A Fast and Rigorous Synthesis Procedure for (Monolithic) Millimeterwave Integrated Circuit Layout

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ABSTRACT

A new versatile and efficient procedure for designing (monolithic) millimeterwave integrated circuits is presented. It is based on a novel supergrid method (SGM). The advantage of this new method is the integration of a MoM simulation and a simplex optimization scheme, which saves 80% of computation time and up to 90% of computer memory. Thus, workstations and PCs instead of supercomputers can be used for the synthesis of complex millimeterwave integrated circuit and antenna layouts. To demonstrate the capability of the method, a novel circularly polarized (CP) integrated W-band detector antenna was designed and experimentally characterized.

INTRODUCTION

Monolithic millimeterwave integrated circuits are key components to meet the requirements of a new high-volume market for PCS/PCN communication systems and automotive sensor applications. Designing layouts requires the use of sophisticated EM optimization techniques. However, currently available CAD programs treat analysis and optimization as separate algorithms, leading to excessively long computation times [7]. Therefore, in the past, millimeterwave integrated circuit layout optimization was carried out mainly on (parallel and vector) supercomputers.

This contribution proposes a novel supergrid method (SGM), which integrates the simulation and the optimization process. This approach saves a considerable amount of computation time (typically more than 80%) while reducing the required memory by a factor of up to 10, compared to [6]. This allows workstations and personal computers to be used for the synthesis of millimeterwave integrated circuits and antennas, thus simplifying and speeding up the design process.

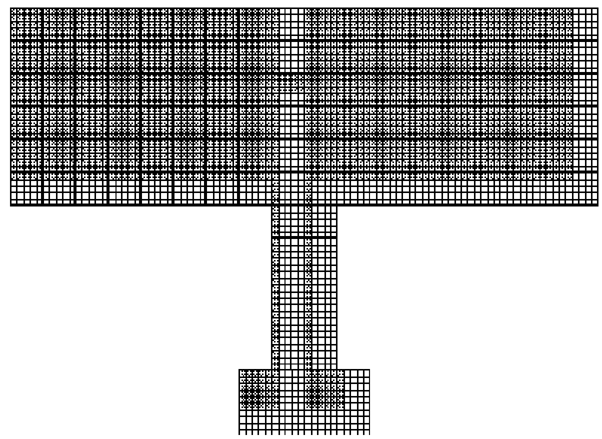

Fig. 1: Printed dipole antenna: Discretization with a supergrid.

EM SIMULATION

The EM simulation is based on a method of moments (MoM) approach to solve an electric field integral equation (EFIE). This includes the construction of a moment matrix and the solution of a matrix equation. Efficient spectral domain methods are available for the calculation of the moment matrix elements [7]. The matrix equation is solved using the quasi-minimal residual (QMR) iterative method [1]. We concentrate on single-layered substrate configurations with backside metallization. Extending the method to the general case of a multilayered structure however is straightforward. To employ the MoM, rooftop-shaped basis and testing function are used.

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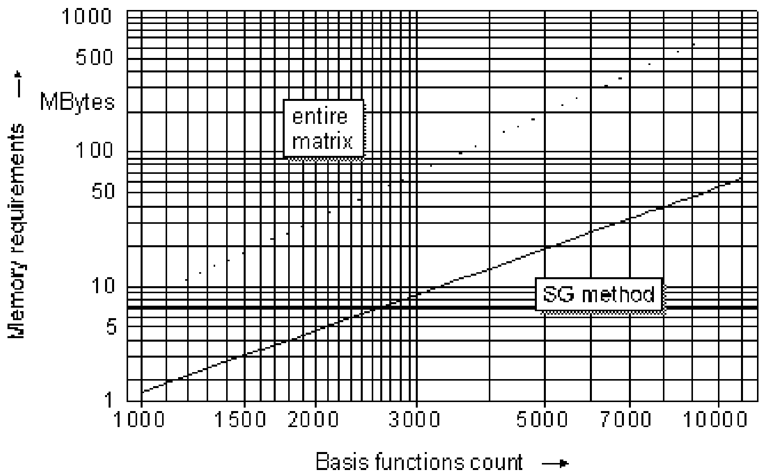

Fig. 2: Memory requirements for the moment matrix vs. basis functions count. Dotted line: entire matrix stored; solid line: SG method.

