# $W$-Band Waveguide Photomixer Using a Uni-Traveling-Carrier Photodiode With 2-mW Output

Akitoshi Ueda, Takashi Noguchi, Hiroyuki Iwashita, Yutaro Sekimoto, Masato Ishiguro, *Senior Member, IEEE*, Shuro Takano, Tadao Nagatsuma, *Senior Member, IEEE*, Hiroshi Ito, *Member, IEEE*, Akihiko Hirata, and Tadao Ishibashi, *Member, IEEE*

***Abstract*—We have developed a $W$-band (75–110 GHz) waveguide photomixer with a uni-traveling carrier photodiode, which can be driven by two 1.5-$\mu$m lasers. It generates an output power of 2.2±0.2 mW at 100 GHz with a laser power of less than 100 mW, and its relative power variation is as small as 3 dB across the entire frequency range of the $W$-band. A 100-GHz superconductor–insulator–superconductor receiver driven by this photomixer shows the same noise temperature around 26 K as that driven by a conventional Gunn oscillator.**

***Index Terms*—Local oscillator (LO), millimeter wave, photomixer, radio astronomy, sub-millimeter wave, uni-traveling carrier photodiode.**

## I. Introduction

MILLIMETER-WAVE and sub-millimeter-wave sources with large output power, high purity of frequency, high stability, and large frequency tunability have many applications in radio astronomy, spectroscopy, information transmission, light computerized tomography, etc. These sources are especially essential for coherent receivers as a local oscillator (LO). The large radio telescope Atacama large millimeter/sub-millimeter array (ALMA) is planned to achieve a large collecting area and high resolution. The ALMA will be constructed at the desert of Atacama, Chile. The observation frequency range is from 30 to 950 GHz. Designed baseline length of the radio interferometer is approximately 14 km. The local source for such a heterodyne detection of a radio-astronomical signal is needed to have high purity of frequency, wide tuning range, ultra-low noise, and transmission capability for long distance. Thus, we have to develop methods of LO signal transmission and local signal generation.

Solid-state oscillators such as a Gunn oscillator have been used for this purpose in millimeter wavelengths. However, they do not have a large tuning range of frequency (typically 10%), and maximum radiation frequency is limited below 150 GHz without a multiplier [1]. Apart from the Gunn oscillator, a high electron-mobility transistor (HEMT) oscillator [2], yttrium–iron–garnet (YIG) oscillator/HEMT power amplifier [3], and flux-flow oscillator [4] are developed in the millimeter wavelength range. In the sub-millimeter wavelength, frequency multipliers with millimeter-wave oscillators are also used [5]. However, they are also limited in tuning range and output power. For the millimeter and sub-millimeter wavelengths range, the photomixer is a promising device because of the wide tuning range and small package. Low-temperature-growth (LTG) GaAs photomixers have been developed for terahertz applications [6]–[9]. They have large tunability and high purity of frequency [10]. Verghese *et al.* demonstrated that the driving of a superconductor–insulator–superconductor (SIS) mixer at 630 GHz with an LTG GaAs photomixer using a Martin–Pupplett interferometer had comparable performance of a Gunn oscillator case with a noise temperature of 331 K [11]. However, these pioneering works are limited in terms of the output power. In addition, an LTG GaAs requires light with a wavelength of 800 nm, which is not suitable for long-distance transmission with a low transmission loss compared with that of 1.55 $\mu$m.

