A Low-Cost Edge-Illuminated Refracting-Facet Photodiode Module with Large Bandwidth and High Responsivity

Hideki Fukano, *Member, IEEE,* and Yutaka Matsuoka, *Member, IEEE*

***Abstract*—We have demonstrated a low-cost, high-speed and high-responsivity photodiode module utilizing an edge-illuminated refracting-facet photodiode (RFPD), in which the incident light parallel to the up-side surface is refracted at an angled facet and absorbed in a thin absorption layer. Since the incident light refracted at an angled facet penetrates at a definite angle to the absorption layer, the absorption length is effectively longer, resulting in high responsivity. In addition, since the RFPD chip has a large tolerance to optical-axis misalignment, the module can be produced with a simple single-lens alignment configuration, which enables low-cost fabrication. The fabricated RFPD module has a large-bandwidth (38 GHz) and high-responsivity (1 A/W). The measured polarization dependence of responsivity is less than 0.2 dB at a wavelength of 1.55 μm.**

***Index Terms*—InGaAs, InP, optical receiver, photodetectors, photodiodes.**

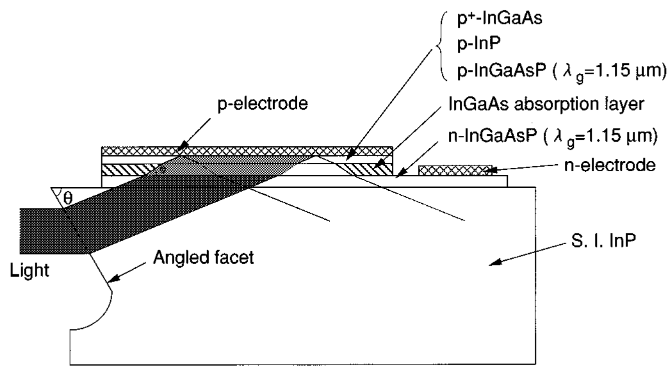


Fig. 1. Schematic cross-sectional view of the fabricated RFPD.

I. Introduction

BOTH ultrahigh-speed time-division multiplexing (TDM) and wavelength-division multiplexing (WDM) have been extensively investigated for ultrahigh-capacity optical communications and total capacities exceeding 1 Tb/s have been reported [1]–[10]. Low-cost and high-speed optical modules are especially important for WDM systems, which need many channels (ranging from several tens to over 100 channels) as well as a very high channel bit rate (ranging from 2.5 to 10 Gb/s in the commercial field and from 10 to 200 Gb/s in the research field). The cost of optical modules could be reduced by simplifying the alignment configuration of the optical axis and reducing the number of optical components such as lenses [11]. A photodiode (PD) with a large optical axis misalignment tolerance would be the most effective way to keep costs low. High-speed operation is possible by reducing the carrier transit time by using a thinner absorption layer. A multimode waveguide structure photodiode (WGPD) has been developed, with reportedly excellent characteristics [12], that has a thin absorption layer and high responsivity. Because its optical axis misalignment tolerance for vertical direction is principally determined by the thickness of the core layers, the tolerance is not so large, resulting in a high module packaging cost. An edge-illuminated refracting-facet photodiode (RFPD) (in which the incident light that is parallel to the top surface is refracted at an inwardly angled facet and then absorbed in an absorption layer) is very attractive because it provides a large optical axis misalignment tolerance [13]. In addition, since the refracted light pass through the absorption layer at a set angle, the absorption length effectively increases. This makes it possible to decrease the absorption layer thickness while keeping responsivity high, resulting in a high operating speed.

In this paper, we describe a successfully fabricated low-cost RFPD module. In Section II, we outline the structure and fabrication of the device. The characteristics of the fabricated RFPD chips are shown in Section III. The modules were produced using a single-lens alignment configuration made possible by their large tolerance to optical misalignment. The module characteristics are described in Section IV. The fabricated RFPD module has a large 3-dB bandwidth of 38 GHz and high responsivity of 1 A/W. The polarization dependence of responsivity for a 1.55-μm-light wavelength was estimated to be less than 0.2 dB.

