High-Efficiency Power Amplifiers: Turning the Pages of Forgotten History

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This article reviews the history of power amplifier techniques that use control of the fundamental and harmonic waveforms to achieve high efficiencies

The appearance of this paper was motivated by the result of an excellent opportunity granted by IEEE to look online at old journals and proceedings including the *Proceedings of IRE* in particular. From my previous experience I know that the new results very often can be the well-forgotten ones, and sometimes those who were pioneering the technical ideas are undeservedly passed over, especially if it was almost a century ago. In some cases, due to the difficulties with accessing the particular periodical publications, especially in different languages, the results are simply unknown. But it is always interesting to know how, where, and when this or that technical idea could firstly appear.

Of course, history also should be learned in order not to repeat it. For example, in view of modern requirements for cost and power saving technologies, it is very important to provide the highly efficient operation of any radio equipment. However, operational efficiency of radio transmitters was already topical at the dawn of high-power radio transmission system development. The possibility of improving efficiency of a vacuum-tube power amplifiers by proper approximation of the anode voltage and current waveforms was discussed in the early 1920s [1]. It was then concluded that, theoretically, three-electrode tubes constitute converters of direct current to alternating current having generally unforeseen efficiencies. This means that, for different waveforms, anode efficiency will be different. For example, it may change from 50% for a purely sinusoidal anode current to 100% for rectangular pulses. Under operation with $\theta = \pi/2$, where θ corresponds to a half-conduction angle in a Class B operation mode, the maximum theoretical anode efficiency achieves $\pi/4$ or 78.5%, characterized by the sinusoidal anode voltage waveform and half-sinusoidal current waveform.

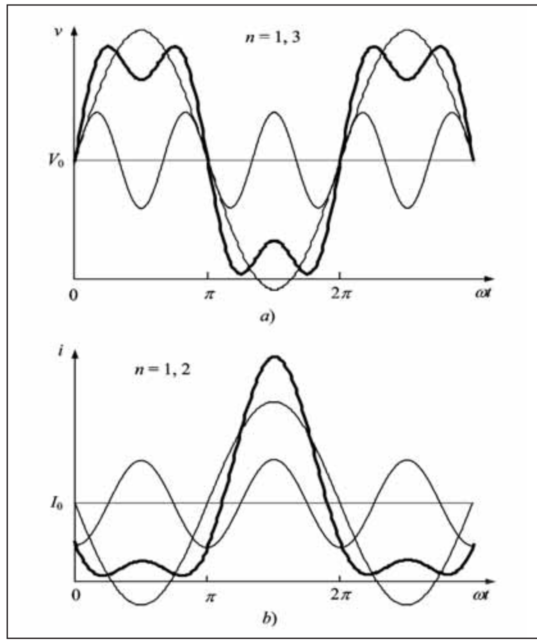

Figure 1 · Fourier voltage and current waveforms with third and second harmonics.

Indeed, in many respects it becomes clear by using a Fourier analysis of the corresponding typical current and voltage waveforms. Figure 1 shows that the shapes of the voltage and current waveforms can be significantly changed with increasing fundamental voltage amplitude by adding even one additional harmonic component with a proper phase. For

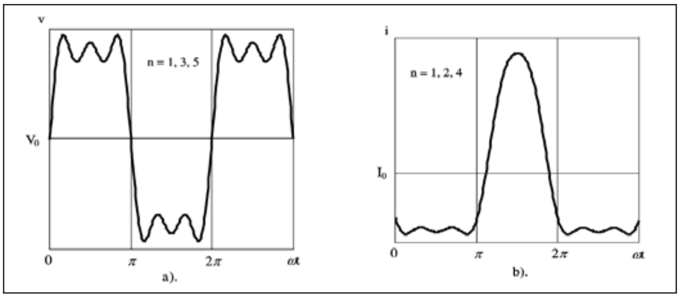

Figure 2 · Fourier voltage and current voltage waveforms with three harmonics.

