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HIGH EFFICIENCY MICROWAVE HARMONIC REACTION AMPLIFIER

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ABSTRACT

The operation mechanism of the novel high efficiency Harmonic Reaction Amplifier (HRA) is clarified. The HRA is basically constructed with a pair of power FETs. The technical originality lies in a provision of an interconnecting circuit concerning a second-harmonic output component between FETs. This additional circuit realizes an efficient and stable switching-mode operation required for the attainment of highly efficient microwave power amplification. Theoretical analysis results indicate that a drain efficiency of 86% is available with an ideal HRA construction of purely class-B biased operation. Experiments on a miniaturized 2-GHz 5-W HRA module are conducted to verify analysis results. A power-added efficiency of over 70% is achieved confirming that the HRA can be practically applied to microwave power amplifiers. Moreover, an HRA capability of high efficiency as a linear amplifier under a class-AB biased condition is shown in the experiments as well.

INTRODUCTION

Microwave power amplifier engineers are constantly trying to improve the power conversion efficiency from DC supply to RF output. The attainable efficiency of the microwave power amplifier is restricted by the transistor device parameters and operating conditions including bias states. As far as device parameters are concerned, steady progress is being made on GaAs power FET devices which have high gain, high power, high f_T and low on-resistance. As a result, depending on the device itself, power dissipation has been improved over the years.

On the other hand, in relation to high efficiency operating conditions, improvement of the switching-mode operation is the technical key to increase operating efficiency. The most effective switching-mode operation for microwave FET amplifiers is to drive the drain current so as to achieve a large second-harmonic component and at the same time to drive the drain voltage so as to have only a fundamental signal component. So-called class-F amplifiers achieve this operating condition with the FET output terminating circuit which has a zero impedance in a second-harmonic frequency band and a matched impedance in a fundamental frequency band(1). Since it is necessary that the zero impedance condition must be established accurately at the FET-chip output point, construction of the output terminating circuit becomes quite difficult in microwave frequencies. Accordingly, to present, no practical class-F amplifier has been constructed for operation above 1 GHz, although possibilities of its operation at 2 GHz were shown(2). Practically, attainable efficiencies are generally below 50% using ordinary class-C or class-B biased amplifiers.

In the MTT 1987 symposium, the authors proposed a new amplifier construction technique named the Harmonic Reaction Amplifier (HRA) to overcome the problems on the conventional class-F amplifier(3). Fundamental experiments were carried out using a 1.7 GHz band HRA, attaining a power-added efficiency of 75 %.

In this presentation, further investigations on the operation mechanism of the HRA are carried out. A theoretical analysis based upon the second-harmonic injection effect reveals the HRA capability of the remarkably high efficiency operation on conventional amplifiers, including the class-F amplifier. Furthermore, a unit packaged 2-GHz HRA module is constructed to conduct the experiments and also to estimate its promising feature as a practical high efficiency microwave amplifier. Moreover, its capability as a high efficiency linear amplifier is also shown in the experiments.

ANALYSIS OF THE OPERATION MECHANISM

The fundamental circuit configuration of the HRA is shown in Fig. 1. The HRA is basically composed of two FETs. Although the configuration is similar to that of the balanced amplifier, there exists a critical difference in that a second-harmonic transmission path is constructed between FETs' output terminals. Here, main signal output paths and second-harmonic path are designed to have matched impedance characteristics with FETs' output impedances in the fundamental frequency band and in the second-harmonic frequency band, respectively.

Under class-B or class-AB biased conditions, there is a large second-harmonic component generated at the output of each FET. This harmonic component flows only into the second-harmonic path. Since the second-harmonic path has impedance characteristics well matched with FETs outputs at the concerned

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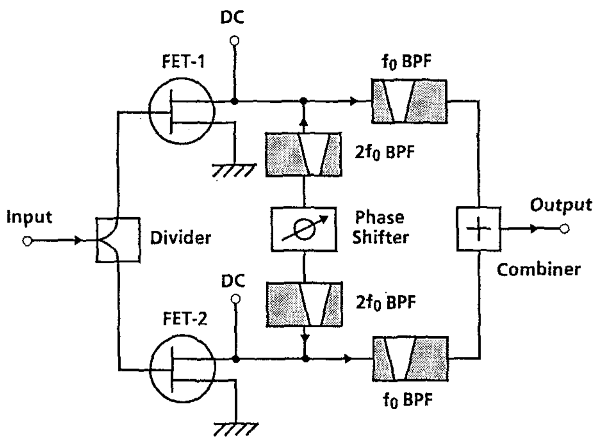

Fig. 1 Fundamental circuit configuration of the HRA.

frequencies, each FET mutually injects a second-harmonic component into the other FET, without reflection, through the second-harmonic path. Assuming that the FETs have the same operation characteristics, a second-harmonic standing wave is excited along the second-harmonic path. Here, the second-harmonic path length can be adjusted so as to locate a voltage null point at both FET-chip output points. This condition coincides with the output terminating condition in the class-F amplifier. Therefore, the required switching-mode operation can be precisely and efficiently realized with the HRA.

