5 Optical Communication Technologies

5-1 Study on Laser Communications Demonstration Equipment at the International Space Station

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This paper summarizes CRL's efforts to perform a mission analysis and a feasibility study of the Laser Communications Demonstration Equipment (LCDE) that would have been attached to the International Space Station. The purpose of the LCDE was to demonstrate the capability of a high-speed two-way optical link with a bit-rate of 2.5 Gbps to communicate with a ground station. The development program, however, was terminated in February, 2003 due to development cost overrun and launch delays. The results reported in this paper will be used for a future multi-gigabit free-space laser communication system

Keywords
Laser communication, International Space Station, Photon counting tracking sensor, Er-doped fiber amplifier

1 Introduction

Multiple-gigabit communications, which have been widely introduced in terrestrial fiber-optic communication networks, will have an important role in future space communications to support man-tended space activities. A laser communications demonstration experiment had been proposed by Communications Research Laboratory (CRL) as an initial capability test at the exposed facility in the Japanese Experimental Module (JEM) that will be attached to the International Space Station (ISS) [1]. The mission equipment, named Laser Communications Demonstration Equipment (LCDE), was to be developed under the cooperation of CRL and the National Space Development Agency (NASDA).

Figure 1 is a perspective picture of a high-bit-rate space communication network based on future free-space laser communications. Figure 2 shows the evolution of the demonstration experiments in laser communications from 1994 to 2004. The LCDE was not only the first multi-gigabit communication experiment in Japan, but also a precursor experiment to show the possibility of an optical feeder link between a satellite and a ground station. Several problems have to be overcome to provide a practical link between a ground station and the ISS. The first issue is that the link duration for each ISS pass is very short; it is expected to be about one or two minutes. The second issue is that the link condition is strongly affected by weather conditions such as a rain, clouds, and fog. Even so, the wide-band and high-speed features of laser communications are still attractive as a substitute for the inter-satellite link from the ISS/JEM.

Unfortunately, the development program for the LCDE was terminated in the year 2002 due to a substantial overrun of the LCDE

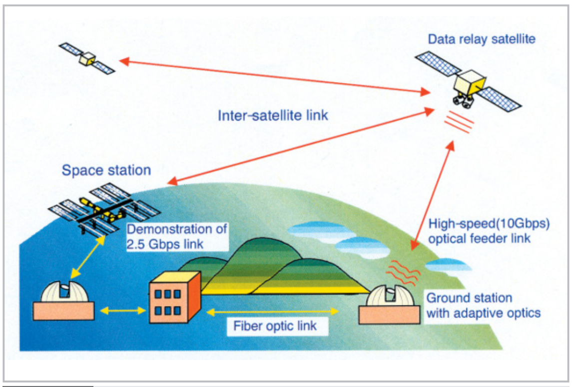


Fig.1 *Multi-gigabit space network based on free-space laser communication*

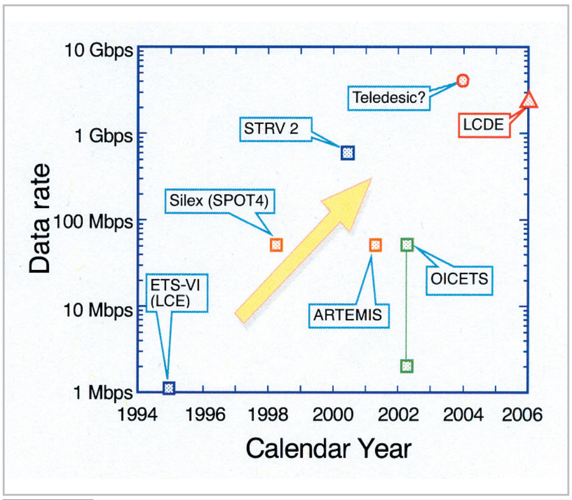


Fig.2 *Evolution of demonstration experiment*

development cost estimate and many launch delays of the JEM exposed facility. Before the project was cancelled, CRL had been involved in performing several evaluations of the key components and subsystems in the LCDE through bread-board model (BBM) trial fabrications. This paper reports the results of those evaluations, as well as an overview of the experimental plan and the primary specifications of the LCDE.

2 Experimental plan

Original work to be performed in this demonstration experiment are listed below [2].

