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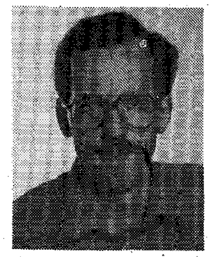

Klaus Solbach (M'80) was born in Witten, West Germany, in 1951. He received the Dipl.-Ing. degree from the Technical University of Aachen, West Germany, in 1974, and the Dr.-Ing. degree from the University Duisburg, West Germany, in 1979.

From 1975 to 1980 he had been employed at the University Duisburg as a Research Assistant. He had been engaged in investigations of the properties and circuit applications of dielectric image lines in the millimeter-wave frequency range.

In 1981 he joined AEG-Telefunken in Ulm, West Germany, where he is engaged in the development of planar antennas for millimeter-waves using microstrip and dielectric image lines, and in the development of integrated millimeter-wave circuits using printed *E*-plane technology.

50-GHz IC Components Using Alumina Substrates

YASUYUKI TOKUMITSU, MEMBER, IEEE, MASAYUKI ISHIZAKI, MIKIO IWAKUNI, AND TOSHIYUKI SAITO

***Abstract*—This paper discusses the feasibility of employing alumina substrates instead of fused quartz or sapphire substrates in millimeter-wave integrated circuits (IC's), an attractive prospect since alumina boasts considerable advantages over either of the other materials.**

Millimeter-wave 50-GHz components were developed on alumina substrates. These included passive components, a mixer, an ASK modulator, and an oscillator. Empirical results for both oscillator stabilization using a dielectric resonator and a new application of a GaAs FET in a millimeter-wave oscillator-doubler are presented.

Examples of integrated systems using millimeter-wave IC's are also presented. These systems include a compact Doppler radar front-end for an automobile ground-speed sensor, and a transmitter/receiver for digital radio equipment. All of them are fabricated on alumina substrates.

I. Introduction

In 1979, THE WORLD Administrative Radio Conference adopted a frequency utilization plan for the millimeter-wave spectrum beyond 40 GHz. This plan opened the door to a broad range of commercial applications for millimeter-wave radio in the 1980's.

Integrated circuit (IC) technique in the millimeter-wave range will be the key to achieving compact and cost-effective systems. Until now most of the millimeter-wave IC's have employed fused quartz, sapphire, and/or other substrate materials, but it would be difficult to commercialize millimeter-wave IC's utilizing these materials. Quartz requires special handling because of its low mechanical strength. Sapphire has high mechanical performance but is very expensive. Other materials such as copper-clad are easy to handle, but it is difficult to accurately form tiny IC patterns and thin-film resistive materials on the substrate. Alumina ceramic material is predominantly used as the IC substrate in the microwave range.

This paper shows that alumina can be used for millimeter-wave IC substrates. The empirical design equation developed for microwave frequencies together with basic properties of microstrip lines on substrates can be extended to the millimeter-wave frequencies.

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The authors are with Fujitsu Laboratories, Ltd., Kawasaki, Japan 211.

Millimeter-wave components have been developed at 50 GHz. These included passive components, a mixer, an amplitude shift keying (ASK) modulator, and an oscillator. A dielectric resonator has been used to stabilize oscillation frequency in order to reduce the size and cost of the oscillator.

The application of a GaAs FET in a millimeter-wave oscillator-doubler and system applications of millimeter-wave IC's are also described.

II. Microstrip Lines on Alumina Substrates

Table I shows the properties of various microwave IC and millimeter-wave IC substrate materials. It shows that the flexural strength of alumina is superior to that of quartz, so it does not require special handling. And compared with sapphire, alumina delivers equivalent electrical and mechanical performance except for surface roughness, while being one hundredth of its cost. Other materials, RT/duroid [1] for example, have disadvantages in regard to fabricating IC patterns. Millimeter-wave IC patterns cannot be formed accurately because it is difficult to fabricate metal conductors that are both narrow and tall, and thin-film resistive material for a dummy load and dc bias circuit cannot be formed on these substrates. However, inexpensive and producible millimeter-wave IC's could be built using alumina.

In order to investigate the electrical performance of alumina in the millimeter-wave range, we measured the propagation loss of a microstrip line and the effective dielectric constant of an alumina substrate.

The thickness of the substrate determines the cutoff frequency of the unwanted mode. It is important to design the microstrip line so that unwanted modes are higher than the upper operating frequency. For this study, the substrate thickness was 0.2 mm and the cutoff frequency of surface TE mode (the lowest of the unwanted modes) was 127 GHz, sufficiently higher than the operating frequency of 50 GHz.

An Au–NiCr metal system was used to form the microstrip line. The gold was electroplated to a thickness of 1.5 μm on 250 Å $\pm$ 50 Å of nichrome layer.

Fig. 1 shows the measured and calculated results of propagation loss in a microstrip line for various line lengths at three different frequencies. The loss per unit length is determined by the slope. The measured loss at 50 GHz was 0.57 dB per centimeter. The difference between measured and calculated loss is within 5 percent. The calculated value includes mainly conductor loss obtained assuming uniform current distribution. And the dielectric loss is negligibly small, less than the 5-percent conductor loss.

