Design of a silicon-based wideband bandpass filter using aggressive space mapping

Xuanxuan Zhang\textsuperscript{1,2}, Yi Ou\textsuperscript{1,3a), and Wen Ou\textsuperscript{1}

\textsuperscript{1} Institute of Microelectronics of Chinese Academy of Sciences, Beijing 100029, China
\textsuperscript{2} University of Chinese Academy of Sciences, Beijing 100049, China
\textsuperscript{3} National Center for Advanced Packaging Co., Ltd

\textsuperscript{a)} ouyi@ime.ac.cn

Abstract: The auxiliary diagnosis and debugging of filters play an increasingly important role in the design of microwave filters. In particular, aggressive space mapping (ASM) is one of the most commonly used debugging methods. This paper introduces ASM and designs a seventh-order microstrip interdigital filter with a center frequency of 24 GHz and a fractional bandwidth of 25\% with ASM. The filter reached design indexes after four iterations, which greatly reduces the number of simulations in fine model, thereby saving time. It was fabricated on high resistance silicon substrate and the size of the chip is 6.8 mm \times 2.4 mm \times 0.4 mm. The measurement results show that the fabricated filter has a center frequency of 24 GHz, a fractional bandwidth of 24.17\%, an insertion loss of 1.95 dB, a return loss of 12 dB, and an out-of-band rejection of 40 dB.

Keywords: interdigital filter, wideband, ASM, silicon-based

Classification: Microwave and millimeter-wave devices, circuits, and modules

References

[1] J. W. Bandler, \textit{et al.}: “Space mapping technique for electromagnetic optimization,” IEEE Trans. Microw. Theory Techn. 42 (1994) 2536 (DOI: 10.1109/22.339794).
[2] J. W. Bandler, \textit{et al.}: “Electromagnetic optimization exploiting aggressive space mapping,” IEEE Trans. Microw. Theory Techn. 43 (1995) 2874 (DOI: 10.1109/22.475649).
[3] Y. H. Xu and T. M. Xiang: “Design of coaxial filter based on aggressive space mapping,” J. Hangzhou Dianzi Univ. (2011).
[4] J. W. Bandler, \textit{et al.}: “Design optimization of interdigital filters using aggressive space mapping and decomposition,” IEEE Trans. Microw. Theory Techn. 45 (1997) 761 (DOI: 10.1109/22.575598).
[5] W. C. Tang, \textit{et al.}: “Design and optimization of microstrip passive circuits by field-based equivalent circuit model with aggressive space mapping.” International Symposium on Microwave, Antenna, Propagation and EMC Technol-
ologies for Wireless Communications (2007) 909 (DOI: 10.1109/MAPE.2007.4393776).

[6] M. S. Farrokh, et al.: “Wideband microstrip passband filter by using ADS software,” IEEE 8th International Colloquium on Signal Processing and Its Applications (2012) 37 (DOI: 10.1109/CSPA.2012.6194686).

[7] R. J. Cameron: Microwave Filters for Communication Systems: Fundamentals, Design, and Applications (Wiley, New York, 2007).

[8] A. Lamecki, et al.: “Efficient implementation of the Cauchy method for automated CAD-model construction,” IEEE Microw. Wireless Compon. Lett. 13 (2003) 268 (DOI: 10.1109/LMWC.2003.815185).

[9] A. G. Lamperez, et al.: “Generation of accurate rational models of lossy systems using the Cauchy method,” IEEE Microw. Wireless Compon. Lett. 14 (2004) 490 (DOI: 10.1109/LMWC.2004.834576).

[10] G. Macchiarella and D. Traina: “A formulation of the Cauchy method suitable for the synthesis of lossless circuit models of microwave filters from lossy measurements,” IEEE Microw. Wireless Compon. Lett. 16 (2006) 243 (DOI: 10.1109/LMWC.2006.873583).

[11] M. S. Sorkherizi, et al.: “Direct-coupled cavity filter in ridge gap waveguide,” IEEE Trans. Compon. Packag. Manuf. Technol. 4 (2014) 161 (DOI: 10.1109/TPCMT.2013.2284559).

[12] S. Berry, et al.: “A Ka-band dual mode dielectric resonator loaded cavity filter for satellite applications,” IEEE MTT-S International Microwave Symposium Digest (2012) 1 (DOI: 10.1109/MWSYM.2012.6259673).

[13] H. H. Ta and A.-V. Pham: “Compact wide stopband bandpass filter on multilayer organic substrate,” IEEE Microw. Wireless Compon. Lett. 24 (2014) 161 (DOI: 10.1109/LMWC.2013.2293672).

