

BROADBAND MICROWAVE AMPLIFIER

5

BACKGROUND OF THE INVENTION

Field of the Invention:

10

The present invention relates to electrical and electronic circuits and systems. More specifically, the present invention relates to microwave Class E power amplifiers.

15

Description of the Related Art:

For a variety of commercial and military applications, highly efficient microwave and radio frequency (RF) power amplifiers are needed. Typical applications include wireless local area networks, cell phones and telecommunication systems as well as advanced airborne active phased array radar systems. The choice of technology, design methodology and manufacturing cycle time are major cost contributors in these systems. Switching mode, Class-E, high-efficiency power amplifiers are useful for these and other applications inasmuch as these amplifiers limit the power and associated cooling costs thereof. A Class-E amplifier is part of the "switching mode amplifiers" such as class D, E, F, etc. In these types of amplifiers, the transistor operates as a perfect switch with no overlapping voltage & current waveforms at its output terminal, thereby ideally dissipating zero DC power. Other classes of amplifiers such as class A, A/B and C, operate as a current-source with overlapping voltage & current waveforms and hence dissipate DC power leading to a lower efficiency.

Class-E amplifiers use a series or parallel resonant load network. The function of the load network in the class E amplifier is to shape the voltage and current waveforms.

35 The current and voltage time-waveforms at the active device output terminal are optimized in such a way as to minimize the DC power dissipation within. The active device, a pHEMT in this case, acts as a switch, driven by the RF input signal to "ON" and "OFF" conditions. The operating point of the device is such that the device is either OFF (in the pinched-off region) or ON (in the linear region). Under an ideal
40 switching operation condition, output voltage and current waveforms at the device output terminal do not exist simultaneously and, therefore, the energy dissipated within the device is zero, yielding a 100 percent theoretical power conversion efficiency.

45 In any event, the maximum efficiency of Class-E amplifiers (i.e. the ratio of the RF output power to the DC input power) and its bandwidth of operation are limited by the tuned loads thereof. The limitation is due to the fact that presence of the tuned load results in a very narrow operational bandwidth for the amplifier.

50 Hence, a need remains in the art for a system or method for increasing the power, power added efficiency (PAE) and bandwidth of Class-E amplifiers.

SUMMARY OF THE INVENTION

55 The need in the art is addressed by load circuit topologies of the present invention suitable for switching mode Power Amplifiers (PAs). In a most general sense, the inventive load includes a shunt inductive element coupled to an output of said amplifier; a series inductive element coupled to said output of said amplifier; and a series capacitive element coupled to said series inductive element.

60

In the illustrative embodiment, the inventive load is operable at frequencies in the range of 8 - 10 GHz and beyond. The shunt inductive element, part of the said load

is suitably chosen to provide two important functions. First, to provide an inductive bias line for said amplifier and second, to provide a parallel resonance with the
65 pHEMT's output drain-source capacitance (C_{ds}).

The invention enables an advantageous Class-E amplifier design comprising an input matching network; an active device coupled to the input matching network and a load coupled to the active device and implemented in accordance with the
70 present teachings.

Also disclosed is a method for designing a load for use with a Class-E amplifier including the steps of: providing a lumped equivalent circuit representation of the load; optimizing the lumped equivalent circuit representation of the load to
75 achieve near ideal current and voltage operational characteristics over a predetermined frequency range using a time domain simulation; transforming the optimized lumped equivalent circuit representation of the load to a distributed circuit representation; and optimizing the distributed circuit representation of the load to achieve near ideal current and voltage operational characteristics over a predetermined frequency range
80 using a time domain simulation.

The unique properties of the inventive load circuits enable Class-E HPAs to maintain a simultaneous high PAE and Power over a broad bandwidth.

85 BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1a is a simplified schematic diagram of an ideal discrete component implementation of a typical Class-E load in accordance with conventional teachings.

90 Fig. 1b is a distributed component implementation of the load depicted in Fig. 1a.

Fig. 2a is a simplified schematic diagram of an ideal discrete component implementation of a typical Class-E load in accordance with the teachings of the present invention.

95

Fig. 2b is a distributed component implementation of the load depicted in Fig. 2a.

Fig. 2c shows graphs of current and voltage waveforms of a lumped equivalent circuit representation of the load designed in accordance with the present teachings.

100

Fig. 3a is a Smith chart showing frequency dependency of a broadband lumped load designed in accordance with the teachings of the present invention.

105

Figure 4 shows a schematic circuit of a distributed representation of a monolithic Class-E amplifier with the broadband Class-E load in accordance with the present teachings.

Figure 5 depicts simulated voltage and current waveforms at the pHEMT output terminals of the amplifier of Fig 4.

