Characteristics of Gbit/s Optical Receiver Sensitivity and Long-Span Single-Mode Fiber Transmission at 1.3 μm

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Abstract—Sensitivity of a 1.3 μm Ge APD receiver was measured at data rates ranging from 100 Mbits/s to 2 Gbits/s, using a high-speed GaAs FET RZ driver, low-noise Si bipolar transistor (BIT) receiver amplifier, and a highly sensitive TD comparator. The required received optical level at a 10^{-9} error rate was −31.9 dBm for 2 Gbits/s with a Ge APD/Si BIT front end having a 50 Ω input impedance. A Ge APD/GaAs FET front end, with a 500 Ω input impedance, brought about 2 dB improvement at 100 Mbits/s, as compared with a Ge APD/Si BIT (50 Ω) front end.

A coupling loss of 4 dB, achieved by a hemispherical microlens tipped on a single-mode fiber, and a low fiber loss of 0.57 dB/km, including splice loss, enabled 44.3 km single-mode fiber transmission at 2 Gbits/s. The 1.3 μm transmission system has a data rate repeater-spacing product of 88.6 (Gbit/s)km. Prospects of Gbit/s receiver sensitivity and the 2 Gbit/s transmission system, with more than 50 km repeater spacing, are also discussed.

I. Introduction

The low-loss [1] and low-dispersion [2] characteristics of single-mode fibers in the long wavelength region have markedly increased repeater spacing in large-capacity digital transmission systems [3], [4]. Although silica single-mode fibers have a minimum loss in the 1.55 μm wavelength band [5], the conventionally designed single-mode fibers have about 20 ps/(km · nm) dispersion in this wavelength band [6]. The multilongitudinal mode oscillation of directly modulated semiconductor lasers brings about a transmitting performance degradation caused by the fiber dispersion after long-distance transmission [7]. Suppression of this degradation is necessary in realizing high-speed transmission systems having long repeater spacings in the 1.55 μm wavelength band. An effective method to suppress the fiber dispersion is to tailor the zero-dispersion wavelength to coincide with the loss minimum wavelength [8]. The best achieved loss in 1.56 μm dispersion free fibers seems to be 0.48 dB/km [9]. Another effective alternative is the light injection technique to enhance a single-longitudinal mode operation in directly modulated semiconductor lasers [10].

In the 1.3 μm wavelength band, single-mode fiber loss of 0.5 dB/km was reported [11], although the loss is larger than that of 0.2 dB/km at 1.55 μm [1]. Furthermore, the sum of material and waveguide dispersions in single-mode fibers is less than a few ps/(km · nm), so that the bandwidth of a single-mode fiber transmission line is larger than 200 GHz · km · nm [4]. No sophisticated technique, except for matching between fiber zero-dispersion wavelength and laser output spectrum peak wavelength, is necessary for realizing optical transmission systems having both large capacity and long repeater spacing at this wavelength.

This paper reports 1.3 μm optical receiver performance for a data rate ranging from 100 Mbits/s to 2 Gbits/s, improved by a GaAs FET RZ pulse driver and a sensitive decision circuit consisting of a tunnel diode pair comparator. The Ge avalanche photodiode (APD) receiver sensitivity dependence on the data rate was measured and compared with the calculated values derived from Personick's theory [12]. Optical sensitivity at 100 Mbits/s and 400 Mbits/s is improved by a Ge APD and a high-impedance FET front end. 2 Gbit/s optical transmission experiments with 44.3 km single-mode fibers are also reported. Future prospects of Gbit/s receiver sensitivity and 2 Gbit/s single-mode fiber transmission systems in the long wavelength region will be discussed.

II. Theoretical Calculation of Optical Receiver Sensitivity

Design of an optical receiver, which consists of a photodetector and an associated amplifier along with an equalizer, were studied by Personick [12] for digital optical fiber communication systems. Optimization of the receiver was discussed in detail by Smith and Personick, taking into account the noise generated by FET and bipolar front end transistors [13]. In this section, 1.3 μm optical receiver sensitivity dependence on data rate from 10 Mbits/s to 10 Gbits/s will be calculated based on these theoretical studies in order to classify the Ge APD optical receiver sensitivity and to elucidate the experimental results in this study.

A Ge APD is selected as an optical detector in order to distinguish between FET and BIT (bipolar transistor) front end noises, avoiding the ambiguity caused by different photodetector sensitivities, such as quantum efficiency η, excess noise factor x, and depletion capacitance C_d. Ge APD's seem to have higher performance in the long wavelength region than other presently available photodetectors, at a high data rate [14]. Ge APD's parameters used in calculations are $\eta = 0.6$, $x = 0.95$, and $C_d = 1$ pF, assuming a p^{+}-n Ge APD used in this study [15]. The dark current effect on optical power penalty is negligibly small, as the optimum avalanche gain becomes low at a high data rate [16]. The dark current noise, accom-

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panying incident optical power, is not proportional to the detector multiplication factor. This noise is observed to be smaller than that calculated from Personick's theory [17]. For these reasons, detector dark current is neglected in this theoretical study. Optical signal extinction ratio degradation is also neglected, since spontaneous emission light is hardly coupled to a single-mode fiber and laser dc bias is selected well below its threshold.

BIT front end parameters, used in the calculation, are as follows: $C_a = 1$ pF, $\beta = 100$, $I_b = 1$ mA, and $r_{bb} = 20\ \Omega$, where C_a includes base-emitter and base-collector capacitances, β is the small signal current gain, I_b is the base current, and r_{bb} is the base resistance. These values correspond to the NEC 2SC2338 transistor parameters.

A high impedance front end and an avalanche photodetector, instead of a PIN photodetector and FET preamplifier, are useful in a low data rate range, since the high impedance front end improves a receiver sensitivity by reducing thermal noise and optimum avalanche gain. An FET front end circuit assumes the following parameters: $C_a = 1$ pF, $g_m = 27$ mS, $\Gamma = 1.1$, and $I_g = 0$, where C_a is the sum of the gate-source and gate-drain capacitances, g_m is the transconductance, Γ is a noise suppression factor depending on bias condition, and I_g is the gate leakage current. These correspond to the NEC 2SK138 GaAs FET values. Optical receiving power level difference between NRZ (nonreturn-to-zero) and RZ (return-to-zero) pulses is below 2 dB at a 10^{-9} error rate and is almost independent of both data rate and front end noise type.

