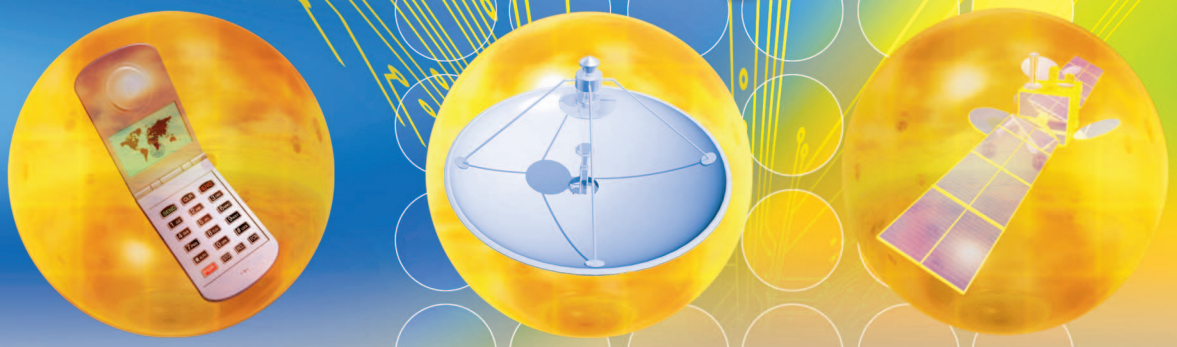
High-Efficiency Class F RF/Microwave Power Amplifiers



S. Gao

The rapid growth of mobile telecommunication services has increased demand for low-cost, high-efficiency, and compact equipment. It is widely known that the RF power amplifier (PA) is one of the most critical building blocks in radio transmitters and is also the most power-hungry component in the RF front end.

An RF PA is a circuit that uses dc power to boost RF/microwave output power. In the early days of radio communication systems (1895–mid 1920s), RF power was generated by spark, arc, and alternate techniques. The year 1907 saw the birth of the triode vacuum tube, the first electronic device capable of amplification. Then the advent of the thermion vacuum tube offered a means of generating and controlling RF signals, and vacuum-tube PAs were popular from the late 1920s through the mid-1970s. Today, vacuum-tube PAs still dominate applications requiring high-power generation at very high frequencies, and they keep being improved. Discrete solid-state RF-power devices appeared at the end of 1960s with the introduction of silicon bipolar transistors such as the 2N6093 by RCA. The dominance of these devices in the 1980s brought about the use of lower voltages, higher currents, and relatively low load resistances.

In the 1970s, gallium arsenide (GaAs) metal semiconductor field-effect transistors (MESFETs) with good RF performance at X band became available, and GaAs revo-

S. Gao (shichang.gao@unn.ac.uk) is with the University of Northumbria, Newcastle Upon Tyne, NE1 8ST, U.K.

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lutionized the RF/microwave market. GaAs monolithic microwave integrated circuits (MMICs) brought integration capability to the predominately chip- and wire-based military and high-frequency markets.

The complementary metal-oxide semiconductor (CMOS) started to have a significant impact on the electronics field in the 1980s, with semiconductor tool capability reaching the 3-μm technology node in the early part of that decade. Today, the advancement of CMOS has made it competitive with bipolar technology. Silicon laterally diffused MOS (LDMOS) devices are used in power amplifiers for GSM and digital cross-connect system (DCS) base stations. The 1990s saw a proliferation of a variety of new solid-state devices, including high-electron mobility transistors (HEMTs), pHEMTs, and heterojunction bipolar transistors (HBTs), in a variety of new materials such as InP, SiC, and GaN. These devices offer amplification to 100 GHz or more and are, in many cases, grown to order in MMIC form. Today, solid-state PAs are widely used in various systems such as communication, radar, navigation, broadcasting, RF heating, magnetic-resonance imaging, laser drivers, and dc/dc converters.

RF PAs are commonly designated as class A, B, AB, C, D, E, F, F^{-1}, and S [1]–[4]. Classes of operation differ in method of operation, efficiency, linearity, and power-output capability. Among different classes of PAs, Class F has become very popular during recent years, due to its high efficiency and output power capability. The benefits of flattening the bottom of the plate-voltage waveform were known in 1919, and Tyler presented the first implementation and general description of a multiresonator Class-F PA [5]. The first application of the class F technique to UHF PAs was proposed in [6] by Snider, who analyzed an optimally loaded PA in which all harmonic impedances are either infinite or zero, as well as an overdriven PA in which harmonic power is delivered to the load.

At RF and microwave frequencies, it becomes increasingly difficult to find transistors capable of switching fast enough for switching-mode Class-D and E operations. Fortunately, it is often possible to control the load impedances at a finite number of harmonics, which allows Class-F PAs to achieve high efficiency at high frequencies. Most PA designs have used transmission line networks to control the impedance at the second [7] or third harmonic [8]. Many designs have used transmission lines to control both the second and third harmonics [9], [10]. Toyoda used dielectric resonators to implement classical Tyler-type third and fifth harmonic–peaking PAs at 900 MHz [11]. Others have demonstrated the effects of harmonic terminations through experiments and simulations [12], [13].

