Advances in Millimeter-Wave Subsystems in Japan

Susumu Kitazume, *Member*, *IEEE*, and Hidetoshi Kondo

Abstract—**With the increase in demand for communication system capacity, the millimeter-wave frequency band has become a valuable resource because of its bandwidth, extending from 30 GHz to 300 GHz, nine times the presently developed communications bands. As a result, research and development on millimeter-wave systems have been promoted in several organizations in Japan (NTT, CRL, NASDA, SCR). This paper describes the development trends and results of millimeter-wave systems in Japan in such fields as communication, radar, and measurement systems. Also, it describes the development of devices such as high-power FET amplifiers, TWTA's, IMPATT amplifiers, low-noise amplifiers, and MMIC devices used in constructing the millimeter-wave systems.**

I. Introduction

APPLICATIONS of millimeter-wave systems in Japan have centered on communications, radar, and measurement systems. In millimeter-wave communications, waveguide transmission systems, ground propagation systems, and satellite communication systems have been developed. In ground communications, millimeter-wave applications have been limited by propagation characteristics, mainly rainfall attenuation and atmospheric absorption. On the other hand, propagation in space is usually straightforward and millimeter waves are well suited for space communication.

In millimeter-wave radar applications, there are weather, harbor, and airport fixed radars and mobile radars for motor vehicles and aircraft. In millimeter-wave measurement system applications, there are radiometer, scatterometer, and interferometer systems.

II. Development of Millimeter-Wave Technology

The development status of millimeter-wave technology in Japan is shown in Fig. 1. Research and development work on millimeter-wave systems in Japan was started about 20 years ago with a W-40G waveguide transmission system [1] by NTT. The development of millimeter-wave propagation systems, 50–250 GHz propagation test equipment [2], and 40–60 GHz ground communication equipment has been under way since 1972 by CRL and NTT. In the space applications, the communication satellite CS series was started in 1973 by NTT, CRL, and NASDA. This series used the 30 GHz band. In millimeter-wave applied engineering, measurement of plasma electron density using JT-60 diagnostic equipment, radiometer applications using the 40–60 GHz band, and collision avoidance radar systems for automobile applications have been developed.

A. W-40G Waveguide Transmission Communication System

The main features of the W-40G system are shown in Table I [1]. The frequency allocation is 43 GHz to 87 GHz and millimeter-wave channel spacing is in 0.8 GHz steps. Transmission capacity is 300 000 telephone channels. Pulse code modulation, 4-phase shift keying modulation, and coherent detection demodulation are used.

B. Propagation System Experiments

In order to study millimeter-wave propagation characteristics, several kinds of test equipment are made in Japan. The transmission frequencies are 82 GHz, 103 GHz, 140 GHz, and 240 GHz, and many valuable data are obtained [2]. Features of these propagation test equipment are given in Table II.

Another example of a millimeter-wave system in Japan is shown in Fig. 2, which is an automobile traffic control system using the 60 GHz band [3]. This system has the capability of isolating the system interference caused by the absorption by oxygen molecules in the atmosphere.

Fig. 3 shows a collision avoidance radar system for an automobile [4]. The FM-CW or pulse Doppler emission is used, and distances of 1 to 150 m are measured by using 50–60 GHz.

The 50 GHz ground communication system named Pasolink 50 [5] is shown in Fig. 4. Television conferencing from building to building is possible with this system.

C. Applied Engineering

With regard to applied millimeter-wave engineering, a plasma electron density measuring system, the JT-60 diagnostic equipment [6], has been developed. Fig. 5 shows a photograph and a summary of the performance of the JT-60 millimeter-wave interferometer. By using a frequency of 137 GHz, plasma electron density of 5×

Manuscript received August 20, 1990; revised December 3, 1990.
The authors are with the NEC Corporation, 4035, Ikebe-cho, Midori-ku, Yokohama 226, Japan.
IEEE Log Number 9143006.

