Optimization design of fragment-type filtering matching network for continuous inverse class-F power amplifier

Jing Xia¹,², Chengxi Bian¹, Wa Kong¹, Yongpeng Zhu¹, Wence Zhang¹, Ruijia Liu², Ziming Zhao², Xiaowei Zhu²

Abstract This paper proposes a filtering matching network optimization design method using the fragment-type structure for continuous inverse class-F (CCF⁻¹) power amplifier (PA). Different from the conventional microstrip matching structure, the fragment-type structure is used to increase the flexibility of optimization for a sharp roll-off at the second harmonic band. By using a multi-objective evolutionary algorithm, a filtering output matching network (OMN) with the fast transition between the passband and stopband is designed and optimized. For verification, a 1.5-3 GHz broadband CCF⁻¹ PA is designed, simulated and measured. Simulated results show that, compared with conventional Chebyshev filtering OMN design, the operational bandwidth of the proposed design can be expanded by about 15%. Experimental results show that measured efficiency of 65%-77% with a corresponding output power of 40.2-42.2 dBm over a fractional bandwidth of 66.7% can be achieved.

key words: Continuous class-F⁻¹, Fragment-type, Broadband, Filtering matching network, Power amplifier

Classification: Microwave and millimeter-wave devices, circuits, and systems

1. Introduction

As wireless spectrum resources grow increasingly constrained, the continuous operational bandwidth in future mobile communication systems is often limited. As a result, the carrier aggregation technology is employed to aggregate discontinuous frequency bands over a broadband spectrum for high-speed data transmission, which requires the power amplifiers (PAs) [1, 2, 3, 4] to be able to operate efficiently over a wider frequency range [5, 6, 7, 8, 9, 10].

In order to meet the expanded bandwidth requirements, several broadband PAs, such as Class J [11, 12, 13], continuous class-F (CCF) [14, 15, 16] and continuous inverse class-F (CCF⁻¹) [17, 18, 19, 20] broadband PAs with improved harmonic control have been proposed. In [14], the theory of the CCF PA was studied with the model of the gate bias voltage, which provided greater impedance matching space for high-efficiency broadband PA design. To achieve the CCF-1 mode over an octave, a resistance-reactive harmonic impedance matching method was proposed [17]. For a swift impedance transition from the higher end of the fundamental frequency band to the lower end of the second harmonic band, a modified filtering matching network was proposed using conventional microstrip lines to achieve a fractional bandwidth of 60% [18]. These conventional design methodologies, on the other hand, have struggled to keep up with the ever-increasing design demands. One of the possible solutions is to use optimization methods in the design of the broadband PA. In [21], a Bayesian algorithm was employed to optimize the output power and efficiency of the high-efficiency broadband PA. However, conventional microstrip lines limit the freedom and flexibility of the optimization. When the optimization goal is relatively strict, the above method may not obtain a satisfactory solution.

Recently, a fragment-type microstrip filter was designed by using the optimization method [22]. This irregular structure has a large degree of freedom and breaks the constraints of conventional circuit topology. Therefore, in order to improve the bandwidth performance, it is necessary to employ the optimization methods using the fragment-type structure in the design of the high-efficiency broadband PA.

In this paper, an optimization design method based on the fragment-type structure and a multi-objective evolutionary algorithm is proposed to design the filtering output matching network (OMN) for the broadband CCF-1 PA design. The designed filtering OMN has the characteristics of fast transition between passband and stopband, which can well meet the requirements of the harmonic impedance matching. Measurement results show that a highly efficient 1.5-3 GHz CCF-1 PA was realized with a drain efficiency of higher than 65% and at least 40 dBm output power, which verifies that the proposed method can extend the operational frequency band compared with the conventional Chebyshev filtering OMN.

¹School of Computer Science and Communication Engineering, Jiangsu University, Zhenjiang, 212013, China
²State Key Laboratory of Millimeter-Wave, Southeast University, Nanjing, 210096, China
³Jiangsu Key Laboratory of Security Technology for Industrial Cyberspace, Jiangsu University, Zhenjiang, 212013, China

a)kongwa@ujs.edu.cn

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Fig. 1. Wideband continuous inverting class F amplifier: (a) load impedance, (b) frequency response of output matching network.

2. Analysis of design requirement for CCF\textsuperscript{1} PA

In order to meet the design requirements of CCF\textsuperscript{1} PA, the desired fundamental and harmonic impedances were analyzed, followed by the low-pass filtering characteristics that the OMN should meet, as shown as follows.

According to the current of the inverse class F mode, the current expression of the CCF\textsuperscript{1} PA can be obtained by using the waveform parameter $\varphi$, given by [18]

$$i(\theta) = (0.37 - 0.43\cos \theta + 0.06\cos 3\theta) \cdot (1 - \varphi \sin \theta),$$

where $-\pi < \theta < \pi$

where the waveform parameter $\varphi$ is in the range of [-1, 1], which corresponds to different CCF\textsuperscript{1} mode current waveforms.

