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FILTER TUNING BASED ON LINEAR DECOMPOSITION OF SCATTERING CHARACTERISTICS

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Abstract—This paper proposes a microwave filter post-production tuning based on an optimization process which finds the vector of deviations of tuning elements that should be applied to tune the filter. To build the system, the coarse set of scattering parameters is collected in such a way that every tuning element is detuned while other elements remain in their proper positions. In the concept, it is assumed that the relation between the positions of tuning elements and filter scattering characteristics can be modelled by the sum of one argument polynomial functions. Each polynomial function depends on the value of only one tuning element. Therefore, the measured filter characteristics can be linearly decomposed to characteristics from the collected coarse set and corresponding tuning element deviations can be found. This is done by way of optimization process. The presented numerical and physical experiments on the 7th order cross-coupled, bandpass filter have verified our approach.

1. INTRODUCTION

Filter tuning is an essential post-production process which is a result of manufacturing and material tolerance. It is time-consuming and expensive, hence many researchers have investigated this issue, trying either to make the tuning faster and easier or to automate the whole process.

In [1], a time domain approach is described. This method requires a skilled operator and a "golden" filter to compare time response between the tuned filter and an ideal one. This method is very fast and easy adaptable to the new filter type but is very limited as it can be

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used only for low-order filters. However, most techniques are based on a frequency domain such as [2, 3] where coupling matrix is extracted. Then, based on its entries, tuning screws which cause detuning are identified. Here, a high complexity of a filter is not a problem but a single iteration computation takes a long time. It is because an optimization must be performed to extract coupling matrix entries.

Another tuning methods are based on mapping of filter characteristic to the deviation of tuning elements responsible for detuning. This mapping is performed with the use of artificial neural network (ANN) multidimensional approximator [4, 5], neuro-fuzzy system [6] or linear matrix operator [7]. Especially [4, 5] methods based on ANN are very well examined and proved to be very fast and able to deal with any type of filter (high complexity, many cross-couplings).

Recently, we have proposed a novel method for filter tuning [8]. Similarly as in methods [4–7], method [8] considers direct correspondence between filter characteristics and tuning elements. Elaboration [8] is motivated by the fact that in methods [4, 6, 7] an inconvenient process of controlled, random filter detuning must be done for each filter type to train, e.g., Artificial Neural Network. That process takes a long time because it makes it necessary to collect a lot of random $\{\Delta\mathbf{z}, \mathbf{s}\}$ pairs containing tuning element deviations $\Delta\mathbf{z}$ and corresponding scattering parameters $\mathbf{s}$. In [8] an approximator A: $\mathbf{s}\rightarrow \Delta\mathbf{z}$ is proposed, which requires a very coarse set of $\{\Delta\mathbf{z}, \mathbf{s}\}$ pairs. These pairs are collected in such a way that only one tuning element is detuned at a time, while the remaining ones are placed in proper positions. Moreover, the method does not need a training phase as the response of the system is based on linear decomposition of reflection characteristics.

In this work the concept presented in [8] is extended and verified by theoretical and numerical proofs. Furthermore, apart from reflection, transmission characteristic is taken into consideration. It allows for building such an optimizer which, based on scattering parameters from vector network analyzer, generates deviations of cavities, couplings and cross-couplings' values as well.

The proposed method by us turned out to be somewhere between the described methods. It is not so fast comparing to ANN and Time Domain methods because a response is obtained by an optimizer. On the other hand it can deal with many types of filters including very complex ones as shown in a tuning experiment, Section 5. An important advantage is a reduction of time needed to prepare a model for new filter type compared to methods [4–7]. A comparison of mentioned methods is depicted in Figure 1.

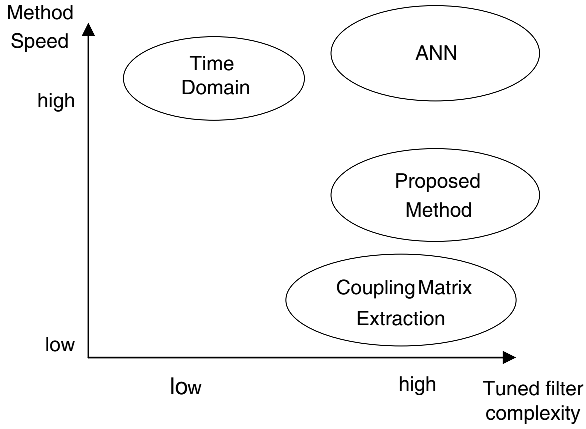

Figure 1. Filter tuning methods comparison.

