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Research Article

Surrogate based design optimization of low noise amplifier for ISM band

Mehmet Ali BELEN*,1, Filiz GÜNEŞ2

[1]*Department of Electrical and Electronic Engineering, İskenderun Technical University, Hatay, Türkiye*
[2]*Department of Electromics and Communications Engineering, Yıldız Techical University, İstanbul, Türkiye*

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ABSTRACT

Design optimization of microwave circuits is a crucial matter for microwave engineers. For the last decades, researchers had been studying surrogate models for a computationally efficient design optimization process. Artificial Intelligence based algorithms had been used for modelling of complex microwave stages such as antenna, amplifiers and frequency selective surfaces. In this study, design optimization of a Low Noise Amplifier (LNA) based on surrogate models for both transistor stage and input & output matching circuits had been presented. Support Vector Regression Machine had been used for creating surrogate models of a microwave transistor and a non-uniform transmission line for having a fast and accurate LNA design optimization process alongside a low profile and high performance LNA using on-uniform transmission lines. By using this methodology, not only designer can create a mapping for missing points in the sparse sample S parameter data points provided by manufacturers but also the overall simulation duration can be significantly reduced thanks to the fast nature of surrogates compared to EM simulators. Here, the proposed surrogate models had been used alongside of Particle Swarm Optimization algorithm to determine optimal geometrical values of input/output matching networks. Then the obtained designs are prototyped and measured. The measured results are also compared with the performance results of counterpart design in literature. As for results, not only the proposed methodology is an effective, fast and reliable method for computationally efficient design optimization process of LNA but also provides better results than the counterpart design in literature.

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INTRODUCTION

Design optimization of microwave circuits is a crucial matter for microwave engineers in order to answer the ever increasing demands of industry. Although with the improvement of computers hardware systems and development of high performance Microwave circuit simulation tools, still computationally efficiency is a challenging problem for design of microwave stages where repetitive calculations that are time consuming [1, 2]. For the last decades, researchers

***Corresponding author.**
*E-mail address: mali.belen@iste.edu.tr

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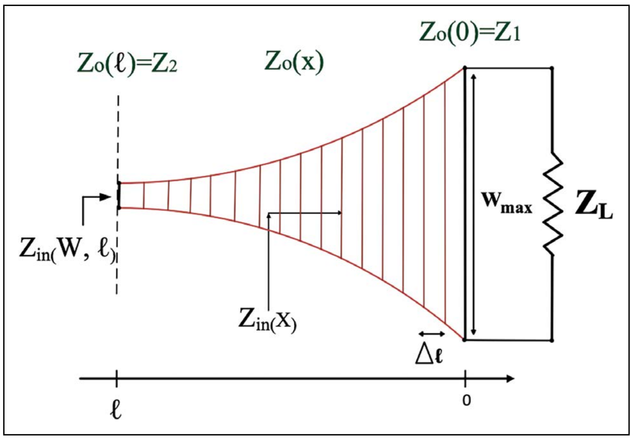

Figure 1. Schematic of an exponentially tapered microstrip line.

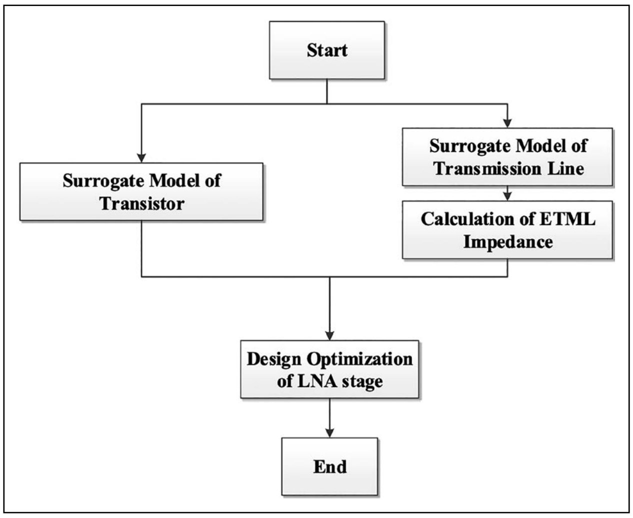

Figure 2. Flow chart of design optimization of the work.

