BROADBAND MATCHING OF CONTINUUM MODE POWER AMPLIFIERS USING PARTICLE SWARM OPTIMISATION

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Designing an amplifier requires a choice of (i) impedances and (ii) realizing them using a matching network. We propose a methodology to simultaneously determine optimal impedances and their corresponding ideal matching networks in the design space of continuum mode amplifiers. We define an entity called "particle" which consists of the impedances in a continuum mode, corresponding S-parameters of the input and output matching network described by polynomials similar to the Simplified Real Frequency Theorem (SRFT), and the corresponding performance (ex. Efficiency, Output power, Adjacent Channel Power Ratio (ACPR), Inter modulation Distortion (IMD) etc.,) of the amplifier. The particle is an array of numbers which describes the amplifier. In our methodology, to begin with, the particles are initialized randomly. Each particle learns or cooperates with other particles to predict the next generation of particles which may improve the objective function and eventually reach the optimal particle after several iterations. Evolutionary and/or machine learning algorithms are suited for finding such optimal particles. We demonstrate Particle Swarm Optimization (PSO) to the design of a continuum mode broadband power amplifier achieving the best achievable constant efficiency and output power between 2.5 - 4.6 GHz. The algorithm can predict ideal topologies of input and output matching which require further optimization at the stage of translation to corresponding layouts. The resulting ideal networks are further optimized in EM simulations and verified by experiment.

INTRODUCTION

Class B/J consists of a continuum of voltage waveforms [1][2] whereas continuous class F^{-1}(CCF^{-1}) is defined by a continuum of current waveforms [3]. Besides these, several continuum-based waveforms relying on voltage and/or current manipulation have been proposed in the literature. Each of these classes require a specific set of impedances at the fundamental, second harmonic and /or third harmonic. Even though continuum modes offer a large choice of impedances in the design of an amplifier, only those impedances which satisfy the Foster reactance theorem can be utilized in practise. A priori selection of impedances which conform to the Foster reactance theorem has been shown to minimize the search space of amplifier design, thereby resulting in a simplified design process. This procedure has been demonstrated in the design of Classes B/J continuum [4] and CCF[5], however, a generic procedure to find impedances does not exit. Additionally, in a typical amplifier design methodology, the step to find the matching network to track the selected impedances, often requires trial and error of several topologies, that may be avoided by the use of the Real Frequency Techniques. In this work, we demonstrate a methodology which simultaneously finds the optimal impedances in the design space of continuum mode as well as the corresponding ideal matching network of RFPAs simultaneously.

Background

A typical methodology of a broadband matching network is shown in the flow-diagram in Fig. 1 (a). To find optimal load and source impedances at sample frequencies over the required bandwidth, load and source pull simulations/measurements of the device can be utilized.