2. GENERAL CONCEPT

The coupling matrix model of microwave filters was presented in [9, 10] for the first time and was applied in filter synthesis [11] and postproduction tuning. The advantage of the coupling matrix is that its entries are directly related to the position of the physically tunable elements. Recently researches have reported new methods of coupling matrix synthesis [12–17]. When dealing with $(N+2)\times(N+2)$ coupling matrix formulas for reflection S_{11} and transmission S_{21} are as follows [18]:

$$S_{11}(\lambda) = 1 + 2j\,[\lambda\mathbf{I}_N - \mathbf{J} + \mathbf{M}]^{-1}_{1,1} \tag{1}$$

$$S_{21}(\lambda) = -2j[\lambda\mathbf{I}_N - \mathbf{J} + \mathbf{M}]^{-1}_{N+2,1} \tag{2}$$

where $\mathbf{M}$ is a coupling matrix and $\mathbf{J}$ a matrix that has all entries equal to 0 except $J_{1,1} = J_{N+2,N+2} = j$, whereas $\mathbf{I}_N$ is a diagonal matrix with the main diagonal given by (0, 1, 1, ..., 1, 0) and λ a normalized frequency.

Let us assume that we have a filter with R tuning elements which adjust cavities, couplings and cross-couplings. Its ideal, tuned characteristic corresponds to the coupling matrix $\mathbf{M}^0$, so for any detuned characteristic we obtain:

$$S_{11}(\lambda) = 1 + 2j\left[\lambda\mathbf{I}_N - \mathbf{J} + \mathbf{M}^0 + \Delta\mathbf{M}\right]^{-1}_{1,1} \tag{3}$$

$$S_{21}(\lambda) = -2j\left[\lambda\mathbf{I}_N - \mathbf{J} + \mathbf{M}^0 + \Delta\mathbf{M}\right]^{-1}_{N+2,1} \tag{4}$$

where $\Delta\mathbf{M}$ is responsible for detuning a filter and consists of deviations of coupling matrix entries (Δm_1, Δm_2, ..., Δm_R) which correspond to deviations of tuning elements. Thus, we can write a general formula for scattering parameters s for a certain normalized frequency λ.

$$s = f\left(\Delta m_1, \Delta m_2, \ldots, \Delta m_R\right) \tag{5}$$

where $f\colon \mathbb{R}^R \rightarrow \mathbb{R}$. Assume that the tuned coupling matrix $\mathbf{M}^0$ is given and know that the values of vector containing deviations of coupling matrix entries $\mathbf{\Delta m} = (\Delta m_1,\ \Delta m_2,\ \ldots,\ \Delta m_R)$ scattering parameters can easily be found using (3) and (4).

Relationships described so far are quite complicated, so let us try to estimate $s = f(\mathbf{\Delta m})$ dependence in a simpler way. Assuming that (5) is a T-times differentiable function at the point $\mathbf{\Delta m}^0 = \{0,\ 0,\ \ldots,\ 0\} \in \mathbb{R}^R$, according to Taylor's theorem for multivariate functions, there exists such $h_\alpha\colon \mathbb{R}^R \rightarrow \mathbb{R}$ that:

$$f(\mathbf{\Delta m}) = \sum_{|\alpha|=0}^{T} \frac{D^\alpha f(\mathbf{\Delta m}^0)}{\alpha!}\left(\mathbf{\Delta m} - \mathbf{\Delta m}^0\right)^\alpha + \sum_{|\alpha|=T} h_\alpha(\mathbf{\Delta m})\left(\mathbf{\Delta m} - \mathbf{\Delta m}^0\right)^\alpha \tag{6a}$$

and

$$\lim_{\mathbf{\Delta m} \rightarrow \mathbf{\Delta m}^0} h_\alpha\left(\mathbf{\Delta m}\right) = 0 \tag{6b}$$

where D is a differential operator

$$D^\alpha f = \frac{\partial^{|\alpha|} f}{\partial \Delta m_1{}^{a_1} \ldots \partial \Delta m_R{}^{a_R}} \tag{7}$$

where α is a R-tuple, hence multi-index notation is applied: $|\alpha| = \alpha_1 + \ldots + \alpha_R$, $\alpha! = \alpha_1! \ldots \alpha_R!$.