Table 1. Training and test data set of BFP 640

V_{CE}	I_C	1(mA)	5(mA)	10(mA)
1 (V)		Train	Train	Train
2 (V)		Test	Test	Test
3 (V)		Train	Train	Train
Frequency		1–10 GHz	Sample size	0.1 GHz
Total number of samples				
Training		180	Test	90

had been studying surrogate models for a computationally efficient design optimization process. Artificial Intelligence (AI) based algorithms had been being used for modelling of complex microwave stages using Artificial Neural Network (ANN), machine learning based algorithms, such as Support Vector regression machines, Symbolic Regression, and state of the art deep learning algorithms like Convolutional Neural Networks. Some of the applications of surrogate base modelling of microwave circuits can be named as scattering parameter prediction of microwave transistors [3–7], estimation of reflection phase value of Reflectarray unit elements [8–11], modelling of Microstrip lines [12, 13], performance estimation of Microstrip antenna designs [14–16], and surrogate Modeling of Low Noise Amplifiers [17].

In this study, design optimization of a Low Noise Amplifier (LNA) based on surrogate models for both transistor stage and input & output matching circuits had been studied. Firstly by using Support Vector Regression Machine a surrogate model of a microwave transistor had been created for having a fast and accurate LNA design optimization process. Furthermore, for having a low profile and high performance LNA design instead of traditionally Microstrip transmission lines, Non-uniform transmission lines (Fig. 1) are taken into consideration. This design had been used for different type of microwave stages for having a wide operation band such as antenna designs [18]. Here, geometrical design parameters and operation frequency of a simple transmission line are taken as the input of the surrogate model while the characteristic impedance and effective dielectric constant of the Microstrip line are taken as the output of the surrogate model. Then, this surrogate model will be used for calculation of the equivalent impedance value of Exponentially Tapered Microstrip Line (ETML) to be used as either input or output matching network of the LNA design (Fig. 1). Then a multi objective optimization process had been carried out using a traditionally optimization algorithm Particle Swarm Optimization (PSO) for design optimization of a LNA design. The flow chart of the proposed work had been presented in Figure 2. As it can be seen from the figure, by using two separate surrogate models of (i) Transistor, for obtaining the Scattering and noise parameter of a microwave transistor at any given DC operation condition, (ii) ETML, for fast and accurate calculation of impedance of a ETML line for any given required input & output impedance at requested operation frequencies, a computationally efficient design optimization process for design of a LNA design can be achieved.

The paper is organized as follows: in the next section Support Vector Regression Machine (SVRM) based surrogate modelling of a microwave transistor (BFP640) and ETML had been studied. In section III, design optimization of the LNA design using generated surrogates as are studied alongside the experimental results of the proposed LNA. Finally work ends with a brief conclusion in section IV.

SURROGATE BASED MODELLINGS

Surrogate Based Modelling of Microwave Transistor

In this section, a surrogate based model for the Scattering and Noise parameters of BFP640 are modelled using SVRM. The data set given in Table 1 had been used for training the surrogate model.