110

DESCRIPTION OF THE INVENTION

Illustrative embodiments and exemplary applications will now be described with reference to the accompanying drawings to disclose the advantageous teachings of the present invention.

115

While the present invention is described herein with reference to illustrative embodiments for particular applications, it should be understood that the invention is not limited thereto. Those having ordinary skill in the art and access to the teachings provided herein will recognize additional modifications, applications, and

120

embodiments within the scope thereof and additional fields in which the present invention would be of significant utility.

125 Fig. 1a is a simplified schematic diagram of an ideal discrete component implementation of a typical Class-E load in accordance with conventional teachings. As shown in Fig. 1a, a typical Class-E amplifier represented by a switch 12' is coupled to a source V_{ds} via an inductive bias line 14'. The switch 12' is coupled to a resistive load 24' via a capacitor 22' and an inverted L type (series L, shunt C) wave
130 shaping load network 20'. The drain bias line 14' is treated independent of the load circuit 20', merely acting as a choke realized by a quarter wavelength length of transmission line.

 The load 20' includes a first shunt capacitor 15' which is the drain to source
135 capacitance (C_{ds}) of the transistor switch 12'. In accordance with conventional teachings, the load 20' includes a series inductor 16' (L) and a shunt capacitor 18' (C).

 Fig. 1b is a distributed component implementation of the load depicted in Fig. 1a. It is worth mentioning that the function of the load network in the class E
140 amplifier is to shape the voltage and current waveforms. Therefore, for the design of a broadband Class-E amplifier, care should be taken to ensure Class-E waveforms exist over the entire frequency band. Choices of a suitable device non-linear modeling tool as well as a design environment tool capable of time domain, robust harmonic balance and envelope simulation are critical for the successful design of highly non-
145 linear circuits such as the switching mode amplifiers.

 Fig. 2a is a simplified schematic diagram of an ideal discrete component implementation of a typical Class-E load in accordance with the teachings of the present invention.

150

Fig. 2b is a distributed component implementation of the load depicted in Fig. 2a. In accordance with the present teachings, a novel broadband Class-E load topology is presented based on the series (L-C) network shown in Fig. 2a. As discussed more fully below, the load is modified to offer a superior broadband performance when compared with the (series L, shunt C) load network of Figs. 1a and 1b. In accordance with the present teachings, the first step in the novel design process is to include the drain bias inductor 14 as part of the Class-E load topology followed by the transformation of the lumped network representation to its equivalent distributed network form. In this critical transformation process which is necessary for the said amplifier to operate at microwave frequencies, the series inductor 16 and series capacitor 18 of Fig. 2a are replaced by a combination of a series transmission line and a shunt shorted stub as shown in Fig 2b. Also, the shunt inductor 14 of Fig. 2a is replaced with a shunt shorted stub to provide a parallel resonance with the pHEMT's output drain-source capacitance (C_{ds}) as well as to provide a bias to the drain of the pHEMT transistor.

Next, starting values for the lumped components of the load network 20 are ascertained. Several authors have published detailed expressions for the starting values of the lumped series (L, C) Class-E load. See for example "Class-E – A new class of high efficiency tuned single-ended switching power amplifier", by N. O. Sokal, *et al.* IEEE JSSC, vol. SSC-10, pp.168-176, June 1975; "Solid State Radio Engineering" by F. H. Raab, *et al.*, John Wiley & Sons, 1980; "Low Voltage, High Efficiency Class E GaAs Power Amplifiers for Mobile Communications", by T. Sowlati, *et al.* IEEE GaAs IC Symposium Digest 1994, pp.171-174; "Switched-Mode High-Efficiency Microwave Power Amplifiers In A Free-Space Power Combiner", by T. Mader, *et al.*, IEEE MTT, vol. 10. Oct. 1998, pp. 1391-1398; and "Ultra-High Efficiency Operation Based On An Alternative Class-E Mode", P. Watson, *et al.*, IEEE GaAs IC Symposium Digest 2000, pp.53-56.

Next, having obtained the starting values for the load network, a time domain
180 simulation is performed to optimize the load with the objective of obtaining near ideal
current and voltage waveforms over a desired operating range (e.g. 8 - 10 GHz).

Fig. 2c shows these simulated waveforms illustrating near ideal performance
over 2.0 GHz of bandwidth. The frequency dependency of the broadband lumped
185 equivalent circuit representation of the load is shown in Fig. 3 (a), depicting an
excellent frequency independent response over 8.0-10.0 GHz compared to the
narrowband Class-E load (series L, shunt C). See "*A Monolithic X-band Class-E
Power Amplifier*", by R. Tayrani, IEEE GaAs IC Symposium, PP 205-208, Oct. 2001.