0018-9480/91/0500-0775$01.00 ©1991 IEEE

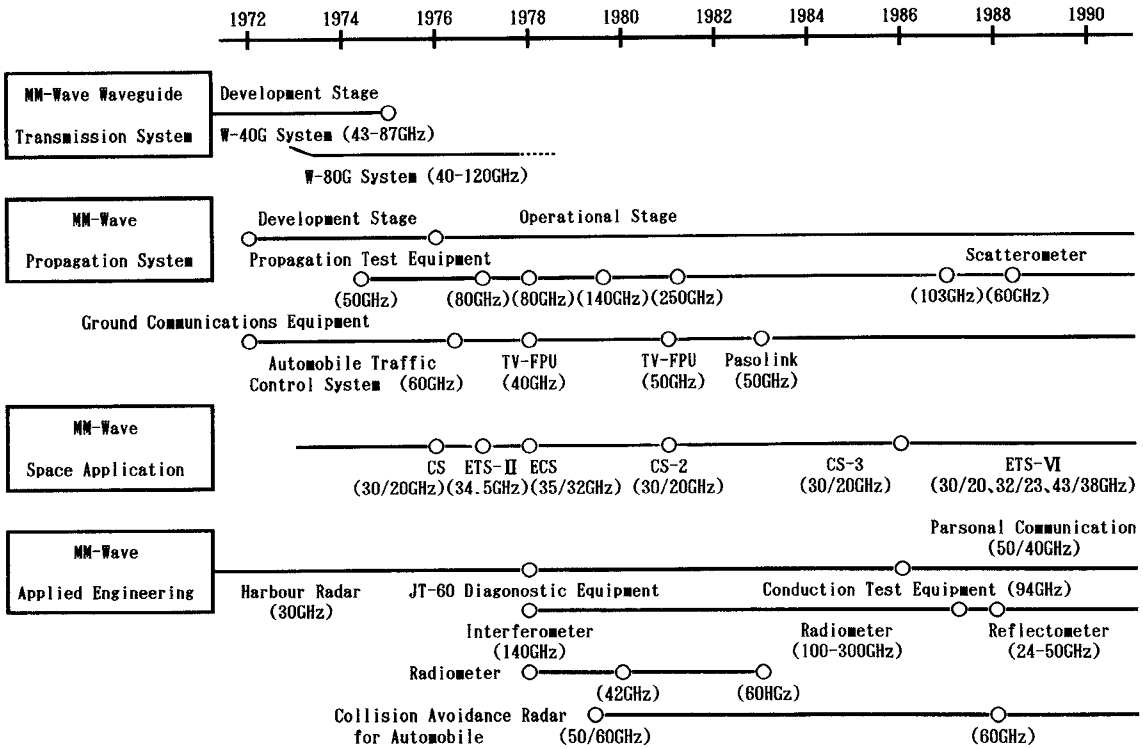


Fig. 1. Development of millimeter technology in Japan.

TABLE I
MAIN FEATURES OF W-40G SYSTEMS

Overall Transmission Band	43.40 ~ 86.74 GHz
Millimeter-Wave Channel Spacing	0.8 GHz
Number of Channels	26 working and 2 standby 300 000 channels
Standard Waveguide	Hybrid-tandem (4 dielectric and 1 helix) 51 mm diameter and 5 m length
Bit Rate	0.8 Gb/s per millimeter-wave channel
Modulation	PCM 4-PSK
Demodulation	Coherent detection

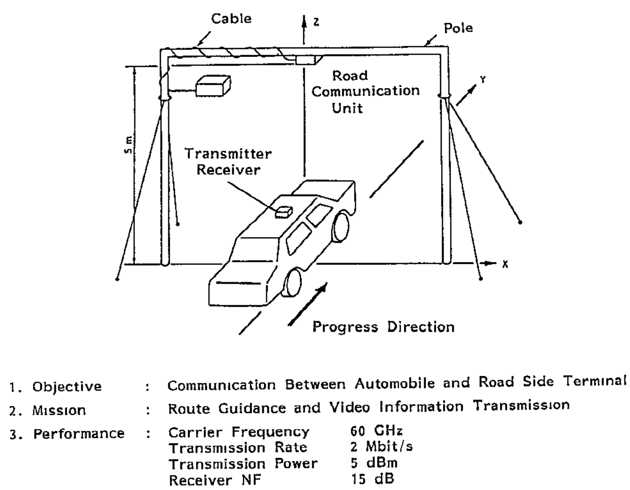
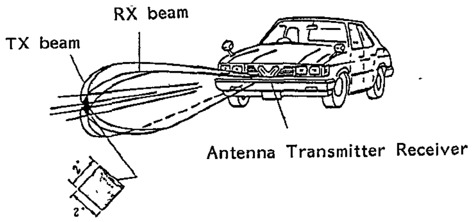


Fig. 2. Automobile traffic control system.

