Novel Linearizer Using Balanced Circulators and Its Application to Multilevel Digital Radio Systems

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Abstract —A new miniaturized RF predistortion linearizer for a GaAs FET power amplifier applicable to 256 QAM digital microwave systems is presented. This linearizer, which is based upon the cuber linearizer technique [1], utilizes circulators and a pair of diodes as fundamental components. It allows not only miniaturization and easy adjustment of the circuit, but also compensation for temperature variation in the circulators. The fundamental characteristics of the linearizer and its effect on the 256 QAM signal are shown. The results show an improvement of more than 6 dB in the output back-off of the amplifier.

I. Introduction

RECENTLY, obtaining more bits per hertz has become a major concern for designers of digital microwave radio systems. In order to increase the number of bits assigned to the frequency band, multilevel modulation systems such as 16 QAM have been developed [2], and higher level modulation schemes such as 64 QAM and 256 QAM are now being investigated [3].

Since high-level modulation schemes have various amplitude levels, they are very sensitive to distortion noise [4]. In addition, since common amplifiers are used in the 256 QAM multicarrier system to reduce the cost and size of the repeater system, it is essential that the power amplifier in this system be highly linearized. Therefore, an effective linearization technique is needed to produce more practical and economical repeater equipment.

The predistortion (PD) method has been recognized as the most effective and practical linearization technique through previous communications system applications, such as microwave SSB-AM systems [5], [6], mobile systems [1], and satellite communications systems [7]–[13]. Several types of linearizers have been proposed. In these linearizers, after dividing an input signal into two paths (linear path and distortion path), the distortion component is produced by the amplifier in the distortion path and combined with the fundamental signal component at the output. Otherwise, as is described in detail in the following section, the double-loop configuration is adopted to suppress the fundamental signal component in the distortion path. However, in the first configuration described above, suppression of the signal component in the distortion path is not sufficient. Therefore, distortion and signal components are simultaneously changed by control signals, resulting in difficulty of adjustment. With the latter configuration, circuit configuration and adjustment become more complex because of the double-loop configuration.

In this paper, a new predistorter is proposed which is suitable with regard to compactness, ease of adjustment, and wide-band compensation. The linearizer uses a circulator in the distortion generator to obtain high signal component isolation, and in the variable phase shifter to compensate for temperature variations. The nonlinearity compensation characteristics of the linearizer and their effect on 256 QAM signal amplification are also described.

II. Circuit Configuration of the Newly Developed Predistortion Linearizer

Fig. 1 shows the basic circuit configuration of the linearized amplifier assuming a cuber linearizer [1]. The vector diagram of the signal and distortion component and that of AM–AM and AM–PM conversions in each stage are also shown [1]. In order to compensate for the distortion component of the amplifier, distortion produced by the linearizer should have equal amplitude and opposite phase to that of the amplifier. When this condition is satisfied, AM–PM conversion of the linearizer has reverse characteristics to those of the amplifier. The phase shifter placed in the cubic path in Fig. 1(a) can be removed into the main path, as shown in Fig. 2.

In the conventional predistortion linearizer [9], the distortion generator includes two amplifiers. By changing the drive level of each amplifier, the distortion it produces is changed. Consequently, if the signal output level is adjusted by attenuators so that each signal component is canceled at the output, this generator can produce only the distortion component. However, to cancel the signal component, the output power and the phase must be adjusted. Accordingly, this configuration is not suitable for easy adjustment and compactness. To overcome these problems, a novel predistortion linearizer, which is based upon the cuber linearizer technique, was invented. It uses a circulator and diodes in the distortion generator to obtain high signal component isolation.

Manuscript received August 10, 1988; revised March 10, 1989
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IEEE Log Number 8928332.

