Integrated Filtering Class-F Power Amplifier Based on Microstrip Multimode Resonator

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Abstract—Filtering power amplifiers (PAs) combine two functions into one circuit and 2-order cascaded structure with two transmission poles (TPs) is the most common form. Multiple TPs can extend bandwidth and minimize in-band ripple. However, more resonators are required for traditional topologies, resulting in large size with high loss. A microstrip filtering Class-F is proposed based on the couple-line multimode impedance transformer (IT) in this paper. Four TPs are created by using only a single resonator. Lengths of the drain bias stub and coupled feed line are carefully chosen to meet the requirement for Class-F operation. The fabricated multimode filtering Class-F PAs is measured at 3.6 GHz for 5G applications. Maximum gain at saturation is 12 dB with output power $P_{out}$>35 dBm. Maximum power added efficiency (PAE) is 63%, while the effective bandwidth is 400 MHz under the condition of PAEs > 50%.

Keywords—bandwidth, Class-F power amplifier, impedance transformer, multimode.

I. INTRODUCTION

Bandpass filters (BPFs) and PAs are indispensable passive and active building blocks found in transmitters. However, they follow their own design philosophy and performance degrades when combined together due to interconnection mismatch. A variety of bandpass structures have been integrated into input/output matching networks (I/OMNs) in order to realize filtering PAs. In [1], a quasi-bandpass quadrature coupler acts as the IMN of the Doherty PA. The patch coupler not only assigns 90º phase shift to the carrier and peaking paths, but also rejects spurious over a broad frequency range. In [2], a microstrip filtering PA shows wideband small-signal gains, but large-signal measurement was only carried out at the center frequency. Advantages of high quality factor (Q) resonators in terms of low loss and steep roll-off, have been used to construct high-efficiency PAs [3]-[5]. However, these designs are only suited to narrow-band applications spanning the center frequency. Advantages of high Q resonators inherently have a large number of high-order spurious due to their 3-D structures.

Reported filtering PAs are normally based on traditional cascaded 2-order topologies. One resonator corresponds to a TP, with wider passband requiring more resonators. This results in large size, high loss and low efficiency. In [6], a wideband 2-order filtering PA is presented, but an obvious dip appears in the large-signal measurements due to insufficient TPs, resulting in a discontinuous bandwidth.

Recently, much effort has been paid to multimode BPFs because they can produce multiple TPs by using only one resonator [7]. Multiple TPs entail minimum ripple in the passband. It is also beneficial to PA designs because a slight deterioration in insertion losses will degrade efficiency dramatically, which is especially serious at high frequencies.

In this paper, the proposed couple-line IT based on the multimode resonator acts as an OMN and is developed to construct a novel multimode filtering PA. The drain bias stub and coupled feed line are tuned to satisfy Class-F operation for high efficiency. The circuit is designed and fabricated on the substrate Rogers RO403C. Measurements for small- and large-signal are done using the Agilent network analyzer E5071C, signal generator E4433B and R&S FSV signal analyzer.

II. COUPLE-LINE BASED ON MULTIMODE RESONATOR

Fig 1 shows the propose couple-line IT, where upper two lines connect to transforming impedances $Z_{in}$ and $Z_{out}$ respectively. Analysis starts with a simple 2-stage cascaded structure shown in Fig 1 (a). The lower blue line can be replaced by the resonator shown in Fig 1 (b) to construct the couple-line multimode IT, which not only convert $Z_{in}$ to $Z_{out}$, but also provide a wideband filtering characteristic.

A. 2-Stage Couple-Line IT

In order to simplify the analysis, assume that the 2-stage IT has identical electrical length ($\theta$) and transforming ratio, i.e. $Z_{in} Z_{out} = Z$. Line width ($w, w_1, w_2$) and coupling gap ($g_1, g_2$) determine the odd-/even-mode impedance $Z_{11} Z_{12}$ and $Z_{21} Z_{22}$. The impedance parameters of a coupled line with four-port open boundary condition can be given as

\[
\begin{pmatrix}
Z_{11}^{(II)} & Z_{12}^{(II)} \\
Z_{21}^{(II)} & Z_{22}^{(II)}
\end{pmatrix} = \begin{pmatrix}
Z_{11} + Z_{22} & \cot \theta & Z_{11} - Z_{22} \\
2 & -\csc \theta & 2
\end{pmatrix}
\]

