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Analysis of an inverted square SRR via design of experiment (DoE) approach

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A design of experiment (DoE) study is presented based on an investigation of the influences of the chosen geometric parameters of an Inverted Square Split Ring Resonator on its resonance frequency. A statistical software was used to determine DoE steps and the values of chosen geometrical parameters for the experiments. The determined experiments were carried out by making simulations with electromagnetic design software. The resonator simulation outputs were analyzed by using normality tests and tools of the statistical software. By using these analyses, mainly a 2-level full factorial DoE approach, the effects of the geometrical parameters (input factors), and their interactions on the resonance frequency (response factor) were presented. In the light of our findings, this study proposes a promising path for microwave studies with several advantages such as being able to understand the dynamics of an optimized RF resonator device system, designing these kinds of devices with a few experiments, and increasing the time efficiency via reducing the number of attempts.

K e y w o r d s: design of experiment (DoE), RF device, split ring resonator (SRR)

1 Introduction

Design of experiment is a statistical method mainly utilized for improving the performance of the product and/or the manufacturing process and optimization of new methodologies in many fields such as medicine, chemistry, biology, agriculture, industry and other fields [1-5]. The DoE approach can be utilized to determine the number of experiments to be performed and to analyze the effects of starting parameters on the outputs, gives researchers an opportunity to avoid unnecessary random trials and to perform their experiments within a plan [6], [7]. Furthermore, it allows designer to notice the overlooked relations between the variables. Consequently, the target design can be achieved with a limited number of experiments via DoE approach [7].

However, it is rare to come across the DoE approach in RF/microwave engineering studies, where parametric studies are intensive such as design of filter, antenna, and resonator [8], [9]. For this microwave DoE study, a resonator, one of the most practiced devices in RF applications, was chosen. Split-ring resonators (SRR) with their unique property of negative magnetic permeability in the resonance region have been subject to many researches [10]. The SRR are structurally composed of different numbers and shapes of metal rings etched on a dielectric substrate [11-13]. In the design of the resonators, the response factors are related to many parameters and to get the desired results it is needed to solve arduous numerical equations, to try many cases or use empirical methods. There are several studies that investigate the resonators generally employed the one factor at a time (OFAT) approach to analyze the effect of each geometric parameter separately [14-16]. In these studies, only influences of a geometric parameter on the response factor are evaluated, while the other factors are kept constant. At these kinds of analyses, the obtained results and system characteristics are not only related to the studied parameter but also related to all other constant variables. If the constant parameters were fixed at different values, the system output could be totally different due to the interaction of parameters [17]. Using OFAT kinds of models to obtain aimed outputs is becoming more challenging and time consuming with the increase of the number of parameters and trials [15], [16]. Additionally, in case of not having a predetermined systematic methodology, generally all or part of experiments need to be repeated which results in wasting the sources and time inefficiently. In order to overcome the mentioned problems, the usage of DoE approaches has been getting important and essential in microwave studies [17-19].

In this research, the effects of selected geometrical parameters on the resonance frequency of a type of SRR, inverted square split ring resonator (hereafter noted as IS-SRR) were investigated and analyzed statistically by using the 2-level full factorial DoE approach. The determined experiments with this design method were implemented in simulations. The obtained results were also compared with a general full factorial DoE approach which includes 80 trials to show efficiency of the proposed method. We believe that this paper will contribute to research and development studies by showing an alternative path to obtain targeted designs systematically for the mi-

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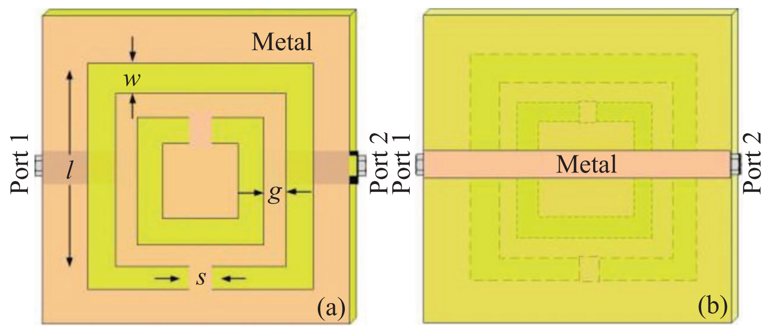