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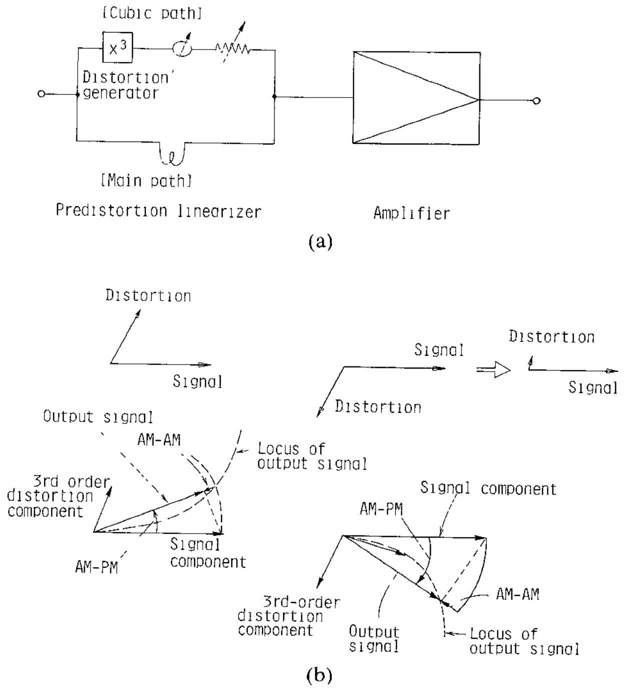

Fig. 1. Basic circuit configuration and vector diagram of the predistortion linearizer. (a) Basic circuit configuration. (b) Vector diagram.

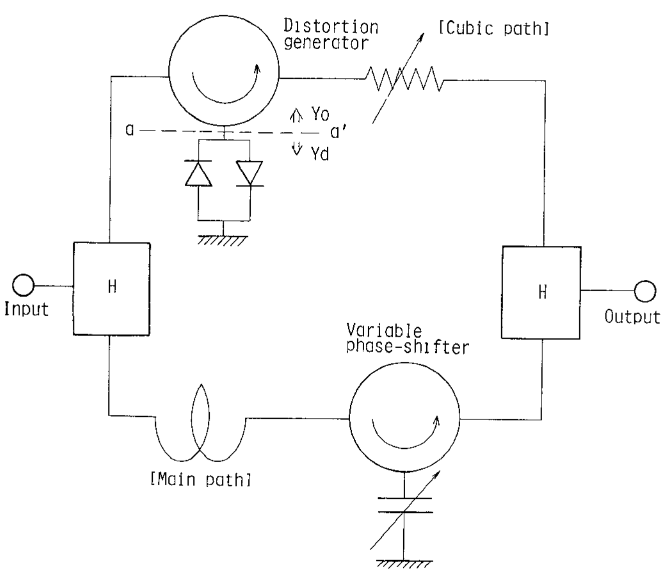

Fig. 2. Configuration of new predistortion circuit.

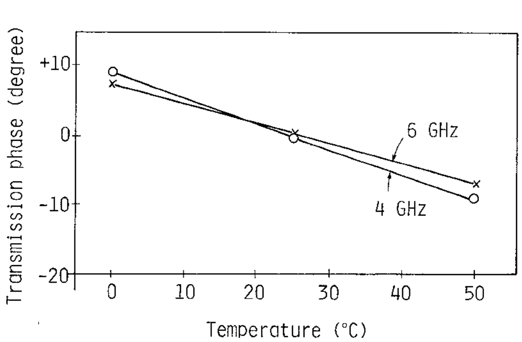

Fig. 3. Temperature characteristics of transmission phase in circulator

The circuit configuration is shown in Fig. 2. The input signal is divided into two paths, the linear path and the distortion path, by the input hybrid. The linear path (main path) is composed of a delay line and a variable phase shifter. The distortion path (cubic path) is composed of a distortion generator and the variable attenuator. In this configuration, the distortion generator is composed of a circulator and a pair of diodes connected in an antiparallel fashion.

The signal from the input port is fed to the nonlinear circuit, composed of diodes and a matching circuit. When the signal level is low, the impedance of the diodes matches that of the circulator. Consequently, the input signal does not come out at the output port. However, as the input level increases, the impedance of the nonlinear circuit changes. As a result, at the output port, the signal comes out due to the mismatching condition. This output signal corresponds to the distortion component of the nonlinear circuit.

The current $i(t)$ which flows into a pair of diodes is given by the following equation using the voltage $v(t)$, which is applied to a pair of diodes connected in an antiparallel fashion:

$$i(t) = I_0 \cdot (\exp(av(t)) - \exp(-av(t))) \tag{1}$$

where I_0 and a are constants.

When the input voltage to the distortion generator V_{in} is applied, the output signal V_{out} becomes (see the Appendix)

$$|V_{out}| = |\Gamma| \cdot |V_{in}| \simeq \frac{ka^3}{2Y_0}|V_{in}|^3 \tag{2}$$

which means that only the third-order distortion will appear, and the signal component V_{in} is suppressed.