Setting T to some constant integer, which ensures sufficient approximation and neglecting a remainder term of (6a), we come to the first degree of approximation of s:

$$s_{Taylor} = \sum_{|\alpha|=0}^{T} \frac{D^\alpha f\left(\mathbf{\Delta m}^0\right)}{\alpha!}\left(\mathbf{\Delta m} - \mathbf{\Delta m}^0\right)^\alpha \tag{8}$$

Next, it can be observed that (8) consists of three kinds of terms:

$$s_{Taylor} = A + f^*\left(\mathbf{\Delta m}\right) + f^{**}\left(\mathbf{\Delta m}\right) \tag{9}$$

where A represents zero degree terms. $f^*(\mathbf{\Delta m})$ has terms dependent on a single variable, and $f^{**}(\mathbf{\Delta m})$ consists of terms dependent on multiple variables. It can be observed that A may be written as

$$A = s^0 = f\left(0, 0, \ldots, 0\right) \tag{10}$$

which is simply a tuned characteristic of a filter.

As the complexity of s_{Taylor} is still high, let us introduce a second degree of approximation of s, in which term $f^{**}(\Delta\mathbf{m})$ is neglected, as it is believed to be small enough for our approximation needs.

$$s_{appr} = s^0 + f^*\left(\Delta\mathbf{m}\right) \tag{11}$$

An assumption that terms dependent on more than one variable may be omitted for tuning purposes will be verified shortly. This important step allows us to write (11) as a sum of one argument polynomials, since $f^*(\Delta\mathbf{m})$ consists of terms dependent only on single variables.

$$\begin{aligned} s_{appr} &= s^0 + \sum_{t=1}^{T} p_{t1}\Delta m_1^t + \sum_{t=1}^{T} p_{t2}\Delta m_2^t + \ldots + \sum_{t=1}^{T} p_{tR}\Delta m_R^t \\ &= s^0 + \sum_{r=1}^{R}\sum_{t=1}^{T} p_{tr}\Delta m_r^t \end{aligned} \tag{12}$$

where p_{tr} are polynomial coefficients of rth polynomial and tth-order term. Using (12) a general formula for scattering parameters s depending on only one variable (e.g., Δm_1) can be written as:

$$f(\Delta m_1, 0, \ldots, 0) = s^0 + \sum_{t=1}^{T} p_{t1}\Delta m_1^t \tag{13}$$

It leads to the following observation:

$$\begin{aligned} s \approx s_{appr} &= f\left(\Delta m_1, 0, \ldots, 0\right) + f\left(0, \Delta m_2, \ldots, 0\right) \\ &\quad + \ldots + f\left(0, 0, \ldots, \Delta m_R\right) - (R-1) * s^0 \end{aligned} \tag{14}$$

where R is the number of tuning elements. All the formulas given so far can be computed for a specified number of normalized frequencies λ. Hence, following notation will be used: $\mathbf{s}$, $\mathbf{s}_{Taylor}$ and $\mathbf{s}_{appr}$ denote vectors which represent a concatenation of reflection and transmission complex characteristics, evenly distributed within a specified frequency band. These signals are computed by (5) — exact characteristic, (8) — Taylor approximation, and (11) — proposed approximation respectively.

The last formula obtained in (14) means that $\mathbf{s}$ can be modelled by a sum of functions which depend only on single variable Δm_r. Keeping in mind that there is a direct correspondence between the coupling matrix entry Δm_r and the tuning element Δz_r a following conclusion can be made. To model scattering characteristic $\mathbf{s}$ the only pieces of information that must be collected are these that stem from detuning a filter on a single element only while the others are set to their proper positions. It would allow us to reduce significantly the number of $\{\Delta\mathbf{z}, \mathbf{s}\}$ pairs which need to be collected comparing to methods presented in [4–7].