II. RFPD Structure and Fabrication

A schematic cross-sectional view of the fabricated RFPD is shown in Fig. 1. The light that is parallel to the up-side surface of the RFPD is refracted at an inwardly angled facet with a mesa angle of θ. According to Snell's law, the refracted light passes through the absorption layer at a certain angle ϕ and is absorbed simultaneously. Therefore, the absorption length effectively increases by an extension factor of $1/\sin\phi$. This results in an increase in internal quantum

Manuscript received July 15, 1999.
The authors are with the NTT Photonics Laboratories, Atsugi, Kanagawa 243-0198, Japan.
Publisher Item Identifier S 0733-8724(00)00394-7.

efficiency. In other words, high responsivity is possible even though the absorption layer thickness is decreased to gain high operating speed from a reduced carrier transit time. Fig. 2 shows calculations for the relationship between the responsivity at a 1.55-μm light wavelength and the mesa angle of the RFPD with a 1-μm InGaAs absorption layer. For the calculations, it was assumed that the absorption of 1.55-μm light can be expressed in an exponential formula with an absorption coefficient of 0.68 μm^{-1} in InGaAs [14]. It was also assumed that all the photogenerated carriers became photocurrents and the facet had an antireflection coat. In addition, only the light refraction at the interface of each layer was taken into account using the refractive index of 3.17 for InP, 3.31 for InGaAsP, and 3.59 for InGaAs. Also shown in Fig. 2 are the calculated results based on the assumption that the p-metal electrode reflects light in a given reflection ratio and the light is reflected symmetrically off the metal surface. Even with no light reflection at the p-metal electrode, a responsivity of 0.85 A/W was estimated at a θ of 55°. This is about 1.4 times larger than the value from the top surface illuminated PD (0.62 A/W) and a further increase in responsivity would be expected when light reflection at the p-metal electrode occurs.

Another important feature is that the misalignment tolerance of the optical axis in the vertical direction is not determined by the thickness of the absorption layer, as in the waveguide photodiodes, but by its length. Therefore, a large misalignment tolerance can be achieved by designing a long absorption region according to the level of tolerance required.

The epitaxial layer shown in Fig. 1 is a so-called pin structure, which consists of an undoped 1-μm InGaAs absorption layer sandwiched between p-semiconductor layers [p-InGaAs cap/p-InP/p-InGaAsP (bandgap wavelength $\lambda g = 1.15$ μm)] and an n-semiconductor layer [n-InGaAsP (bandgap wavelength $\lambda g = 1.15$ μm)]. The mesa of the absorption region was defined by dry etching. The size of the absorption region was 14 μm wide and 20 μm long. After forming the p- and n-electrodes, mesa formation of the angled facet was carried out. To fabricate the angled facet, we utilized the feature that a (111)A plane is produced with an angle of 54° 44′ in the (001) surface of InP by anisotropic chemical etching. Finally, the incident facet was antireflection coated with SiN_x film.

III. RFPD Chip Characteristics

It is expected that thin absorption layer, with which a high responsivity can be achieved at the RFPD, leads low-bias-voltage operation. The responsivity of the fabricated RFPD coupled with a 1.7-μm spot-size ($2w_s = 3.4$ μm) light was measured at a wavelength of 1.55 μm as shown in Fig. 3. The responsivity reached as high as 1 A/W with almost no bias dependence. From Fig. 2, light reflection was thought to have occurred at the p-metal electrode and was estimated to be about 50%. As expected, this RFPD provided high responsivity due to increased effective absorption length. The measured responsivity curves for the fabricated RFPD is shown for the horizontal (X) direction in Fig. 4(a) and for the vertical (Y) direction in Fig. 4(b). The horizontal and vertical misalignment tolerances