An example of the temperature characteristics of the transmission phase in a circulator is shown in Fig. 3. As can be seen from this figure, the phase shift in a circulator decreases as the temperature increases. When a circulator is used only in the distortion path, the phase relation between the signal component and the distortion component also decreases with increasing temperature.

To compensate for temperature changes in a circulator, the phase shifter in the linear path includes another circulator. As a result, the phase shifts in the linear path and the cubic path change by the same amount as the temperature changes. Therefore, the temperature characteristics of the phase shift in both circulators are canceled at the output.

III. Characteristics of the Newly Developed Predistortion Linearizer

The output of the fundamental signal component and fifth-order distortion component in the distortion generator in Fig. 2 should be small to construct a cuber linearizer. However, the third-order distortion component

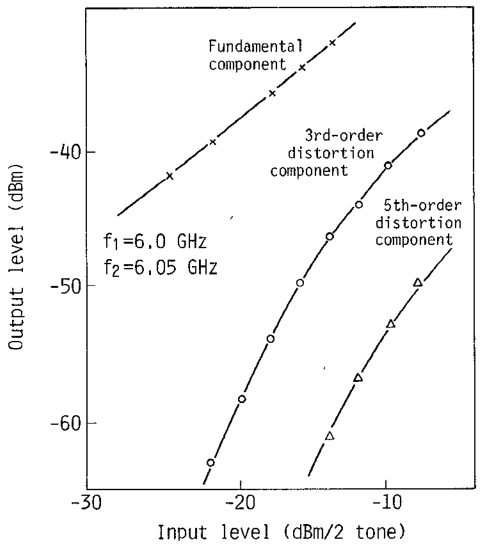

Fig. 4. Input–output characteristics of distortion generator.

should be large so that the distortion component of the next amplifier can be compensated by it.

The input–output characteristics of the distortion generator are shown in Fig. 4. More than 15 dB suppression of the fundamental signal component was achieved, which was sufficient to make the distortion path independent of the signal component. The fifth-order distortion component was more than 12 dB smaller than the third-order distortion component, which was adequate for the cuber linearizer. The deviation of the third-order distortion from 5.9 to 6.2 GHz was less than 1.0 dB, and a very broad band third-order distortion generator could be constructed.

The distortion improvement factor when the predistortion linearizer is equipped with a high-power amplifier is shown in Fig. 5. The linearizer was adjusted at the point where output back-off was 8 dB, where third-order distortion reduction of more than 20 dB was achieved. Fig. 6 shows the frequency characteristics of the distortion improvement factor. In the frequency range from 5.9 to 6.2 GHz, an improvement factor of more than 10 dB was achieved.

One of the authors has evaluated the distortion reduction U as a function of amplitude error δ and phase error $\Delta\Theta$ [1]. This is expressed as follows:

$$U = 10\log\left(1 + 10^{\delta/10} - 2\cdot 10^{\delta/20}\cdot\cos\Delta\Theta\right) \quad \text{(dB)} \quad (3)$$

where δ is the error from the equal amplitude condition, and $\Delta\Theta$ is the error from the inverse phase condition.

When the amplifier is excited with a single-tone signal,

$$e_i(t) = a\cos(\omega_0 t) \quad (4)$$

a unique relationship between AM–AM and AM–PM conversions can be obtained [5]:

$$\Psi(a) = \tan^{-1}\left[\frac{\{R^2(a)-1\}\tan\Phi_3}{R^2(a)+1}\right] \quad (5)$$

where $R(a)$ is the AM–AM conversion, $\Psi(a)$ is the AM–PM conversion, and Φ_3 is the third-order distortion phase. From this equation, the AM–AM conversion $R(a)$ and the AM–PM conversion $\Psi(a)$ are related through the third-order distortion phase Φ_3. Measurement results of the nonlinearities of a 6 GHz band FET are shown in Fig. 7. Additionally, the calculated relationship between gain compression and phase lag for the third-order distortion phase Φ_3 is plotted. It is found from this figure that the deviation of the third-order distortion phase Φ_3 of a 6 GHz band FET in the frequency band is about 10°. Fig. 8 shows the input–output characteristics of a 6 GHz band FET amplifier. When output back-off is more than 4 dB, the deviation of the third-order distortion amplitude component is less than 2 dB. Considering these results, the