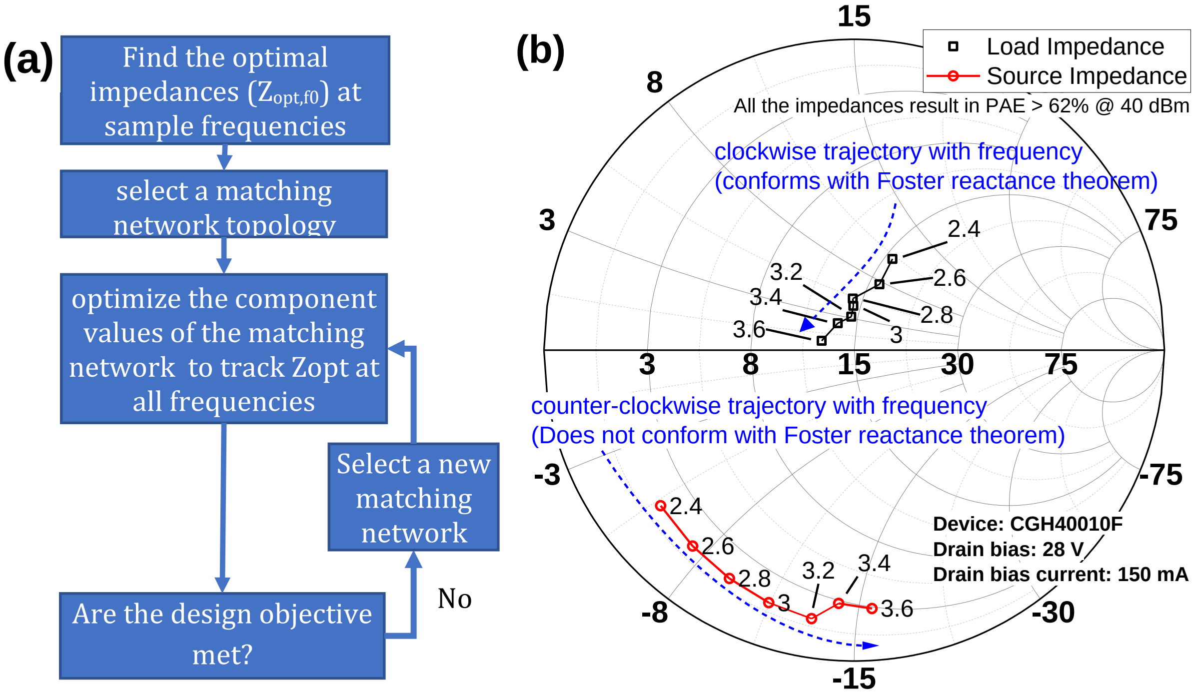


Fig. 1. (a) A flowchart illustrating a typical design steps in an amplifier design. (b) An example illustrating the impedances selected in the first step of a typical amplifier design.

As an illustration, target impedances (for efficiencies greater than 62% at an output power of 40 dBm) using the CGH40010 between 2.4 -3.6 GHz are plotted in Fig. 1 (b). It can be seen that load impedances vary clockwise whereas source impedances vary counter-clock wise with frequency. This indicates that the trajectory of the impedances in the latter case can never be achieved by a passive matching network; this is because, as postulated by the Foster reactance theorem, that the impedances of a passive network of inductances and capacitances always shows clockwise trajectory with frequency. Nevertheless, the aim of matching then becomes one of minimizing the difference between the target impedances and those realizable by the matching network.

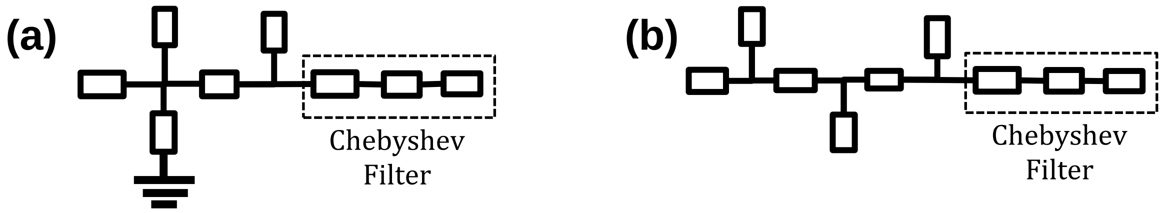
The next step in the design process is to select a matching network topology (a specific combination of transmission lines, short and open stubs) that might track these required impedances. A thorough understanding of the commonly used and simple topologies such as single stub, pi-shaped, T-shaped, double stub network may allow to select an initial topology (sections 3.1.2 and 3.1.3 in [6])(chapter 5 in [7]). Alternatively, the initial matching network topology can be obtained graphically using the Smith chart (sections 3.1.2 and 3.1.3 in [6]), implemented for example as a Smith chart tool in ADS [8]. However, in this method, the matching can only be performed at a single frequency. A third way to obtain the initial design is to synthesize a filter using well established synthesis tables available in any standard microwave book [9], implemented for example as filter synthesis tools in ADS [8], Genesys[10] etc .. However, the matching property of the synthesized filter is restricted to resistive terminations and not reactive parts as required in a typical power amplifier design. Hence, the synthesised network may need to be tweaked further or additional sections may be added to achieve the required matching performance (section 3.4 in [6])(section 7.2.2 in [11]).