Table 2. Performance Benchmarking of the SVRM model for scattering parameters

Parameter	MAE				Average MAE value	Total RME
	S_{11}	S_{21}	S_{12}	S_{22}		
Magnitude	0.232	0.017	0.027	0.07	0.086	0.099
Phase	0.107	0.195	0.39	0.228	0.23	

Table 3. Data set

Parameter	Range	Step size
εr	1–4	0.25
H (mm)	0.5–2	0.25
W (mm)	0.2–4	0.1
fr (GHz)	1–5	0.1

The performance measures of the SVRM based surrogate for the given data set are presented in Table 2. As it is well known, modelling of noise parameters of a LNA transistor is not a challenging problem, here the used SVRM based surrogate model had achieved a high accuracy of almost perfect estimation in Noise parameter with a Mean Absolute Error (MAE) value of almost zero. However it also should be noted that the SVRM had shown good performance on modelling of scattering parameters. Visualized estimation performance of the SVRM based surrogates are presented in Figure 3. Following error metrics had been used for performance measuring of the SVRM surrogate MAE and Relative Mean Error (RME). The hyper-parameters of the SVRM model are taken as Nu-SVR, with a radial basis kernel function, the Nu parameter is taken as 0.5. By using mentioned hyper-parameters, the Mean Absolute error of the model had been achieved as 0.086 for Magnitude and 0.23 degree for phase of 4 scattering parameters.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|T_i - P_i| \quad (1)$$

$$RME = \frac{1}{n}\sum_{i=1}^{n}\frac{|T_i-P_i|}{|T_i|} \quad (2)$$

As it can be seen from the figures the SVRM based surrogate transistor model had achieved a remarkable performance in estimation of both Scattering and Noise parameters of a microwave transistor. In the next subsection surrogate modelling of ETML will be studied.

Surrogate Based Modelling of ETML

In this section, using 3D EM simulation tool SONNET a surrogate model of a simple transmission line is modelled. This unit element then will be used for obtaining the equivalent impedance value of the ETML based on Figure 1 [19].

$$\frac{Z_{in}}{Z_0} = \frac{Z_L + jZ_0\tan(\beta x)}{Z_0 + jZ_L\tan(\beta x)} \quad (3)$$

$$\beta = \frac{2\pi}{\lambda}, \qquad \left(\lambda = \frac{c}{f\sqrt{\varepsilon_{eff}}}\right) \quad (4)$$

Here, it should be noted that, for input matching network, the input impedance value is taken equal to 50 ohm while the output impedance of the input matching network should be equal to the required source impedance of the transistor to operate at requested performance measures. Similarly to input matching network for output matching networks, the output impedance of network should be equal to 50 ohm while the input impedance of the matching network should be equal to the transistors required load impedance value for the requested performance measures.

The SVRM based surrogate of transmission line (Fig. 4) had been created based on the given data set in Table 3. A cross validation of K=5 (K: number of folds that the training data had been divided) had been used for training and testing the SVRM model using data set (Table 3) had been done.

Here, an epsilon type SVRM model with kernel function of radial basis had been used for modelling of the transmission line. Other user defined parameters are taken as default. With such a model a mean absolute error of 0.5 and 0.2 had been achieved for Characteristic impedance and effective dielectric constant values. Thus, it can be concluded that with a mean absolute error of less than "0.5" for each of the outputs, SVRM based surrogate has a high accuracy rate in prediction of impedance values with respect to the geometrical design variables and operation frequency. In the next section a design optimization process had been achieved using the obtained SVRM surrogate.

DESIGN OPTIMIZATION OF LOW NOISE AMPLIFIER

In this section, design of LNA stage is taken as a multi objective multi variable optimization problem [20] to determine the geometrical design parameters of ETML to satisfy the required ZS and ZL termination. In Table 4, targeted load and source terminations of transistor had been given for the requested performance measures. These values are obtained by solving the transistor Feasible Design Target Space of transistors [21–23].