It should be noted here that high efficiency switching-mode operation in the HRA is possible only when the FETs are driven with coherent and equal amplitude input signals. When the input signals are coherent and of equal amplitude, short circuited conditions occur at each FET drain terminal through the second-harmonic path, which cancel the second-order drain voltage components. When there are no real input signals, load circuits of FETs exhibit well matched terminations not only in fundamental frequencies but also in second-harmonic frequencies. Hence, the HRA is quite stable against noise generated by the FETs and all fluctuations of FET operation parameters such as gate bias voltage, transconductance and so on. By comparison, since the standard class-F amplifier always has a true short-circuited output terminating circuit, which makes transconductance very large, its operation becomes unstable when high gain FETs are utilized. Consequently, the HRA permits more efficient and more stable operations when applied to microwave amplifiers than when applied to conventional class-F amplifiers.

Moreover, since each FET of the HRA injects a second-harmonic component into the other, a drain current modulation is induced by the injected second-harmonic current. As a result, additional fundamental signal components are generated which increase the HRA output power, as has been predicted[4].

In order to verify this effect, a fundamental experiment of the harmonic signal injection was performed. Circuit

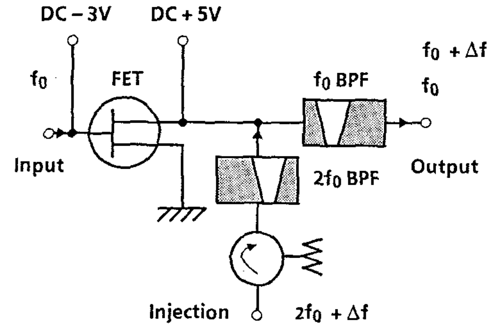

Fig. 2 Second- harmonic injection effect measurement setup.

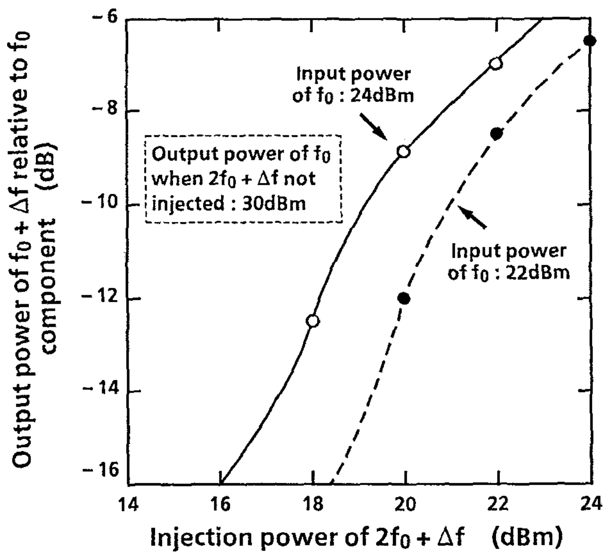

Fig. 3 Fundamental frequency conversion characteristics.

configuration of the experiment is shown in Fig. 2. The output circuit of the FET is composed of two branch circuits, one of which is the terminating path for the fundamental signal while the other is for the second-harmonic component. As shown in the figure, a frequency component of $2f_0 + \Delta f$ is injected into the FET drain through the second-harmonic terminating path. According to this theory, an additional fundamental frequency component bearing the frequency of $f_0 + \Delta f$ should be generated as well as the original fundamental signal output. Experiment results are shown in Fig. 3. From the figure, the output power level of the converted signal from the injection is proportional to the injection power level and also to the depth of the bias voltage. For example, this converted signal component shows a considerably high power level which is only 9~12 dB below the original fundamental signal output when a pure class-B bias is applied and when the injection power is 10 dB below the original fundamental signal output. Therefore, it can be confirmed that when the injection frequency coincides with that of the second-harmonic component the fundamental signal

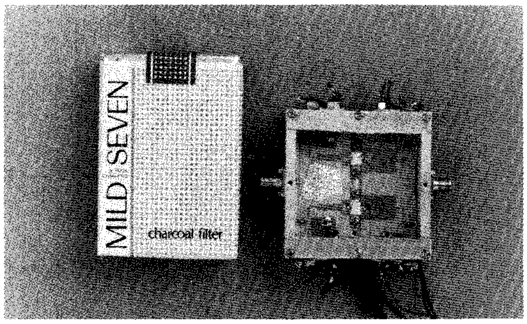

Fig. 4 A unit packaged 2-GHz HRA.

component is increased and the efficiency is improved.