Recently, an ultrafast InP/InGaAs photodiode called a uni-traveling-carrier photodiode (UTC-PD), which is sensitive to the light covering a wavelength of 1.55 $\mu$m, has been developed [12]. Photogenerated holes in this photo diode do not dominate the response speed due to the collective motion of majority holes in the absorption layer, and only electrons play as active carriers. Therefore, it has a fast response compared with a conventional p-i-n photodiode. The InP/InGaAs UTC-PD, which has a p-type photo-absorption layer and a wide-gap electron-collection layer, has a higher saturation output while maintaining a fast response. Recently, Ito *et al.* reported a pulse response for the InP/InGaAs UTC-PD of 0.97 ps [full width at half maximum (FWHM)] [13], which corresponds to a 3-dB down bandwidth of 310 GHz. The UTC-PD is driven by lasers whose emission wavelength is 1.55 $\mu$m. The amplification and a low-loss transmission of the 1.55-$\mu$m signal is viable so that the UTC-PD is a promising device for a millimeter and submillimeter photomixer [14]. This paper reports on the performance of a $W$-band waveguide photomixer using the UTC-PD.

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A. Ueda, T. Noguchi, H. Iwashita, Y. Sekimoto, M. Ishiguro, and S. Takano are with the National Astronomical Observatory of Japan, Tokyo 181-8588, Japan.

T. Nagatsuma and A. Hirata are with the NTT Microsystem Integration Laboratories, Kanagawa 243-0198, Japan.

H. Ito is with the NTT Photonics Laboratories, NTT Corporation, Kanagawa 243-1098, Japan.

T. Ishibashi is with the NTT Electronics Corporation, Kanagawa 243-0198, Japan.

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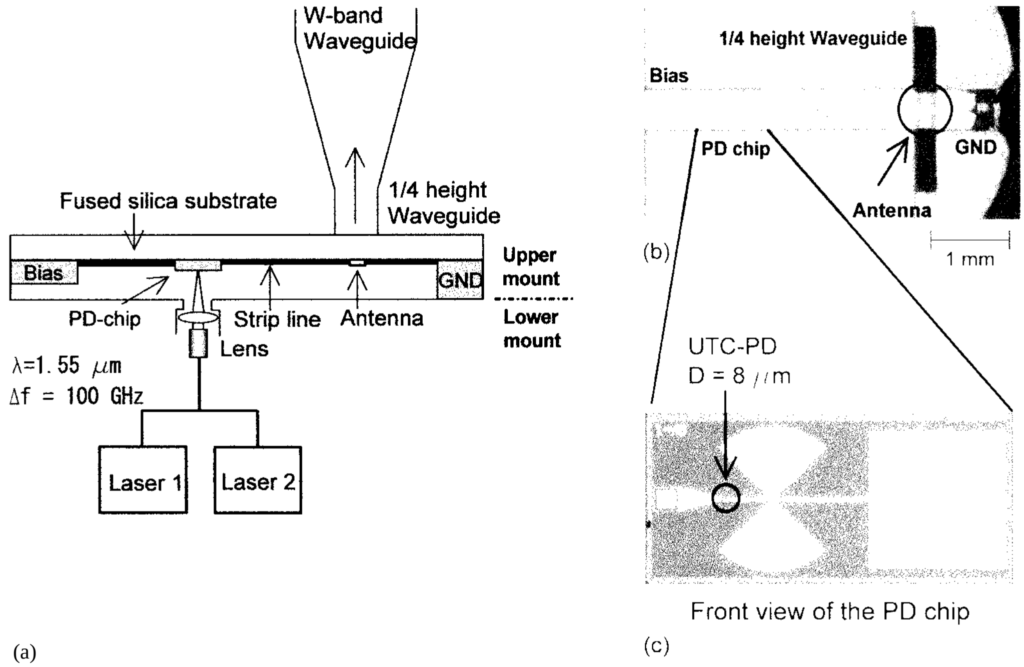



Fig. 1. (a) Schematic drawing of the photomixer. The photomixer consists of two parts of an upper mount and a lower mount. The broken line shows a separation surface of the photomixer. The waveguide size is a quarter height of the WR-10. The laser beam spot size on the UTC-PD is approximately 10 $\mu$m in diameter. (b) Picture of the upper mount. The fused quartz substrate is 6-mm long, 0.6-mm wide, and 0.15-mm thick. A simple cross-shaped antenna of microstrip-to-waveguide transition is printed on the substrate. (c) Picture of the UTC-PD chip. Diameter of the UTC-PD is 8 $\mu$m. The UTC-PD chip is soldered upside down on a fused-quartz substrate.