Fig. 1. Schematic drawing of: (a) – dimennsions and front side of the designed IS-SRR, (b) – back side of the IS-SRR

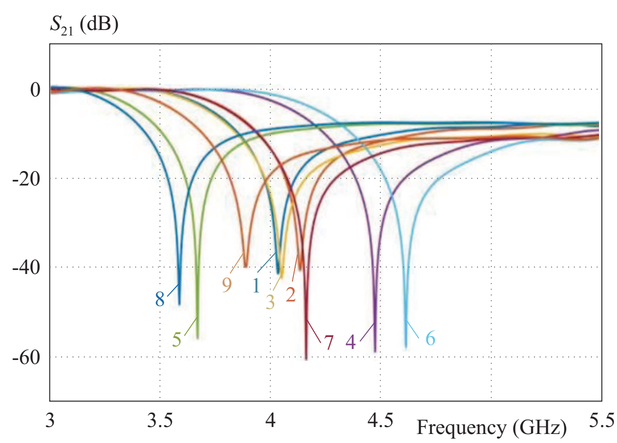

Fig. 2. Resonant S_{21} spectra simulated by CST as the geometric parameters are varied with the defined run order

crowave devices with a limited number of trials by using the DoE approach.

2 Material and method

IS-SRR was chosen to show the utilization of the DoE approach in design and optimization of a microwave device. IS-SRR is one of the members of the split ring resonator family which has characteristics of metamaterial and many uses in RF filters to sensors. The resonator consists of a microstrip line (0.55 mm) on the backside and a pattern of two concentric etched square rings with slits on opposite sides as shown in Fig. 1. The split width of the rings (split_width, s), the width of the rings (ring_width, w), and the distance between the rings (ring_gap, g) were selected as the dimension of IS-SRR to investigate. These parameters arranged to keep the length of the outer square ring ($l = 5\ mm$) constant. To preserve the shape of the pattern of the resonator and considering fabrication limitations, the upper and lower limits of the parameters s, g, w were chosen 0.2, 0.2, 0.5 mm and 0.5, 0.5, 0.9 mm, respectively. In simulations, the RO3003 model substrate was used with dimensions of 15 mm $\times$ 20 mm $\times$ 0.25 mm, dissipation factor 0.0010 at 10 GHz, thickness of copper cladding 17 μm, and relative dielectric constant 3.

The correct use and selection of the DoE method to investigate parameters on resonance frequency are also important in terms of time efficiency and obtaining reliable results [3]. Factorial experiment designs are generally appropriate methods for a DoE with more than 2 variables to investigate the influence of variables on the response factor. A fractional or 2-level ($2k$) DoE approach in which only 2 levels for every factor are considered can be chosen to prevent the drawback of a high number of experiments in OFAT approaches [20]. 2-level designs meet the experimental requirements of this study [1-3], [7]. For this reason, a set of 9 trials, 2-level DoE of 8 experiments with 2 levels and 1 experiment with intermediate values, was designed and analyzed by taking correlations of factors into account. OFAT like the general full factorial DoE method, consisting of 80 experiments with $4 \times 4 \times 5$ levels was also examined to compare with the proposed method. All DoE input parameters were determined and resonance frequency outputs of CST simulations were investigated by using Minitab Statistical Software (MSS v.17).

3 Results

In order to show the advantages of DoE approach, first the 2-level DoE input parameters were studied. The set of experiments for the chosen 3 factors and the S21 simulation results of the designed IS-SRR for the experiment set are presented in Tab. 1. The simulation results of

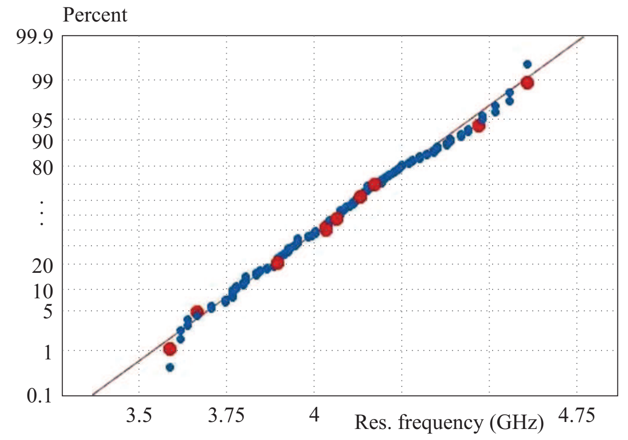

Fig. 3. Normality test for both general full factorial (blue dots) and $2k$ factorial (red dots) design