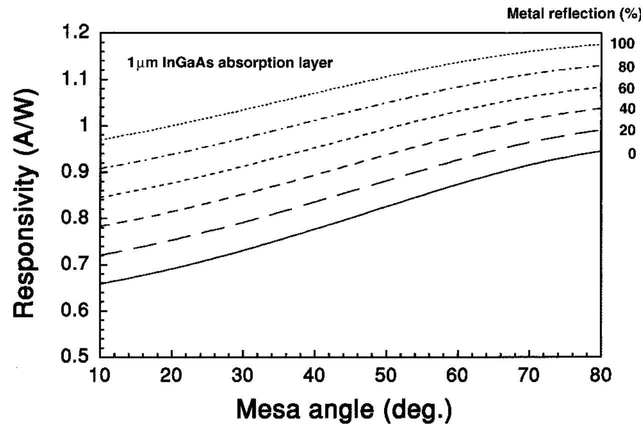


Fig. 2. Dependence of calculated responsivity on the mesa angle.

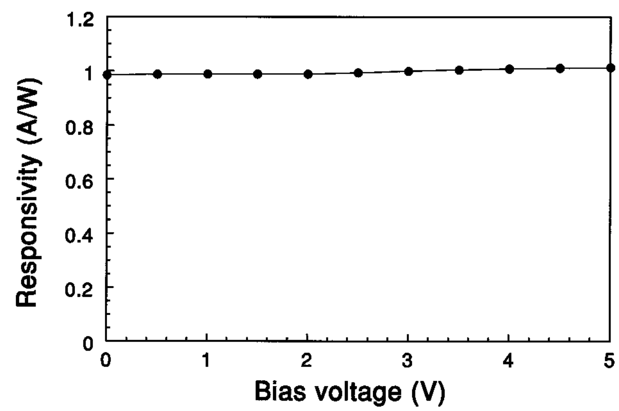
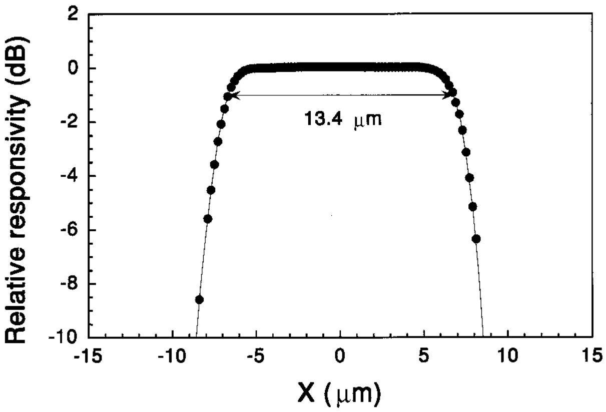


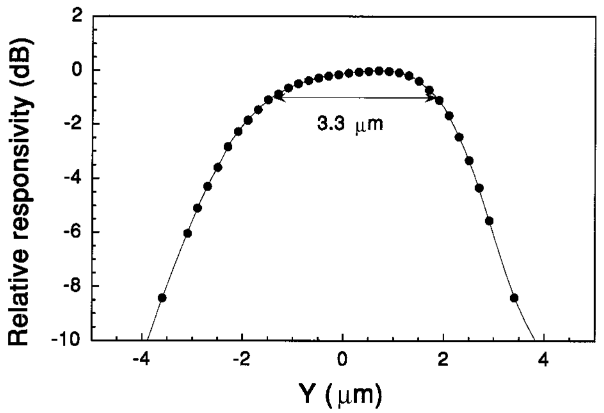
Fig. 3. Measured responsivity dependence on the bias voltage.

for 1 dB down are as large as 13.4 and 3.3 μm, respectively. Fig. 4(c) shows the measured misalignment tolerance curve for the longitudinal (Z) direction. The 1-dB-down tolerance was as large as 17.5 μm. Although the tolerance curve for the X direction has symmetric characteristics, those for Y and Z directions have asymmetric characteristics. By simulating the beam propagation, we concluded that the dominant reason for the asymmetry was due to the finite area of the angled facet. When the position of the light position is moved, a part of the light beam falls outside the angled facet area, resulting in the asymmetric decrease in responsivity. Therefore, increasing the area of the angled facet should produce nearly symmetric characteristics and increase the tolerance to misalignment.