Fig. 1 shows optical receiver sensitivity dependence on data rate, ranging from 10 Mbits/s to 10 Gbits/s. The Ge APD avalanche gain is optimized. When a nonmultiplication detector (PD) is used, the avalanche gain is unity. Input impedances for BIT front ends are assumed to be 50 Ω or R_{CL}. When C_T is the sum of C_a, C_d, and the stray capacitance and f_{CL} is the clock frequency, R_{CL} is given by

$$R_{CL} = 1/(2\pi C_T f_{CL}).$$

R_M is an FET front end impedance when thermal noise power due to the input load becomes equal to the noise associated with the channel conductance of FET devices [13]. When C_T is equal to 3 pF, R_M/R_{CL} is given by about $10^{10}/f_{CL}$.

This figure shows that optical receivers, having a photodiode with an avalanche gain (APD), have 10 dB higher sensitivity than those with no avalanche gain (PD), except for an FET front end having an R_M input impedance. When input front end impedance in the APD receivers is selected as R_{CL}, an FET front end is superior to a BIT front end below 100 Mbits/s. Although the APD/FET front end having an R_M input impedance has the highest performance, it is difficult to realize an ideal equalization in this front end at a Gbit/s data rate. PD/FET front ends with high input impedance R_M has higher sensitivity than APD/BIT front ends at lower data rate. This advantage has been confirmed experimentally [18].

Total capacitance C_T is reduced by using the hybrid integrated circuit in the receiver front end. The capacitance reduction effect on optical receiver sensitivity is shown in Fig. 2. In the APD/BIT front end with an R_{CL} input impedance, the effect of capacitance reduced from 3 pF to 1 pF is small

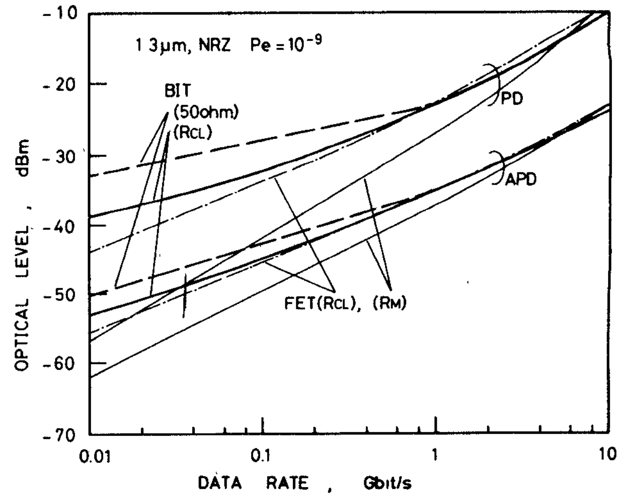

Fig. 1. Optical receiver sensitivity dependence on data rate. $R_{CL} = 1/(2\pi C_T \cdot f_{CL})$. R_M is an FET input impedance whose thermal noise is equal to the noise associated with the channel conductance. Total input capacitance C_T is 3 pF.

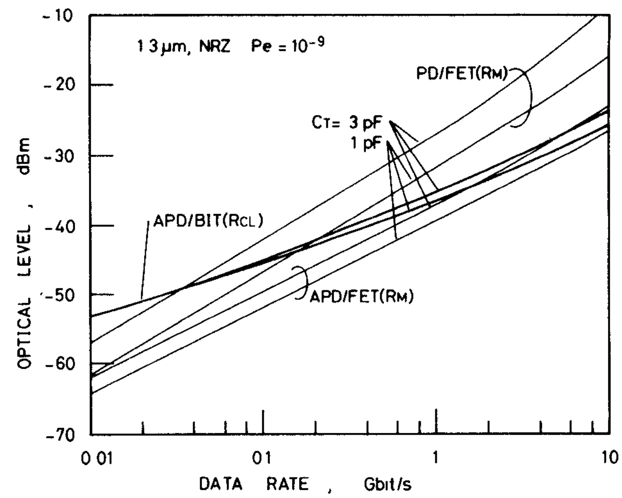

Fig. 2. Capacitance reduction effect on optical receiver sensitivity.

and the sensitivity improvement of about 1 dB is expected only beyond 1 Gbit/s. The integrated circuit design in the PD/FET front end, however, will result in an about 5 dB optical sensitivity improvement in a wide data rate range, studied here. These figures show that APD/BIT front end, without hybrid integrated circuit design nor complicated ideal equalization, is expected to have higher sensitivity at 1.3 μm than a PD/FET front end with an R_M input impedance, beyond 200 Mbits/s. Front end capacitance reduction by a hybrid integrated circuit design and ideal equalization for a high impedance front end at Gbit/s will give the highest sensitivity to an APD/FET front end with an R_M input impedance.

III. Optical Receiver Sensitivity Experiment at 1.3 μm

An optical transmission system, improved mainly by a GaAs FET laser driver with a high-speed RZ pulse output and a tunnel diode (TD) comparator with high sensitivity, was prepared in order to measure the error rate characteristics up to 2 Gbits/s. Ge APD/Si BIT receiver sensitivities for both RZ and NRZ pulses were experimentally studied at 1.3 μm, ranging from 400 Mbits/s to 2 Gbits/s. Receiver performances in Ge

APD/FET front ends with R_{CL} input impedance were also measured at 100 and 400 Mbits/s. These experimental results are compared with the theoretical values mentioned in Section II.

A. Gbit/s Optical Transmission System Configuration

The experimental setup to measure the error rate characteristics is shown in Fig. 3. A transmitter consists of an external clock oscillator, a pulse pattern generator, a laser drive amplifier, and an InGaAsP semiconductor laser. The PCM signal source is a high-speed pulse generator clocked by a stable oscillator. The pulse generator produces 2^{15}-1 pseudorandom pulses with 50 percent mark density or 24 bit programmable pulse patterns in an NRZ waveform. Although a laser drive amplifier using Si BIT's in the previous experiment had a 1.6 Gbits/s maximum modulation speed for NRZ pulses [16], the improved laser driver, including an NRZ-RZ code convertor, uses GaAs FET's (NEC 2SK281) and can deliver 85 $mA_{0\text{-peak}}$ signal current to a 50 Ω load at up to 2 Gbits/s. The RZ modulating signal has a 50 percent duty factor.