2.1 Demonstration of laser communication

A small and light-weight laser communication equipment was to be developed using advanced optical component technologies at 1.5 μm wavelength based on the recent research and development in terrestrial fiber optic networks. The accuracy of the ATP system was, at first, to be verified by tracking bright fixed stars and then the two-way laser communication between the JEM and a ground would have been established. These experiments would demonstrate the feasibility of the high-bit-rate laser communication under the conditions of the vibration environment in JEM. For the reception of the downlink laser beam, atmospheric turbulence effect would be compensated with adaptive optics [4].

2.2 Evaluation of laser communication device in space

The device used in the LCDE, such as high-speed logic ICs, laser diodes, a lithium-niobate external modulator and fiber-amplifiers, were to be operated and tested under the conditions of the space environment around the JEM/ISS. After the experiment was completed, they were to be recovered to the ground in order to evaluate their degradation or aging.

2.3 Demonstration of high-date-rate application

A large amount of the data, such as high-definition videos generated and compressed at the space station, were to be down-linked with an error correction code to the ground stations by using the laser communication link. This experiment would have shown the capability of high-data-rate optical communications. A two minutes transmission at the rate of 2.5 Gbps amounts to 37.5 Giga-bytes corresponding to the total downlink throughput for one day from JEM.

2.4 Detection of space debris

A preliminary experiment to detect small sized (from 0.1 cm to 10 cm in diameter) debris around the space station was to be performed by using a small-sized but high-power pulsed laser transmitter and a sensitive receiver. If debris was illuminated by the sun and was within the field of view (FOV) of the acquisition sensor, +/- 0.3 degrees, it could have been tracked with the ATP system in the LCDE. A focused and pulsed laser beam would be pointed to the debris and return-reflected laser light could be received by the LCDE. The distance between the debris and the space station could have been measured using the turn around time. The relative velocity of the debris could also have been calculated by measuring its Doppler shift.

3 Configuration and external view

As shown in Fig. 3, the LCDE consists of (i) a telescope (optical antenna), (ii) an acquisition, tracking and pointing system, (iii) an optical transceiver, (iv) a laser debris detector and (v) a vibration isolator. The telescope is mounted on two axes gimbals. A Si-CCD photo detector is used for an acquisition and coarse tracking sensor. A quadrant photo diode array and two-axis fine steering mirror are used for the fine tracking system. The vibration isolator is used to realize an accurate and robust tracking performance under the vibration environment on JEM [3].

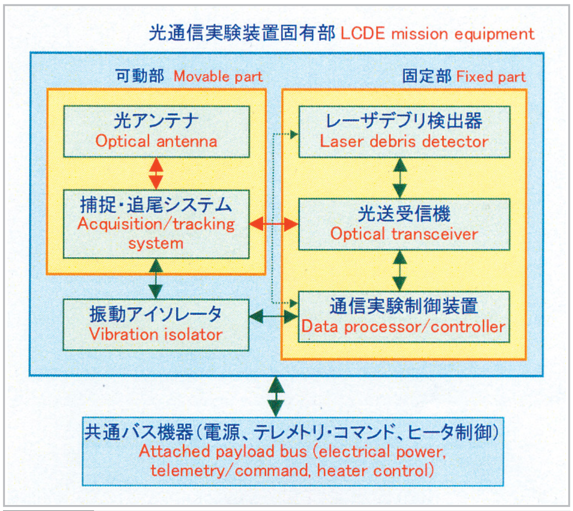


Fig.3 Configuration of LCDE

Table 1 summarizes the primary performance of the LCDE. Table 2 shows an example of the link budget calculation between LCDE and a ground station. In order to achieve 2.5-Gbps transmission rate, we assumed about 10-dB link improvement could be obtained by using low order adaptive optics compensation. We also assumed that the atmospheric absorption is less than 3.0 dB, because no strong atmospheric absorption bands are found in the 1.5-μm wavelength region. A large amount of link margins for both up and down link in the Table 2 should be considered as fading margins to withstand the atmospheric turbulence, because the calculation is based on the mean value for both the up and down link.