190 Having obtained a nearly frequency independent magnitude and phase
response for the lumped equivalent circuit representation of the load network, we can
now proceed to the next step by transforming this load to its equivalent distributed
network. (See Fig. 2b.)

195 To optimize the distributed load, the time domain optimization process
described for the lumped load is repeated for the distributed load.

Figure 3b is a diagram which illustrates the time domain simulation of the
distributed load network illustrating near ideal performance at 8 GHz. As shown in
200 Figure 3b, the voltage waveform across the switch rises slowly at switch-off and falls
to zero at the end of the half-cycle. It also has a zero rate of change at the end of half-
cycle, thereby ensuring a "soft" turn-on condition.

Furthermore, it is shown that the integral of the capacitor (C_{ds}) current over the
205 half-cycle is zero and that the capacitance current has dropped to zero by the end of
the half-cycle, both indicative of Class-E operation for the distributed load at 8.0 GHz.
Similar simulated waveforms were obtained over the desired 2.0 GHz frequency band.
Although not shown, the frequency response of the distributed load (Figure 2b) should

also be broadband having a nearly frequency independent response similar to its
210 lumped version shown in Figure 3 (a).

In the illustrative application, the load circuit is synthesized for medium power
PAs (~ 30 dBm, 1.0 W max). A single 0.25 μm x 720 μm pHEMT device is used in
this circuit. Such PAs are suitable as a single stage PA and/or as the first stage of a
215 two stage Class-E High Power Amplifiers (HPAs).

Figure 4 shows a schematic circuit of a distributed representation of a
monolithic Class-E amplifier with the broadband Class-E load in accordance with the
present teachings. The amplifier 30 of Fig. 4 includes an active device 12 with the
220 inventive load 20. In the illustrative embodiment, the active device 12 is a Gallium-
Arsenide pseudo-morphic, high-electron mobility transistor (GaAs pHEMT).

An input matching network 40 is provided at the input to the active device 12.
The load 20 and input matching network 40 are designed with the width and length
225 dimensions shown in microns for operation at 8 – 10 Ghz. Those of ordinary skill in
the art may extend the present teachings to other frequencies without departing from
the scope thereof.

For accurate and robust non-linear simulation of switching mode amplifiers,
230 the device non-linear model should have the following properties:

Bias dependency of drain-to-source $C_{ds}(V_{ds}, V_{gs})$ and gate-to-drain C_{gd}
(V_{ds}, V_{gs}) capacitances;

Bias dependency of input channel resistance $R_i(V_{ds}, V_{gs})$; and

235 Bias dependency of output channel resistance $R_{ds}(V_{ds}, V_{gs})$.

Also the device model should be able to accurately model the dispersion
associated with the drain current, g_m , and R_{ds} . If the pulsed DC IV technique is used

for the model development, this requirement may be unnecessary. For this purpose,
240 the EEHEMT model available in ICCAP (Agilent ICCAP, V.5.1) and ADS (Agilent
Advanced Design Systems (ADS), V. 2003C).

A $0.3\text{ }\mu\text{m} \times 6 \times 120\text{ }\mu\text{m}$ pHEMT device having a gate-drain breakdown
voltage of greater than 18 V may be designed using currently available technology in
245 accordance with the present teachings to meet performance goals for very large
($>100,000$ T/R elements) space based phased array radar requiring simultaneous
broadband power (min. 200.0 mW) and PAE (min. 60%) over 8.0 - 10.0 GHz.

Figure 5 depicts simulated voltage and current waveforms at the pHEMT
250 output terminals of the amplifier of Fig 4. The waveforms show a switching mode
behavior of the pHEMT device at 8.5 GHz. Similar waveforms may be provided over
8 - 10 GHz to confirm broadband operation.

Thus, the present invention has been described herein with reference to a
255 particular embodiment for a particular application. Those having ordinary skill in the
art and access to the present teachings will recognize additional modifications
applications and embodiments within the scope thereof. For example, the present
teachings are not limited to Class-E amplifiers. That is, the present teachings may be
used in connection with any switching amplifier or circuit design.

260

It is therefore intended by the appended claims to cover any and all such
applications, modifications and embodiments within the scope of the present
invention.

265 Accordingly,

WHAT IS CLAIMED IS:

CLAIMS

1. A method for designing a load for use with a Class-E amplifier including the steps of:
 - providing a lumped equivalent circuit representation of said load;
 - optimizing the lumped equivalent circuit representation of said load to achieve near ideal current and voltage operational characteristics over a predetermined frequency range using a time domain simulation;
 - transforming said optimized lumped equivalent circuit representation of said load to a distributed circuit representation; and
 - optimizing the distributed circuit representation of said load to achieve near ideal current and voltage operational characteristics over a predetermined frequency range using a time domain simulation.