The optical source is an InGaAsP buried-heterostructure semiconductor laser emitting at 1.303 μm [19]. Threshold current I_{th} is 40 mA at 16°C. Impedance matching between the laser and the driver is achieved with a 47 Ω resistor connected in series with the laser. The laser is directly modulated by a pulse signal current I_p superimposed upon dc prebias current I_{dc}. Optimum I_p and I_{dc} values are selected at each data rate by minimizing the error rate under a constant receiving optical power condition.

The laser output is coupled into single-mode fibers. The optical signals, transmitted through 1 m long fiber or long-span fibers, are led into a receiver. A variable optical attenuator and focusing objective lens system are mounted in front of a Ge APD. The attenuator adjusts receiving optical power levels to measure error rate characteristics for the systems. The receiver consists of a Ge APD, a receiving amplifier, low-pass Thomson filters, a decision circuit, and an error detector. The optical detector is a p^+-n Ge APD, whose quantum efficiency η and excess noise factor x are 60 percent and 0.95 at 1.3 μm, respectively [15]. The preamplifier, connected to the Ge APD, consists of wide-band Si BIT amplifiers with a 50 Ω front end impedance and 5.3 dB noise figure.

A decision circuit includes a comparator and a regenerator. The comparator uses a pair of tunnel diodes (GE TD251A), whose valley current discrimination [20] is utilized. TD comparator circuit design is shown in Fig. 4. Operating biases for two tunnel diodes are supplied through terminals V_{T1} and V_{T2} by two constant voltage regulated sources. Tunnel diodes operating current is selected at about 5 mA. Fig. 5 shows NRZ input and output eye pattern waveforms for the TD comparator at 2 Gbits/s. It is necessary for keeping a high performance in the TD comparator to optimize the power level of the input clock signal. This figure shows that the comparator improves the eye opening for the 2 Gbit/s signal output at each sampling time. The TD comparator enabled measuring the optical receiver sensitivity up to 2 Gbits/s and brings about 5 dB improvement in the optical receiver sensitivity at 1.6 Gbits/s, as compared with the previously reported experimental results [14].

The timing is supplied directly from the transmitter to the decision circuit, the regenerator, and the error detector in order to measure the optical receiver sensitivity dependence on the data rate.

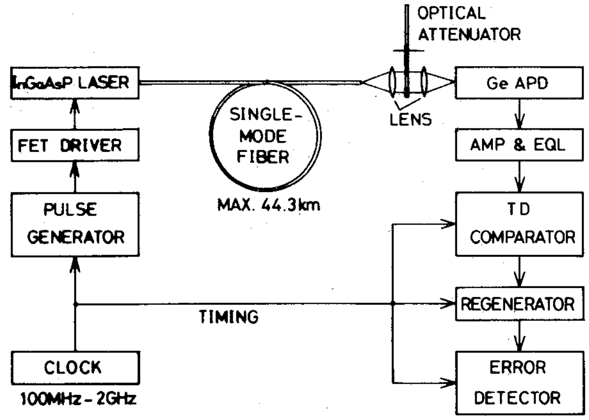

Fig. 3. Gbit/s optical transmission system configuration.

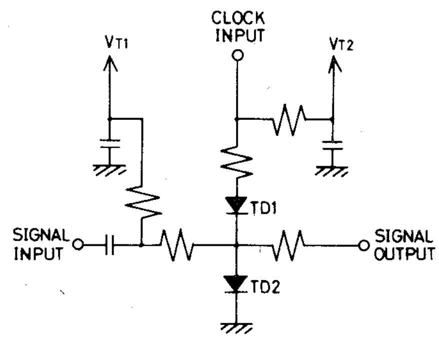

Fig. 4. Tunnel diode comparator circuit.

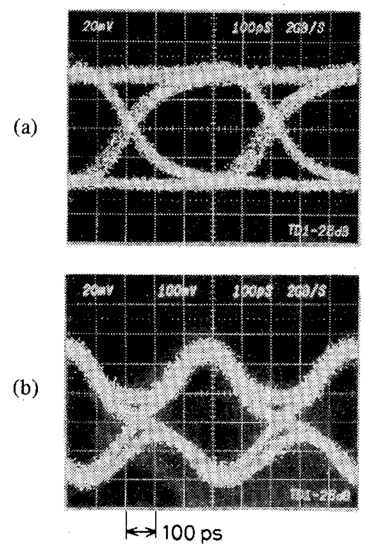

Fig. 5. Input and output eye patterns for TD comparator at 2 Gbits/s. (a) NRZ input waveform. (b) Output waveform.

B. 2 Gbit/s Error Rate Characteristics

The performance of both laser transmitter and the Ge APD optical receiver with a 50 Ω front end impedance was measured with a 1 m long single-mode fiber stripped of cladding modes. Fig. 6 shows 2 Gbit/s error rate dependence on average received optical power levels for both RZ and NRZ pulses. Solid lines are theoretical values. For RZ pulses, measured results are about 1 dB worse than calculated values and optical power level to give a 10^{-9} error rate is −31.9 dBm. For NRZ the required received optical level for a 10^{-9} error rate is, how-

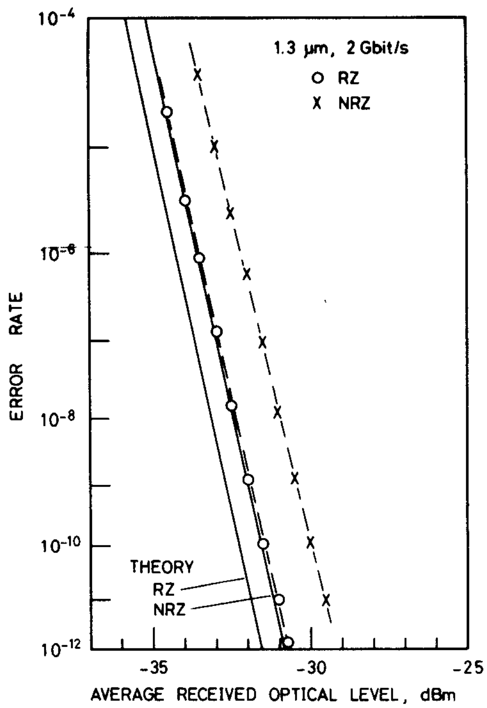

Fig. 6. 2 Gbit/s error rate characteristics at 1.3 μm. Solid lines are theoretical curves.

ever, −30.5 dBm, and 2.5 dB optical level degradation exists from the theoretical value. Laser drive waveforms and received eye patterns for RZ and NRZ pulses are shown in Fig. 7, when the InGaAsP semiconductor laser is directly modulated under the optimum prebias conditions. When the RZ pulse is selected, the laser is modulated by $I_p = 56$ $mA_{0\text{-peak}}$ superimposed on prebias $I_{dc} = 34$ mA. Drive conditions for NRZ pulses are $I_p = 50$ $mA_{0\text{-peak}}$ and $I_{dc} = 26$ mA.

