A Planar 4.5-GHz DC–DC Power Converter

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***Abstract*—In this paper, we present two dc–dc converters that operate at a microwave frequency. The first converter consists of a Class-E switched-mode microwave amplifier, which performs the dc–ac conversion, and two half-wave diode rectifier outputs. The Class-E MESFET amplifier has a maximum power-added efficiency of 86%, corresponding drain efficiency of 95%, and 120 mW of output power at 4.5 GHz. The diode rectifier has a maximum conversion efficiency of 98% and an overall efficiency of 83%. The second converter consists of a high-efficiency Class-E oscillator and a diode rectifier. The Class-E oscillator has a maximum efficiency of 57% and maximum output power of 725 mW. The dc–dc converter is planar and compact, with no magnetic components, and with a maximum overall dc–dc conversion efficiency of 64% for a dc input of 3 V, and the output voltage across a 87-Ω load of 2.15 V.**

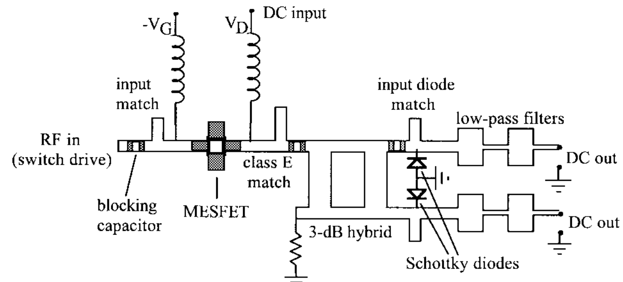

Fig. 1. Layout of the 4.5-GHz microwave dc–dc converter. The dc–ac part of the circuit is a class-E amplifier (or class-E oscillator), the output of which is divided between two half-wave diode rectifiers. The two dc outputs can be connected in series or parallel. The bias feeds are the part of the planar circuit.

I. Introduction

In the area of power electronics, there has been considerable effort in performing the switching operation at higher frequencies in order to reduce the size of the converter. Primarily due to copper and core losses in magnetic components fabricated on ferrite cores, optimum switching frequency in present-day power converters is from several hundred kilohertz to low megahertz [1]. With surface-mount packaging, power density (output power capability per unit volume) of up to approximately 100 W/in^3 can be achieved. The need for discrete magnetic components, including inductors and isolation transformers, is the main limitation to achieving monolithic integration and, thus, further reduction in size and cost of power converters.

In the work reported in this paper, our objective is to investigate feasibility of dc–dc power converters operating at microwave (gigahertz) frequencies, thus eliminating the need for discrete magnetic components. This approach has potential for planar very high-density low-profile realizations. In addition, dc isolation, which is often required in power converters, can also be achieved without discrete ferrite transformers. Widespread potential applications are in many types of electronic systems, including power supplies for low-voltage (1–3 V) microprocessor loads. High efficiency is particularly critical for battery-operated systems.

In the microwave range, efficiency drops with increased frequency due to inherent transistor and diode losses. In order to maximize efficiency, the converter presented here consists of a switched-mode class-E microwave amplifier and efficient diode rectifiers. Class-E amplifiers, traditionally used at lower frequencies [2], have recently been implemented at microwaves, using transmission lines instead of lumped elements [3], [4], and with power-added efficiency (PAE) up to 75% at 5 GHz with 0.7 W of output power. A 5-GHz class-E amplifier with appropriate feedback has been demonstrated as an oscillator with 59% conversion efficiency and 650 mW of output power [5]. Microwave rectifiers integrated with antenna arrays (rectennas) have been developed for power transmission over the past few decades. A good review is given in [6], and subsequent developments are presented, e.g., in [7]–[13]. Rectennas developed in the 1970's achieved conversion efficiencies greater than 90% at 2.45 GHz [13]. The first C-band antenna achieved 70% overall efficiency and 80% conversion efficiency [8].

In this paper, we first integrate a class-E amplifier with a two-element array of Schottky diode rectifiers, as shown in Fig. 1, with an overall conversion efficiency of 64%. To the best of our knowledge, this is the highest frequency dc–dc converter reported to date. We then integrate a class-E oscillator with a diode rectifier with an overall efficiency of 49%, demonstrating no need for an input RF signal (switch control signal).

II. Class-E Amplifier DC–AC Converter

In this section, we briefly discuss the design and performance of the class-E amplifier, which performs the dc–ac conversion. In this class of amplifiers, the transistor is used as a switch, and the switch voltage is filtered at the output with an appropriate tuned circuit. A Fujitsu FLK052WG packaged MESFET was used for the amplifier. As in [3] and [4], the output capacitance and lead inductance of the transistor are used as part of the output high-efficiency tuning circuit. For optimum class-E operation at a switching frequency f_s, the

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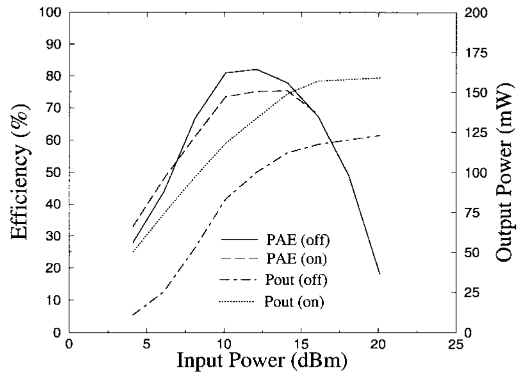

Fig. 2. Measured PAE and output power for a drain bias of 3 V. In one case, the transistor is biased for a drain current of 50 mA, and in the other, the gate is pinched off.

tuned circuit needs to have an impedance given by

$$Z_{\rm net} = \frac{0.280\,15}{2\pi f_s C_s} e^{j49.0524^\circ} \tag{1}$$

in order to ensure that the current and voltage waveforms across the transistor are never nonzero at the same time, and that the turn on of the device is soft (first derivative in time equal to zero). This impedance, including the $C_s = 0.4$ pF output device capacitance and 0.25-nH drain lead inductance, was implemented using microstrip transmission lines. The initial circuit is fabricated on an RT Duroid 0.508-mm-thick substrate with $\epsilon_r = 2.2$.

The amplifier was measured for two 3-V drain bias points: with the gate bias on ($V_{\rm DS} = 3$ V, $I_D = 50$ mA), and with the gate pinched off ($V_{\rm DS} = 3$ V, $V_{\rm GS} = -1.8$ V). We define the PAE by

$$\text{PAE} = \frac{P_{\rm rf\,out} - P_{\rm rf\,in}}{P_{\rm dc\,in}}. \tag{2}$$

The measured PAE and corresponding output powers for the two cases are shown in Fig. 2. As expected, when the transistor is turned on by the input RF wave, the amplifier operates in the desired mode with the highest PAE of 86%, with a lower output power than in the biased case. For a dc–dc converter, the bias point of interest is when the gate is pinched off and the transistor is off with no input RF drive signal.

III. Class-E DC–AC Oscillator

A class-E oscillator can be designed by providing the correct feedback between output and input of a class-E amplifier. Using a quasi-linear design techniques, as in [5], it can be shown that approximately 4 dB of gain compression satisfies the oscillation condition at 4.5 GHz. As in [5], appropriate feedback to the amplifier can be accomplished with an asymmetric directional coupler (for the feedback amplitude), and specified electrical delay along a 50-Ω line (for the phase of the feedback signal). The maximum measured efficiency for such a class-E oscillator using a Fujitsu FLK052WG packaged MESFET was 57% for $V_{\rm DS} = 8.6$ V, $I_D = 71$ mA. The maximum output power was 725 mW for $V_{\rm DS} = 11.9$ V, $I_D = 132$ mA. This oscillator can be redesigned for lower power and higher efficiency.

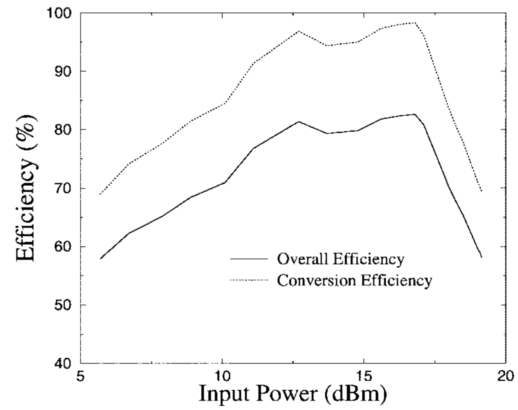

Fig. 3. Measured conversion and overall (total) efficiency of a single half-wave diode rectifier at 4.5 GHz, using a 135-Ω load. The lower curve includes the reflected wave due to input mismatch.

IV. Rectifier

The half-wave rectifier is implemented using MA/Com MA4E2054A-287 Schottky diodes. The input is matched to measured diode s-parameters, and a low-pass filter follows the diode placed in shunt. The filter is implemented with 15- and 130-Ω quarter-wave sections.

Efficiency of a half-wave rectifier is limited by conduction losses on the diode. If we neglect all other losses, the overall efficiency approaches

$$\eta_{\rm total} = \frac{1}{1 + \frac{V_D}{2V_{\rm out}}} \tag{3}$$

where $V_{\rm out}$ is the dc output voltage, and V_D is the voltage drop across the conducting diode. In our example prototype, $V_D \approx 0.3$ V, and the target dc output is $V_{\rm out} \approx 2$ V, thus, the maximum possible overall rectifier efficiency is 87%.

We measured both the conversion and overall (total) efficiency of the rectifiers, defined as [9]

$$\eta_{\rm conv} = \frac{P_{\rm dc\,out}}{P_{\rm rf\,in} - P_{\rm rf\,refl}} \tag{4}$$

$$\eta_{\rm total} = \frac{P_{\rm dc\,out}}{P_{\rm rf\,in}}. \tag{5}$$

The conversion efficiency is higher, as it does not include the power lost in the wave reflected from the diode. The conversion efficiency is close to the theoretical maximum predicted by (3). The input reflection coefficient of the diodes was measured in small-signal mode using an HP8510 network analyzer with a thru-reflection line (TRL) calibration, and was found to be −8 dB at 4.5 GHz. However, in the rectifier, the diodes operate in large-signal mode, and we anticipate a higher reflection. The measured conversion and total efficiency as a function of input power at 4.5 GHz are shown in Fig. 3, indicating that there is room for improvement in the input matching for the diode. The highest overall efficiency of 83% was achieved with a 135-Ω load, with the corresponding conversion efficiency of 98%. The measured output open-circuit voltage as a function of input RF power is shown in Fig. 4.

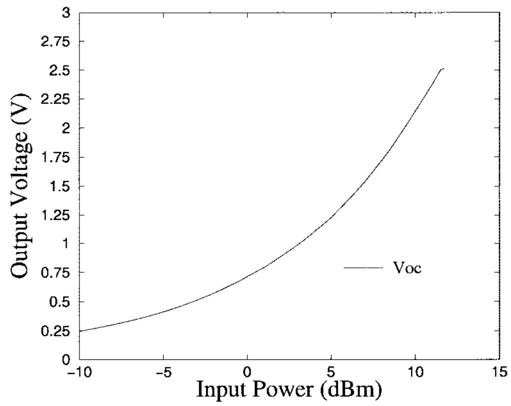

Fig. 4. Measured dc output open-circuit voltage as a function of input RF power.

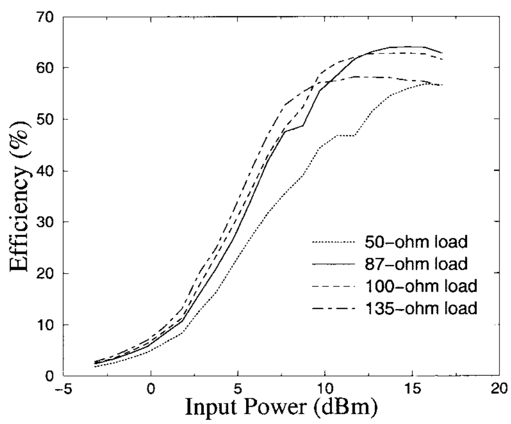

Fig. 5. Measured dc–dc conversion efficiency.

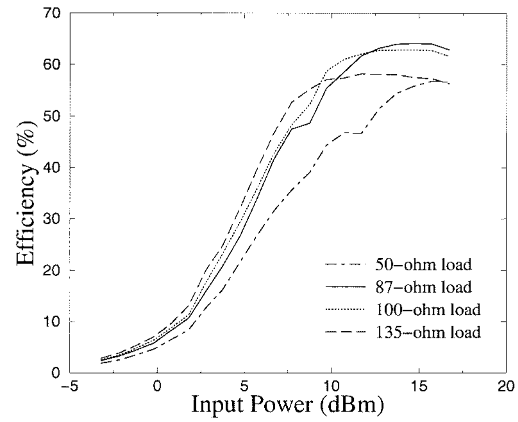

Fig. 6. Total dc power at the two outputs.

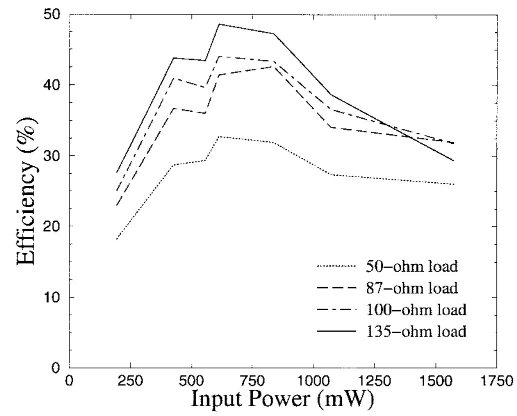

Fig. 7. Total dc–dc converter efficiency using class-E oscillator.

V. DC–DC Converter Performance

After the switching amplifier, oscillator and rectifier were measured as separate circuits, two integrated converter circuits were fabricated. In the first circuit, the output power of the class-E amplifier is divided between two rectifiers using a 3-dB hybrid, as shown in Fig. 1. There were two reasons for this architecture: the output power from the amplifier is too high for a single Schottky diode that was available, and we are interested in the long term in investigating power distribution from arrays of amplifiers to arrays of rectifiers with possibly different output voltages. In addition, the two dc outputs can be connected in series or in parallel, giving more choices for the value of the output voltage or current. The overall dc–dc conversion efficiency was 64% for a 87-Ω load. Figs. 5 and 6 show the converter performance when loaded with different resistor values.

In the second circuit, the output power of the class-E oscillator was coupled through a 10-dB directional coupler to a single rectifier circuit. The reason was again the low power-handling capacity of this particular diode. The maximum overall dc–dc conversion efficiency was 49% for a 135-Ω load. Fig. 7 shows the circuit performance using different load values.

The converter is planar and contains no magnetic components. It is 14-cm long, 7-cm wide, and 0.508-mm thick. The size of our circuit is bigger than originally anticipated because the diodes used have a low power-handling capacity (75 mW per diode), thus, a 3-dB hybrid and 10-dB directional coupler had to be used to lower the power input to the diodes. Using diodes with higher power-handling capability, as well as higher permittivity material, would further reduce the size of the circuit considerably. For example, on a substrate with $\epsilon_r = 10.2$, and of the same thickness (0.508 mm), the same circuit would measure approximately 0.2 cm^3, providing approximately 100 W/in^3.

VI. Discussion and Conclusions

A 64% efficient dc–dc converter at a microwave switching speed is presented. To the best of our knowledge, this is the highest frequency dc–dc converter reported to date. The principal reason for using a microwave switching frequency is the fact that the circuit is planar and compact, and that power conversion is accomplished without any discrete magnetic components. The approach is amenable to monolithic integration, which would enable very small overall dimensions. There may be other advantages to the high frequency: the harmonics are well beyond the highest clock frequencies so that such a power-distribution circuit would not interfere with digital circuitry, and electromagnetic coupling can be used for distributing dc power between layers of a printed circuit board with perfect dc–dc isolation. We also presented

49% efficient dc–dc converter using a class-E oscillator. This configuration eliminates the need for the microwave drive signal. We are currently further improving the efficiency of this attractive approach. The size of the converter can be further reduced by using a higher switching speed. Class-E and Class-F switched-mode amplifiers have been demonstrated with 72% drain efficiency and 60% PAE up to X-band (see, e.g., Bryerton *et al*. in this TRANSACTIONS). However, as the switching frequency increases, the efficiency for a given device degrades due to nonideal class-E (or class-F) operation. It has been shown in [4] that the optimal efficiency is obtained up to approximately one-third of the cutoff frequency for a given device.

The following are several improvements that we are currently implementing.

1) The diode large-signal input impedance measurement will enable a better rectifier input match, resulting in higher overall efficiency.
2) A coupler with built-in isolation between the dc input and output will be used instead of the hybrid.
3) The circuit will be a multilayer architecture on substrates with higher relative permittivities, for reduced overall size.

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