Broadband Microwave Amplifier Design Using Particle Swarm Optimization

Sadık Ülker
Electrical Engineering Department, Girne American University, Girne, Mersin-10, Turkey
Email: sulker@gau.edu.tr

***Abstract* - This short paper presents the concept of particle swarm optimization technique applied for the design of broadband microwave amplifiers. The method that is developed is based on Particle Swarm Optimization (PSO) technique applied to a compensated matching network on a single stage transistor amplifier to get the best optimized result in the design. To prove the concept four different operating points were considered on the microwave amplifier design. The designs were verified via simulation results obtained by different simulators. It is shown that PSO is a fast and an efficient method and can be used in the design of broadband microwave transistor amplifiers.**

***Index Terms* – Optimization Algorithms, Particle Swarm Optimization, Broadband Microwave Amplifier Design.**

I. INTRODUCTION

Particle Swarm Optimization (PSO) was initially developed by Kennedy and Eberhart in 1995 as a method for the optimization of continuous nonlinear functions [1]. It is based on swarming behaviors observed in flocks of birds, schools of fish or swarms of bees. It has been shown to be effective in optimizing multidimensional problems. Since the discovery of particle swarm optimization many researchers tried to improve the method by analyzing the method with different settings [2]-[3]. Also methods have been developed to handle the optimization problems with complex functions [4]. Over the past few years some researchers worked on the application of PSO to some antenna and propagation problems [5]-[7]. It has also recently been started to gain an increasing interest and use in microwave circuits and applications as an optimizing and design tool [8]-[10]. For amplifier design there are not many work which uses optimization tools for design in literature though recently some papers started to arise recently[11]. In this work, to the authors knowledge, the particle swarm optimization method is applied for the design of broadband microwave transistor amplifiers for the first time.

A. General Design Approach

The main optimization process for particle swarm optimization is well known and can be described in Figure 1 [10].

```
Step 1: Initialize particles
Step 2: Calculate the fitness value for each particle
Step 3: If fitness value is better than the particles best fitness value (pbest) in history
        set current value as the new pbest
Step 4: Repeat steps 2-3 for all particles
Step 5: Choose the particle with best fitness value compared to all the particles and
        label this as the global best (gbest)
Step 6: Calculate and update each particles velocity and position according to equations
        (1) and (2) for all particles
Step 7: Calculate the fitness value for each particle
Step 8: If minimum error criteria (i.e. desired fitness value of 90% of all particles)
        is not achieved goto Step 3
Step 9: Display the particles
```

Figure 1: General Particle Swarm Optimization Technique Algorithm

The optimizer is started with a group of particles being initialized randomly. Fitness values, which show how close the particles are to the desired solution are calculated at every iteration for each particle. For each particle there is a local best solution (pbest) that is achieved so far in iterations, and among all of the solutions there is a global best solution (gbest). According to the equations

$$v[\,] = w * v[\,] + c * rand\,() * (pbest[\,] - present[\,]) + c * rand\,2() * (gbest[\,] - present[\,]) \quad (1)$$

$$present[\,] = present[\,] + v[\,] \quad (2)$$

the particle updates its velocity and position and iteration continues until all particles reach to the optimized solution. In this work, inertia weight *w*, is set to 0.65 and learning parameter *c*, is set to 2.05. In this work, these values gave the best convergence to an answer compared with other values. Though different settings for inertia weight and learning parameter can be tried, and this depends on the problem at hand, analyzing different values was not the aim of this work, a good reference for this kind of research can be found in Shi and Eberhart's work [2]. *rand()* and *rand2()* are random numbers generated by computer and they are between 0 and 1.

B. Broadband Microwave Amplifier Design

Broadband microwave amplifiers are required for many commercial (like wireless LANs, telecommunication systems) and military system applications (e.g. airborne active phased array radar). Broadband microwave amplifier design usually requires properly design of impedance matching networks, use of negative feedback, use of balanced amplifiers or distributed amplifiers [12]-[15]. Although these methods exist, the design is not a very straight forward process

doi:10.4304/jcp.6.11.2272-2276

which needs compromises in gain and in return loss, in order to achieve a good band of operation. In this paper, the design of proper impedance matching networks is done using an optimization procedure to meet the desired goals. Specifically, the design of a single stage broadband microwave transistor amplifier using the particle swarm optimization technique is described.