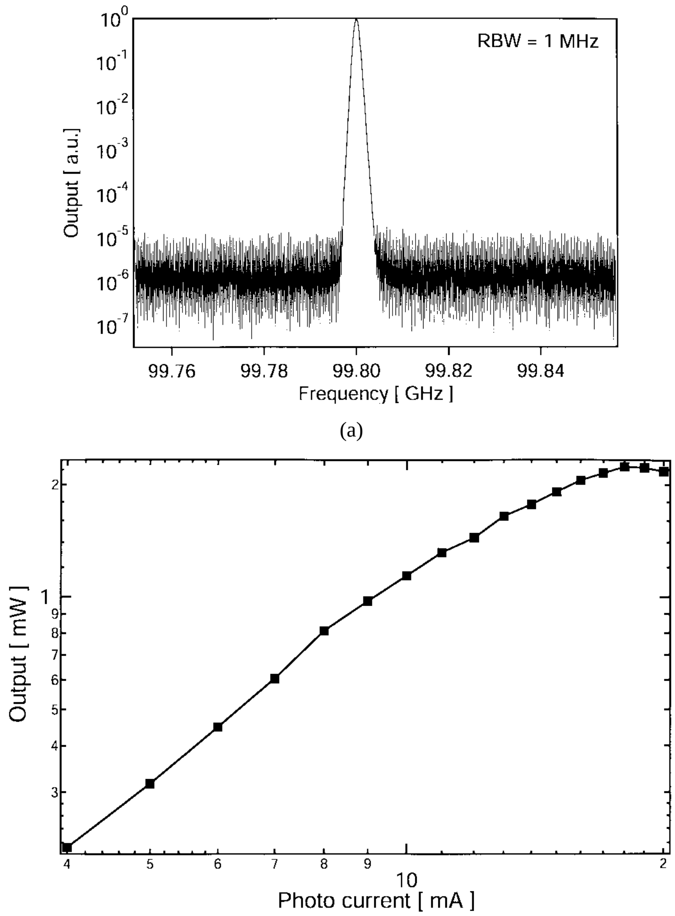
## II. Waveguide Photomixer

An InP/InGaAs UTC-PD is fabricated on an InP substrate with dc and RF signal lines, and the chip is mounted upside down on a fused quartz substrate. The substrate is then placed across a microstrip channel and a quarter-height $W$-band waveguide.

A simple cross-shaped microstrip waveguide transition formed on the quartz substrate is designed to couple the output power into the waveguide [15]. A return loss between the microstrip channel and quarter-height waveguide is calculated to be approximately $-15$ dB for the frequency range of 75–110 GHz with the High Frequency Structure Simulator (HFSS) (Agilent Technologies, Palo Alto, CA). In designing the RF circuit, the UTC-PD was modeled to have a current source with a parallel capacitor (20–30 pF) and a series resistance. An effective load resistance value for the UTC-PD was chosen to be 25 $\Omega$. The UTC-PD is coupled with a tapered strip-line transition, which transforms an output impedance of the UTC-PD to 50 $\Omega$. Schematic drawing of the waveguide mounted UTC-PD is shown in Fig. 1. The photodiode diameter is 8 $\mu$m. The UTC-PD is driven by the optical beating of the combined output of two distributed feedback lasers whose emission wavelengths are around 1.55 $\mu$m and the output power is 20 mW. The output power is amplified with an Er-doped fiber amplifier to 100 mW. The laser linewidth is a few 100 kHz at free running. A polarization controller is inserted in an optical path in order to improve contrast of the interference. Output of the fiber coupled semiconductor laser diodes are combined to a single-mode fiber using a 3-dB coupler. The beam from the single-mode fiber through relay lenses of a self-focus and plano-convex irradiates the UTC-PD. Estimated beam size on the device is approximately 10 $\mu$m in diameter.

