Millimeter-Wave Wide-Band Amplifiers Using Multilayer MMIC Technology

Toshikazu Imaoka, *Member, IEEE*, Seiichi Banba, *Member, IEEE*, Akira Minakawa, *Member, IEEE*, and Nobuaki Imai, *Member, IEEE*

***Abstract*— This paper describes millimeter-wave wide-band single-ended and balanced amplifiers using novel multilayer monolithic microwave/millimeter-wave integrated circuit (MMIC) technology. The fundamental characteristics of thin-film transmission lines and a 50-GHz-band multilayer MMIC directional coupler are described through measurements up to 60 GHz. A single-ended amplifier fabricated in a 1.1 mm $\times$ 0.8 mm area, shows a gain of about 12 dB with a noise figure of better than 5 dB around 50 GHz. A balanced amplifier fabricated using the multilayer MMIC directional couplers and single-ended amplifiers, shows a gain of 10–17 dB with input and output return losses of better than 14 dB from 33 to 53 GHz. The transmission lines and directional couplers can be effectively combined with millimeter-wave active circuits without degrading the circuit performance or increasing the circuit area. To our knowledge, these are the first millimeter-wave active circuits employing multilayer MMIC technology.**

I. Introduction

RECENTLY, millimeter-wave frequencies have attracted much attention as the next frequency range for telecommunications systems. Millimeter-wave systems have inherent advantages over lower frequency systems, such as a reduction in equipment size, a wide available bandwidth, and the ability to effectively reuse the frequency resources in micro/pico cellular or wireless LAN systems due to large penetration and diffraction losses. On the other hand, so many base stations and portable sets are required that the components in these systems need to be more compact and cost-effective. Monolithic microwave/millimeter-wave integrated circuits (MMIC's) are particularly attractive as essential components for meeting this need.

As an approach to this miniaturization, multilayer or three-dimensional (3-D) MMIC technologies utilizing thin dielectric layers fabricated on a semiconductor wafer surface have been reported [1]–[12]. Furthermore, as a means of fabricating unique and multifunctional circuits, which are difficult in single layer configurations, these technologies have shown considerable capability [8]–[11]. For example, a wide-band amplifier [8] has been reported in which its bandwidth over 10 GHz at the Ka-band is obtained by only using low-impedance transmission lines, which are difficult to utilize in conventional MMIC's due to their wide conductor width. Tight coupling directional couplers [11] have also been reported in which a 3-dB coupler has coupling losses of 3.7 dB at the 20-GHz band. However, most of these reports have been limited to the microwave frequency range ($\sim$30 GHz), especially in active circuits.

In this paper, millimeter-wave wide-band single-ended and balanced amplifiers, which are designed and fabricated utilizing novel multilayer MMIC technology [8], [11], are presented. The fundamental characteristics of thin-film transmission lines (microstrip and triplate lines) used in amplifiers are described through measurements up to 60 GHz. A fabricated 3-dB multilayer MMIC directional coupler [11], designed for a center frequency of 50 GHz is also described. The suitability of these passive elements for use in millimeter-wave active circuits is demonstrated. A two-stage single-ended amplifier is designed utilizing these transmission lines. An active circuit design method peculiar to multilayer MMIC's that provides good performance in the higher frequency range is presented in the design. A single-ended amplifier and a balanced amplifier, which is constructed with two single-ended amplifiers and couplers, are fabricated and their performance is also demonstrated. To our knowledge, the fabricated amplifiers are the first millimeter-wave active circuits employing multilayer MMIC technology.

II. Thin-Film Transmission Lines

The fundamental characteristics of thin-film transmission lines, especially microstrip and triplate lines used in amplifiers, are discussed in this section. A schematic cross-sectional view of these transmission lines [8] is shown in Fig. 1. Each transmission line is formed on a 400-μm GaAs wafer surface (without back-processing). In our fabrication, four 2.5-μm-thick polyimide films are used for the thin dielectric layers to construct five 1-μm-thick gold films for the conductor metals. The microstrip line (a) is the most basic transmission line. The triplate line (b) has a low characteristic impedance with a narrow conductor width and an electrically shielded structure, since the strip conductor is sandwiched between two ground planes. The characteristics of these lines have no dependency on the wafer properties such as the dielectric constant and the thickness. The fundamental characteristics of these transmission lines are calculated by an in-house-

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T. Imaoka and N. Imai were with ATR Optical and Radio Communications Research Laboratories, Kyoto 619-02, Japan. They are now with ATR Adaptive Communications Research Laboratories, Kyoto 619-02, Japan.

