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RESEARCH ARTICLE

Broadband multi-section stepped tapered microstrip transformers design using seeker optimization algorithm

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Abstract

This work applies an evolutionary searching algorithm of Seeker Optimization Algorithm for designing multi-band multi-section stepped tapered microstrip lines that maximally match real load impedance to a transmission line in a pre-described range of frequencies. Seeker Optimization algorithm has been verified to be very effective algorithm in finding the solutions for such multi-objective functions. Herein the design process aims to select the values of the matching impedances between real load and transmission line among a continuous range of values under tapering constraints. The obtained results have been verified by PUFF simulator and the design parameters have been calculated using the PUFF microwave simulator.

1. Introduction

Recently, near-optimal solutions for many complex engineering problems have been successfully reached using different computational algorithms. Hence, optimization techniques take their pivotal role in many raising electromagnetic problems. In particular, bio-inspired based algorithms have been successfully applied in constrained and unconstrained electromagnetic design problems, due to their ease of application, and robustness [1-6].

In this paper, a recently developed optimization algorithm named as SO algorithm has been used to find the design values of the tapered impedances among pre-defined continuous limited intervals. Under the tapering constraint of the decreasing order from the load to the transmission line. To the best of the authors knowledge, this is the first time to apply SO algorithm to solve the aforementioned problem.

The outline of this study is organized as follows: In section II we formulate the design problem and the design constraints also SO algorithm has been presented in its mathematical simplest way and also brief summary about the SO algorithm advantages over the other evolutionary-based algorithms when applied to various benchmark functions has been presented. In section III optimization results have been presented and verified by the PUFF simulator, and finally, in section IV, we conclude the work, and future suggested work has been presented in section V.

2. Materials and methods

This section has been divided into two subsections; where the formulation of the problem has been presented in the first subsection and the theoretical background of the SO Algorithm been presented in the second.

2.1 Problem formulation and design constraints

Matching circuits have been considered as essential parts in microwave systems design. Basically, impedance matching circuits are lossless circuit placed between a load impedance and a transmission line (Fig. 2) to avoid the unnecessary transmission losses when the load is mismatched from the line as well as to protect the generator from the effects caused by the reflected waves at the load and in some applications (such as antenna arrays) it is used to reduce amplitude and phase errors. Matching network is usually designed so that the impedance seen looking into the matching network is Z_0 then the reflection will be eliminated on the transmission line to the left of the matching network. [7].

According to many different considerations different matching methods can be applied to the system in hand, the most important factors in selecting particular matching are complexity of the circuit, bandwidth, ease of implementation and their adjustability. As per the bandwidth aspects; impedance matching network can be designed to be effective for specific frequency of operation (narrowband) or for a given frequency spectrum (broadband) [8]. In this work we will use the multi-section technique in tapered manner for enhancing the bandwidth of the quarter wave transformer. So that it can be considered as simplified combination between the multi-section and the tapered design. Bandwidth enhancement for the matching circuit has been considered in the literature using different methods such as graphical techniques [9-11] or by optimization techniques [12, 13]. The motivation of this work is to propose a simple and broadband matching circuit alternative to the one presented in [14] where narrowband design has been considered. Using the tapered multi-section impedances bandwidth will be enhanced in a given range of frequencies. Where the SO optimization algorithm has been used to specify the values of the matching impedances values.

In this work we will consider the tapering condition in designing the matching network, which means that successive impedances in the network will be increased from the line impedance up to the load impedance. Mathematically tapering could be described as:

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$$Z_0 < Z_M < Z_{M-1} < Z_{M-2} < \cdots < Z_1 < Z_L$$

So, to minimize the reflection coefficient over the selected range of frequencies, the impedance seen looking into the matching network has to be as near as possible in its value to Z_0. Referring to Fig. 4 the overall reflection coefficient is:

$$\Gamma_{in} = \frac{Z_{in}(\text{M}) - Z_0}{Z_{in}(\text{M}) + Z_0} \qquad (1)$$

Where,

$$Z_{in}(\text{M}) = \frac{{Z_M}^2}{Z(M-1)} \qquad (2)$$

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$$Z_{in}(1) = \frac{{Z_1}^2}{Z(L)} \qquad (3)$$

So, to minimize the reflection coefficient Γ_{in} over the selected range of frequencies, the impedance seen looking into the matching network has to be as near as possible to Z_0.