Reference [2] gives propagation loss of the microstrip line on the 0.76-mm thick quartz substrate at 30 GHz. From comparison with these results, measured loss and calculated loss are almost the same in alumina at 50 GHz and in quartz at 30 GHz. Thus, the loss factor of a microstrip line on an alumina substrate is similar to that on a quartz substrate.

It is necessary to know the accurate value of an effective dielectric constant in order to determine the circuit dimensions necessary in the design of millimeter-wave IC's. A ring type resonator like that shown at the bottom of Fig. 2 was used to get an effective dielectric constant. Based upon the frequency response of the resonator, the effective dielectric constant was determined by the following equation:

$$\epsilon_{\text{eff}} = \left\{ \frac{nC}{\pi(2r + w) f_n} \right\}^2 \tag{1}$$

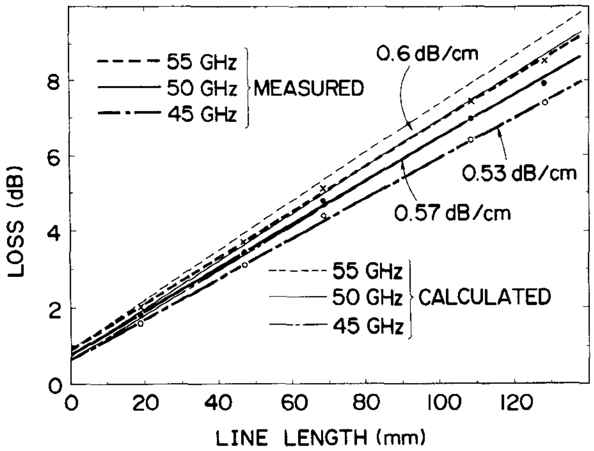

Fig. 1. Measured and calculated propagation loss in a microstrip line on a 0.2-mm thick alumina substrate as a function of line length at three different frequencies.

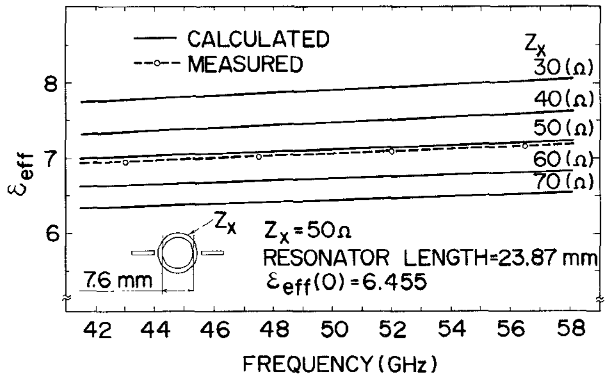

Fig. 2. Frequency response for effective dielectric constants of an alumina substrate as parameters of the line impedance of the ring type resonator.

TABLE I
Material Properties for IC Substrates

Material	Alumina	Quartz	Sapphire	RT/duroid® 5880
ε_r	9.7	3.8 - 4.0	9.3 - 11.7	2.2
$\tan\delta$ (at 10 GHz)	2×10^{-4}	1×10^{-4}	$< 1 \times 10^{-4}$	9×10^{-4}
Flexural strength (kg/cm²)	3100	700	7000	—
Thermal conductivity (cal/cm·s·°C)	0.06	0.003	0.09	—
Surface roughness CLA (μm)	0.4	0.03	003	—
Relative cost	1	0.1 - 0.5	20 - 100	0.3 - 0.5

where n is the resonant number, C is the light velocity, f_n is the resonant frequency at n, r is the inner radius of the resonator, and w is the line width of the resonator.

The dotted line in Fig. 2 shows changes in the effective dielectric constant with respect to the frequency for the characteristic impedance of 50 Ω. The solid lines in the figure show the values calculated by the following equation [3]:

$$\epsilon_{\text{eff}} = m(f - f_d) + \epsilon_{\text{eff}}(0) \tag{2}$$

where m is the coefficient determined by line dimension, f_d is the lowest frequency value at which the frequency dependence is significant, and $\epsilon_{\text{eff}}(0)$ is the static dielectric constant.

The measured result curve agrees well with the calculated one in this figure. Equation (2) is empirical and derived in the microwave range. Results show that this equation can be applied to the millimeter-wave range.

Alumina is suitable as the substrate of millimeter-wave IC's, considering things such as electrical performance, cost, and mechanical strength. The surface roughness of alumina has a negligible effect on pattern accuracy.

III. Millimeter-Wave IC Components on Alumina Substrates

A. Passive Components

A branch-line type 3-dB hybrid was developed to study the effects of small dimensions. As the line width and diameter of the circle were very small and about the same size, it was assumed that the lines would interact and that actual line impedance would differ from the calculated value. A hybrid was first designed, then the line width was iterated based on experimental results. The diameter and line width of the hybrid were 1.1 mm and 0.4 mm, respectively. Fig. 3 shows the characteristics of the hybrid. The isolation and dead loss are more than 20 dB and less than 0.6 dB over the frequency range from 45.5 to 52.5 GHz, respectively.

