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Idealized Operation of Third-Harmonic-Peaking Class-EF Power Amplifier with Extended Maximum Operating Frequency

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Abstract — **A new variant of Class-EF power amplifier (PA), the so-called third-harmonic-peaking Class-EF, is presented. It inherits a soft-switching operation from the Class-E PA and a low peak switch voltage from the Class-F PA. More importantly, the new topology allows operations at higher frequencies and permits deployment of large transistors which is normally prohibited since they are always accompanied with high output capacitances. Using a simple transmission-line load network, the PA is synthesized to satisfy Class-EF impedances at fundamental frequency, third harmonic, and all even harmonics as well as to simultaneously provide an impedance matching to 50-Ω load.**

Index Terms — **Class-E, Class-EF, Class-F, power amplifier, third-harmonic-peaking, transmission line.**

I. INTRODUCTION

The Class-EF PA recently introduced in [1]-[4] offers a low peak switch voltage of $2 \times V_{DC}$ as in the Class-F as well as soft-switching operation as in the Class-E, see Fig. 1. However, the total series inductance $L + L_0$ is typically of large value. This large inductance is accompanied with (i) large electrical series resistance (ESR) which leads to efficiency degradation and (ii) low self-resonance frequency which restricts high-frequency implementations. Another major challenge in the Class-EF PA design is that for a given output power and DC supply voltage, the maximum operating frequency (f_{MAX}) is constrained by C_{OUT}, i.e., at high frequencies the value of C_{OUT} is typically larger than the required C value resulted from the Class-EF synthesis. The fact that large devices with high-power-handling capability are always accompanied with high C_{OUT} would render the Class-EF PA topology unsuitable for high power applications.

In order to address the aforementioned issues, we introduce a new variant of Class-EF PA, namely third-harmonic-peaking Class-EF PA, Fig. 2. Synthesized in the frequency domain, this PA employs a simple transmission-line load network and most importantly it allows operation at higher f_{MAX}. The PA is designed to satisfy the Class EF impedances at fundamental frequency, third harmonic, and all even harmonics as well as to simultaneously provide an impedance matching to 50Ω load thus dispensing the need for an additional output matching circuit (i.e. unlike the PA in Fig. 1). In addition, the new PA employs novel λ/8 open and shorted stubs which replace the traditional λ/4 transmission line (TL). These combined two stubs offer a number of practical advantages due to their unique ability to independently control open and short circuit terminations at the collector of the transistor which would in turn improve the PA's efficiency.
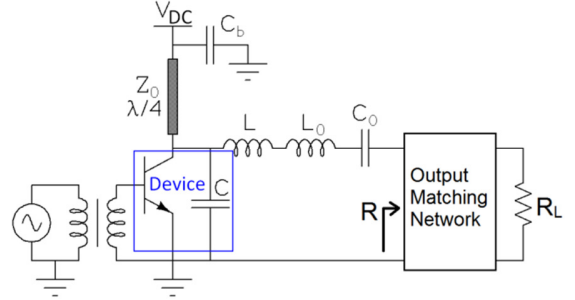

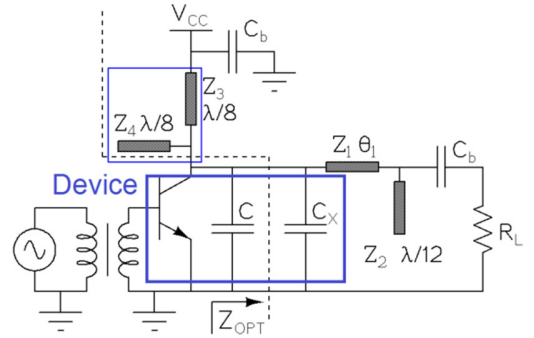Fig. 1. Class-EF PA with lumped-element load network.

Fig. 2. Proposed third-harmonic-peaking Class-EF PA with extended maximum operating frequency.

II. OPTIMUM IMPEDANCES OF CLASS-EF PA

The circuit schematic of the Class-EF PA with lumped-element load network is illustrated in Fig. 1. The shunt capacitance C may entirely or partially furnish the transistor output capacitance C_{OUT} and its value can be determined using (1). By substituting $C = C_{OUT}$ into (1), the expression for f_{MAX}, (2), can be obtained. The optimum load impedances, Z_{OPT}, seen by the device at fundamental frequency and higher harmonics are given in (3). The load network will present R in series with L at f_0, a short circuit at all even harmonics, and an open circuit at all odd harmonics. For prescribed output power (P_O), DC supply voltage (V_{DC}), and operating frequency (f_0), the optimum load resistance R and series inductance L can be calculated using (4) and (5).