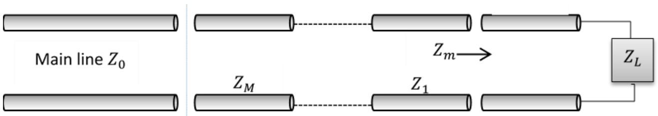

Figure 1. Multi-section transformer model

2.2 Seeker Optimization Algorithm

In engineering, optimization consists of trying variations of parameters and using information gained in different iterations to get the best results, those best results (solution) are relative to the problem in hand, the solving method, and the tolerance allowed. Mathematically, optimization could be defined as adjusting inputs to a mathematical process to find minimum or maximum desired output.

SO algorithm is a new promising technique for the real parameter optimization which mainly imitate the concept humans searching. As humans are using their memory, experience, and uncertainty reasoning SO algorithm is working with the same concept. SO algorithm divides the solution set randomly into K sub-populations with the same size, each individual in this sub-populations is called individually as a searcher or equally as seeker, where all those seekers in one sub-population constitute a neighborhood socially sharing searching information among themselves. When the algorithm starts to work, search direction, as well as the radius of the search for each seeker (step length), and trust degree will be determined for each seeker. Every seeker finds its a new position based on three factors: Namely, the seekers social learning, cognitive learning, as well the uncertainty reasoning. SO algorithm operates on a search population of s D-dimensional position vectors [15], that could be considered potential solutions of the optimization problem that we are trying to solve (represented by the fitness function), i.e., $\vec{x_i} = [x_{i1}, \dots, x_{ij}, \dots, x_{iD}]$; $i = 1, 2, \dots, s$ where x_{ij} is the j^{th} element of $\vec{x}_i$ and s is the population size. The flow chart of the seeker optimization is shown in Figure 2. Firstly, it generates s positions that are uniformly distributed and randomly selected in the solution total space (defined by the maximum and minimum values of the parameters). Next step is to calculate the fitness of each seeker, then calculates the search direction $dij(t)$ and the search radius $\alpha_{ij}(t)$, for the i^{th} seeker at time step t. Then the j^{th} element of the i^{th} seeker is calculated as per equation 4 [16]:

$$x_{ij}(t+1) = x_{ij}(t) + \alpha_{ij}(t) d_{ij}(t) \qquad (4)$$

To avoid converging to a local minimum, SOA uses an inter sub population strategy which described by:

$$x_{k_n j,worst} = \begin{cases} x_{lj,best} & if\ R_j \leq 0.5 \\ x_{k_n j,worst} & else \end{cases} \qquad (5)$$

Where R_j is a U, R number in the interval [0,1], $x_{k_n j,worst}$ is defined as j^{th} element of n^{th} worst position in k^{th} sub-population, $x_{lj,best}$ is the j^{th} element of the superior position in l^{th} sub-population.

