cavity, it is easy to see that changing the cavity length will primarily affect the resonance frequency. To change the input-output couplings there are two options, namely the coupling aperture widths or the thicknesses. Both choices will affect the coupling level but the former will also change the resonance frequency. Changing the coupling window thickness, on the other hand, will not affect the stored energy so that (to a first order) the resonance frequency will not be affected.

V. Application Example

The filter chosen as an example is a six-pole Chebyshev filter with approximately 200-Mhz bandwidth, centered at 12 Ghz. The initial values used for the waveguide dimensions are shown in Fig. 1. The optimization process is begun by starting with the first cavity [6]. Running the SW optimizer with twenty points in frequency spanning the filter passband will give an initial error approximately equal to 23 [$W = 0$ in (1)]. After 20 iterations acting only on the first cavity length the error is decreased to 1.284. The thickness of the input and output windows can now be added, and the SW process can continue. After 21 iterations the error is equal to 0.553. At this point, one can run the FP algorithm. After eight FP iterations the error achieved is 0.013. One can now go to two cavities and run the SW optimizer on the second cavity length only. The error goes from 18 to 0.755 in about ten iterations. The next step is to add the thickness of the output coupling of the second cavity and perform another SW optimization. After 11 iterations the error will be about 0.195. Four additional FP iterations will now bring the error to 0.017. Next, the third cavity is added and one selects only its length for an SW optimization. The error goes from about 19 to 1.160 with ten iterations. At this point, the output thickness is added and with 12 more SW steps an error equal to about 0.248 is obtained. The FP algorithm can now be used to bring the error to 0.021 in six iterations.

At this point the filter design is completed. In fact, adding three more cavities to the filter with the same dimensions of the first three (the filter is symmetric), the result shown in Fig. 2 are obtained, where one can clearly see that the simulated performance of the waveguide filter is essentially identical to the performance of an ideal six-pole Chebyshev filter. A more complex nine-pole nonuniform filter was also designed and manufactured. The dimensions obtained are shown in Fig. 3, while the measured electrical performance is shown in Fig. 4. As one can see, a very good performance is obtained even though some deviation from the ideal Chebyshev return loss can be observed because of manufacturing tolerances.

VI. Conclusion

In this paper, the authors describe a simple filter design procedure which is based on the integration of a fast EM solver and two optimization routines. One optimization routine is based on the well-known FP algorithm, the other is based on a simple and robust algorithm, called the SP algorithm, which is used to get close to the desired target value when the starting point is considerably distant. In addition, the authors propose a choice of the structural parameters to be optimized which facilitates the optimization process. An application example is then discussed in detail indicating how the procedure described is indeed simple and effective. Finally, measured results are presented for a more complex filter showing very good hardware performance.

Acknowledgment

The authors would like to acknowledge the contribution of Alcatel Espacio, Madrid, Spain, in connection with the nine-pole nonuniform filter.

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Improved Design of Passive Coaxial Components Using Electromagnetic 2-D Solver in an Optimization Loop

Przemyslaw Miazga and Wojciech Gwarek

***Abstract*—In this paper a new approach to the design of passive coaxial components, based on finite-difference time-domain (FDTD) electromagnetic (EM) analysis in an optimization loop is presented. A specialized coaxial EM solver has been modified for combined use with three optimization methods. Algorithms proved to be accurate and effective producing significantly improved circuits designs in a reasonable computing time. Practical examples illustrate advantages of the present approach.**

I. Introduction

Electromagnetic (EM) analysis has become a well-established tool of microwave engineering enabling very accurate modeling of physical reality inside the designed devices. However, this method is time and memory consuming. The optimization algorithms usually require hundreds or even thousands of calculations of so-called objective function (circuit analysis), while converging to the optimal solution (corresponding to the circuit fulfilling given specifications). Therefore, the design process has usually been based on simplified models with EM analysis used only for final verification of the design before the hardware prototype is produced. With the development of fast computers the analysis time in some practical two-dimensional (2-D) cases has been reduced to minutes or even seconds.