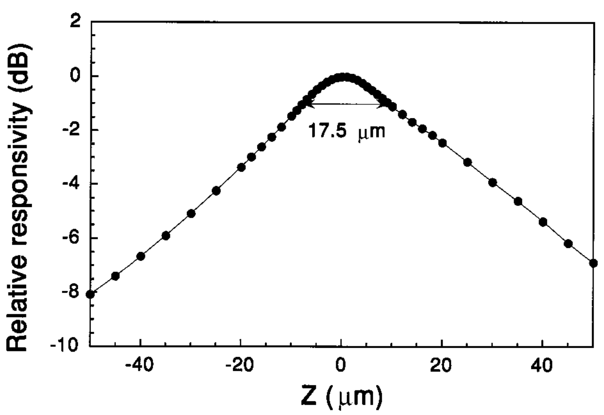
The small signal frequency responses of the fabricated RFPD's were measured using a lightwave component analyzer (HP-83 467C) up to 50 GHz. Fig. 5 shows the frequency response at different bias voltages. The 3-dB-down frequency $(f_{3\,\mathrm{dB}})$ dependence on the bias voltage (V_{bias}) is shown in Fig. 6. The $f_{3\,\mathrm{dB}}$ increased with increase in bias voltage and tended to saturate at a V_{bias} over 3 V. An $f_{3\,\mathrm{dB}}$ of 32 GHz was obtained at a V_{bias} of 5 V. Although the dc responsivity was not bias dependent, $f_{3\,\mathrm{dB}}$ was bias dependent in the low V_{bias} region. To clarify the reasons of this, capacitance dependence on V_{bias} was measured using an LCR meter (Fig. 7). Since the capacitance was almost constant at a V_{bias} above 0.5 V, the absorption layer was depleted at a V_{bias} of 0.5 V. This means that the CR time constant was almost unchanged at a



(a)



(b)



(c)

Fig. 4. Misalignment tolerance curves of the fabricated RFPD for: (a) horizontal (X), (b) vertical (Y), and (c) longitudinal (Z) directions.

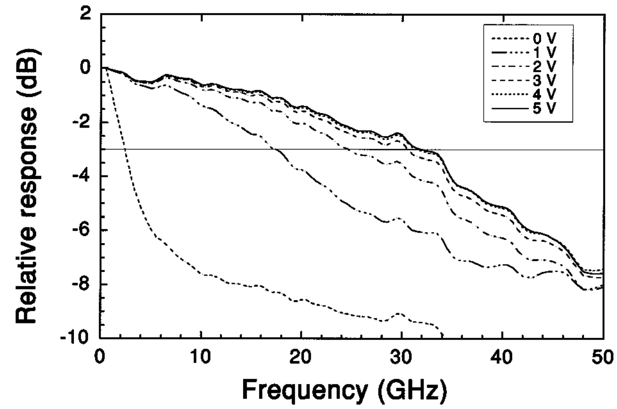


Fig. 5. Frequency response of the fabricated RFPD chip at different bias voltages.

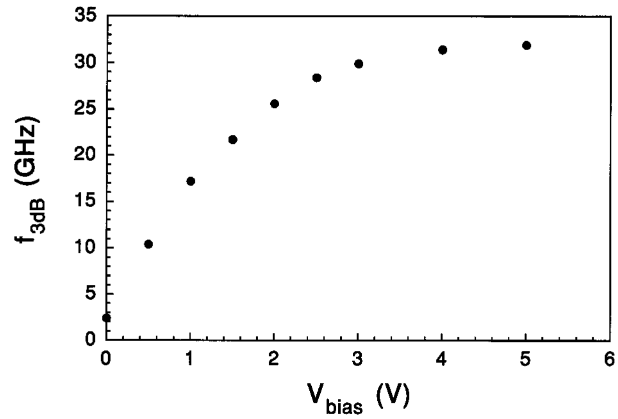


Fig. 6. 3-dB-down bandwidth ($f_{3\,\mathrm{dB}}$) dependence on the bias voltage (V_{bias}).