The detected photocurrent waveforms, similar to the laser drive signals, confirm that both the semiconductor laser and Ge APD frequency bandwidths are quite broad at 1.3 μm. Optical signal amplitude for an isolated pulse with an NRZ waveform is larger than that at continuous marks, as shown in Fig. 7. The eye pattern degradation in NRZ photocurrent signals gives rise to about an 1.5 dB optical power penalty. About 1 dB optical level, degraded from theoretical curves, is caused by Ge APD dark current, optical signal extinction ratio degradation, nonideal equalization, and electrical circuit impairment.

C. Optical Sensitivity Improvement Using a High Impedance FET Front End

When a higher than 50 Ω front end impedance is selected, receiver sensitivity is improved by thermal noise reduction, as shown in Fig. 1. The transimpedance amplifier is the commonly employed front end design in optical receivers [21], [22].

The front end circuit design used in this experiment, having a Ge APD and GaAs FET, is shown in Fig. 8. Resistor R_B is used to bias the gate of the transistor and to provide a dc return path for the detector current. The transimpedance is comprised of feedback resistor R_F and capacitor C_F. When optimum R_F and C_F are selected at 100 Mbits/s, 500 Ω effective input impedance, derived from the amplifier output signal amplitude, is realized.

The effective impedance value is nearly equal to resistor R_{CL}, calculated by taking into account 3 pF total input capacitance C_T and 100 MHz clock frequency f_{CL}. RZ eye pattern waveforms detected by the Ge APD/GaAs FET front end with 500 Ω, before and after low-pass filtering, are shown in Fig. 9. This figure shows eye pattern signals detected by the Ge APD/Si BIT front end with 50 Ω in order to compare with the high impedance FET front end outputs. The moderately high impedance used in the present circuit gives rise to an advantage wherein no critical equalization is required. The equalizer has the same Thomson characteristics as described in the previous section.

Fig. 10 shows 100 Mbit/s RZ error rate characteristic improved by the high impedance front end. Error rate data, measured by the 50 Ω Si BIT front end, are also plotted. Required optical received levels for a 10^{-9} error rate are −45.1 dBm with the 500 Ω GaAs FET front end and −43.1 dBm with the 50 Ω Si BIT front end. 2 dB optical sensitivity improvement is achieved by the high impedance receiver design. Larger degradation from theoretical values at higher error rates is due to the large dark current in the APD. Dark current degradation becomes larger at lower data rate [16]. A high impedance GaAs FET front end for 400 Mbit/s data rate has a 120 Ω effective input impedance and improves optical sensitivity by about 1 dB.

D. Ge APD Receiver Sensitivity Dependence on Data Rate

Fig. 11 shows optical receiver sensitivity dependence on a data rate ranging from 100 Mbits/s to 2 Gbits/s measured by the Ge APD optical receiver. The recent experimental results obtained with a GaInAs PD/GaAs FET hybrid optical receiver [18] are plotted to compare with the present results measured in the optical receiver based on Ge APD. Solid lines are theoretical values. Receiver parameters, $C_T = 0.7$ pF, $g_m = 20$ mS, and $\eta = 50$ percent are used in calculating theoretical values for a PD/FET front end with R_M input impedance.

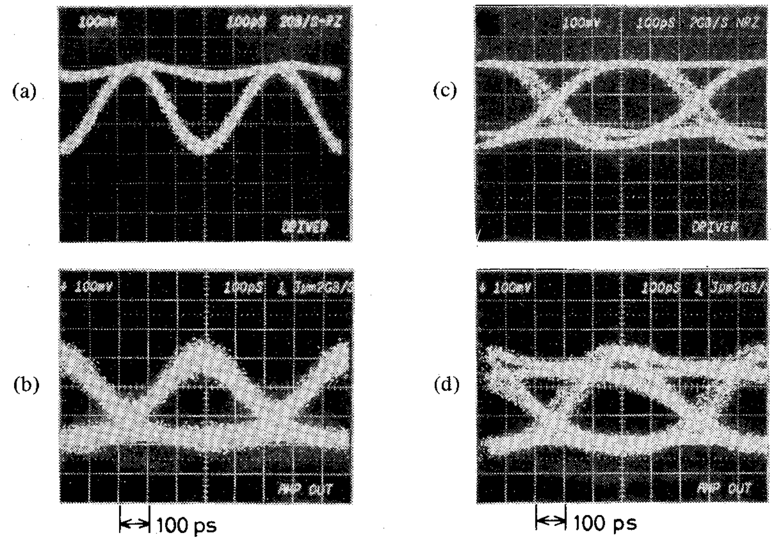

Fig. 7. 2 Gbit/s eye pattern waveforms. (a) RZ laser drive current. (b) RZ photocurrent. (c) NRZ laser drive current. (d) NRZ photocurrent.

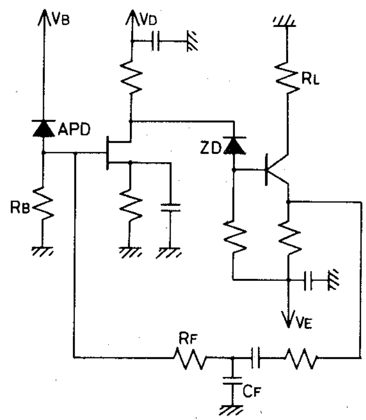

Fig. 8. Ge APD/GaAs FET front end circuit with transimpedance, R_F, and C_F.