[14] Y. Z. Chang, et al.: “Miniaturizing the size of microwave filter by using LTCC technology with hybrid dielectrics,” Proc. IEEE Asia-Pacific Microwave Conference, APMC (2005) (DOI: 10.1109/APMC.2005.1606281).

[15] G. H. Liu and C. M. Kang: “Developing status and trend of MEMS technology,” J. Transducer Technol. (2001).

[16] J. S. Hong: Microstrip Filters for RF/Microwave Applications (Wiley, New York, 2001).

[17] X. X. Zhang, et al.: “Design of a K-band two-layer microstrip interdigital filter exploiting aggressive space mapping,” J. Electromagn. Waves Appl. 32 (2018) 2281 (DOI: 10.1080/09205071.2018.1505559).

1 Introduction

Filter is widely used in many microwave and millimeter-wave systems. With the rapid development of wireless communication technology, quick and efficient design of a filter poses unprecedented challenges to engineers. Therefore, the auxiliary diagnosis and debugging of filters play more and more important role in the design of microwave filters. Space mapping is a commonly used microwave filter tuning method, it was first proposed in 1994 and called original space mapping (OSM) [1], whose algorithm required a great quantity of samples to establish a linear mapping relationship between two spaces. To solve this problem, the author of literature [2] improved this algorithm and proposed ASM. In literature [3], space mapping was used to study rectangular waveguide filter, which demonstrated the great advantages of designing this type of filter with space mapping. In
literature [4], the author studied microstrip filter with space mapping and achieved good results.

An important process in ASM is parameter extraction. For the design of coupled resonant microstrip filters, the traditional approach is to construct an equivalent circuit of the microstrip filter and import the response of the fine model into the circuit model. And then the response of the coarse model is approximated to the response of the fine model, thereby obtaining the coarse model parameters corresponding to the fine model. However, there are two main disadvantages of this method. Firstly, the coarse circuit model is not unique. This will result in different parameters extracted by different coarse circuit models. It sometimes leads to the algorithm not converging. Secondly, because it is an approximation response between two spaces, so generally curve fitting method is used, this method takes a long time, which reduces the advantage of the space mapping algorithm in efficiency [5, 6]. In the parameter extraction process, the Cauchy method is introduced in this paper. This method obtains an overdetermined equation by finite sampling of the fine model response. By solving the equation, two polynomials $P(s)$ and $F(s)$ representing the filter response can be obtained (where $S_{11}(s) = \frac{F(s)}{\epsilon_{R}E(s)}$, $S_{21}(s) = \frac{P(s)}{\epsilon_{E}(s)}$) [7], and the coefficient $E(s)$ is calculated through Feldtkeller equation [7]. Then, through the synthesize method of the cross-coupling filter, the coupling matrix corresponding to the S-parameters can be obtained very quickly [8, 9, 10]. In this way, not only the efficiency of parameter extraction is greatly improved, but also the non-uniqueness of the extracted parameters is avoided because the theoretical model of the rational parameters of the filter is used. Therefore the standard is consistent every time and the fast convergence of the algorithm is ensured.

Traditional cavities and LC filters are bulky, expensive to manufacture, and difficult to integrate with multi-chip interconnects [11, 12]. LTCC filters and multi-layer dielectric plate filters have poor consistency and low rectangularity due to poor processing accuracy [13, 14]. In contrast, silicon-based technology as the product of the cross-fusion of microelectronics, chemistry, mechanics and optics, is small in size, flexible in structure and easily integrated [15]. In this paper, a seventh-order interdigital filter with a center frequency of 24 GHz and a relative bandwidth of 25% is designed with space mapping method. After four iterations, the filter achieves design specifications and is processed on a high-resistance silicon substrate. The volume and quality of the silicon-based filter is a few hundredth of traditional LC filters and waveguide filters. And it also has a high degree of inhibition and good consistency, and is easily integrated.

2 General formulation of ASM

Space mapping is a technique extensively used for the design and optimization of microwave components. It uses two simulation spaces [7]: 1) the optimization space, where the variables are linked to a coarse model, which is simple and computationally efficient, although not accurate and 2) the validation space, where the variables are linked to a fine model, typically more complex and CPU intensive, but significantly more precise. Let $x_c$ represent the parameter of coarse model, $x_f$
the parameter of fine model, $x_c^*$ the optimal design parameter of coarse model, $R_c(x_c)$ coarse model response, and $R_f(x_f)$ fine model response. The mapping relationship between the fine model and the coarse model is $x_c = P(x_f)$. And the difference is minimized [7]

$$\min \| R_f(x_f) - R_c(x_c) \|$$

(1)

ASM can solve the problem of nonlinear mapping. The space solution of fine model is obtained by solving the following nonlinear equation:

$$P(x_f) - x_c^* = 0$$

(2)