The short-circuit requirement at even harmonics will be enforced by a λ/4 transmission line that is connected at the collector of the transistor. The relationship between the parameter τ_D in (1)-(5) and duty ratio D is given by $D = 0.5 - \tau_D/(2\pi)$. For example, $\tau_D = \pi/2$ rad or 90° corresponds to $D = 0.25$ meaning that the transistor will be switched ON only for a 25% period of the full cycle.

$$C = \frac{\pi}{2} \left(\frac{\sin \tau_D}{1 + \cos \tau_D} \right)^2 \frac{P_o}{\omega_0 V_{DC}^2} \qquad (1)$$

$$f_{MAX} = \frac{1}{4} \left(\frac{\sin \tau_D}{1 + \cos \tau_D} \right)^2 \frac{P_o}{C_{OUT} V_{DC}^2} \qquad (2)$$

$$Z_{OPT} = \begin{cases} R + j\omega_0 L & \text{at } f_0 \\ 0 & \text{at } 2nf_0, n = 1,2,3,\dots \\ \infty & \text{at } (2n+1)f_0, n = 1,2,3,\dots \end{cases} \qquad (3)$$

$$R = \frac{2(1 + \cos \tau_D)^2}{\pi^2} \frac{V_{DC}^2}{P_o} \qquad (4)$$

$$L = \frac{\tau_D - 0.5\sin(2\tau_D)}{\sin^2 \tau_D} \frac{R}{\omega_0} \qquad (5)$$

III. ANALYSIS OF THIRD-HARMONIC-PEAKING CLASS-EF PA

A new Class-EF PA circuit topology with transmission-line load network is depicted in Fig. 2. In practice, it is impossible to realize a transmission-line load network that would satisfy Class-EF impedance requirements at fundamental frequency as well as all even and odd harmonics, (3), since that would require an infinite number of transmission lines. However, as will be shown shortly, a good approximation to the idealized Class-EF operation can be achieved by satisfying the required impedances at f_0, all even harmonics, and only the first few odd harmonics. Here, a third-harmonic-peaking Class-EF PA is proposed with the open-circuit requirement satisfied at $3f_0$ alone. The circuit is also analyzed to simultaneously provide an impedance matching to 50-Ω load.

An extra capacitance C_X is added to the circuit and, as a result, the device output capacitance C_{OUT} now increases to $C + C_X$. This translates into higher f_{MAX} expressed in (6) where C_X is defined as kC ($k > 0$).

$$f_{MAX} = \frac{1}{4} \left(\frac{\sin \tau_D}{1 + \cos \tau_D} \right)^2 (1 + k) \frac{P_o}{C_{OUT} V_{DC}^2} \qquad (6)$$

The electrical length of the open-circuit stub TL_2 in Fig. 2 is 90° at $3f_0$ (i.e. 30° at f_0) and therefore it provides a short-circuit termination to the series line TL_1. This shorted series line behaves like an inductance (L_1). This inductance must be resonated with C_X in order to provide the required Class-EF open circuit at $3f_0$, from which we can derive (7).

$$3\omega_0 C_X \tan(3\theta_1) = Y_1 \qquad (7)$$

At fundamental frequency, the 50 Ω load resistance (R_L) is transformed by TL_1 and TL_2 to an admittance of $1/Z_{OPT}$ - $j\omega_0 C_X$ where Z_{OPT} is given in (3). This results in:

$$G_{OPT} = \frac{G_L Y_1^2 \sec^2 \theta_1}{(Y_1 - B_L \tan \theta_1)^2 + G_L^2 \tan^2 \theta_1} \qquad (8)$$

$$\frac{B_{OPT} - \omega_0 C_X}{Y_1} = \frac{(Y_1 \tan \theta_1 + B_L)(Y_1 - B_L \tan \theta_1) - G_L^2 \tan \theta_1}{(Y_1 - B_L \tan \theta_1)^2 + G_L^2 \tan^2 \theta_1} \qquad (9)$$

$$G_{OPT} = \frac{R}{R^2 + (\omega_0 L)^2} \qquad (10)$$

$$B_{OPT} = \frac{-\omega_0 L}{R^2 + (\omega_0 L)^2} \qquad (11)$$
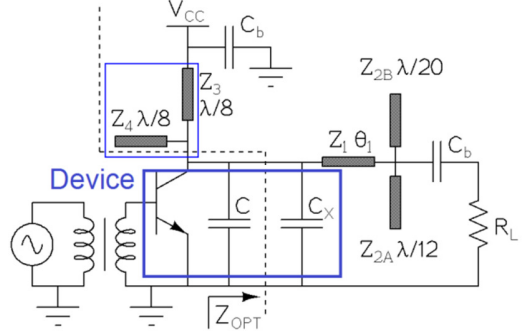

