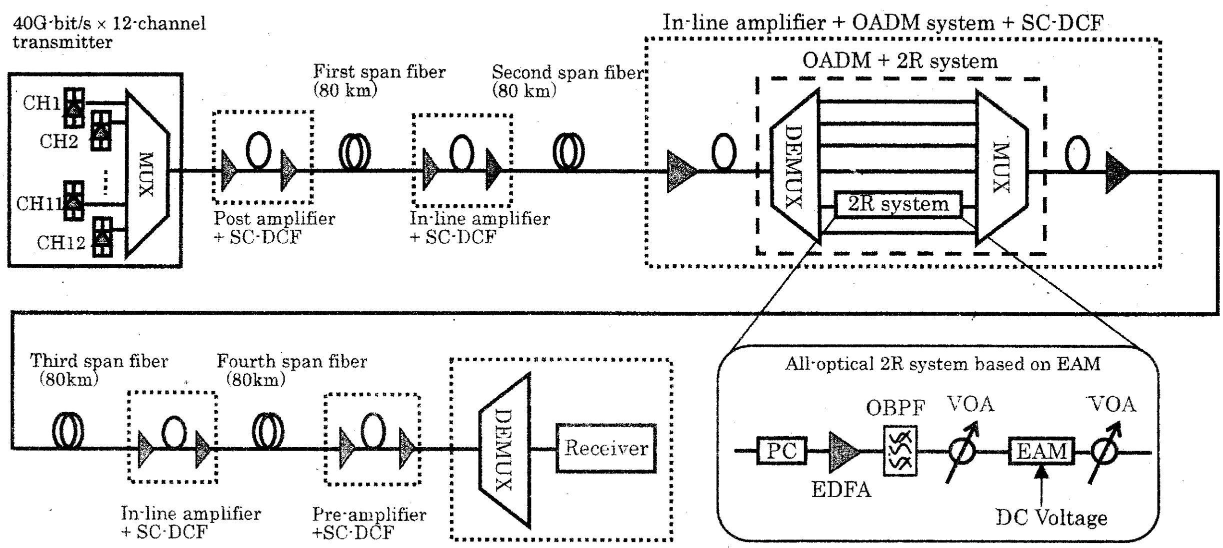


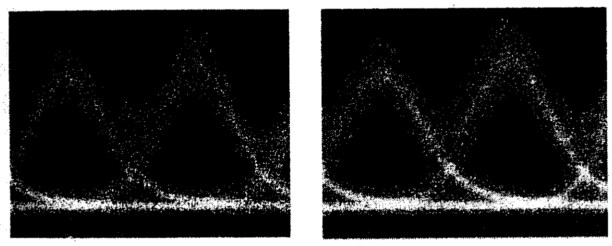
Fig. 6 Field trial setup.

conditions, we measured the BER characteristics for the following three conditions:

- Condition 1: without transmission line (back-to-back),
- Condition 2: 320-km transmission without all-optical 2R regeneration system (320-km w/o 2R)
- Condition 3: 320-km transmission with all-optical 2R regeneration system (320-km with 2R).

Figures 7(a) and (b) show the eye diagram for the Condition 2 and Condition 3, respectively. Moreover, Fig. 8 shows the results of BER characteristics measurement in three cases. In these measurements, the optical input power of EAM was +9 dBm and the DC bias voltage of EAM was −0.5 V.

The Q-factors for the system without and with the all-optical 2R regeneration system were 17.2 dB and 17.7 dB, respectively. We can see that a Q-factor was improved by about 0.5 dB by applying the all-optical 2R regeneration system. The BER characteristics measurement results show that by applying the all-optical 2R regeneration, the receiver sensitivity can be improved by about 1 dB at a BER of 10^{-9}. Several dBs receiver sensitivity improvement can be expected by the use of more sophisticated devices. From these results, we can confirm that all-optical 2R regeneration system in this study is effective also in the field environment.



(a) (b)

Fig. 7 Optical eye diagrams at a received optical power of −26 dBm, (a) 320-km w/o 2R, (b) 320-km with 2R.