An example of the measured spectrum at 100 GHz from the photomixer is shown in Fig. 2(a). The generated RF signal is measured by use of a harmonic mixer HP11970W (Agilent Technologies, Palo Alto, CA) and spectrum analyzer HP-8562 (Agilent Technologies, Palo Alto, CA). The spectrum has approximately 50-dB signal to noise ratio at 1-MHz frequency resolution. A fiber is aligned to the PD so that the photocurrent is maximized using a three-axis stage. The allowance of this setting is around a few micrometers. A relation of photocurrent and output power is shown in Fig. 2(b). The output power is also measured by use of a calibrated Schottky diode. Calibration of the Schottky diode (waveguide detector DXP-08-RPFWO, Millitech, Northampton, MA) is performed using a backward-wave oscillator and a power meter (PS-28-6A, Dorado, Seattle, WA). The maximum output power is 2.2$\pm$0.2 mW at the frequency of 99.8043 GHz. At this point, the photocurrent of the UTC-PD was 20 mA and the bias voltage was $-2$ V. Output power saturation is observed at a photocurrent of around 20 mA for a bias voltage of $-2$ V. Detected output power may be slightly higher than true output power because the Schottky diode is a broad-band detector, but no spurious signal is observed around the signal in Fig. 2(a). This output power is approximately ten times larger as compared with other types of photomixers.

Measurements of output power are made over a wide frequency range from 75 to 110 GHz ($W$-band). The frequency dependence of the output power is shown in Fig. 3. Relative output power variation of the photomixer as a function of frequency is less than 3 dB over the entire range of the $W$-band without any mechanical tuning commonly used for the Gunn oscillator.




(a)

(b)

Fig. 2. (a) Example of a measured 100-GHz signal from a photomixer. During the experiments, the lasers are operated at free running. The spectrum is obtained with a resolution bandwidth of 1 MHz. (b) The output power versus photocurrent. Bias point of the UTC-PD is $-2$ V. The maximum output power is 2.2±0.2 mW.

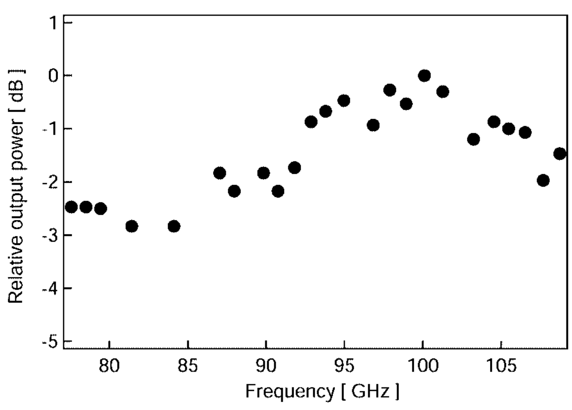



Fig. 3. Frequency characteristics of the photomixer. The relative output power change is less than 3 dB across the entire frequency range of the $W$-band waveguide.

## III. Photomixer as an LO

An SIS mixer is driven by the photomixer signal of 100 GHz. The photomixer signal is fed to an SIS mixer by quasi-optical coupling with a coupling efficiency of 5% and through a 50-$\mu$m Mylar film. The IF frequency is 4.5–7 GHz and the output power is measured by a power meter. The maximum $Y$-factor, which is the difference of the IF output power between the hot load (300 K) and cold load (77 K), is close to 5 dB at the lowest temperature of the SIS mixer. This corresponds to the noise temperature of 26 K in the double-sideband (DSB) condition. The result is almost the same as that obtained by a Gunn oscillator. We did not find out any significant differences of characteristics between a Gunn oscillator and the photomixer in this experiment. The excess noise generated by the photomixer is less than 10 K. The relationship between the frequency and $Y$-factor is measured by a power meter. Systematical errors of the measurements are approximately 0.2 dB.

