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HARMONIC REACTION AMPLIFIER
- A NOVEL HIGH-EFFICIENCY AND HIGH-POWER MICROWAVE AMPLIFIER -

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ABSTRACT

A newly proposed high efficiency amplifier, the Harmonic Reaction Amplifier (HRA), is presented. Power-added efficiency of 75% (85% drain efficiency) is achieved with a 3-W HRA using GaAs FETs in the 1.7 GHz band. The operation principle is derived from a novel second-harmonic injection technique enabling purely class-B biased operation. Amplifier circuits for attaining high efficiency operation can easily be constructed with ordinary microstrip circuits. Besides, precise circuit adjustment is available to maximize the efficiency. The HRA makes high power and high efficiency microwave power amplifiers with zero quiescent current possible. Experimental test results show the feasibility of a quasi-microwave transmitting amplifier for the next generation mobile radio system However, the HRA can be applied to radio equipment of various fields such as terrestrial microwave radio systems and satellite communications systems using microwave frequency bands

INTRODUCTION

To deal with a rapid increase in subscribers in recent years, development of a new land mobile radio system using a quasi-microwave band has been initiated by NTT Electrical Communications Laboratories [1]. Since portable radio phone units are expected to be widely utilized in this system, the attainment of a high efficiency transmitting amplifier becomes one of the most important research areas concerning mobile radio equipment. This is because increased efficiency makes it possible to reduce the size and lower the power dissipation of radio transmitters.

By using so called class-F operation, power-added efficiency of 70% (80% drain efficiency) has been achieved in the 900 MHz band GaAs FET PA [2]. The class-F operation is performed under a special terminating condition in which the amplifier output terminal is short-circuited at even harmonics and open-circuited at odd harmonics. With zero FET on-resistance, this output circuit configuration enables ideal switching operation, resulting in 100% drain efficiency. It should be noted, however, that sufficiently high efficiency performance can be attained only when the second-harmonics condition is considered [2].

For higher microwave frequencies--including quasi-microwave bands--it is difficult to obtain a high level of efficiency even with a class-F amplifier. Since it is required that the short-circuit condition be established accurately at the FET-chip output point, construction and adjustment of the output termination circuit is quite difficult in microwave amplifiers. In addition, class-F amplifiers need to be biased to class-AB (a quiescent current I_{dq} approximately 10% of I_{dss} [3]), accordingly, they are not applicable for high power amplifiers.

The HRA proposed here is capable of easily realizing the terminating condition necessary for achieving ideal switching operation. Further, ideal class-B biased operation with zero quiescent current is performed perfectly without incurring any efficiency losses and output power losses are kept to a minimum. This leads to realization of a high efficiency and high power amplifier having over 10 W output power.

This paper describes the HRA's operation principles. Experimental investigations on 1.7 GHz band GaAs FETs are conducted to confirm the high efficiency performance projected.

HARMONIC REACTION AMPLIFIER

The fundamental conceptional structure for the HRA is shown in Fig. 1. The HRA is basically composed of two FETs. Although the fundamental structure is similar to the balanced amplifier [4], a critical difference is that a second-harmonic resonance transmission path, with adjustable length, is added between the two FETs in the HRA. Moreover, in the second-harmonic path there are two band reject filters to reflect fundamental signal components. Also, a harmonic reject filter acting as a high impedance termination for harmonic components is inserted into each FET output signal path. Fundamental signals are combined in an in-phase manner at the output combiner and put out as a main signal without sustaining any power loss.

Under class-B operation conditions, there are large second-harmonics generated at each FET output. These harmonics flow only into the second-harmonic path, which is composed of reactive components Path length can be adjusted to excite a second-harmonic standing wave which has magnetic wall conditions at both FET-chip output points. Therefore, reactive second-harmonic energy is stored in the second-harmonic path. The magnetic wall condition coincides with the ideal short-circuit condition with regard to second-harmonic output components. In addition, the second-harmonic current at the short circuit becomes twice as large as that of the class-F amplifier. This means that an almost ideal switching operation can be achieved.

Here, FETs behave as a kind of push-pull amplifier with respect to second-harmonics. That is, the two FETs inject second-harmonic current into each other, which causes drain current amplitude-modulation. As a result, the converted fundamental frequency component and third-order harmonic component increase switching operation efficiency. Therefore, the HRA achieves greater efficiency than the conventional class-F amplifier in spite of the employment of the purely class-B biased operation. Since each FET's second-harmonic current works as a reaction force to increase efficiency, this device is called a Harmonic Reaction Amplifier.