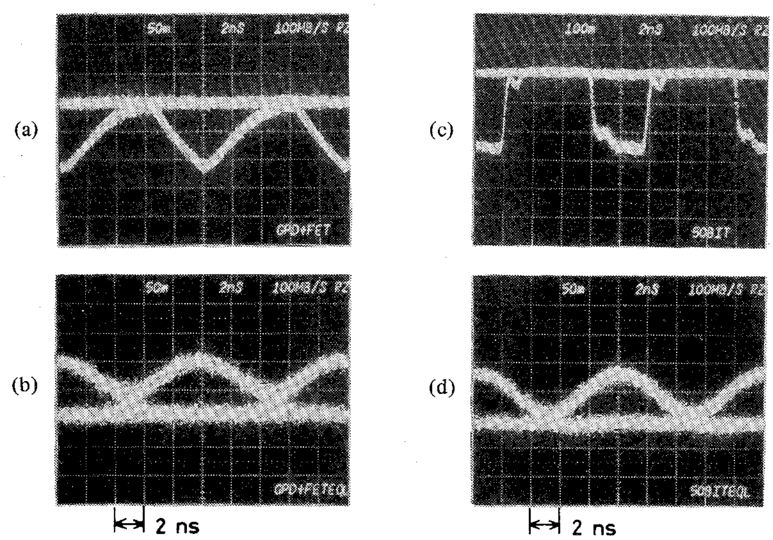

Fig. 9. 100 Mbit/s eye patterns with an RZ waveform. (a) Detected signal for Ge APD/GaAs FET front end with a 500 Ω input impedance. (b) Equalized signal for (a). (c) Detected signal for Ge APD/Si BIT front end with a 50 Ω input impedance. (d) Equalized signal for (c).

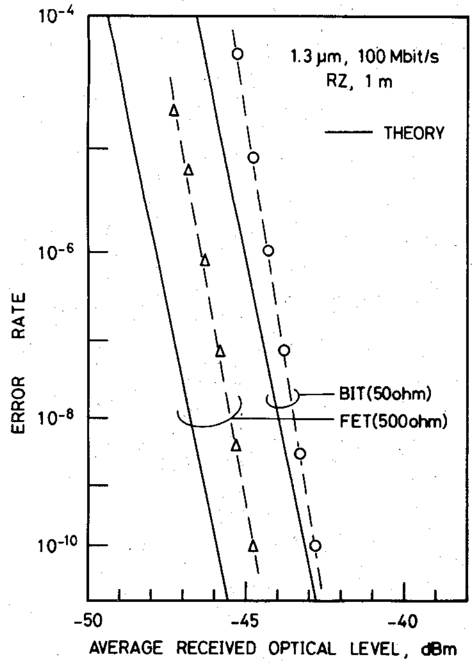

Fig. 10. 100 Mbit/s error rate characteristics. Solid lines are theoretical.

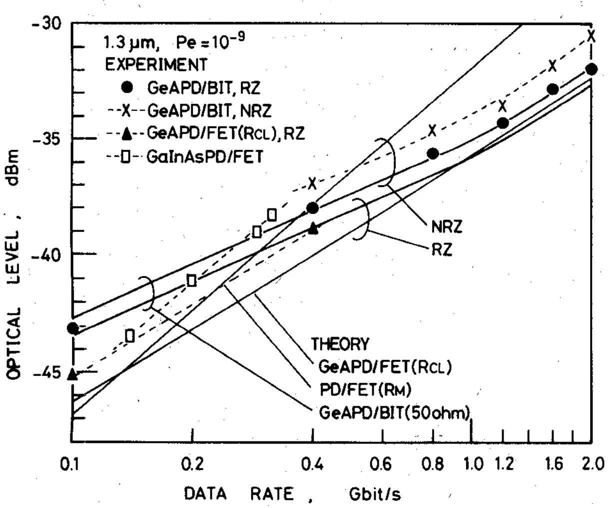

Fig. 11. Optical receiver sensitivity dependence on data rate at 1.3 μm. Solid lines are theoretical values.

Experimental results are in good agreement with theoretical lines within 2 dB degradation. This figure shows that RZ waveform signals are expected to result in about 1 dB improved sensitivity, relative to NRZ signals, at each data rate. The Ge APD/Si BIT front end with a 50 Ω input impedance, using an RZ pulse, exhibits higher performance than the GaInAs PIN/GaAs FET receiver, beyond 300 Mbits/s. Furthermore, the advantage of the optical receiver, based on Ge APD is extended to the 100 Mbit/s data rate by using a GaAs FET front end with an R_{CL} input impedance ($R_{CL} \ll R_M$). These experimental results, in the 1.3 μm optical sensitivity performance study, confirmed that Ge APD's, even with about a 100 nA dark current and a 0.95 excess noise factor, have higher sensitivity than the GaInAs PIN/GaAs FET, as the optical detector in the optical receiver at from a 100 Mbit/s to 2 Gbit/s range data rate.

IV. 2 Gbit/s Single-Mode Fiber Transmission

2 Gbit/s optical transmission experiments were carried out using the high-speed optical receiver, consisting of a Ge APD/Si BIT front end with a 50 Ω input impedance and long-span low-loss single-mode fiber with 44.3 km length. Fiber characteristics and results in fiber transmission experiments will be discussed in detail.

A. Single-Mode Fiber Characteristics

The single-mode fibers used in the experiment were fabricated by the MCVD method [11]. They have GeO_2 doped-silica core and pure silica cladding. Fiber unit length is typically about 5 km. Fibers have a polyurethane primary coating and a silicone buffer layer. They are loosely wound on drums in order to prevent microbending loss. Eight fiber strands were spliced by the fusion splice method [23], while being monitored by a He–Ne laser emitting at 1.52 μm. The parameters of each fiber strand are shown in Table I. The total fiber length is 44.3 km. The overall losses for the fibers, including splice loss, are 25.3 dB at 1.3 μm and 17.7 dB at 1.55 μm. Average fiber loss values are 0.57 dB/km at 1.3 μm and 0.40 dB/km at 1.55 μm, respectively.

A hemispherical microlens tipped on a single-mode fiber is used to couple the semiconductor laser output into the single-mode fiber [24], as shown in Fig. 12. Optical coupling loss, by the microlens with an 8.5 μm lens radius and an optimum separation, is 4 dB. A 6 dB improvement over the butt joint method was achieved.