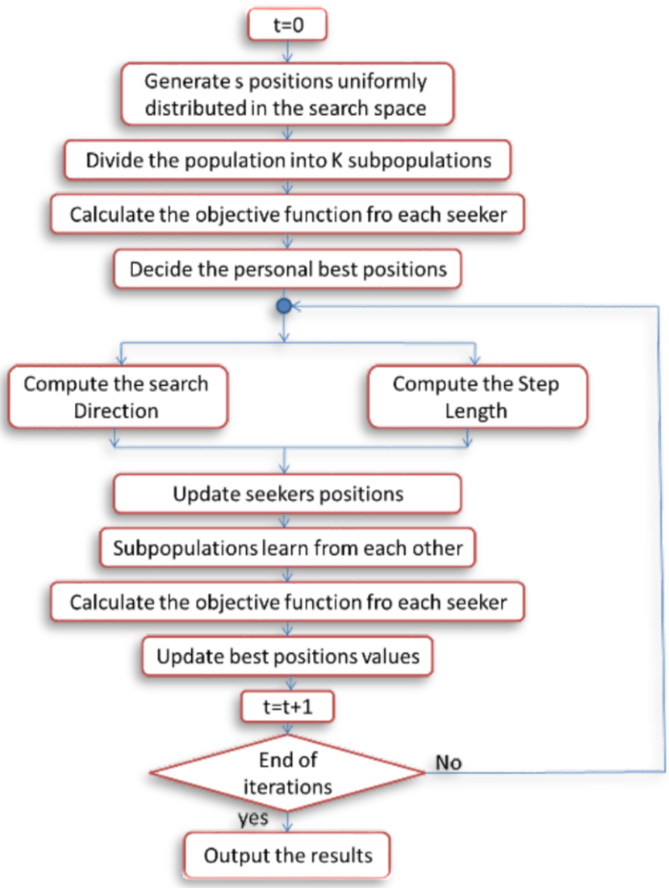

Figure 2. SOA Flow Chart

A. Search Direction

An empirical gradient is used when the fitness function can't be differentiated [17] by in which the direction of increment/ decrement could be determined. In this way, and so seekers are leading their search. In SO algorithm model three different searching manners are used to find the search direction namely they are called as egotistic, altruistic and proactive.

For Egotistic part, is a totally depending on the seeker itself self-behavior which depends on the seeker self-cognitive learning [18]. And this could be calculated using the equation (6) as:

$$\vec{d}_{i,ego}(t) = sgn(\vec{p}_{i,best}(t) - \vec{x}_i(t)) \qquad (6)$$

Secondly, altruistic behavior, where the seekers communicating their neighbors to adjust their behavior and to reach their goal, Mainly, a seeker i in the sub-population is associated with two altruistic directions, i.e., $\vec{d}_{i,alt1}(t)$, $\vec{d}_{i,alt2}(t)$ given by:

$$\vec{d}_{i,alt1}(t) = sgn(\vec{g}_{best}(t) - \vec{x}_i(t)) \quad (7)$$
$$\vec{d}_{i,alt2}(t) = sgn(\vec{l}_{best}(t) - \vec{x}_i(t)) \quad (8)$$

Lastly, seekers also use the proactiveness property, as the seekers are able to use a goal-directed behavior [19]. Also, foreseeing the future behavior depending on their previous behavior and so, each seeker will be anticipating to change its own search direction according to the seeker itself previous recorded behavior. And so, any seeker i is connected to an empirical direction named as proactiveness direction $\vec{d}_{i,pro}(t)$:

$$\vec{d}_{i,pro}(t) = sgn(\vec{x}_i(t_1) - \vec{x}_i(t_2)) \quad (9)$$

Where $t_1, t_2 \in t, t-1, t-2$ and $\vec{x}_i(t_1)$ has better fitness value than $\vec{x}_i(t_2)$. As per the human reasonable judgment, the real search direction of the i^{th} seeker, i.e., d_i(t) = [d_{i1} , d_{i2}, …, d_{iD}] is based on a compromise among the previously explained four types of the empirical directions. In this work, the j^{th} element of $d_i(t)$ is selected by applying the following selection rule:

$$d_{ij}(t) = \begin{cases} 0 & if\ r_j \le p_j^{(0)} \\ +1 & if\ p_j^{(0)} < r_j \le p_j^{(0)} + p_j^{(1)} \\ -1 & if\ p_j^{(0)} + p_j^{(1)} < r_j \le 1 \end{cases} \quad (10)$$

$p_j^m, m \in (0,1,-1)$ is defined as: in the set $(d_{ij,ego}, d_{ij,alt1}, d_{ij,alt2}, d_{ij,pro})$, let $num^{(m)}$ is the number of "m" then $p_j^{(m)}/4$.