S. Banba was with ATR Optical and Radio Communications Research Laboratories, Kyoto 619-02, Japan. He is now with SANYO Electric Company, Ltd., Osaka 573, Japan.

A. Minakawa was with ATR Optical and Radio Communications Research Laboratories, Kyoto 619-02, Japan. He is now with NTT Wireless Systems Laboratories, Yokosuka-shi 238-03, Japan.

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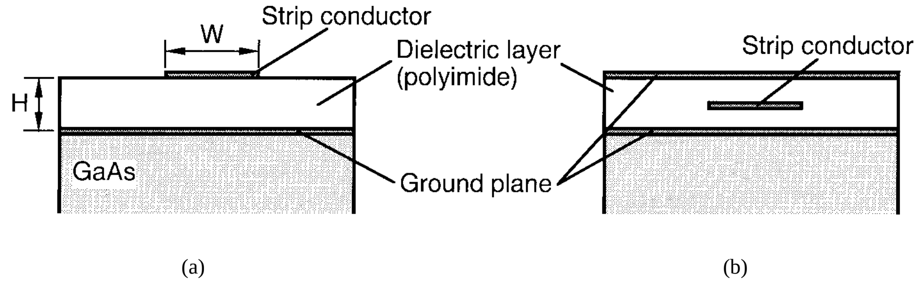


Fig. 1. Configurations of thin-film transmission lines. (a) Microstrip line. (b) Triplate line.

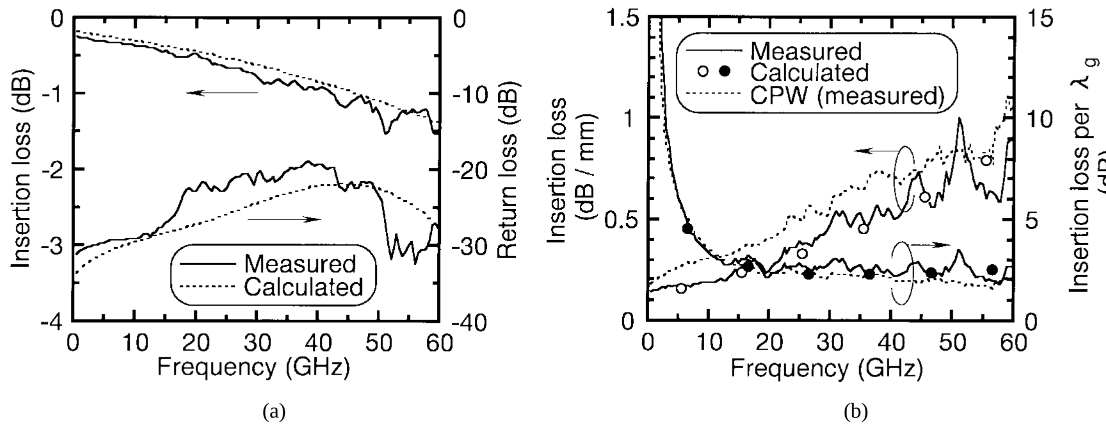


Fig. 2. Calculated and measured frequency characteristics of a 50-Ω microstrip line ($H = 10\,\mu$m, $W = 20\,\mu$m). (a) Line length = 1.5 mm. (b) Per unit length and guided wavelength as compared with CPW.

TABLE I
STRUCTURAL PARAMETERS AND CALCULATED AND MEASURED CHARACTERISTICS OF TRANSMISSION LINES. THE CONDUCTOR LOSSES ARE CALCULATED AT 50 GHz

Type	Polyimide thickness and line width (μm)	Calculated results			Measured insertion loss (at 50 GHz)	
		Characteristic impedance (Ω)	Effective dielectric constant	Conductor loss (dB / mm)	Per unit length (dB / mm)	Per wave-length (dB / λ_g)
Microstrip line	10 / 20	50.9	2.84	0.298	0.71	2.5
Microstrip line	10 / 10	73.1	2.71	0.337	—	—
Triplate line	10 / 18	21.1	3.70	0.771	—	—
CPW	Width / Gap = 20 / 14	48.3	6.67	0.247	0.88	2.0

developed two-dimensional (2-D) quasi-static and full-wave finite-element method (FEM) [13]. The structural parameters and calculated characteristics of the transmission lines are summarized in Table I. Those of a coplanar waveguide (CPW) formed on a 400-μm GaAs wafer surface are also summarized in the same table. The conductor losses are calculated at 50 GHz. A low-impedance triplate line $(Zo = 21\,\Omega)$, which is difficult to utilize in conventional MMIC's due to its wide conductor width, can be realized with a suitable width $(W = 18\,\mu\text{m})$ for MMIC fabrication.