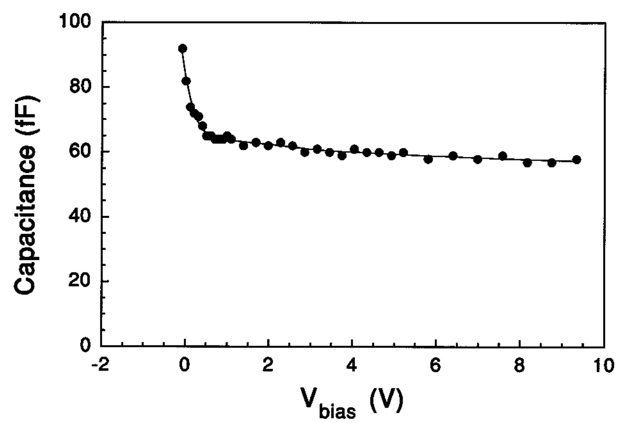


Fig. 7. Measured capacitance dependence on the bias voltage (V_{bias}).

V_{bias} over 0.5 V. Nevertheless, $f_{3\,\mathrm{dB}}$ increased with increase in V_{bias} from 0.5 to 3 V. This fact suggests that this change of $f_{3\,\mathrm{dB}}$ was determined by the carrier transit time. Therefore, this RFPD chip had to be biased above 3 V to ensure a high-speed operation.

IV. RFPD Module Characteristics

High-speed waveguide photodiode modules require a double-lens alignment configuration due to their small misalignment tolerance, but this RFPD module can be produced with a single-lens alignment configuration because its misalignment tolerance is large. This enables low-cost module fabrication. A photograph of the module is shown in Fig. 8. It has a small body, 22 mm wide ×15 mm long × 14 mm high, and a single mode fiber with an SC optical connector. The optical parts were spot-welded to the module block using a YAG laser to give high reliability. An electrical signal from the chip travels through the bonding wire to a ceramic waveguide and is outputted through a K-connector.

Fig. 9 shows the module responsivity distribution of 17 fabricated modules. Most of modules have a responsivity ranging from 0.8 to 1 A/W. This clearly demonstrates that the misalignment tolerance of the fabricated RFPD's is large enough to con-

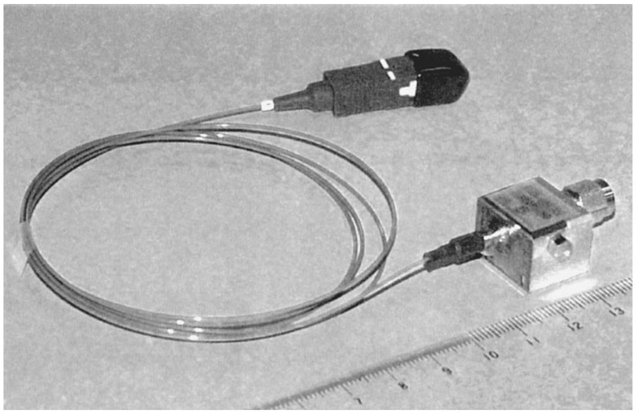


Fig. 8. The fabricated RFPD module.

struct modules with a single-lens alignment configuration. Fig. 10 shows the small signal frequency response of an fabricated RFPD module at a $V_{\rm bias}$ of 5 V. An $f_{3\,{\rm dB}}$ of 38 GHz was obtained. The $f_{3\,{\rm dB}}$ was slightly larger than that in the RFPD chip shown in Fig. 5 and the response sharply decreased at a frequency above 42 GHz, probably because of the weak peaking characteristics caused by inductance at the bonding wire.