This article provides a tutorial and review of recent developments in high-efficiency class F RF/microwave PAs. The principles of Class-F RF PAs are explained first. Recent progress in their theory and in design techniques is then presented. Different approaches of Class-F PA designs are explained, and some examples of practical designs are illustrated. Finally, an attempt is made to discuss the future developments of Class-F RF/microwave PAs.

Fundamentals of an Ideal Class-F PA

Figure 1 shows the basic topology of a PA, which includes an active device, dc feed, output-matching network, and input-matching network. The active device is controlled by its drive and dc bias to act as a current source. The active device can be an field-effect transistor (FET) or a bipolar-junction transistor (BJT), but all of the figures and device terminal names in this article correspond to using an FET as the active device. DC drain current is supplied from supply voltage (drain bias) V_d through the RF choke. The output network transforms the 50-Ω load to the optimum load at the drain.

A Class-F PA boosts both efficiency and output power by using harmonic resonators in the output network to shape the drain waveforms such that the load appears to be a short at even harmonics and an open at odd harmonics. The drain voltage waveform includes one or more odd harmonics and approximates a square wave, while the drain current waveform includes even harmonics and approximates a half sine wave. Because there is no overlap between the drain voltage and current, an ideal efficiency of 100% is achieved. In the case of its dual, i.e., Class F^{-1}, the shapes of drain voltage and current are swapped, i.e., the drain voltage waveform is close to a half sine wave while the drain current is close to a square wave [14].

The output network of a classical Class-F PA is shown in Figure 2, which consists of a quarter-wavelength transmission line and a parallel-tuned inductance-capactiance (LC) output tank [15]. The output tank is tuned to resonance at the fundamental frequency f_0. At f_0, the drain sees a pure resistive load of R_L, since the output tank is an open circuit, and the quarter-wave transformer transforms the 50-Ω load to R_L at the drain. The load resistance R_L is chosen as the optimum load impedance for the PA, which can lead to maximum excursions of drain current and voltages. R_L can be determined from load-pull measurement or simulations.

At even harmonics $2nf_0 (n = 1, 2, \cdots)$, the output tank becomes a short, and the transmission line appears to be a length of $n\lambda_g/2$ to the drain, where λ_g is the guided wavelength of the transmission line. Therefore, the drain

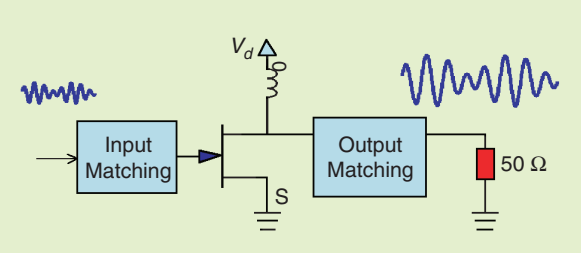

Figure 1. *Basic topology of a PA.*

Table 1. Maximum efficiency of class-F PAs [16].

m, n Denotes Maximum Order of Harmonics in Drain Current and Voltage, Respectively	$n = 1$	$n = 3$	$n = 5$	$n = \infty$
$m = 1$	50%	57.7%	60.3%	63.7%
$m = 2$	70.7%	81.7%	85.3%	90.0%
$m = 4$	75%	86.6%	90.5%	95.5%
$m = \infty$	78.5%	90.7%	94.8%	100%

sees a short at all even harmonics, which would result in a half-rectified sinusoid current output as desired. Conversely, at odd harmonics $(2n+1)f_0 (n = 1, 2, \cdots)$, the output tank also becomes a short, and the transmission line appears to be a length of $((2n+1)\lambda_g)/4$ to the drain. Due to the quarter-wavelength transformer, the drain sees an open circuit at odd harmonics.

The drain voltage contains only the odd harmonics, while the drain current includes only the even harmonics. Thus, the harmonic impedance is zero at even harmonics and infinite at odd harmonics.

Recent Development in Theoretical Analysis and Designs

The ideal Class-F PA assumes the inclusion of an infinite number of harmonics, which is, however, unrealistic in real-world designs. For example, the drain-source capacitance C_{ds} will make most high-order harmonics at microwave frequencies shorted-circuited. Also, the parasitic capacitance and inductance at the drain output make it nearly impossible to make even harmonics short-circuited and odd harmonics open-circuited. Usually, many harmonic traps at the output network are needed to realize the impedance at each harmonic frequency, which, however, would lead to a more complicated circuit and more loss at the output, thus degrading the efficiency. For this reason, most real-world designs of Class-F RF PAs consider only a few harmonics, mostly the second and third harmonics, which have the most effects on the efficiency and output power.