It may be thought that the use of these lines will result in large losses. For certain, thin-film transmission lines show relatively high insertion losses, dominated by conductor losses, due to the narrow width of the strip conductors. To investigate the transmission loss, the losses of a 50-Ω impedance microstrip line and a CPW having the same conductor width $(W = 20\,\mu\text{m})$ were measured. The lines were tested up to 60 GHz using on-wafer probes and the WILTRON MODEL 360B network analyzer. Fig. 2(a) shows the calculated and measured characteristics of a microstrip line (line length: 1.5 mm). The frequency characteristics of the total attenuation were calculated by the sum of the conductor loss $\alpha_c(f)$ and the dielectric loss $\alpha_d(f)$ [8]. A good agreement between these values is obtained up to 60 GHz. The measured losses per unit length and guided wavelength (λ_g) are shown in Fig. 2(b). The insertion loss per λ_g decreases and reaches almost a

TABLE II
(a) STRUCTURAL PARAMETERS AND (b) CALCULATED CHARACTERISTICS OF COUPLED SECTION. THE CONDUCTOR LOSSES ARE CALCULATED AT 50 GHz

Structural parameters (μ m)					
h1	h2	Ws	Wf	G1	G2
2.5	7.5	15	44	10	110

(a)

Calculated characteristics			
	Characteristic impedance (Ω)	Effective dielectric constant	Conductor loss (dB/mm)
Even-mode	122.6	4.66	0.35
Odd-mode	20.9	3.88	1.12

(b)

constant value over 20 GHz. Against the CPW, the microstrip line shows a slightly high insertion loss per λ_g, due to the low effective dielectric constant. These measured results at 50 GHz are also summarized in Table I. However, there would be no serious influence in the active circuit design. Taking miniaturization into consideration, the thin-film transmission lines offer the capability of a narrow line-spacing due to the thin-film dielectric layers, against the fact that the CPW has a limitation with the center conductor and grounds being on the same surface of the substrate. The insertion loss can be reduced further by simply using thicker dielectric separation (resulting in a wider conductor width).

III. COUPLER CONFIGURATION AND PERFORMANCE

A cross-sectional view of the multilayer MMIC directional coupler [11] is shown in Fig. 3. The directional coupler is constructed with coupled microstrip lines, a ground conductor with a tuning septum, and a floating conductor located over the microstrip lines. Each conductor is formed on its own dielectric layer. The even-mode characteristics are strongly dependent on the tuning septum. On the other hand, the tuning septum has little effect on the odd-mode characteristics. Therefore, it is possible to get a high ratio of even- to odd-mode impedance since each mode impedance can be determined independently. The characteristics of the coupled section are calculated by the same methods as those used for the thin-film transmission lines. Table II summarizes the structural parameters of a 3-dB coupler with 50-Ω impedance, and the calculated characteristics of the coupled section. In this configuration, the thickness of the GaAs wafer has little effect on the coupler performance, in contrast with constructions in a single-layer planar configuration.

Using this coupler configuration, a 3-dB coupler was designed for a center frequency of 50 GHz and fabricated on a GaAs wafer surface. The structure has a coupling length of 720 μm, determined by the mean of the even- and odd-mode quarter wavelengths. The coupled section has a meander-like configuration to reduce the circuit area, and each microstrip conductor is connected to CPW input/output ports on the GaAs surface through via-holes (15 μm $\times$ 15 μm). A microphotograph of a fabricated coupler is shown in Fig 4. The intrinsic chip area is only 1.0 mm $\times$ 0.5 mm. The coupler was tested using on-wafer probes and a network analyzer. Termination-probes with return losses of better than 14 dB up to 55 GHz were also used. The measured and calculated frequency characteristics of the coupler are shown in Fig. 5. Note that the calculated values include discontinuities in the transition regions between the coupled sections and the input/output ports, and also include the characteristics of the imperfect termination-probes which are used in the measurements. At higher frequencies, the effects of the imperfect terminations are not negligible, especially in isolation. Also plotted in the figure are all of the frequency characteristics not including coupling losses calculated with perfect terminations. The measured coupling losses are within 3.9 ± 0.3 dB, and the phase difference between the coupling-port and through-port is $93^\circ \pm 2^\circ$ in the frequency range of 45–55 GHz. Furthermore, isolation is better than 14 dB and return losses are better than 21 dB in the frequency range of 0–55 GHz. The measured results closely match the calculated results, so the intrinsic isolation with perfect terminations can be considered to be better than 30 dB. Excellent performance is obtained within a small area of less than 0.50 mm^2.

