Advances in Millimeter-Wave Systems in Japan

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***Abstract*—This paper discusses recent applications of millimeter waves and the relating subsystems in Japan. Also, the recent advancement of millimeter-wave active and passive components in Japan is included.**

I. Introduction

IN RECENT YEARS, utilization of radio waves for communications has greatly increased, and countless uses of radio waves have evolved due to rapid social and economical advancement accompanied by the remarkable evolution of science and technology. These developments have caused saturation of the lower frequency bands, and, therefore, it is extremely important to develop frequency resources in the millimeter-wave region. However, utilization of millimeter waves has been severely limited, primarily due to the large atmospheric attenuation and expensive hardware.

In the World Administrative Radio Conference in 1979, the frequency spectrum from 40 to 275 GHz was allocated for terrestrial radio systems. In Japan, the 50-GHz band was first opened to simple radio communication systems in June 1983. This is the first operational use of frequencies higher than 40 GHz.

In this decade, manufacturing techniques for millimeter-wave hardware such as MIC have been developed gradually in Japan. Hardware for frequencies up to about 100 GHz is now commercially available.

It is expected that frequency utilization in the millimeter-wave region will be developed gradually by using several unique features in this region, such as propagation characteristics, the possibility of wide-band communication, devices with small size and light weight, and high antenna directivity. Some typical subsystem designs for special applications as well as recently developed components are presented below.

II. Applications and Typical Subsystems

A. Communications/Broadcasting

A radio relay system for high-definition TV (HDTV) signals has been developed by NHK (Japan Broadcasting Corporation) [1]. A 38-GHz (Gunn) oscillator is directly modulated by the HDTV video signal. The power amplifier consists of two injection-locked amplifiers with double-drift Si IMPATT diodes. The basic transmitter specification is shown in Table I. The frequency is stabilized by an AFC circuit.

Satellite TV broadcasting, which is currently operating in the *Ku*-band (BS-2), will be extended into the 22-GHz band and higher millimeter-wave bands in the future. The receiver for 22 GHz is now under research and development at NHK utilizing a planar circuit mounted in a waveguide, with a noise figure of 5 dB [2]. It is expected to be one of the best candidates for low-cost receivers in the millimeter-wave band (Fig 1).

Though not in the millimeter-wave region, a *terrestrial digital radio subscriber system* is in service in the 26-GHz band. The transmitter is composed of an IMPATT oscillator which is frequency modulated by a varactor diode-coupled dielectric resonator (Fig 2(a)) [3]. The receiver makes use of a single balanced mixer mounted on a microstrip/slotline circuit (Fig. 2(b)) [3].

Simple radio communication system: The 50-GHz band is assigned for communications and, is used mainly for TV and data transmission. The block diagram of a typical receiver is shown in Fig 3 [4]. A 13-GHz FM signal which is generated by a directly modulated GaAs FET oscillator, coupled with a dielectric resonator, is multiplied four times to yield a 50-GHz signal.

A compact 60-GHz transmitter–receiver system is also developed for civilian use. Since this frequency is close to the absorption band of oxygen molecules, the system will be best for use in short-range communications such as a "Comprehensive Automobile Control System" [5]. The transmitter–receiver block diagram is illustrated in Fig. 4.

B. Sensing

Oil pollution on the sea surface could be detected by use of millimeter waves. Since oil damps the water wave of short wavelengths very effectively, a sudden decrease of 35-GHz scattering tells the location of oil film when a transmitted beam is swept on the water surface [6]. It was experimentally found that the maximum decrease of scattering takes place by 0.6-μm-thick oil film.

An airborne rain scatterometer/radiometer system operated at 10 and 34.45 GHz is being developed for the investigation of vertical and horizontal profiles of rain structure [7]. The information will be very useful for the site-diversity communication-systems design or weather forecast. The receiver for each frequency band is alter-

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TABLE I
BASIC TRANSMITTER SPECIFICATIONS FOR HDTV RELAY SYSTEM [1]

Carrier frequency	38.0 GHz
Output Power level	0.4 W
Modulation type	FM
Baseband input signal	HD - TV signals Max freq. 30 MHz
Deviation	50 MHzp-p
RF bandwidth	110 MHz

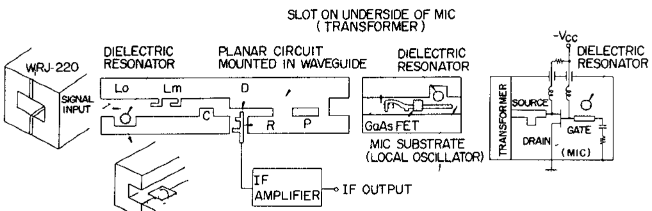

Fig. 1. Construction of 22-GHz band low-noise down converter for *Ku*-band satellite TV broadcasting [2].