The HRA achieves the highest efficiency on the condition that the second-harmonic injection phase is $(2n+1)\pi$, where n is integer. Assuming that the on-resistance of FET is zero and the output circuit is free from power loss and that pure class-B biased operation is employed, the drain efficiency η of the HRA is approximately given as next:

$$\eta = 1 - \frac{P_{diss}}{P_{DC}} = \frac{\pi}{4} \cdot \frac{3-\cos\phi}{9-2\cos\phi} (\times 100\%) \qquad (1)$$

where, P_{DC} is the supplied DC power, P_{diss} is the internal power dissipation of the FET, and ϕ takes the value around $(2n+1)\pi$. Power series representations up to the second order and Parseval's theorem are used to calculate P_{DC} and P_{diss}.

Efficiency characteristics versus second-harmonic injection phase ϕ are calculated in Fig. 7. Here, the maximum efficiency reaches 86%. In addition, when ϕ is $2n\pi$, η becomes 56%, since the drain current contains only a fundamental frequency component. Maximum efficiency of the HRA is larger than that of conventional pure class-B biased amplifiers. This means that the HRA has a possibility of high efficiency performance as a linear amplifier.

2-GHz HRA MODULE

An HIC module of 2-GHz HRA is constructed to confirm analysis results and to estimate performance as a practical amplifier as well. The HRA as developed here is shown in Fig. 5, using GaAs FETs mounted in a ceramic package without internal matching circuits. These FETs have f_T of about 9 GHz, I_{dss} of about 2 A, and V_P (pinch off voltage) of -4 V. Input and output circuits including the second-harmonic transmission path, filters, matching circuits, divider and combiner are all constructed on ceramic substrates having a specific dielectric constant of 9. Employment of higher dielectric constant substrate, lumped element circuit construction, and direct mounting of FET chips will enable further miniaturization of the HRA module.

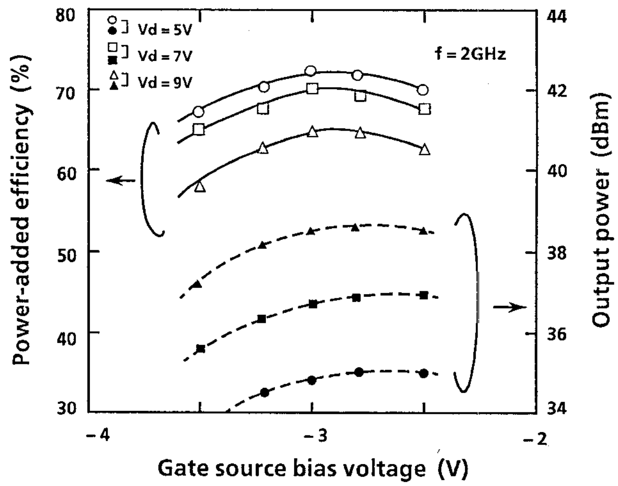

Fig. 5 Efficiency and output power versus input power.

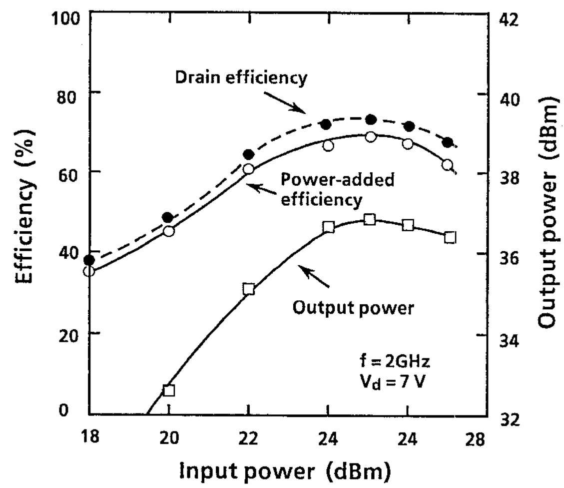

Fig. 6 Efficiency and output power versus input power.