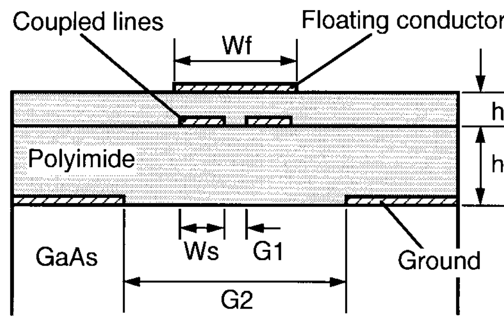


Fig. 3. Cross-sectional view of directional coupler.

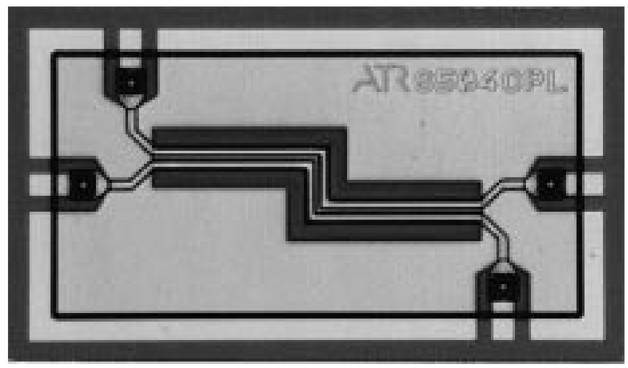


Fig. 4. Microphotograph of a fabricated 3-dB coupler.

IV. AMPLIFIER DESIGN

A millimeter-wave wide-band two-stage single-ended amplifier was designed using the thin-film transmission lines described above. The active devices are 0.2 $\times$ 100 μm het-

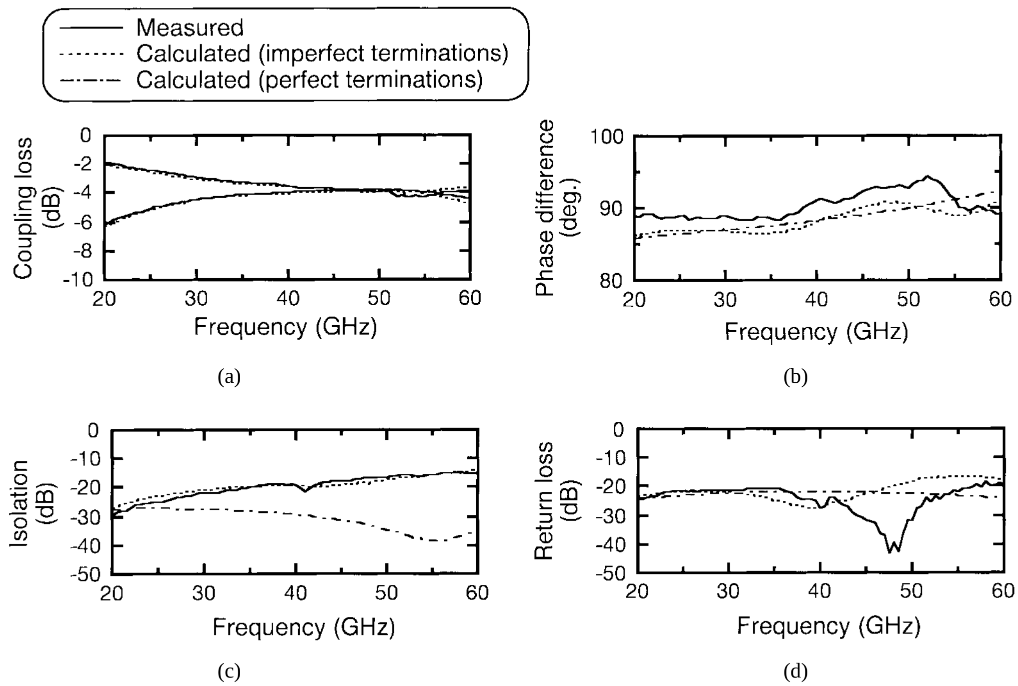


Fig. 5. Measured and calculated characteristics of a fabricated 3-dB coupler. (a) Coupling losses. (b) Phase difference. (c) Isolation. (d) Return loss.

