Time-Domain Optical Sampling of Nonlinear Microwave Amplifiers

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Abstract—

Time domain measurements of the output waveforms of two 8-GHz high-efficiency power amplifiers are presented. A new photoconductive probe has enabled nonintrusive absolute voltage measurements which confirm switched-mode class-E and F operation. In order to analyze nonlinear amplifiers designed to deliver a sinusoidal wave to the load, voltages at characteristic points inside the circuit need to be known. The high-impedance probe used here is an optoelectronic sampler which can sense the charge on an exposed interconnect or the field associated with a buried interconnect. This field data is then converted into voltage.

I. Introduction

IN high-efficiency class-E and class-F power amplifiers, the transistor is used as a switch and the harmonics of the switched voltage are reflected back towards the transistor before reaching the load [1], [2]. This is usually accomplished by the use of matching circuits and filters, and produces switch current and voltage waveforms which are exactly out of phase with each other. The losses within the switching transistor are thus minimized. If large signal models of the transistor are available, the time-domain waveforms at the switch can be simulated using harmonic balance methods to demonstrate the offset between the current and voltage waveforms. In [3], such simulations are used in the design of the power amplifier.

Class-F and E amplifiers using Fujitsu FLK202MH-14 and FLK052WG packaged power MESFETs, respectively, were designed at 8 GHz for this study. The principal difference between these two classes of operation is that in class-F the second harmonic is shorted and in class-E it is terminated in an open circuit. Since the transistor does not have gain at higher harmonics, it is sufficient to consider only the second harmonic termination in both designs.

At low frequencies (up to about 500 MHz), these switch waveforms can be measured by introducing a large resistor between the drain and source and measuring the voltage across this resistor using an oscilloscope [4]. At higher frequencies it is not possible to measure these waveforms due to the difficulty in making high-impedance probes at these frequencies. One verification of class-E or class-F performance is simply obtaining high efficiency. This, however, leaves an ambiguity in the proper operation of the circuit. Recent advancements in photoconductive probing of microwave circuits [5], [6] have paved a way to make such measurements up to very high frequencies.

II. Photoconductive Probing

The photoconductive probe utilized in the time-domain measurement of the high-efficiency amplifier response is a micromachined, optical-fiber-coupled, optoelectronic sampling head. It can sense the charge on an exposed interconnect or the field associated with a buried interconnect, acting as a 4-ps-resolution sampling gate and converting current signals into voltage signals.

The current to voltage conversion is accomplished by a JFET source follower circuit with an input resistance of 1 TΩ and an input capacitance of 3 pF. This high input resistance avoids charge drainage from the DUT so that measurement with minimal invasiveness is achieved. Due to the small amount of charge necessary to load the source follower input, the actual voltage level is built up in a short time, allowing a higher modulation bandwidth and the ability to measure absolute voltage levels. In addition, the high input resistance of the source follower allows the instantaneous dc voltage at the probe node to be determined at the outout of the source follower, and thus both ac and dc signals can be measured simultaneously.

In this measurement system, shown in Fig. 1, the probe is illuminated by a train of femtosecond-duration laser pulses, and the output voltage is recorded on a low-frequency oscilloscope. The output voltage is a down-converted replica of the unknown microwave signal. If a frequency-domain output is required, a lock-in amplifier or a spectrum analyzer can be used in place of the oscilloscope. For an unknown microwave signal

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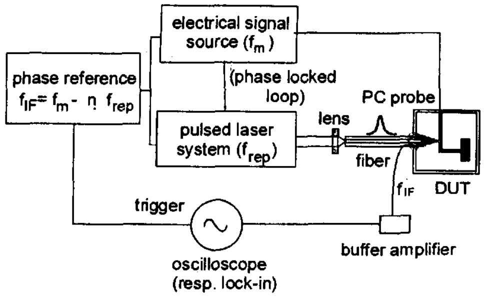

Fig. 1. Optical sampling measurement setup.

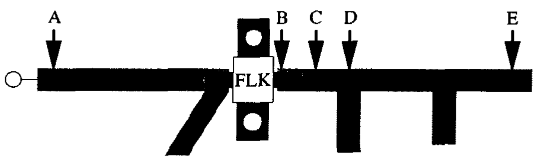

Fig. 2. General outline of class-E and F amplifier circuits.

with frequency f_m, heterodyne mixing and equivalent time-sampling dictate that the following relationship between the microwave frequency and the intermediate frequency be fulfilled:

$$f_m = nf_{rep} \pm f_{IF}, \tag{1}$$

where n is an integer and $f_{rep} = 80\,\text{MHz}$ is the laser pulse repetition frequency. The intermediate frequency f_{IF} is typically in the kHz range and provides a replica of the unknown microwave signal. The Ti:sapphire laser used in this system is phase locked to the microwave source so that the in-circuit electrical signal can be determined in amplitude and phase. The probe has a 3.5 ps time response, which relates to a bandwidth over 100 GHz. Therefore, the probe should exhibit a frequency response which extends into the mm-wave region.

