Optimization of Lowpass Filters Using the Coupling Matrix Approach

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***Abstract* — This paper presents a novel approach for designing lowpass filters using the coupling matrix technique. First, a relationship is established between the coupling coefficients and a surrogate model consisting of lumped elements. Applying a coupling matrix extraction to simulated or measured data, such a surrogate model approximating the characteristics of a planar filter geometry can be created. Comparing the surrogate model with the desired filter prototype, adjusting the filter geometry can be done in a purposive manner. The feasibility of this method is demonstrated by the design, fabrication, and testing of lowpass filters, realized on a multilayer printed circuit board.**

***Index Terms* — Lowpass filter, coupling matrix, surrogate model.**

I. Introduction

In the last years the application of wireless systems, primarily in the communication and sensor area, has vastly increased, leading to a very crowded frequency spectrum. This development imposes more and more constraints on filter components which always play a major role in those systems, usually seriously affecting their performance. One very common approach for designing filters is to use experience and cut and try methods, usually supported by full wave simulation tools. With increasing demands on filters this method tends to fail for two reasons. First, the growing number of variables describing the filters prohibits employing cut and try methods. Moreover, the simulation time needed by full wave simulators to calculate filter responses grows extremely fast with filter complexity, making these tools futile for direct optimization.

All this has led to the introduction of hybrid optimization strategies in the field of filter design. The most familiar representatives are the space mapping technique introduced by Bandler [1] and the coupling matrix approach. The latter was presented first by Atia and Williams [2] as a means for describing bandpass waveguide filters. Later on the coupling matrix approach was incorporated in hybrid optimization tools [3, 4] for the treatment of bandpass filters. The advantage of the coupling matrix approach is the use of a surrogate model whose structure is both flexible in topology and closely related to the respective filter geometry allowing for aim-oriented modification of the latter.

To the authors knowledge no publication exists until now, which proposes the use of the coupling matrix technique for the design of lowpass filters. Since lowpass filters are equally important as bandpass filters the intention of the presented work is to fill this gap. The following section will demonstrate how the coupling matrix approach can be extended for the design of lowpass filters. Finally, an example demonstrating the viability of the approach will be shown.

II. Theory

The usual starting point in designing a lowpass filter is a lumped element circuit, like the one shown in Fig. 1 for the case of a three-element filter. The values of the dimensionless g-parameters (filter coefficients) can be taken either from tables or from a filter synthesis tool. Afterwards, impedance- and frequency-scaling to the desired values is carried out to obtain the inductances and capacitances to be realized. The remaining task of planar filter design is then to create a distributed filter geometry which approximates the behavior of the lumped circuit as best as possible.

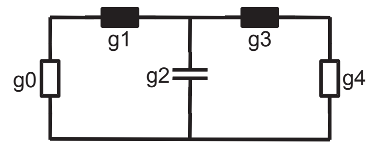

Fig. 1. Filter prototype of third order starting with an inductor.

In order to make use of the coupling matrix approach, a relationship between the coupling coefficients and a surrogate model has to be established, sharing the same topology as the circuit shown in Fig. 1. This can be achieved by consequently eliminating either all series or shunt elements contained in Fig. 1. The resulting circuit consists only of the remaining type of elements and inverters. In Fig. 2 each of the series inductances has been replaced by a shunt capacitance and a pair of inverters. Although the number of parameters of the circuit in Fig. 2 has increased, the filter order is still three. Therefore, the number of independent parameters (including the impedance level) is still four. Hence, the filter behavior may be entirely described by freely picking four elements and setting all others to unity. For our purpose it is mandatory to choose the inverter constants as independent parameters.

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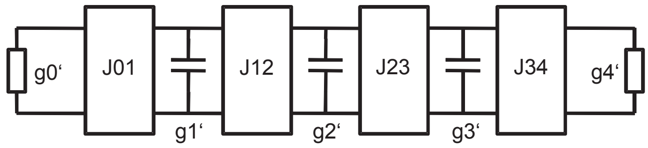

Fig. 2. Filter prototype of third order with series elements replaced by inverters and shunt elements.