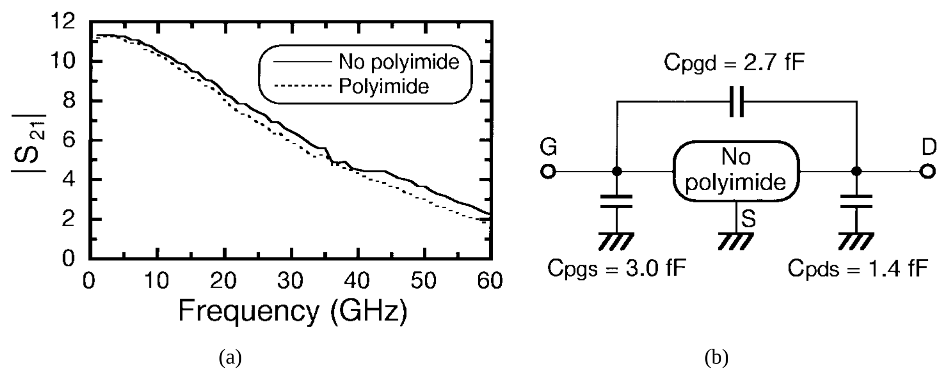
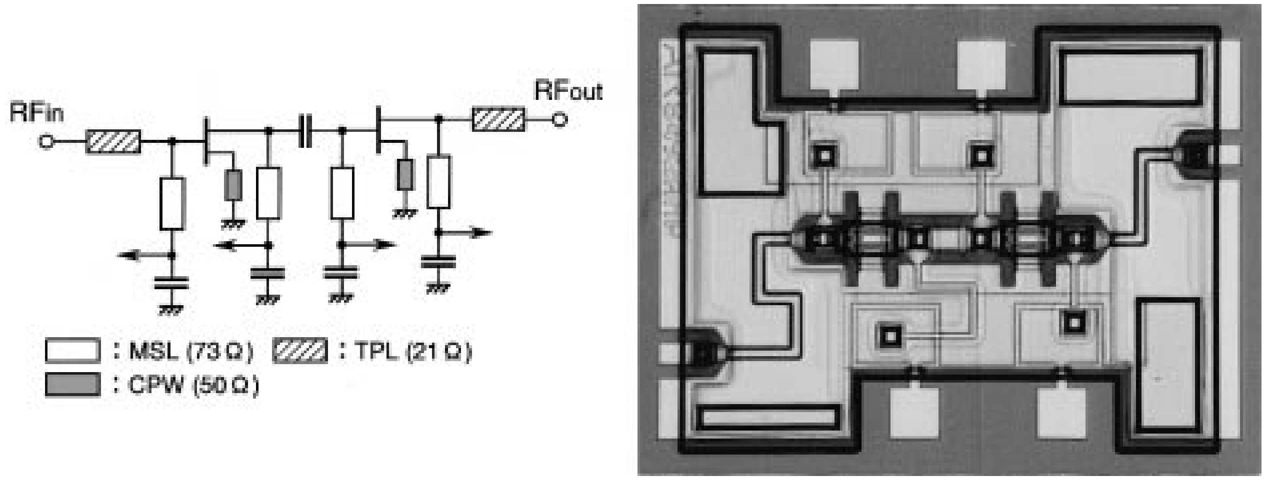


Fig. 6. (a) Measured $|S_{21}|$ and (b) equivalent circuit of transistors.

erojunction field-effect transistors [14]. In order to obtain a higher-frequency band gain, transistors in the U-layout were applied to amplifiers, because the measured S-parameters of the two layout types (U- and T-layout [15]) exhibited differences.