TABLE II
MILLIMETER-WAVE PROPAGATION TEST EQUIPMENT

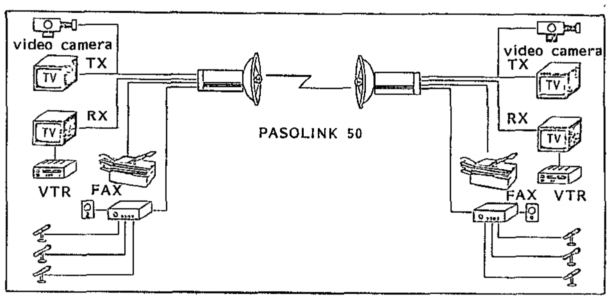
ITEM	A	B	C	D
Organ.	NTT	CRL	CRL	NDTK
TX Frequency	82 GHz	140 GHz	80/240 GHz	103 GHz
TX Orig. OSC	X'TAL 5 MHz	X'TAL 26.6 MHz	IMPATT 81.8 GHz	X'TAL 107 MHz
HPA	FET AMP 2 GHz	IMPATT 70.3 GHz	IMPATT 81.8 GHz	IMPATT 51.5 GHz
FINAL ST	MLT/×41	MLT/×2	MLT/×3	MLT/×2
TX Power	+7.9 dBm	−3 dBm	+15/−4.9 dBm	+6.5 dBm
RX Front end	MIX	MIX (2nd)	MIX (F/3rd)	MIX



ITEM	SAMPLE 1	SAMPLE 2
Radar Mission	FM-CW	Pulse-Doppler
Frequency	50 GHz	60 GHz
Transmitter	GUNN OSC	GUNN OSC
Transmission Power	50 mW	50mW
Receiver	Homodyne Detect	Homodyne Detect
Distance Measuring Range	1~100 m	5~150 m

Fig. 3. Collision avoidance radar for automobile.

TV Conference System Between Two Buildings



Frequency : 50.44 ~ 51.10 GHz
Transmission Rate : 2.048 Mb/s or 6.312 Mb/s
Modulation : FSK
Transmission Power: 12 dBm

Fig. 4. 50 GHz Pasolink system.

$10^{13}/cm^3$ can be measured. A block diagram is shown in Fig. 6.

D. Space Applications

In systems for millimeter-wave satellite communication, the 30 GHz band is used for the Communication Satellite CS series [7] (CS, ECS, CS-2, CS-3), and a 43 GHz/38 GHz millimeter-wave transponder [8] has been developed for the Engineering Test Satellite VI (ETS-VI). These are to demonstrate personal satellite communication and establish millimeter-wave intersatellite link technology (CRL, NASDA).

III. Millimeter-Wave Communication Satellites

A summary of millimeter-wave communication satellites in Japan is shown in Table III. An experimental communications satellite, Sakura, was launched in 1977, followed by two successors in 1983. These were the CS-2a and the CS-2b, and both carried six Ka-band transponders. They operated well, and in 1988 their successors, the CS-3a and the CS-3b, were put into orbit. These have ten Ka-band transponders.

Japanese communications satellites have used 30/20 GHz, that is, Ka-band transponders in addition to C-band transponders. Although millimeter waves have been used only in the up-link frequency, it has been predicted that satellite communications will use higher frequencies in the future.

The Engineering Test Satellite, ETS-VI, to be launched in 1993, will be equipped with 43/38 GHz transponders and will be used to promote the development of mobile communication satellite technology.

A. Engineering Test Satellite VI

The ETS-VI is the first millimeter-wave communication test satellite after the ECS in Japan [8]. The experiment will be conducted using the millimeter-wave transponder, the feeder link transponder, and a millimeter-wave antenna with beam steering function. The millimeter-wave transponder electrical model has been completed. The satellite is scheduled for launch in 1993.

The experimental system's space segment, as shown in Fig. 7, is composed of a millimeter-wave antenna, a millimeter-wave transponder, a feeder link transponder, and two large antennas [9], [10]. In the millimeter-wave transponder, a 43 GHz low-noise amplifier and a 38 GHz solid-state power amplifier are used.

The performance of the millimeter-wave transponder is summarized in Table IV. The noise figure is 6.7 dB at diplexer input and the output power is 27.6 dBm at diplexer output. The power consumption is 31.5 W or less, and the weight excluding the antenna is 9.7 kg. The millimeter-wave transponder electrical model is shown in Fig. 8.

B. Application System of MMW Satellite Communication

The advantages of millimeter-wave satellite communications are wide frequency band, compact earth terminal, and less interference between communications systems caused by absorption by oxygen molecules in the atmosphere. Personal satellite communications and intersatellite communications links are envisioned for the future.

Millimeter-wave personal satellite communications systems are now being considered [11]. Personal satellite communication will be used for portable video phone systems, portable news gathering and distribution systems, medical and health consultation systems, and information exchange systems.

The intersatellite communication systems are used for communicating from geostationary orbit to geostationary orbit, from spacecraft to geostationary orbit, and from low earth orbit to geostationary orbit.

The millimeter-wave transponder for the geostationary platform consists of a 50 GHz receiver, a baseband switch, a 40 GHz transmitter, and RX/TX antennas.