EXPERIMENTS ON A 1.7GHz BAND GaAs FET HRA

Experimental investigations were conducted using the 1.7 GHz band HRA constructed to confirm projected high efficiency performance. The constructed HRA had a circuit configuration basically the same as shown in Fig. 1. Here, simple single-stage LC resonance circuits were used as band-reject filters. For active devices, GaAs FETs with f_T of about 9 GHz were employed. The I_{dss} and V_p (pinch-off voltage) were about 2 A and -4 V, respectively. Gate-source bias voltage V_{gs} was set to -3.6 V to operate purely as class-B (I_{dq} was below 1 mA). Drain-source bias voltage V_{ds} was set to 5 V. Maximum available FET power at this drain voltage was 2~2.5 W.

Input-output power and -efficiency characteristics of the developed HRA are shown in Fig. 2. Power-added efficiency of 75% (85% drain efficiency) was achieved at 2.7 W output power level, where about 9 dB power gain was obtained. Assuming that on-resistance is equal to that of the DC characteristics, it takes a value of about 0.5 Ω. Accordingly, maximum drain efficiency in the ideal switching operation could be calculated to be 97%. On the other hand, as HRA net drain efficiency (the efficiency when output circuit loss is assumed to be zero) is estimated at 91%, it can be recognized that an almost ideal switching operation is realized in the HRA.

Efficiency characteristics versus signal frequency are shown in Fig. 3. More than 70% power-added efficiency was obtained in the 50 MHz band width. This band width restriction was attributed to the narrow band frequency characteristics of the band-reject filters used. Therefore, frequency characteristic can easily be improved by utilizing wide-band filters.

Efficiency characteristics versus the second-harmonic path length variation are shown in Fig. 4. Efficiency varies with changes in second-harmonic path length. Pass length between maximum efficiencies coincides with second-harmonic component wave length. This is because HRA efficiency depends mainly on the second-harmonic current phase condition injected at the FET output terminal.

As mentioned previously, high efficiency HRA performance was confirmed. Then, to examine the superiority of HRA over the