B. Step Length (search Radious)

Among the whole solution searching space, there are always fitness points that are closer to the extreme point, such that fitness values obtained by using those input variables are connected to their relative distances from the optimum value, so the search must be intensified in regions with relatively good solutions [19]. Then it will be definitely of great logic to find the better values as moving to the optimum point and vice versa.

During the solving procedure, optimization problems in general have ranges of values obtained in each iteration. To able to design a system that can be applied to a wide range of optimization problems (to make SO algorithm widely used), the obtained fitness values of all the seekers are ordered in descending manner and then turned into the sequence numbers from 1 to s as inputs to a fuzzy reasoning system. A membership function of linear type is usually used in the conditional part, this mathematically represented by:

$$\mu_i = \mu_{max} - \frac{s - I_i}{s-1}(\mu_{max} - \mu_{min}) \quad (11)$$

Where I_i is the sequence number of $\vec{x}_i(t)$ after ordering the fitness values, where μ_{max} is defined as the maximum membership degree value. This value is equal to or little less than 1.0. In this work, $\mu_{max} = 0.95$. and the minimum value $\mu_{min} = 0.0111$ will be considered as often used.

3. Results and discussion

To illustrate the idea, we considered two examples; In the first one the impedance transformer consists of three impedance segments, while in the second one there is five segments. After applying the optimization process, the simulation of both examples has been demonstrated by the PUFF simulator, and the microstrip parameters has been calculated. PUFF [20] is an RF and microwave CAD program for laying out and analyzing micro-strip and stripling circuits. The program uses the frequency domain and calculates the s-parameters, it also includes a simple component sweep for optimization.

A. Three-segments Quarter Wave Transformer

According to the aforementioned discussion in section III, the design constraint matrix can be summarized as:

$$\begin{bmatrix} -1 & 1 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & -1 & 1 \end{bmatrix} \times \begin{bmatrix} Z_L \\ Z_1 \\ Z_2 \\ Z_3 \\ Z_0 \end{bmatrix} < \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Applying the aforementioned equations, while the Z_L = 100 and Z_0 = 50, the cost function is:

$$f(Z_1, Z_2, Z_3) = \log\left[\frac{1}{Z_L}\left(\frac{Z_3 . Z_1}{Z_2}\right)^2 - Z_0\right] \quad (12)$$

Figure.3 shows the reflection coefficient(dB) of the three-segment tapered design in the selected frequency range (2-8 GHz), while the microstrip line parameters values for each segment has been tabulated in Table 2.

For the sake of comparison, the reflection coefficient over the band of 2-8 GHz has been plotted for both SOA as well PSO in the same figure (Figure 3), where it could be seen that the SOA result is superior to the one in the literature, moreover few trials have been listed along with the best fitness obtained in Table 1, where it could be noticed that the results reached by the Seeker Optimization Algorithm are superior to the ones listed in Ref [14].

Worth mentioning that the length and width of the microstrips defined by the PUFF simulator depends also on the materials used in the design. This also could be controlled using the PUFF design options.

Table 1. Obtained microstrip impedances from different trials

Z1	Z2	Z3	Best Fitness
83.157	69.875	58.614	-23.859
84.235	70.685	59.344	-23.909
85.334	70.752	60.067	-23.843
84.439	70.120	59.459	-23.876

Table 2. Microstrip parameters for 3-segment tapered design

	Z_1	Z_2	Z_3
L (mm)	9.248	9.138	9.033
W(mm)	0.686	0.986	1.360
Value (**Ω**)	84.528	70.955	59.554