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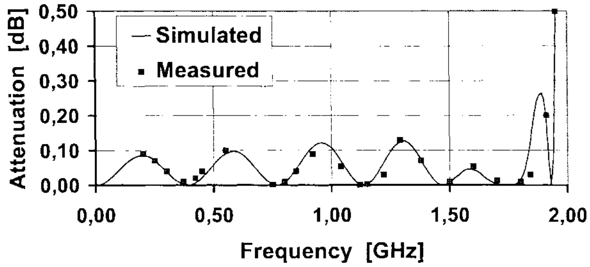
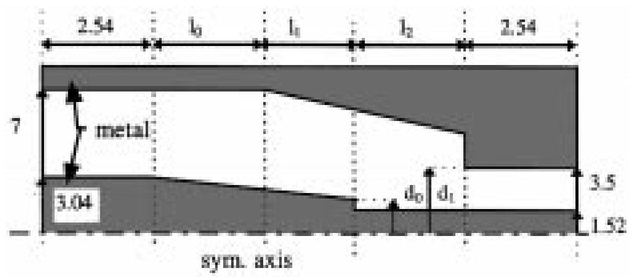
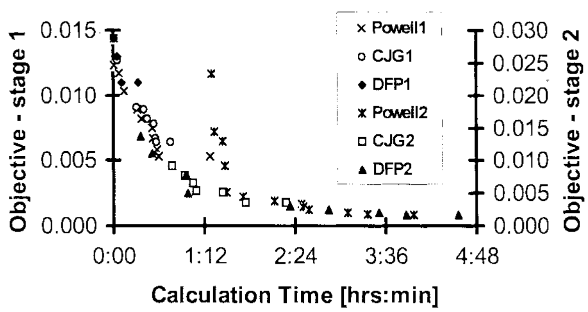


Fig. 1. Experimental verification of an EM simulator for the low-pass filter. Design and measurements after [11].



(a)



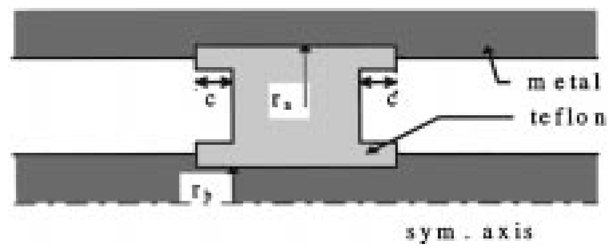
(b)

Fig. 2. (a) Coaxial 7–3.5-mm transition. (b) Comparison of optimization algorithms.

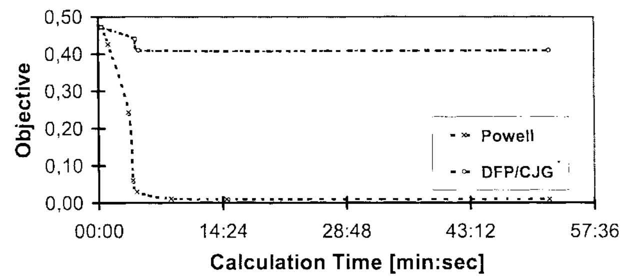
It has become attractive to use available finite-difference time-domain (FDTD) simulators, including those for coaxial applications, [1], [2] as a modeling tool providing scattering parameters for calculating objective function. However, such an approach poses on the EM analysis a number of requirements including continuity of the variables and the objective function. Such requirements are in conflict with the discrete nature of the methods used in most EM solvers.

Very recently, this area of research started to gain ground in the scientific literature. In [3] and [4], the authors give an example of optimization of a bandpass filter, which uses a TLM parameterized simulator and stochastic programming optimization package [4]. However, even with the computing time corresponding to tens of hours (three-dimensional (3-D) EM solvers) it seems to be difficult to obtain accuracy which is fully satisfactory for the industrial application. A significant progress has been achieved using the space-mapping technique and parallel computing [5], [6], reducing run time to hours for some practical circuits.

