A Novel EER Structure for Reducing Complexity Using Negative Resistance Amplifier

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***Abstract*—This letter presents a novel envelope elimination and restoration (EER) structure using the negative resistance class F power amplifier. Due to the extremely high gain characteristic of the negative resistance amplifier in very narrow bandwidth, it operates in saturation mode. This characteristic is applied to the proposed EER. Using this technique, a limiter, a drive amplifier, and a class F power amplifier in conventional EER can be substituted with the negative resistance class F power amplifier. This technique greatly reduces the complexity of conventional EER without degradation of efficiency and linearity. The measured results show efficiency of 60% and less than—26 dBc IMD levels for two-tone test in PCS band at 27-dBm output power.**

***Index Terms*—EER, negative resistance amplifier.**

I. Introduction

MODERN digital communication systems such as cellular, PCS, and satellite communication systems widely use modulation formats of which signal envelopes are not constant any more. Therefore, linear RF power amplifiers are required in those applications. However, unfortunately, conventional linear power amplifiers such as class A, AB, and B have poor efficiency. Various techniques have been proposed and studied for linear amplification with much better efficiency.

Envelope elimination and restoration (EER) technique is one of the most efficient linear RF power amplification system, and its efficiency is ideally 100%. In the EER system, the RF signal input is decomposed into low-frequency envelope and RF phase by envelope detector and limiter, respectively. A class S amplifier, such as dc–dc converter, amplifies the low-frequency envelope, while a class E/F amplifier amplifies the constant-envelope RF phase. The amplified low-frequency envelope modulates the drain bias of the class E/F amplifier, which results in restoring the RF input signal if the envelope and the phase are synchronized [1], [2].

Although the EER system can amplify the variable envelope signal with very high efficiency, many components such as the envelope detector, the limiter, the drive amplifier, etc. are needed to implement it. Therefore, the EER system is very complex, and there are degradation of efficiency and linearity if these components are not ideal ones [3].

In this letter, a novel EER structure that simplifies the conventional EER system is suggested. A negative resistance class F power amplifier, instead of the limiter, the drive amplifier, and the class F power amplifier, was used to simplify the conventional EER system. Because, the gain of the negative resistance amplifier is very large enough to saturate the output signal, it serves as the drive amplifier and the limiter in conventional EER systems. Additionally if the negative resistance amplifier is designed as class F type, it serves as constant-envelope RF phase power amplifier in conventional EER systems. Therefore, the drive amplifier, the limiter, and the class F power amplifier in conventional EER can be integrated into the negative resistance class F power amplifier.

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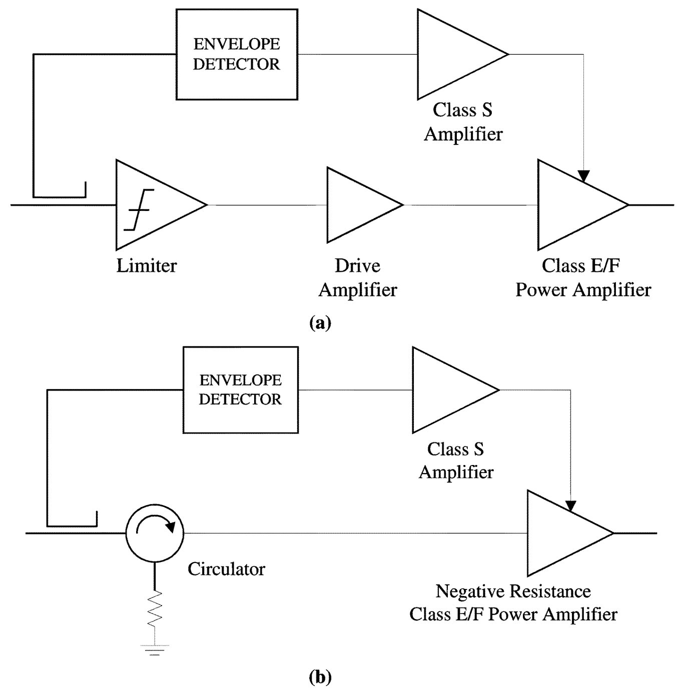

Fig. 1. Block diagrams of the (a) conventional EER system and (b) proposed novel EER system.

