Optimization of FSS Filters

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***Abstract*—**This work aims at description of the optimization process of frequency selective surfaces. The method of moments is used to analyze the planar periodic structure and thus to estimate the corresponding transmission coefficients. The algorithm of Levenberg-Marquardt is chosen as a local optimization method. The approach of combination of the method of moments and optimization allows to automate the whole process of the filter design and frees the users from the detailed knowledge of the filter design theory. This work also contains an example of a band-stop filter which is optimized to reflect the Wi-Fi signal. S-parameters of the initial and optimized filters are presented in the paper. This work compares three possible geometries made of simple elements, rectangles. It is a simple cross, a Jerusalem-cross and an H-element. Whole process of automation was implemented in Matlab.

***Keywords*—**band-stop filter, frequency selective surface, local optimization, planar periodic structures, Wi-Fi signal

I. Introduction

Frequency Selective Surfaces (FSSs) are important spatial filters which can efficiently filter desired band of frequencies. Therefore these can play a significant role in electromagnetic related problems.

To briefly sketch the history, the beginning of FSS relates to Ben A. Munk who was the guru of this approach [1]. In the last decade, the idea of FSS has spread out into many applications. Example of a band-pass FSS is in [2], [3] where the goal was to transmit GSM signals through energy efficient windows. The first FSS absorber was presented by Salisbury and Jaumann [4], [5]. Ghaffer et. al., [6] and Umair et. al., [7] proposed a novel and compact design to obtain stable frequency response by absorbing 5 GHz Wi-Fi signals.

Great research has been already done in the field of FSS including also the analysis of frequency characteristics of dielectric period structures [15] and another analysis of characteristics of dielectric grating of left-handed and right-handed materials [16]. FSS are also used in the antenna theory and experiments like analysis of ultra wide band planar monopole antenna and its design [17].

In this paper there are several aims. The first one is to describe the possibility of filtering of 2.4 GHz Wi-Fi signal (approach presented in [8]). The second aim is to examine three different FSS geometries. And the last goal is to figure the influence of the number of the metallic layers of which the FSS filter consists.

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II. Statement of the Problem

Assume that there is a need to prevent transmission of Wi-Fi signal so that it cannot spread out of a given room.

A Wi-Fi device communicating under standard 802.11b or 802.11g uses a specific channel which has frequency between 2.412 and 2.484 GHz [8]. Therefore the goal is to design a band-stop filter (ideally a wallpaper) which does not transmit mentioned band of frequencies.

III. Design of an Appropriate FSS

In this paper three geometries are examined. It is a simple cross, a Jerusalem-cross and an H-element. Initially, these schemes are double-layer to provide a narrower band-stop filter. The schema is presented in Fig. 1. Theoretically, the second geometry may have better reflection in comparison with a simple cross. Also another geometry was tested in this work, it is a simple H-element. All the models consist of simple rectangular elements.

In Fig. 1, a represents the width and height of a cell (a_j and a_h respectively for other geometries; a cell is just one element of the whole FSS), l is the total width and height of the cross (l_j and l_h respectively for other geometries), w is the width of an arm (w_j and w_h respectively for other geometries) and l_{ej} represents the length of the bar connected to the end of an arm of the Jerusalem-cross.

The electrical conductivity of the metallization is 56 MS/m and the thickness is 17 µm. The relative permittivity of the dielectric layer (between conductive layers) is 1.0 and the thickness is 1.57 mm.

IV. Optimization

A frequency range, an initial geometry with design variables (e.g. width and height of the arms of the cross) and optimization goals must be set before performing the optimization of an FSS filter.

The transmission coefficient depends on frequency and other parameters forming the parameter vector of the filter which specifies the geometry (defined by design variables). An optimization method searches for the set of parameters which satisfies the given objectives, at least approximately, being thus in a certain sense optimal.