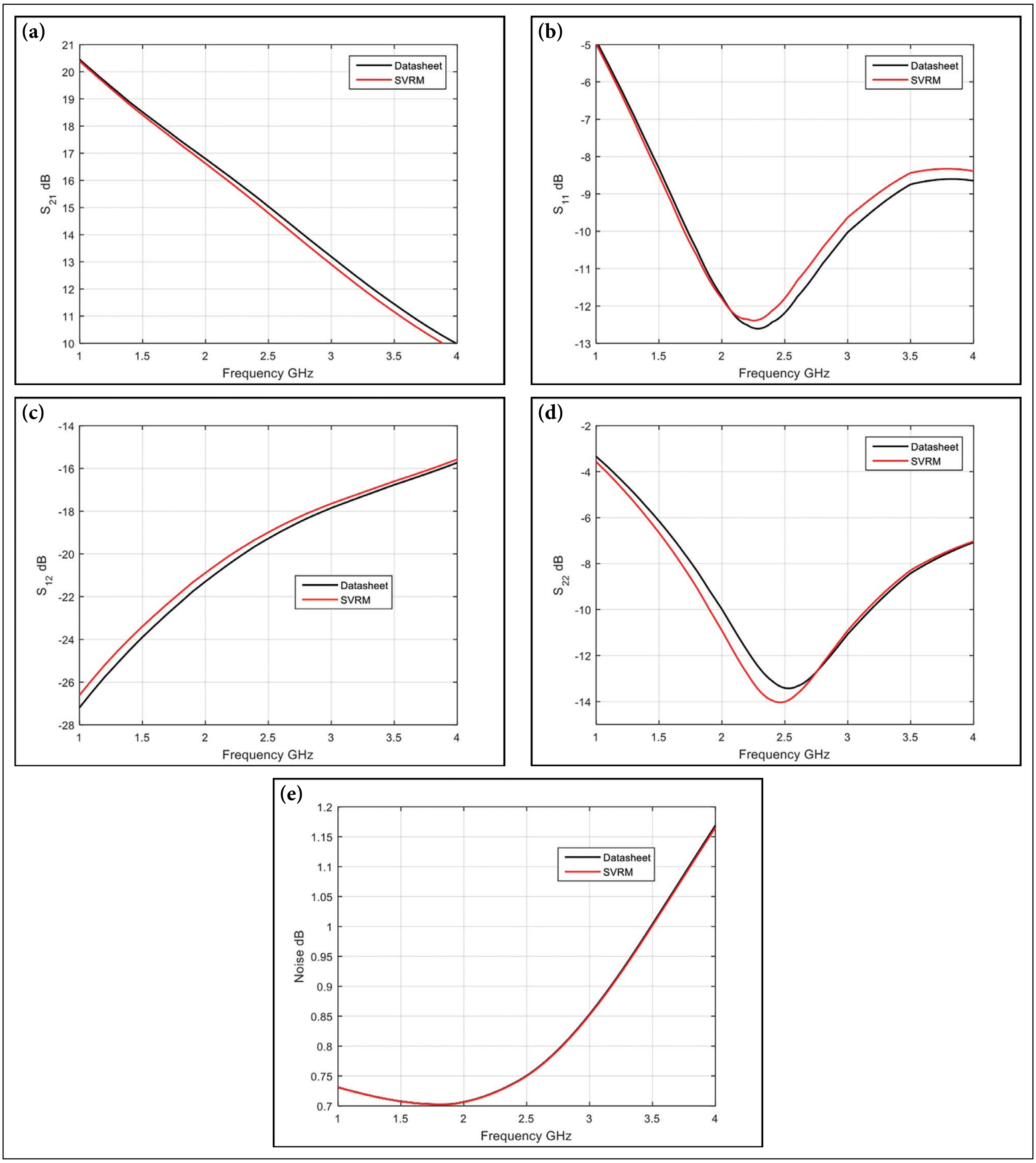

Figure 3. Predicted and measured (datasheet) **(a)** S_{21}, **(b)** S_{11}, **(c)** S_{12}, **(d)** S_{22}, **(e)** Noise Figure, at the bias condition of V_{CE}=2V, I_C= 5mA.