Table 1 Primary performance for laser communication equipment (LCDE)

Optical antenna		Cassegrain telescope and Coude optics
Antenna diameter		15 cm
Acquisition and tracking system	Coarse tracking	Two-axis gimbals with DC servo-motor, Si-CCD detector. FOV: 0.6 degrees
	Fine tracking	Quadrant photo-detector and two-axis fine tracking mirror. FOV: more than 0.02 degrees
Gimbals angle		Az: -30～210deg., El: -30～120deg.
Tracking error		Less than 1 μradian (rms, for communication) Less than 5 μradian (rms, for tracking/debris detection)
Filter bandwidth		Laser tracking: 0.801/0.68 μm, Satellite tracking: 0.65 μm
Required optical power		From -62 to -92 dBm (acquisition and tracking)
Communication rate		Transmission: 2.48832 Gbps, Reception: 1.24416 Gbps
Laser wavelength		Transmission: 1.552 μm, Reception: 1.562 μm
Transmitting power		400 mW (at 1.55 μm)
Detectable debris size		1cm at 2-km distance from the ISS
Power consumption		Less than 115 W
Total weight		Less than 90 kg

Table 2 Link budget between JEM and ground station

	Downlink (JEM → ground)	Uplink (ground → JEM)
Wavelength	1.552 μm	1.562 μm
Laser output power	0.4 W	1 W
Transmitting antenna(1)	15 cm	10 cm
Antenna gain	106.64 dB	103.06 dB
Distance	1,000 km	1,000 km
Free-space loss	-258.17 dB	-268.11 dB
Receiving antenna(1)	50 cm	15 cm
Antenna gain	117.09 dB	106.58 dB
Atmospheric loss, etc.	-10.1 dB(2)	-19.6 dB
Receiving power	-18.51 dBm	-38.07 dBm
Sensitivity	90 photons/bit	90 photons/bit
Bit rate	2.5 Gbps	1.2 Gbps
Required power	-45.41 dBm	-48.62 dBm
Margin	26.9 dB	10.6 dB

(1) Antenna efficiency is assumed to be 50%.

(2) Absorption loss: 3.0 dB, Strehl ratio due to the atmospheric turbulence: 0.27, coupling loss for wavefront sensing : 0.5 dB.

Figure 4 shows an external view of the onboard laser communication equipment including the telescope and the ATP sub-system with the vibration isolator. The earth stations would be accessed via a small window on the earth-faced panel. The link duration to CRL's earth station would be about one or two minutes. On the other hand, a link duration of more than 10minutes would be available from the terminal on JEM to a zenith direction target, such as a geostationary satellite.

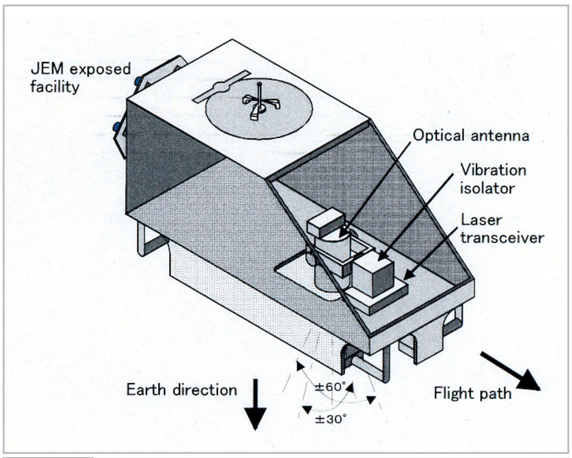


Fig.4 *External view of LCDE*

4 Design modifications

In the preliminary design study of the LCDE, several modification of the primary performance requirements had been made. Major issues in this study were as follows.

(1) Wavelength and bit-rate

Though the LCDE originally included a pulsed laser source and a heterodyne receiver independent of the optical transceiver for the 2.5Gbps communication, the space debris measurement was changed so that it would be performed by the communication transceiver. This change was made to reduce the total development cost.

(2) Coude optics

In order to reduce the weight of the movable parts such as a telescope and two-axis gimbals and to separate the mechanical parts and the inner optics, Coude optics were introduced.

(3) Thermal design

To dissipate the heat amounting to 280W from the LCDE in the communication experiment was initially considered to be difficult. This issue was resolved by reducing the power consumption and increasing the thermal radiation panel.

(4) Vibration isolator

To reduce the development cost, the vibration isolator was deleted from LCDE. The tracking system performance, such as band-width of the feedback servo control, was enhanced to compensate this modification.