3. NUMERICAL PROOFS OF THE CONCEPT

To make sure that the above-mentioned assumptions can lead to reasonable solutions numerical experiments have been performed on a 4th order cross-coupled filter described by the coupling matrix below, which is taken from [11, Figure 10.33(a)].

$$\begin{pmatrix} 0 & 1.1506 & 0 & 0 & 0 & 0 \\ 1.1506 & 0.0530 & 0.9777 & 0.3530 & 0 & 0 \\ 0 & 0.9777 & -0.4198 & 0.7128 & 0 & 0 \\ 0 & 0.3530 & 0.7128 & 0.0949 & 1.0394 & 0 \\ 0 & 0 & 0 & 1.0394 & 0.0530 & 1.1506 \\ 0 & 0 & 0 & 0 & 1.1506 & 0 \end{pmatrix} \tag{15}$$

Let us denote the matrix (15) as $\mathbf{M}^0$. According to (3) and (4) and letting $\Delta\mathbf{M}$ be a null matrix a scattering characteristic of a tuned filter which is depicted in Figure 2 may be calculated.

Firstly, an integer parameter T must be specified for further tests. It determines the order of Taylor polynomial (8) and the higher it is, the more accurate the approximation $\mathbf{s}_{Taylor}$ (8) is. Next, 10 random vectors $\Delta\mathbf{m} = (\Delta m_1, \Delta m_2, \ldots, \Delta m_R)$ which describe the matrix $\Delta\mathbf{M}$ were generated. The values of Δm_r ranged from -0.2 to 0.2 to simulate a significantly detuned filter. For each vector $\Delta\mathbf{m}$ a Taylor approximation $\mathbf{s}_{Taylor}$ was computed using (8) and $\mathbf{s}_{appr}$ using (11) for different orders of Taylor polynomial up to the 4th order. The exact characteristics $\mathbf{s}$ were also identified, using (3) and (4), for assumed frequency range. For each case a root mean square error (RMSE) was computed to obtain the information how close the resulted approximated characteristics are to the real one. For instance,

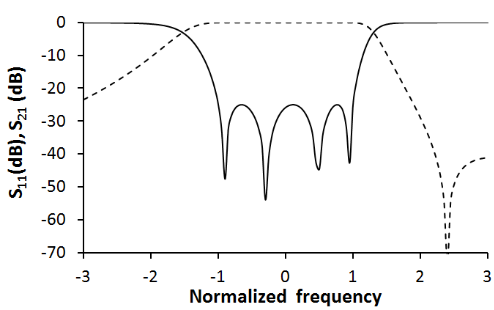

Figure 2. Scattering characteristics of the 4th order filter used in numerical experiments. Solid line — reflection characteristic (S_{11}). Dashed line — transmission characteristic (S_{21}).

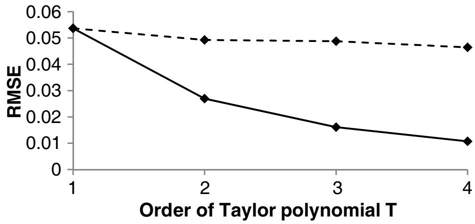

Figure 3. RMSE between approximated and exact characteristics. Solid line — RMSE between $\mathbf{s}_{Taylor}$ and $\mathbf{s}$. Dashed line — RMSE between $\mathbf{s}_{appr}$ and $\mathbf{s}$.

when comparing exact characteristic $\mathbf{s}$ with $\mathbf{s}_{appr}$ RMSE equals:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{M}\left(\mathrm{Re}(\mathbf{s}_{\mathit{diff}}\,(i)\,)\right)^2 + \sum_{i=1}^{M}\Big(\mathrm{Im}(\mathbf{s}_{\mathit{diff}}\,(i)\,)\Big)^2}{2M}} \tag{16}$$

where $\mathbf{s}_{\mathit{diff}} = \mathbf{s} - \mathbf{s}_{appr}$, M is the length of vector $\mathbf{s}_{\mathit{diff}}$. Real and imaginary parts of signals are analysed separately, therefore term $2M$ is placed in denominator of above formula.