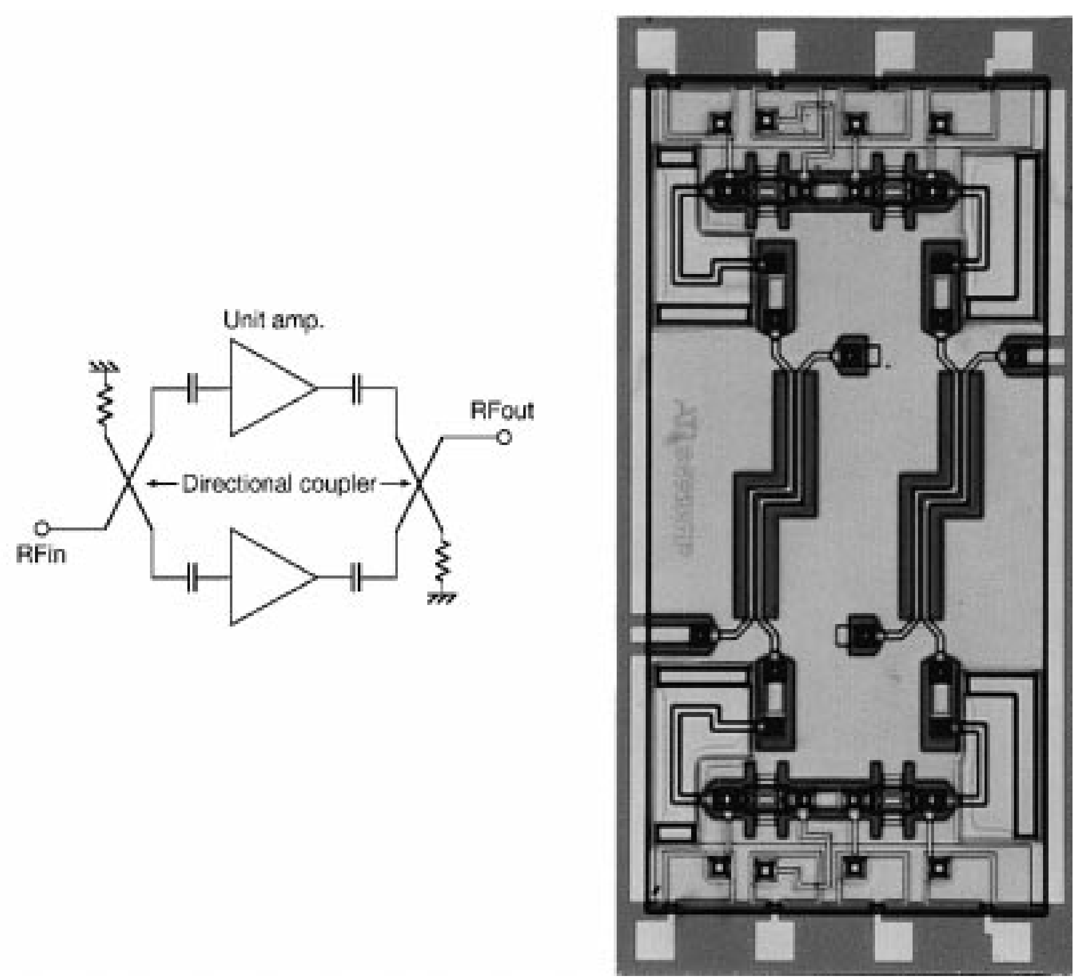
Furthermore, to investigate the parasitic effect of polyimide films upon transistors, transistor test structures with and without a 10-μm-thick polyimide film were fabricated close to each other on the same wafer. The results of the measured $|S_{21}|$ of each transistor having the same dc characteristics are shown in Fig. 6(a). Comparing the two structures, the transistor with polyimide film exhibits a lower $|S_{21}|$ than that without polyimide. Fig. 6(b) shows an equivalent circuit of transistors in which parasitic capacitances $(C_{pgs}, C_{pgd},$ and $C_{pds})$ due to the polyimide instead of air were added between each electrode to the measured S-parameters of the transistor without polyimide. Using this equivalent circuit, the S-parameters were calculated to fit with the measured results of the transistor with polyimide. The values of the extracted capacitances were only several femtofarads, as shown in Fig. 6(b), and all the calculated S-parameters including $|S_{21}|$ fitted well. Therefore, these parasitic effects can be considered as lossless. In fabricated amplifiers, the polyimide films upon the transistors were removed in the final wafer process, to prevent a decrease in amplifier gain. The amplifier is biased at a drain voltage of 3 V and a drain current of 25 mA for each device. At this bias condition, the devices without polyimide have an f_T and $f_{\max}$ of 74 and 140 GHz, respectively.

The circuit diagram and a microphotograph of the two-stage single-ended amplifier are shown in Fig. 7. The matching networks were designed with 73-Ω microstrip lines (MSL) and 21-Ω triplate lines (TPL). Low-impedance triplate lines connected directly to the transistors in the input and output matching networks were chosen to achieve amplifier gain flatness in the wide-band range by matching them with the low impedance of the transistors in the high-frequency range. The transistors have short source feedback CPW lines to improve circuit stability slightly, so as not to cause large gain reduction.



(a) (b)

Fig. 7. (a) Circuit diagram and (b) photograph of two-stage single-ended amplifier.



(a) (b)

Fig. 8. (a) Circuit diagram and (b) photograph of balanced amplifier.

MIM capacitors were added for RF bypass and dc blocking. The intrinsic chip area is 1.1 mm $\times$ 0.8 mm.