Fig. 3. Modified third-harmonic-peaking Class-EF PA.

$$G_L = 1/R_L = 1/50 \qquad (12)$$

$$B_L = Y_2 \tan 30^\circ = Y_2/\sqrt{3} \qquad (13)$$

By solving (7)-(9) simultaneously, the values of Z_1 (= $1/Y_1$), θ_1, and Z_2 (= $1/Y_2$) can be obtained. Further, to facilitate for fifth-harmonic suppression, the open-circuit stub (Z_2, 30°) in Fig. 2 is modified into two open-circuit stubs with electrical lengths of 30° and 18°, Fig. 3. The new characteristic admittances Y_{2A} and Y_{2B} can be calculated as follows

$$Y_{2A} = Y_{2B} = \frac{Y_2 \tan 30^\circ}{\tan 30^\circ + \tan 18^\circ} \approx 0.64 Y_2 \qquad (14)$$

where $Y_{2A} = 1/Z_{2A}$ and $Y_{2B} = 1/Z_{2B}$.

IV. ANALYSIS OF λ/8 OPEN AND SHORTED STUBS

Novel λ/8 open and shorted stubs depicted in Figs. 2-3 are proposed to replace the traditional λ/4 line, Fig. 1. The λ/8 open stub will short circuit the collector of the transistor at $(4m-2)^{th}$ harmonics whereas the λ/8 shorted stub will short circuit the collector of the transistor at $4m^{th}$ harmonics where $m = 1, 2, 3,$ etc. Together they will facilitate a short-circuit termination at all even harmonics. At fundamental frequency, the λ/8 shorted stub behaves like an inductance (15) while the λ/8 open stub behaves like a capacitance (16). This parallel $L_3 - C_4$ circuit should resonate at f_0 (17).

$$j\omega_0 L_3 = jZ_3 \tan 45^\circ = jZ_3 \qquad (15)$$

$$j\omega_0 C_4 = jY_4 \tan 45^\circ = jY_4 \qquad (16)$$

$$\omega_0^2 L_3 C_4 = 1 \qquad (17)$$

Substitutions of (15) and (16) into (17) would result in $Z_3 = Z_4$. By setting Z_3 equal to Z_4, it can be proven that this stub arrangement will provide an open circuit not only at f_0 but also at all odd harmonics. The characteristics of the λ/8 open and shorted stubs at f_0, even and odd harmonics are compared with the λ/4 line in Fig. 4. It can be observed that the former offers wider rejection band but narrower pass band than the latter.

The bypass capacitor C_b in Fig. 1 should in theory provide a short circuit at the fundamental frequency as well as at all even and odd harmonics. However, in practice, one capacitor can only be used to provide low impedance (~1 Ω) at a single frequency. For example, in order to provide a short circuit at f_0, $2f_0$,…, $6f_0$, six capacitors of different values connected in parallel are needed. In contrast, the PAs in Figs. 2-3 only need 4 capacitors since the short-circuit terminations at the collector at $2f_0$ and $6f_0$ are enforced by the λ/8 open stub and therefore
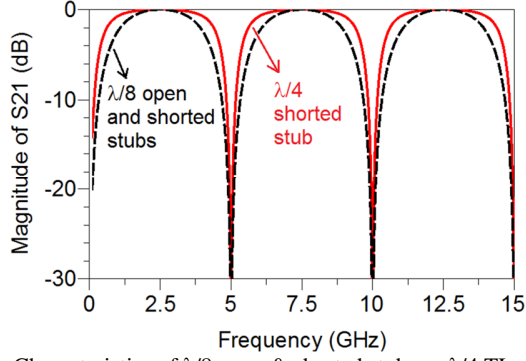
Fig. 4. Characteristics of λ/8 open & shorted stubs vs λ/4 TL.

no capacitors are required. Another practical advantage is that the λ/8 open stub will present lower impedance (close to 0 Ω) at the collector resulting in better 2nd and 6th harmonics suppressions than the case when a λ/4 TL and C_b are used, i.e., due to the ESR of C_b.