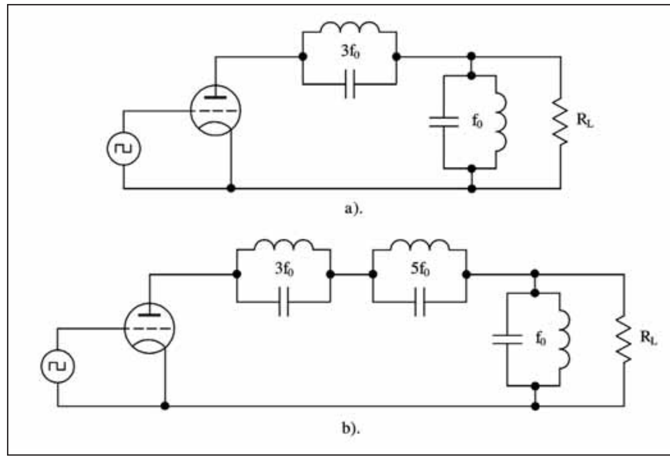

Figure 3 · Biharmonic and polyharmonic vacuum-tube power amplifiers with odd-harmonic resonant tanks.

example, from Figure 1(a) it follows that the combination of the fundamental and third harmonic components being out of phase at the center point results in a flattened voltage waveform with depression in its center. By optimizing the harmonic ratio, the flattened voltage waveform with minimum depression and maximum difference between its peak amplitude and amplitude of the fundamental harmonic can be achieved. Similarly, the combination of the fundamental and second harmonic components, being in phase at the center point, flattens the current waveform corresponding to maximum values of the voltage waveform and sharpens the current waveform corresponding to minimum values of the voltage waveform, as shown in Figure 1(b). The optimum ratio between the amplitudes of the fundamental and second current harmonic components can maximize a peak value of the current waveform, with its minimized value determined by the device saturation resistance in a practical circuit. Thus, power loss due to the active device can be minimized since the results of integration over the period when minimum voltage corresponds to maximum current will give a small value compared with the power delivered to the load. In a common case, the same result can be achieved by adding the second harmonic into the voltage waveform and the third harmonic into the current waveform, thus resulting in an inverse operation mode.

Ideally, the half-sinusoidal current waveform does not contain the third harmonic component, because its third-harmonic Fourier current coefficient is equal to zero, that is $\gamma_3(\theta) = 0$. However, a load line analysis of a Class B power amplifier with sinusoidal output voltage waveform under overdriven condition—when an active device operates in pinch-off, active, and saturation modes during one oscillation period—shows that operation in the saturation mode is characterized by a depression in the output current waveform. Therefore, when an additional resonant circuit tuned to the third harmonic is included in the anode circuit operating in a saturation mode, the voltage drop with opposite phase will appear across this resonant circuit, resulting in a similar depressed voltage waveform, shown in Figure 1(a) by the solid line. Hence, for the increased fundamental voltage amplitude, the output power and anode efficiency can be increased for the same input drive. Physically, an efficiency improvement can be explained by the fact that fundamental voltage or current has negative values during some part of the period, corresponding to the negative power as an integration of the product of instantaneous fundamental voltage and current. This means that the power loss on the active device is partly compensated by the reactive power provided by the harmonic resonator. Adding one or more higher-order harmonic components can further improve the voltage or current waveform. Figure 2(a) shows the voltage waveform with third and fifth harmonic peaking, which is close to an ideal rectangular waveform, while Figure 2(b) shows the current waveform with second and fourth harmonic peaking, which is close to an ideal half-sinusoidal waveform.

Thus, based on the results of a Fourier analysis, it was concluded at that time that efficiency and output conditions may be changed materially if the load circuit is made to be responsive to certain harmonics, so that all input on this harmonics need not be absorbed as a tube loss. Figure 3 shows the type of a load network with a third-harmonic trap which was discussed and first published in 1923 as a journal paper with regard to a vacuum-tube oscillator [2]. At the same time, it was experimentally found that applying the biharmonic driving signal containing the fundamental and second harmonic components produces signal amplification more efficiently because of the much steeper driving waveform [3]. In this case, the resultant driving waveform consists of the fundamental and second harmonic components being in phase at their maximum amplitudes, as shown in Figure 1(b), with the amplitude of the second harmonic chosen as approximately one-quarter the amplitude of the fundamental.

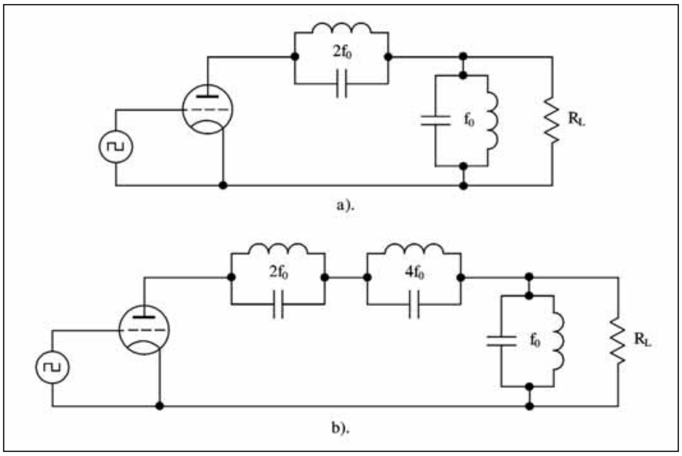

Figure 4 · Biharmonic and polyharmonic vacuum-tube power amplifiers with even-harmonic resonant tanks.