(5) Link duration and data storage

The limited size of the window through which LCDE telescope looks at the ground station determines the communication link duration with the ground station as one minute. Hence, the corresponding amount of data storage is reduced to about 128 Mbytes.

5 Evaluation of the key technology

5.1 Photon counting tracking sensor

We need a high-speed and sensitive optical sensor to acquire and to track a faint beacon signal from the opposite terminal for distances greater than 1,000-km. In the LCDE, the beacon signal is assumed to be reflected solar illumination from the opposite terminal body. Hence, the tracking sensor is required to have near shot-noise-limited performance as well as a response band-width up to several kHz. While specially designed Si-APD's have been used for this purpose, a newly developed Hybrid Photo-Detector (HPD) [5] was chosen as a quadrant-tracking detector for LCDE.

Figure 5 explains the principle of single photon detection in the HPD. A photon incident onto the photo-cathode made of III-V semiconductor (GaAsP in this case) will be at first converted into a photoelectron with a 40% probability. The photoelectron then will be accelerated by an 8-kV electric field and injected into the quadrant Si-APD. This bombardment will cause about 1,200 times multiplication and further a 50-times multiplication will occur in the APD [5]. Ultimately, a single photon will be converted into about 60,000 electrons. This electric charge can be detected as an electric pulse by a trans-impedance amplifier. Quadrant outputs from the APD provide the information of the tracking-beam position; a single photon pulse will appear at one of the APD's quadrant outputs.

Figure 6 shows a quadrant HPD tracking sensor unit. The HPD, which has an effective

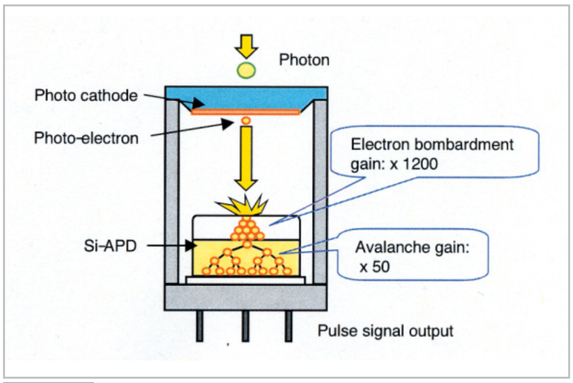


Fig.5 *Operational principle of HPD*

aperture 5 mm in diameter, is located on the left and is connected to the trans-impedance amplifiers. A DC-DC converter to generate an 8-kV bias voltage is located on the right. Figure 7 presents the spectral response of the GaAsP photo-cathode used in the HPD. The cut-off wavelength of the quantum efficiency is 700 nm and the maximum quantum efficiency, 40%, appears in the visible wavelength. Figure 8 shows three examples of the output signal from the trans-impedance amplifier, where each curve corresponds to trans-impedance of 82, 150, and 330 kilo-ohms. The 150-kilo-ohm trans-impedance exhibits the best waveform. The result of a pulse height analysis for this case is shown in Fig. 9. The bias voltage for the APD was 153.0 V and bombardment bias voltage was 8.0 kV. The figure’s vertical axis indicates the total pulse counts within a 10 second interval. The horizontal axis shows the pulse height in mV.

A single photon peak at the pulse height of 100-200 mV appears in the figure. The distribution with a pulse height less than 100 mV is