The two amplifiers are built on RT Duroid substrates with $\epsilon_r = 2.2$ and 0.508 mm thickness. The general outline of the two circuits is given in Fig. 2. The points at which the circuit is probed are shown as **A**, **B**, **C**, **D**, and **E** in this figure and correspond to plots given in this paper. The gate and drain gold leads were soldered to the rest of the circuit so that an exposed gold area exists for the probe to make contact to.

III. Class-F Nonlinear Amplifier

A. Design

Class-F amplifier design requires an output impedance given by

$$Z_L = \frac{V_{dd}}{2I_{dss}} \tag{2}$$

at the fundamental switching frequency [7], to present a short circuit at all even harmonics and an open circuit at all odd harmonics. V_{dd} and I_{dss} are the drain bias voltage and the maximum current of the transistor respectively. The impedance given by Eq. (2) provides maximum power transfer between the transistor and the output. The voltage at the switch of a class-F amplifier is a square wave because the voltage contains negligible second harmonic content but significant third harmonic contribution. Electrical measurements at 8.0 GHz show a drain efficiency of 73%, a power-added efficiency (PAE) of 61%, and 28.6 dBm output power. The input power was 22 dBm. Harmonic balance simulations of the waveforms were not possible because a large signal model for the transistor was not available.

B. Optical Time-Domain Measurements

The input waveform measured at point **A** in Fig. 2 is a sine wave biased at about -1.0 V, as is shown in Fig. 3. These waveforms cannot be used to calculate power since the local impedance is unknown. However, they are very useful in analyzing which harmonic components are contained in the waveform.

Fig. 4 shows the voltage waveforms at points **B**, **C**, and **D** in Fig. 2. For point **B**, the probe was placed on the gold output lead of the of the transistor, as close to the transistor as possible. Therefore, this waveform can be considered as the switch voltage variation with time. Although the gold lead acts as a small inductance in series the switch, it is not significant enough to drastically change the switch waveform. Fig. 4 shows the square shape of the switch voltage, which is consistent with class-F operation. The two peaks in the waveform are due to the fundamental frequency and the third harmonic, as is evidenced by the spacing between peaks. The second harmonic does not appear in this waveform since it is presented with a short at the output. Higher harmonics are not present because the transistor does not have gain at these harmonic frequencies.

However, in Fig. 4, it is evident that there is a significant second harmonic contribution at point **C** (Fig. 2). This is due to the standing wave between the transistor output and the first stub, which provides the second harmonic short.

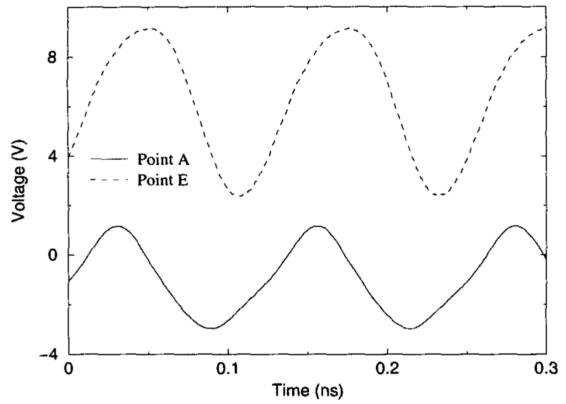

Fig. 3. Optically sampled waveforms at points **A** and **E** in the class-F ciruit, corresponding to the input and output respectively. The input and output waveforms are both sinusoidal signals.

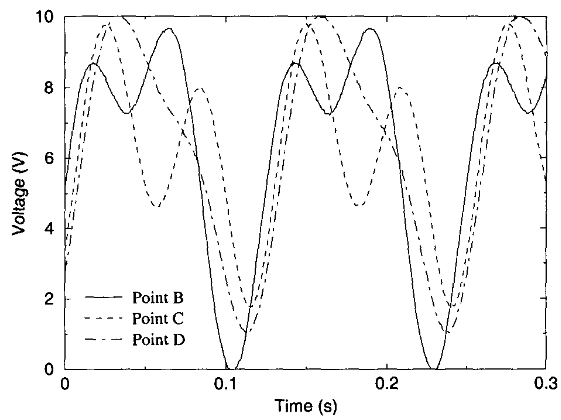

Fig. 4. Optically sampled waveforms at points **B**, **C** and **D** in the class-F circuit. In the switch waveform at **B**, the fundamental and third harmonic approximate a square wave. At **C**, which is before the second harmonic shorting stub, there is a significant second harmonic component, and at **D**, the harmonics have mostly been filtered out.