B. Experimental Results

Error rate dependence on laser prebias I_{dc} was measured, before and after long-distance transmission, in order to optimize the semiconductor laser drive condition. Experimental results in the laser bias optimization at 2 Gbits/s are shown in Fig. 13, when the laser is directly modulated by an RZ waveform signal and −33 dBm received optical power is detected by the optical detector. When $I_{dc} = 0.85 \times I_{th}$, the error rate is the lowest before transmitting through long-span fibers. After the 44.3 km transmission, optimum I_{dc} bias condition, however, exists at $0.95 \times I_{th}$ near the laser threshold current. When the laser dc bias is selected at below $0.95 \times I_{th}$, error rate is degraded by fiber dispersion effect due to laser output spectrum broadening. Output spectra for the directly modulated semiconductor laser at 2 Gbits/s are shown in Fig. 14. A laser prebias increase is needed to make the laser output spectrum narrow. Full width at half maximum (FWHM) of the spectrum was reduced from 2.5 to 1.5 nm as the laser bias was increased.

Fig. 15 shows the 2 Gbit/s error rate characteristics after the 44.3 km transmission. By optimizing the laser prebias ($I_{dc} = 0.95 \times I_{th}$) after 44.3 km transmission, the error rate is measured using a 1 m fiber under the same laser drive conditions. The −29.4 dBm required optical received level for a 10^{-9} error rate agrees with that after 44.3 km transmission. These results show that no receiver sensitivity degradation is caused by fiber dispersion, even after 44.3 km transmission at 2 Gbits/s.

TABLE I
SINGLE-MODE FIBER CHARACTERISTICS

Fiber no.	Length km	Rel. Index Diff. Δ, %	Core Dia. 2a, μm	Cutoff Freq. λ_c, μm	Loss dB/km
1	5.25	0.17	11.3	1.14	0.52
2	6.49	0.19	11.0	1.19	0.51
3	6.81	0.21	10.2	1.19	0.53
4	5.31	0.21	10.7	1.14	0.49
5	4.13	0.23	11.2	1.17	0.49
6	5.72	0.20	10.9	1.17	0.47
7	5.40	0.26	10.5	1.13	0.54
8	5.23	0.20	10.9	1.19	0.63

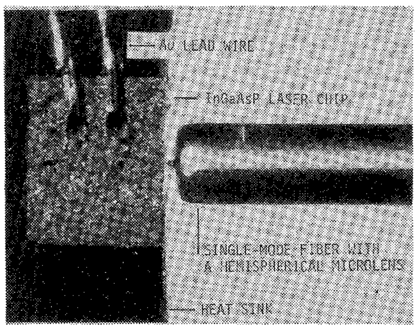

Fig. 12. Coupling InGaAsP semiconductor laser output into a single-mode fiber having a hemispherical microlens. The microlens has 8.5 μm lens radius and is set at an optimum position.

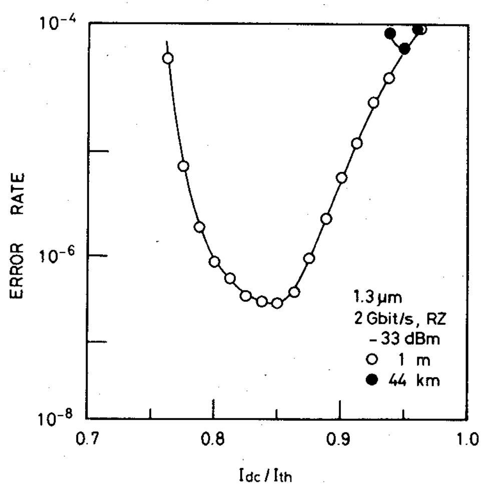

Fig. 13. Error rate dependence on laser prebias. Optimum bias condition exists at lowest error rate.

A laser dc drive current increase gives rise to an optical power penalty of 2.5 dB, due to an optical extinction ratio degradation and an increase in the RZ duty factor in optical signal waveform, as shown in Fig. 13. Fig. 16 shows eye patterns at 2 Gbits/s for received photocurrent signals after 1 m and 44.3 km transmission. Pulse waveforms detected after the 44.3 km transmission are slightly broadened, as shown in Fig. 16(b). Fiber dispersion at this wavelength is estimated to be 2.2 ps/(km · nm) from the pulse broadening of received eyepatterns and FWHM for laser output spectrum.

Fig. 17 shows an optical power level diagram for the present system at 2 Gbits/s. As coupling efficiency between the semi-

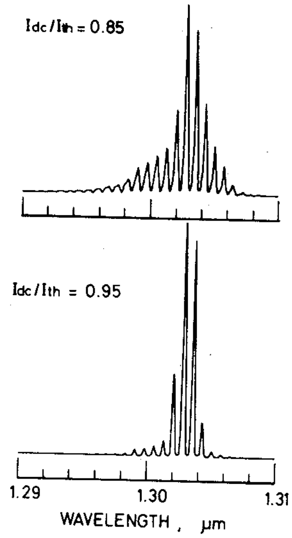

Fig. 14. Output spectra for a directly modulated InGaAsP semiconductor laser at 2 Gbits/s.

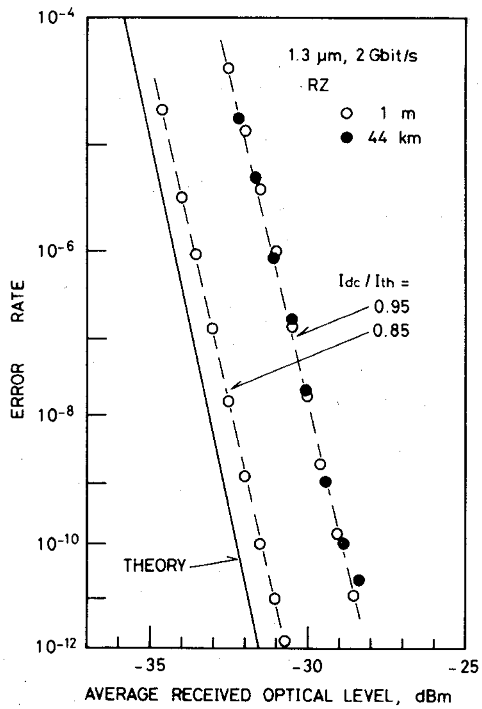

Fig. 15. 2 Gbit/s error rate characteristics after transmitting through 44.3 km single-mode fibers.

conductor laser and single-mode fiber is improved, in comparison with that by the butt joint [14], a 28.2 dB repeater gain with 2.9 dB system margin is achieved in the 2 Gbit/s system.