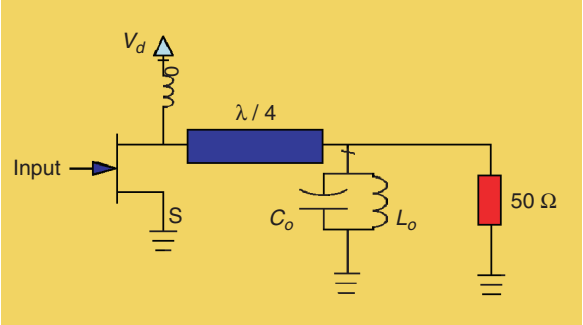

Figure 2. *Output network of a classical class-F PA.*

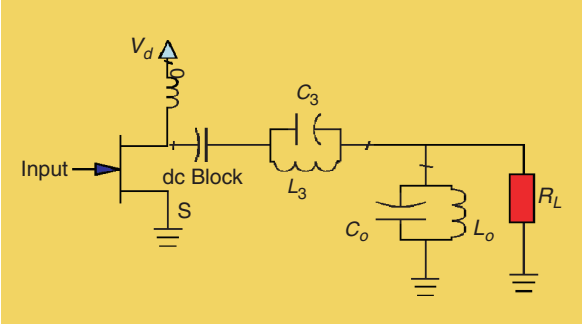

Figure 3. *Output network of third-harmonic peaking circuit [15].*

Although using Class F has become a popular technique for improving the efficiency of RF PAs, the impact of using a different number of harmonics remains only partially understood. Recently, Raab investigated the effects of finite harmonics on the output power capability and efficiency [16]–[18], which would be useful for designers to make a tradeoff between output-network complexity and efficiency. The maximum efficiency for a given set of harmonics is shown in Table 1 [16]. As we can see, the maximum efficiency of an ideal PA is 50% for Class A, where only the fundamental frequency components are considered, i.e., $n = 1$ for both drain voltage and current. The maximum efficiency increases from 50% (Class A) towards unity (e.g., 70.7, 81.7, 86.6, and 90.5%, for second, third, fourth, and fifth harmonics, respectively), and the utilization factor increases from 0.125 to $1/2\pi$. The required harmonics arise naturally from nonlinearities and saturation in the transistor. A frequency-domain analysis is also given for the ideal Class-C, -E, and -F PAs in [18], which are based on a finite number of harmonics. It is shown that the number of harmonics determines the maximum attainable efficiency. The harmonic impedances determine the power-output capabilities, which is the highest for ideal Class-F operations.

In the case of considering only the second and third harmonics (i.e., third-harmonic peaking), the maximum efficiency reaches 81.7%. An output network that includes a third-harmonic peaking circuit is shown in Figure 3. The quarter-wavelength transformer in Figure 2 is removed here, and, instead, a parallel resonant tank at $3f_0$ is added in series with the drain output, which provides a short at $2f_0$ and an open at $3f_0$. Another parallel resonant tank at f_0 is added in parallel with the load resistance, the same as in Figure 2, which ensures optimum load at f_0. Here R_L is the optimum load required by the drain port.

Theoretical designs of third-harmonic peaking load networks for Class-F PAs are presented in [19] and [20], where the component values in the load network are derived. For practical applications, it is important to take into account the active device output capacitance C_{ds}, which should be a part of the output loading network. Figure 4 shows two possible circuit configurations with additional parallel resonant circuit (a) or series resonant circuit (b) and derived values of their

parameters [20]. Figure 4(c) gives an equivalent microstrip impedance-peaking circuit with derived values of its elements, which could provide short-circuit termination for all even harmonics and open-circuit termination for the third harmonic [20]. However, the practical designs of Class-F PAs are further complicated by parasitic reactance of the device packages, the nonlinearities of drain current I_{ds} and nonlinearities of C_{gs} and C_{ds}. The equations in Figure 4 can serve as a good starting point for practical Class-F RF PA designs.

Class F Amplifier Design Approaches

There are several different ways of designing Class-F PAs, as summarized in Figure 5. Figure 5(a) shows the conventional approach of Class-F PA design, which uses the output harmonic tuning. The output network provides a short at even harmonics and an open at odd harmonics, while the input network provides a conjugate match at the gate input. An optimum load at the fundamental frequency is obtained at the drain output, by using the output network.

Recent years have seen some work on the impact of input driving signals or input harmonic tuning on Class-F PA performances [7], [21], [22]. RF transistors usually have a severe nonlinear variation of C_{gs} with respect to applied input voltage. This becomes the main cause of signal distortion at the gate terminal, especially when the bias is set around the pinch-off voltage and the input voltage variation is large, as in PA applications. In [21], this nonlinearity is compensated by putting an extra diode in parallel with the gate. In [7] and [22], improvements in gain and efficiency are reported by using short-circuit harmonic terminations at the input of the device, which eliminates the distortions in the input voltage and resultant output current waveform. Today, it has been widely accepted that Class-F PA designs should consider both input- and output-harmonics tuning, as shown in Figure 5(b).

Figure 5(c) shows the two-stage amplifier, which includes a driver/waveform-shaping stage and a final stage. The first stage will serve two functions: one is to provide enough power at the input of the final stage and the other is to shape the input voltage waveform for the final amplifier stage, so that the input voltage waveform is a half sinusoid at the input of the final stage. The waveform shaping could be achieved by using appropriate proportions of the fundamental component and the second harmonic, as in [23]. This is also called the harmonic-controlled amplifier [23], which has the advantages of the high gain of Class A and the high efficiency of Class F, due to the elimination of the negative V_{gs} at the input of the final stage. The problem is the complexity of its design and circuit layout, which may also introduce some losses. An alternative way of realizing the diver/waveform shaping is to use the Class-F^{-1} PA at the first stage and the Class-F PA at the final stage. The Class-F^{-1} PA produces the output voltage as a half sinusoid, which feeds directly into the input of the final stage through a capacitance as dc block.