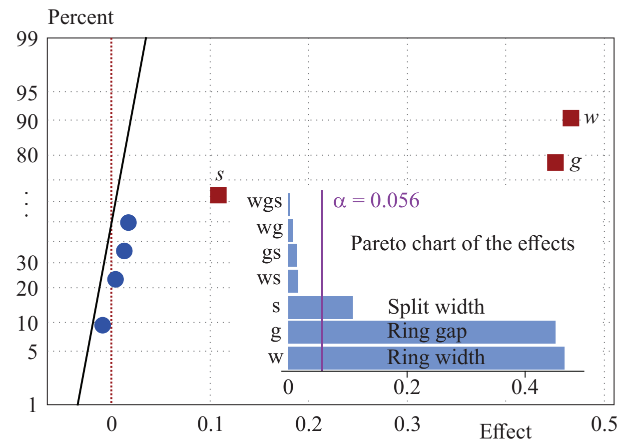

Fig. 4. Normal plot of the effects (inset: Pareto chart of the effects)

frequency responses of the designed resonator were also shown in Fig. 2.

Table 1. Simulaton results for the varied dimensions

Run order	Ring_width w (mm)	Split_width s width (mm)	Ring_gap g (mm)	Frequency (GHz)
1	0.5	0.50	0.20	4.04
2	0.5	0.50	0.50	4.14
3	0.9	0.20	0.20	4.05
4	0.9	0.50	0.20	4.48
5	0.5	0.20	0.50	3.67
6	0.9	0.50	0.50	4.62
7	0.9	0.20	0.50	4.16
8	0.5	0.20	0.20	3.59
9	0.7	0.35	0.35	3.89

The distribution of the data set was analyzed in order to obtain a meaningful relationship between inputs and output. A normal probability plot as a normality test, one of the best ways for determining the distribution of the data especially for a less number of experiments [21], was obtained for our data as shown in Fig. 3. The x -axis represents the output data, and the y -axis shows the ratio of the number of data, which is smaller than an obtained output value, to the total number of data. For normally distributed data, the probability plot should produce a roughly straight line and the density of data should decrease as you go towards the ends. As can be seen, the results of both 2-level full factorial DoE (9-trials-set) and traditionally employed 80-trials-set of general full factorial DoE approaches illustrate parallel outcomes and fit to the normally distribution criteria.

As a next step the parametric tests were applied to determine the significance of input parameters and their interactions on the output parameter. The normal plot of the effects given in Fig. 4 shows both how much the parameters affects the output parameter and in which way the response is affected. The effects located on the right side of the zero are positive effects which increase the output with the increasing values of them and vice versa. All the effects except $w{*}g$ are on the right side of the zero line and are called positive effects. The significant effects are signed with red square dots and not/less significant ones are signed with blue dots in Fig. 4. The intensity of the effect is evaluated with its distance to the zero line, so the most effective parameter is the furthest one, w.

Another way to analyze the significance of parameters is the Pareto chart of geometric parameters with respect to effects on the resonance frequency. This relationship is given in inset of Fig. 4. The effects, magnitudes higher than the statistically calculated reference line (denoted by $\alpha = 0.056$, automatically assigned by the software), are called significant effects such as w, g and s. On the contrary, the interacting terms (cross products) such as $w*g, w*s, g*s$ and $w*g*s$ are determined to have less significant effects. Both data analyses show that for the studied frequency range ring width (w) and ring gap (g) are the most important variables for the resonance frequency and also split width (s) is an important parameter [16]. The less significant 2-way and 3-way interaction terms could not be totally ignored because it is shown in the following results that they cause local minimums at the resonance frequency function [22].