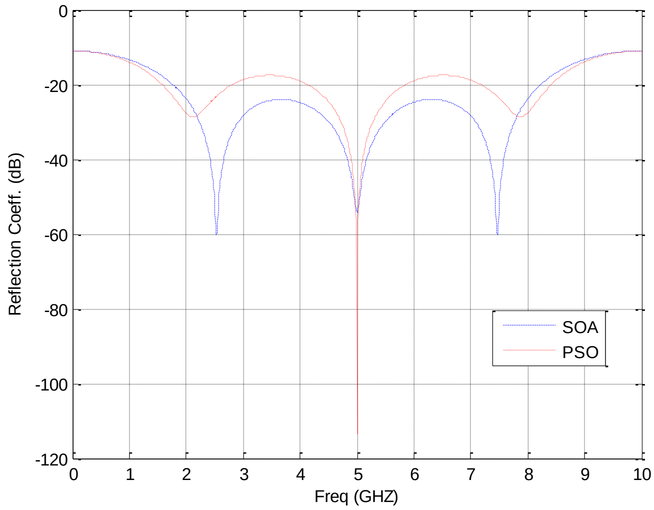

Figure 3. Reflection Response of 3-Segment Tapered Design obtained by SOA compared to the one in Ref. [14]

B. Five-segments Quarter Wave Transformer

Using the same procedure of section III, the design constraint matrix of the 5-segment quarter wave transformer can be summarized as:

$$\begin{bmatrix} -1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 1 \end{bmatrix} \begin{bmatrix} Z_L \\ Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \\ Z_5 \\ Z_0 \end{bmatrix} < \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Applying the aforementioned equations, while the ZL = 100 and Z0 = 50, the cost function can be written as:

$$f(Z_1, Z_2, Z_3, Z_4, Z_5) = \log\left[\frac{1}{Z_L}\left(\frac{Z_5 . Z_3 . Z_1}{Z_4 . Z_2}\right)^2 - Z_0\right] \quad (13)$$

Figure 4 shows the reflection coefficient(dB) of the five-segment tapered design in the selected frequency range (2-8 GHz), while the microstrip line parameters values for each segment have been tabulated in Table 3.

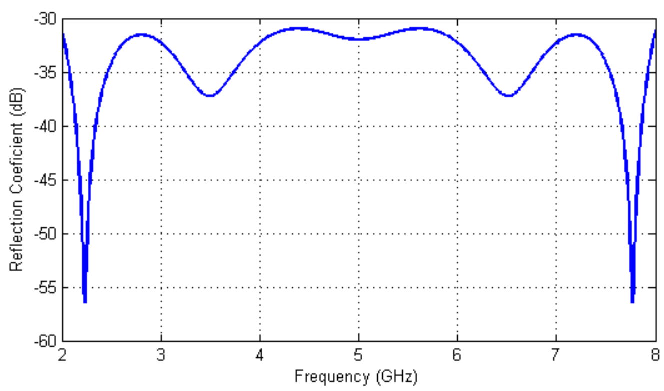

Figure 4. Reflection Coefficient of 5-segment model

Table 3. Microstrip parameters for the 5-segment tapered design

	Z_1	Z_2	Z_3	Z_4	Z_5
L (mm)	9.315	9.229	9.138	9.034	8.696
W(mm)	0.540	0.743	0.988	1.356	1.637
Value (Ω)	93.764	81.993	70.877	59.675	53.371

4. Conclusions

In this work, a newly developed optimization technique has been used to for designing multi-band multi-section stepped tapered microstrip lines that maximally match real load impedance to a transmission line in a pre-described range of frequencies. Seeker Optimization algorithm has been verified to be very effective algorithm in finding the solutions for such multi-objective functions.

Herein the design process aims to select the values of the matching impedances between real load and transmission line among a continuous range of values under tapering constraints. The obtained results have been verified by PUFF simulator and the design parameters have been calculated using the PUFF microwave simulator.

Author contributions

The article main goal is to design a broadband multi-section stepped tapered microstrip transformers, using a new optimization algorithm, the first author Mrs. Mona worked on the Seeker optimization algorithm coding as well the PSO as a competitive algorithm coding comparison (40%) as well Visualization; Roles/Writing - original draft; Writing - review & editing. The Second author works on the problem formulation and the matching circuit design and formulation using the MATLAB environment (30%) and Software; Supervision; Validation; as well. To be able to apply the design and get real values of the microstrip line parts new part has been added related to the PUFF simulation, and the third author has the main contribution in this part (30%).

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