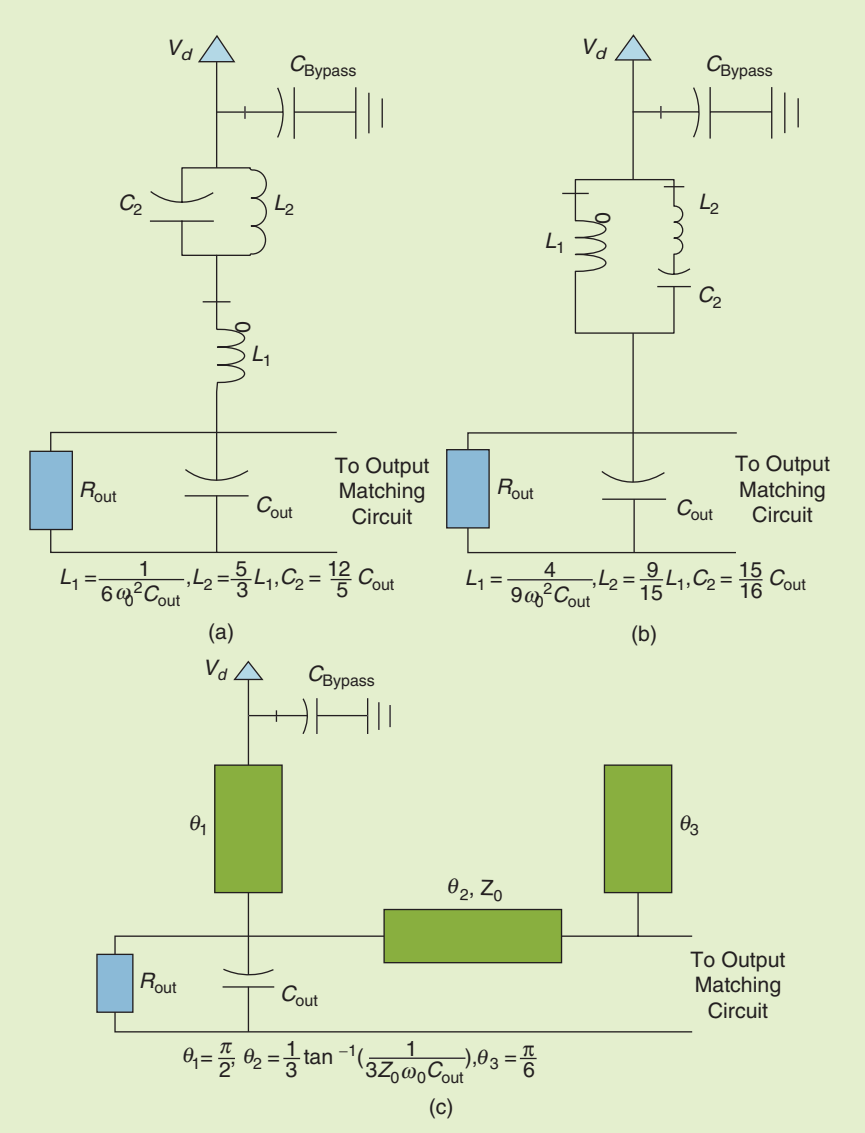

Figure 4. *Third-harmonic peaking circuit of ideal class-F PA [20].*

Figure 5(d) shows the active-antenna approach for Class-F PA designs [24]. The principle is to treat the antenna, the active device, and the input network as a single entity. In addition to its original function as a radiator, the antenna is used to achieve both the harmonics tuning and the filtering without using an additional output-matching network between the antenna and the drain output. This leads to a functional compact design, eliminating the cable and matching network loss, thus improving the overall system efficiency and output power. The active antenna approach is very promising, enabling high-efficiency, compact RF front ends.

Recent Examples of Practical Designs

During recent years, many different designs of Class-F PAs have been reported. The results are too numerous to discuss exhaustively here. The following examples have been chosen to highlight some of the many promising results in each of the key design approaches summarized in Figure 5.