In addition to matching impedances at the fundamental frequency as in the case of class AB shown for illustration in Fig. 1 (b), continuum modes require matching to a reactive load at the second and/or third harmonic frequency. Rather than being a curse, this can be a boon, as the low pass or band pass filters are most suitable for this requirement such as for example the Chebyshev filter matching network in [12]. This is a slightly modified version of the methodology in Fig. 1 (a) as the matching network topology is fixed first rather than the target impedances.

Once an initial matching network is obtained, CAD solutions can accurately simulate and optimize it. However, this matching network might not meet the design objectives. In such a case, the initial matching network may require tweaking, or the designer may need to come up with a new network topology altogether. As a result, the designing a matching network for an amplifier may need to go through several iterations.

An example of this design process is illustrated in Fig. 2. A 10W GaN HEMT, CGH40010, is chosen for this example for a fundamental frequency of 2.6 GHz and a bias current of 150mA. Three output matching networks (V1, V2 and V3) at f0 and corresponding second harmonic frequency 2f0 are designed using the Smith chart tool in ADS. All matching networks consist of a Chebyshev filter, synthesized using the filter synthesis tool in ADS, to act as impedance transformer from 50 ohms to 35 ohms. The same topology, shown in Fig. 2. (a), is used for V1 and V2 but they differ in the length and width of the transmission lines and target different regions of the design space. As a result, V1 can only achieve 400 MHz whereas V2 achieves a 900 MHz bandwidth as shown in Fig. 2. (c). On the other hand, V3 utilizes a different topology, shown in Fig. 2. (b), but targets a similar region as V2. V3 achieves a bandwidth of 600 MHz as seen in Fig. 2. (d), 300 MHz lower than V2. This illustrates that to completely utilize the design space of continuum modes, the following two choices should be simultaneously made, rather than in two separate steps (as in Fig. 1 (a)):

1) Selection of the impedance region in design space that will satisfy the design goal.
2) Selection of a topology that can achieve the impedances in 1)



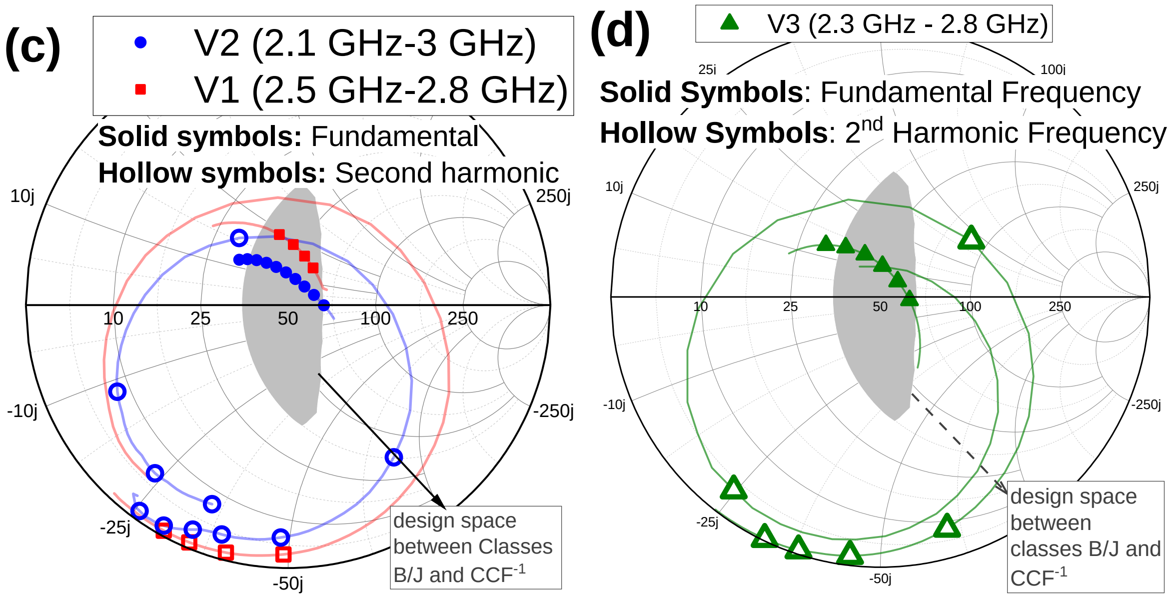


Fig. 2. Topology of the output matching network used for the design of (a) amplifier versions V1 and V2 (b) amplifier version V3. The measured impedances (translated to the intrinsic plane of the device) of (c) V1 and V2 (d) V3.