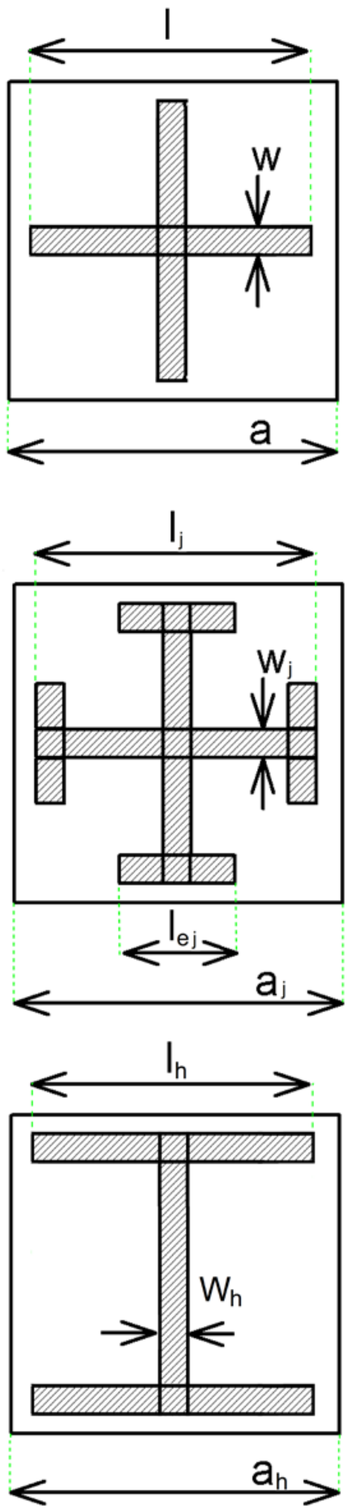

Fig. 1 schema of a cell containing the simple cross (on the left) and the Jerusalem-cross (on the right)

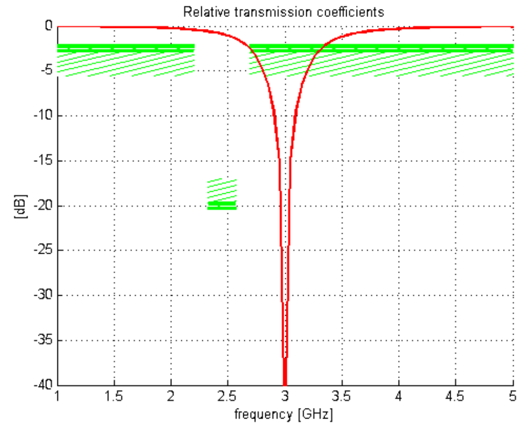

Fig. 2 transmission coefficients of the initial simple cross FSS Wi-Fi filter (to be optimized)

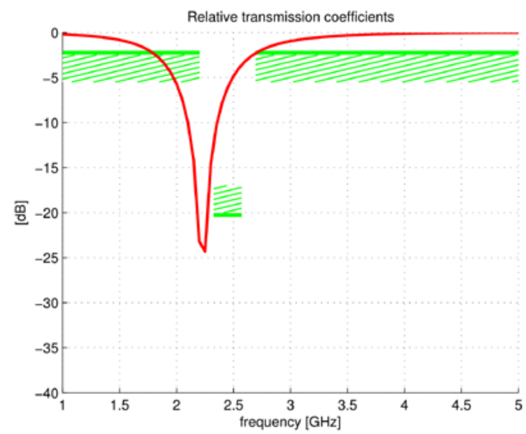

Fig. 3 transmission coefficients of the initial Jerusalem-cross FSS Wi-Fi filter (to be optimized)

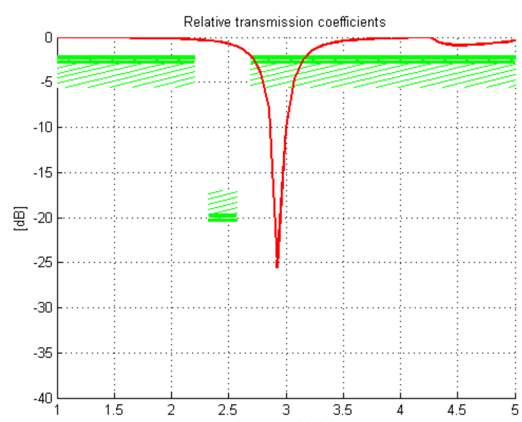

Fig. 4 transmission coefficients of the initial simple H-element FSS Wi-Fi filter (to be optimized)

An optimization goal is defined by a frequency range where the transmission coefficient must be lower or greater than a threshold value set by the user.