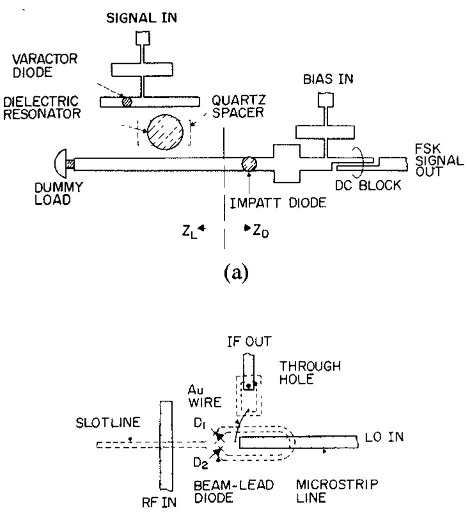

Fig. 2. (a) MIC FSK modulator for a terrestrial digital radio subscriber system [3]. (b) Single-balanced mixer for a terrestrial digital radio subscriber system [3].

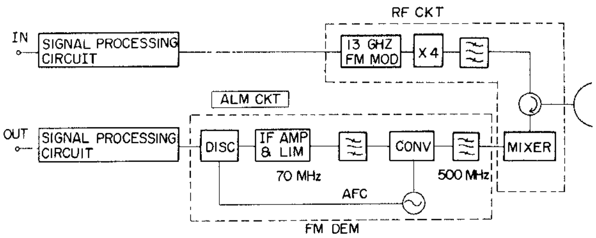

Fig. 3. Block diagram of a transmitter-receiver for a 50-GHz radio communication system [4].

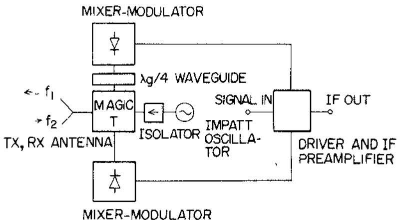

Fig. 4. Transmitter–receiver block diagram for a compact 60-GHz system [5].

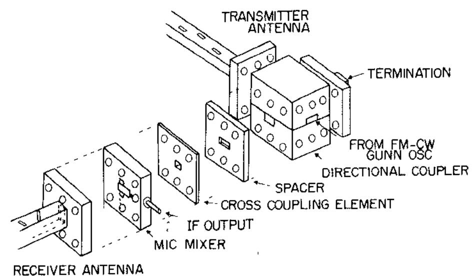

Fig. 5. Detailed configuration of the transmitter–receiver unit for an automotive collision avoidance system [8].

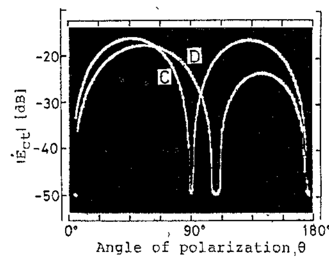

Fig. 6. Cross-polarized output from four-layered CFRP [9]. (C: all layers aligned in one direction. D: fourth layer is tilted by 20°.)

nately connected to the antenna circuit by a ferrite switch, driven by timing signals from a microprocessor. The observation by the scatterometer and radiometer are also performed in turn by time sharing.

Automotive collision avoidance systems can be made compact by use of millimeter waves. A 50-GHz radar system has been developed using a varactor-tuned Gunn oscillator [8]. The transceiver is installed directly on the V-shaped antenna (2° ×2° beam width) without interconnecting feed lines (Fig 5). The use of a high frequency results in reduced clutter and higher reliability.