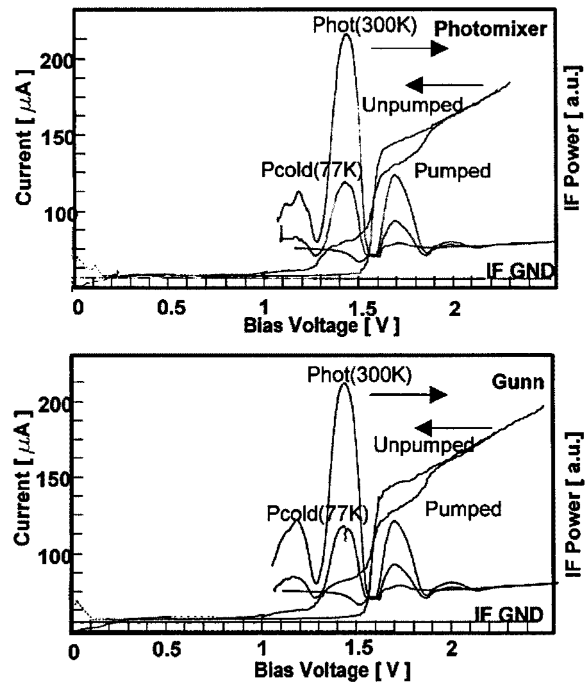



Fig. 4. Example of the current–voltage curve and IF output power for a hot load (300 K) and cold load (77 K). The upper panel shows the result of the photomixer pumping and the lower one shows a case of the Gunn oscillator pumping. The IF output power was recorded under the condition that the water vapor in the atmosphere was attached on an RF window during the measurements. Ordinate for the IF output is not scaled.

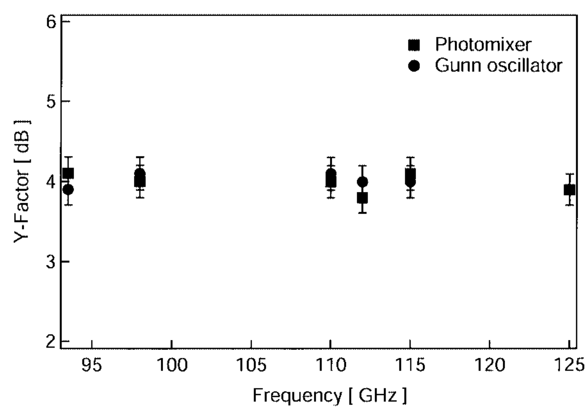



Fig. 5. Frequency dependence of $Y$-factors obtained with a photomixer and Gunn oscillator.

Examples of the plotted current–voltage curve and IF output power for the hot (300 K) and cold load (77 K) conditions are shown in Fig. 4. The upper panel shows the result of the photomixer pumping and the lower panel shows a case of the Gunn oscillator pumping. On a steady state, the Gunn oscillator and photomixer show $Y$ factors of around 4.2 dB, such as shown in Fig. 5. In this experiment, no significant difference is observed between the Gunn oscillator and photomixer case.

## IV. Conclusions

A waveguide photomixer at 100 GHz has been fabricated and demonstrated using the UTC-PD. The photomixer is driven by two lasers ($\lambda = 1.55$ $\mu$m) having slightly different frequencies. The maximum output power is 2.2$\pm$0.2 mW at the frequency of 100 GHz. This output power is approximately ten times larger as compared with other types of photomixers. The frequency range of the output signal covers the entire $W$-band (75–110 GHz), and relative variation of the output power is less than 3 dB. These results suggest that the UTC-PD is very promising for fabrication of a wide-band millimeter and sub-millimeter LO. The photomixer and a Gunn oscillator have almost the same characteristics in heterodyne mixing using SIS mixers with a noise temperature of 26 K.