Here, Eqs. (5–6) had been used for determination of geometrical parameters of the ETML. As it shown in Figure 5, a combination of two powerful Artificial Intelligence algorithm Particle Swarm Optimization and SVRM had been used for determination of optimal geometrical design parameters of ETML ($w_{\min}$, $w_{\max}$, minimum and maximum width of the transmission line, l length of the transmission line, a the coefficient of the exponential curve of the line) to satisfy the requested source and load termination of LNA transistor given in Table 4 using Eqs. (3–7) using the methodology presented in Figure 5 [19].

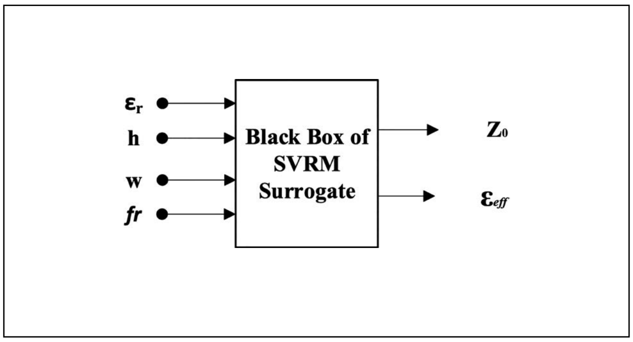

Figure 4. Black box model of the SVRM based ETLM surrogate.

Table 4. Required load and source terminations of transistor for selected performance measures

R_L= 102.331	X_L= 72.869	$F=F_{min}$=0.74 dB	G_T=15.5 dB
R_S= 63.364	X_S= 24.857	V_{out}=1.5	V_{in}=1.62

Table 5. Solutions of the exponential type microstrip IMC and OMC elements

Section	w_{max}(mm)	w_{min}(mm)	ℓ (mm)	α
Input matching	3	1.3	5.14	0.162
Output matching	2	0.8	4.8	0.19