Efficiency and output power versus gate bias voltage with a parameter of drain voltages are shown in Fig. 6. These values were measured at the saturated output power point. Efficiencies at each drain voltage took maximum values at the constant gate-source bias voltage of -3 V where FET operated under pure class-B biased condition. Although output power is almost proportional to the drain supply voltage, over 10 V drain voltage supply is difficult due to FET break down. On the contrary, efficiency is inverse proportional to the drain supply voltage due to constant on-resistance. Maximum efficiency of this HRA is 70~72% with an output power of 2.5~5 W.

One example of efficiency and output power characteristics versus input power at class-B biased operation is shown in Fig. 6. Here the drain supply voltage was 7 V. A power-added efficiency of 70% and a drain efficiency of 75% are obtained at a 5 W output level.

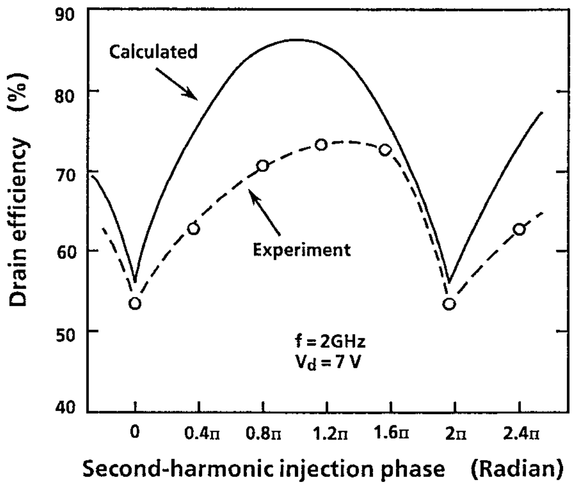

Fig. 7 Efficiency versus second-harmonic injection phase.

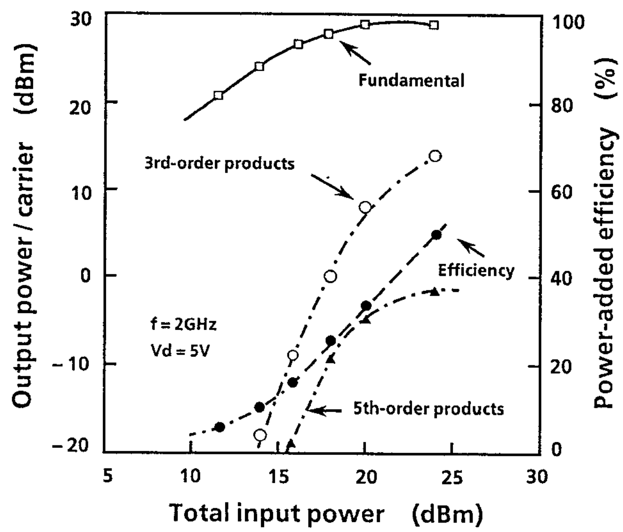

Fig. 8 Two tone measurement test results.

Efficiency versus phase variation of an injected second-harmonic component is shown in Fig. 7. Calculated values are also plotted in the same figure. Here, good agreement of phase dependency characteristics is observed. If on-resistance influences upon calculated values are considered, better agreement could be obtained.

Additionally, two tone tests were performed to estimate the suitability of the HRA as a linear amplifier. Here, a class-AB biased operation was employed to achieve both high efficiency and linearity. Measured output characteristics are shown in Fig. 8. At the 1 dB gain compression point, where linear amplifiers generally show a 3rd-order intermodulation distortion attenuation to the signal component of about 20 dB, more than 30% power-added efficiency is attained.

CONCLUSION

It is clarified that the HRA achieves a stable and highly efficient switching-mode operation. Theoretical analysis showed that a drain efficiency of 86% can be obtained in the ideal case where the second-harmonic injection effect is considered as well. The realized HIC module of 2-GHz HRA achieved a power-added efficiency of 70% with an output power of 5 W, demonstrating HRA applicability on practical high efficiency amplifiers.

The HRA technique can be effectively applied to various devices such as higher frequency amplifiers, high-power amplifiers with the output power of more than 10 W, and even linear amplifiers. Moreover, simple circuit construction enables further miniaturization of the HRA module. Since HRA performance has been confirmed only in 1~2 GHz bands so far, the next study is to attempt to confirm its high efficiency operation in other frequency bands.

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