High Efficiency Amplifiers for 8 GHz Band

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Abstract

This paper describes newly devised high efficiency amplifiers. They are single and push−pull power amplifiers operating in 8 GHz band. In the single amplifier, a trapezoidal voltage waveform is produced at an FET1 in the first stage of the circuit, and the operating angle is set to 74°. This voltage is amplified in the exciting stage and the power amplification is performed by a power FET in the final stage. Using an FET whose characteristics are the same as those of an FET used in the proposed amplifier, the conventional class A and class C power amplifiers are also constructed. For the three (new and conventional) amplifiers, the comparison is made in the output power and the power added efficiency, and the predominance of a new high efficiency power amplifier is demonstrated. The operating frequency is in 8 GHz band, and the output power is 2 W, 2.35 W, and 3 W for class A and class C amplifiers, and a new amplifier, respectively. For these amplifiers, the power added efficiency is 30 %, 48.5 %, and 60 %. A high efficiency push−pull power amplifier is also constructed, and the maximum power 7 W and the power added efficiency 76 % are obtained.

1. Introduction

Recently, a high efficiency power amplifier is required in order to reduce the power consumption of the DC source for a portable telephone and a transceiver and to increase the time to be used for these devices. Moreover, a high efficiency power amplifier is indispensable to reduce the amount of heat arising from semiconductors in the power amplifiers of the transmitter which is loaded on a communication satellite. To reduce the DC power, it is not enough to make the efficiency high only for the final stage, and it is necessary to consider a circuit system for which the total efficiency through the first to the final stages is high. Such systems have been reported in Refs. [1]−[3].

Here the author proposes a new high efficiency single power amplifier for 8 GHz band. In the circuit system of this amplifier, we can produce a trapezoidal waveform at FET1 of the first stage, and at the same time, the operating angle of the waveform can be set to 74°. In order to preserve the trapezoidal waveform at the drain side of FET1, we couple $TE_{01\delta}$ mode dielectric resonators with the resonance frequencies f_0, $3f_0$, and $5f_0$ to a transmission line which is connected between the drain and the drain source, where f_0 is the resonance frequency of the fundamental wave. The power of the trapezoidal wave is amplified at the exciting and final stages. In these stages, $TE_{01\delta}$ mode dielectric resonators with f_0, $3f_0$, and $5f_0$ are employed to maintain the trapezoidal waveform at the drain sides of FET2 and FET3. In order to extract the fundamental wave of f_0 from the output of a power amplifier in the final stage, a $TE_{01\delta}$ mode dielectric resonator with f_0 is loaded between the parallel transmission lines. Namely, this circuit operates as a band−pass filter. We compare the output power and the power added efficiency of the proposed amplifier with those of the conventional class A and class C power amplifiers. First, the measured values of the output power and the power added efficiency of the class A power amplifier are compared with those of the class C power amplifier. Secondly, the measured output power and the power added efficiency of the class C power amplifier are compared with those of a new high efficiency power amplifier, and the predominance of a new amplifier is pointed out. Moreover, the operation of a new high efficiency push−pull power amplifier is described.

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2. Class C Single Power Amplifier

In the transmitters for broadcasting and communication devices, the class C power amplifiers are employed. This type amplifier has a merit that, when there is no signal, the drain current does not flow in the power amplifier of the final stage. Figure 1 shows the circuit structure of a class C single power amplifier, and a photograph of this circuit is shown in Fig. 2. In the following, the operation of the amplifier is explained. The bias voltage of FET1 in the first stage and that of FET2 in the exciting stage are so chosen that these FETs operate as class A amplifiers. Two parallel resonators with resonance frequency f_0 are connected between the drains and the DC source V_{DS}. These resonators are $TE_{01\delta}$ mode dielectric resonators. Since the resonators with f_0 are connected, they operate as single tuning amplifiers, and the degree of amplification A is given by $A = -g_m Z_L$, where Z_L consists of the inner resistance r_d of FET, the gate resistance R_{GS}, and the impedance of a $TE_{01\delta}$ mode dielectric resonator. At resonance, Z_L becomes large, and from $A = -g_m Z_L$, the gain also becomes large at resonance. The FET3 in the final stage is a class C power amplifier. As shown in Fig. 3, the bias voltage was set to a value for which the operating angle of exciting voltage waveform is 74° to make the power added efficiency as large as possible. The operating point is determined by the bias voltage. As seen from Fig. 3, the exciting voltage waveform is slightly enter into the positive

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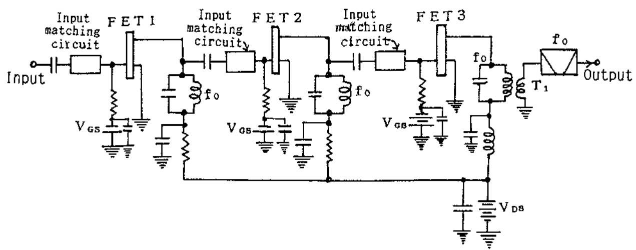

Fig. 1 Circuit system of the class C power amplifier.