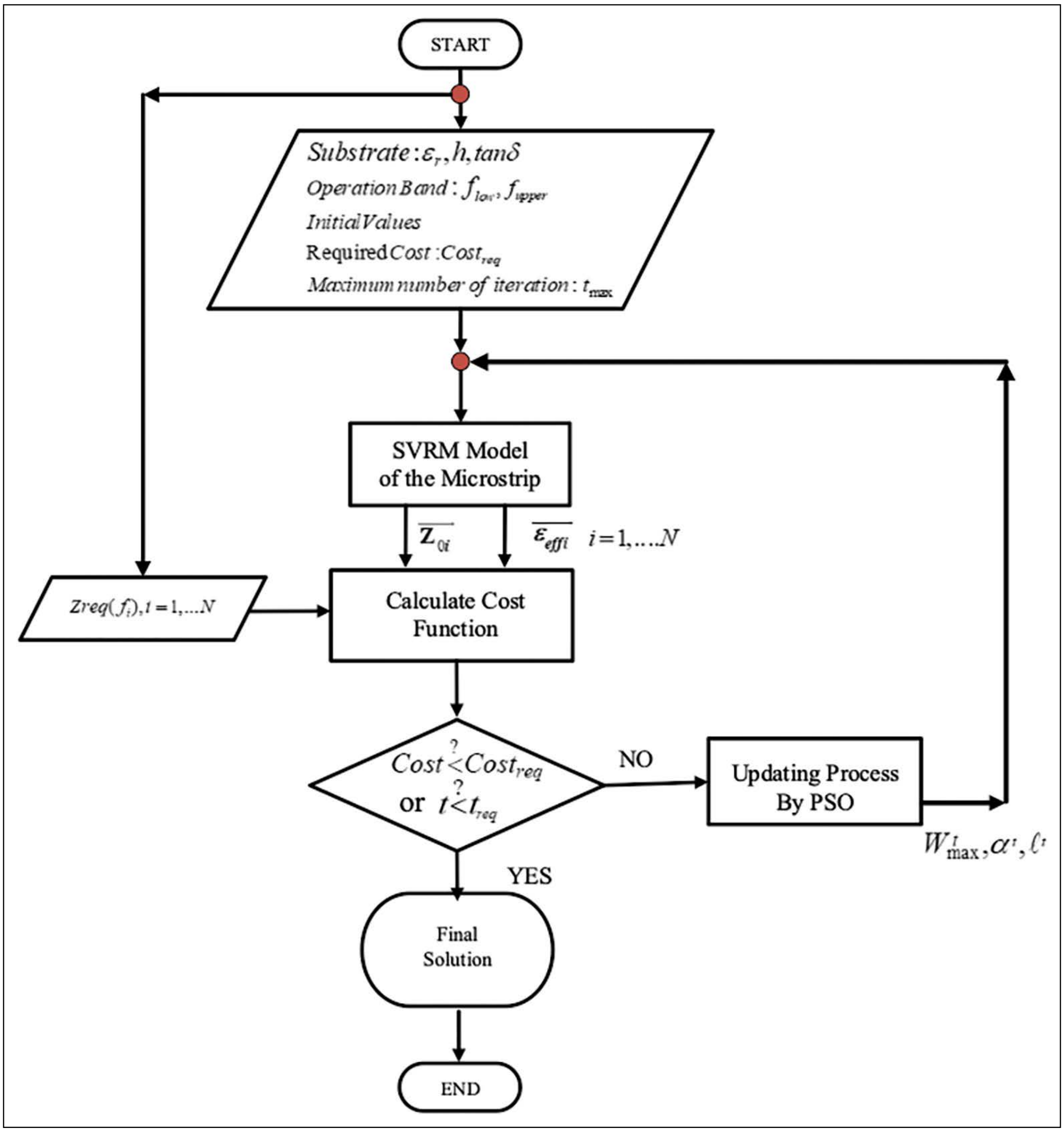

Figure 5. Flow chart of design optimization of the ETML Based on SVRM surrogate.

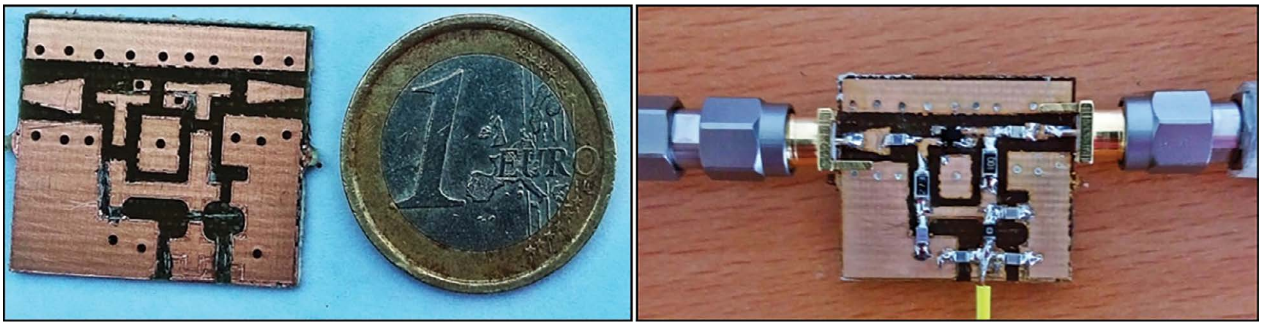

Figure 6. Fabricated LNA circuit.

Table 6. Table of comparison of proposed LNA design with counterpart design in literature