If $P^{(j)}$ represents mapping results after the $j$th iteration, the corresponding design parameter of fine model is

$$x_f^{(j+1)} = (P^{(j)})^{-1}(x_c^*)$$

(3)

The next vector of the iterative process is obtained by a quasi-Newton iteration according to

$$x_f^{(j+1)} = x_f^{(j)} + h^{(j)}$$

(4)

where $h^{(j)}$ is given by

$$h^{(j)} = -(B^{(j)})^{-1}f^{(j)}$$

(5)

and $B^{(j)}$ is an approach to the Jacobian matrix, which is updated according to the Broyden formula [7].

$$B^{(j+1)} = B^{(j)} + \frac{f^{(j+1)}h^{(j)}^T}{h^{(j)}^Th^{(j)}}$$

(6)

3 Design procedure

The design property of this article is a seventh-order microstrip interdigital filter with a center frequency of 24 GHz, a fractional bandwidth of 25%, and an in-band return loss of 20 dB. The structure of this filter is shown in Fig. 1.

![Fig. 1. Structure of the seventh-order filter](image)

The cross-section view of substrate is shown in Fig. 2.

The equivalent circuit diagram of the filter is shown in Fig. 3.

Get normalized coupling matrix based on filter specifications:
As initial value of optimization variables, the theoretical center frequency, external quality factor $Q_e$ and coupling coefficients of filter were calculated as below, $c$ is a vector representing the ideal center frequency, coupling coefficient and external quality factor:

$$c = [f_1 = 24 \text{ GHz}, f_2 = 24 \text{ GHz}, f_3 = 24 \text{ GHz}, f_4 = 24 \text{ GHz}, K_{12} = 0.2305, K_{23} = 0.1578, K_{34} = 0.1463, Q_e = 3.343]$$

Accordingly, eight physical parameters need to be optimized:

$$x = [L_1, L_2, L_3, L_4, S_{1,2}, S_{2,3}, S_{3,4}, L_t]^T$$

CST software’s eigenmode simulation function is used to extract the single-cavity resonant frequency of the filter, the coupling coefficient between the two cavities, and the external quality factor of the cavity resonator. Coupling coefficient is extracted by establishing a two-cavity coupling model in CST with eigenmode simulation and Number of Modes set as 2. When two identical interdigital resonators are placed side by side, their original natural resonance frequency $f_0$ is split into two new resonance frequencies $f_1$ and $f_2$ due to mutual coupling effect. Therefore, the new resonance frequencies can be used to determine the coupling coefficient $K$ as [16]
As shown in Fig. 4, the simulated relationship between physical parameters (center frequency, coupling coefficient, and external quality factor) and optimization variables is established.

\[ K = \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2} \]  

Fig. 4. (a) Relationship between center frequency \( f_0 \) and resonator length \( L \)  
(b) Relationship between coupling coefficient \( K \) and distance \( S \)  
(c) Relationship between external quality factor \( Q_e \) and tap position \( L_t \)

Based on Fig. 4, the initial physical dimension was found \( x = [622, 622, 622, 622, 77, 170, 191, 958]^T \). The unit is \( \mu m \). The filter was simulated by using three-dimensional electromagnetic simulation software and the initial response of the filter was plotted in Fig. 5(a). It can be seen that the initial response did not meet the filter specifications, so ASM was used to optimize the physical parameters of the filter.

The diagnosis process is based on diagnostic debugging that combines ASM and Cauchy method. Parameter of the coarse model is physical parameter corresponding to the coupling matrix extracted through Cauchy method, which can be realized through MATLAB programming. The fine model is the model in CST. The fine model simulation response was imported into the coarse model as a SNP file. The corresponding coupling matrix was extracted with Cauchy method, and the physical parameter \( x_c^{(i)} \) of extracted coarse model was obtained according to Fig. 4. And then ASM algorithm was used to predict the physical parameter \( x_f^{(i+1)} \) of the
next fine model [17]. The process of applying this optimization algorithm to the bandpass filter is described in detail below. The unit of design parameter \( x \) is \( \mu \text{m} \).