Assuming that each harmonic load is short-circuited, the optimal fundamental load impedance $R_{\text{opt}}$ in class B mode can be expressed as

$$R_{\text{opt}} = \frac{V_{\text{DC}} - V_k}{I_{\text{max}}}$$

where $I_{\text{max}}$ is the maximum value of the output current, and $V_k$ is the voltage at the inflection point of the amplifier.

Taking into account the waveform parameter $\varphi$, the admittance of the fundamental and harmonic impedances in the CCF\textsuperscript{1} mode is

$$Y_{1,\text{CF}^1} = 0.43\sqrt{2G_{\text{opt}}} + j0.37\sqrt{2\varphi G_{\text{opt}}}$$
$$Y_{2,\text{CF}^1} = -j0.98\varphi G_{\text{opt}}$$
$$Y_{3,\text{CF}^1} = \infty$$

where $G_{\text{opt}}$ is the optimal load admittance and its value is $1/R_{\text{opt}}$, When $\varphi$ changes from -1 to 1, the load impedance of the resulting CCF\textsuperscript{1} mode is shown in Fig. 1(a). It can be seen from the impedance distribution in the figure that the fundamental impedance is located on the center of the Smith chart, while the second harmonic impedance is distributed on the edge. Therefore, the OMN of the CCF\textsuperscript{1} PA should have an ideal low-pass characteristic.

When the fractional bandwidth of the CCF\textsuperscript{1} PA is increased to an octave (i.e. 66.7\%), the OMN should have a swift impedance transition from $f_1$ to $2f_1$. Fig. 1(b) shows the expected frequency response of the OMN of a CCF\textsuperscript{1} PA over a wideband. However, the Chebyshev low-pass filter structure, which is often used in the CCF\textsuperscript{1} PA designs, cannot meet the design requirements of the sharp roll-off between the fundamental and second harmonic bands, as shown in Fig. 1(b). Therefore, it is necessary to design the OMN with better low-pass filtering characteristics for the CCF\textsuperscript{1} PA design.

3. Optimization of fragment-type matching network

To obtain the desired low-pass filtering characteristics, the fragment-type structure is introduced to the OMN design of the CCF\textsuperscript{1} PA. Then, an optimization design process for the fragment-type OMN was given based on a multi-objective evolutionary algorithm. Finally, a filtering OMN using the fragment-type structure was designed for a 1.5-3 GHz CCF\textsuperscript{1} PA.

3.1 Fragment-type structure and its optimization design process

For conventional PAs, the microstrip lines with regular shapes are always employed in the OMN designs, which are not flexible enough and limit further performance improvement of the PAs [23, 24]. On the contrary, the
Fig. 3. OMN with fragment-type structure.

TABLE I
S-PARAMETER REQUIREMENTS FOR DESIGN CIRCUITS

| Frequency  | 1.5GHz-3.0 GHz | 3.4GHz-6.0GHz |
|------------|---------------|--------------|
| $S_{11}$   | $\leq -10\text{dB}$ | -           |
| $S_{21}$   | $\geq 1\text{dB}$   | $\leq -10\text{dB}$ |

Fig. 4. Optimization process: (a) mean value of the fitness functions, (b) number of feasible solutions.

fragment-type structure has a large degree of freedom and breaks the constraints of conventional circuit topology, which has been wildly used in passive circuit designs, such as antennas and filters [25, 26, 27]. The fragment-type structure is shown in Fig. 2(a), which discretizes the design space into several rectangular sub-grids represented by binary codes. For example, 1 indicates that the mesh area is made of metal, and 0 indicates that no metal is attached.

Based on the multi-objective evolutionary algorithm (MOEA) [25], an optimization design process of the fragment-type OMN is given, as shown in Fig. 2(b).

3.2 Optimization Design of fragment-type OMN for CCF-1 PA
To validate the proposed optimization design process, a fragment-type OMN for the CCF-1 PA was designed and optimized.

For the frequency band of 1.5-3 GHz, the initial OMN of the PA with CGH40010F was designed using the conventional microstrip structure firstly [23]. In order to increase the transmission zero point between the passband and the stopband for the expected sharp roll-off, a fragment-type structure is added on the traditional Chebyshev low-pass filtering OMN, as shown in Fig. 3. To enhance its optimization diversity, a 9.1 mm × 4.3 mm area surrounded by a red dotted line is divided into 30 × 14 grids and used to optimize the OMN.

The above fragment-type OMN is modeled and simulated in HFSS, and the results are output to the optimization algorithm program for individual fitness evaluation. The reference impedance of port 1 is set to the optimal fundamental impedance of $19\div10$ $\Omega$ in the HFSS simulation, so that the $S_{21}$ parameter in the passband meets the requirements. Considering the requirements of the passband and stopband in Table I, the fitness function in the optimization can be set as (4)-(6).

$$F_1 = \frac{10}{\min_{f \in [1.5\text{GHz},3.0\text{GHz}]} |S_{11}(f)|_{\text{dB}}}$$ (4)

$$F_2 = \max_{f \in [1.5\text{GHz},3.0\text{GHz}]} |S_{21}(f)|_{\text{dB}}$$ (5)

$$F_3 = \frac{10}{\min_{f \in [3.4\text{GHz},6.0\text{GHz}]} |S_{21}(f)|_{\text{dB}}}$$ (6)

To illustrate the process of using a fragment-type structure to optimize the OMN, Fig. 4 shows the mean value of the fitness function and the number of optimum solutions. The results show that three fitness functions can be reduced to below 1, which means the design requirements in (4)-(6) can be met.