V. DISCUSSION

Future prospect for Gbit/s optical receiver sensitivity and 2 Gbit/s single-mode fiber transmission systems will be discussed, taking into account experimental and theoretical results in this study.

A. Prospect for Optical Receiver Sensitivity

Fig. 11 shows that the 1.3 μm Ge APD receiver sensitivity is improved by using the TD comparator and that the experimental results approach the theoretical values within 2 dB. It is also confirmed that Ge APD's have higher performance than the

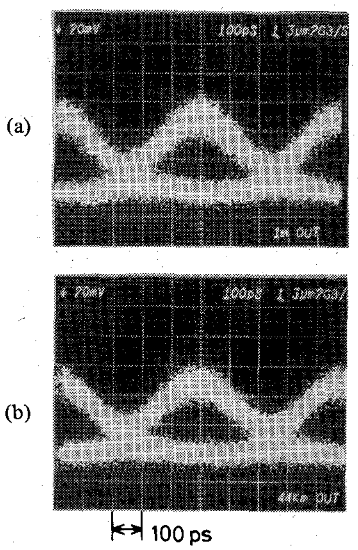

Fig. 16. 2 Gbit/s eye patterns after detection. (a) Photocurrent after 1 m transmission. (b) Photocurrent after 44.3 km transmission.

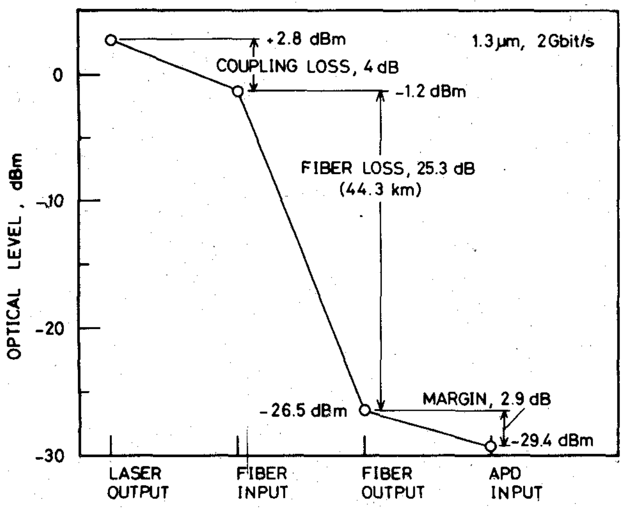

Fig. 17. Optical level diagram for 2 Gbit/s single-mode fiber transmission system.

PIN/FET, as the 1.3 μm optical detector beyond 100 Mbits/s, taking into account the high impedance design of a Ge APD/GaAs FET front end. Ge APD's, however, have a dark current of about 100 nA and an excess noise factor of 0.95 at 1.3 μm. Furthermore, quantum efficiency and frequency response for Ge APD's rapidly degrade beyond 1.55 μm [25], [26].

Shortcomings in the dark current, excess multiplication noise, and poor quantum efficiency beyond 1.55 μm for Ge APD's are expected to be overcome by employing III-V compound semiconductor materials. The impact ionization coefficient ratio for electrons and holes in the materials seems to be favorable for low multiplication noise. An InGaAs/InP photodiode with an InGaAs light absorption layer and an InP avalanche multiplication region has a wide sensitivity spectral range, extending up to 1.7 μm and low dark current [27]. Excess noise factor x reduced to 0.7 and uniform multiplication factor of 45 were observed. A relatively flat spectral response versus wavelength and 80 percent quantum efficiency are realized in an InP/InGaAs photodiode with the depletion layer reaching the InGaAs layer and antireflection coating [28].

Realization of InGaAs APD's, with 80 percent quantum efficiency, excess noise factor $x = 0.7$ and 1 pF total input

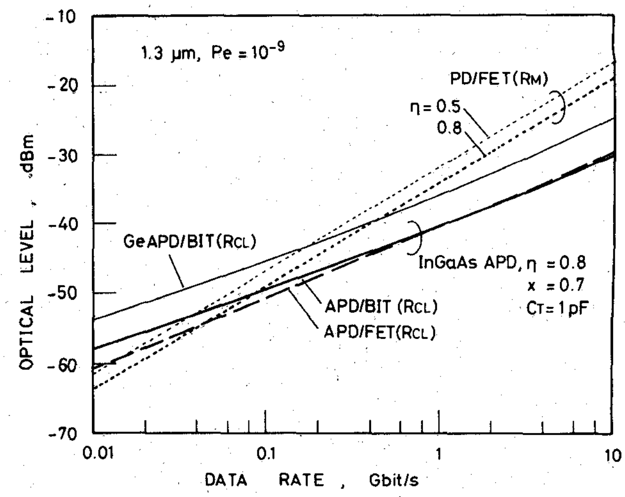

Fig. 18. Optical receiver sensitivity dependence on data rate, assuming an improved GaInAs APD with $\eta = 0.8$, $x = 0.7$, and $C_T = 1$ pF.

capacitance, brings about the 1.3 μm receiver sensitivity shown in Fig. 18. Optical receivers having a PD/FET hybrid front end design have an operational advantage of being more insensitive to temperature and of requiring lower power supply voltage than the APD optical receivers [18]. Since the FET hybrid front end has sufficiently low input capacitance (C_T = 0.7 pF), a highly efficient photodiode with 80 percent quantum efficiency brings about only 2.5 dB sensitivity improvement.

On the other hand, the APD optical receivers require high voltage source and automatic bias control circuit to get an optimum avalanche gain and to suppress the temperature-dependent level fluctuation. This circuit design is technologically established. Ge APD optical receivers have higher performance than the improved InGaAs PD/GaAs FET front end beyond 400 Mbits/s.

If high performance InGaAs APD's are available as an optical detector in the 1.3 μm, the APD receiver will bring about sensitivity improvement beyond 5 dB for all data rates. Optical receivers with a GaAs FET front end have higher sensitivity than the improved InGaAs PD/GaAs FET front end receiver beyond 40 Mbits/s. Optical receiving level at a 10^{-9} error rate in 2 Gbit/s transmission systems is expected to be about −37 dBm for an RZ pulse.