II. EER System Using Negative Resistance Amplifier

The proposed EER structure is different from the conventional one in that it uses negative resistance class E/F power amplifier instead of the complex combination of the limiter, the drive amplifier and the class E/F amplifier. Fig. 1(a) and (b) show a conventional EER system and the proposed EER system respectively. The roles of limiter and the drive amplifier in the conventional EER system are generating the constant envelope signal and amplifying it, respectively, so that the class E/F power amplifier operates efficiently. Those roles can be covered easily

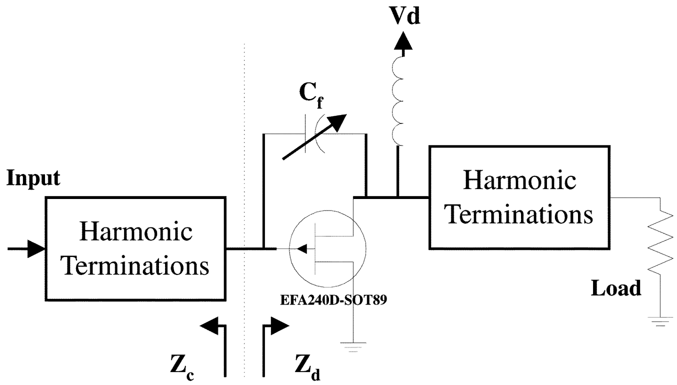

Fig. 2. Simplified topology of the negative resistance amplifier.

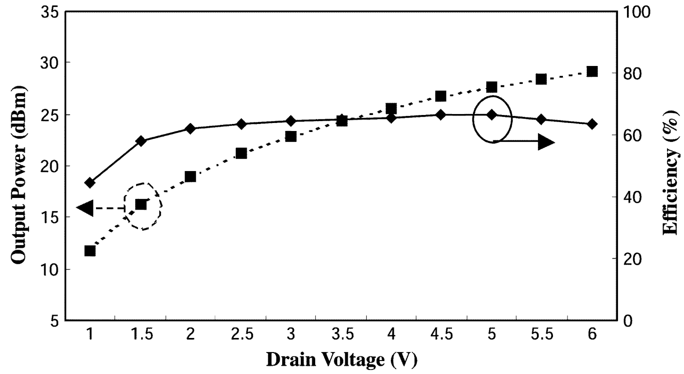

Fig. 3. Measured efficiency and output power of the negative resistance class F power amplifier.

if a negative resistance amplifier is used as shown in Fig. 1(b). A circulator in Fig. 1(b) is for isolation and not necessary. The gain of the negative resistance amplifier is so extremely high in a narrow bandwidth that it operates in saturation mode, which results in limiting the output signal with the signal amplified sufficiently.

Unlike the conventional EER, as the limiter, the drive amplifier and the class E/F power amplifier are not required, the proposed EER system can be implemented in a quite simple way.

III. Negative Resistance Class F Power Amplifier

The voltage gain of the negative resistance amplifier is expressed by (1), [4]

$$G = \left(\frac{Z_c - Z_d^*}{Z_c + Z_d}\right)^2 \tag{1}$$

where $\mathrm{Z_c}$ is one of the input impedance when a circuit is divided into arbitrary two parts, and $\mathrm{Z_d}$ is the other input impedance. To obtain extremely high gain enough to saturate the output signal, the sum of two impedances of two ports should be almost zero.

A class F power amplifier for PCS band was designed. Fig. 2 shows the topology of the negative resistance amplifier. Parallel capacitive feedback topology was adopted in order to obtain high gain and facilitate harmonic terminations. The capacitive feedback in Fig. 2 forces the $\mathrm{Z_d}$ to have negative real value, and the sum of port impedances, $\mathrm{Z_c + Z_d}$, can be near zero. Because the feedback capacitor $(\mathrm{C_f})$ can control the real value of the sum of the two impedances, the gain of the negative resistance amplifier can be controlled easily by adjusting it. But, if the $\mathrm{Z_c + Z_d}$ has negative real value, the circuit starts to oscillate. And the circuit can operate in injection-locked mode.[5].

The principle of the negative resistance amplifier is similar to that of the injection-locked oscillator (ILO), but the negative resistance amplifier operates in stable area, while the ILO in unstable area. This means the ILO has output signal without input signal, which is not adequate for zero crossing signals, for example two tone signal. In this circuit, the feedback capacitor was determined to 0.3 pF in order that the amplifier has enough high gain, and simultaneously is stable regardless of input signal.

Harmonic terminations for class F1 operation, that is short at second harmonic and open at third harmonic between drain and source of a transistor, were done to improve efficiency. A GaAs FET device from Excelics (EFA240D-SOT89) and teflon substrate ($\mathrm{thickness} = 0.364$ mm, $\varepsilon_\mathrm{r} = 2.6$) were selected to implement the power amplifier.

RF input signal at 1.8695 GHz was applied to the negative resistance class F power amplifier to measure the gain, efficiency, and output power. The measured gain is over 30 dB in very narrow bandwidth. This is very high value as has been expected. Efficiency is about 63%–67% at the various drain bias condition, and output power is up to 29 dBm at the drain bias of 6 V (Fig. 3).

IV. EER Using Negative Resistance Amplifier

The roles of the limiter and the drive amplifier in conventional EER systems can be summarized as follows:

1) limiter—generating constant-envelope;
2) drive amplifier—amplifying constant-envelope signal so that the amplified constant-envelope signal drives the class F power amplifier in saturation mode.