Other passive components such as a backward-wave type 10-dB directional coupler, a coupled line for dc blocking, and a dummy load were also developed as reported in [4].

The important considerations in the design of the directional coupler were that the 50-Ω line width widens to the 1/8 wavelength at 50 GHz and that the even- and odd-mode characteristics are different from those in the microwave range. The effective coupling coefficient is larger than the calculated one for these reasons, and corrections become necessary.

A circulator is an important component in radio equipment. A ferrite-disk type IC circulator has been developed for the 26-GHz band [5]. However, it is difficult to manufacture because of its complex configuration. We developed a 50-GHz IC circulator on a ferrite substrate. Ni-Zn ferrite with a saturation magnetization of about 5000 Gauss was used. The circulator pattern was 4 mm square and the ferrite substrate was 0.2 mm thick. The diameter of the junction was determined to be 0.9 mm from theoretical and empirical results. The ferrite substrate was magnetized to a

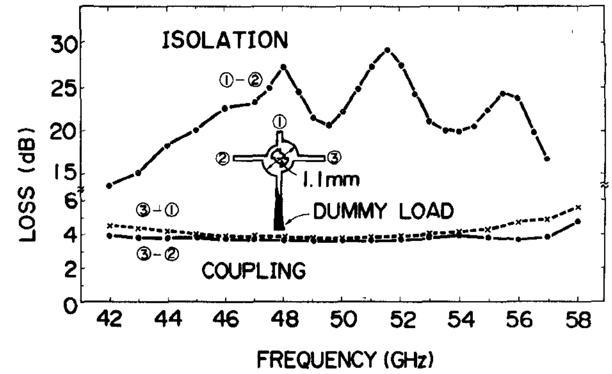

Fig. 3. Characteristics of a branch-line type 3-dB hybrid.

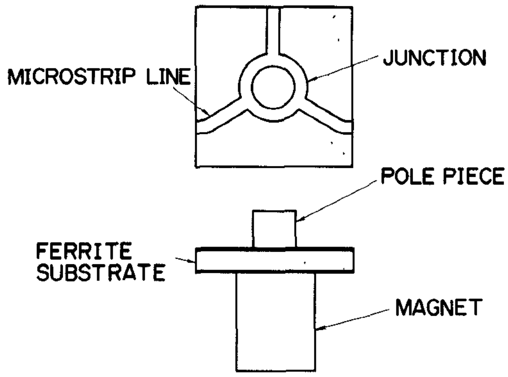

Fig. 4. Structure of a 50-GHz IC circulator using a ferrite substrate. A pole piece is made of iron and is fixed with epoxy adhesive.

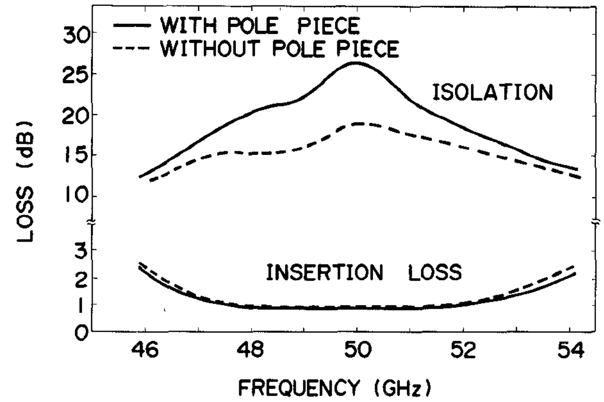

Fig. 5. Characteristics of a 50-GHz IC circulator. Both insertion loss and isolation of the circulator with a pole piece are superior to those without a pole piece.

value of more than 1800 Oe by a magnet made of rare-earth material. A pole piece with a diameter less than the junction diameter was fixed on the junction conductor with epoxy adhesive as shown in Fig. 4. Fig. 5 indicates that the pole piece improved circulator performance. The circulator with the pole piece has an insertion loss of less than 0.9 dB and an isolation of greater than 20 dB over the frequency range from 48 to 51.5 GHz.

B. Mixer and ASK Modulator

A single-ended type IC mixer was also developed. The diodes were commercially available silicon- (Si-) or GaAs-Schottky-barrier diodes (SBD) of the beam-lead type. Con-

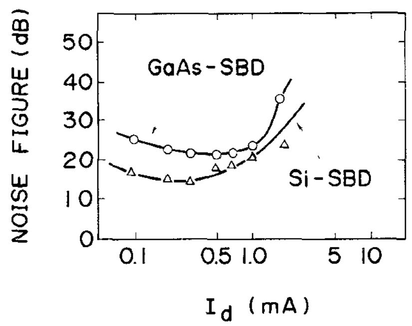

Fig. 6. Noise figures at the bias currents for GaAs-SBD and Si-SBD in the IF frequency range (Doppler frequency) from 2 to 58.6 kHz.

version loss from 50 GHz to 70 MHz at a local level of 7 dBm was 8 dB for Si-SBD and 6.5 dB for GaAs-SBD over the frequency range from 47.5 to 50.5 GHz. At very low output frequencies, however, Si-SBD showed a better noise figure than GaAs-SBD. Fig. 6 shows measured noise figures at diode bias conditions in frequencies of 2–58.6 kHz. These results show that GaAs-SBD is superior to Si-SBD as a down converter for communications equipment, and that Si-SBD is suitable as a mixer in a homodyne receiver.