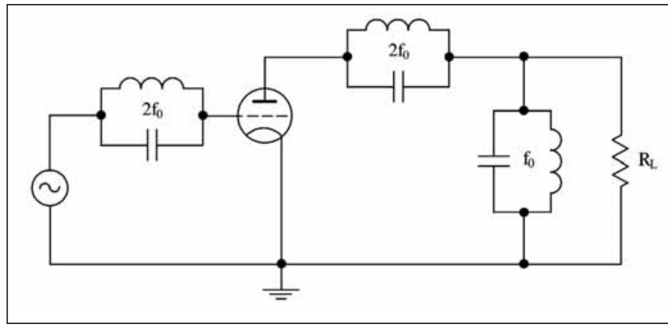

Figure 5 · Biharmonic power amplifier with input second-harmonic resonator.

To maximize efficiency of the vacuum-tube amplifier it was also suggested to use a square voltage driving waveform and an additional resonator tuned to the fifth harmonic, as shown in Figure 3(b) [4]. The effect of the inclusion of the parallel resonant circuit tuned to the third harmonic component and located in series to the anode was then described in a textbook [5]. From this work, we can see that the basic theoretical background and potential circuit solutions to increase efficiency of vacuum-tube power amplifiers and oscillators were generally understood more than eight decades ago in the 1920s!

Nevertheless, in next few decades, the basic operating mode for the vacuum tubes in power amplifiers of amplitude-modulated broadcasting radio transmitters was the Class B with a resonant tank tuned to the fundamental. In this case, in order to improve efficiency, different transmitter architectures were proposed, based on Chireix and Doherty power amplifiers. However, during 1930s, some Russian papers stating efficiency improvement of 25-30% in broadcasting radio transmitters by using a biharmonic mode for power amplifiers were published. It was shown that the symmetrical anode voltage waveform and minimum level of its depression for a biharmonic power amplifier shown in Figure 3(a) can be provided with opposite phase conditions between the fundamental and third harmonic and an optimum ratio between their voltage amplitudes. Also, it was noted that high efficiency can be achieved even when impedance of the third-harmonic resonator is equal or slightly greater than impedance of the fundamental tank circuit. In addition, such an approach can slightly improve the modulation properties of the power amplifier using either grid or anode modulation techniques because saturation for the fundamental frequency part of the flattened anode voltage waveform occurs later than the sinusoidal anode voltage [6].

As an alternative, an effect of the inclusion of the second-harmonic resonator connected in series to the anode, shown in Figure 4(a), was first described and analyzed in [7]. It was shown that the symmetrical anode current waveform and minimum level of its depression can be provided with the opposite phase conditions between the fundamental-frequency and second harmonic components ($\theta > 100°$ for anode current) and an optimum ratio of their voltage amplitudes. In this case, high operating efficiency can also be achieved when the impedance of the second-harmonic resonator is equal or slightly greater than impedance of the fundamental tank circuit. Such an approach can also improve the anode modulation properties of the power amplifier. The simple solution to realize out-of-phase conditions between the fundamental-frequency and second harmonic components at the device output is to use a second-harmonic tank connected in series with the device input, as shown in Figure 5. This makes it possible to flatten the anode current waveform in active region, avoiding the device saturation mode. Due to the diode-type input of the vacuum tube, the resultant grid current pulse will contain a strong second harmonic component resulting in a second harmonic voltage component across the input resonator. The loaded Q of the second-harmonic resonator must be high enough to neglect the voltage drop at the fundamental frequency. As a result, the second-harmonic resonator has no effect on the fundamental-frequency component, however it provides a phase shift of 180° for the second harmonic component, since increasing the voltage drop across the resonator results in decreasing of the voltage drop across the grid-cathode electrodes.