For 10 mentioned random cases of $\Delta\mathbf{m}$ and for three values of the parameter T, the results of RMSE were averaged and are depicted in Figure 3.

As it was expected, it can be noticed that $\mathbf{s}_{Taylor}$ (8) is better approximated if the parameter T is bigger. Changes of RMSE between $\mathbf{s}$ and $\mathbf{s}_{appr}$ (11), which lacks terms dependent on multiple variables, are very small. For $T>3$ required calculations were very time consuming. Taking all these observations into account, $T=3$ was chosen for further tests. Figure 2 also shows that the obtained RMSE is small enough for quiet good match between the exact characteristics and the approximated ones. To provide better intuition with the scale of defined RMSE, one of random vectors $\Delta\mathbf{m} = (0.164, 0.042, 0.058, -0.194, -0.176, 0.062, -0.032)$ was chosen and $\mathbf{s}_{appr}$, $\mathbf{s}_{Taylor}$ and $\mathbf{s}$ were again computed with $T=3$. RMSE between $\mathbf{s}_{Taylor}$ and $\mathbf{s}$ was 0.032 and RMSE between $\mathbf{s}_{appr}$ and $\mathbf{s}$ was 0.06. Reflection and transmission characteristics of $\mathbf{s}_{appr}$, $\mathbf{s}_{Taylor}$ and $\mathbf{s}$ are plotted in Figure 4.

While analyzing Figure 4 it may be observed that for such detuned filter the approximation given by $\mathbf{s}_{appr}$ (11) is satisfactory. It seems that, in this situation, terms dependent on more than one variable can indeed be omitted. But more tests have to be performed, e.g., how well $\mathbf{s}_{appr}$ fits with the real characteristic in different cases of detuning.

To answer that question the following numerical experiment was performed. Let us introduce a random vector $\Delta\mathbf{c} =$

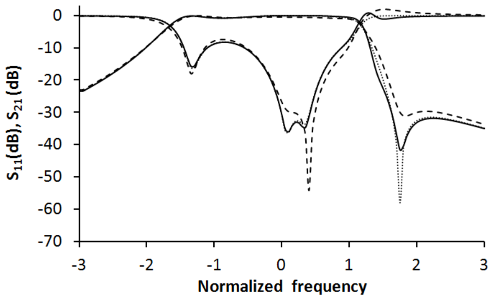

Figure 4. Reflection an transmission characteristics after applying the vector of coupling matrix changes $\Delta\mathbf{m}$. Solid line — $\mathbf{s}$. Dotted line — $\mathbf{s}_{Taylor}$. Dashed line — $\mathbf{s}_{appr}$.

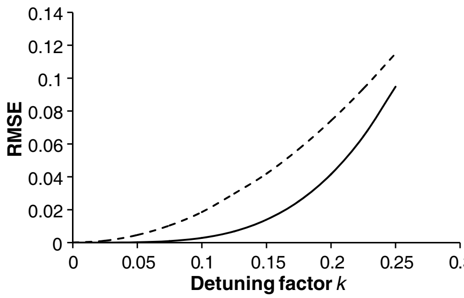

Figure 5. RMSE between approximated and exact characteristics. Solid line — RMSE between $\mathbf{s}_{Taylor}$ and $\mathbf{s}$. Dashed line — RMSE between $\mathbf{s}_{appr}$ and $\mathbf{s}$.

$(\Delta c_1, \Delta c_2, \ldots, \Delta c_R)$ with real numbers ranging from -1 to 1. $\Delta\mathbf{c}$ represents how the elements of $\Delta\mathbf{m}$, thus $\Delta\mathbf{M}$, are detuned. Then, let the k parameter vary from 0 to 0.25. It corresponds to the detuning range of coupling matrix since $\Delta\mathbf{m} = k\Delta\mathbf{c}$. Next, 10 random vectors $\Delta\mathbf{c}$ were generated and vectors $\Delta\mathbf{m}$ were computed for the whole range of the detuning factor k. Similarly to the previous tests, for all vectors $\Delta\mathbf{m}$ Taylor approximations $\mathbf{s}_{Taylor}$ were computed using (8) and $\mathbf{s}_{appr}$ using (11). For each detuning factor k RMSE between $\mathbf{s}_{Taylor}$ and $\mathbf{s}$ and RMSE between $\mathbf{s}_{appr}$ and $\mathbf{s}$ were computed using (16). The averaged results are depicted in Figure 5.