The obtained contour plots, show the influences of input parameters, are presented in Fig. 5. In these plots, the general tendency of increase at resonance frequencies with increase of the value of input parameters is one of the expected inferred from the interpretation of the Fig. 4. The results of Fig. 5(a), where the maximum change at resonance frequency is observed, support that the most significant effects are g and w parameters as found before. The data in Fig. 5(b) and 5(c) follow the same pattern as in Fig. 5(a) in terms of the resonance frequency increase. The decrease of equivalent capacitances and inductances by the increase of the input parameters is expected to increase the resonance frequency in computational equivalent circuit models [13], [22], [23]. It is satisfactory that

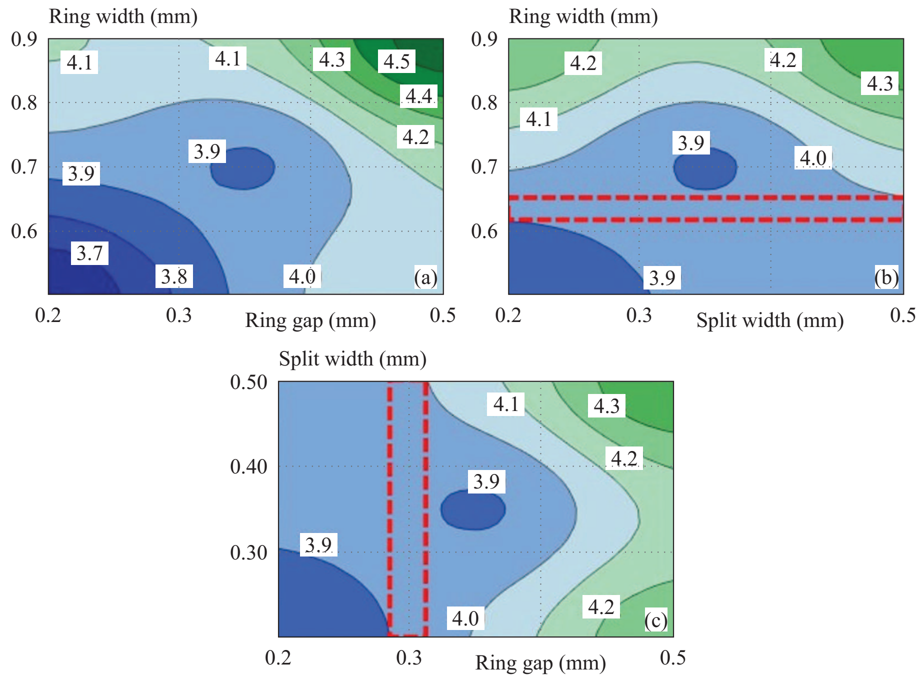

Fig. 5. The contour plots of resonance frequency versus geometrical parameters of IS-SRR

the reported results in Fig. 5 are consistent with the earlier studies where the OFAT approach used [12-14]. In addition, these figures also illustrate that the influence of the s parameter is lower than the g and w parameters in that when s is taken as a common variable the change of the output is lower as seen in these figures. In Figure 5 it is seen that a local minimum area exists in each subplot owing to the interaction of parameters. There are also some areas (shown with red dotted rectangular) where one of the parameters has relatively small influence on the output parameter. In this regime, such as in Fig. 5(c) when the (g) value is around 0.3 (shown with red rectangular), s is a nearly ineffective parameter. It is possible to reduce the number of variables and increase efficiency by setting one of the parameters between these ineffective values. Furthermore, by fixing the resonance frequency around the less effective parameter it is possible to optimize other possible output parameters by changing the less effective parameter. These kinds of possibilities/scenarios give insight and so freedom to choose the optimum value of other parameters within the region of response factor.

As an important remark, when we compare results of the 80 experiments set (similar to OFAT) with the 2-level 9 experiments set we mainly observed just the resolution change whereas the general pattern remains the same. Furthermore, to the best of our knowledge, this is the first time; interactions between factors have been taken into consideration for a RF resonator device design. Therefore this proposed DoE method may give RF researchers a new perspective to examine the effects of parameters in their designs.

4 Conclusions

In this paper, 2-level factorial designed experiments were set, implemented and the effects of parameters and their interactions on resonance frequency were examined statistically by using the DoE approach to investigate IS-SRR, a RF resonator, with a few experiments. The most significant parameters were found to be the width of the rings and the distance between rings whereas the split width is relatively less significant. As a conclusion, this study presents that using the DoE approach in the microwave/RF studies has several advantages like examining the influence of generally overlooked factor interactions, being able to understand the dynamics of an RF device with a few experiments, and so increasing the time efficiency of an optimized design.

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