SRFT for the matching network synthesis

The selection of a topology can be avoided by using Real Frequency Technique (RFT) or SRFT. These techniques rely on the fact that the driving point impedance in the former and the S parameters in the latter of an ideal lossless passive network can be expressed as rational polynomials of frequency [13]. The S-parameters in the λ-domain are given by

$$S = \frac{1}{g(\lambda)}\begin{bmatrix} h(\lambda) & f(\lambda) \\ \pm f(-\lambda) & \mp h(-\lambda) \end{bmatrix} \qquad (1)$$

Where, $h(\lambda) = h_n\lambda^n + h_{n-1}\lambda^{n-1} + \cdots + h_1$,

$f(\lambda)f(-\lambda) = \lambda^{2(n_{dc})}(1-\lambda^2)^k$,

$g(\lambda)g(-\lambda) = f(\lambda)f(-\lambda) + h(\lambda)h(-\lambda)$,

n denotes the number of elements in the matching network, $h_n, h_{n-1}, \ \ldots, \ h_1$ are real numbers, $n_{dc}(\in \mathbb{Z})$ denotes the number of DC zeros which will be synthesized as short stubs, and k denotes the number of transmission lines in the matching network. To ease the synthesis of the distributed matching network, frequency is mapped onto the λ-domain using Richard's Transformation ($\lambda = \tan\left(\frac{2\pi f l}{v_p}\right)$; where l and v_p denote the length of the transmission line and the propagating velocity in the transmission line). This mapping allows synthesis of the characteristic impedances of the transmission lines of the matching network directly from the coefficients of the polynomial $(h_n, h_{n-1}, \ \ldots, \ h_1)$ [14]. It can be seen that a network is completely defined as an array $\widehat{S} = [n, n_{dc}, k, \ h_n, h_{n-1}, \ \ldots, \ h_1]$. SRFT has the following steps:

1) Express the required S parameters of the matching network as rational polynomials (ie., $h(\lambda)$, $f(\lambda)$, and $g(\lambda)$) based on the array $\widehat{S}$.

2) Optimize $\widehat{S}$ such that the error between the target impedances (Z_{f0}) and actual impedances can be minimized.
3) network can be synthesized from $\widehat{S}$.

SRFT can remove the need for iterations required for searching the topology. The problem of the matching network simplifies to the optimization of an array of numbers. However, SRFT based methodologies still require prior selection of target impedances, typically obtained from load/source pull [14], even for the continuum modes [15]. In this paper we present a methodology based on SRFT to simultaneously find the impedances and the corresponding matching network to obtain the desired amplifier performance over the selected frequency range.

Proposed Methodology

The proposed methodology is illustrated by a flow diagram in figure 3. The SRFT coefficients of the output matching network ($\hat{S}_L$) can be optimized to minimize the error between the selected impedances from the design space of the continuum mode. An example is plotted in the Smith chart in Fig. 3. The small signal gain of the amplifier can be calculated from the S-parameters of transistor, the s-parameters of the output matching network from $\hat{S}_L$ and the s-parameters of the input matching network from ($\hat{S}_S$). We optimize the SRFT coefficients of input matching network ($\hat{S}_S$) to achieve flat gain over the frequency range. The performance (efficiency, output power, ACPR etc.,) of the amplifier can be obtained by performing large signal simulations using the device model and S-parameters of the input and output matching networks from $\hat{S}_L$ and $\hat{S}_S$. The parameters in the particle form an objective function depending upon the design requirement and the optimization algorithm. The matching networks can then be synthesized from $\hat{S}_L$ and $\hat{S}_S$.