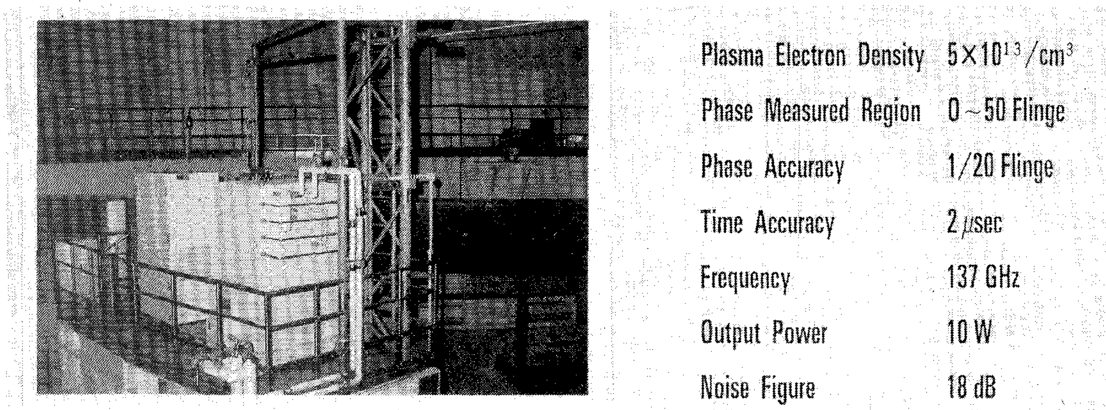


Fig. 5. JT-60 millimeter-wave interferometer.

TABLE III
SUMMARY OF MILLIMETER-WAVE COMMUNICATION SATELLITES IN JAPAN

ITEM	CS	ECS	CS-2	CS-3	ETS-6		
Mission	Fixed	Fixed	Fixed	Fixed	Fixed	Mobil	ISL
Launch	1977	1979	1983	1988		1993	
Frequency (GHz)	30/20	35/32	30/20	30/20	30/20	43/38	32
Output Power	2.5 W	2.5 W	2.5 W	4.2 W	10 W	0.5 W	2.6 W
Output Element	TWTA	TWTA	TWTA	TWTA	TWTA	SSPA	SSPA
No. of Transponders	6	1	6	10+5	4 Beam	1	1

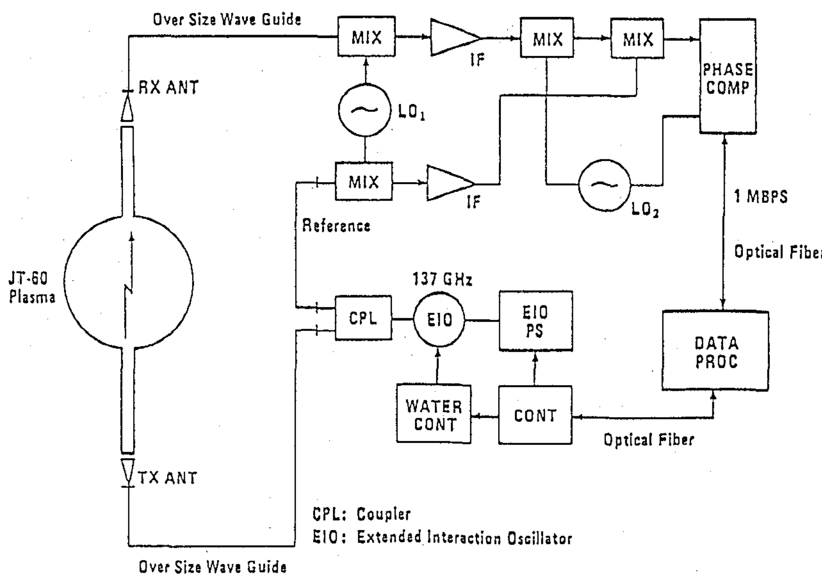


Fig. 6. Block diagram of JT-60 plasma diagnostic system.

The performance of the millimeter-wave transponder for geostationary platform is summarized in Table V. The up-link frequency is 50 GHz and a receiver noise figure of 3 dB will be obtained. The down-link frequency is 40 GHz and a transmit power of more than 20 W will be obtained.

IV. DEVELOPMENT OF MILLIMETER-WAVE DEVICES

A. High-Power Devices

The development of millimeter-wave devices is proceeding in Japan. The performance of the solid-state power amplifier used in the ETS-VI satellite is summarized in Table VI [8]. At 38 GHz, an output power of 29 dBm is obtained. The configuration of this SSPA is shown in Fig. 9. At the final stage, four GaAs FET's are connected in parallel.

Fig. 10 shows the advances in output performance of GaAs FET amplifiers. At 30 GHz, an output power of 1 W has been obtained and predictions are that it will increase to 2 W in 1992.

For higher frequencies, the InP MISFET is suitable because of its high cutoff frequency, f_T. For example, an f_T of 100 GHz is obtained, as summarized in Table VII.