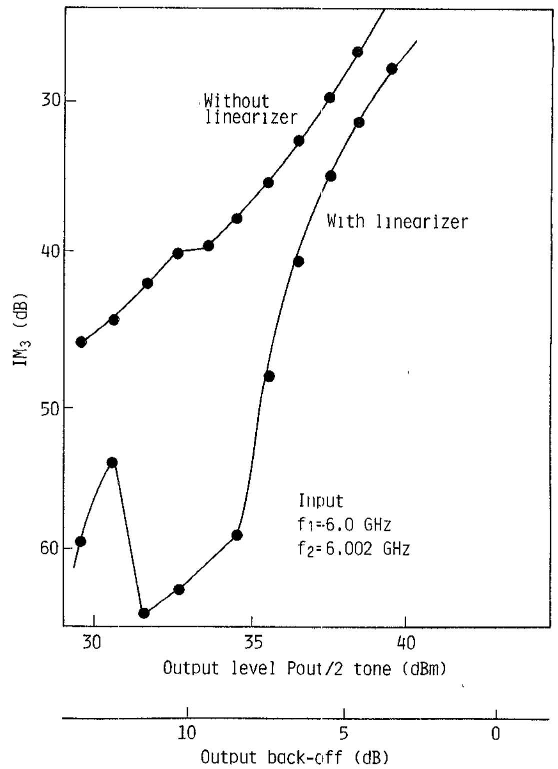

Fig. 5. Distortion characteristics of amplifier with and without linearizer.

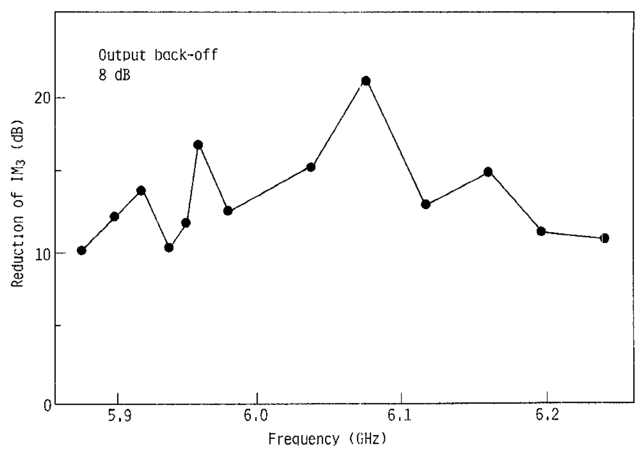

Fig. 6. Frequency response of reduction in IM3.

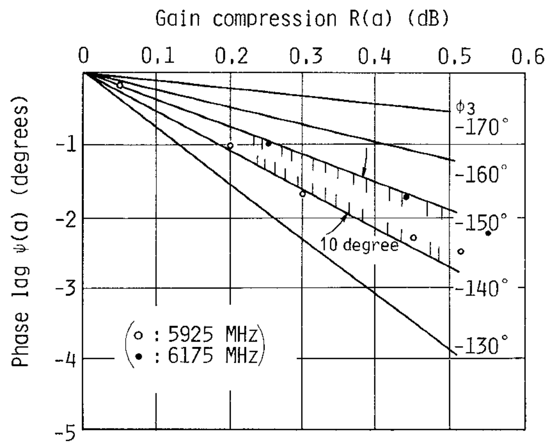

Fig. 7. Frequency characteristics of third-order distortion phase Φ_3 of 6 GHz band FET.