Some of the literature has addressed the critical issue of parameterization of the circuit layout [7], [8]. However, advances within this area are relatively slow and the applicability of these methods is limited to the structures which can be decomposed into simple basic elements like triangles and rectangles.

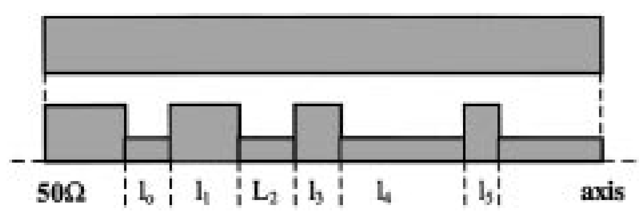


(a)

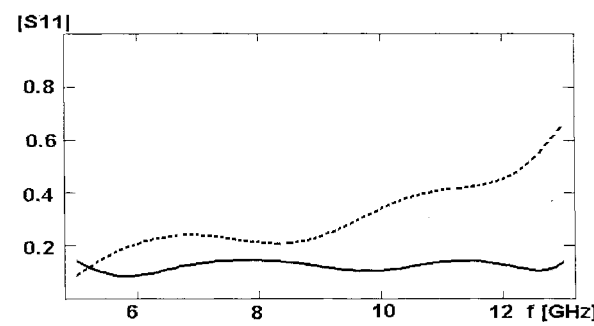


(b)

Fig. 3. (a) Dielectric support. (b) Optimization of dielectric support from near staring point.



(a)



(b)

Fig. 4. (a) Shape of six-section nonsynchronous transformer and (b) optimized frequency characteristics of the six-section transformer in a 5–13 GHz band.

The specialized literature available up to now does not clearly answer an important question: should special optimization methods be developed to be used with available EM solvers or should these solvers be modified to adapt them to application with classical optimization methods which have proved to be effective in circuit theory problems. The latter approach has been used in [8]. This paper continues along this line by investigating the application of three classical optimization methods of automatic design to coaxial passive components like connectors, impedance transformers, and filters. Consecutive simulations by the FDTD method are performed in a loop in which the component's parameters are modified using one of three classical algorithms of nonlinear programming: nongradient, conjugate gradient, and variable metrics [9], [10].