Using the above-mentioned multilayer MMIC directional couplers and single-ended amplifiers as unit amplifiers, a balanced amplifier was fabricated. The circuit diagram and a microphotograph of the balanced amplifier are shown in Fig. 8. 50-Ω mesa semiconductor resistors were used as terminations. The intrinsic chip area is 1.0 mm $\times$ 2.1 mm, although the balanced amplifier is constructed with two directional couplers and two unit amplifiers.

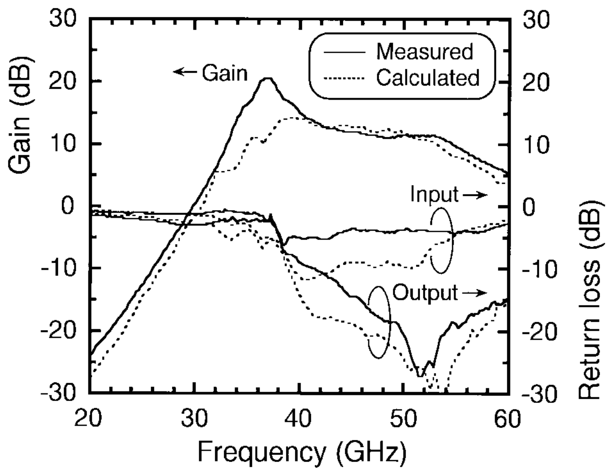


Fig. 9. Measured and calculated frequency characteristics of a fabricated single-ended amplifier.

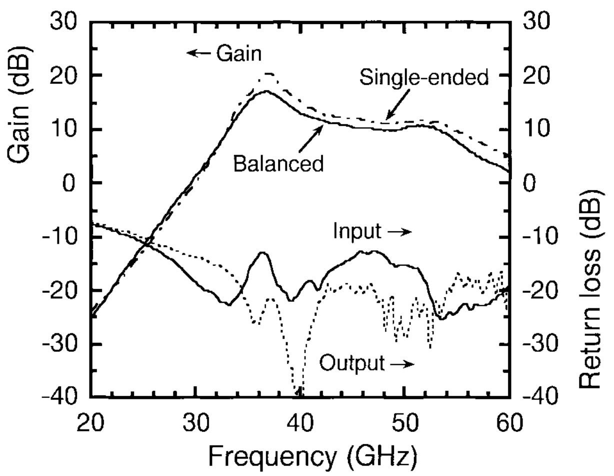


Fig. 10. Measured frequency characteristics of a fabricated balanced amplifier (as compared with the gain of a single-ended amplifier).

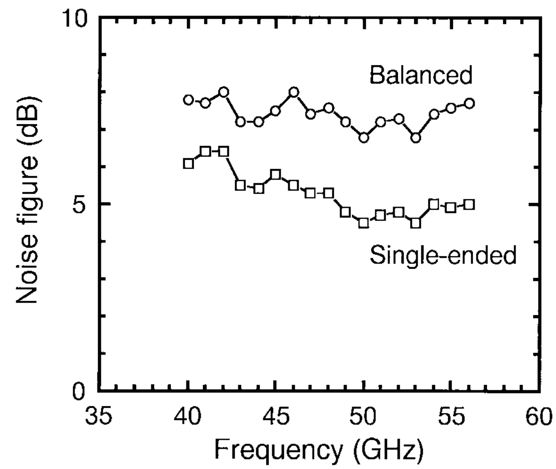


Fig. 11. Measured noise figures of amplifiers.

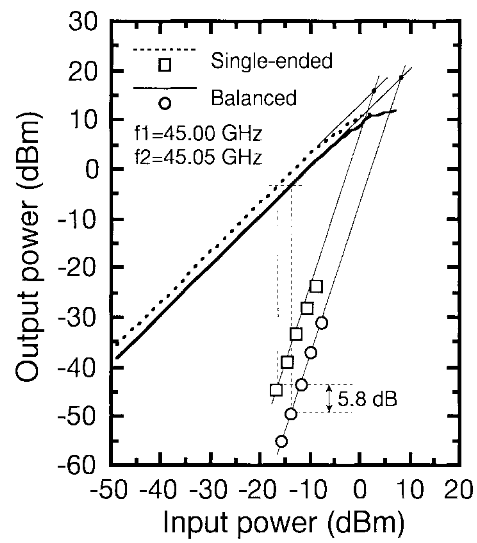


Fig. 12. Output power of the fundamental and third-order intermodulation products as a function of input power.