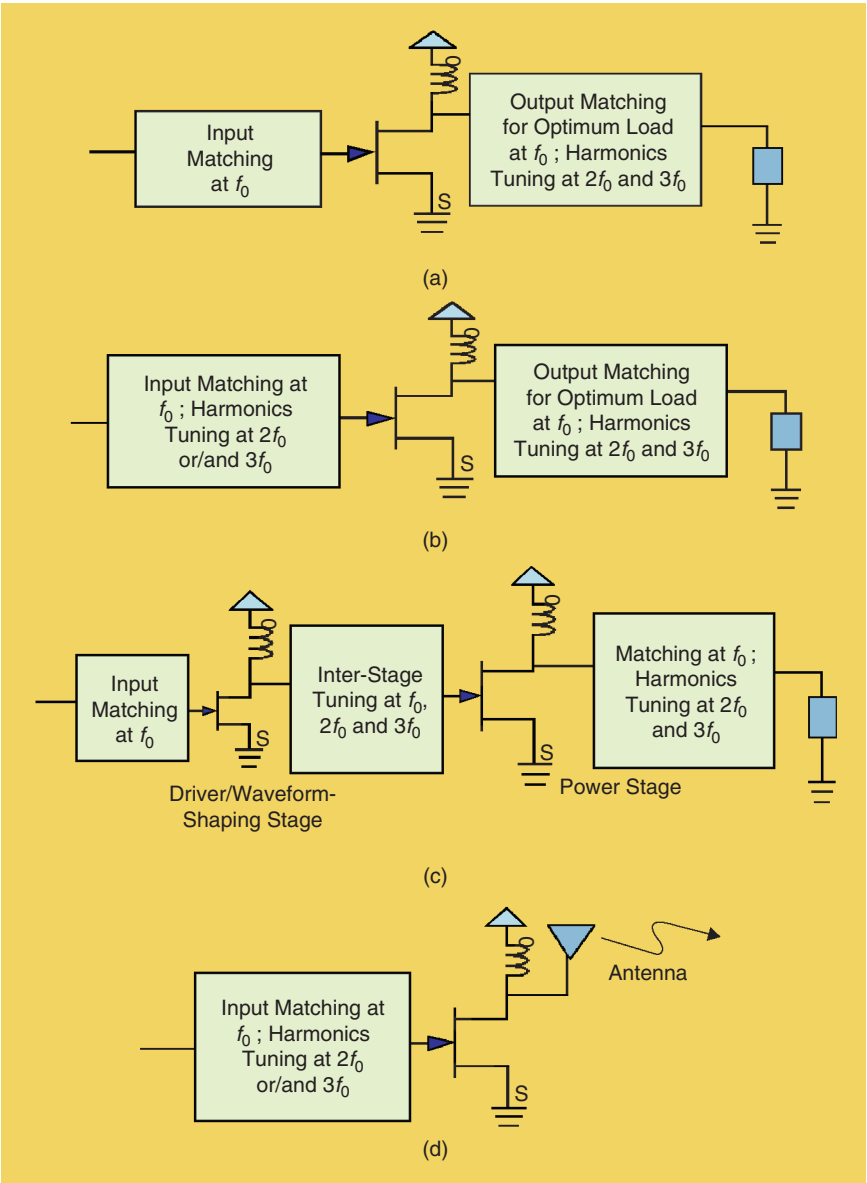

Figure 5. *(a) Output harmonics tuning strategy. (b) Both input and output harmonics tuning. (c) Multistage class-F PAs. (d) Active-antenna approach for class-F PAs.*

High-Efficiency Class F GaAs FET PA at Low Voltages for Mobile Phones at 1.75 GHz

Mobile phones must be lightweight, highly efficient, and small. The reduction in size and weight is mainly limited by the battery cells. Low bias voltage allows the use of a small-sized battery. Therefore, it is crucial to optimize the PA efficiency for low bias voltage.

In [25], Duvanaud et al. reported a high-efficiency Class-F GaAs FET amplifier operating with a very low drain bias voltage of 3 V. It requires the modification of load lines and the use of a transistor with high gate periphery. The transistor used has an optimized gate periphery of 2,000 μm and a gate length of 0.7 μm.

Figure 6 shows a photo of the Class-F amplifier optimized at 1.75 GHz. The output matching network consists of three microstrip lines. First, a short-circuited stub connected to the drain port provides a suitable second-harmonic impedance. This stub is nearly one- quarter wavelength long at the fundamental frequency. It also provides the drain bias, and its influence on the fundamental and third harmonic impedance is minimal.

Second, a quarter-wavelength open stub at third-harmonic frequency achieves a short circuit at the third-harmonic frequency at the transmission-line plane. A third microstrip line transforms this short circuit into the suitable impedance at the third-harmonic frequency at the transistor access. The optimizations of the fundamental, second, and third harmonic terminations lead to a Class-F operation.

The drain and gate voltages are set at 3 and −3 V, respectively. The power-added efficiency (PAE) of the amplifier reaches 71%. The corresponding performance is as follows: 24.5 dBm output power, 11 dB gain at 1.75 GHz, and 75% drain efficiency. In the 80 MHz bandwidth from 1.71 to 1.79 GHz, PAE is greater than 67% for an input power of 13 dBm.

Another example using GaAs pHEMT at 900 MHz is presented in [26], where a PAE of 71.7% is achieved.

Input/Output Multiharmonics Tuned Amplifier

Starting from the power-balance considerations approach, design criteria to improve the efficiency of high-efficiency PA are presented by Colantonio et al. in [27]–[29]. High-efficiency power amplifier design criteria imply a synthesis of input and output networks, with particular emphasis on their harmonic behavior, and a simplified approach to clarify the relevance of such harmonic terminations is presented. It is demonstrated that the output network needs to be designed to maximize the fundamental output power through proper harmonic-load terminations. Moreover, the relevance of input harmonic terminations for generating output harmonic components with proper phase relationships has been stressed by using closed-form expressions [27]–[29].