To apply the supergrid method (SGM), a fine grid and a coarse grid ("supergrid") are used to discretize the metallized areas of the circuit. This is depicted in Fig. 1, which shows a dipole antenna including the bias network. Metallized areas are gray-shaded. Each rooftop function covers two adjacent cells of the fine grid. The supergrid (bold lines) is constructed by combining $q \times q$ adjacent cells of the fine grid (thin lines). In this example, we used $q = 5$. The benefit of employing the SGM is threefold. First, a reduction of the memory requirement to store the moment matrix is achieved by exploiting the translation invariance property of the matrix elements (up to 90% reduction). This can be seen in Fig. 2, which compares the memory needed to store the entire matrix (dotted line) and the memory needed by the SGM (solid line) vs. the number of basis functions. Secondly, a reduction of the CPU time needed to solve the matrix equation is accomplished by using a high-efficient "matrix $\times$ vector" multiplication scheme (typically 2.5 times faster, compared to [6]). This is achieved by exploiting the block toeplitz structure of the moment matrix which is induced by the supergrid. Thirdly, the CPU time needed for the circuit synthesis is reduced by reusing the solution of the matrix equation in the optimization process (typically 3 to 4 times faster). This is depicted in Fig. 3 showing the number of iterations needed by the QMR solver to calculate the current distribution of a printed dipole vs. the length of the dipole. The dotted line represents the iteration count for the solver starting with random numbers as an initial guess. The solid line shows the iteration count when SGM is used. In this case, an initial guess is calculated based on the solution obtained for the length of the dipole used during the preceding step.

OPTIMIZATION

The optimization is based on the nonlinear simplex algorithm due to Nelder and Mead [4], which we found to be robust and flexible for a vast variety of circuit layouts. In contrast to genetic and simulated annealing algorithms [2,3,5], the simplex algorithm produces gradual changes in the circuit layout throughout the optimization process. Thus, only moderate changes in the current distribution occur between the iterations of the optimization. We exploited this for a further reduction of the execution time of the optimization code: Due to the locality property of the SGM and the monotonous behavior of the QMR algorithm, reusing the solution of the matrix equation as an initial guess for the QMR solver in the next iteration step of the optimization results in a faster convergence of the solver. We observed a typical 5 times faster calculation of the solution.

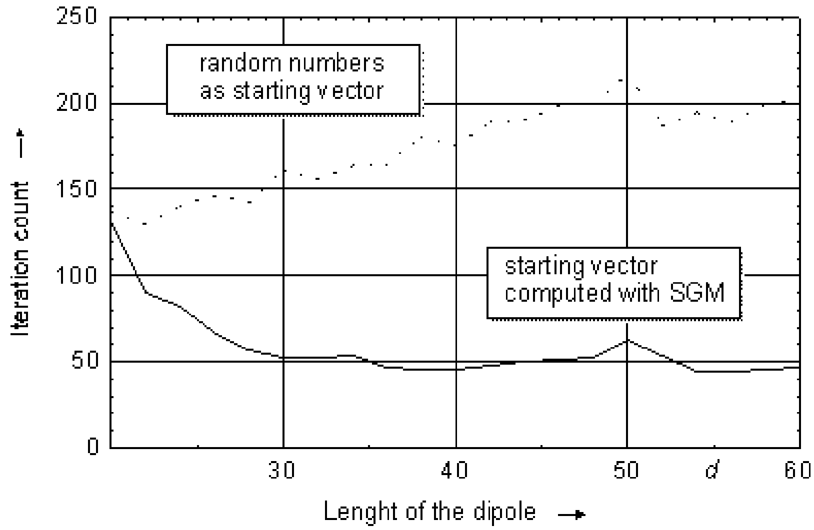

Fig. 4: Speed-up of the QMR solver by using SG method.