An experimental ASK modulator consists of two 3-dB hybrids and two switches, as shown in Fig. 7. It is a balanced type modulator for good input and output impedance matching when the switches are operated. This construction has the advantage of no interference with other circuits. The fan-shaped open stub is used in a dummy load to reduce the dimension. The dotted line indicates a switch in the figure. Each switch has two p-i-n beam-lead diodes which are placed at one end of two open stubs. The open stubs have the length of three quarter-wavelengths and are placed at opposite sides of a transmission line, and are faced each other in order to get a high on–off switching ratio (ON/OFF ratio). The switch operates as a band rejection filter when the diodes are forward-biased. The modulator had an ON/OFF ratio of more than 20 dB, insertion loss of less than 2 dB, and input VSWR of less than 1.2. The pulse rise and fall time of the modulator was less than 7 ns.

C. Oscillator

1) Frequency Stabilization by Dielectric Resonator: Temperature stability is an important consideration in oscillator design. Various stabilization methods have been reported using a cavity resonator, a microstrip line resonator, or feedback loop using a discriminator associated with two bandpass filters [6]. A cavity resonator has the best temperature stability but is large. A microstrip-line resonator is much less stable, and a feedback loop is complex. A dielectric resonator is suitable as a frequency stabilizer for an IC oscillator. It was used in a highly stable oscillator in the microwave range [7]–[10].

We measured the frequency response of unloaded Q for disk-shaped dielectric resonators. At lower frequencies (below 10 GHz), the unloaded Q was measured using a cylindrical cavity. At high frequencies, a dielectric resonator with a thin quartz spacer was coupled with a microstrip

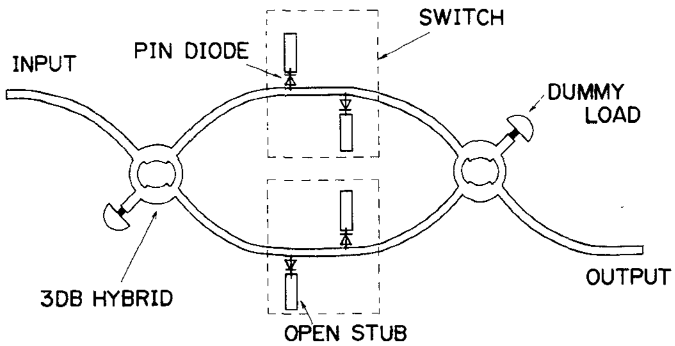

Fig. 7. Illustration of a circuit pattern for a balanced type ASK modulator.

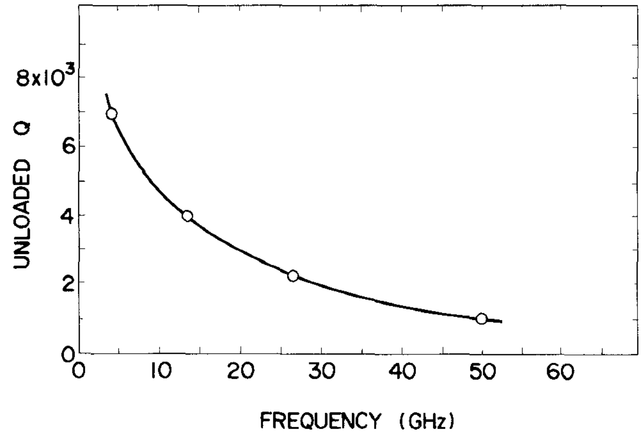

Fig. 8. Frequency response of the unloaded Q of a disk-shaped dielectric resonator.

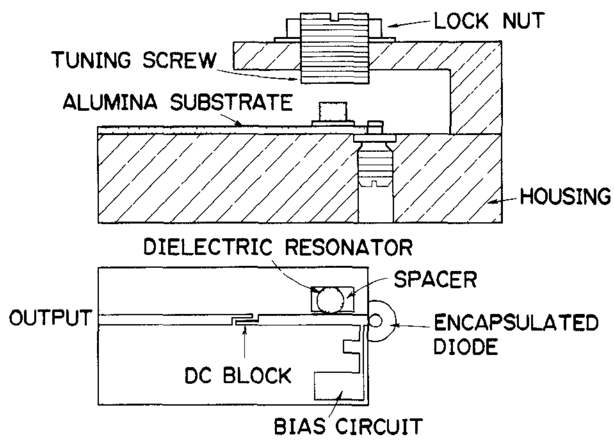

Fig. 9. Structure and pattern configuration of a 50-GHz Gunn oscillator stabilized by a dielectric resonator.

line on the alumina substrate [11]. A dielectric resonator with a dielectric constant of 30–40 [11], [12] has a temperature coefficient of ± 2 to ± 4 ppm/°C at each resonant frequency. The unloaded Q decreased from 7000 at 4 GHz to 1200 at 50 GHz, as shown in Fig. 8.