Figure 7 shows a photo of the input/output harmonics-tuned amplifier at 5 GHz, which is also called Class FG in [27]. The fundamental, second- and third-harmonic terminations at both the input and output network are considered. The input network is designed to satisfy the conjugate matching at fundamental frequency, while its second- and third-harmonic terminations are synthesized to generate the correct drain current harmonics, consequently allowing the harmonics-manipulation technique to be used. For the output network, its second- and third-harmonic terminations are synthesized to properly shape the drain voltage waveforms. The active device used is a $10 \times 100\,\mu m$ medium-power GaAs MESFET (0.5 μm gate length) with a Class AB bias ($I_{dd} = 80$ mA and $V_{dd} = 5$ V). A full nonlinear device model is used, accounting for the knee voltage of 1.8 V, both in the simplified analysis and nonlinear simulation. Several different amplifiers are designed at 5 GHz, and the Class-FG amplifier achieves a drain efficiency of 61.56% at 1 dB compression, and an output power of 25 dBm.

Harmonic-Control Class-F Amplifier

In most of the Class-F designs reported, the device is biased at Class B or near Class AB, and harmonics are controlled in such a way that the device output voltage becomes rectangular. These amplifiers operate at Class B near input level and use the sinusoidal input signal, where up to half of the input power is lost. This affects the gain, which is about 3–6 dB less than the corresponding Class-A gain and, therefore, the PAE is drastically decreased as compared with the high device efficiency. Furthermore, device reliability is limited due to high negative gate-to-source voltage.

Ingruber et al. proposed an amplifier that uses a half-sinusoidal input signal to operate the transistor as a switch [23]. With suitable output harmonic terminations—a short circuit at even harmonics and an open circuit at odd harmonics—the amplifier achieves the drain voltage and current waveforms as a Class-F amplifier. Ideally, an efficiency of 100% can be achieved as in Class F but with the gain of Class A. It is referred to as a harmonic-control amplifier in [23].

Figure 8 shows a photo of the two-stage PA at 1.62 GHz [23], where both the driver/waveform shaping stage and the power stage are shown. The half-sinusoidal input signal is approximately formed by using the fundamental-frequency component along with the right portion of the second harmonic. At the output of driver stage, the fundamental and second harmonic signals are separated from each other by an appropriate filtering network. The desired input signal at the second stage is generated by a pulse-shaping stage, which operates as a resistively loaded Class-B amplifier. With two continuously variable attenuators and a continuously variable phase shifter, a half-sinusoidal input signal can be synthesized at the gate of a power FET for the second stage. In the output network of the second stage, the fundamental, second and third harmonics are used to shape the drain waveforms, as required in Class F. The realized two-stage amplifier at 1.62 GHz has demonstrated 71% overall efficiency, 27.9-dBm output power, and 22.4-dB gain. Intermodulation distortion is low, even in saturation where its overall efficiency is

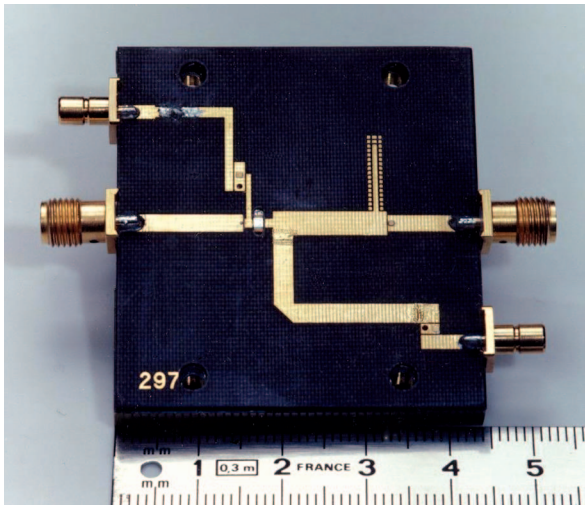

Figure 6. *Class-F GaAs FET PA for mobile phones, by Duvanaud et al. [25].*

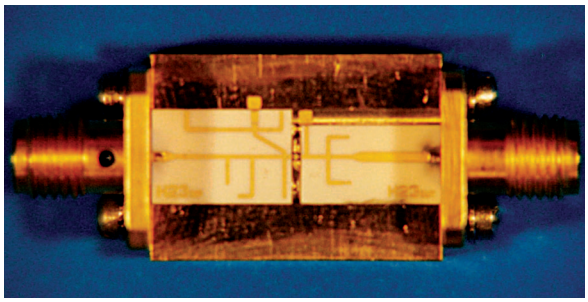

Figure 7. *Photo of the input/output harmonics-tuned amplifier, by Colantonio et al. in [27].*

high. In addition to the advantages of high efficiency, the above amplifier also has better reliability, as the gate of the device is stressed much less due to reduced input power and lower negative input voltage.

Two-Stage Class-F GaAs MMIC Amplifier at Ku-Band

High-efficiency PAs at high microwave or millimeter-wave frequencies are a key enabling technology for the realization of transmit array for high data rate airborne communications. Recently, Ozalas proposed a two-stage high-efficiency Class-F MMIC PA at Ku-Band for applications in active phased arrays [30]. A photo of such an amplifier is shown in Figure 9.