In our experiment three optimization goals were modelled (what is also illustrated in Fig. 2, Fig. 3 and Fig. 4 together with results of the initial configurations):

- To pass frequencies from 1.0 to 2.2032 GHz (threshold: -2.5 dB)
- To stop frequencies from 2.3256 to 2.5704 GHz (this range relates to the Q factor equal to 10, threshold: -20.0 dB)
- To pass frequencies from 2.6928 to 5.0 GHz (threshold: -2.5 dB)

The initial values of design parameters with lower and upper bounds are mentioned in Table 1 where

$$l = k\, a \quad (1)$$

$$l_j = k_{1j}\, a_j \quad (2)$$

$$l_{ej} = k_{2j}\, l_j \quad (3)$$

$$l_h = k_h\, a_h \quad (4)$$

Table 1 description of design parameters related to the simple cross, Jesrusalem-cross and simple H-element FSS filters (see Fig. 1; index *j* relates to the Jerusalem-cross geometry and index *h* relates to the simple H-element geometry)

Param.	Description	Initial Value	Lower Bound	Upper Bound
a	The width and height of a cell [m]	0.06	0.04	0.08
w	The width of an arm [m]	0.003	0.001	0.006
k	The width parameter ($k = l / a$)	0.8	0.6	1.0
a_j	The width and height of a cell [m]	0.05	0.03	0.07
w_j	The width of an arm [m]	0.002	0.001	0.003
k_{1j}	The width parameter ($k_{1j} = l_j / a_j$)	0.85	0.7	1.0
k_{2j}	The length parameter ($k_{2j} = l_{ej} / l_j$)	0.35	0.2	0.5
a_h	The width and height of a cell [m]	0.07	0.05	0.09
w_h	The width of an arm [m]	0.003	0.001	0.006
k_h	The width parameter ($k_h = l_h / a_h$)	0.8	0.6	1.0

In this work, optimization was performed numerically using an implementation of local optimizer Levenberg-Marquardt (a possible alternative is *fmincon* [14] or *fminsearchbnd* [13] which can be directly used in Matlab or it can also be an evolutionary algorithm).

The settings of the optimization process:

- Optimization technique: Levenberg-Marquardt
- *FunTol* = 10^{-3}, this represents the threshold tolerance
- *MaxIter* = 100, this constant is the maximal number of iterations
- *NormStep* = 0.06, this is the constraint on maximal norm of a step
- Constraints on design variables a, w, k, a_j, w_j, k_{1j}, k_{2j}, a_h, w_h, and k_h respect the lower and upper bounds mentioned in Table 1
- Cost function used the method of moments [1], [9], [10], [11] to analyze and estimate the FSS transmission coefficients

All computations by optimization were based on perpendicular angle of incidence only (the influence of the angle of incidence may be examined in a further work).

In this study, we used FSSMR software [12] which was developed at Tomas Bata University in Zlin and which analyses the planar periodic structures and tries to optimize them with respect to the optimization goals.

V. Results

The optimization procedure results in good filters in the all three cases.

The process of optimization in Matlab took at about four hours using an average computer (for one geometry; mainly depends on the number of tested frequency points and the complete number of mesh cells in the computation therefore the computation of the transmission coefficients of the most complicated geometry in this study — the Jerusalem-cross — took more time than the computation of the coefficients of the other geometries).