(1)

For reciprocity, $Z_{12}^{(II)} = Z_{21}^{(II)}$, $Z_{11}^{(II)} = Z_{22}^{(II)}$. The first-stage couple-line IT is terminated with $Z_{in}$ and $Z_{s}$ while the current-basis S-parameters are introduced to analyze this structure [8].

\[
S_{11}^{1} = \left[\frac{Z_{11} - Z_{in} (Z_{22} + Z_{s}) - Z_{12} Z_{21}}{\Delta}\right]
\]

(2a)

\[
S_{12}^{1} = \left[\frac{Z_{11} + Z_{in} (Z_{22} - Z_{s}) - Z_{12} Z_{21}}{\Delta}\right]
\]

(2b)

\[
S_{12}^{2} = Z_{11} Z_{22} Z_{12}/\Delta
\]

(2c)

\[
S_{12}^{2} = Z_{11} (Z_{in} + Z_{s})/\Delta, \Delta = (Z_{11} + Z_{in}) (Z_{22} + Z_{s}) - Z_{12} Z_{21}
\]

(2d)
Finally, the reflection and transmission characteristics of the couple-line IT can be expressed as

\[
\begin{bmatrix}
A' & B' \\
C'T & D'T
\end{bmatrix} = \begin{bmatrix}
A' & B' \\
C' & D'
\end{bmatrix} \begin{bmatrix}
A'' & B'' \\
C'' & D''
\end{bmatrix} = \begin{bmatrix}
A'A'' + B'C'' & A'B'' + B'D'' \\
C'A'' + D'C'' & C'B'' + D'D''
\end{bmatrix}
\] (5)

Finally, the reflection and transmission characteristics of the couple-line IT can be found as

\[
\begin{bmatrix}
S_{11}' & S_{12}' \\
S_{21}' & S_{22}'
\end{bmatrix} = \begin{bmatrix}
A' & B' \\
C' & D'
\end{bmatrix} \begin{bmatrix}
A'' & B'' \\
C'' & D''
\end{bmatrix} = \begin{bmatrix}
A'A'' + B'C'' & A'B'' + B'D'' \\
C'A'' + D'C'' & C'B'' + D'D''
\end{bmatrix}
\] (6)

B. Resonator Analysis

The bisection of the multimode resonator is shown in Fig. 2. The resonator without shaded stubs can be divided into two \(\lambda/4\) resonators with physical lengths \((l_1+2l_2)\) and \((l_1+l_2)\), respectively. On the contrary, the resonator with loaded shaded stubs can be bisected twice and the odd-/even-mode equivalent subcircuits are shown in Fig. 2 (c)-(f), resulting in multiple TPs without increasing circuit size. Fig. 3 shows the \(S\)-parameters of the multimode resonator. The two low resonant frequencies in Fig. 2 (f) and (e) can be expressed as

\[
f_1 = \frac{c}{4(l_1 + 2l_2)\sqrt{\varepsilon_{ef}}}, \quad f_2 = \frac{c}{4(l_1 + l_2)\sqrt{\varepsilon_{ef}}},
\]

respectively, where \(c\) is the speed of light in free space, and \(\varepsilon_{ef}\) denotes the effective dielectric constant of the substrate. It is obvious that \(f_1\) is controlled by \(l_1\) and \(l_2\), while only \(f_1\) is related to \(l_3\) by comparison between the blue dashed and black solid lines. The two subcircuits in Fig. 2 (c) and (d) have identical dimension, resulting in only one resonant frequency \(f_3 = c/(4l_3\sqrt{\varepsilon_{ef}})\). Nevertheless, \(l_3\) is very small in this design, and mutual coupling occurs between the two shaded stubs. It can be seen that \(f_3\) is split into \(f_{31}\) and \(f_{32}\), as shown in Fig. 3, and exhibits four resonant frequencies. Furthermore, a small \(l_2\) leads to a strong coupling, thus \(f_{31}\) and \(f_{32}\) deviate away from each other, as shown in the blue and black solid lines.
III. MULTIMODE FILTERING CLASS-F PA

Fig. 4 shows the schematic of the proposed multimode filtering Class-F PA, where stepped-impedance lines are used as the IMN. A 100-pF capacitor is inserted into the IMN to block the DC supply at gate $V_{gs}$. A 10-pF capacitor is in parallel with a $5\,\Omega$ resistor for stabilization to prevent oscillation. The couple-line multimode IT is used for the OMN. Bias stubs with DC supply at drain $V_{ds}$ is connected to the OMN directly to minimize loss in efficiency. A section of tuning line is used to compensate for the parasitic effects of lumped components. Another benefit of the couple-line structure is that the DC-block capacitor can be omitted at the output port.