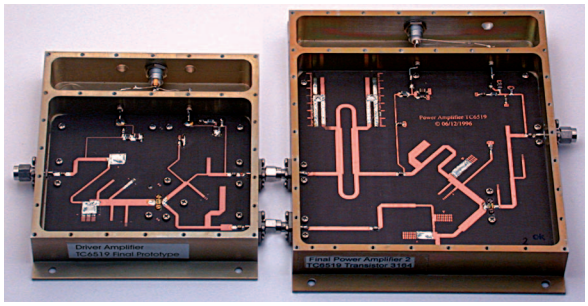

Figure 8. *Photo of the two-stage harmonic-control amplifier, by Ingruber et al. [23].*

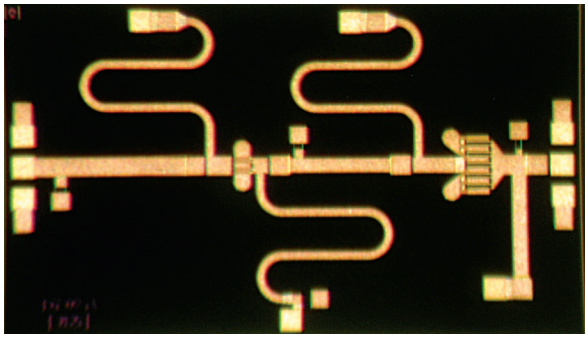

Figure 9. *Photo of two-stage class-F MMIC amplifier at Ku-Band by Ozalas [30].*

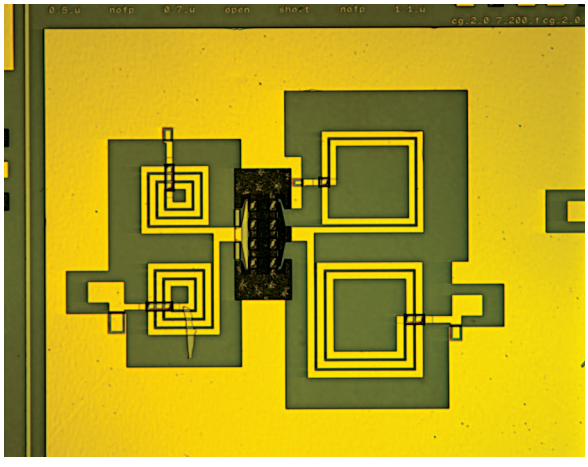

Figure 10. *Photo of the GaN class-F PA by Gao et al. [31].*

A 0.25-μm T-gate GaAs pHEMT process was used, and a 1 mm device was chosen for the design of the power stage. At the output of the power stage, an *LC* network is attached in shunt to the drain of the device to invoke a short circuit resonance at the second harmonic. Additionally, the parallel combination of the internal capacitance C_{ds} and the *LC* network presents a high impedance at the third harmonic, as required by Class-F operation. EM simulations were done to accurately characterize the matching networks.

To achieve high gain, a driver stage was added to the existing Class-F amplifier power stage. The driver was implemented using a 300-μm FET operating under suboptimal drain bias conditions to provide a minimal impact on PAE. The low-pass interstage matching network between the transistors provides a loadline power match to the output of the driver stage and a conjugate match to the input of the power stage.

A maximum efficiency of 50.4% is achieved at 14.3 GHz, with 19.7-dB associated gain and 27.5-dBm output power. The PAE is above 50% over a 300 MHz bandwidth. Such high-efficiency PAs have the potential to significantly reduce the thermal load in a phased array.

GaN HEMT MMIC Class-F Amplifier

Several Class-F MMIC PAs in GaN-HEMT technology have been designed [31]. Figure 10 shows a photo of the GaN Class-F MMIC PA at 2.0 GHz, which occupies a size of 1.9 × 1.5 mm. The circuit was fabricated on a SiC substrate using MOCVD-grown GaN. The transistor in the 2.0 GHz Class-F PA is a field-plated GaN HEMT device with a 0.7-μm gate length, 8 × 125 μm gate width, and 0.7-μm field-plate length. A harmonic trap directly at the drain output is used to tune the second harmonic, and the output network is used to terminate the third harmonic and transform the 50-Ω load to optimum impedance at the drain output, as required for Class-F operation. A harmonic trap at the gate is also employed for input harmonic tuning. As the device is potentially unstable, a stability resistance is added at the gate input. The circuit was simulated using the harmonic-balance simulator in Advanced Design System (ADS). A bias-dependent and scalable large-signal EEHEMT1 model was used for simulations.

The circuit was measured with a drain voltage of 35 V [31]. The circuit achieved a maximum power of 38 dBm, corresponding to a power density of 6.2 W/mm. The gain was about 10 dB, and a maximum PAE of 50% was achieved.

Active Antenna Integration for Class-F Amplifiers

The active antenna approach has been proposed to design the Class-F PAs [24], [32]. This is promising for compact, high-efficiency transmitter designs, where the impedance levels of the antenna are optimized for highest efficiency of the PAs, and the interconnection cables between the antenna and the amplifier are removed.