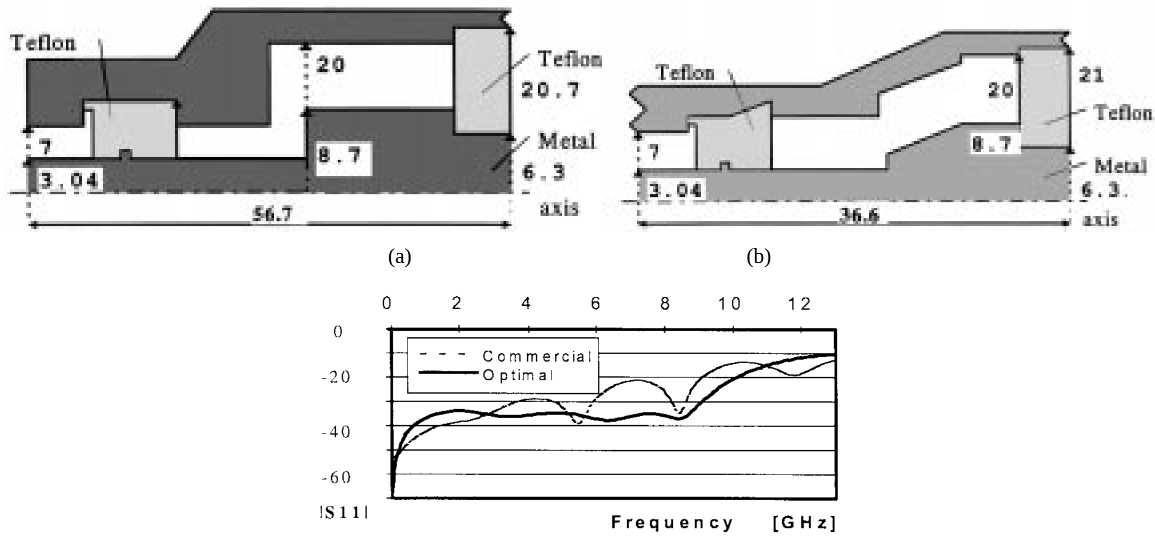


Fig. 5. (a) Commercial connector N to LCM20. (b) Optimized connector N to LCM20. (c) Comparison of frequency characteristics of S_{11} [dB] versus frequency [GHz] of commercial and optimal N to LCM20 connector.

II. The Method of Electromagnetic Simulation Used for Analysis of the Coaxial Device

To be able to perform the optimization well, one needs a method of EM simulation which fulfills the following requirements:

- must be sufficiently accurate and reasonably fast;
- must allow automatic application based on parametrized circuit description;
- must give sufficiently smooth objective function versus defined variables for a particular method of optimization.

The method applied here is a 2-D FDTD method based on the assumption of axial symmetry. The version of this method for coaxial devices has been first reported in [1], [2] and since then it has been extremely well verified in practice and applied in industry. For the present application a new version has been developed allowing automatic mesh generation from a file describing its dimensions. Some of these dimensions are treated as variables and are being changed during the optimization process, taking into account the technological constraints.

The accuracy of the new version has been verified on a variety of different examples of filters, connectors, and discontinuities. In all cases when sufficiently fine discretization was applied, the obtained results of simulation agreed with the measurements within the boundaries of the measurement error—to quote an example from open literature [11]—a coaxial line low-pass filter composed of 15 low- and high-impedance sections with tapered input and output. A comparison of measured and simulated frequency characteristics are presented in Fig. 1. This example has been chosen because it is a complicated resonant structure in which even small simulation errors would considerably change the obtained result. Even under these circumstances the result is fully satisfactory and proves that one can be confident that the applied method of EM analysis reflects exceptionally well the physical reality.

The FDTD grid used for the above example was 17 $\times$ 181 cells. Such a high accuracy with a relatively coarse FDTD grid was obtained by application of conformal FDTD using modified boundary cells with parameters obtained by local integral applications [12]. The modified cells also permit obtainment of the quasi-continuous goal function when dimensions are changed. If a change of dimensions forces the addition of a new cell (or row of cells) the resulting discontinuity of the goal function is nearly two orders of magnitude lower than the one which would appear when using the simple staircase approximation.

TABLE I
Comparison Between Initial and Optimized Dimensions for the Six-Section Transformer

Dimension	$\lvert\Gamma\rvert$	l_0	l_1	l_2	l_3	l_4	l_5
Starting	0.62	0.87	4.52	2.43	2.43	4.52	0.87
Optimal	0.14	0.65	4.36	1.98	2.09	3.70	0.1

III. The Optimization Process

The applied optimization process consists of minimizing the goal function as being a norm describing reflections in a specified frequency range. In this case, the so-called least pth norm [9] was used with quadratic penalty function for handling variable constraints [10]. To minimize the above goal function three methods of nonlinear programming were used, each one representative of a class of methods. The first method is the nongradient Powell method [10]. The two other methods are the conjugate-gradient method (CJG) [10] and the Davidon–Fletcher–Powell (DFP) method [10]. These techniques are regarded as very efficient in their classes. However, with nonsmooth and noisy objective function they may behave differently. To speed up convergence, reduce the influence of a poor starting point, and emulate a minimax objective (in order to obtain an equal ripple frequency characteristics) a two-stage optimization is conducted. At the beginning, the FDTD cell size is relatively large and a quadratic norm as objective is used. The first stage is used to find a "coarse" solution. Then the circuit is optimized with a finer mesh and least pth objective ($p = 4$ or 8). Gradients used in the gradient algorithms are estimated by finite differences.