At frequencies over 50 GHz, the IMPATT diode amplifier is used. Fig. 11 shows the output performance of an

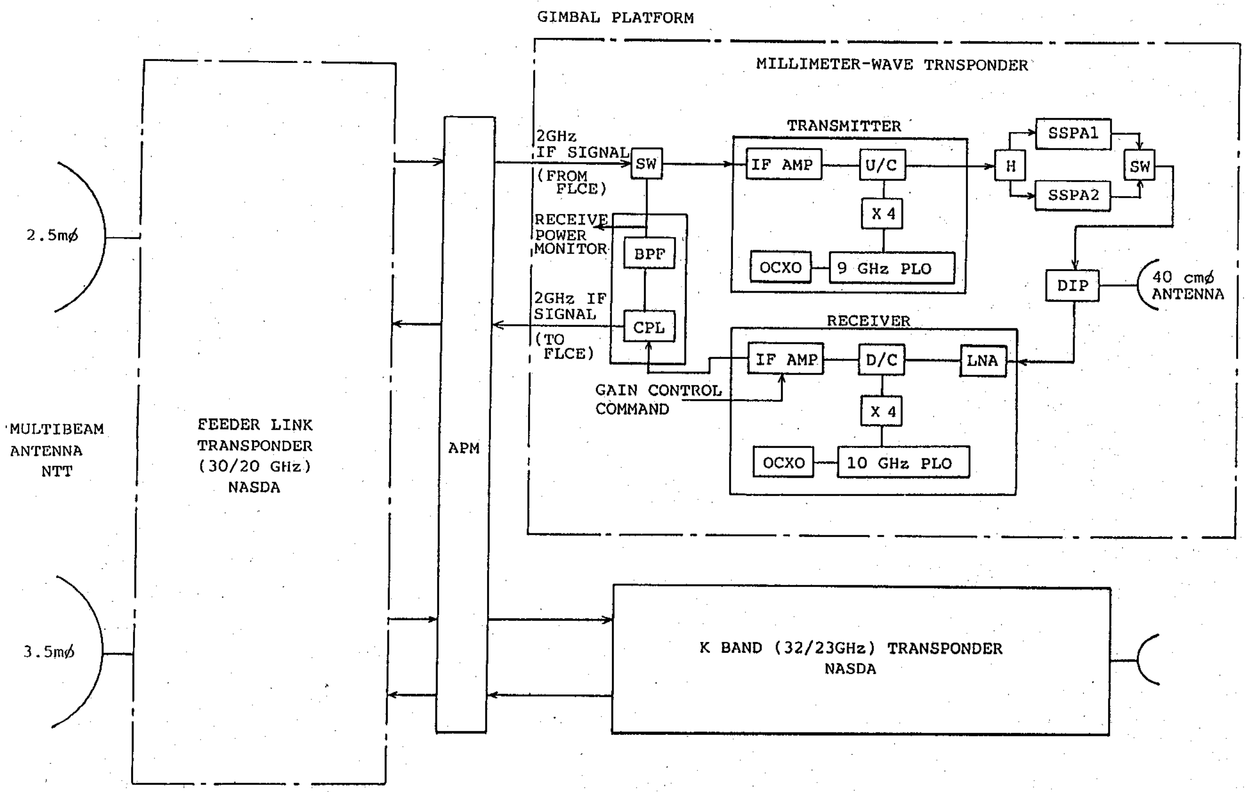


Fig. 7. Configuration of ETS-VI on-board millimeter-wave satellite communications experimental system.

TABLE IV
PERFORMANCE OF MILLIMETER-WAVE TRANSPONDERS

	Item	Performance
1	Input Frequency	43.0 ± 0.05 GHz
2	Output Frequency	38.0 ± 0.1 GHz
3	IF Frequency	1.98 GHz
4	Bandwidth	1.2 MHz
5	Noise Figure	6.7 dB
6	Input Power	−70 dBm max
7	Output Power	27.6 dBm
8	Weight	9.7 kg
9	Power Consumption	31.5 W

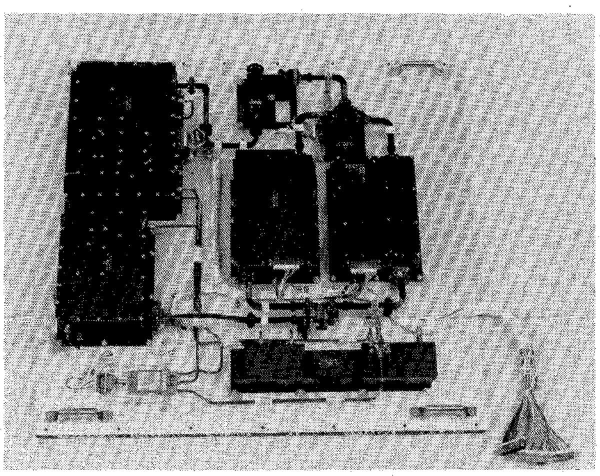


Fig. 8. Millimeter-wave transponder.