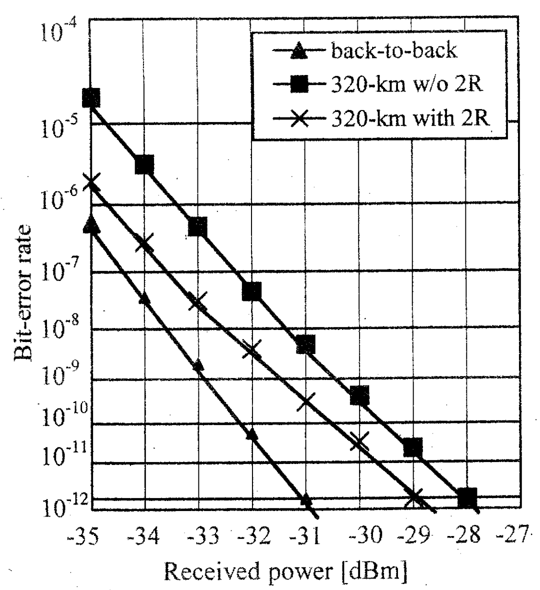


Fig. 8 BER characteristics vs. received optical power without/with all-optical 2R regeneration system.

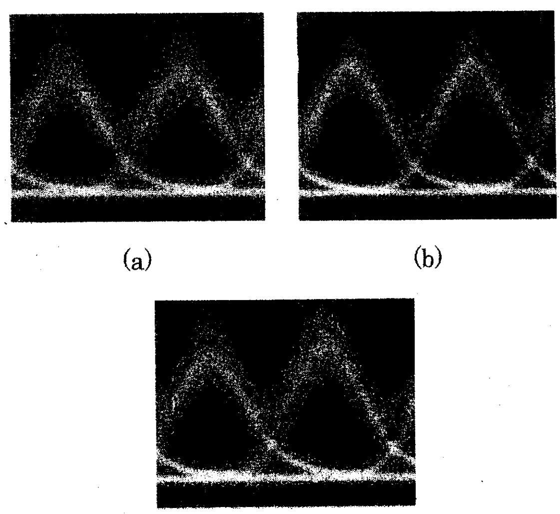
3.4 Experimental Results of All-Optical 2R Regeneration with OADM Systems

Then, we performed the experiments by applying the all-optical 2R regeneration system to the OADM systems. We measured the transmission characteristics for the following conditions:

- Condition 1: without transmission line (back-to-back),
- Condition 2: dropped at the OADM system after 160-km transmission (160-km dropped),
- Condition 3: without all-optical 2R regeneration in the OADM system over 320-km transmission (320-km without 2R),
- Condition 4: with all-optical 2R regeneration in the OADM system over 320-km transmission (320-km with 2R).

Figures 9(a), (b) and (c) show the eye diagrams for Condition 2, Condition 3, and Condition 4, respectively. A Q-factor for Condition 2, Condition 3, and Condition 4 were 18.8 dB, 16.9 dB, and 17.7 dB, respectively. Figure 10 shows the measured BER characteristics for the above four conditions.

As compared with Condition 2, Condition 3 was degraded by 1.9 dB in terms of a Q-factor and degraded by 2.5 dB in terms of receiver sensitivity at a BER of 10^{-9}. However, when we applied all-optical 2R regeneration system in the OADM (Condition 4), Q-factor and receiver sensitivity have been improved by 0.8 dB and 1.0 dB, respectively as compared with Condition 3. Moreover, we can see that the BER characteristic for Condition 4 was improved to



(a) (b) (c)

Fig. 9 Optical eye diagrams under following conditions at −26 dBm received optical power, (a) 160-km dropped, (b) 320-km without 2R applying OADM system, (c) 320-km with 2R applying OADM system.