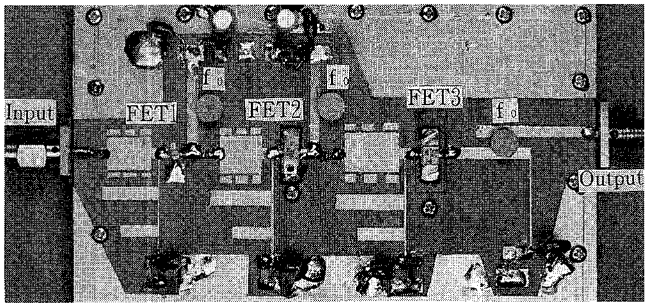

Fig. 2 Photograph of the class C power amplifier shown in Fig. 1.

region and, as a result, the gate current I_{gs} flows. Hence the current I_{DSS} flowing between the drain and source is not sinusoidal and contains higher-order harmonics besides the fundamental wave, namely, the current is distorted. Since the amplifier employs this synthesized wave, the power added efficiency is much larger than that of a class A amplifier. Although a parallel resonator with resonace frequency f_0 is connected between the drain of a power FET3 and the DC source V_{DS}, the resonators for higher-order harmonics are not connected. Hence the load impedances for the higher-order harmonics are small and these harmonics are by-passed through a capacitance of the parallel resonator with f_0. As a result, only the fundamental wave is obtained at the output.

A circuit system for compensating the odd-order harmonics is not employed. Since these harmonics do not form a trapezoidal wave, we cannot obtain large power added efficiency. For obtaining large power added efficiency, the operating angle should be small. However, too small operating angle makes the wave amplitude small and the output power becomes low. To obtain high output power, we should make the wave amplitude large, namely, the gain should be large. Since the high gain results in large DC power consumption, the power added efficiency decreases. From the above mentioned reasons, it is clear that we cannot make the operating angle too small. When we employ a circuit systemwhich compensates the fundamental and higher-order harmonics using distorted wave, large power added efficiency is obtained. Such an amplifier will be described in Section 3.

As a circuit for extracting the fundamental wave of f_0 from the drain of FET3, a $TE_{01\delta}$ mode dielectric resonator with f_0 is loaded between the two microstrip lines as shown in Fig. 2. This circuit operates as a band-pass filter. Since the higher-order harmonics are contained a little in the output of the filter, another band-pass filter with f_0 is connected to the output terminal of the filter to suppress the higher-order harmonics completely.

The experiment on a class C amplifier was performed in 8 GHz band. The voltage V_{DS} between the drain and source of FET3 was 10 V, and the bias voltage V_{GS} was set to -4.3 V. This bias voltage is larger than a cutoff point V_p and corresponds to the operating angle 74°. The amplifier operates as a class C amplifier. When the input power was fixed to 20 dBm and the frequency was changed from 7 GHz to 9 GHz, the output power of 31.8 dBm, the pass band of 82 MHz, and the power added efficiency of 28 % were obtained. When the input power was changed from 13 dBm to 24 dBm, the output power changed from 24.6 dBm to 33.7 dBm and the power added efficiency changed from 12 % to 48.5 % as shown in Fig. 6.

3. High Efficiency Single Power Amplifier

A high efficiency single power amplifier for 0.8-0.9 GHz band has been reported in Refs. [1]-[3]. When the distorted waveform described in these references is used, it is possible to make the power added efficiency and output power high. Especially, if we use the rectangular waveform shown in Ref. [3], the most favorable characteristics are obtained. However, it is difficult to produce a precise rectangular waveform in 8 GHz band. So the author adopted the trapezoidal waveform shown in Ref. [2]. Here, instead of using two diodes and two bias voltages

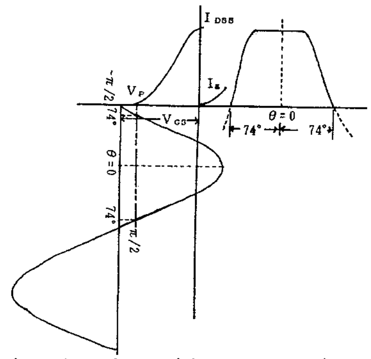

Fig. 3 Bias voltage for obtaining the synthesized voltage whose operating angle is 74°.