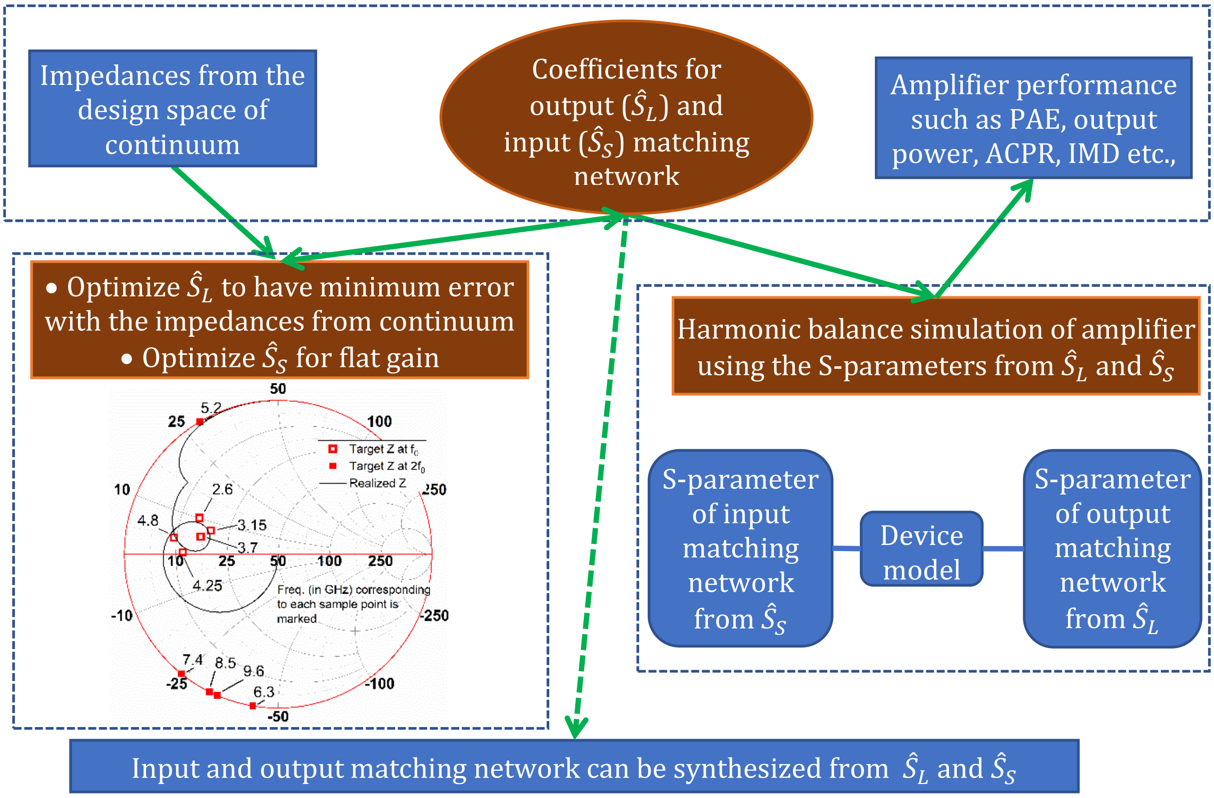


Fig. 3. A block diagram illustrating the proposed methodology.

In this way, impedances from the continuum are mapped to the amplifier performance and to the matching network via $\hat{S}_L$ and $\hat{S}_S$. We define this mapping as a "particle".

In our methodology, we pass the design space of the continuum to evolutionary or machine learning algorithms. These algorithms initially select the impedances at random from the design space and create particles corresponding to these impedances as shown in figure3. In evolutionary algorithms, these initial particles learn/cooperate with each other to predict the impedances for the next generation of particles. On the other hand, machine learning is supposed to learn the mapping between the impedances and amplifier performance that exists in these initial particles to predict the next generation. The best particle is expected as the output of the algorithms after several iterations.