A. Results of Various Geometries

The final transmission coefficients of optimized FSS filters are presented in Fig. 5 (simple cross), Fig. 6 (Jerusalem-cross) and Fig. 7 (simple H-element).

The Jerusalem-cross FSS filter performs a little bit better in comparison with the simple cross filter.

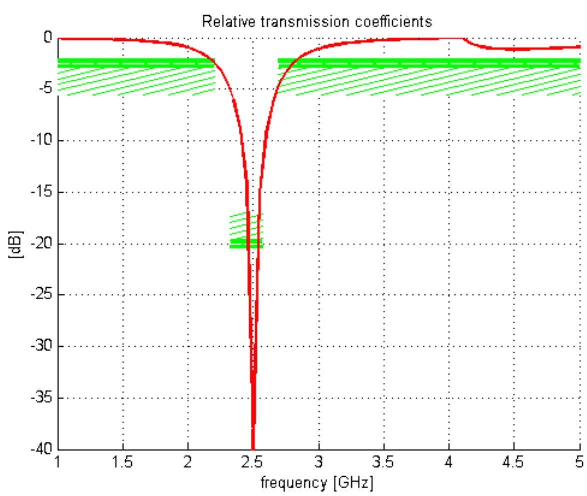

Fig. 5 transmission coefficients of the optimized simple cross FSS Wi-Fi filter (two metallic layers)

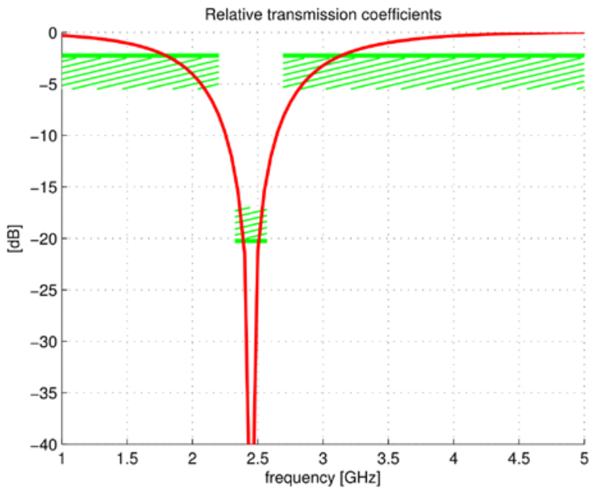

Fig. 6 transmission coefficients of the optimized Jerusalem-cross FSS Wi-Fi filter (two metallic layers)

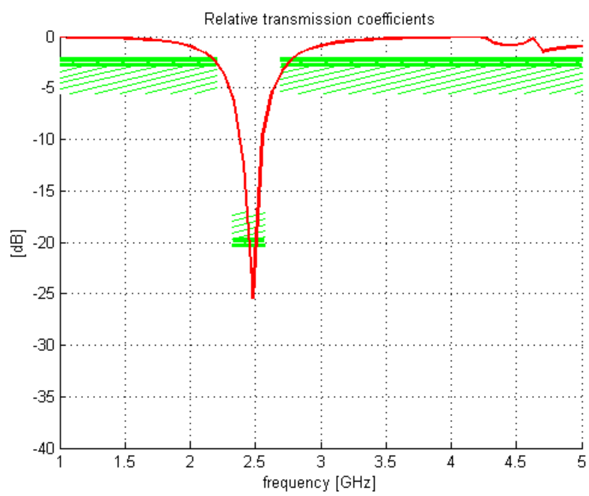

Fig. 7 transmission coefficients of the optimized simple H-element FSS Wi-Fi filter (two metallic layers)

The optimized simple cross filter is a too narrow band-stop filter which does not reflect the lower channels of Wi-Fi signal well. There is also some kind of a low subsidiary attenuation between 4 and 6 GHz. This attenuation is also similar to the one in the resulting transmission coefficients of the simple H-element. This filter was expected to the worst one but the results are not so flat. This filter is a quite narrow-band filter but could also reflect the central Wi-Fi frequencies sufficiently.