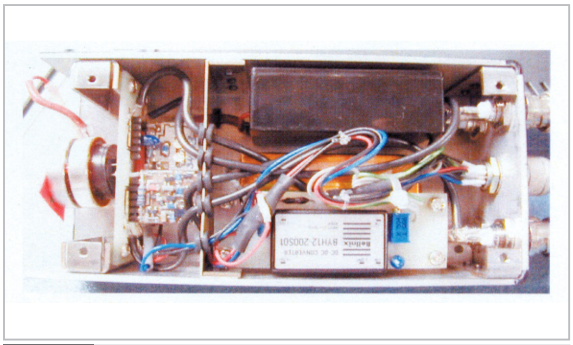


Fig.6 *Internal layout of HPD tracking sensor unit*

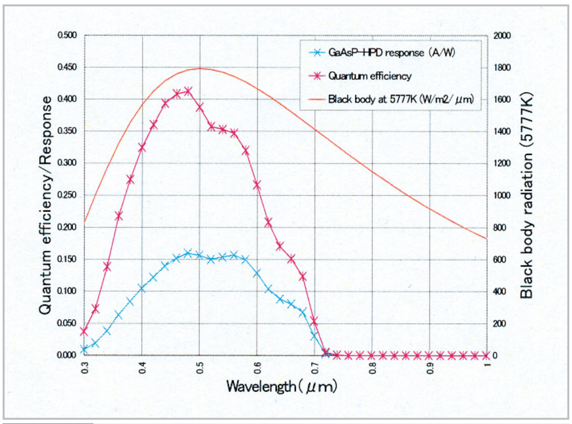


Fig.7 *Spectral response of GaAsP photo-cathode*

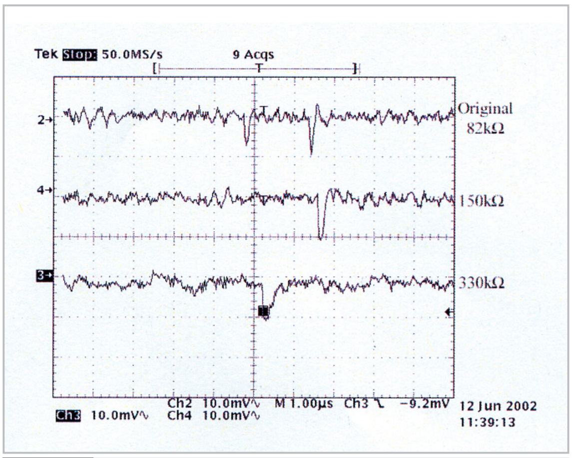
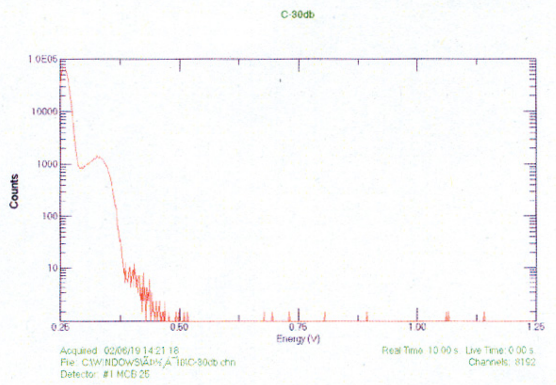


Fig.8 *Output signals from trans-impedance amplifier*

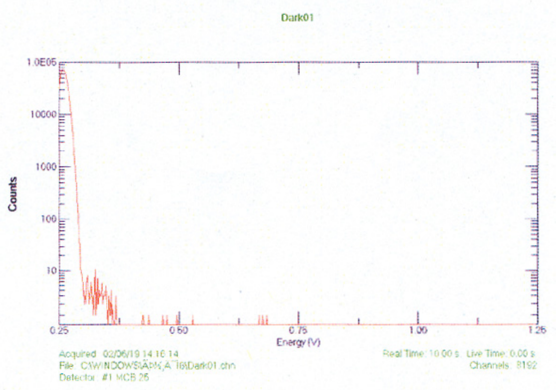
due to thermal noise. A few giant pulses also appear with pulse heights more than 1 V. The result of a counting statistics measurement of a single HPD using a 650-nm pulsed LED source is shown in Fig. 10. More than a three decade dynamic range in counting performance and about 20% overall quantum efficiency were obtained.

5.2 Optical transceiver using Er-doped fiber amplifier

To obtain a high performance optical transceiver in a short period, an Er-doped fiber amplifier (EDFA), one of the advanced technologies in terrestrial fiber optic communications, was used in the transmitter and the receiver [6]. The basic block diagram of the transmitter/receiver is shown in Fig. 11. A high-power EDFA, with the gain of about 30