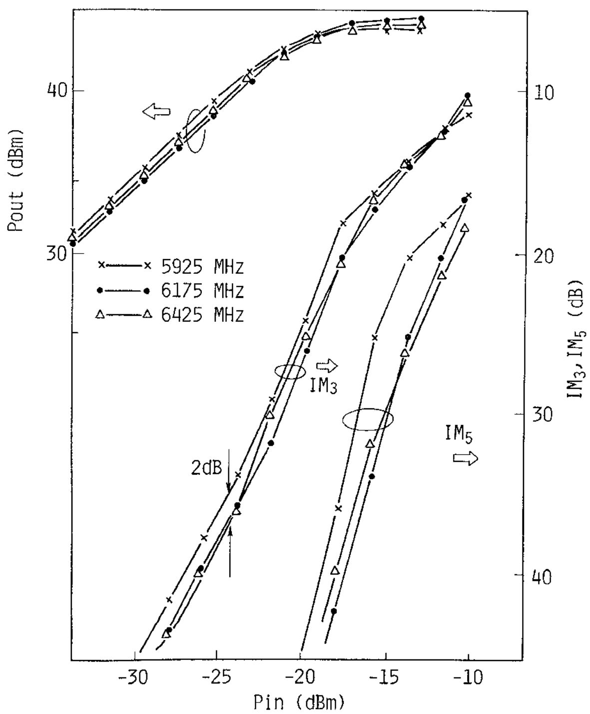

Fig. 8. Input–output characteristics of 6 GHz band FET amplifier.

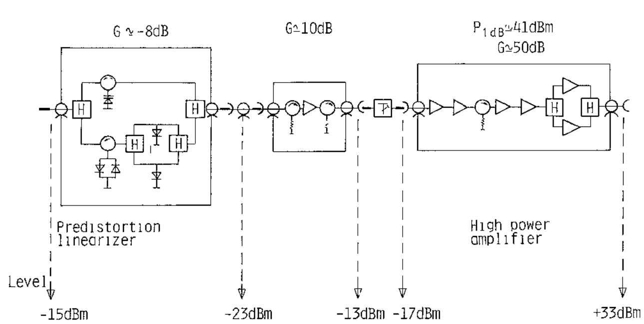

Fig. 9. Block diagram and level diagram of linearized FET amplifier

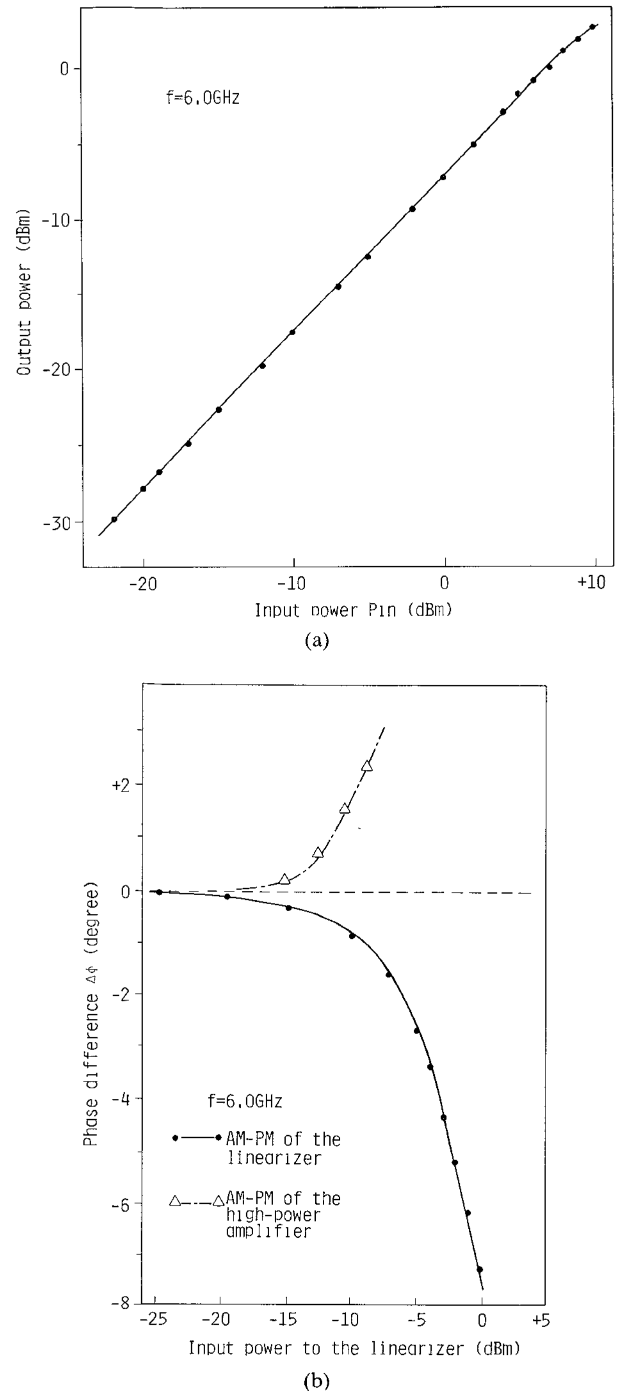

Fig. 10. Input to output transfer characteristics of the linearizer. (a) Input to output power transfer characteristics. (b) AM–PM characteristics

distortion reduction U is estimated to be 10 dB from (3), which is consistent with the results shown in Fig. 6.