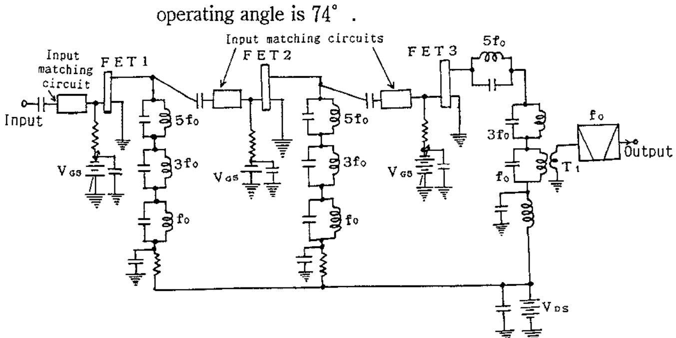

Fig. 4 Circuit of the newly devised high efficiency single power amplifier.

employed in Ref. [2], we use a single FET and set the operating angle to 74° to produce the trapezoidal waveform. The circuit for producing this waveform is shown in Fig. 4, and Fig. 5 is a photograph of the circuit. In the following, the operation of the circuit is explained.

When microwave is supplied at the input terminal, the operating point of FET1 sets the bias voltage to a point where the operating angle $\theta_1 = 74°$ in a positive half period of the

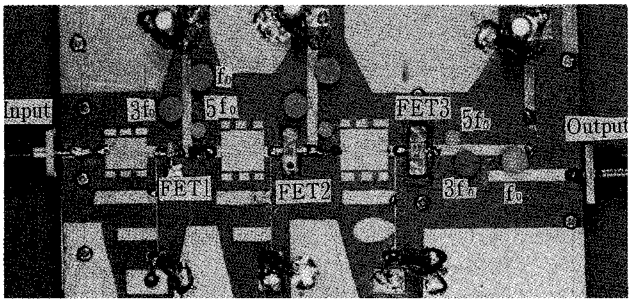

Fig. 5 Photograph of the class C power amplifier shown in Fig. 4.

input wave (see Fig. 3). Since the input amplitude is large and enters into the positive region of a characteristic curve, the current I_{gs} flows between the gate and source of FET1 and the waveform at the drain of FET1 becomes a trapezoidal one. To maintain this waveform at the drain, $TE_{01\delta}$ mode dielectric resonators with resonance frequencies f_0, $3f_0$, and $5f_0$ are coupled to a microstrip line which is connected between the drain and drain source. Using a digitizing oscilloscope, the gaps between the three resonators and the strip line (the degree of coupling) are so adjusted that the trapezoidal waveform is obtained. Through a coupling capacitance C, this wave is supplied to the gate of FET2 which operates as a class A amplifier. To obtain the same waveform as that of the input wave at the drain of FET2, $TE_{01\delta}$ mode dielectric resonators with f_0, $3f_0$, and $5f_0$ are coupled to a transmission line. The gaps between the resonators and the line are adjusted to have the trapezoidal waveform. Through the capacitance, this wave is supplied to the gate of a power amplifier FET3 which operates as a class B amplifier. Three $TE_{01\delta}$ mode dielectric resonators are used also at the drain side of this FET3. To extract the fundamental wave from this amplifier, a $TE_{01\delta}$ mode dielectric resonator with f_0 (a band-pass filter) is loaded between the two microstrip lines. Since a small amount of the higher-order harmonics are contained in the output of the filter, another band-pass filter with f_0 is connected to the output terminal of the filter.

The experiment on the amplifier was carried out in 8 GHz band. The voltage V_{DS} across the drain and source of FET is 10V and the bias voltage V_{GS} is -3.5 V. This bias voltage corresponds to the cutoff point V_p and the amplifier operates as a class B amplifier. When the input power was fixed to 20 dBm and the frequency was changed from 7 GHz to 9 GHz, the output power of 33.2 dBm, the pass band of 80 MHz, and the power added efficiency of 60 % were obtained. When the input power was changed from 13 dBm to 24 dBm, the output power changed from 26.2 dBm to 34.7 dBm and the power added efficiency changed from 24 % to 60 % as shown in Fig. 6.