At Nobeyama, in the middle part of Japan, two advanced *millimeter-wave radio telescopes* were constructed. One is a single-dish telescope with a 45-m diameter, whose surface accuracy is 0.18 mm and maximum frequency is 120 GHz. The other is a five-element interferometer with 10-m dishes. The maximum spacing is 560 m, and the operating frequencies are 22 and 115 GHz.

C. Physical Measurement

Besides well-known plasma diagnostics, *material investigation* by millimeter waves is being studied. The nondestructive examination of Fiber Reinforced Plastic (FRP) is one example [9]. Polarized millimeter-wave energy is applied to an FRP sheet which contains carbon fiber. In the

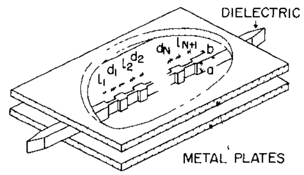

Fig. 7. Structure of alternating width NRD-guide filter [10].

TABLE II
MEASURED RESULTS OF ϵ_r AND $\tan\delta$ [14]

MATERIAL	TFE (TEFLON)	Al_2O_3 (99.9%)	$MgTiO_3$ -$CaTiO_3$ -La_2O_3	$Ba(ZnTa)O_3$
ϵ_r	2026±0.002	9.95±0.01	21.48±009	29.69±0.04
$\tan\delta (\times 10^{-5})$	20±2	4.4±0.4	40±3	21±2
τ_d (ppm/°C)	100±10	5.4±0.5	8.5±05	105±0.5
τ_ϵ (ppm/°C)	-220±20	100±20	-24±10	-25±11

transmitted wave, the orthogonally polarized component is induced. The cross-polarized output is sensitive to the change of orientation, as in Fig. 6.

III. COMPONENTS AND MATERIALS

The NRD (nonradiative dielectric) guide is a kind of H-guide which is narrow enough to cut off all the higher modes and radiation mode in the nondielectric region. Therefore, it does not lose energy by radiation at bends or discontinuities. Almost all the functions of conventional waveguide components are realized by the NRD structure. Though their Q values are a little less than those of waveguide components, the advantage is that they are easily integrated into millimeter-wave IC's. Fig. 7 shows, as an example, a bandpass filter recently developed by Yoneyama *et al.*, [10], where the Q value is 3400.

Periodic structures in millimeter-wave frequency have been extensively investigated by Itoh at the University of Texas [11]. In Japan, Shigesawa *et al.* developed a new equivalent-circuit method to study a periodic structure of finite length [12]. Tsutsumi's study on a corrugated ferrite slab antenna is also to be noted [13]. The change of the dc transverse magnetic field by 1.0 Wb/m^2 steers the direction of the radiated beam by 20 degrees.

Complex permittivity was recently measured by the dielectric disk resonator method by Kobayashi [14]. Both real and imaginary parts are correctly measured, as shown in Table II.

Low-noise amplifiers were constructed using GaAs FET and HEMT devices in some major companies. Typical GaAs FET amplifier performance has a 20-dB gain and less than 12-dB noise figure in 18–26.5-GHz band with 0.25-μm device gate [15]. An HEMT amplifier exhibits a better result of 17-dB gain and 7-dB noise figure with a 0.4-μm gate device in the same frequency band [15]. Another amplifier, using a Peltier-cooled HEMT, produced 37-dB gain and 1.7-dB noise figure from 17.7 to 19.45 GHz [16].

Millimeter-wave tubes: The gyrotron is now used as a powerful millimeter-wave source for electron cyclotron heating of nuclear fusion plasmas. Gyrotrons operating at 28-GHz with 200 kW and 70 GHz with 25 kW have been developed [17], [18]. A high-power TWT was also developed. In the 35-GHz frequency band, more than 600-W output was obtained with a 59 coupled-cavity TWT, having 10.6-percent efficiency [19]. In the 30-GHz band, a TWT of more than 700 W has been reported [20].

Tunnel-type junctions with a magnetic barrier which do not show a Josephson effect are being studied as submillimeter-wave *super-conducting junctions* [21].

IV. CONCLUSIONS

Various applications of millimeter waves are currently being investigated in Japan: one practical example is a 50-GHz band simple radio communication system as mentioned above. It is important that the semiconductor devices and other passive components used at millimeter-wave frequencies become less expensive in order to be able to use them in practical applications. In this way, the advantageous characteristics of the millimeter waves can be utilized effectively.

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