The fundamental and harmonic impedances of the antenna are optimized to yield an integrated Class-F PA. Figure 11 shows the integrated structure combining the antenna with the GaAs-based power amplifier at 2.55 GHz [24]. The microstrip circular sector antenna is used to achieve optimal fundamental and harmonic impedances for high-efficiency Class-F amplifiers. It achieves 63% PAE, and an output power of 24.4 dBm. The active-antenna approach has also been used to the integration of the microstrip antenna with the AlGaN/GaN HFET-based amplifier [32].

Future Development

In modern PAs, a high efficiency performance, coupled with the requirement for a high level of output power, gain, bandwidth, and, in particular, linearity, becomes the major challenge of the design. These problems are especially acute in base station and satellite transmitters, where multiple carriers must be amplified simultaneously, resulting in peak-to-average ratios of 10–13 dB and bandwidths of 30–100 MHz. There is still much work to be done to further improve PA performances so as to satisfy practical system requirements.

The combination of high-efficiency Class-F design technique with new device technology/new materials is promising for high-efficiency high-power PA applications. Developments of device technology (MESFET, pHEMT, HBT) and material (GaAs, InP, GaN, SiC) are ensuring major progress in power devices performance. One of the promising technologies is the wideband gap device, such as AlGaN/GaN HEMT [31], [33]. Due to its high breakdown field, high electron saturation velocity, high power density, and high operating temperature, AlGaN/GaN HEMTs offer superior RF power performances, compared to GaAs MESFET or Si transistors. For example, by field-plate optimization, AlGaN/GaN HEMTs on SiC achieved a breakdown voltage over 120 V, output power density of 32.2 W/mm at 4 GHz, and output power density of 30.6 W/mm at 8 GHz [33]. A few Class-F PAs using GaN have been given in [31]. However, the GaN devices are still immature, and further improvements in GaN devices are on the way. These improved GaN devices will lead to better performance in microwave PAs. The applications of other new materials, such as metamaterial, to Class-F PAs are also promising. A Class-F PA at 2.4 GHz using a novel harmonic tuner based on a composite right/left handed (CRLH) transmission line has been proposed in [34], which reduces the complexity of the amplifier tuner and achieves a drain efficiency of 64%.

While the theory of an ideal Class-F amplifier with finite harmonics has been developed, and the general bases of the harmonic manipulation procedure have been clarified, very few hints are provided to assist in solving the practical problems in real-world RF/microwave Class-F PA designs using the nonlinear device. For example, while using a nonlinear active device, how do you design the input network and manipulate the input harmonics so as to achieve the optimal proportions of drain-current harmonic components? How do you realize the optimal input/output harmonics-tuned network, while taking into account the nonideal effects like parasitic reactance of the device packages, the nonlinearities of drain current I_{ds}, and nonlinearities of C_{gs} and C_{ds}? What are the effects of nonlinear C_{gd} and drain-output resistance g_{ds} on the input/output harmonics tuning? Further understanding of the harmonic-generation mechanism is still needed, and the design methodologies of practical RF/microwave Class-F PAs are still under development.

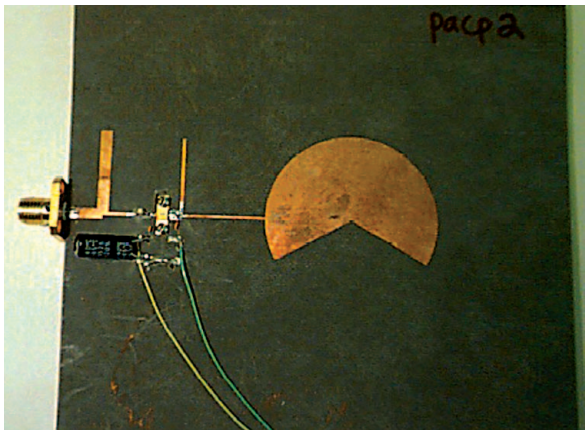

Figure 11. *The active-antenna structure combining the antenna with the GaAs power amplifier [24]. (Used with permission from IEEE.)*

To achieve both high efficiency and high linearity, several advanced architectures can be used; for example, the linear amplification using nonlinear amplification (LINC), and Kahn envelope elimination and restoration (EER) technique [2]. Recently, some progress on LINC has been made, and the implementation of Class-F amplifiers could achieve the high efficiency of practical LINC systems [35]–[37]. Doherty architecture can achieve high average power efficiency, which is also useful for multicarrier systems. In modern PAs, digital signal processing (DSP) can be used to control the drive and bias, resulting in more precise control and high linearity [38]. Various linearization techniques, such as predistortion, feedforward, and digital predistortion have been developed, and they are still developing fast to meet the further stringent system requirements.

Reconfigurable PAs are another area deserving attention [4]. Electronic tuning allows frequency agility, matching of variable loads, and amplitude modulation. Components for electronic tuning include varactors, microelectromechanical system (MEMS) switches, MEMS capacitors, PIN diodes, and ceramic capacitors (BST, BZN). Load modulation uses an electronically tuned output network to vary load impedance and thereby the instantaneous amplitude of the output signals [39]. Some reconfigurable power amplifiers have been reported. The continuous development in new

material, device technology/device modeling, design methodologies, and DSP will make the RF/microwave power amplifiers achieve more functions and better performances, thus satisfying the requirements of advanced wireless systems.

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