The general microwave single stage transistor amplifier circuit is shown in Figure 2.

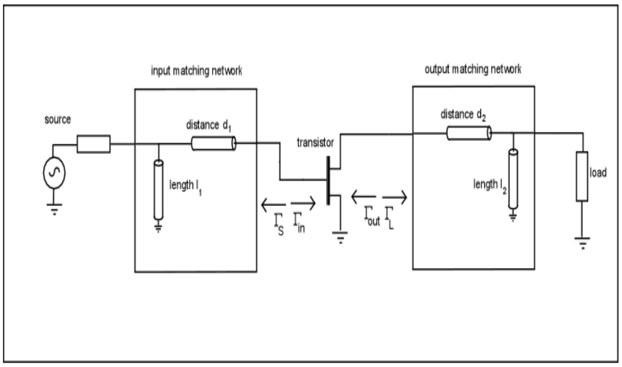

Figure 2: General Microwave Single Stage Transistor Amplifier Circuit

Transducer power gain (G_T) which is defined to be the ratio of the power delivered to the load, to the power available from the source is given by the equation :

$$G_T = \frac{|S_{21}|^2 \left(1-|\Gamma_S|^2\right)\left(1-|\Gamma_L|^2\right)}{\left|(1-S_{11}\Gamma_S)(1-S_{22}\Gamma_L)-(S_{12}S_{21}\Gamma_S\Gamma_L)\right|^2} \quad (3)$$

This equation is used in determining the fitness (i.e. calculating the gain and checking how close this value is to the desired gain) where Γ_S is reflection coefficient looking toward the source, Γ_L is reflection coefficient looking toward the load and S_{11}, S_{12}, S_{21}, S_{22} are the transistor s-parameters.

In this configuration, the relationships for Γ_S and Γ_L are related to the transmission line lengths (d_1, d_2, l_1 and l_2) and can be obtained via these equations:

$$\Gamma_S = \frac{Zsource-1}{Zsource+1} \quad (4)$$

$$\Gamma_L = \frac{Zload-1}{Zload+1} \quad (5)$$

where

$$Zsource = \frac{\mathrm{Re}(Zprs)+j(Zo\tan(2\pi d_1)+\mathrm{Im}(Zprs))}{Zo-\mathrm{Im}(Zprs)*\tan(2\pi d_1)+j\,\mathrm{Re}(Zprs)*\tan(2\pi d_1)} \quad (6)$$

$$Zprs = \frac{jZo\tan(2\pi l_1)}{1+j\tan(2\pi l_1)} \quad (7)$$

and similarly

$$Zload = \frac{\mathrm{Re}(Zprl)+j(Zo\tan(2\pi d_2)+\mathrm{Im}(Zprl))}{Zo-\mathrm{Im}(Zprl)*\tan(2\pi d_2)+j\,\mathrm{Re}(Zprl)*\tan(2\pi d_2)} \quad (8)$$

$$Zprl = \frac{jZo\tan(2\pi l_2)}{1+j\tan(2\pi l_2)} \quad (9)$$

Since the s-parameters of the device is fixed for a specific frequency and operating condition, the design becomes finding the dimensions for the transmission lines which would produce Γ_S and Γ_L values that would be used in determining the gain. In this case, the desired gain value is needed to be optimized at several frequencies rather than only one. In order to do this, a search for the length parameters directly, which will satisfy the desired gain at all of the predetermined frequencies is done.