The results give a clear view of the correspondence between filter detuning and the quality of approximation given by $\mathbf{s}_{Taylor}$ and $\mathbf{s}_{appr}$. In general, the quality of approximation is higher for filters which are not significantly detuned and, within a certain range, it becomes lower almost linearly, together with the detuning factor. As in the previous experiment, $\mathbf{s}_{appr}$ provides a worse match to the real characteristics than $\mathbf{s}_{Taylor}$. It is due to lack of terms dependent on more than one variable in $\mathbf{s}_{appr}$. However, the RMSE is still low and seems to be sufficient for the approximation requirements.

4. CHARACTERISTICS LINEAR DECOMPOSITION

As it has been mentioned before, there is direct correspondence between coupling matrix entries and tuning screw elements, and therefore also between its deviations Δm_r and Δz_r. The previous section proved that filter characteristics may be represented by $\mathbf{s}_{appr}$ (14) without losing much information about the signal within a certain detuning range. That is why scattering parameters may be written as

$$\begin{aligned} \mathbf{s} \approx \mathbf{s}_{appr} \;=\; & f_z(\Delta z_1, 0, \ldots, 0) + f_z(0, \Delta z_2, \ldots, 0) \\ & + \ldots + f_z(0, 0, \ldots, \Delta z_R) - (R-1) * \mathbf{s}^0 \end{aligned} \tag{17}$$

where f_z is a general function for $\mathbf{s}$ with regard to tuning element deviations, Δz_r the tuning element deviation, R the number of tuning elements, and $\mathbf{s}^0 = f_z(0,\, 0,\, \ldots,\, 0)$ the tuned characteristic. It means that in order to model each lth function f_z and thus the whole $\mathbf{s}$, we have to collect only such pairs $\{\Delta\mathbf{z},\, \mathbf{s}\}$ for which $\Delta z_{r=l} \in \langle -K,\, K\rangle$ and the remaining $\Delta z_{r\neq l} = 0$. K is an integer representing how much the screw is detuned in order to collect the data. Let us denote the set collected in such way a coarse set $P_C = \{\Delta\mathbf{z},\, \mathbf{s}_C\}$.

The described coarse set $P_C = \{\Delta\mathbf{z},\, \mathbf{s}_C\}$ has a very big advantage over the set $P_F = \{\Delta\mathbf{z},\, \mathbf{s}_F\}$, collected randomly in the whole $\mathbb{N}^R$ space considered in [4]. The random set P_F has maximum $(2K+1)^R$ pairs, so it grows very fast with the filter tuning elements R and we are never certain that we have collected "appropriate" pairs to model the scattering characteristic optimally. The coarse set proposed by us has only $2KR+1$ pairs, which is a linear dependence in R and describes all f_z in the same manner.

Having collected P_C, from the point of view of $\Delta\mathbf{z}$, the only available samples lie on axes of a vector $\Delta\mathbf{z}$. But considering the above-mentioned assumptions P_C gives enough information to approximate any characteristic $\mathbf{s}$ corresponding to any screw deviation $\Delta\mathbf{z}$. This may be obtained by linear decomposition of characteristic $\mathbf{s}$ to characteristics $\mathbf{s}_C$ from P_C set. Such decomposition can be written as below, which is, according to our assumptions, complementary to (17)

$$\mathbf{s} \approx \mathbf{s}_{appr} = \mathbf{s}_C^{(1)}(\Delta z_1) + \mathbf{s}_C^{(2)}(\Delta z_2) + \ldots + \mathbf{s}_C{}^{(R)}(\Delta z_R) - (R-1) * \mathbf{s}^0 \tag{18}$$

where $\mathbf{s}_C^{(r)}(\Delta z_r)$ indicates the characteristic from the P_C, corresponding to $\Delta\mathbf{z}$, which is non-zero only on rth element and has the value Δz_r on this element.