APPLICATION

To demonstrate the capability of the supergrid optimization method, a circularly polarized integrated W-band detector antenna (dual-patch antenna, DPA) was synthesized and experimentally characterized. Fig. 4 shows the layout of the antenna. Both almost-quadratic patches support two orthogonal current modes, which have to be 90° out of phase for circular polarization of the antenna. This is achieved by optimizing the dimensions *l*, *b* and *o* of the antenna layout. The Schottky diode located at the center of the antenna converts the received RF power to DC. The initial layout was designed using a simple transmission line equivalent circuit of the DPA. The cross polarization discrimination (XPD) of this initial layout was as low as 4.8 dB. Using the supergrid optimization scheme, XPD was increased to 19.1 dB (simulation). To verify experimentally the dual-patch approach, the antenna was fabricated on a high-resistivity silicon substrate. Fig. 5 shows the measured XPD in the frequency range 71 – 84 GHz. The antenna exhibits an XPD of 12 dB @ 76.5 GHz (nominal frequency) and 14.8 dB @ 76.0 GHz. Thus, the deviation from the optimum frequency is as low as 0.65%

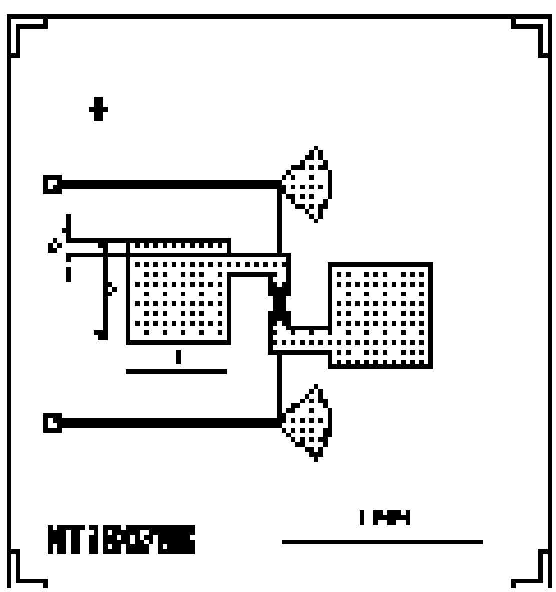

Fig. 3: Layout of the DPA.

CONCLUSION

The rapidly growing interest in (monolithic) millimeterwave integrated circuits and antennas calls for powerful and easy-to-use CAD tools for layout synthesis, based on a rigorous EM simulation and optimization. Supercomputers were used in the past to meet the memory and CPU time requirements of

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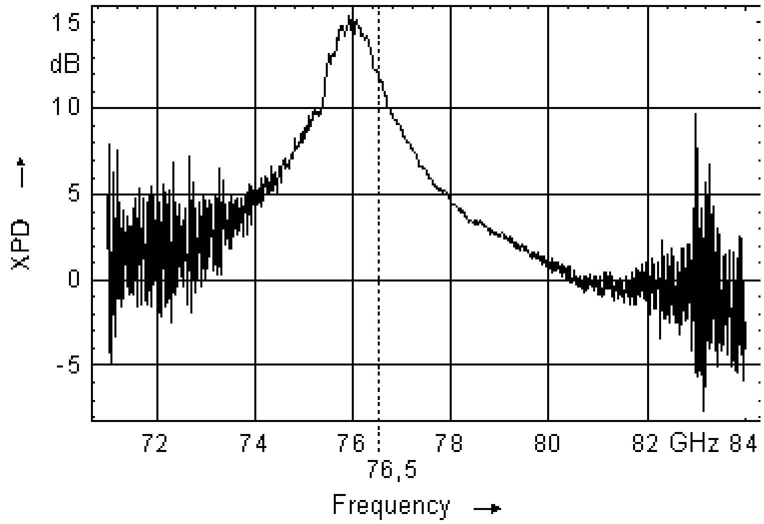

Fig. 5: Measured crosspolarization discrimination (XPD) vs. frequency of the DPA.

available optimization algorithms. To make layout synthesis feasible on workstations and PCs, a new efficient and versatile optimization method was developed, which is based on the integration of the analysis and the optimization algorithm using the supergrid method (SGM). A typical 80% reduction of the computation time and a 90% reduction of the memory requirement have been achieved using this approach. The successful synthesis of an integrated W-band detector antenna with circular polarization was demonstrated. The simulated cross polarization discrimination (XPD) was increased from 4.8 to over 19 dB and a measured XPD of 14.8 dB was obtained. The measured deviation from the optimum frequency is as low as 0.65%

ACKNOWLEDGMENT

This work was supported by the Deutsche Forschungsgemeinschaft.

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