II. WORK DONE

A set of 20 'particles' which holds four values; the values of input matching networks distance and length and output matching networks distance and length, (i.e. lengths d_1, d_2, l_1 and l_2) are created randomly. These are created with a random number generator between the lengths 0 and $0.1\lambda_c$ (λ_c being the corresponding wavelength for the design center frequency). Then with these values, for each particle three fitness values are calculated: one at the design center frequency, one at 1 GHz less than the center design frequency and one at 1 GHz above the center design frequency. Lengths of the transmission lines, and s-parameters of the device are modified to take into account the different frequencies. In order to find the global best (gbest), the one with the lowest fitness value (i.e. closest to the desired center gain) is chosen while checking whether these parameters are also satisfying the gain criteria at the lower and upper ends. Extra considerations are put as a stability criteria that for the whole range overall reflections in the system should all be below 0 dB. For each particle its own 'best' solution is also kept track of as particle's best (pbest) and these values are used in updating the velocity and position of each particle for the next iteration.

In this work, a high-electron mobility transistor (HEMT), FHX35X, which is manufactured by Fujitsu Cooperation, was used in the test for designing broadband amplifiers. For testing this methodology, four different center frequencies were selected and optimization rules for these were all set at the beginning, before starting the iterations. The first test was done for a desired gain of 13 dB at 3 GHz center frequency, with maximum of 1 dB variations at 2 GHz and at 4 GHz. The second test was done for a desired gain of 11 dB at 7 GHz center frequency, with maximum 0.5 dB variations at 6 GHz and at 8 GHz. The third test was done for a desired gain of 10 dB at 11 GHz center frequency, with maximum 1 dB variations at 10 GHz and at 12 GHz. The fourth test was done for a desired gain of 9.5 dB at 15 GHz with maximum 1dB variations at 14 and 16 GHz. Sample program result, obtained at 11 GHz, which shows particles reaching to an optimum solution (i.e. progress) per iteration is shown in Figure 3.

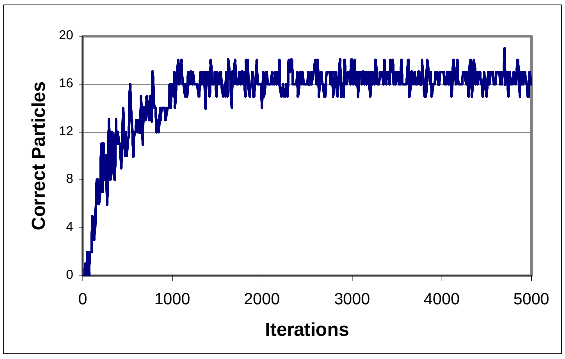

Figure 3: Solutions reaching to Correct Answer with number of iterations

Convergence to a result was considered if the center frequency gain was within 0.02 dB deviation from the desired gain as well as all the other criteria (like input and output stability and deviation of gain at other two frequencies being within 1 dB) as outlined were met. Similar graphs can be obtained for each of the selected center frequencies. There is a consistency in number of particles reaching to a solution in certain amount of iterations. Graph shows that usually the first convergence to a solution occurs after about 40-50 iterations, about half of the particles reach to correct solutions in 200 iterations, and after about 1000 iterations majority of the particles reach to a convergence point, i.e. an optimum result, and the lengths which satisfy all the criteria is found. The dimensions that were obtained by the program are given in Table I.

Although these dimensions are given as examples, in most of the runs the following values are obtained. If we compare these values with different runs we had, we see that those answers also satisfy all the predetermined criteria.

Table 1. Design values for lengths obtained by PSO program

Center Frequency	**Input Matching Network**		**Output Matching Network**	
	Length (l_1)	*Distance (d_1)*	*Length (l_2)*	*Distance (d_2)*
3 GHz	68.47°	11.17°	91.60°	90.57°
7 GHz	104.18°	80.60°	78.28°	12.69°
11 GHz	21.58°	6.28°	86.30°	11.10°
15 GHz	19.65°	2.91°	39.47°	8.31°

These values were used in circuit simulators AWR Design Environment 2006, Microwave Office [16] and in PUFF [17]. The simulated response for first circuit is shown in Figure 4. At 3 GHz, the gain was 12.997 dB and the predicted system reflection values were –0.63128 dB for $|S_{11}|$ and –5.84996 dB for $|S_{22}|$. It was also observed that at 2 GHz the gain is within the predetermined limit, 12.37669 dB with both reflections being below 0 dB and also at 4 GHz the gain was 12.23022 dB with the reflections being below 0 dB again.