(1) Height distribution with optical attenuation : −30dB



(2) Height distribution with optical attenuation : −50dB

Fig.9 *Pulse height distribution from HPD*

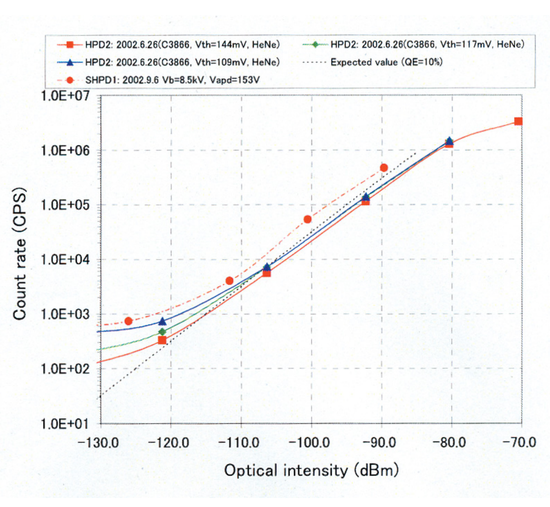


Fig.10 *Counting statistics for quadrant-HPD and single HPD*

dBs, was used in the transmitter to amplify weak optical signal from the Lithium-Niobate (LN) external modulator, while a low noise EDFA with the gain of more than 50 dBs based on a two stage amplifier was also used. The pumping wavelength for the low noise EDFA should be at 0.98 μm to provide good noise figure (NF). The NF of all EDFAs are generally more than 3.0 dB due to the amplified stimulated emission (ASE), and all the component and device loss at the front end of the EDFA will degrade the NF performance. The best achieved NF value obtained in this evaluation was 3.8 dBs.

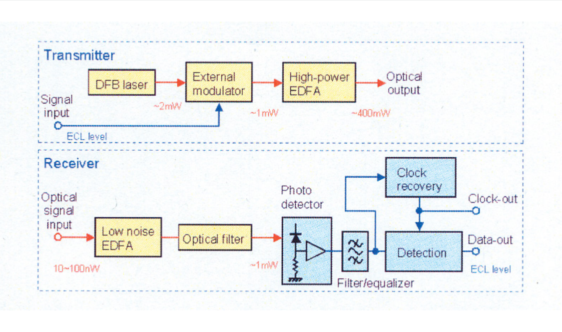


Fig.11 *Block diagram of optical transceiver using EDFAs*

Figure 12 shows an example of the optical signal waveform in the transmitter and the receiver, where short-pulse RZ signaling was used to achieve good sensitivity at the receiver [7]. A narrow band optical filter was placed immediately after the low noise EDFA to remove the ASE spectrum and background spectrum. A Fabry-Perot type optical filter with a passband wavelength less than 0.1 nm was used, which is close to a matched filter for 2.5 Gbps optimum signal detection. To provide stable receiver operation with good sensitivity, adaptive filter tuning is very important. The noise variance for a mark and space optical signal is different at the discriminator in the receiver in the case of shot-noise-limited operation. The noise variance for a mark signal depends also on the optical signal intensity. Hence, an adaptive threshold control should be required. The results of the bit error performance measurement and improvement based on the considerations described above are shown in Fig. 13. The theoretical limit of the receiver sensitivity, assuming the NF of 3.0 dBs, would be 36 photons/bit at the bit error rate (BER) of 10^{-9}. The actual performance achieved at CRL was 54 photons/bit at the BER of 10^{-9}. The penalty on the actual sensitivity making it less than the theoretical value is due to the larger bandwidth of the optical filter and the less than ideal NF performance of the actual low noise EDFA.

Since the overall power efficiency (wall-plug efficiency) of the high-power EDFA is also important for space applications, a design without thermal electric (TE) cooling was used in the pumping unit, by using a wavelength stabilization method for the 1.48-μm pumping laser diodes with the fiber brag reflector. The internal layout of the high-power EDFA is shown in Fig. 14. Two eight-way WDM combined high-power pumping units (HPU) were used for bi-directional pumping. Figure 15 shows the result of evaluating EDFA power efficiency. Wall-plug efficiency of 8% was achieved at the output power of 400 mW, while the saturated output power is more than 800 mW. Power efficiency is strongly depends on the output power and the temperature.