Fig. 9 shows a block diagram and level diagram of a linearized FET amplifier equipped with the new linearizer. In order to increase the gain of the high-power amplifier in the final stage, another one is installed before it. The output power of the high-power amplifier is 41 dBm at the 1 dB gain compression point.

A variable attenuator is inserted between the two amplifiers so that the operating point of the high-power ampli-

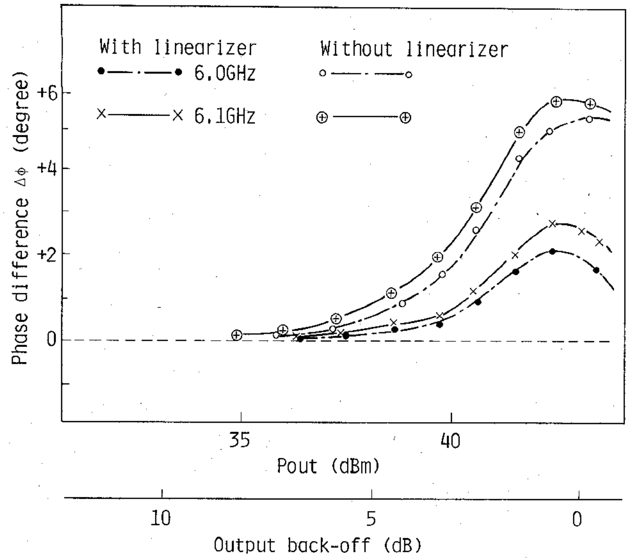

Fig. 11. Improvement of AM–PM by the linearizer.

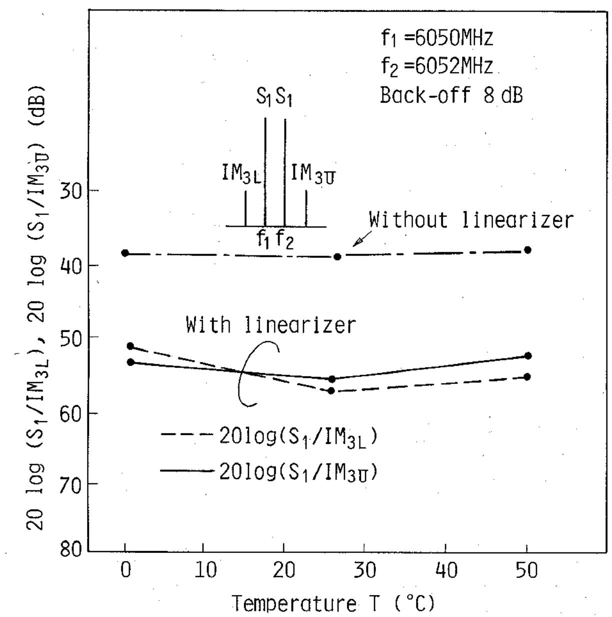

Fig. 12. Temperature characteristics of the third-order distortion.

fier can be changed. Fig. 10 shows input-to-output transfer characteristics of the new linearizer. Fig. 10(a) shows input-to-output power transfer characteristics, and Fig. 10(b) shows AM–PM characteristics of the linearizer. The gain expansion characteristic can be seen near the saturation point in Fig. 10(a), although it is small. As was explained in Fig. 1, the distortion produced in the linearizer has reverse phase to that of the amplifier. Therefore, AM–PM produced in the linearizer also has reverse characteristics to that produced in the subsequent amplifier. The insertion loss of the linearizer was about 8 dB, and the deviation of the gain of the linearizer and linearized FET amplifier at small signal was less than 1.0 dB in the frequency band between 5.9 and 6.2 GHz. Improvement in AM–PM when the linearizer is equipped is shown in Fig. 11. AM–PM conversion is improved to 1/3 at the point where output