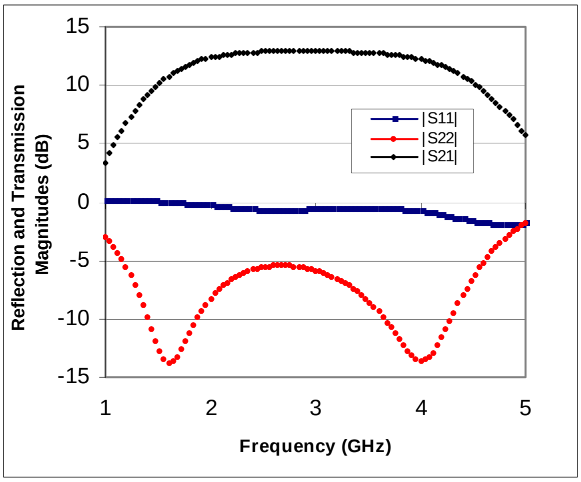

Figure 4: Frequency Response of Amplifier 1, Reflection and Transmission are indicated

For the second circuit, the design center frequency was 7 GHz with a predetermined gain of 11dB. The simulated response is shown in Figure 5. At the center design frequency the gain was 11.00129 dB with the predicted system reflection values both being well below 0 dB: $|S_{11}|$ being –2.18934 and $|S_{22}|$ being –8.93715. When the values at the edges are observed the gain was 10.78084 dB at 6 GHz and 10.8755 dB at 8 GHz with the reflections again being well below 0 dB in either side of the reflections.

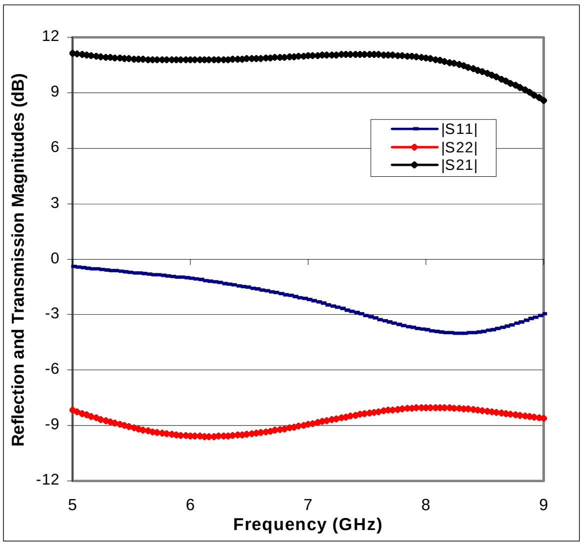

Figure 5: Frequency Response of Amplifier 2, Reflection and Transmission are indicated

For the third circuit, the simulated response is shown in Figure 6. The predetermined gain 10 dB was achieved at the center frequency of 11 GHz as 9.984969 dB, and the system reflection values at this frequency were $|S_{11}|$= -7.83954 dB and $|S_{22}|$=-2.73259 dB. At 10 GHz the gain dropped to 9.505606 dB with the reflections being below 0 dB as wanted. At 12 GHz the gain was 9,539558 with the reflections being well below 0 dB. At this frequency when we compare our result with the previous amplifier design responses we can see that the drop in gain from either of the sides of the peak are more noticeable. This is partially because in this design the value that was chosen as a target gain was closest to the maximum possible gain of this amplifier at the center design frequency.