As shown in Fig. 4, the second harmonic is not strong in the waveform at point **D**. The distortion in the waveform indicates that there is some second harmonic leakage beyond the first stub.

Beyond the second output stub, at point **E**, the output waveform is sinusoidal. This is shown in Fig. 3 along with the input waveform for comparison. This is part of the design of a class-F circuit, in which the output circuit must filter out the harmonics in the switched waveform. These measurements verify the proper waveforms inside the power amplifier and therefore substantiate the class-F design.

IV. Class-E Nonlinear Amplifier

A. Design

Transmission-line class-E amplifiers require the fundamental load impedance to be given by

$$Z_L = \frac{0.28015}{2\pi f_s C_s} e^{j49.0524^\circ}, \tag{3}$$

where f_s is the fundamental frequency, and C_s is the transistor switch output capacitance approximated by C_{ds}. All harmonics are terminated in an open circuit [8], [3]. This is determined by specified boundary conditions in time-domain.

The value of C_{ds} to be used in the class-E amplifier design is de-embedded from low frequency s-parameters. Since C_{ds} is a geometry based capacitance, this is a reasonable approximation for the switch capacitance, even though the nonlinear capacitance C_{gd} affects the total output capacitance. The lack of a large signal model for this transistor prohibits waveform simulations which would aid in the design of these circuits.

Power measurements result in a drain efficiency of 64%, PAE of 48%, and 31.5 dBm output power at 8.35 GHz. The optical measurements were made at 8.32 GHz, since the microwave frequency must be a multiple of the laser repition frequency of 80 MHz according to Eq. (1).

B. Optical Time-Domain Measurements

For the class-E circuit, only voltages at points **B** and **E** in Fig. 2 are shown, since they are the salient waveforms of class-E operation.

Fig. 6 shows the voltage at point **B**, which is the voltage waveform across the switch. For comparison, a harmonic balance simulation at 500 MHz for a different class-E amplifier [9] is shown in Fig. 5. A suitable nonlinear model was available for this MESFET (Siemens CLY5). The switch voltage waveform in this case is not square, but has considerable fundamental and second harmonic content, giving it the shape of a narrow, left-skewed half-sinusoid. The measurement also shows the large second harmonic portion of the waveform, which produces the left-skewed voltage wave. The simulated voltage is close to zero for nearly half of the period, approaching ideal class-E operation. The measured voltage, however, is not flat in this half of the period, resulting in a higher *vi* product (loss). This is consistent with nonoptimal class-E operation, since the circuit is operated above the critical frequency for class-E operation, in this case, about 1.5 GHz [10], [3]. The measured class-E waveform is very different from the class-F switch voltage in Fig. 4 which depicts a square wave

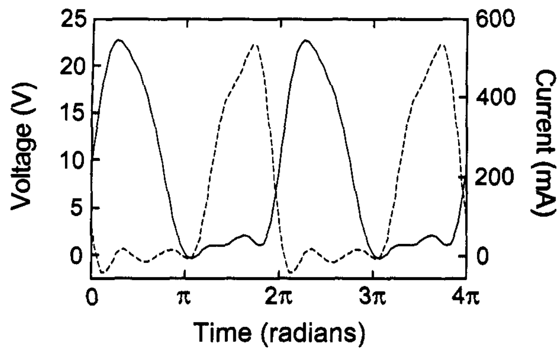

Fig. 5. Simulated waveform of a 500 MHz class-E circuit using a Materka-Kacprzak nonlinear model for a Siemens CLY5 MESFET. The solid line is voltage and the dashed line denotes current.

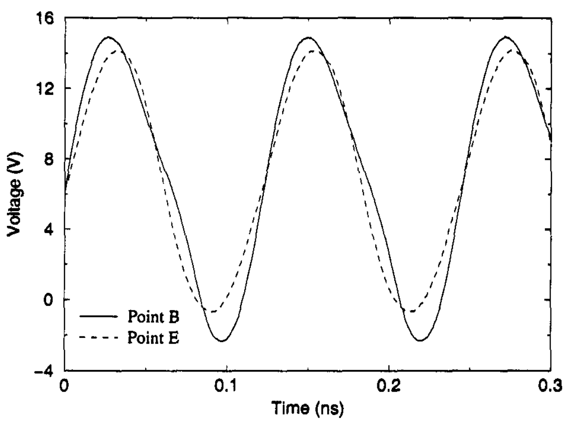

Fig. 6. Measured waveforms at points **B** and **E** in the class-E circuit. The shape of the voltage wave at **B** is similar to that in Fig. 5, with a second harmonic component in the waveform. The output wave at **E** is sinusoidal.

consisting of the fundamental and third harmonic.

At point **E**, the filtered output waveform appears as a sinusoidal pattern as shown in Fig. 6. This analysis verifies that the power amplifier is indeed operating in the desired class-E mode.

V. Acknowledgements

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