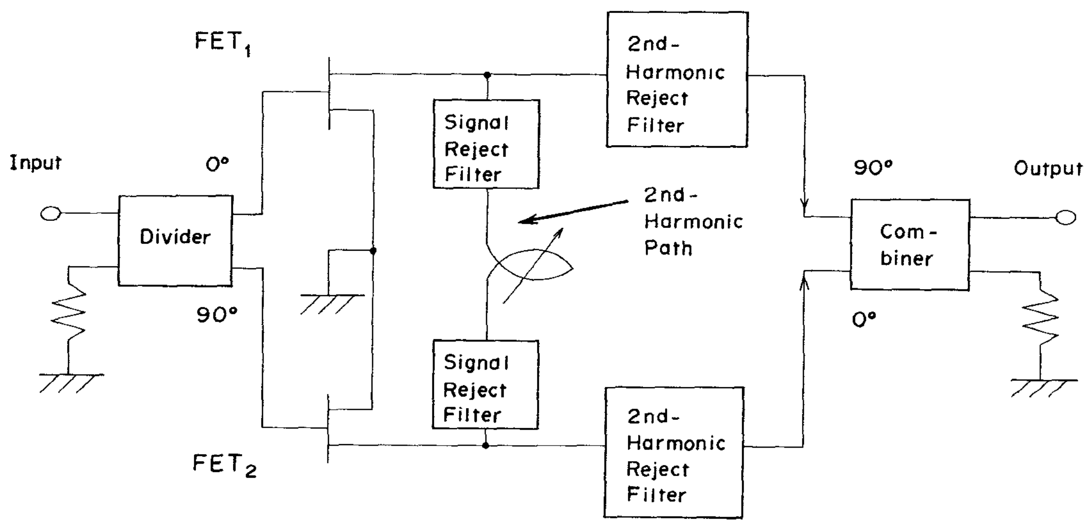

Fig. 1 Fundamental circuit structure of HRA

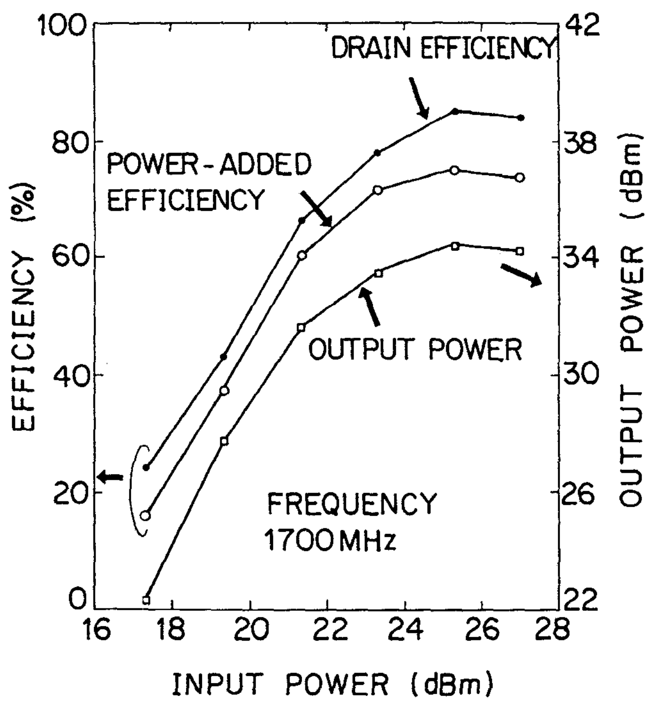

Fig.2 Output power and efficiency versus input power

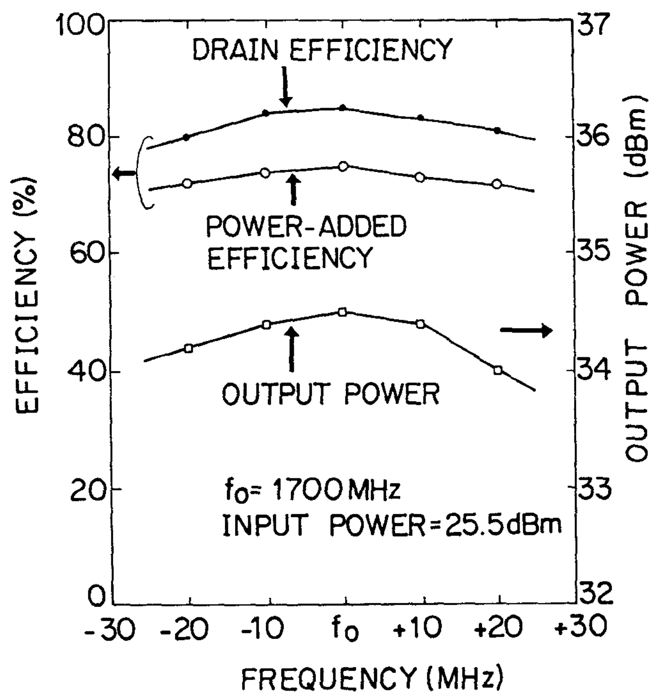

Fig.3 Output power and efficiency versus frequency

conventional class-F amplifier, a single stage class-F amplifier was constructed at the same frequency band. The class-F amplifier circuit configuration is shown in Fig. 5. The same FET device as used in the HRA was utilized to construct the amplifier.

Input-output power and -efficiency characteristics of the developed class-F amplifier are shown in Fig. 6. Power-added efficiency of 65% (73% drain efficiency) was achieved at above 1.5 W output power level, where about 10 dB power gain was obtained. A class-AB (I_{dq} approximately 10% of I_{dss}) bias point was selected as the optimum bias point to achieve maximum efficiency. When biased to a class-B point, however, efficiency decreased by about 5%. Therefore, the HRA has achieved about 10% higher power-added efficiency than the conventional class-F amplifier in this frequency band. In higher frequency band ranges, the difference in efficiency between the HRA and class-F amplifier increases substantially.