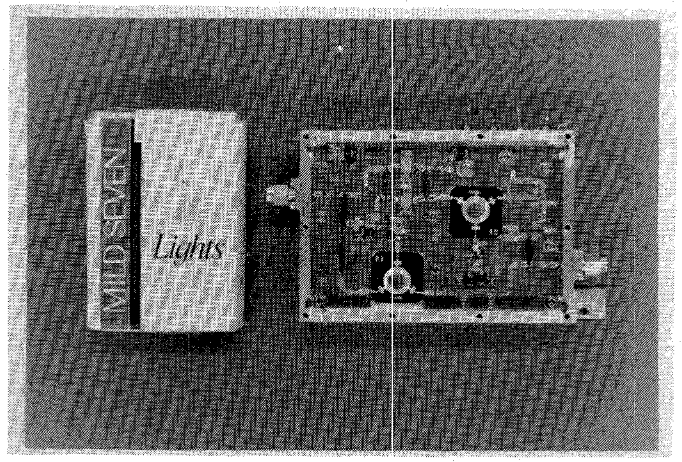

Fig. 13. Circuit configuration of the linearizer fabricated on a Teflon substrate.

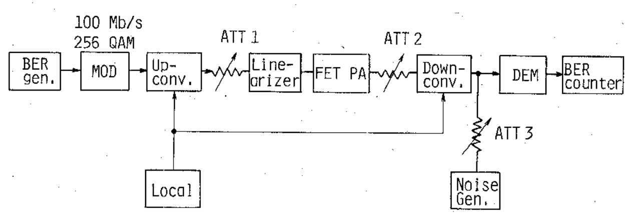

Fig. 14. Block diagram of experimental 256 QAM transmission system.

back-off is more than 3 dB. Fig. 12 shows the temperature characteristics of third-order distortion in a 20 W high-power amplifier equipped with the linearizer described in the previous section. When the temperature of the linearizer was changed, a distortion improvement factor of more than 10 dB could be obtained in the temperature range between 0 and 50°C. Changes in circulator characteristics due to temperature variations could be eliminated over a wide temperature range.

IV. Application of the Linearizer to 256 QAM System

In this section, the transmission characteristics of 256 QAM signals in a nonlinear amplifier are investigated, and the effect of the predistortion linearizer described in the earlier section is examined. A photograph of the linearizer fabricated on a Teflon substrate is shown in Fig. 13.

The experimental setup for examining 256 QAM transmission characteristics is shown in Fig. 14. One primary carrier has a transmission capacity of 100 Mb/s, the symbol rate is 12.5 Mbaud, and the spectral shaping is 50 percent cosine roll-off. ATT1 and ATT2 are used to change output back-off with the input power for the receiver fixed. ATT3 is used for changing the CNR ratio.

AM–PM conversion of FET amplifiers is smaller than that of TWT's, as has been reported elsewhere [14]. Therefore, we can use FET amplifiers at a lower back-off point than TWT amplifiers when multilevel QAM signals pass through them [15]. We used FET amplifiers for amplification of multilevel QAM signals. The characteristics of the FET amplifier used for the experiment were the same as those shown in Fig. 8.

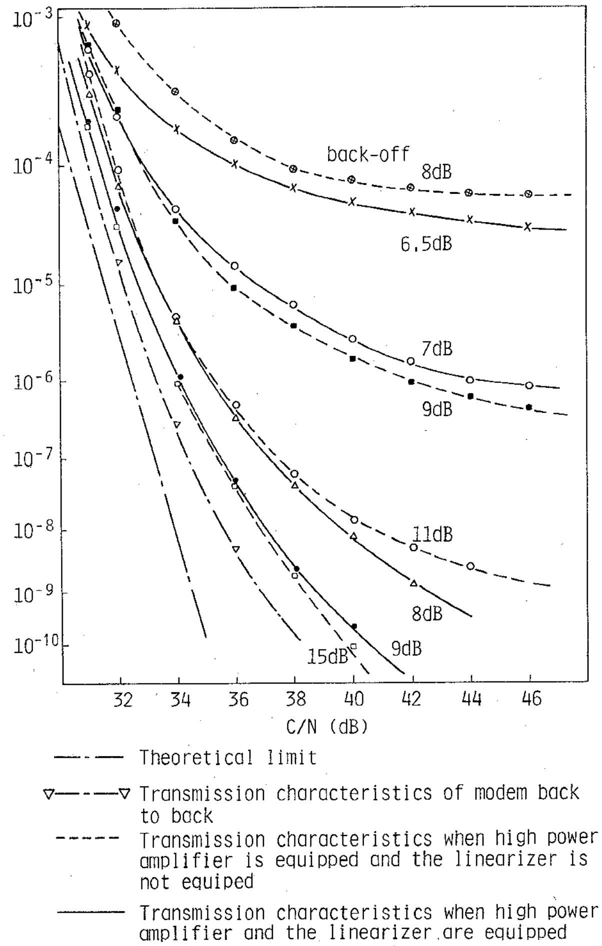

Fig. 15. Transmission characteristics of 256 QAM signal.