According to [5] the filter coefficients can be related to the inverter constants as follows:

$$g_{i+1} = \frac{g_i^{'} \cdot g_{i+1}^{'}}{g_i \cdot J_{i,i+1}^2} \quad (1)$$

Following the steps in the synthesis of a resonator bandpass filter illustrated in [6] where the transition from Fig. 1 to Fig. 2 appears as an intermediate step, it is obvious that the inverter constants in Fig. 2 are equivalent to the mainline-coupling coefficients. Since we are considering in this work lowpass filters without any transmission zeros at finite frequencies, no cross-coupling coefficients have to be taken into account. Furthermore, the lowpass responses obtained from simulations or measurements have to be extended into the negative frequency domain in a complex-conjugate fashion. The resulting magnitude and phase functions are even and odd respectively, leading to an all-zero main diagonal of the coupling matrix.

In summary, the filter response is fully described by the mainline-coupling coefficients and both the input and output coupling. In the case of the lowpass of third order illustrated in Fig. 1 this accounts to two mainline-coupling coefficients, yielding a total of four independent parameters which is consistent with the description in Fig. 1. The design flow of a lowpass filter using the coupling matrix approach shall be exemplified by the following enumeration. It is assumed that a initial filter geometry has been created, and its response is available in terms of scattering parameters.

1) From the response at hand extract a coupling matrix model which approximates the behavior of the filter geometry.
2) With the help of (1) determine a surrogate model of the filter. Scale its elements with respect to cutoff frequency and impedance level.
3) Compare the elements of the surrogate model with those of the filter prototype. This usually gives direct hints where to alter the filter geometry.
4) Repeat steps 1) to 3) if the modified filter does not show the desired performance yet.

III. Example Lowpass

In order to demonstrate the feasibility of this novel approach, several lowpass filters have been designed, fabricated, and tested. The filters were realized using a multilayer setup with two RO4003 substrates bonded together by a RO4450 prepreg. Thicknesses and layer designation are given in Fig. 3. Layers L1 and L4 are completely metallized to achieve top and bottom shielding. Lateral shielding is done by via-rows.

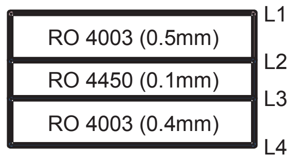

Fig. 3 Multilayer setup with designation of layer thicknesses and metallization layers.

For the presented filter, the prototype comprises seven reactive elements starting with a capacitor and exhibiting a Chebyshev characteristic. Cutoff-frequency and minimum return loss are set to 5 GHz and 20 dB, respectively. Fig. 4 shows the layout of the filter whose inductive sections are bent in an Omega fashion for space saving purposes. The filter comprises some additional vias for blocking waveguide modes which are penetrating the capacitive sections. However, these vias do not have an influence on the filter response within the frequency range presented in this paper. The starting geometry for the filter was deliberately constructed in a crude manner. Capacitive sections for example were dimensioned as parallel plate capacitors neglecting fringe fields.

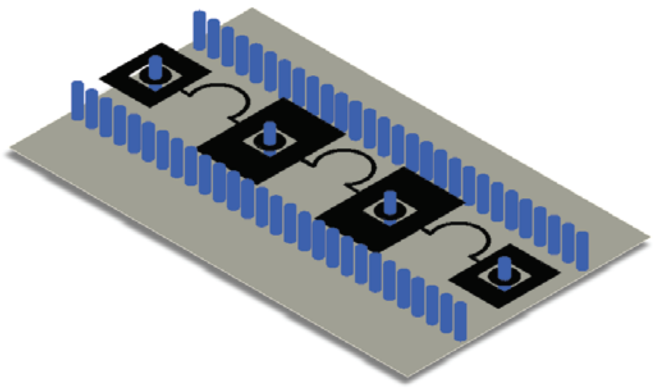

Fig. 4. Isometric view of the filter layout. Filter metallization is located on layer L2 (see Fig. 3).