Parameters	Here	[24]	[25]	[26]	[27]	[28]	[29]	[30]
Frequency [GHz]	2.4	2.45	2.4	3	5.8	5.75	5.8	2.4
Gain (dB)	15	14.3	15.45	15	15.2	14.2	16.7	>10
Input return loss (dB)	<-10	-24	-25.7	<-7	-51.6	-8	-23	<-10
Output return loss (dB)	<-12	-32	-6	<-7	-40.7	-19	-25	<-10
1 dB compression point (dBm)	-10	-7	---	3	-17	---	-15.6	-
Stability (K)	>1	>1.5	---	---	>1	>1	>1	-
Simulated noise figure (NF) (dB)	0.74	0.9	0.8	3	2.5	0.9	1.4	0.6
Technology	SiGe			SiGe BiCMOS HBT		0.18 mm CMOS		E-PHEMT

$$Z_{0\,SVRM} = f(w_{\min}, w_{\max}, l, a) \tag{5}$$

$$\varepsilon_{eff\,SVRM} = f(w_{\min}, w_{\max}, l, a) \tag{6}$$

$$\mathrm{Cost} = \sum_{i}^{m}\left(\left|R_{in_{SVRM}}(f_i) - R_{inreq}(f_i)\right| + \left|X_{in_{SVRM}}(f_i) - X_{inreq}(f_i)\right|\right) \tag{7}$$

After the definition of operational conditions of the optimization problem (Frequency band, Requested cost, stopping criteria etc.) for a randomly selected initial population cost function (Eq. 7) will be calculated using the proposed SVRM surrogate model of transmission line. Then based on the obtained cost values the position of these initial solutions had been updated using the PSO algorithm. This process is repeated until either the requested cost function or the other stopping criteria such as maximum iteration or maximum computation time have been achieved. For each of the matching networks, an optimization process had been done. The results of the optimally selected geometrical design variables for each of the matching networks are presented in Table 5. The selected material as substrate is FR4 (h=1.6 mm and εr= 4.6).

In order to justify the performance of the proposed methodology, the proposed LNA design with ETML matching network had been prototyped (Fig. 6) and measured. The prototyped design has a size of 21.5x25.75 mm^2. The measured experimental results of the prototyped, LNA design with ETML matching network had been presented in Figures 7, 8. The Rohde & Schwarz vector network analyzer with a bandwidth of 9 KHz–13.5 GHz had been used for measurements.

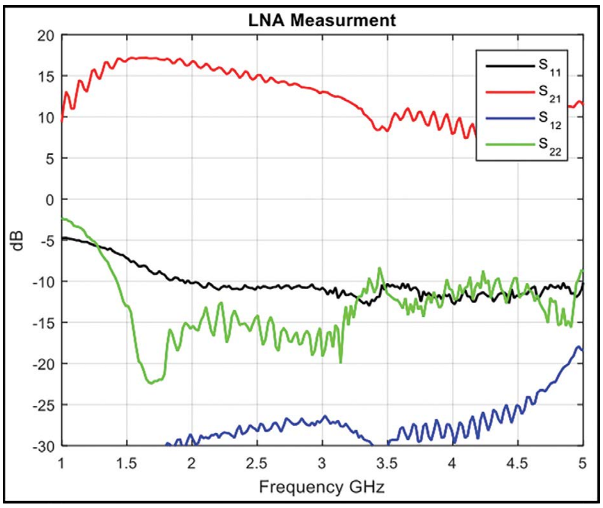

Figure 7. Measured S parameters of the LNA.