In [8] a numerical experiment was performed on a 9th order filter, which confirmed that reflection characteristics from a collected random set P_F can be linearly decomposed to reflection characteristics from the set P_C, with high accuracy of approximation of $\mathbf{s}$, using (18).

The main goal of our elaboration is to propose an optimizer O: $\mathbf{s}\rightarrow \Delta\mathbf{z}$, based on a coarse set P_C, which is able to model screw deviations values $\Delta\mathbf{z}$ for any scattering characteristic $\mathbf{s}$ extracted from the vector network analyzer. Applying such vector $\Delta\mathbf{z}$ to a physical filter would result in tuning the filter. In general, for the given $\mathbf{s}$ characteristic the optimizer finds such $\Delta\mathbf{z}_{opt} = \{\Delta z_1, \Delta z_2, \ldots, \Delta z_R\}$ for which the given cost function evaluates the smallest value:

$$C = \|\mathbf{s}_{appr} - \mathbf{s}\| \tag{19}$$

where $\mathbf{s}_{appr}$ is given by (18).

In other words, the characteristic $\mathbf{s}$ is linearly decomposed using (18) in such way that C is as small as possible, i.e., $\mathbf{s}_{appr}$ is very similar to the real signal $\mathbf{s}$. To find a minimum of C, different optimization techniques were tested and the best results were obtained using Nelder-Mead method [19].

5. TUNING EXPERIMENT

A tuning experiment was performed with the use of the optimizer described in the previous section. The filter used in the tuning experiment is an 850 MHz cavity filter of the 7th order, with three tunable cross-couplings. This filter is the RX part of an 850 MHz duplexer. The topology of this filter is depicted in Figure 6. The total number of tuning elements is $R = 18$. K — integer representing the maximum screw deviation — equaled 7. An optimizer was built based on the collected coarse set P_C, which gave $2KR + 1 = 253\{\Delta\mathbf{z}, \mathbf{s}_C\}$ pairs.

S_{11} and S_{21} characteristics (Figure 7, dashed line) of the detuned filter was given to the optimizer which computed the initial screws deviations $\Delta\mathbf{z}_{opt}$ — the distances from properly tuned filter.

$$\Delta\mathbf{z}_{opt} = \{0, 4, 0, 7, -3, -3, 3, -1, -7, -1, -2, -1, -2, -1, 3, 0, 4, 1\}$$

Then, after all tuning iterations, all optimized screw deviations were minimized to 0, one by one. The resulting characteristics are also depicted in Figure 7.

It can be seen in Figure 7 that following the process of adjusting filter elements according to the optimizer output, the

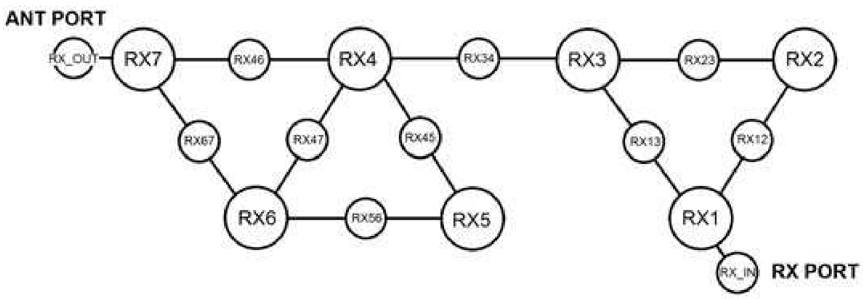

Figure 6. Topology of a 7th order filter used in the experiment. Large circles represent cavities, small circles represent couplings and cross-couplings.