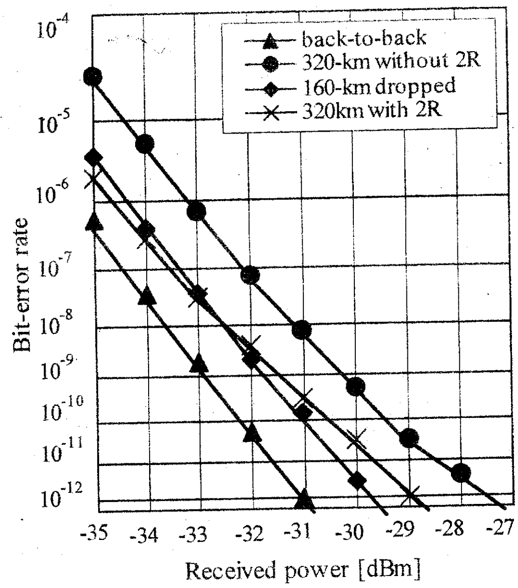


Fig. 10 BER vs. received optical power characteristics at 320 km transmission with OADM system.

be nearly the same as that of the condition 2 at a BER of 10^{-9}.

By these results, we can confirm that all-optical 2R regeneration system is effective to improve the quality of the signal with the OADM system.

Here, we briefly discuss the EAM drive conditions. In fundamental characteristics examination in Sect. 2, we set a DC bias voltage of the EAM at −3.5 V. However, in the filed trial, we have chosen a different DC bias voltage of −0.5 V. The reason for that is described in the following.

From the fundamental measurement, we have predicted that the transmission characteristics cannot be improved in the field trial if we set a DC bias voltage of the EAM at −3.5 V since the transmission loss of the EAM at that DC bias voltage is relatively large. Moreover, in the transmission experiments, we have predicted that signal-to-noise ratio (SNR) will be degraded by ASE noise of optical amplifiers.

Then, we changed the DC bias voltage to −0.5 V. From the results in Sect. 2, we could also expect to suppress the mark level noise efficiently with a relatively small loss level at this DC bias voltage as was discussed in Sect. 2. As a result, we could improve the transmission characteristics at an optical input power of +9 dBm to the EAM as shown in this section.

We can also say that more detailed examination is necessary for the optimum condition of the EAM used in the field trial since the device shows complicated phenomena as shown in Sect. 2.

4. Conclusion

In this paper, we have reported the fundamental characteristics examination results of the EAM as an all-optical 2R regeneration device. We have also reported the results of 40-Gbit/s, 12-channel WDM field trial over 320-km-long installed fibers with all-optical 2R regeneration technology in the OADM system.

Fundamental experiments have shown that the EAM-based simple all-optical regeneration system with a relatively low input power regime is effective for the suppression of the noise in the mark level.

In 40-Gbit/s, WDM transmission field trial, we confirmed that the all-optical 2R regeneration system using the EAM was also effective in the field environment.

We have made sure that the use of all-optical 2R regeneration in the WDM transmission systems makes it possible to enhance the 3R-regeneration distances. This point is quite important from the system design point of view since the cost of 3R-regeneration is dominant in total transmission systems cost.

Moreover, the field trial with the OADM system have shown that the transmission signal quality degraded by the OADM system can be improved to be nearly the same as the signal quality of the dropped signal at the OADM system by applying the all-optical 2R regeneration system with the EAM.

We have also pointed out some problems in the system with an all-optical 2R regeneration system with the EAM, i.e., the solution for the polarization dependency of the EAM, analysis of optimum EAM drive conditions, and theoretical analysis about transmission characteristics (absorption edge wavelength behavior with EAM bias conditions).

As a conclusion, we can say that the all-optical 2R regeneration system with the EAM is one of the promising technologies for the future protocol/bit-rate independent transport network.

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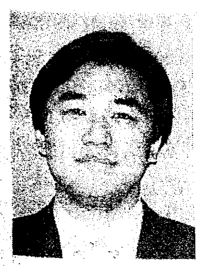

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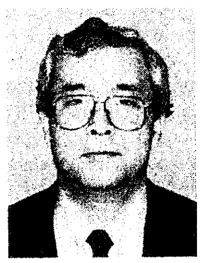

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