As an example of two-stage optimization a design of 7–3.5 mm transition shown in Fig. 2(a) is presented. The variables to be optimized are section lengths l_0, l_1, l_2, and diameters d_0, d_1. The chart presented in Fig. 2(b) shows the behavior of the above-mentioned optimization algorithms. In each case, the optimization starts with stage 1 (left scale). When stage 1 is terminated stage 2 starts (of which the norm should be read using the right scale). In the considered case, all three algorithms perform well. The goal for the norm of the objective function (which is comparable to the maximum reflection coefficient in the considered band) to fall below 0.003 is obtained after approximately 2 h of calculations. The program was run on a PC 486DX/66 MHz with 8 Mbytes of random access memory (RAM).

Presented here is another example to show the different performance of the investigated methods with different starting points. Optimization of a dielectric support in the 7-mm coaxial line is considered. The structure is presented in Fig. 3(a). In case of optimization with a bad (far from optimum) starting point, both gradient methods (DFP and CJG) fail [as seen in Fig. 3(b).] while the Powell method, after 10 min, produces a result sufficiently good to start the second (precise) stage of optimization. It should be noted that using the first stage results of the Powell method as the starting point of the second stage produces good convergence of any of the three methods. Comparison of the performance of the three above-mentioned methods in application to the considered problems can be summarized in the following way.

- The Powell method was found to be slightly less efficient than gradient methods but more reliable when starting from a distant point. It was also found more robust when strong constraints imposed on circuit dimensions are considered. It was found to be the most universal and practically useful of the three considered methods.
- Both considered gradient methods were found less useful. It is also worth noting that out of the two gradient methods considered, the DFP method performs slightly better.

IV. More Examples of Application

An example of a transformer presented originally in [13] is considered here. This type of transformer provides very good performance and small size. However, at very high frequencies the fringing fields at the junctions of the consecutive sections may have a very important effect on the characteristics of the device. This effects would be very difficult to estimate and correct in the classical model. In the example presented in Fig. 4, a six-section nonsynchronous transformer is taken for a 5–13 GHz frequency band to match 20 Ω line (left) to 80 Ω line (right), composed of the sections of 80 and 20 Ω lines of lengths l_0–l_1. In this case, the noncompensated application of the design after [13] produces quite a poor result due to the presence of the fringing fields. This design has been used as the starting point of the authors' optimization. The final result presented as a continuous line in Fig. 4(b) is much better and very close to the expectations. Table I presents the lengths l_0–l_1 before and after optimization.

Another example is a commercial N to LCM connector. The authors have taken the original dimensions [Fig. 5(a)] and run the optimization, with 14 variables, assuming the usable frequency band up to 8 GHz. The calculation time was approximately 6.5 h on a Pentium 100 MHz. The resulting dimensions are shown in Fig. 5(b) and the improvement in the $|S_{11}|$ performance is shown in Fig. 5(c).

V. Conclusion

In this paper, the approach to the improved design of passive coaxial devices based on EM analysis in an optimization loop proved both accurate and effective. In simple cases, it produces the results with industrially acceptable accuracy on a fast PC within 0.5–2 h. Even in the cases of complicated structures with up to 14 variables, good results were obtained within 5–10 h. The method has been applied in industrial design with very positive feedback from engineers.

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Automated Optimization of a Waveguide-Microstrip Transition Using an EM Optimization Driver

Min Zhang and Thomas Weiland

***Abstract*—An electromagnetic (EM) optimization driver is introduced which makes optimization of electromagnetic components fully automatic. The driver is composed of an EM simulator and an optimizer. As a test example, an optimum design of a waveguide–microstrip transition using the driver is demonstrated. The numerical design is verified by the measurement.**

I. Introduction

In recent years, the rapid development of numerical techniques brings a lot of practical software packages available either in the

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