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**Akitoshi Ueda** received the Ph.D. degree in electrical engineering (in the field of quantum electronics) from the University of Electro-Communications, Tokyo, Japan, in 1999.

From 1999 to 2000, he was engaged with the Gravitational Wave Detector Project with the National Astronomical Observatory. In 2000, he joined the Radio Observatory Division, National Astronomical Observatory, Tokyo, Japan. His current research involves the photonic local system and development of ultra-stable lasers.

Dr. Ueda is a member of the Physical Society of Japan, the Japan Society of Applied Physics, the Institute of Lasers, and the Astronomical Society of Japan.

**Takashi Noguchi** was born in Saitama, Japan, on April 3, 1952. He received the B.S., M.S., and Ph.D. degrees in applied physics from Tohoku University, Sendai, Japan, in 1976, 1978, and 1981, respectively.

In 1981, he joined the Central Research Laboratory, Mitsubishi Electric Corporation, where he was engaged in the research and development of superconducting devices for analogy applications. In 1981, he joined the Nobeyama Radio Observatory, National Astronomical Observatory of Japan, Nagao, Japan. His current research interest is in the area of development of superconducting devices for millimeter- and submillimeter-wave receivers.

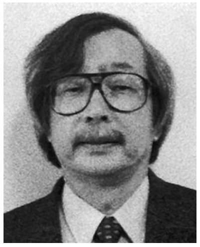
Dr. Noguchi is a member of the Institute of Electrical, Information and Communication Engineers (IEICE), Japan, and the Japan Society of Applied Physics.

**Hiroyuki Iwashita** was born in Nagano Prefecture, Japan, in February 1964. He received the Electrical Engineering degree from Iwamurada High School, Nagano Prefecture, Japan, in 1982.

In 1982, he joined the Nobeyama Radio Observatory, National Astronomical Observatory of Japan, Tokyo, Japan.

**Yutaro Sekimoto** received the Ph.D. in physics (in the field of gamma-ray astronomy) from the University of Tokyo, Tokyo, Japan, in 1994.

From 1994 to 1999, he was engaged with the Mt. Fuji Submillimeter-Wave Telescope Project with the University of Tokyo. In 1999, he joined the National Astronomical Observatory of Japan, Tokyo, Japan, where he is currently an Associate Professor of radio astronomy. His current research involves submillimeter astronomy and submillimeter receivers.



**Masato Ishiguro** (A'81–SM'85) received the B.S. and M.S. degrees in electrical engineering from Nagoya University, Nagoya, Japan, in 1968 and 1970, respectively, and the Ph.D. degree in physics from the University of Tokyo, Tokyo, Japan, in 1980.

From 1970 to 1980, he was with the Research Institute of Atmospherics, Nagoya University, where he was involved in the construction of the 3.75-GHz radioheliograph and solar radio astronomy. In 1980, he became an Associate Professor of radio astronomy with the University of Tokyo. From 1980 to 1990, he was in charge of construction and operation of the Nobeyama Millimeter Array (NMA), Nobeyama Radio Observatory (NRO). In 1988, he became a Professor of radio astronomy with the National Astronomical Observatory of Japan (NAOJ), Tokyo, Japan. From 1990 to 1998, he served as the Director of the NRO. Since 1998, he has been promoting the Japanese part of the Atacama Large Millimeter/submillimeter Array (ALMA) as the Japanese Project Director. His major research and development interest is instrumentation for millimeter/submillimeter astronomy, with an emphasis on radio interferometry systems, large precision antennas, and photonics technologies.

Dr. Ishiguro is a member of the International Astronomical Union (IAU), the International Union of Radio Science (URSI), the Astronomical Society of Japan, and the Institute of Electronics, Information and Communication Engineers (IEICE), Japan.

**Shuro Takano** received the Ph.D. degree in astrophysics (in the field of microwave molecular spectroscopy and astrochemistry) from Nagoya University, Nagoya, Japan, in 1991.