A low polarization dependence of responsivity is usually required for photodetectors used in optical communication systems. The polarization dependence of the fabricated RFPD module was measured. Light from the wavelength variable source was fed into the RFPD module through an HP8169A polarization controller composed of a polarizer, a quarter-wave plate, and a half-wave plate. The polarization dependence of responsivity (PDR) was calculated using the maximum and minimum responsivity measured by changing the polarization state. The measured PDR versus the illuminated light wavelength (λ), which ranged from 1.53 to 1.565 μm, is shown in Fig. 11. Although the PDR slightly increased with increase in wavelength, the absolute value was low; the measured PDR was less than 0.2 dB at a λ of 1.55 μm. It should be noted that the measurement system had an ambiguity of about 0.2 dB because of the polarization dependence of the inserted attenuator and isolator. An intensity fluctuation in both the polarization controller during quarter- and half-wave plate rotation and the wavelength variable source also contributed to the ambiguity. Therefore, the actual PDR of the RFPD module may be lower than the above results. The results indicate, however, that the measured PDR is sufficiently low for using this RFPD module in optical communication systems.

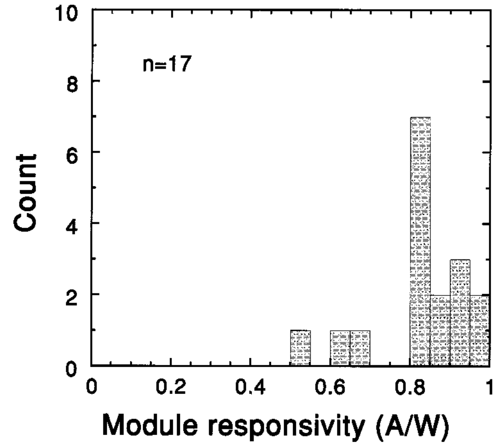


Fig. 9. Module responsivity distribution of 17 fabricated modules.

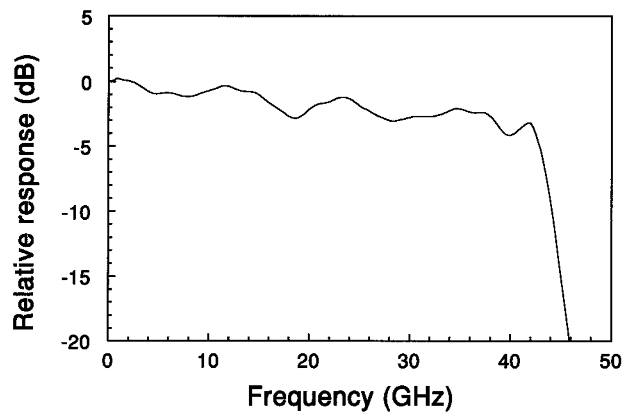


Fig. 10. Frequency response of a fabricated RFPD module at a bias voltage of 5 V.

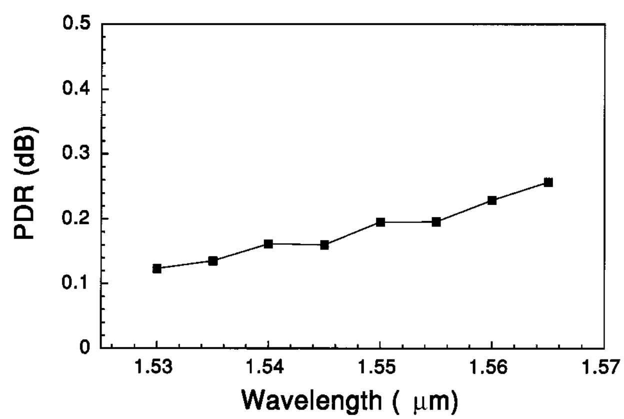


Fig. 11. Measured polarization dependence of responsivity (PDR) versus illuminated-light-wavelength ranging from 1.53 to 1.565 μm.