4. Comparison between the Three Power Amplifiers

By referring to Fig. 6, we compare the characteristics (the output power and power added efficiency) of the three amplifiers. Although the class A amplifier is not described in this paper, its characteristics have been measured, and we use them for comparison. First, let us compare the output power and the power added efficiency of the class A amplifier with those of the class C amplifier. When the input power is fixed to 20 dBm, the output power is 0.6 W (27.5 dBm) and 1.5 W (31.8 dBm) for

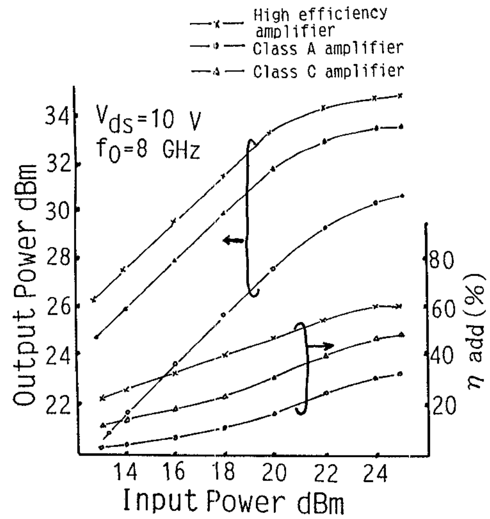

Fig. 6 Dependence of the output power and the power added efficiency on the input power for the amplifiers of Fig. 1 and Fig. 4.

the class A and C amplifiers, respectively. Namely the output power of the class C amplifier is about 2.5 times of that for the class A amplifier. The reason is that the tuning circuit (parallel resonators) is employed in the class C amplifier and hence the gain is large. The power added efficiency of the class C amplifier is 28 % and is about 1.75 times of 16 % for the class A amplifier. The reason is that in the class C amplifier the distorted waveform is used and the operaing angle is set to 74°.

Next, we compare the output power and the power added efficiency of the class C amplifier with those of the high efficiency amplifier. When the input power is 20 dBm, the output power is 1.5 W (31.8 dBm) and 2.1 W (33.2 dBm) for the class C amplifier and the high efficiency amplifier, respectively. The output power of the high efficiency amplifier is 1.4 times of that of the class C amplifier. The power added efficiency of the high efficiency amplifier is 48 %, which is 1.71 times of 28 % for the class C amplifier. The reason is that (1) $TE_{01\delta}$ dielectric resonators with f_0, $3f_0$, and $5f_0$ were coupled to the transmission line to obtain the identical waveform at the drain side of each FET and (2) the degree of coupling was so adjusted that the trapezoidal waveform was obtained by putting the three resonators closely to the transmission line. On the other hand, in the class C amplifier, the parallel resonators for compensating the higher-order harmonics are not employed, and hence both the output power and the power added efficiency are low even though the distorted waveform is used.

5. High Efficiency Push-Pull Power Amplifier

Figure 7 shows a circuit configuration for a new high efficiency push-pull power amplifier and its photograph is shown in Fig. 8. The operation of this amplifier is explained in the following. An FET in the exciting stage operates as a class A amplifier. The trapezoidal voltage wave arising at the drain of FET is transmitted to the terminal 1 of a 3dB 180° hybrid coupler through capacitance C. As a result, the trapezoidal waveforms with phase angles 0° and 180° arise at the terminals 2 and 3, respectively. These waves are supplied to the gates of the power amplifiers FET1 and FET2. The bias voltages V_{GS} of these FETs are set to the cutoff points V_p to operate them

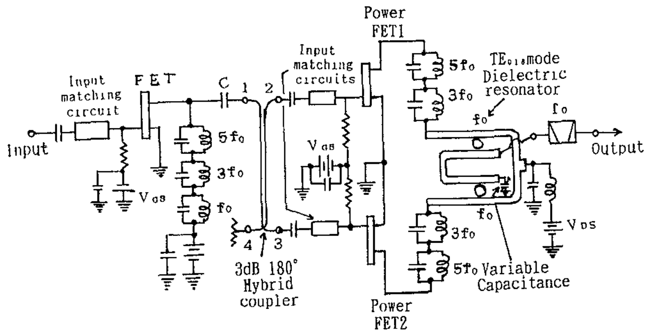

Fig. 7 Circuit structure of the high efficiency push-pull power amplifier.