The response of the starting geometry, obtained by full wave simulation using [7], is depicted in Fig. 5, showing a disturbed equal ripple pattern and a cutoff-frequency of 4.66 GHz. To mitigate the discrepancy to the prototype response, which is also shown in Fig. 5 as dashed lines, a surrogate model of this filter is constructed, following the outline given in Section II. The element values of the surrogate model are summarized and compared to the prototype in Table I.

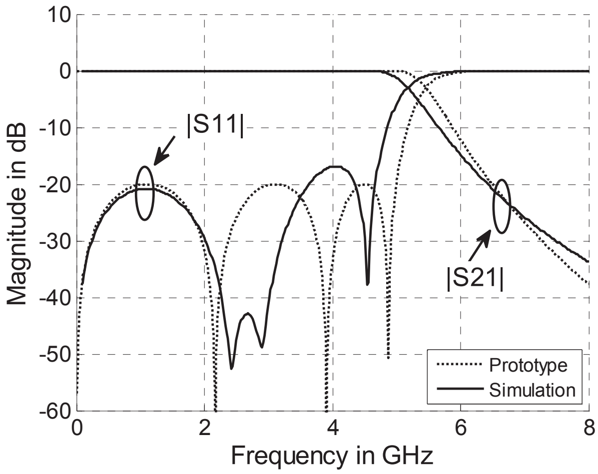

Fig. 5. Simulated results of the initial lowpass filter geometry.

Major differences can be noticed for the inductances, which are all too high for the surrogate model. This can be explained by the negligence of the bends during the design of the initial geometry. Additionally, the values of the inner capacitances C3 and C5 are also found to be too large, which might be due to negligence of fringing capacitances. With this information taken from the surrogate model, modification of the geometry is straightforward.

TABLE I. ELEMENT VALUES OF INITIAL SURROGATE MODEL COMPARED WITH ELEMENT VALUES OF THE PROTOTYPE.

Element	Prototype	Surrogate	Deviation
C1	0.064 pF	0.064 pF	0%
L2	2.287 nH	2.578 nH	+12%
C3	1.236 pF	1.344 pF	+9%
L4	2.581 nH	2.698 nH	+5%
C5	1.236 pF	1.334 pF	+8%
L6	2.287 nH	2.566 nH	+12%
C7	0.0643 pF	0.064 pF	0%

The simulated response of the modified geometry is shown in Fig. 6, which now agrees very well with the response from the prototype. For the purpose of verification, a surrogate model for the modified geometry is calculated, with its elements presented in Table II. The remaining differences are seen to be in the range of 2% or less. After the successful design the filter was fabricated. The measured results are depicted in Fig. 7 and show good agreement with the results from simulation. The extracted coupling matrices for this filter are given in Figs. 8-11. The detailed filter geometry, both for the initial and final state, is given in Fig. 11.

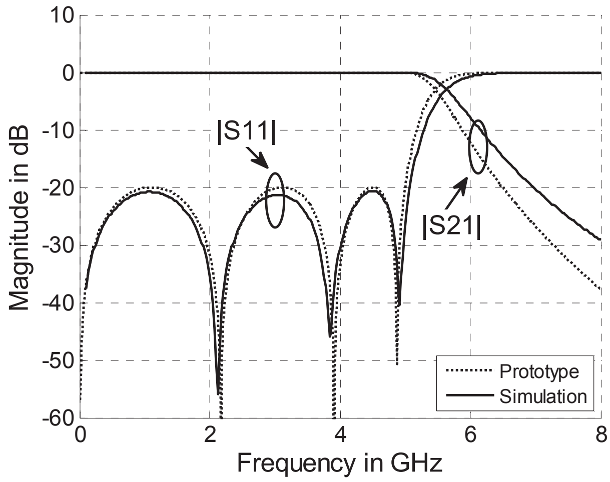

Fig. 6. Simulated results of the lowpass filter geometry after the first iteration.

TABLE II. ELEMENT VALUES OF SURROGATE MODEL AFTER FIRST ITERATION COMPARED WITH ELEMENT VALUES OF THE PROTOTYPE.