V. Summary

We have developed a low-cost, high-speed, and high-responsivity photodiode module utilizing an edge-illuminated refracting-facet photodiode (RFPD). Since the incident light refracted at an angled facet penetrates at a definite angle to the absorption layer, the absorption length is effectively longer, resulting in a higher internal quantum efficiency. Therefore, high responsivity can be ensured even when the absorption layer is made thinner to gain a high operating speed from a reduced carrier transit time. Another advantage of the RFPD is that the misalignment tolerance of the optical axis in the vertical direction is determined not by the thickness of the absorption layer, as in waveguide photodiodes, but by its length. Therefore, a large misalignment can be tolerated. This enables the RFPD module to be constructed with a single-lens alignment configuration, which reduces the number of optical alignment processes and the number of optical components, resulting in a low-cost module. The RFPD module has a responsivity as high as 1 A/W for 1.55-μm-wavelength light and a 3-dB bandwidth as large as 38 GHz. The measured polarization dependence of responsivity is less than 0.2 dB at a 1.55-μm wavelength. The low cost RFPD module with these excellent characteristics should play an important role in developing large-capacity photonic networks.

ACKNOWLEDGMENT

The authors would like to thank H. Sanjo for his help with the measurements. They also would like to thank K. Kato and O. Nakajima for their helpful discussions and support, and J. Yoshida, H. Iwamura, and S. Mitachi for their encouragement throughout this work.

REFERENCES

[1] H. Onaka, H. Miyata, G. Ishikawa, K. Ostuka, H. Ooi, Y. Kai, S. Kinoshita, M. Seino, H. Nishimoto, and T. Chikama, "1.1 Tb/s WDM transmission over a 150 km 1.3 μm zero-dispersion single mode fiber," in *Proc. OFC'96*, 1996, PD19.

[2] A. H. Gnauck, A. R. Chraplyvy, R. W. Tkach, J. L. Zyskind, J. W. Sulhoff, A. J. Lucero, Y. Sun, R. M. Jopson, F. Forghieri, R. M. Derosier, C. Wolf, and A. R. McCormick, "One terabit/s transmission experiment," in *Proc. OFC'96*, 1996, postdeadline paper PD20.

[3] T. Morioka, H. Takara, S. Kawanishi, O. Kamatani, K. Takiguchi, K. Uchiyama, M. Saruwatari, H. Takahashi, M. Yamada, T. Kanamori, and H. Ono, "100 Gbit/s × 10 channel OTDM/WDM transmission using a single supercontinuum WDM source," in *Proc. OFC'96*, 1996, postdeadline paper PD21.

[4] Y. Yano, T. Ono, K. Fukuchi, T. Ito, H. Yamaguchi, and K. Emura, "2.6 Tb/s WDM transmission experiment using optical duobinary coding," in *Proc. ECOC'96*, 1996, paper ThB3.1.

[5] A. K. Srivastava, Y. Sun, J. W. Sulhoff, C. Wolf, M. Zirngibl, R. Monnard, A. R. Chraplyvy, A. A. Abramov, R. P. Espindola, T. A. Strasser, J. R. Padrazzani, A. M. Vengsarkar, J. L. Zyskind, J. Zhou, D. A. Ferrand, P. L. Wysocki, J. B. Judkins, and Y. P. Li, "1 Tbit/s transmission of 100 WDM 10 Gbit/s channels over 100 km of TrueWave fiber," in *Proc. OFC'98*, 1998, postdeadline paper PD10.

[6] S. Aisawa, T. Sakamoto, M. Fukui, J. Kani, M. Jinno, and K. Oguchi, "Ultra-wide band, long distance WDM demonstration: 1 Tbit/s (50 × 20 Gbit/s), 600 km transmission using 1550 and 1580 nm wavelength bands," in *Proc. OFC'98*, 1998, postdeadline paper PD11.