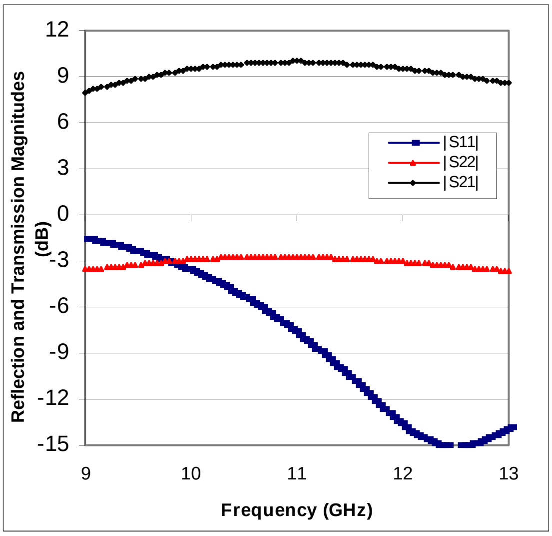

Figure 6: Frequency Response of Amplifier 3, Reflection and Transmission are indicated

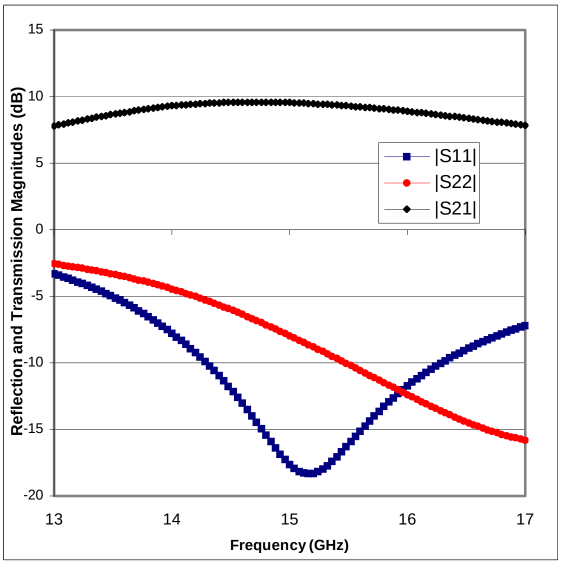

Figure 7: Frequency Response of Amplifier 4, Reflection and Transmission are indicated

For the fourth circuit, the simulated response is shown in Figure 7. The predetermined gain 9.5 dB was achieved at the center frequency of 15 GHz as 9.545349 dB, and the system reflection coefficient values at the design frequency were obtained as $|S_{11}|$= -17.6546 dB and $|S_{22}|$=-7.98403 dB. At 14 GHz a gain of 9.307687 dB was obtained whereas at 16 GHz the gain of 8.896972 dB was observed. It is also noticable that the system reflection values are well below 0 dB. Similar to the third design, when we compare this result with the first two designs, the drop in gain on either of the sides of the peak is more noticable.

III. CONCLUSIONS

In this work, particle swarm optimization, which was originally proposed by Kennedy and Eberhart [1], is applied for the design of broadband microwave transistor amplifier circuits, for the first time. Specifically the design is based on proper design of matching networks with no additional circuitry on a single stage microwave transistor amplifier. The idea is to find the transmission line lengths using particle swarm optimization technique to meet the desired gain at multiple frequencies at the same time. The values obtained by the method were used in two different simulators to verify their correctness. In all of the four test cases, the optimized values were obtained very fast, within few seconds (tested on AMD Turion 64-bit processor with 2.0 GHz processor speed and 1.00 Gbyte of RAM), and these values gave an excellent response with all the predetermined criteria being met. The results indicated that the PSO algorithm works very well and can be used as a design tool in the design of broadband microwave amplifier circuits efficiently.

REFERENCES

[1] Kennedy J., Eberhart R., 'Particle Swarm Optimization', *Proc. of IEEE Intl. Conf. Neural Networks*, Piscataway, NJ, pp. 1942-1948.

[2] Shi Y. H., Eberhart R., 'A Modified Particle Swarm Optimizer', *IEEE Intl. Conf. on Evolutionary Computation*, Anchorage, Alaska.

[3] Hu X., Eberhart R. C., 'Multiobjective Optimization Using Dynamic Neighborhood Particle Swarm Optimization', *Proceedings of the IEEE Congress on Evolutionary Computation (CEC 2002),* Honolulu, Hawaii USA, pp. 1677-1681.