Element	Prototype	Surrogate	Deviation
C1	0.064 pF	0.064 pF	0%
L2	2.287 nH	2.316 nH	+1.2%
C3	1.236 pF	1.227 pF	-0.8%
L4	2.581 nH	2.592 nH	+0.4%
C5	1.236 pF	1.218 pF	-1.4%
L6	2.287 nH	2.313 nH	+1.1%
C7	0.0643 pF	0.064 pF	0%

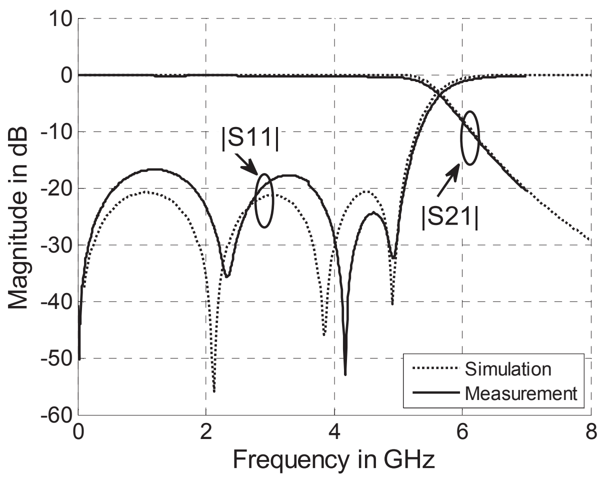

Fig. 7. Measured results of the fabricated lowpass filter geometry.

IV. Conclusion

The coupling matrix technique has been shown to be a valuable tool for the design [3] and diagnosis [8] of bandpass filters. In this paper, a method has been presented which makes the coupling matrix technique available to the treatment of lowpass filters. After establishing a relationship between the coupling coefficients and a surrogate model approximating filter behavior, an algorithm for optimizing lowpass filters was introduced. Finally, the advantages of the proposed procedure were illustrated with an example. Only one optimization step was necessary to obtain a design whose both simulated and measured results show good agreement with the filter prototype.

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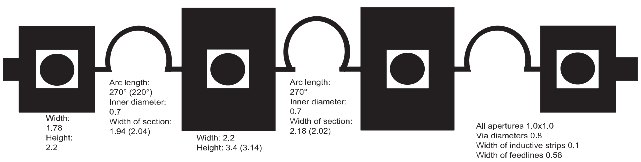

Fig. 11. Detailed geometry of the example lowpass filter. All units not shown are in mm. Dimensions are given for the initial geometry. Changes to the final geometry, if any, are given in parentheses.

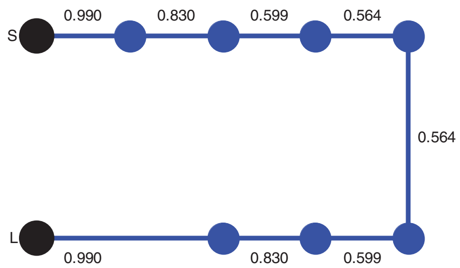

Fig. 8. Coupling matrix scheme for the prototype filter used for designing the example lowpass filter.

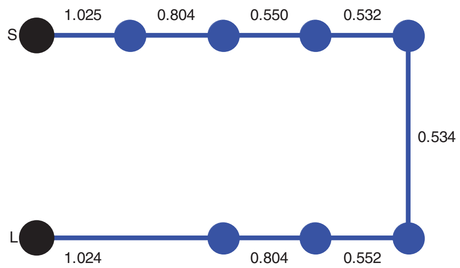

Fig. 9. Coupling matrix scheme extracted from the initial lowpass filter geometry.

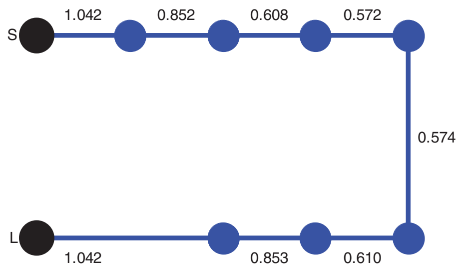

Fig. 10. Coupling matrix scheme extracted from the final lowpass filter geometry.