TABLE V
MILLIMETER-WAVE TRANSPONDER FOR GEOSTATIONARY PLATFORM

Item	Performance
Frequency	Up-Link 50 GHz Down-Link 40 GHz
Antenna Diameter	2 m
Beam Number	20 or more
Communication Type	Up-Link SCPC/FDMA Down-Link TDM Baseband Switch
Modulation	PSK
Transmission Rate	64 kb/s
Bit Error Rate	1×10^{-4}
Transmit Power	20 W min
Receiver NF	3 dB max

TABLE VI
PERFORMANCE OF SSPA

	Item	Performance
1	Saturation Output Power (at −10 dBm input)	0.79 W (+29 dBm)
2	Amplitude Response (at −10 dBm input)	0.14 dB_{p-p}
3	Small-Signal Gain	43.5 dB
4	Power Consumption (at −10 dBm input) (No RF emission)	 16.8 W 14.2 W
5	Dimensions	185 × 135 × 90 mm
6	Weight	1636 g
7	Frequency	38 GHz

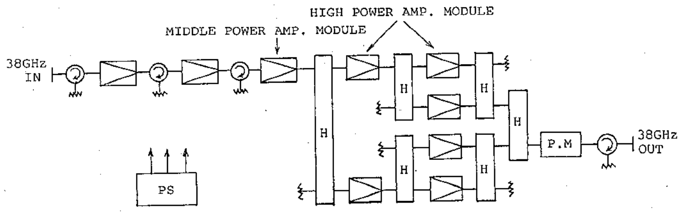


Fig. 9. Configuration of SSPA.

TABLE VII
PERFORMANCE OF InP MISFET

Item	A	B	C
Gate Width	280 μm	420 μm	420 μm
Gate Length	0.6 μm	0.6 μm	0.6 μm
Gate (at 38 G)	8.1 dB	2.5 dB	4.1 dB
Output Power	—	100 mW	85 mW
f_T	100 GHz	—	—

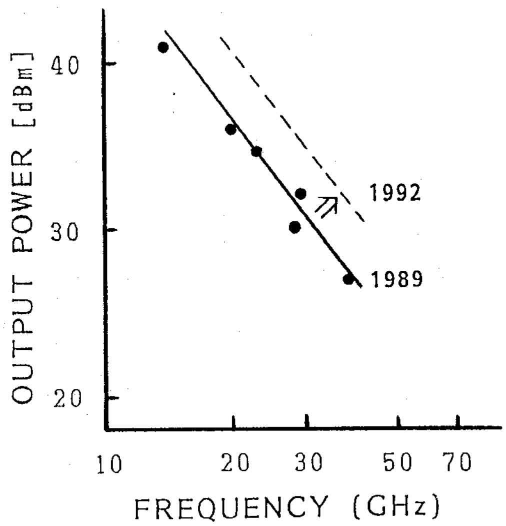


Fig. 10. Output performance of GaAs FET amplifier.

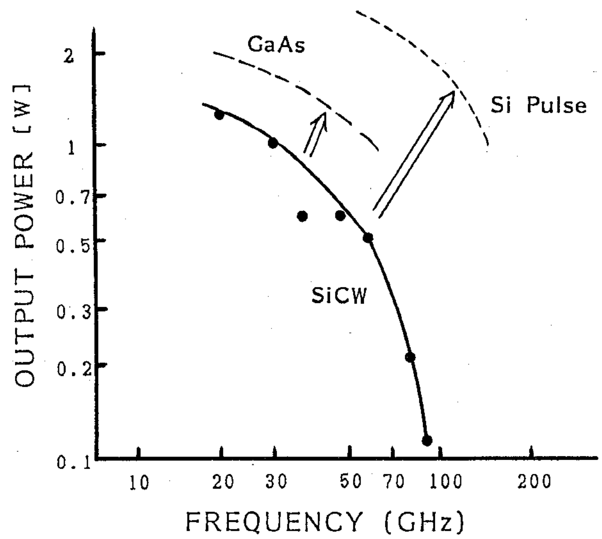


Fig. 11. Output performance of IMPATT diode.