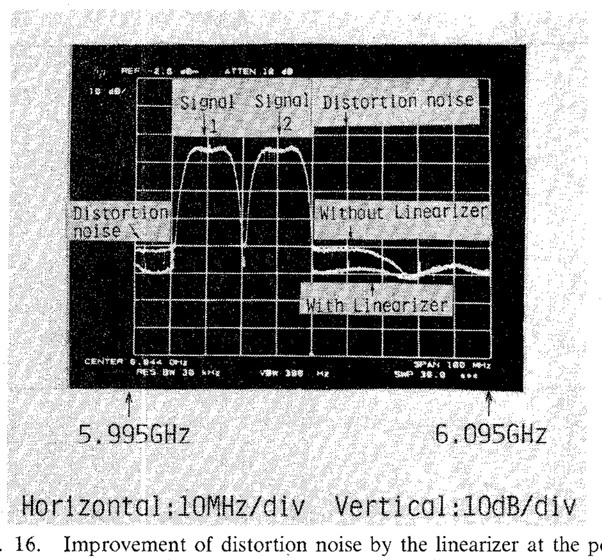

Fig. 16. Improvement of distortion noise by the linearizer at the point where the output back-off is 8 dB.

The transmission characteristics of 256 QAM signal in a nonlinear amplifier with and without the predistortion linearizer are shown in Fig. 15. When the linearizer was used, output back-off was improved by 3 dB at the point where the bit error rate was 10^{-6}, and by more than 6 dB at the point where the bit error rate was 10^{-9}. Thus, the linearizer should prove very effective for high-power amplification for a multilevel modulation system.

Improvement in distortion noise with the linearizer when two 256 QAM multicarriers are commonly amplified is shown in Fig. 16. The upper spectrum is that without the linearizer, and the lower one is that with it at the point where output back-off is 8 dB. Distortion noise was reduced 10 dB for the wide-band signals by using the linearizer.

V. Conclusion

A new miniaturized RF predistortion linearizer for a GaAs FET power amplifier used in 256 QAM digital microwave systems was presented. This linearizer, based upon the cuber linearizer technique, utilizes circulators and a pair of diodes as fundamental components. Using the configuration proposed in this paper, distortion reduction of more than 10 dB can be obtained over the 300 MHz bandwidth. It was also verified that distortion reduction could be achieved over a wide temperature range from 0 to 50°C. Additionally, the effect of the linearizer on 256 QAM signal was investigated. The results showed a more than 6 dB improvement in output back-off.

Appendix

Equation (1) is expanded by Tayler series into

$$i(t) = 2I_0\left\{ a\cdot v(t) + \frac{a^3}{3!}v^3(t)\right\}. \tag{A1}$$

As a result, the admittance of a pair of diodes is given by

$$Y_d = \frac{i(t)}{v(t)} \simeq 2I_0\left\{ a + \frac{a^3}{3!}v^2(t)\right\}. \tag{A2}$$

If the matching circuit transforms $2I_0a$ into the admittance of the circulator, Y_d is expressed as follows:

$$Y_d \simeq Y_0 + ka^3v^2(t) \tag{A3}$$

where k is a constant. Therefore, in the circuit configuration of the distortion generator shown in Fig. 2, the reflection coefficient at the plane $a-a'$ is given by the following equation:

$$\Gamma = \left|\frac{Y_0 - Y_d}{Y_0 + Y_d}\right| \simeq \left|\frac{ka^3v^2(t)}{2Y_0}\right|. \tag{A4}$$

Acknowledgment

The authors would like to thank Dr. O. Kurita, Dr. T. Sugeta, and Dr. H. Yamamoto for their encouragement and guidance.

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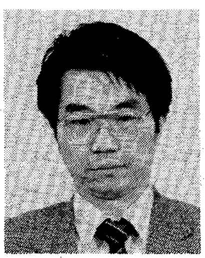

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