1. Obtain the optimal solution of the coarse model with the coupling matrix of the ideal filter \( x_c^c \), let \( x_{f}^{(1)} = x_c^c \) and simulate in the fine model. The initial responses are shown in Fig. 5(a), which do not meet the design criteria;

2. Initialize \( j = 1 \), \( B^{(1)} = I \), use the Cauchy method to extract coupling matrix, get \( x_c^{(1)} \) according to Fig. 4 and work out the current mapping error \( f^{(1)} = x_c^{(1)} - x_c^c = [-146 21 -3 -15 -15 -25 -105]^T \);

3. Work out the incremental step size of the design parameter of the fine model \( h^{(1)} = [146 -21 3 15 15 6 25 105]^T \) through \( B^{(1)} h^{(1)} = -f^{(1)} \);

4. The new design parameter of fine model space \( x_f^{(2)} = x_f^{(1)} + h \). Perform a fine-model simulation and get the responses in Fig. 5(b), which do not meet design criteria. Therefore, the algorithm continues;

5. Extract the execution parameter \( x_c^{(2)} \), re-evaluate the error \( f^{(2)} = x_c^{(2)} - x_c^c = [-31 0 6 1 -45 -1 -2 -81]^T \);

6. Update mapping matrix \( B^{(1)} \) to \( B^{(2)} \) with Broyden formula;

7. \( j = j + 1 \), return to step 3 till the responses meet the design criteria.
Repeat steps 3–7 and get $x_f^{(4)}$. Its responses are shown in Fig. 5(h), which meet the design criteria, so the algorithm stops.

Fig. 5 shows the responses of the filter after each iteration.

In comparison, CST software’s optimization function is used to perform full-wave electromagnetic simulation. The design goal is set as $S_{11} < -20\, \text{dB}$ and the optimization variable range is set as $\pm 10\%$ based on initial design parameter. It takes 10 minutes to perform each fine model simulation, and a total of 50 minutes for optimization using the ASM algorithm. In contrast, the optimization time for full-wave electromagnetic simulation software CST is 15 hours. Computing times refer to a computer with an Intel(R) Core(TM) i7-4700MQ CPU at 2.40 GHz, with 8 GB of RAM. The results are shown in Fig. 6, optimized parameter after doing full-wave electromagnetic (EM) simulation is $x = [822.571, 626.065, 630.486, 623.145, 159.9, 194.01, 220.313, 1189.29]^T$.

The physical size of the filter after each iteration is shown in Table I.

**Table I.** Filter size in each iteration (Unit: $\mu$m)

| No. of iterations | $L_1$ | $L_2$ | $L_3$ | $L_4$ | $S_{1,2}$ | $S_{2,3}$ | $S_{3,4}$ | $L_t$ |
|-------------------|-------|-------|-------|-------|-----------|-----------|-----------|-------|
| Initial value     | 622   | 622   | 622   | 622   | 77        | 170       | 191       | 958   |
| 1st iteration     | 768   | 601   | 625   | 637   | 92        | 176       | 216       | 1063  |
| 2nd iteration     | 820   | 601   | 623   | 627   | 167       | 178       | 219       | 1199  |
| 3rd iteration     | 842   | 641   | 638   | 635   | 165       | 192       | 222       | 1221  |
| 4th iteration     | 837   | 631   | 632   | 629   | 162       | 198       | 227       | 1219  |

4 Fabrication and measurement

We make the optimized layout size into a graphic on the silicon wafer. The silicon wafer is made of 400 $\mu$m thick high-resistance silicon ($>10 \, \text{K}\Omega\text{-cm}$) with a dielectric constant of 11.9, with 4 $\mu$m thick Au as metal signal line and CPW input and output. The fabricated filter is shown in Fig. 7. Its size is $6.8\, \text{mm} \times 2.4\, \text{mm} \times 0.4\, \text{mm}$. Measurements of the filter were performed on an HP8510C Vector Network Analyzer with an HPS5105A millimeter wave controller. On-wafer
probing was achieved on a probe station using Model 120 Picoprobes with 400 µm pitch. Fig. 8 shows measurement results of the fabricated filter. According to the measurement results, the fabricated filter has a center frequency of 24 GHz, a fractional bandwidth of 24.17%, an insertion loss of 1.95 dB, a return loss of 12 dB, and an out-of-band rejection of 40 dB. Influence on parasitic quantity caused by the flatness error of cavity processing leads to resonance peaks outside the band, which can be improved by process control. The measurement results are basically consistent with the simulation results. Due to material characteristics and process errors, the loss of measured product is slightly larger and the bandwidth is slightly narrower, but these do not affect the correctness of the method in this paper.

5 Conclusion

This paper introduces aggressive space mapping method and studies the fast design of microwave filters using this algorithm. A K-band wideband bandpass filter is designed with space mapping method and successfully produced with silicon-based technology after four iterations. The silicon-based filter is characterized by small size, easy for integration, high performance, etc. Compared with direct optimization by means of full-wave electromagnetic simulation software, space mapping algorithm not only reduces the number of full-wave electromagnetic simulations and design time, but also offers efficient optimization and design flexibility.
Acknowledgments

This work was supported by The National Key Research and Development Program of China Project (2017YFF0107206).