[4] Gao S., Zhang Z., Cao C., 'Multiplicate Particle Swarm Optimization', *Journal of Computers*, Vol. 5, No. 1, January 2010, pp.150-157.

[5] Baskar S., Alphones A., Suganthan P. N., Liang J. J., 'Design of Yagi-Uda Antennas using Comprehensive Learning Particle Swarm Optimisation', *IEE Proceedings - Microwaves, Antennas and Propagation*, vol. 152, issue: 5, 7 October 2005, pp. 340-346.

[6] Nanbo J., Rahmat-Samii Y., 'Advances in Particle Swarm Optimization for Antenna Designs: Real-Number, Binary, Single-Objective and Multiobjective Implementations', *IEEE Transactions on Antennas and Propagation*, vol. 55, no:3, March 2007, pp. 556-567.

[7] Najjar Y., Moneer M., Dib N., 'Design of Optimum Gain Pyramidal Horn with Improved Formulas Using Particle Swarm Optimization', *International Journal of RF and Microwave Computer Aided Engineering*, vol. 17, no. 5, September 2007, pp. 505-511.

[8] Huang T., Mohan A. S., 'A Microparticle Swarm Optimizer for the Reconstruction of Microwave Images', *IEEE Transactions on Antennas and Propagation*, vol. 55, no. 3, March 2007, pp. 568-576.

[9] Wang W., Lu Y., Fu J. S., Xiong Y. Z., 'Particle Swarm Optimization and Finite Element Based Approach for Microwave Filter Design', *IEEE Transactions on Magnetics*, vol. 41, no. 5, May 2005, pp. 1800-1803.

[10] Ulker S., 'Particle Swarm Optimization Application to Microwave Circuits', *Microwave and Optical Technology*

Letters, volume:50, issue5, pp.1333-1336, doi: 10.1002/mop.23369

[11] Cengiz Y., Kiliç. U., 'Memetic Optimization Algorithm Applied to Design Microwave Amplifier for the Specific Gain Value constrainted by the Minimum Noise Over the Available Bandwidth', *International Journal of RF and Microwave Computer-Aided Engineering*, volume: 20, pp 546–556, doi: 10.1002/mmce.20460

[12] Gonzales G., *Microwave Transistor Amplifiers Analysis and Design*, G. Gonzales, 2nd Edition, Prentice Hall, 1997.

[13] Collin R. E., *Foundations for Microwave Engineering*, IEEE Press, John Wiley & Sons Inc.

[14] Pozar D. M., *Microwave Engineering*, D. M. Pozar, 3rd Edition, John Wiley & Sons Inc.

[15] Maas S. A., *Nonlinear Microwave and RF Circuits*, S. A. Maas, 2nd Edition, Artech House Inc.

[16] *AWR Design Environment 2006, Microwave Office*, Applied Wave Research Inc. , 1960 E. Grand Avenue, Suite 430, El Segundo, CA 90245.

[17] Wedge S. W., Compton R. C., Rutledge D. B., Gerstlauer A., *Puff: Computer Aided Design for Microwave Integrated Circuits*, version 2.1, California Institute of Technology, 1998.

Sadık Ülker received the B.Sc., M.E. and Ph.D. degrees in electrical engineering from University of Virginia, Charlottesville, VA, USA, in 1996, 1999 and 2002 respectively. He worked in the UVA Microwaves and Semiconductor Devices Laboratory between 1996 and 2001 as a research assistant. Later he worked in UVA Microwaves Lab as a Research Associate for one year. He joined Girne American University, Girne, Cyprus in September 2002. He was a member of Electrical Engineering Department as an Assistant Professor until 2009. Since 2009, he has been promoted to the Associate Professor status and he has also been the vice-rector of the Girne American University responsible from academic affairs since 2009. His research interests include Microwave Active Circuits, Numerical Methods, and Metaheuristic Algorithms and their applications to design problems. He has authored and co-authored technical publications in the areas of submillimeter wavelength measurements and particle swarm optimization technique. He is a member of IEEE and Eta Kappa Nu. He is also the recipient of Louis T. Rader Chairpersons award in 2001.