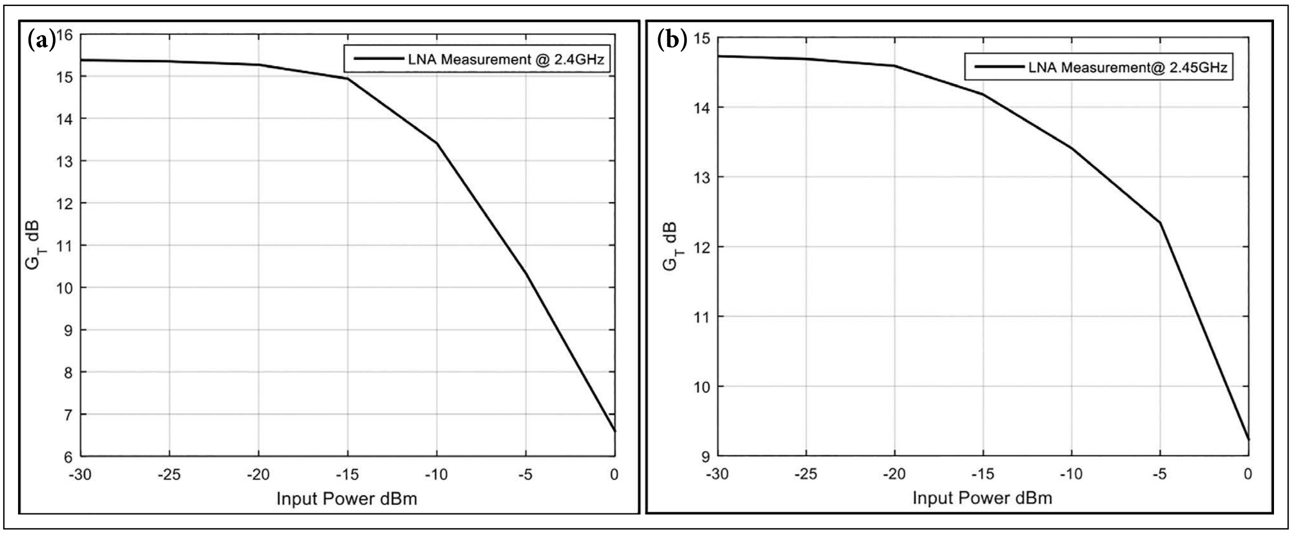

Figure 8. Measured 1 dB compression point **(a)** @2.4GHz, **(b)** @2.45GHz.

As it can be seen from Figures 7, 8, the proposed design not only achieves a good performance on aimed 2.4 GHz but it also has a good operation band between 2.2 and 2.8 GHz (a return loss level of less than 10 dB). Furthermore as it can be seen from Figure 8, the proposed LNA has a 1 dB comparison point of almost -10 dBm which make it a good candidate to be used in many wireless applications for ISM band.

A further analysis on the performance of the proposed LNA design had been presented in Table 6, where the performance measures of the proposed design had been compared with counterpart design in literature [24–30]. When compared to [24], the proposed design achieves better gain performance, while the other performance measures seem a bit better, it should be noted that the results given in [24] are only simulated results. In comparison between [25, 26, 28] although the designs have similar gain the counterpart either has worse return loss or 1 dB compression points compared to the proposed design. In [27] although both designs have similar performance 1 dB compression is much lower than the proposed design. Finally compared with [30], the proposed design achieves much better gain. Thus as it can be seen from Table 6, the proposed design achieved a good overall performance compared to the design in literature in means of 1 dB comparison point (-10 dBm) without having any deterioration in input or output return loss. The stability and gain performance of the proposed design are the same with other designs, even though the proposed design has a better 1 dB compression point and low measured return loss characteristics with a profile size of 21.5x25.75 mm^2.

CONCLUSONS

Here in, by using SVRM based surrogate model design optimization of a LNA stage for ISM band applications had been studied. Firstly a selected microwave transistor (BFP 640) had been modelled using the measured data gathered by manufacturers using SVRM surrogate. As a result it has been seen that SVRM achieves a very good estimation performance for both scattering and noise parameters, which make it a good candidate to create microwave transistors surrogate models. After that, a SVRM based surrogate model of a Microstrip transmission line had been created to be used for calculation of impedance value of ETML in a computationally efficient way. Thus, a very accurate surrogate model for estimation of impedance value of Microstrip transmission line with respect to its geometrical design parameters. Finally the surrogate models had been used alongside of the PSO algorithm to determine optimal geometrical values of input/output matching networks. Then the obtained designs are prototyped and measured and the experimental results had been compared with counterpart designs in literature. As it can be seen from the experimental results, the proposed methodology is an effective, fast and reliable method for computationally efficient design optimization process of microwave stages such as LNA.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The published publication includes all graphics and data collected or developed during the study.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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