A 50-GHz Gunn oscillator stabilized by a dielectric resonator was developed. This structure is shown in Fig. 9. The oscillation circuit is the band-rejection type. The dielectric resonator is set at a distance of about three-quarters of a wavelength from an encapsulated Gunn diode, and is mounted on a fused quartz spacer, preventing degradation

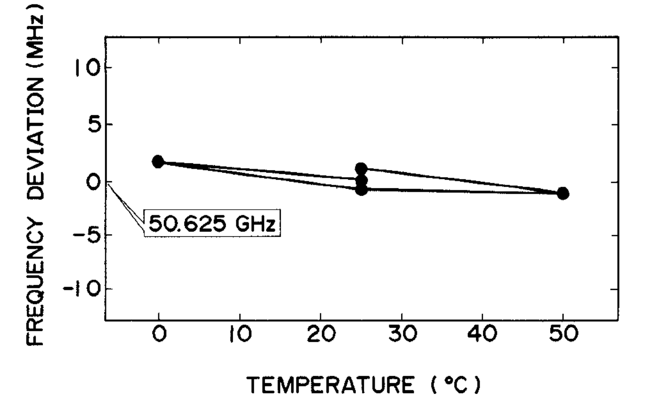

Fig. 10. Frequency stability against temperature of a 50-GHz IC oscillator using a dielectric resonator. Operating voltage and current are 4.6 V and 930 mA. Output power is 13 dBm.

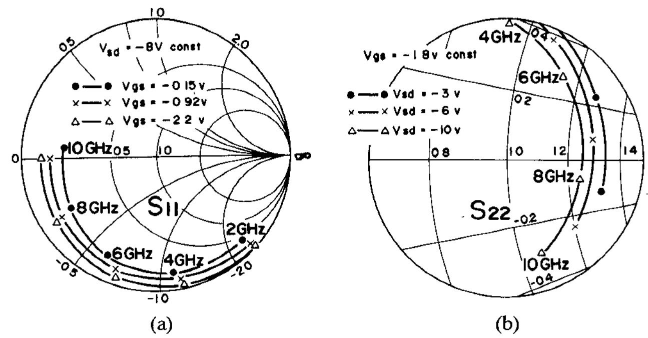

Fig. 11. Input and output impedances for various bias conditions of a common-drain GaAs FET. (a) Input (gate) impedance S_{11}. (b) Output (source) impedance S_{22}.

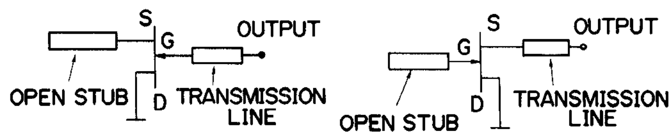

Fig. 12. Schematic illustrations for two types of output port configurations of oscillator-doublers using common-drain GaAs FET's. (a) A gate output oscillator-doubler. (b) A source output oscillator-doubler.

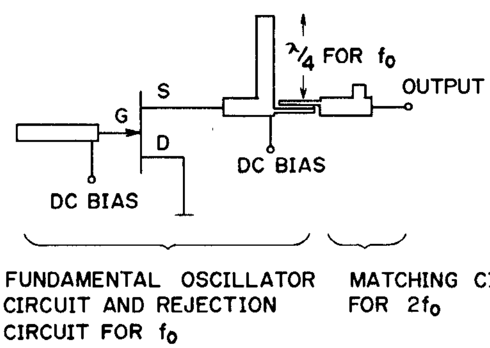

Fig. 13. The pattern configuration of a 45-GHz source output oscillator-doubler. For the gate output the pattern configuration is similar to this figure.

of unloaded Q and spurious response. The resonator has a diameter of 1.1 mm and thickness of 0.6 mm. Oscillator temperature coefficient compensation was achieved by optimizing the size and using the appropriate material for the tuning screw and housing. The oscillator has a frequency stability of less than ± 100 ppm over a temperature range from 0 to 50 °C, as shown in Fig. 10. The external loaded Q value of the oscillator is about 500. The output power is about 13 dBm.

This frequency stability is sufficient for sensor applications [13] and small channel radio equipment. For use in communications systems, however, the stability must be improved by one order magnitude. Further improvement in the unloaded Q factor of the dielectric resonator is also necessary.

2) A New Millimeter-Wave Oscillator Using a GaAs FET Oscillator-Doubler: Applications of GaAs FET's to microwave oscillators have already been demonstrated [7]–[9]. Highly stable millimeter-wave oscillators using GaAs FET's, however, have not been reported.

We experimented with a 45-GHz millimeter-wave IC oscillator-doubler [14] using a common-drain GaAs FET. An oscillator can give high frequency stability because it uses an oscillator-doubler and dielectric resonator. At *K*-band, the value of the unloaded quality factor of the dielectric resonator is two to three times larger than at millimeter-wave frequencies, as shown in Fig. 8.