Figure 6(a) shows the combination of the fundamental-frequency component and second harmonic component shifted by 180°. In comparison with Figure 1(b) where the fundamental-frequency and second harmonic components are in phase at maximum point of the fundamental-frequency component resulting in a waveform bottom flattening, this voltage waveform at the device input is characterized by its top flattening when the second harmonic

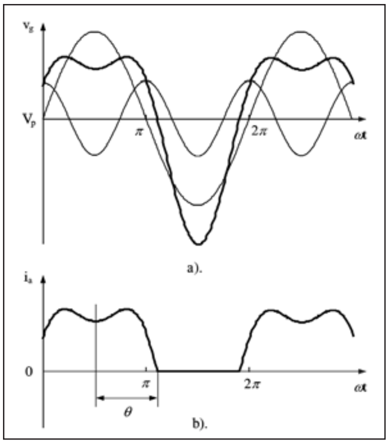

Figure 6 · Input and output voltage and current waveforms with second harmonic.

has minimum value at maximum point of the fundamental-frequency component. Then, choosing the bias point V_g equal to the device pinch-off voltage V_p that corresponds to a Class B mode with the conduction angle of 180° (θ = 90°) for monoharmonic operation, will result in the anode biharmonic current pulses with conduction angle $2\theta > 180°$, as shown in Figure 6(b). At the same time, using a second-harmonic resonator in the load network contributes to the anode voltage waveform, as shown in Figure 1(b).

In the comprehensive research given in [8] it was confirmed that the second- or third-harmonic voltages introduced into the anode or grid circuits in the proper phase improve the vacuum tube performance. The proper phasing can be done by various means including an auxiliary tube, and the power output and overall efficiency of the main tube acting as a Class C power amplifier is increased. Fourth- and higher-order harmonics were at best of a little value in improving the path of operation. Generally, however, in view of the parasitic anode-cathode capacitance comprising the interelectrode and case capacitances and series plate inductance, the entire anode circuit should be tuned to the third harmonic, not only a single resonator. For example, such an anode circuit may include a parallel third-harmonic resonator, which is slightly mistuned in this case, and an additional series *LC* circuit connected in parallel to the tube, which has a capacitive reactance at the fundamental frequency and inductive reactance at the third harmonic component tuned to the resonance with other elements in the anode circuit [9].

The load parallel resonator tuned to the third harmonic can be replaced by a low-pass filter with two series inductors and shunt capacitor, as shown in Figure 7(a) [10]. In this case, the ratio between the series inductor *L*/2 and shunt capacitor *C* can be chosen to resonate the third harmonic

$$\omega = 3\omega_0 = \sqrt{2} / \sqrt{LC} = \omega_c / \sqrt{2}$$

where

$$\omega_c = 2 / \sqrt{LC}$$

is the filter cutoff frequency, thus providing an ideally infinite impedance seen by the device anode at the third har-

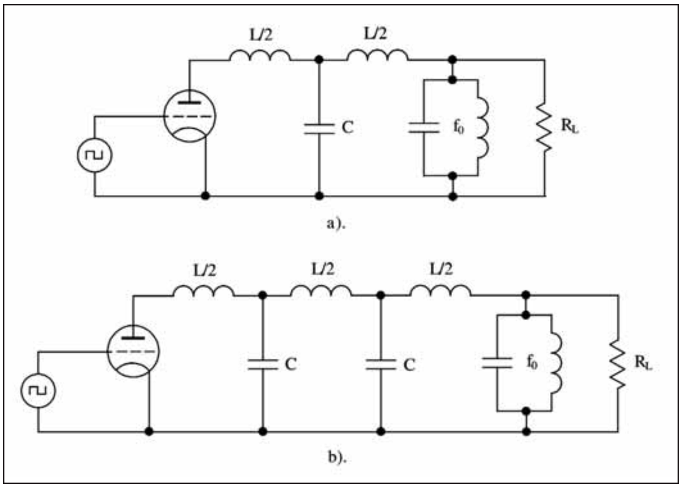

Figure 7 · Biharmonic and polyharmonic vacuum-tube power amplifiers with low-pass filters.

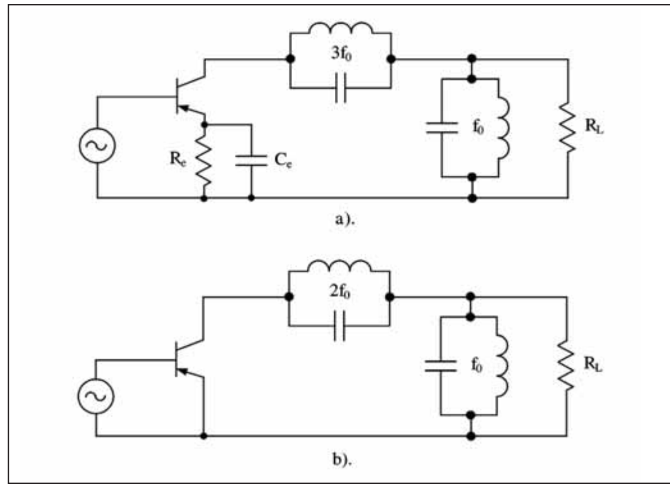

Figure 8 · Biharmonic bipolar-transistor power amplifiers.