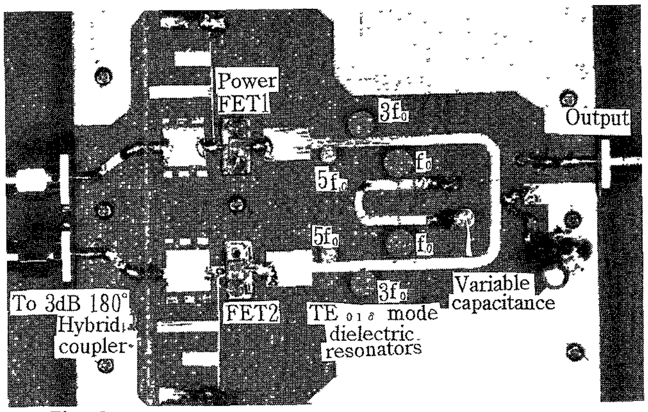

Fig. 8 Photograph of the high efficiency push-pull power amplifier shown in Fig. 7.

as class B amplifiers.

In order to preserve the trapezoidal waves arising at the drain sides of FET1 and FET2, the TE $_{01\delta}$ mode dielectric resonators with resonance frequencies f_0, $3f_0$, and $5f_0$ are coupled to the transmission line which is connected between the drain and the drain source V_{DS}. The microstrip line whose structure is shown in Fig. 9 is designed so that the only fundamental wave is picked up from the wave amplified by FET1 and FET2. As seen in Fig. 9, the two terminals of a U-shaped transmission line are connected to the drains of FET1 and FET2. A capacitance C is mounted between the midpoint of the U-shaped line and the earth. By connecting the drain voltage V_{DS} to the midpoint through the inductance, the DC voltage is supplied to the drains of FET1 and FET2. Owing to this structure, the even-order harmonics are canceled.

The TE $_{01\delta}$ mode dielectric resonators with resonance frequencies $3f_0$ and $5f_0$ are placed near the transmission line. By changing the distance between the resonators and the line, the degree of coupling is adjusted to a suitable value to obtain the trapezoidal wave. This adjustement is performed using a digitizing oscilloscope. In order to extract the fundamental wave, we formed a small U-shaped transmission line between the two TE $_{01\delta}$ mode resonators with f_0. Matching is taken by connecting a variable capacitance to the one terminal of the U-shaped line. The distance between the two resonators is set to around $\lambda_g/2$, and the two outputs with phase angles 0° and 180° are combined. This output is taken out from the other terminal of the line. Since a small amount of the higher-order harmonics are contained in the output, we use a band-pass filter to extract the fundamental wave of f_0. The voltage V_{DS} between the drain and source of the power FET1 and is 10 V, and the bias voltage V_{GS} is -3.5 V. This bias voltage is at a cutoff point V_p and the amplifier operates as a class B amplifier.

The experiment was performed on the high efficiency push-pull power amplifier. When the input power was fixed at 20 dBm, and the frequency was varied from 7 GHz to 9 GHz, we obtained the output power of 37 dBm, the bandwidth of 80 MHz, and the power added efficiency of 66 %. When the input power was varied from 12 dBm to 24 dBm, the output power changed from 29.8 dBm to 38.4 dBm, and the power added efficiency changed from 20 % to 76 % as shown in Fig. 9.

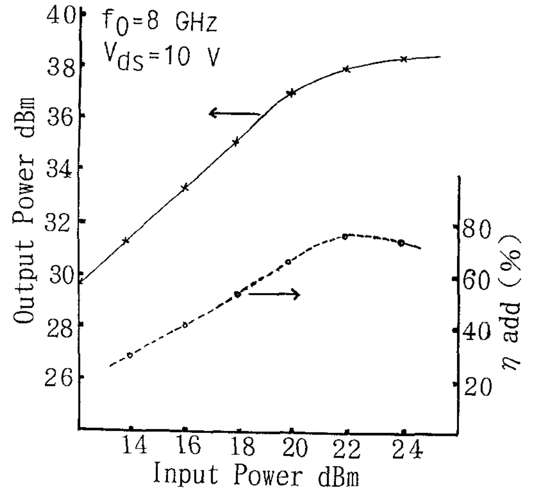

Fig. 9 Dependence of the output power and the power added efficiency on the input power for the amplifier of Fig. 7.

6. Conclusion

New high efficiency single and push-pull power amplifiers for 8 GHz band have been proposed. Using an FET whose characteristics are the same as those of an FET used in the proposed amplifier, the conventional class A and class C power amplifiers were also constructed. For the three (new and conventional) amplifiers, the comparison was made in the output power and the power added efficiency, and the predominance of a new high efficiency power amplifier was demonstrated. A high efficiency push-pull power amplifier was also constructed, and the operation of this amplifier was described. It is a future subject to make the power added efficiency of this amplifier a little more higher.

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