The oscillator-doubler is based on nonlinearity between the gate and the drain, or the source and the drain of the common-drain GaAs FET. Fig. 11(a) shows the input (gate) impedance S_{11} plotted as a function of gate voltage at a constant source voltage of -8 V at various frequencies. Fig. 11(b) gives the output (source) impedance S_{22} as a function of source voltage at a gate voltage of -1.8 V. These figures indicate that nonlinearity of the gate-to-drain is similar to that of the source-to-drain for bias voltage variations. These results show, therefore, that two types of output port configurations can be realized for an oscillator-doubler, as shown in Fig. 12(a) and (b). One is a gate output oscillator-doubler based on gate-to-drain nonlinearity. The other is a source output based on source-to-drain nonlinearity. These two types of oscillator-doubler configurations were first studied using 9-GHz oscillator-doublers, then 45-GHz oscillator-doublers were made in both configurations. Fig. 13 shows the pattern configuration for the source output for a 45-GHz IC oscillator-doubler. A fundamental oscillator circuit, a dc-bias circuit, and a rejection circuit for the fundamental frequency f_0 are integrated in a compact unit. An open stub with a quarter-wavelength is the low impedance at the fundamental frequency and reflects the power to a device. At the doubler frequency $2f_0$, this open stub has no effect on transmitting power because of its very high impedance.

Fig. 14 gives the experimental results of the oscillator-doubler. A GaAs FET chip with a gate length of 0.7 μm and a width of 1200 μm (fabricated by electron-beam lithography [15]) was used in the experiment. The output power for both the gate output and the source output was 7 dBm at 25 °C. At 0 °C, the output power of the gate output increased to 11.6 dBm with power efficiency of 1.6 percent. The output power of the source output could not be determined at 0 °C because the GaAs FET chip was

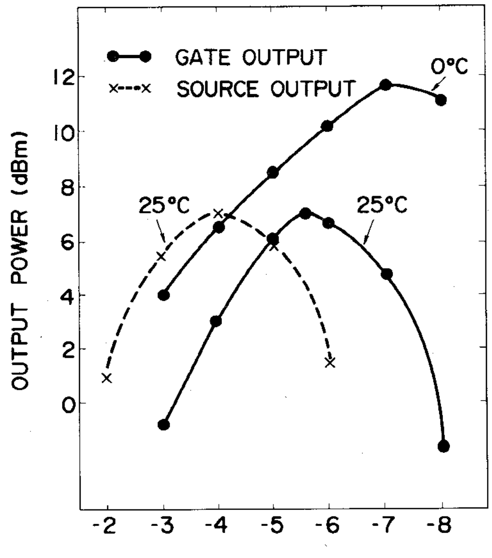

Fig. 14. Characteristics of a 45-GHz oscillator-doubler using a common-drain GaAs FET.

broken during the experiment. The reasons for maximum output power with the source voltage at room temperature are being investigated.

It could not be shown which configuration was most suitable as a GaAs FET oscillator-doubler.

If a dielectric resonator with a high unloaded Q value is used in the circuit to stabilize fundamental oscillation at K-band, the oscillator-doubler provides a highly stable millimeter-wave local oscillator for use in radio equipment. The oscillator-doubler will provide new applications for GaAs FET as highly stable oscillators in the millimeter-wave range.

IV. System Integration of Millimeter-Wave IC's

A 26-GHz IC transmitter and receiver using alumina substrates has been developed [16]. IC radio equipment for 50 GHz using alumina substrates has not been reported. Two examples of system applications of 50-GHz millimeter-wave IC's are discussed here.

A prototype 50-GHz band Doppler radar front-end for an automobile ground-speed sensor was successfully fabricated on an alumina substrate [13]. Fig. 15(a) shows the exterior of a front-end module with a pyramidal horn antenna and a front-end mount. The circuit pattern and an interior view of the front-end mount are shown in Fig. 15(b). A Gunn oscillator, a single-ended type mixer, and a 10-dB directional coupler are integrated on a tiny substrate 2.5 mm wide and 10.8 mm long. A 10-dB directional coupler is used for diplexing transmitting and receiving signals to reduce cost. The pattern of 50-Ω resistive material, Ta_2N, is tapered obliquely to the 50-Ω line for good impedance matching.

This front-end is a so-called homodyne receiver, with a Doppler shift signal extracted from the mixer. The minimum detectable signal level of the radar is mainly determined by the noise figure of the mixer at Doppler frequencies. The mixer has a Si-SBD because that Si-SBD is superior to GaAs-SBD in the noise figure at Doppler frequencies, as mentioned before.

The oscillator is stabilized by a simple strip-line resonator, and has a frequency stability less than ±300 ppm. Table II summarizes performance of the front-end.