B. Prospect for 1 Gbit/s Transmission System

The 1.3 μm transmission system in this article has a data rate by a repeater spacing product of 88.6 (Gbits/s) km. Fiber dispersion of 2.2 ps/(km · nm), caused by only 20 nm wavelength difference between zero dispersion wavelength and laser output wavelength, however, exists in the single-mode fiber. Transmission bandwidth for the 44.3 km single-mode fiber is calculated to be about 3 GHz from the fiber dispersion and FWHM in the laser output spectrum [4]. When the product of fiber dispersion s, fiber length L, and laser output spectral FWHM λ_w is below 150 ps, transmission bandwidth for the single-mode fiber with length L was broader than 3 GHz.

In order to extend the repeater spacing for the 2 Gbit/s digital transmission system at 1.3 μm beyond 50 km, it is necessary to reduce fiber loss and fiber dispersion degradation. When a fiber with 0.5 dB/km average loss is used, the present system has a 3 dB system margin, after the 50 km transmission. However, it is necessary to reduce fiber dispersion by laser spectral width product $s \cdot \lambda_w$ to below 3 ps/km. Matching between zero dispersion wavelength and laser output wavelength is important for a 2 Gbit/s transmission system design having long repeater spacing. Alternatively, purely single longitudinal mode operation of the semiconductor laser is desired under pulse modulation. Furthermore, a 2 Gbit/s transmission system, having the improved InGaAs APD/Si BIT front end receiver, will make the repeater spacing extended to 65 km, with a 3 dB system margin. Realization of 2 Gbit/s transmission systems having 100 km repeater spacing seems to depend on whether the 1.55 μm zero dispersion fiber loss can be reduced below 0.3 dB/km and whether high-speed, high-efficiency, and low-noise APD's at 1.55 μm, such as the improved InGaAsP APD, can be fabricated.

VI. Conclusion

Optical receiver performance from 100 Mbits/s to 2 Gbits/s and 2 Gbit/s single-mode fiber transmission experiments were studied at 1.3 μm. Optical receiver sensitivity dependence on data rate from 10 Mbits/s to 10 Gbits/s were calculated from Personick's theory. Calculated results show that APD/FET front ends, having an R_M input impedance, have higher sensitivity than the other front ends and that PD/FET front end receivers with an R_M impedance are superior to APD/BIT front end receivers below 30 Mbits/s. APD/BIT front ends without complicated ideal equalization are expected to have high receiver sensitivity at 1.3 μm, in the Gbit/s data rate range.

The 1.3 μm optical transmission system was improved by a high-speed RZ pulse GaAs FET laser driver and a highly sensitive tunnel diode comparator, in order to measure receiver sensitivity up to 2 Gbits/s. At 2 Gbits/s, optical power levels at a 10^{-9} error rate are -31.9 dBm at an RZ code and -30.5 dBm at an NRZ code, respectively, by using a Ge APD/Si BIT front end with a 50 Ω input impedance and a 1 m long single-mode fiber. 2 dB optical sensitivity improvement is achieved at 100 Mbits/s, by using the high impedance Ge APD/GaAs FET front end design. Experimental results in the front ends with Ge APD were compared with those of the GaInAs PIN/GaAs FET hybrid optical receiver. Ge APD's seem to have the highest performance as the available optical detector in the 1.3 μm optical receiver at data rates from the 100 Mbit/s up to 2 Gbit/s range.

The 2 Gbit/s optical transmission experiment was achieved by using single-mode fibers with 44.3 km length and 0.57 dB/km loss at 1.3 μm. The required optical received level for a 10^{-9} error rate of -29.4 dBm, with optimized laser prebias after 44.3 km transmission, agrees with that measured using a 1 m fiber under the same laser drive conditions. A 4 dB coupling loss, achieved by a hemispherical microlens, brought about a 28.2 dB repeater gain with 2.9 dB system margin in the 2 Gbit/s system.

If high performance InGaAs APD's, with $\eta = 0.8$, $x = 0.7$, and $C_T = 1$ pF are available as an optical detector in the Si BIT or GaAs FET front end receiver, the 1.3 μm APD optical receiver with an R_{CL} front end impedance will bring about 5 dB sensitivity improvement and have higher sensitivity than the improved InGaAs PD/GaAs FET front end receiver, beyond 40 Mbits/s. In order to realize the 2 Gbit/s optical transmission systems with repeater spacing beyond 50 km, it is necessary to reduce fiber loss and to match laser output wavelength with zero dispersion wavelength. Furthermore, improvement in the 1.55 μm zero dispersion fiber with loss below 0.3 dB/km and APD's with high performance at loss minimum wavelength will bring about 2 Gbit/s fiber transmission systems having 100 km repeater spacing.

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Tatsuya Kimura (S'63–M'68–SM'78), for a photograph and biography, see p. 64 of the January 1982 issue of *IEEE J. Quantum Electron.*

Single-Mode Fiber Design for Long Haul Transmission

LUC JEUNHOMME

Abstract—**By using simple yet accurate approximations for the propagation characteristics of a single-mode optical fiber, we obtain a simple model for the total loss and chromatic dispersion of single-mode fiber transmission lines as a function of the operating conditions such as splice offset, microbending loss, bends, etc. This model is then applied to typical cases of terrestrial and submarine systems and we obtain single-mode fiber designs which are stable with respect to slight operating condition changes for both 1.3 and 1.55 μm wavelengths. It appears that the same fiber can be used at 1.3 μm for both terrestrial and submarine systems, and even for 1.55 μm terrestrial systems if monochromatic sources become available at this wavelength. A general comparison between the two wavelengths is carried out and shows under which conditions the 1.55 μm wavelength is of practical interest. It is emphasized that the availability of monochromatic sources at 1.55 μm would make a major breakthrough for the repeater spacing.**

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I. Introduction

The achievement of very low loss single-mode optical fibers and the improvements in the knowledge of light propagation inside these fibers make them very attractive for long distance transmission in the telecommunication network. This means that system designers begin to be practically interested in implementing single-mode fiber based systems. At this point several questions are raised among which are the following:

1) For a given application and given operating conditions, what are the optimum parameters for the single-mode fiber structure (namely core radius and index difference). This question obviously stems from the fact that many transmission characteristics of the fiber depend on these basic parameters in a complicated and apparently opposite way (e.g., microbending losses and splicing losses).

2) Between the two well-known low attenuation windows

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