V. DESIGN PROCEDURES AND SIMULATION RESULTS

To validate the theoretical synthesis treated in Sections III-IV, a design example of the third-harmonic-peaking Class-EF PAs with extended f_{MAX} (Figs. 2-3) is given here. The design specifications are $f_0 = 2.5$GHz, $V_{DC} = 5$V, $P_O = 0.5$W. $\tau_D = 48.5°$ is chosen so as the P_{MAX} is 35% higher than the Class-E's [3].

Step 1: Calculate the values of C, R and L using (1), (4) and (5) respectively.

Step 2: Calculate $C_X = C_{OUT} - C$. C_{OUT} can be obtained from the device manufacturer catalogues, device model simulations, or from device sample measurements.

Step 3: Calculate the transmission-line parameter values Z_1, θ_1, and Z_2 using (7)-(13).

Step 4: Calculate the characteristic impedances Z_{2A} and Z_{2B} using (14).

Step 5: Following the derivation and discussion in Section IV, Z_3 and Z_4 should be set equal and their values should be selected as high as the practical implementation would allow.

The optimal circuit component values for the case when f_{MAX} is increased by 25% ($k = 0.25$) are given in Table I. The steady-state waveforms and the output power spectra obtained using the harmonic balance simulations in Agilent Advanced Design Systems (ADS) are illustrated in Figs. 5-6. Aligned with the theory, the peak switch voltage is $2×V_{DC} = 10$ V and clean output power spectra is achieved up to as high as sixth harmonic, i.e., 2nd and 6th harmonics are suppressed by the λ/8 open stub, 4th harmonic is suppressed by the λ/8 shorted stub, 3rd and 5th harmonics are suppressed by TL$_{2A}$ and TL$_{2B}$. As a result, an undistorted sine wave was obtained at the output.

VI. CONCLUSIONS

The analysis and design of the third-harmonic-peaking Class-EF PA including the method to increase the PA's maximum operating frequency have been presented. The validity of the analytical derivation has been confirmed through harmonic-balance simulations.

TABLE I
OPTIMAL CIRCUIT COMPONENT VALUES

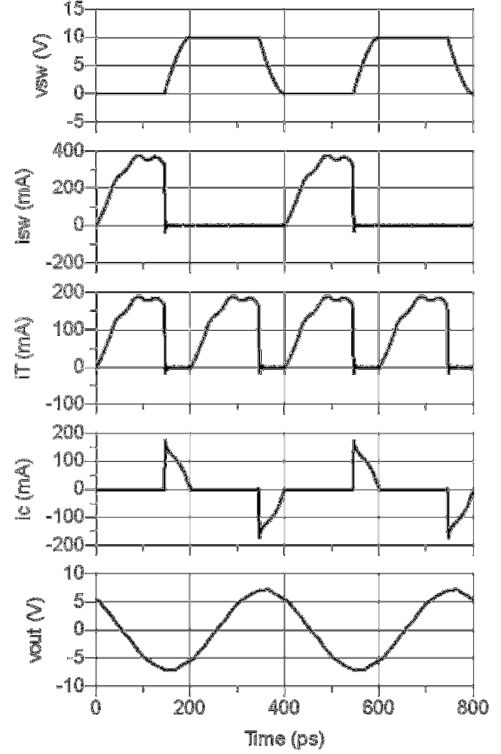| k	0.25	$Z_3 = Z_4$	80 Ω
C	0.4 pF	θ_1	19.2°
Z_1	132.4 Ω	$\theta_2 = \theta_{2A}$	30°
Z_2	31.2 Ω	θ_{2B}	18°
$Z_{2A} = Z_{2B}$	48.8 Ω	$\theta_3 = \theta_4$	45°

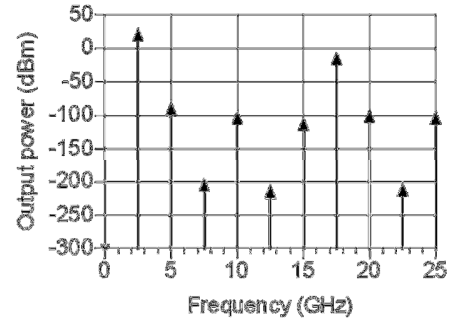Fig. 5. Idealized steady-state voltage and current waveforms.

Fig. 6. Output power spectra up to $10 f_0$.

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