After 50 generations of the optimization process, the optimized fragment-type OMN was selected as the final optimization result, as shown in Fig. 5. The current distribution at 3.7 GHz was also simulated and depicted. The results show, for the frequency of 3.7 GHz, the current is confined to the area where the fragment-type structure is located, and the signal cannot be transmitted. Thus, the structure plays a role in blocking the frequency signal between the passband and the stopband.

Fig. 6 shows the simulated S-parameters of the
optimized filtering OMN. For comparison, the simulated results of the Chebyshev filtering OMN designed by the method in [23] are also given. The results show that the S-parameters of the proposed fragment-type OMN can meet the requirements at the target frequencies shown in Table I. Compared with the conventional Chebyshev design method, the proposed method can achieve a transmission zero point ($S_2 < -40$ dB) at 3.7 GHz with steeper out-of-band rejection characteristics, while $S_{11} < -10$ dB, $S_{11} > -1$ dB can be achieved within the passband. Therefore, the desired impedance matching can be achieved at the fundamental and harmonic frequency band for CCF-1 mode.

4. Simulation and Measurement of CCF-1 PA

In order to verify the above optimization methods and results, a 1.5-3 GHz CCF-1 PA using the fragment-type OMN was designed. The schematic and design parameters are shown in Fig. 7. A stepped-impedance structure was employed in the input matching network (IMN) design to meet the source impedance requirements over a wide frequency band. To characterize the performance of the proposed PA, the output power and efficiency at saturation within the entire operational frequency band were simulated, as shown in Fig. 8. For comparison, the results of the PA designed by using the Chebyshev filtering OMN were also depicted. In the simulation, the input signal power of the two PAs is 26 dBm, while the gate and drain bias voltages are -3 and 28 V, respectively.

The results show that the proposed PA has a saturated output power of greater than 40 dBm over the frequency band from 1.5 to 3 GHz, and the corresponding maximum efficiency is higher than 65%, which means a fractional bandwidth (FBW) of 66.7% can be achieved. On the contrary, the conventional design using the filtering OMN has an operating bandwidth of only 1.7-2.9 GHz (52% FBW) when the maximum efficiency is higher than 65%, which means about 15% FBW expansion can be achieved by using the proposed method.

For verification of the performance of the proposed design, the 1.5-3 GHz CCF-1 PA using the fragment-type OMN was fabricated, as shown in Fig. 9. The DC blocking capacitors at the input and output terminals are ATC600S 20pF capacitors. A Murata 18nH inductance was used in the gate bias circuit, and a Coilcraft A04T inductance was employed for the drain feeding.

To obtain the large-signal characteristics of the designed PA, Fig. 10(a) shows the saturated output power and efficiency within the entire operating bandwidth measured by a sine wave signal with an input power of 28 dBm. In the measurement, the gate bias voltage was determined based on a quiescent current of 50 mA, and the drain voltage is 28 V. The results show that the designed PA achieves an efficiency of 65%-77% for the frequency band of 1.5-3 GHz with corresponding output power within the range of 40.2 to 42.2 dBm. For the characteristics of the gain and efficiency as a function of output power, the output power, gain and efficiency were measured at 1.5, 2.25 and 3 GHz, as depicted in Fig. 10(b). The saturated output powers at the lowest, center and highest frequencies all exceed 40 dBm, and the
Fig. 10. The designed CCF$^1$ PA: (a) measured output power and efficiency at saturation, (b) gain and efficiency versus output powers at different frequencies.

highest efficiencies at saturation are 65.9%, 72.5%, and 65%. The small signal gain is about 15 dB with a gain fluctuation of less than 3 dB.

The comparison with published broadband PAs is shown in Table II. The results show that the proposed CCF$^1$ PA using the fragment-type OMN can achieve the widest operating bandwidth while maintaining a good efficiency performance of higher than 65% at saturation.

5. Conclusion

This paper proposed an optimization design method for the OMN of the CCF$^1$ PA using the fragment-type structure. The transmission zero point between the fundamental and second harmonic band was achieved by using the proposed method, which can make the transition between the passband and the stopband faster so as to meet the fundamental and harmonic impedance requirements of CCF$^1$ mode. For verification, a 1.5-3 GHz broadband high-efficiency PA was designed and measured. Experimental results show that the proposed PA can achieve a measured efficiency of 65%-77% with a corresponding output power of 40.2-42.2 dBm over the FBW of 66.7%.

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