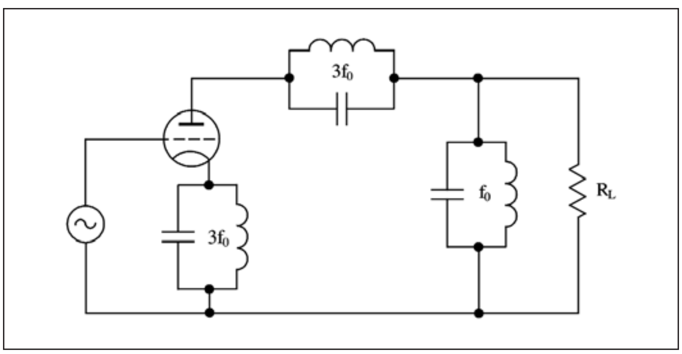

Figure 9 · Biharmonic power amplifier with cathode harmonic control.

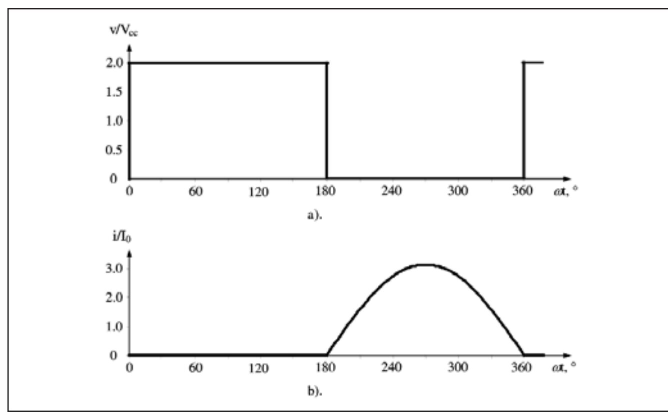

Figure 10 · Idealized voltage and current waveforms.

monic when it is assumed an infinite Q-factor for the parallel fundamentally-tuned resonant circuit. The parallel resonators tuned to the third and fifth harmonics can be replaced by a low-pass filter with the three sections, as shown in Figure 7(b), to resonate the third and fifth anode voltage harmonics. However, it is difficult to correctly specify the impedances at these harmonics seen by the anode circuit. This may result to a situation when a square-top anode voltage waveform cannot maintain its form in a circuit having inductive or capacitive reactance or both, even though, in the latter case, the reactive elements are so chosen that the circuit would be resonant for any one of the three frequencies including fundamental. The reactances cause phase shifting of the harmonic components with consequent distortion of the resultant waveform and loss of efficiency.

Figure 8(a) shows the biharmonic bipolar-transistor power amplifier with an additional resonant tank in the load network tuned to the third harmonic [11]. Since the third-harmonic current coefficient $\gamma 3(\theta)$ is positive for $\theta < 90°$, it is necessary to operate partly in a slightly saturated mode to obtain $\gamma 3(\theta) < 0$. Besides, higher efficiency can be achieved in a Class C with smaller θ that can easily be provided by the emitter *RC* circuit. As a result, the output power of about 300 mW with collector efficiency of 88% was achieved at the operating frequency of 106 kHz. It was then noted that an ideal solution requires the switched-mode amplifying circuit when the current flows through the device at minimum collector voltage (switch is ON), but the current is zero at maximum collector voltage (switch is OFF). Higher efficiency of 92% and output power of about 400 mW were achieved for the similar biharmonic bipolar-transistor power amplifier shown in Figure 8(b) where an additional resonant tank in the load network is tuned to the second harmonic [12]. The required phase shift between the fundamental and second voltage harmonics at the collector is achieved due to the device inertia provided by its input capacitance and operation in a slightly saturated mode. However, in this case, the collector voltage peak factor is higher compared to that of for a power amplifier with the third-harmonic resonator. In addition, an additional resonator tuned to the fourth harmonic can be connected in series with the second-harmonic resonator, as shown in Figure 4(b), to maximize efficiency of the vacuum-tube amplifier with a square voltage driving waveform [13].