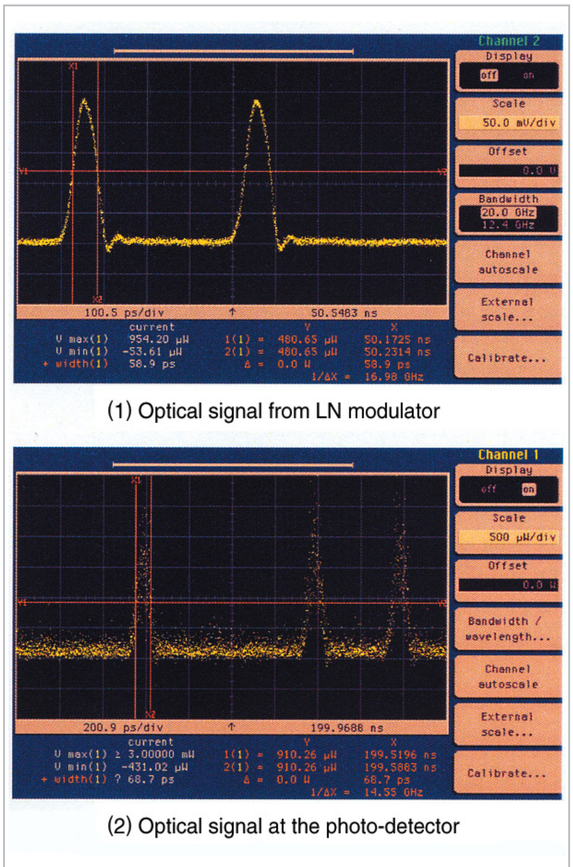


Fig. 12 Optical wave form in transceiver

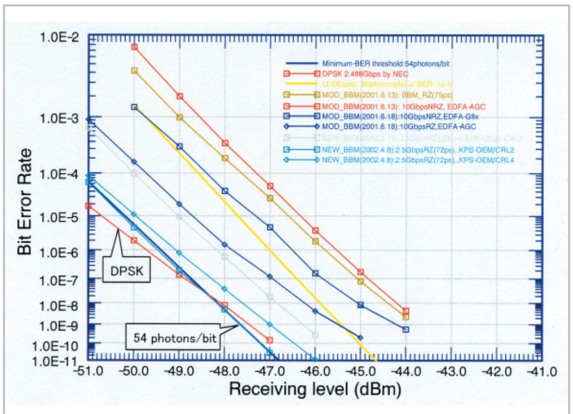


Fig. 13 Sensitivity measurement of LCDE-BBM transceiver

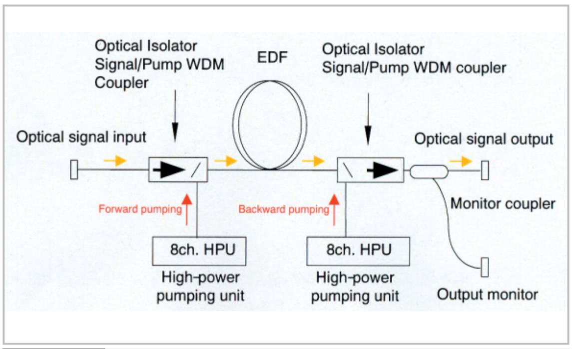


Fig. 14 Internal configuration of high-power EDFA

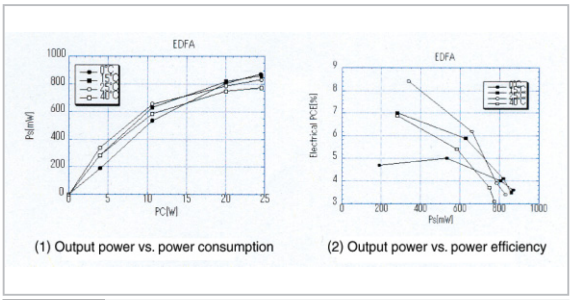


Fig. 15 Power efficiency evaluation of high power EDFA

6 Conclusion

The result of feasibility study performed to evaluate the key technology for the Laser Communications Demonstration Equipment was described, including the trial fabrication and the performance evaluation of the photon counting tracking sensor and optical receiver using EDFAs. Though the development program was terminated in 2002, the results reported in this paper will be used for the future multi-gigabit free-space laser communication system.

This project started from a proposal by CRL in 1997, and the development program was promoted by the close relationship between CRL and NASDA. The author wishes to thank all the members of CRL and NASDA, who have been participated in the LCDE program, and to thank the technical staff at manufacturers who have contributed greatly to the trial fabrication and the evaluation experiment.

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