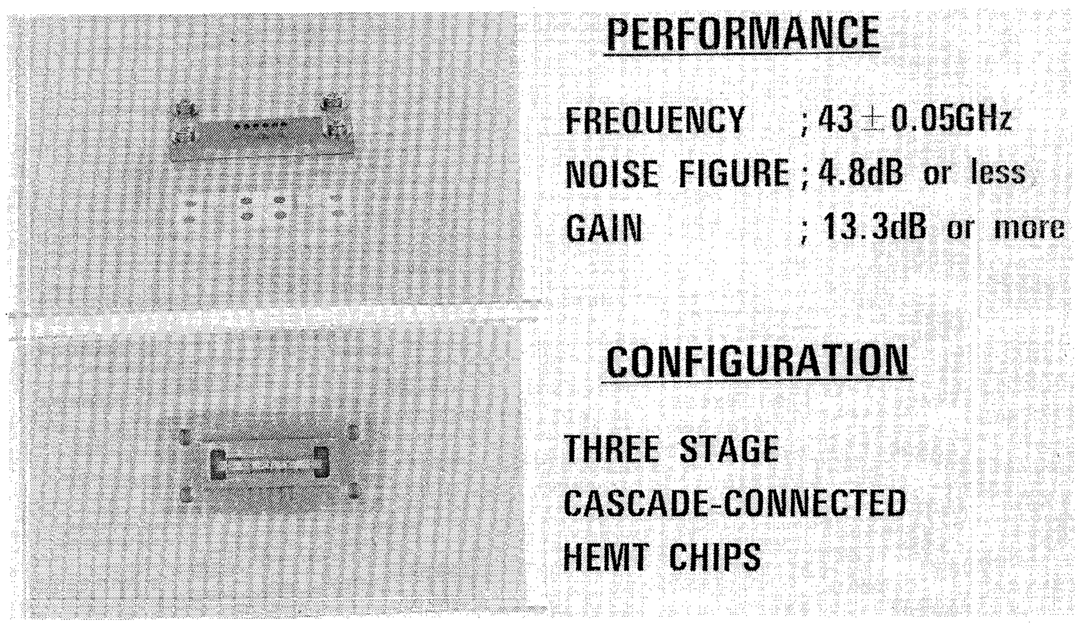


Fig. 12. LNA hybrid IC module.

IMPATT diode. At 90 GHz, an output power of 0.1 W in CW and an output power of 2 W in pulse operation have been obtained, with a pulse width 500 ns and a duty factor 1.25% [12].

In order to obtain a higher power output, millimeter-wave TWT amplifiers are being developed. As a millimeter-wave TWTA for space use, 20 W output over the frequency range of 43 to 45 GHz has been obtained, with an efficiency of 30%.

B. Low-Noise Devices

A low-noise amplifier constructed using a GaAs FET hybrid integrated circuit module is shown in Fig. 12 [13]. This module is used in the ETS-VI satellite and has a noise figure of 4.8 dB at 43 GHz.

Fig. 13 shows advances in the noise performance of GaAs FET amplifiers. At 40 GHz, a noise figure of 4 dB has been obtained, and it is predicted that this will decrease to 2 dB in 1992.

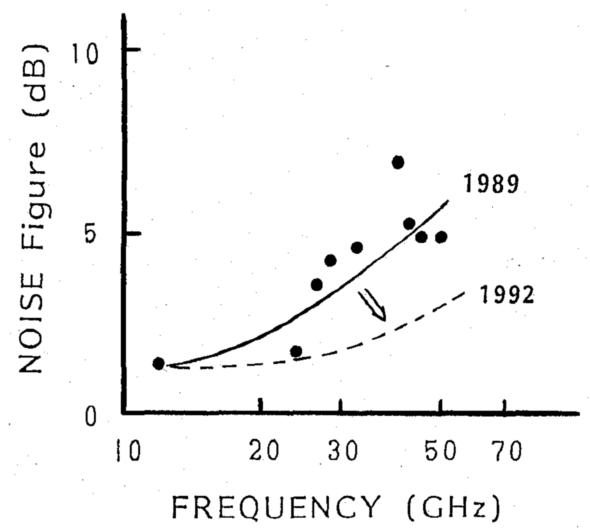


Fig. 13. Noise performance of GaAs FET amplifier.

TABLE VIII
MMIC MODULE PERFORMANCE

Chip	Function and Performance
30 GHz MIXER	Single-balance type. $L_c = 10$ dB
30 GHz AMP.	$f = 29 \sim 31$ GHz; $G = 27$ dB
30 GHz MULT.	Doubler $L_c = 5$ dB
15 GHz VCO	$f = 14.2 \sim 15.7$ GHz
15 GHz AMP.	$f = 14 \sim 16$ GHz; $G = 10$ dB
15 GHz DIVIDER	1/2 Divide $f_{in} = 14 \sim 15$ GHz

C. MMIC Devices

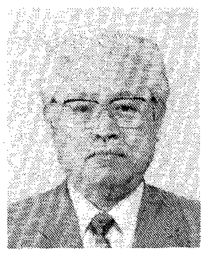
At the present time the development of MMIC devices has proceeded in order to take advantage of the small size and light weight. For example, 30-GHz-band MMIC modules (amplifiers, mixers, frequency multipliers, VCO's, dividers) are under development by NTT [14]. The functions and performance of these MMIC modules are shown in Table VIII. This technology will be applied to the millimeter-wave region in the near future.