The transistor CGH40006P is selected which has a flat small-signal gain at high frequency. A copper flange is welded to the bottom of the transistor to ensure a good grounding. Source- and load-pull simulations are carried out using Keysight ADS. The impedances at 3.6 GHz are selected as 20-16j and 20+10j, respectively, for a compromise between maximum efficiency and output power. The proposed multimode filtering PA occupies a size of $46.6\times32.7\,\text{mm}^2$ ($0.87\lambda_g \times 0.61\lambda_g$).

Harmonic-impedance control can increase PA’s efficiency and theoretical efficiency can be up to 90.7% if impedances at $2\nu_0$ and $3\nu_0$ are presented with short and open circuits, respectively [9]. In this design, point ‘B’ is an RF ground, while point ‘C’ is an open circuit, as shown in Fig. 4. These two special points can be used to achieve a Class-F operation. It is a $\lambda/4$ transformer if the length ‘AB’ is an odd multiple of $\lambda/4$ at $3\nu_0$. The drain impedance at point ‘A’ presents a corresponding open-circuit condition. Similarly, a section $3\lambda/4$ microstrip line (‘AC’) at $2\nu_0$ can contribute a short-circuit condition. It is noteworthy that there exist multiple choices for lengths ‘AB’ and ‘AC’. The selection of lengths follows several principles: 1) maximizing PA efficiency and output power; 2) providing proper coupling strength; 3) miniaturization.

IV. SIMULATED AND MEASURED RESULTS

In order to verify Class-F operation, drain impedances at intrinsic plane are simulated, and are marked on the Smith chart, shown in Fig. 5 (a). The second- and third-harmonic impedances approach the short- and open-circuit areas, respectively, complying with the Class-F condition. Fig. 5 (b) shows simulated voltage and current waveforms at the drain. The voltage presents a quasi-square wave, while current is an approximate half-sinusoidal shape.

Fig. 6 (a) shows a photo of the proposed multimode filtering circuit. They agree well and a slight deviation appears at high frequency due to parasitic effects of the lumped components and fabrication tolerance. A wideband filtering characteristic with minimum ripple can be observed and two measured transmission zeros are realized at both sides of the band edges to improve selectivity. The maximum meas-
ured small-signal gain is 16.8 dB from 3.45–3.85 GHz with $S_{11}$<-8 dB.

Fig. 7 (a) shows the PA performance versus continuous wave input power at the central frequency, including output power, gain, drain efficiency (DE) and PAE. Large-signal gain is about 11 dB at $P_{\text{out}}$ of 39.5 dBm. Measured maximum DE and PAE are 70.9% and 62.8%, respectively. Effective bandwidth with PAE>50% occurs from 3.45 to 3.85 GHz, that is a bandwidth of 400 MHz, as shown in Fig. 7 (b), which is larger than most other filtering PAs [1]-[5]. This would make it suitable for 5G applications.

A single carrier WCDMA 3GPP test signal with PAPR of 6.5 dB at 0.1% probability of complementary cumulative distribution function is generated. Adjacent channel power ratio (ACPR) is measured with a 3.84 MHz channel bandwidth at a 5-MHz offset to verify the linearity of the proposed filtering PAs. The measured results are plotted in Fig. 8 where only the lower-band ACPR performance is shown. The upper-band one is similar and omitted for clarity. The measured ACPRs are greater than -20 dBc at saturation over the whole frequency range.

Using traditional cascaded topologies for wider bandwidth that relies on more resonators, inevitably results in larger size, higher loss and lower efficiency. The proposed multimode structure has similar performance without increasing circuit size, but with an effective bandwidth that is significantly extended.

V. CONCLUSION

This paper has presented a novel filtering Class-F PA by using a couple-line multimode IT, which combines two functions into one circuit. Measured results agree well with simulation, which verifies that the proposed circuit can simultaneously realize high efficiency, compact size, sharp frequency selectivity and wide effective bandwidth. This work is attractive for 5G wireless communication applications.

REFERENCES