An experimental model of a transmitter/receiver [17] was designed for 10.7-Mb/s digital radio equipment. It consisted of a Gunn oscillator stabilized by a dielectric resonator, 3-dB hybrids, an ASK modulator, a waveguide-to-IC transition, a small pyramidal horn antenna, a mixer, and a pre-IF amplifier, as shown in Fig. 16. This system adopted the ASK modulation method in order to simplify

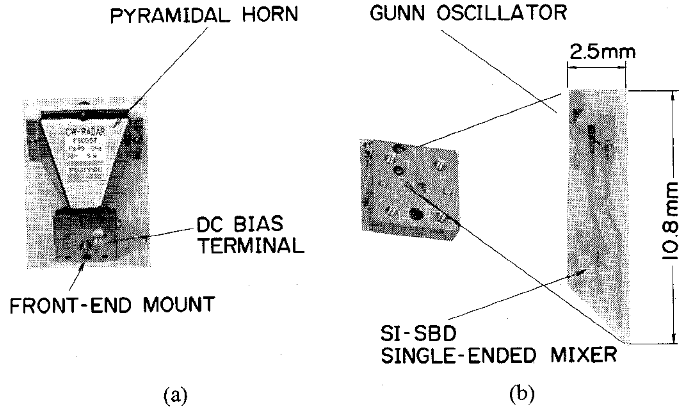

Fig. 15. A 50-GHz IC Doppler radar front-end module for an automobile ground-speed sensor. (a) Exterior of a 50-GHz IC Doppler radar front-end module. (b) Circuit pattern and interior of a front-end mount.

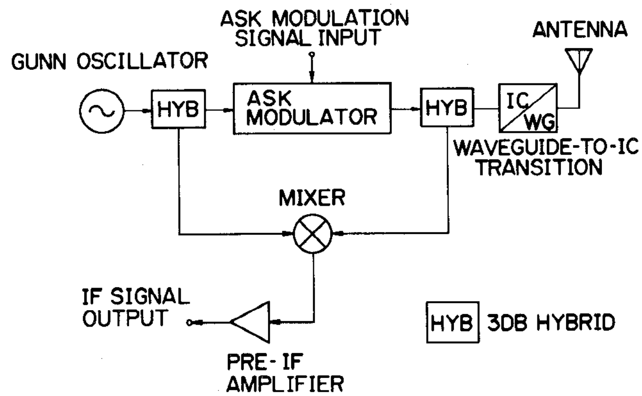

Fig. 16. Block diagram of a 50-GHz IC transmitter/receiver.

TABLE II
Summarized Performance of a 50-GHz IC Doppler Radar Front-End

Operating frequency	49.4 GHz
Output power (Gunn oscillator)	2.8 dBm (14.4 dBm)
Minimum detectable signal level	-105.7 dBm (IF : 0.4-4 kHz)
Doppler shift frequency	79.4 Hz/(km/hour)
Antenna (Gain)	Pyramidal horn (22 dB)
Dimensions	40 x 50 x 35 mm
Weight	57 g

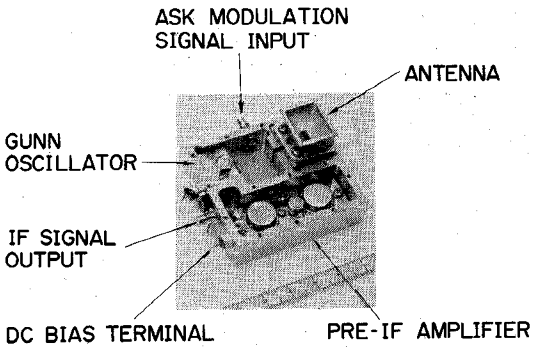

Fig. 17. Interior view of a 50-GHz IC transmitter/receiver.

TABLE III
SUMMARIZED PERFORMANCE OF A 50-GHz IC TRANSMITTER/RECEIVER FOR 10.7-MB/S DIGITAL RADIO EQUIPMENT

Frequency	T: 50.625 GHz R: 51.100 GHz
Output power	+ 5 dBm
Frequency stability	< ± 100 PPM (0-50°C)
Modulation	ASK
Transmission capacity	10.7 Mb/s
Antenna gain	14 dB (horn)
Noise figure	17 dB
IF frequency	475 MHz
Dimensions	54 x 48 x 15 mm
Weight	200 g

the hardware configuration. A GaAs-SBD used in the mixer was biased for low-power operation. A conversion loss of 6.5 dB was obtained at 0-dBm local power when 1.5-mA current was applied. Fig. 17 shows an interior view of the IC unit.

Table III summarizes characteristics of the transmitter/receiver. Output power of 5 dBm was obtained when the two switches were on-state. The noise figure of the receiver was 17 dB, which could be improved 2 or 3 dB if an IC circulator was used as a diplexer. The dimensions of the transmitter/receiver were only 54×48×15 mm. The size of the millimeter-wave IC's was about half that of the transmitter/receiver.

This transmitter/receiver is suitable for a low-cost digital radio system such as a local data distribution system.

V. CONCLUSION

Several basic parameters, such as propagation loss and an effective dielectric constant, were measured to validate the feasibility of millimeter-wave IC's using alumina substrates. Results show that empirical equations obtained in the microwave region are also applicable in the millimeter-wave region.

Millimeter-wave IC passive components using alumina or ferrite substrate, such as a branch-line type 3-dB hybrid, a backward-wave type 10-dB directional coupler, a coupled line for dc blocking, a dummy load, and a circulator, were successfully developed.