V. CONCLUSION

In Japan, millimeter-wave systems will be applied to many areas in the next ten years. In space, communications systems for satellite to satellite, satellite to platform, and personal communications are promising. Remote sensing systems for use in radiometry, collision avoidance radar for automobiles, and earth observation will be developed. Ground communication systems for use in building to building communication and automobile traffic control systems will be put into commercial use. MMIC devices will contribute strongly to millimeter-wave system development in every phase of development and production, particularly in providing low-cost systems such as collision avoidance radar.

REFERENCES

[1] K. Miyauchi *et al.*, "Transmitter–receivers for the millimeter-wave transmission system in the 43–87 GHz range," in *Proc. 4th European Microwave Conf.*, 1974, pp. 624–628.
[2] Y. Furuhama *et al.*, "Propagation experiment program at millimeter waves," *Radio Res. Lab. Tech. J. Japan*, vol. 26, no. 138, pp. 507–553, June 1980.
[3] "Study of Road to Automobile Millimeter-wave Communication System," Automobile Electronics Tech. Soc. Report, Japan, No. 5, pp. 4–7, May, 1982.
[4] T. Takehana *et al.*, "Automotive radar using MM-wave," presented at 3rd Int. Conf. Automotive Electron., Oct. 1981.
[5] M. Ohsako *et al.*, "50 GHz millimeter wave communication system PASOLINK 50," *NEC. Tech. J. Japan*, vol. 39, no. 7, pp. 111–117, July 1986.
[6] A. Nagashima *et al.*, "Design and performance of waveguides for the JT-60 2 mm interferometer," in *Proc. 9th Int. Conf. IR and MM Waves*, Oct. 1984, pp. 264–265.
[7] N. Fugono *et al.*, "Design for the satellite transponder for the experimental communication satellite (ECS)," in *Proc. 12th Int. Symp. Space Technol. and Sci.*, 1977, pp. 661–666.
[8] M. Shimada *et al.*, "Experimental millimeter-wave satellite communication system," PTC-90, Jan. 1990.
[9] M. Tanaka *et al.*, "Experimental intersatellite data relay and tracking system for ETS-VI," in *Nat. Convention Rec., IEICE Japan*, Autumn 1989, B-109, pp. 2–109.
[10] M. Kawai *et al.*, "ETS-VI multibeam satellite communications systems," in *Proc. 40th Congress Int. Astronaut. Fed., IAF-89-520*, 1989.
[11] Y. Suzuki *et al.*, "Experimental millimeter-wave satellite communication system," in *Proc. 13th Int. Commun. Sat. Syst. Conf., AIAA-90*, Mar. 1990.
[12] H. Uchida *et al.*, "W-band double-drift pulsed IMPATT by advanced Si MBE," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1990.
[13] Y. Suzuki *et al.*, "43 GHz-band low noise amplifiers for satellite transponders," *IEICE Japan*, C-341, Oct. 1988.
[14] H. Kato *et al.*, "A 30 GHz-band full MMIC receiver for satellite transponders," *IEEE MTT-S Int. Microwave Symp. Dig.*, May 1988, pp. 565–568.



Susumu Kitazume (M'75) is a vice president of the NEC Corporation, Japan. He joined NEC in 1960 and has been engaged in research and development work on microwave communications equipment, in particular microwave devices. His work has dealt with the transponders for the Japanese Communications Satellite-2 (CS-2), the Commercial Communication Satellite (CS-3), the Aeronautical Maritime Engineering Satellite (AMEX), and INTELSAT VI. He has also worked on millimeter-wave communications equipment.

Mr. Kitazume is a member of the American Institute of Aeronautics and Astronautics and the Institute of Electronics and Communication Engineers of Japan. In 1971, he won the Invention Encouragement Prize from the Society of Invention for his work on temperature-compensated multielement waveguide devices having susceptance elements. He also won the Ichimura Special Prize from the New Technology Development Foundation in 1986 for his work on on-board equipment for satellites.

Hidetoshi Kondo is the engineering manager of the Space and Laser Communications Development Division at the NEC Corporation, Japan. He joined NEC in 1968 and has been engaged in the research and development of microwave/millimeter-wave communications equipment, especially solid-state microwave/millimeter-wave devices and circuits. He is currently developing millimeter-wave applied systems for space communications and radar sensors.