V. Amplifier Performance

The measured and calculated frequency characteristics of the fabricated single-ended amplifier are shown in Fig. 9. In the frequency range of 40–53 GHz, the single-ended amplifier shows a gain of 12–15 dB, and its input/output return losses are better than 4 and 8 dB, respectively. As compared with the calculated results, the measured gain presents a higher gain ripple and the input return loss is not close. The reason for this discrepancy is that we failed to estimate the effect of the source feedback lines. The use of longer and higher-impedance thin-film transmission lines instead of CPW's was certain to ensure stability. The measured frequency characteristics of the balanced amplifier are shown in Fig. 10. The balanced amplifier shows a gain of 10–17 dB, and its input/output return losses are better than 14 dB in the frequency range of 33–53 GHz. Its gain is approximately 2 dB smaller than that of the single-ended amplifier. The gain reduction corresponds to the losses of the MIM capacitors for dc blocking and the couplers. Fig. 11 shows the measured noise figures. In the frequency range of 43–53 GHz, the single-ended amplifier and balanced amplifier show a noise figure of better than 5.5 and 7.5 dB, respectively. Fig. 12 shows the output power of the fundamental and third-order intermodulation products as a function of the input power. The frequencies of the input signals were 45.00 and 45.05 GHz. The saturation output power of the balanced and single-ended amplifier are about 13 and 11 dBm, respectively. The output power improvement of the third-order intermodulation at the same fundamental output power is about 5.8 dB.

Thus, multilayer MMIC technology provides excellent electrical characteristics with considerable designability even in the millimeter-wave frequency range.

VI. Conclusion

Millimeter-wave wide-band amplifiers were designed and fabricated using novel multilayer MMIC technology. A single-ended amplifier gain of 12–15 dB between 40–53 GHz was achieved within a small area of less than 0.9 mm^2. A balanced amplifier gain of 10–17 dB with good return losses between 33–53 GHz was achieved within a small area of less than 2.1 mm^2. Transmission lines and directional couplers can be effectively combined with millimeter-wave active circuits without degrading the circuit performance or increasing the circuit area. To our knowledge, these are the first millimeter-wave active circuits employing multilayer MMIC technology. The fabricated amplifiers can be applied to the high-density and multifunctional integration of millimeter-wave MMIC modules.

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Toshikazu Imaoka (M'96) received the B.E. degree in electrical engineering from Osaka Prefecture University, Osaka, Japan, in 1984.

In 1984, he joined the Microelectronics Research Center, SANYO Electric Company, Ltd., Osaka, Japan, where he did research and development work on microwave devices. From 1994 to 1996, he has worked in research on millimeter-wave integrated circuits for personal communication systems at ATR Optical and Radio Communications Research Laboratories, Kyoto, Japan. He is now with ATR Adaptive Communications Research Laboratories.

Mr. Imaoka is a member of the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan.

Seiichi Banba (M'91) received the B.E. and M.S. degrees in electrical and electronic engineering from Toyohashi University of Technology in 1982 and 1984, respectively.

In 1984, he joined the Microelectronics Research Center, SANYO Electric Company, Ltd., Osaka, Japan, where he did research and development work on microwave devices. From 1990 to 1993, he investigated optical/microwave monolithic integrated circuits for personal communication systems at ATR Optical and Radio Communications Research Laboratories, Kyoto, Japan. Since 1994, he has been researching microwave devices at SANYO Microelectronics Research Center.

Mr. Banba is a member of the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan.

Akira Minakawa (M'96) received the B.S. and M.S. degrees in electrical engineering from Ibaraki University, Ibaraki, Japan, in 1984 and 1986, respectively.

He joined the NTT Radio Communications Networks Laboratories, Yokosuka, Japan, in 1986. He has been engaged in research and development of monolithic microwave integrated circuits. From 1993 to 1995, he worked in research on millimeter-wave integrated circuits for personal communication systems at ATR Optical and Radio Communications Research Laboratories. Since 1996, he has been researching monolithic microwave integrated circuits for communication satellites at NTT Wireless Systems Laboratories.

Mr. Minakawa is a member of the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan.

Nobuaki Imai (M'86) received the B.S. degree in electrical engineering from Nagoya Institute of Technology, Nagoya, Japan, in 1975, and the M.S. degree from Kyoto University, Kyoto, Japan, in 1977.

He joined Yokosuka Electrical Communications Laboratories, Japan, in 1977, where he was engaged in research on microwave and millimeter-wave integrated circuits and the development of digital microwave radio systems. In 1993, he moved to ATR Optical and Radio Communications Research Laboratories, where he has been engaged in research of millimeter-wave personal communication systems using optical fiber. He is now with ATR Adaptive Communications Research Laboratories.

Mr. Imai is a member of the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan.