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Planar C-Band DC-DC Converter

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Abstract—**In this paper, we present a DC-DC converter which operates at a microwave frequency. The 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 (PAE) of 86%, corresponding drain efficiency of 95% and 120 mW of output power at 4.5 GHz. The diode rectifier has a conversion efficiency of 91% and an overall efficiency of 77%. The DC-DC converter is planar and compact, with no magnetic components, and with an overall DC-DC conversion efficiency of 50%. The DC input is 3 V, and the output voltage across a 115 Ω load is 2 V.**

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 kHz to low MHz [1]. With surface-mount packaging, power density (output power capability per unit volume) of up to about 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 (GHz) 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. Microwave rectifiers integrated with antenna arrays (rectennas) have been developed for power transmission over the past few decades. A good review is given in [5], and subsequent developments are presented, e.g., in [6-12]. Rectennas developed in the 70's achieved conversion efficiencies greater than 90% at 2.45 GHz [12]. The first C-band antenna achieved 70% overall efficiency and 80% conversion efficiency [8].

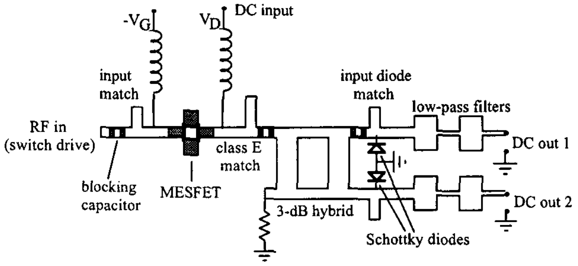

Fig. 1. Layout of the 4.5-GHz microwave DC-DC converter. The DC-AC part of the circuit is a class-E amplifier, the output of which is divided between two half-wave diode rectifiers. The two DC outputs can be connected in series.

In this work, we 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 50%. To the best of our knowledge, this is the highest frequency DC-DC converter reported to date.

II. DC-AC CLASS-E AMPLIFIER 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 Fu-

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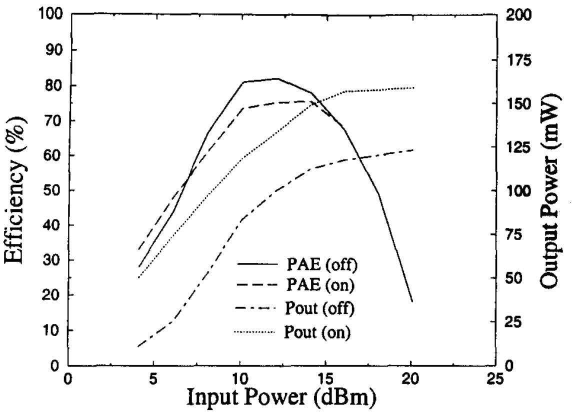

Fig. 2. Measured PAE and output power for a drain bias of 3 V. In one case, the transistor is biased for a drain current on 50 mA, and in the other, the gate is pinched off.

jitsu FLK052WG packaged MESFET was used for the amplifier. As in [3,4], the output capacitance and lead inductance of the transistor are used as part of the output high-efficiency tuning circuit. For class-E operation at a switching frequency f_s, the tuned circuit needs to have an impedance given by

$$Z_{\text{net}} = \frac{0.28015}{2\pi f_s C_s} e^{j49.0524^\circ}, \tag{1}$$

in order to ensure that the current and voltage waveforms across the transistor are never non-zero 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 a 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 ($V_{DS} = 3\,\text{V}$, $I_D = 50\,\text{mA}$), and with the gate pinched off ($V_{DS} = 3\,\text{V}$, $V_{GS} = -1.8\,\text{V}$). The measured PAE efficiencies 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.

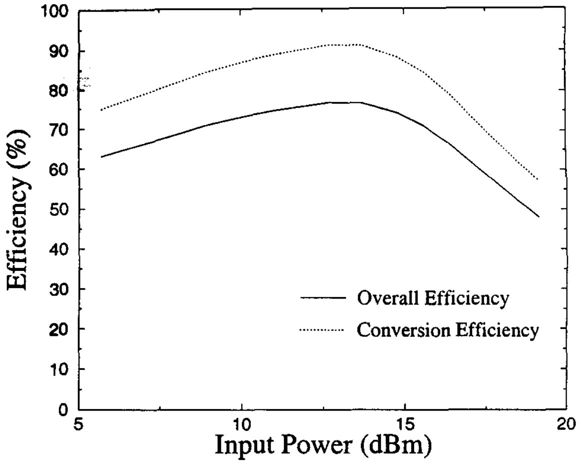

Fig. 3. Measured conversion and overall (total) efficiency of a single half-wave diode rectifier at 4.5 GHz. The lower curve includes the reflected wave due to input mismatch.

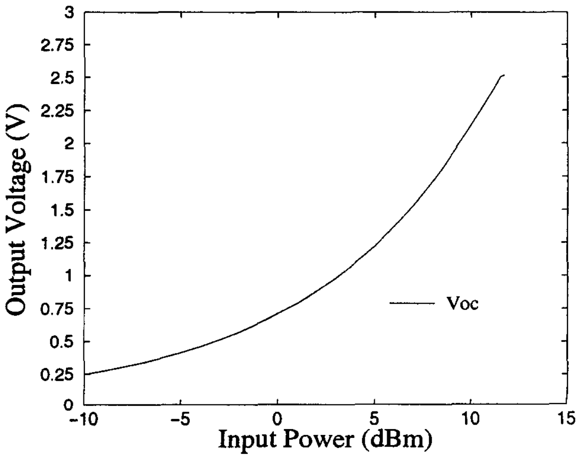

Fig. 4. Measured DC output open-circuit voltage as a function of input RF power.

III. 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 $15\,\Omega$ and $130\,\Omega$ 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:

$$\eta_{\text{total}} = \frac{1}{1 + \frac{V_D}{2V_{\text{out}}}}, \tag{2}$$

where V_{out} is the DC output voltage, and V_D is the

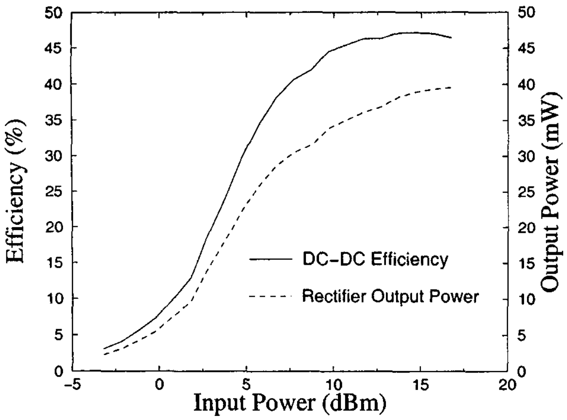

Fig. 5. Measured DC-DC conversion efficiency and DC power at one of the DC outputs, using a 4.5 GHz switching frequency. The efficiency is measured including the DC power at both rectifiers.

voltage drop across the conducting diode. In our example prototype, $V_D \approx 0.3\,\mathrm{V}$, and the target DC output is $V_{\mathrm{out}} \approx 2\mathrm{V}$, so that the maximum possible rectifier efficiency is 87%.

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

$$\eta_{\mathrm{conv}} = \frac{P_{\mathrm{DC\ out}}}{P_{\mathrm{RF\ in}} - P_{\mathrm{RF\ refl}}}, \tag{3}$$

$$\eta_{\mathrm{total}} = \frac{P_{\mathrm{DC\ out}}}{P_{\mathrm{RF\ in}}}. \tag{4}$$

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 Eq.(2). The input reflection coefficient of the diodes was measured in small signal mode using a HP8510 network analyzer with a 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 measured output open-circuit voltage as a function of input RF power is shown in Fig.4.

IV. DC-DC CONVERTER PERFORMANCE

After the switching amplifier and rectifier were measured as separate circuits, an integrated converter circuit was fabricated. In the final 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 of 50% is about 10% lower than the product of the efficiencies of the amplifier and rectifier when measured alone (before integration).

V. DISCUSSION AND CONCLUSIONS

A 50% 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 pc board with perfect DC-DC isolation.

There 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; and (3) the circuit will be a multi-layer architecture on substrates with higher relative permittivities, for reduced overall size.

VI. ACKNOWLEDGEMENT

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