Results and Discussion

For demonstration, we have chosen a 10 W GaN HEMT from Cree, CGH40010F. The device is biased in deep class AB mode (V_{dsq}=28 V, I_{dsq}=150 mA) and the optimal loadline resistance (R_{opt}) is found to be 38.1 Ω. The target frequency range is chosen as 2.6-4.5 GHz. We have divided the output matching network into two sections; SS and SF. SF matches the impedances at fundamental frequency only, whereas SS matches the impedances at both fundamental and second harmonic frequencies. SS is placed close to the device to minimize the loss at second harmonic frequency, thereby achieving reactive loads as required by the continuum modes. The order of the networks SS, SF, and SFin is fixed to 3, 6 and 7 respectively while optimizing $\widehat{SS}$, $\widehat{SF}$, and $\widehat{SFin}$. We have used class BJF^{-1} continuum proposed in [16] which encompasses class B/J continuum, CCF^{-1}, extended CCF^{-1}, and saturated PA modes, offering a wide design space.

In this work, we have used the particle swarm optimization (PSO), available in MATLAB, to find the optimal particle. In PSO, the position of each particle in the solution space (class BJF^{-1}) is predicted based on its own best position and the global best position achieved by all the M particles; the algorithm mimics the social behaviour of a flock of birds or a school of fish. Since it is a single-valued optimization problem, we defined an objective function (OF) for flat PAE over the bandwidth as

$$\mathrm{OF} = \left(1 + 100\left\|\Gamma_{Load}(f_i) - \Gamma_{1,ext}(f_i)\right\|_2^2\right)\left(\frac{\sigma_{PAE}}{2} + \frac{200}{\mu_{PAE}}\right) \tag{2}$$

Where, μ_{PAE} and σ_{PAE} denote the mean and standard deviation of PAE at P3dB over the frequency range, respectively. $\Gamma_{Load}(f_i)$ and $\Gamma_{1,ext}(f_i)$ denote the reflection coefficient corresponding to $\mathrm{Z}_{\mathrm{Load}}(f_i)$ and $\mathrm{Z}_{1,ext}(f_i)$.

The optimal particle obtained from the particle swarm optimization is given in table I. The first term in the array of *h* for SF and SF*in* have a near zero value indicating that the network is realized

TABLE I. THE FINAL CHOICE OF VALUES FROM THE ALGORITHM

<table>
<tr><td>Frequency</td><td colspan="3">2.6 GHz</td><td>3.15 GHz</td><td>3.7 GHz</td><td>4.25 GHz</td><td>4.5 GHz</td></tr>
<tr><td>Z_{f_0} $(fundamental)$</td><td colspan="3">14.64 + 10.06i</td><td>18.82 + 7.41i</td><td>16.18 + 5.03i</td><td>11.77 + 0.46i</td><td>9.43 + 3.85i</td></tr>
<tr><td>Frequency</td><td colspan="3">5.2 GHz</td><td>6.3 GHz</td><td>7.4 GHz</td><td>8.5 GHz</td><td>9 GHz</td></tr>
<tr><td>Z_{2f_0} $(second\ harmonic)$</td><td colspan="3">0.01 + 28.51i</td><td>0.01 - 42.30i</td><td>0.01 - 23.88i</td><td>0.01 - 30.96i</td><td>0.01 - 32.86i</td></tr>
<tr><td></td><td>n</td><td>k</td><td>n_{dc}</td><td colspan="4">h</td></tr>
<tr><td>$\widehat{SS}$</td><td>3</td><td>2</td><td>0</td><td colspan="4">[0.44,-0.23,-3.12 ,0]</td></tr>
<tr><td>$\widehat{SF}$</td><td>6</td><td>3</td><td>0</td><td colspan="4">$[10^{-6}, -0.90, -1.58, -4.38, -3.19, \ -2.98, 0]$</td></tr>
<tr><td>$\widehat{SFin}$</td><td>7</td><td>4</td><td>0</td><td colspan="4">$[-2.0X10^{-06}, 1.39\ , -5.29, -10.26, -5.88\ , -5.8\ , 0.15, 0]$</td></tr>
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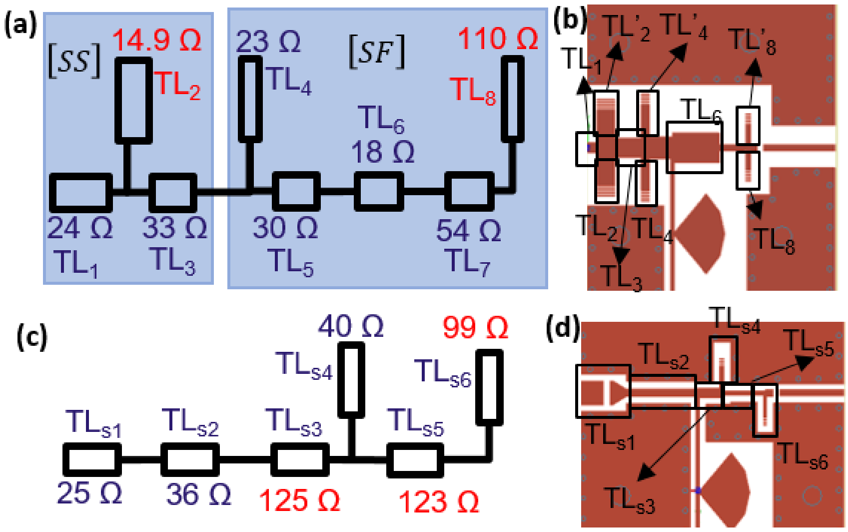