CONCLUSION

The operation principles of a newly devised high efficiency amplifier called the Harmonic Reaction Amplifier was presented. Validity of HRA performance was confirmed with the 1.7 GHz band GaAs FET HRA. One well known technique for constructing a high power amplifier operating with zero quiescent current is a

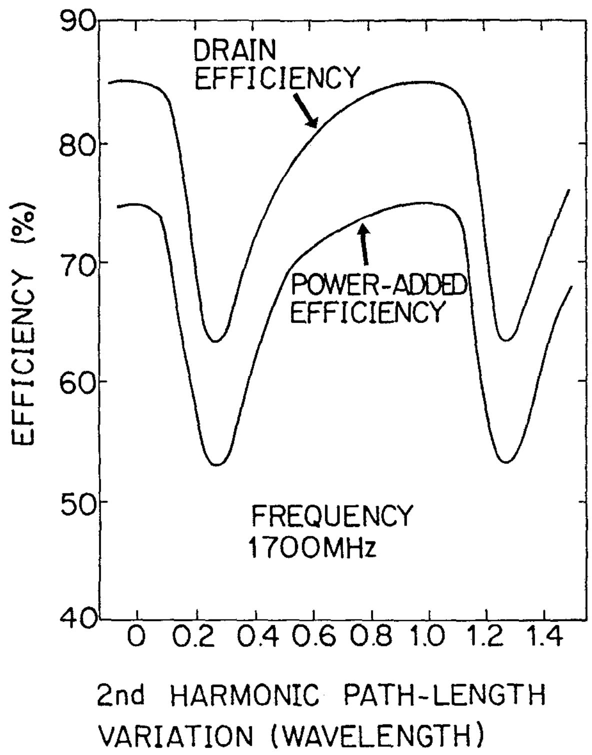

Fig.4 Efficiency versus second harmonic path-length

class-B biased push-pull amplifier. However, it has not been realized in microwave frequency yet [5]. The HRA features a true class-B biased operation. More importantly, efficiency even higher than that of conventional class-F amplifiers can be attained. A 75% power-added efficiency was measured in 1.7 GHz band experiments, though it can well be expected to attain higher efficiency than this by improving circuit component characteristics. In addition, utilization of high power GaAs FET devices with high f_T above 20 GHz are available today for HRA construction. Therefore, it is quite possible to realize high-power and high-efficiency microwave amplifiers utilizing the HRA technique at frequency bands up to X-band. Completion of this kind of amplifier is our next target.

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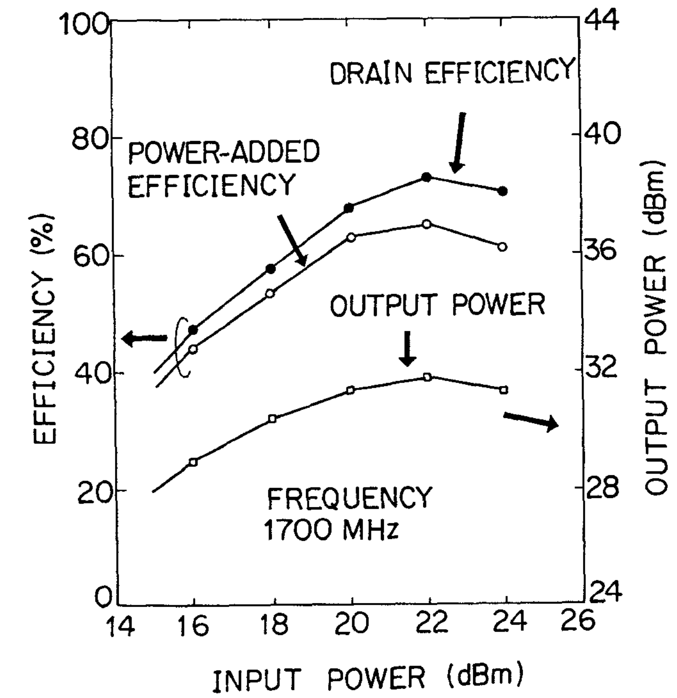

Fig. 6 Output power and efficiency versus input power (class-F amplifier)

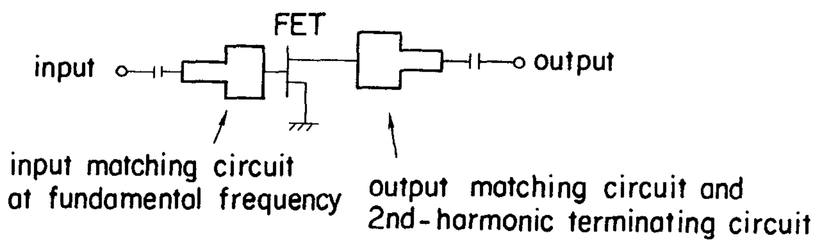

Fig. 5 Fundamental circuit configuration of class-F amplifier