These components make the EER complex. Furthermore, if they are not ideal components, degradations occur in efficiency and linearity of the EER system. For example, additional power is required in order to operate the drive amplifier, which results in degradation of efficiency. And the higher the peak-to-average ratio of the input signal is, the more harmonics the hard limiter generates, which also results in degradation of linearity. Because the proposed EER system does not use the drive amplifier and the limiter, it has a great advantage over the conventional one in efficiency and linearity as well as simplification.

A 10-dB coupler, an envelope detector and a dc–dc converter as a class S amplifier were used to detect the envelope signal and amplify it. And the output of the dc–dc converter modulates the drain bias of the negative resistance class F power amplifier. A buck-type dc–dc converter was designed according to the input impedance of the drain bias of the negative resistance class F power amplifier. The envelope and the RF phase were synchronized with a coaxial type phase shifter.

The Measured efficiency of the dc–dc converter was about 95%, and its bandwidth was about 50 kHz. Therefore, the bandwidth of the EER is limited to 25 kHz.

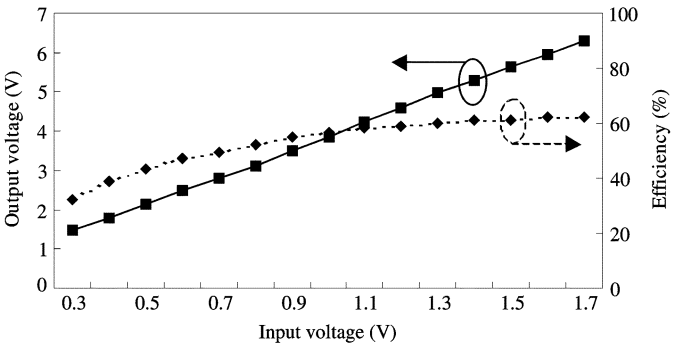

Fig. 4. Measured efficiency and output voltage of the proposed EER system.

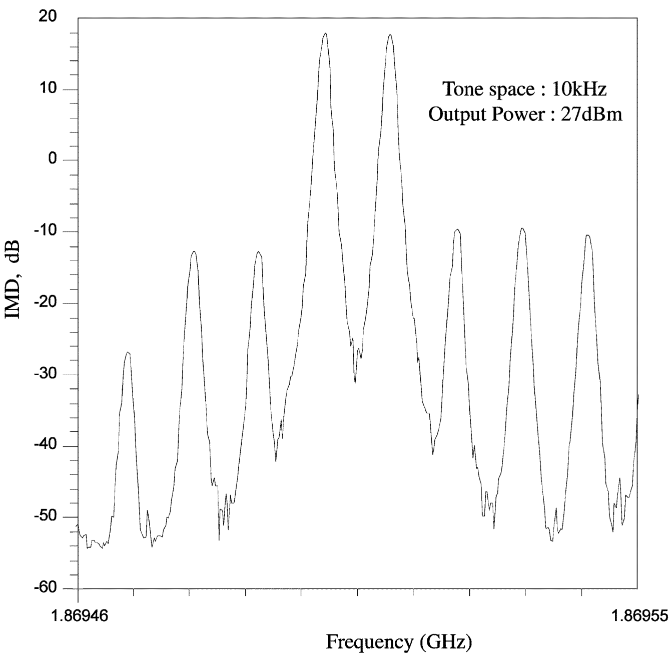

Fig. 5. Measured IMD spectrum for two-tone test.

V. Measured Performances of the Proposed EER System

Fig. 4 shows output voltage and efficiency of the proposed EER system. In this figure, input voltage and output voltage are amplitudes of envelopes of RF input and output signal each other. The efficiency of it is over 50% at wide input range, and AM-AM is quite good. But, as the negative resistance amplifier in the EER operates in class F mode, the AM-PM problem is severe like other conventional class F amplifiers.

Two-tone test has been performed to measure the linearity of the proposed EER. Because the bandwidth of the dc–dc converter is about 50 kHz, tone space of the two-tone is to be less than about 15 kHz to ensure the good linearity of the EER system [6]. Fig. 5 shows the restored two-tone signal at the output of the proposed EER system. The center frequency of the input signals is 1.869 505 GHz, and the tone space is 10 kHz. The level of the maximum IMD products is no more than -26 dBc with efficiency of 60% for the two-tone input power of 3 dBm. Asymmetry in Fig. 5 is likely due to extremely narrow band and AM–PM distortion of the negative resistance amplifier.

VI. Conclusion

A novel EER system structure using the negative resistance class F power amplifier has been proposed. Extremely high gain characteristic of the negative resistance class F power amplifier enables it to operate in saturation mode, which covers the roles of the drive amplifier, the limiter, and the class F power amplifier in conventional EER system. Therefore, those components in the conventional EER can be integrated to the only one component, negative resistance class F power amplifier. It is expected that the proposed EER system can excellently reduce the complexity of conventional EER systems without degradation in efficiency and linearity.

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