Fig. 4. Synthesized network and the corresponding optimized layout of the output (Top) and input (Bottom) matching networks. Stubs (TL'2, TL'4, and TL'8) in the layout of the load matching network in (b) have the same lengths and widths as TL2, TL4, and TL8 respectively

with 5 and 6 elements; one element lower than the initial assumption. The network synthesized from $\widehat{SS}$, $\widehat{SF}$, and $\widehat{SFin}$ is shown in Fig. 4.[14][6]. The length of all lines is $\lambda_0/8$; λ_0 is the synthesis frequency, λ_0=5.2 GHz, in this case. The impedances of some lines are beyond the limits of the foundry which are highlighted in red. However, this network does not have a biasing structure. A quarter wavelength line at 3.75 GHz (at the center of bandwidth) with a radial stub is added to the matching networks. The matching networks are optimized in EM simulation to match impedances predicted by the particle and fabricated on Rogers 4003C substrate.

The impedances from Table I, ideal matching network, EM simulation, and measurement are plotted Fig. 5 (a). A slight discrepancy between impedances from theory and ideal at the fundamental frequency (f_0) is expected because the latter is a realizable approximation of the former. However, a large difference at second harmonic is because we have given only 1/10 weightage to the matching of the second harmonic impedance. The discrepancy between ideal matching network and in the EM simulation is due to further optimization of the layout. The measured impedances closely match with the EM simulation result. The PAE, output power and Gain of the amplifier with ideal matching (predicted by the particle) and after layout optimization