The Jerusalem cross filter suppresses well the central channels of 2.4 GHz Wi-Fi b/g. The first and the last channels are partially transmitted, the attenuation is around -15 dB for the Jerusalem cross filter what can be considered as not a perfect but still good filter. Perfect suppression of signals on these boundary frequencies may be also processed in a further research.

Comparing the results the verdict is clear. The Jerusalem-cross is the best performing FSS filter from the presented test set.

B. Comparison of Various Numbers of Layers

Also another experiment has interesting results. Considering the transmission coefficients of Jerusalem-cross FSS filter with increased number of metallic layers from two to three the results are not better (without running optimization in this case again; see Fig. 8). Also after repeating the whole process of optimization when using three layers did not give better results.

Fig. 9, Fig. 10 and Fig. 11 continue in this experiment in using one, four and five metallic layers respectively (to have complete study of impact of one to five layers). It is interesting to observe some kind of parasitic behavior of FSS filter consisting of higher odd number of metallic layers (three and five, Fig. 9 and Fig. 11) around 2.4 GHz.

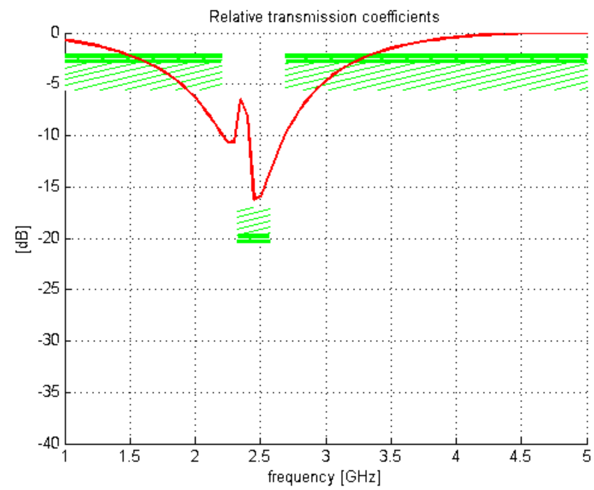

Fig. 8 transmission coefficients of the final Jerusalem-cross filter with one more metallic layer (without running the optimization process again)

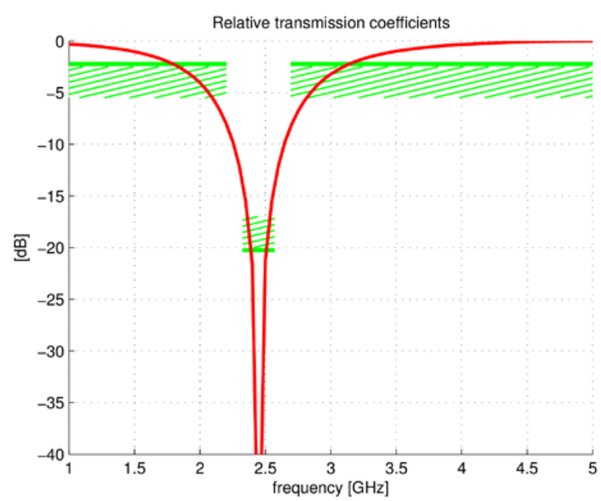

Fig. 9 transmission coefficients of the Jerusalem-cross consisting of only one metallic layer

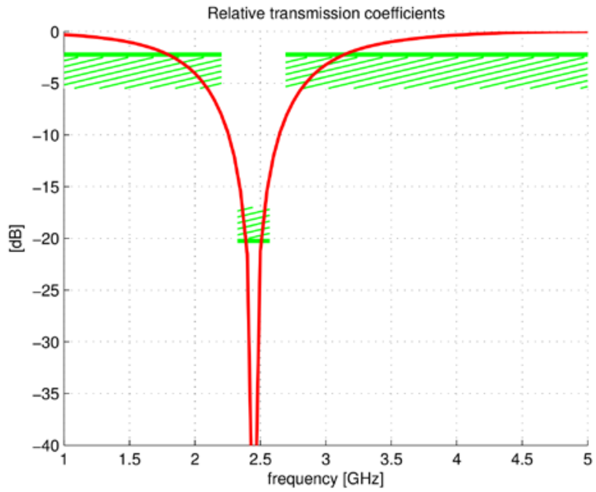

Fig. 10 transmission coefficients of the Jerusalem-cross consisting of four metallic layers