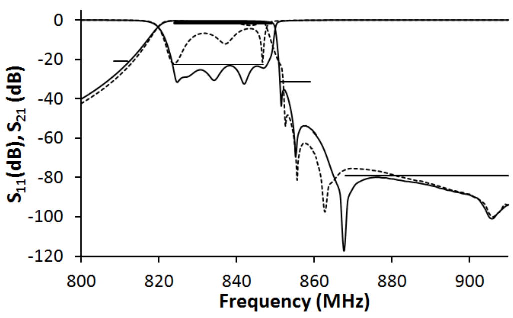

Figure 7. Reflection and transmission characteristics before and after tuning. Dashed line — characteristics before tuning, Solid line — characteristics after tuning. Solid, horizontal lines — tuning limits.

tuning requirements were achieved. They were fulfilled for reflection characteristics and for transmission as well. In [8] an analogous experiment was conducted on the 9th order filter, but all couplings were initially pre-tuned and only cavities were taken into consideration. Filters used in this experiment, as many others on the market, also require strict control of transmission characteristic and transmission zeros. Therefore, all tuning elements including couplings and cross-couplings showed in Figure 6 were taken into consideration.

6. PERFORMANCE OF THE METHOD

The proposed method turned out to be convergent which is also visible in Figure 8 where a tuning process is depicted along the

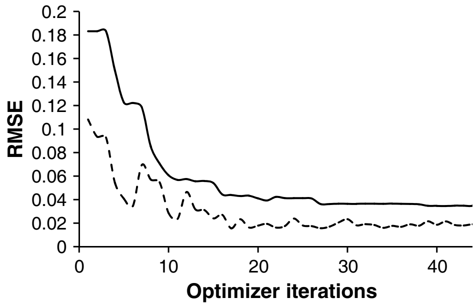

Figure 8. RMSE of characteristics during tuning process. Dashed line — RMSE between $\mathbf{s}$ and $\mathbf{s}_{appr}$. Solid line — RMSE between $\mathbf{s}$ and $\mathbf{s}^{\mathbf{0}}$.

optimizer iterations. The dashed line represents an RMSE (16) between current real characteristic $\mathbf{s}$ and $\mathbf{s}_{appr}$ which is created from a decomposition (18), hence it tells us how good the approximation of $\mathbf{s}_{appr}$ is. The solid line represents an RMSE between current real characteristic $\mathbf{s}$ and an ideal, tuned one $\mathbf{s}^0$, so it may be viewed as a tuning error — how much the filter is detuned. Note that the optimizer ran continuously so there is no correspondence between the optimizer iteration and the number of screw changes. It depends on the operator how many changes he/she manages to do in one optimizer iteration.

Apart from the fact that the method converges to its minimum, Figure 8 shows that the experiment confirmed the correspondence between the detuning of a filter and the quality of the approximation given by $\mathbf{s}_{appr}$, which was also considered in Section 3. Namely, the less detuned the filter, the better approximation is given by $\mathbf{s}_{appr}$. Fluctuations, seen especially at the beginning of a dashed line in Figure 8, stem from the fact that the optimizer used in the method does not always find the global minimum of the cost function (19). Thus, the current characteristic $\mathbf{s}$ is not always decomposed into proper, the best available terms and $\mathbf{s}_{appr}$ do not match the current characteristic well. It happens in particular when a filter is significantly detuned. However, the applied Nelder-Mead method [19] was the best among other tested optimizers, taking into consideration the accuracy of decomposed signal and computation time.

7. CONCLUSION

In this paper, we suggest that the relation between filter scattering characteristic and the position of tuning elements can be successfully approximated by the sum of one argument polynomial functions proposed by us. It has been numerically confirmed with the use of exemplary coupling matrix. Based on this assumption, it has been proved that an efficient optimizer can be built with the use of a coarse set. This set is prepared in such a way that the tuning element positions are detuned only on single element. The optimizer linearly decomposes characteristic $\mathbf{s}$ into characteristics from the coarse set and finds proper screw deviations $\Delta\mathbf{z}_{opt}$. Furthermore, this optimizer was successfully used in a filter tuning experiment which took into consideration reflection and transmission, whereas values of cavities, couplings and cross-couplings were the optimization variables. The advantage of this method is that a coarse set $\{\Delta\mathbf{z}, \mathbf{s}_C\}$ have to be collected instead of a much bigger random set $\{\Delta\mathbf{z}, \mathbf{s}\}$. Moreover, a training phase of the algorithm is not required. On the other hand, the response of the proposed optimizer is not immediate as in, e.g., [4]. Some time is needed in each optimizer iteration to find proper $\Delta\mathbf{z}_{opt}$ values.

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