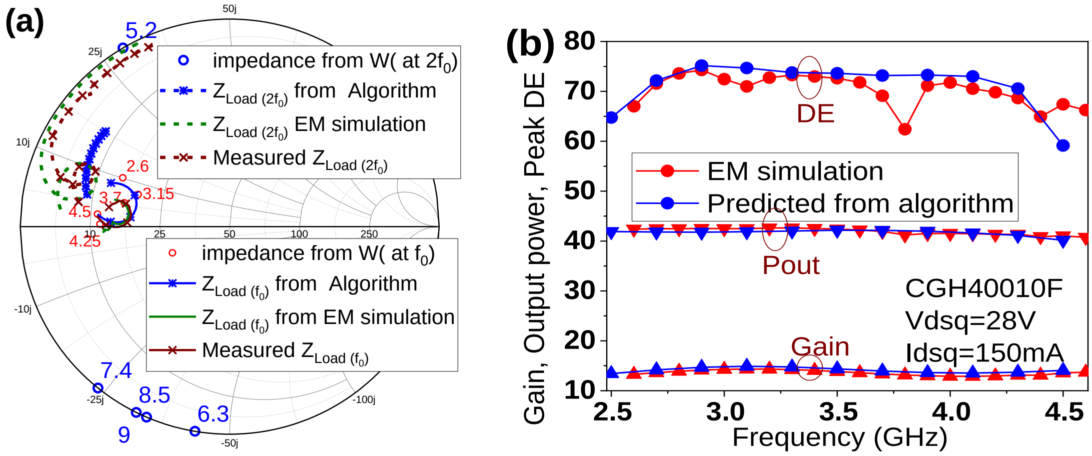

Fig. 5. (a) A comparison of the impedances from theory, EM simulation, and measurement obtained for the optimal particle. (b) Gain, Output power, and DE from the algorithm and EM simulation.

are plotted in Fig. 5 (b). A good match is observed between the two albeit a drop in efficiency noted at 3.6 GHz. The gain and output power in both cases remain constant over the bandwidth.

Measured S parameters of the amplifier are plotted in fig. 6. The amplifier achieved a bandwidth of 2 GHz (2.6 GHz – 4.6 GHz). 4.6 GHz is the highest frequency at which this device has been utilized (previous reported max. is 3.9 GHz [17]) . The small signal gain shows a variation of 2dB over the bandwidth. The output reflection is lower than -12.8 dB over the bandwidth.

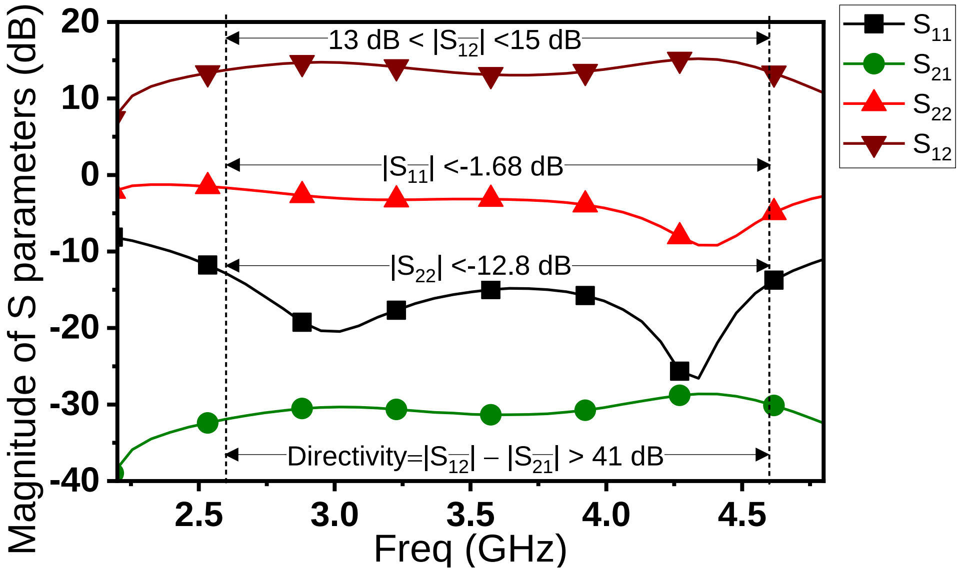

Fig. 6. Measured S-parameter of the design amplifier

CONCLUSION

A methodology to find optimal impedances in a continuum mode and a corresponding matching network simultaneously is demonstrated. In this methodology, we have utilized the fact that the critical parameters of the amplifier (intrinsic impedances, matching networks, and the performance) can be represented by an array of numbers referred to as “particle”. A random set of particles is initialized, and the particles learn and co-operate with each other to find the optimal amplifier design. The algorithm can predict ideal topologies of input and output matching. However, these topologies require further optimization while creating the corresponding layout. Even though PSO algorithm is used in this work, any of the evolutionary algorithms or machine learning can be used to implement the proposed methodology.

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