Frequency stabilization using the dielectric resonator of an oscillator is feasible at 50 GHz, although the unloaded Q of the dielectric resonator must be improved for complete system employment.

A 45-GHz GaAs FET IC oscillator-doubler was demonstrated, which was based on nonlinearity of either the gate-to-drain or the source-to-drain for a common-drain GaAs FET. The results indicate that a GaAs FET will be able to replace the Gunn diode and IMPATT diode oscillator in the millimeter-wave region.

Examples for system applications of millimeter-wave IC's, such as a Doppler radar front-end for an automobile ground-speed sensor and a transmitter/receiver for digital radio equipment, were also fabricated on alumina substrates.

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Yasuyuki Tokumitsu (M'79) was born in Shimonoseki, Japan, on May 15, 1943. He received the B.E. and M.E. degrees from Kyushu Institute of Technology, Kitakyushu, Japan, in 1966 and 1968, respectively.

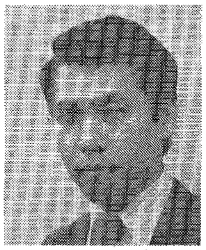
In 1968 he joined Fujitsu Laboratories, Ltd., Kawasaki, Japan, where he has been engaged in the research and development of passive and active components for microwave communication equipment. Currently, he is interested in millimeter-wave hybrid integrated circuits, millimeter-wave radio communication equipment, and satellite communication equipment. He is now leading the Radio and Satellite Communications System Components Development Group in the Radio and Satellite Communications Systems Laboratory of Fujitsu Laboratories Ltd.

Mr. Tokumitsu is a Member of the Institute of Electronics and Communication Engineers of Japan.

Mikio Iwakuni was born in Hyogo, Japan, on December 8, 1953. He was graduated from the electrical engineering department of Himeji Technical High School, Japan, in 1972, and Fujitsu Technical College in 1976.

He joined Fujitsu Laboratories Ltd., Kawasaki, Japan, in 1972, and has been engaged in the research and development of microwave system components for radio communication systems, mainly solid-state sources. He is now an Engineer at the Radio and Satellite Communications Systems Laboratory, Integrated Communications Division, Fujitsu Laboratories Ltd.

Mr. Iwakuni is a member of the Institute of Electronics and Communications Engineers of Japan.



Masayuki Ishizaki was born in Yokohama, Japan, on Oct. 18, 1951. He was graduated from the electrical engineering department of Kanagawa Technical High School, Yokohama, Japan, in 1970, and Fujitsu Technical College in 1974.

He joined Fujitsu Laboratories Ltd., Kawasaki, Japan, in 1970, and has been engaged in the research and development of microwave integrated circuits and millimeter waveguide components for a guided millimeter-wave transmission system. He is presently engaged in the research and development of millimeter-wave radio communication equipment, and is an Engineer at the Radio and Satellite Communications Systems Laboratory in Fujitsu Laboratories Ltd.

Mr. Ishizaki is a Member of the Institute of Electronics and Communication Engineers of Japan.

Toshiyuki Saito was born in Mie, Japan, on August 11, 1945. He received the B.S. degree from Tokyo Denki University, Tokyo, in 1970, and the M.S. degree from Chiba University, Chiba, Japan, in 1972.

In 1972 he joined Fujitsu Laboratories Ltd., Kawasaki, Japan, where he has been engaged in the research and development of microwave system components for radio communication systems, mainly solid-state components, and microwave and millimeter-wave integrated circuits. He is now a Senior Engineer at the Radio and Satellite Communications Systems Laboratory, Integrated Communications Division, Fujitsu Laboratories Ltd.

Mr. Saito is a member of the Institute of Electronics and Communication Engineers of Japan.

Design of Dielectric Ridge Waveguides for Millimeter-Wave Integrated Circuits

TAICHI WANG, STUDENT MEMBER, IEEE, AND S. E. SCHWARZ, SENIOR MEMBER, IEEE

Abstract —**All-dielectric ridge waveguides may be useful as elements of millimeter- and submillimeter-wave integrated circuits. A planar metallic V-coupler can be used to couple energy between the guide and small circuit elements such as diodes. Desirable characteristics in such a guide/coupler system are: a) quasi-single mode propagation; b) low radiation loss in bends; c) low coupling loss between guide and devices; and d) adequate physical strength. In this paper, we discuss the general problem of designing guides and couplers to obtain the desired characteristics. The principal method used is simulation in the range 2–7 GHz. We find that with good compromise designs, typical coupling loss between waveguide and a small device is about 1.4 dB, exclusive of dielectric loss and ohmic loss in the coupler.**

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The authors are with the Department of Electrical Engineering and Computer Sciences and the Electronics Research Laboratory of the University of California, Berkeley, CA 94720.

I. Introduction

DIELECTRIC waveguides are potentially useful alternatives to metallic guides at high frequencies, where metallic conduction losses become excessive. Various kinds of dielectric waveguides, such as rectangular waveguide [1], [2], image guide [3]–[5], strip guide [6], [7], inverted strip guide [8], [9], and trapped image guide [10] have been proposed and analyzed. A general method for analyzing

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