He then joined the Nobeyama Radio Observatory, as a Post-Doctoral Fellow. He then joined the Institute for Molecular Science, as a Research Associate. From 1995 to 1998, he was with the University of Cologne, Cologne, Germany, where he continued his studies of astrochemistry and molecular spectroscopy. In 1998, he rejoined the Nobeyama Radio Observatory, National Astronomical Observatory of Japan, Tokyo, Japan, where, since 2001 he has been a Research Associate. His current research involves astrochemistry, mainly with the 45-m radiotelescope.

**Tadao Nagatsuma** (M'93–SM'02) received the B.S., M.S., and Ph.D. degrees in electronic engineering from Kyushu University, Fukuoka, Japan, in 1981, 1983, and 1986, respectively.

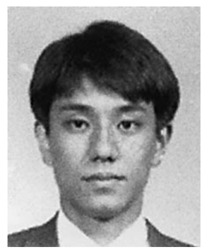
In 1986, he joined the Atsugi Electrical Communications Laboratories, Nippon Telegraph and Telephone Corporation (NTT), Kanagawa, Japan. He is currently a Distinguished Technical Member, Senior Research Scientist, and Group Leader with the NTT Microsystem Integration Laboratories, Kanagawa, Japan. His current research involves ultrahigh-speed electronics and millimeter-wave photonics and their application to sensors and communications.

Dr. Nagatsuma is a member of the Optical Society of America and the Institute of Electronics, Information and Communication Engineers (IEICE), Japan. He was the recipient of the 1989 Young Engineers Award presented by the IEICE, the 1992 IEEE Andrew R. Chi Best Paper Award, the 1997 Okochi Memorial Award, the 1998 Japan Microwave Prize, and the 2000 Minister's Award of the Science and Technology Agency.

**Hiroshi Ito** (M'92) received the B.S. and M.S. degrees in physics, and Ph.D. degree in electrical engineering from Hokkaido University, Hokkaido, Japan, in 1980, 1982, and 1987, respectively.

Since joining NTT Photonics Laboratories, Kanagawa, Japan, in 1982, he has been involved in research on growth and characterization of III–V compound semiconductors using molecular beam epitaxy (MBE) and MOCVD and their applications to devices such as HBTs, FETs, lasers, and photodiodes. From 1991 to 1992, he was a Visiting Scientist with Stanford University. His current research interests focus on ultrafast optoelectronic devices.

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



**Akihiko Hirata** was born in Kyoto, Japan, on August 24, 1968. He received the B.S. and the M.S. degrees in chemistry from Tokyo University, Tokyo, Japan, in 1992 and 1994, respectively.

In 1994, he joined the NTT LSI Laboratories (now NTT Microsystem Integration Laboratories), Kanagawa, Japan, where he has been engaged in the research of millimeter-wave antenna and photonics technologies.

Mr. Hirata is a member of the Japan Society of Applied Physics.

**Tadao Ishibashi** (M'89) was born in Sapporo, Japan, in 1949. He received the Ph.D. degree in applied physics from Hokkaido University, Hokkaido, Japan, in 1986.

Since joining NTT Laboratories, Musashino, Tokyo, Japan, in 1973, he has been involved in research of semiconductor devices and related material processing. His work has included submillimeter-wave Si IMPATT diode oscillators, LPE growth of InP–InGaAs materials and their application to FETs, MBE growth of multiple quantum well (MQW) structures for laster diodes, GaAs- and InP-based HBT integrated circuits (ICs), ultrahigh-speed photodetectors, and integrated optical switches based on electroabsorption modulators. From 1991 to 1992, he was with the Max-Planck-Institute, Stuttgart, Germany, as a Visiting Scientist. In 2001, he joined the NTT Electronics Corporation, Kanagawa, Japan, where he is currently involved with the development of semiconductor optical components for fiber-optic systems. He is also a Visiting Professor with Tohoku University since 2001.