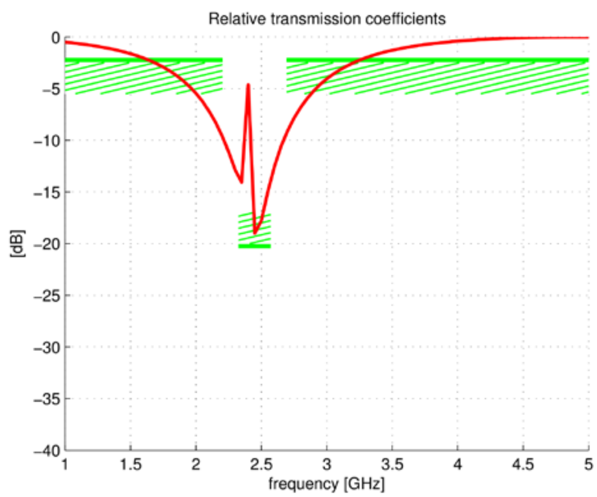

Fig. 11 transmission coefficients of the Jerusalem-cross consisting of five metallic layers

C. The Final Values

The optimized values of design parameters are presented in the list below:

1) *Simple cross FSS filter*
- $a = 0.072745$ m
- $w = 0.005$ m
- $k = 0.801129$

2) *Jerusalem-cross FSS filter*
- $a_j = 0.042554$ m
- $w_j = 0.002991$ m
- $k_{1j} = 0.900435$
- $k_{2j} = 0.403906$

3) *Simple H-element FSS filter*
- $a_h = 0.070426$ m
- $w_h = 0.0037676$ m
- $k_h = 0.95005$

Furthermore, from the design parameters we can compute the lengths l, l_j, l_{ej} and l_h in the following way:

1) *Simple cross FSS filter*
- $l = k\ a;\ l = 0.038317111$ m (the total width and height of the simple cross geometry)

2) *Jerusalem-cross FSS filter*
- $l_j = k_{1j}\ a_j;\ l_j = 0.038317111$ m (the total width and height of the Jerusalem-cross)
- $l_{ej} = k_{2j}\ l_j;\ l_{ej} = 0.015476511$ m (the total length of an outer arm)

3) *Simple H-element FSS filter*
- $l_h = k_h\ a_h;\ l_h = 0.066908221$ m (the total width and height of the simple H-element in the cell)

VI. Conclusion

A method of optimization of an FSS filter was described and tested on a problem of filtering of 2.4 GHz Wi-Fi signal. Three possible relatively simple geometries (the simple cross, the Jerusalem-cross and the simple H-element) of FSS filters were compared. The initial proposed solutions of all designed FSS filters were optimized and corresponding transmission coefficients of optimized filter were shown. All geometries were successfully optimized to suppress the Wi-Fi signal. With respect to the results presented in this study the Jerusalem-cross geometry is the best performing filter from the test group.

Moreover, the influence of number of metallic layers was discussed and estimated transmission coefficients of the Jerusalem-cross FSS filter consisting of one, two, three, four and five metallic layers were also presented. From the results is obvious that only one or two layers are sufficient in reflecting the Wi-Fi signal (in the case of perpendicular incident wave). No more layers are needed, higher number of layers would only make a construction of such a filter more difficult with no special impact on the attenuation of the desired band of frequencies.

The results presented in this paper are quite promising. Presented method seems to be suitable in design of many band-stop or band-pass filters and could help to find solutions of other complicated electromagnetic problems. Anyway, further work in this direction should prove this theoretical study by results of real measurements.

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