In practice, the effective driving waveform may differ from the idealized square wave depending on what types of the harmonic resonators are used in the load network. Normally, the biharmonic driving signal for the final stage is formed in previous amplifying stages by the proper harmonic tuning. However, if the driving signal source represents a sine wave output voltage, the formation of the biharmonic driving signal can be done by the subtracting the voltage of the same harmonic component from the sinusoidal input voltage, as used in the anode circuit. Figure 9 shows the biharmonic power amplifier, in which a resonator of low reactance compared with the anode resonator, but tuned to the same third harmonic frequency component, is inserted in the cathode circuit [13]. The high degree of negative feedback developed makes it impossible for any significant third-harmonic current to develop, no matter what grid-voltage waveform is employed. In practice, with a sine wave input, correctly related in amplitude with the grid bias, the relative voltages developed between grid and cathode are self-adjusting to provide the flattened voltage waveforms.

Theoretically, an infinite number of odd-harmonic tank resonators can maintain a square voltage waveform shown in Figure 10(a), also providing a half-sinusoidal current waveform at the anode shown in Figure 10(b), where V_{cc} is the DC supply voltage and I_0 is the DC current [13]. Here, a sum of odd harmonics approximates a square voltage waveform and a sum of the fundamental and even harmonics approximates a half-sinusoidal current waveform. As a result, the shapes of the anode current and voltage waveforms provide a condition when the current and voltage do not overlap simultaneously. Such a condition, with symmetrical anode voltage and current waveforms, corresponds to an idealized operation mode with 100% anode efficiency.

It was shown by Snider that, in optimum efficiency Class B operation, the collector efficiency approaches 100% as, for a half-sinusoidal collector current, the transition time for collector voltage between the cutoff (or pinch-off) mode when ideally collector voltage is zero and the saturation mode when ideally collector voltage is equal to $2V_{cc}$ approaches zero [14]. Then, the impedance conditions seen by the device output (anode, collector, or drain) are necessarily

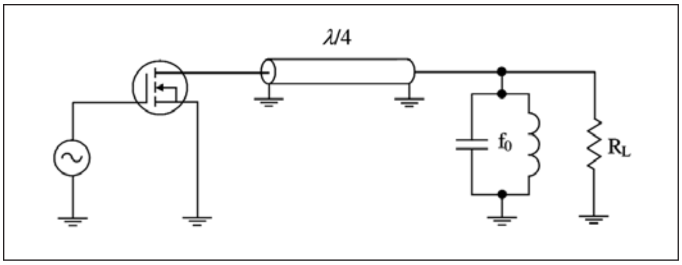

Figure 11 · Class F power amplifier with series quarter-wave transmission line.

$$Z_1 = R_1 = \frac{8}{\pi^2}\frac{V_{cc}}{I_0} \quad (1)$$

so that the fundamental load impedance Z1 is all real and

$$Z_{2n} = 0 \ \text{ for even harmonics} \quad (2)$$

$$Z_{2n+1} = \infty \ \text{ for odd harmonics} \quad (3)$$

when the load impedance must be a perfect short circuit at even harmonics and a perfect open at odd harmonics.

Ideally, a control of an infinite number of the harmonics maintaining a square voltage waveform and a half-sinusoidal current waveform at the device output can be provided by using a quarterwave transmission line. Methods for using transmission lines in conjunction with lumped-element tuned circuits first appear in the original paper by Tyler [13]. It was suggested to use either a short-circuited quarterwave line to develop high impedance at the third harmonic or an open-circuited quarterwave line to produce low impedance at every even-harmonic frequency. However, only in the mid 1970s the practical configuration with a serious quarterwave transmission line and a parallel-tuned resonant circuit at its end, as shown in Figure 11, which can provide ideally the drain efficiency of 100%, was introduced and described by Raab in detail [15]. It was called a Class F power amplifier. Since the parallel-tuned resonant circuit produces a short circuit for all harmonic frequencies, then the quarterwave transmission line converts this into short circuits at the even harmonics and open circuits at the odd harmonics at the device drain. As a result, a square voltage waveform containing the fundamental and odd harmonic components can characterize the device operating as a switch rather than a saturating current source in a biharmonic power amplifier. A half-sinusoidal current waveform contains the fundamental and odd harmonic components, and power is generated only at the fundamental frequency. This was really a breakthrough technique followed then by the significant achievements in the design and development of the high-efficiency Class F power amplifiers in different frequency ranges from RF to microwaves and later to millimeter waves. But this is what we already know very well.

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