[7] C. D. Chen, I. Kim, O. Mizuhara, T. V. Nguyen, K. Ogawa, R. E. Tench, L. D. Tzeng, and P. D. Yeates, "1.2 Tb/s WDM transmission experiment over 85 km fiber using 40 Gb/s line rate transmitter and 3R receiver," in *Proc. OFC'98*, 1998, postdeadline paper PD21.

[8] Y. Miyamoto, K. Yonenaga, A. Hirano, N. Shimizu, M. Yoneyama, H. Takara, K. Noguchi, and K. Tsuzuki, "1.04-Tbit/s DWDM transmission experiment based on alternative-polarization 80-Gbit/s OTDM signals," in *Proc. ECOC'98*, vol. 3, 1998, postdeadline papers, p. 55.

[9] D. Le Guen, S. Del. Burgo, M. L. Moulinard, D. Grot, M. Henry, F. Favre, and T. Georges, "Narrow band 1.02 Tbit/s (51 × 20 Gbit/s) soliton DWDM transmission over 1000 km of standard fiber with 100 km amplifier spans," in *Proc. OFC'99*, 1999, postdeadline paper PD4.

[10] S. Kawanishi, H. Takara, K. Uchiyama, I. Shake, and K. Mori, "3 Tbit/s (160 Gbit/s × 19 channel) optical TDM and WDM transmission experiment," *Electron. Lett.*, vol. 35, no. 10, pp. 826–827, 1999.

[11] J. Yoshida, M. Kawachi, T. Sugie, M. Horiguchi, Y. Itaya, and M. Fukuda, "Strategy for developing low-cost optical modules for the ONU of optical subscriber systems," in *Proc. 7th Int. Workshop Optical Access Networks*, 1995, paper 6.1-1.

[12] K. Kato, S. Hata, K. Kawano, J. Yoshida, and A. Kozen, "A high-efficiency 50GHz InGaAs multimode waveguide photodetector," *IEEE J. Quantum Electron.*, vol. 28, pp. 2728–2735, 1992.

[13] H. Fukano, A. Kozen, K. Kato, and O. Nakajima, "High-responsivity and low-operation-voltage edge-illuminated refracting-facet photodiodes with large alignment tolerance for single-mode fiber," *J. Lightwave Technol.*, vol. 15, pp. 894–899, 1997.

[14] J. E. Bowers and C. A. Burrus, "Ultrawide-band long-wavelength p-i-n photodetectors," *J. Lightwave Technol.*, vol. LT-5, pp. 1339–1350, 1987.

Hideki Fukano (M'90) was born in Fukuoka, Japan, on February 17, 1960. He received the B.E. and M.E. degrees in electrical and electronic engineering from Toyohashi University of Technology, Japan, in 1982 and 1984, respectively, and the Ph.D. degree from the Tokyo Institute of Technology, Tokyo, Japan, in 1994.

He joined the NTT Electrical Communications Laboratories (now NTT Photonics Laboratories), Kanagawa, Japan, in 1984. Since then, he has been engaged in research on heterojunction bipolar transistors (HBT's), heterojunction phototransistors (HPT's), laser diodes, photodiodes, and high-speed receiver OEIC's composed of InP material systems.

Dr. Fukano is a member of the Japan Society of Applied Physics and the Institute of Electronics, Information, and Communication Engineers (IEICE) of Japan.

Yutaka Matsuoka (M'92) received the B.S. and M.S. degrees in physics from Tokyo Institute of Technology, Tokyo, Japan, in 1974 and 1976, respectively.

In 1976, he joined the Musashino Electrical Communication Laboratory, Nippon Telegraph and Telephone Public Corporation, where he worked on electrical characterization of Si and GaAs substrates. From 1982 to 1986, his research focused on high-speed GaAs MESFET's and IC's. He is currently with NTT Photonics Laboratories, Kanagawa, Japan, where his research interests include high-performance photodiodes, InP-based heterostructure bipolar transistors, OEIC's, and microwave/millimeter-wave photonics.