Design of Dual-Frequency Probe-Fed Microstrip Antennas With Genetic Optimization Algorithm

Ozlem Ozgun, Selma Mutlu, M. I. Aksun, *Senior Member, IEEE*, and Lale Alatan, *Member, IEEE*

***Abstract*—Dual-frequency operation of antennas has become a necessity for many applications in recent wireless communication systems, such as GPS, GSM services operating at two different frequency bands, and services of PCS and IMT-2000 applications. Although there are various techniques to achieve dual-band operation from various types of microstrip antennas, there is no efficient design tool that has been incorporated with a suitable optimization algorithm. In this paper, the cavity-model based simulation tool along with the genetic optimization algorithm is presented for the design of dual-band microstrip antennas, using multiple slots in the patch or multiple shorting strips between the patch and the ground plane. Since this approach is based on the cavity model, the multiport approach is efficiently employed to analyze the effects of the slots and shorting strips on the input impedance. Then, the optimization of the positions of slots and shorting strips is performed via a genetic optimization algorithm, to achieve an acceptable antenna operation over the desired frequency bands. The antennas designed by this efficient design procedure were realized experimentally, and the results are compared. In addition, these results are also compared to the results obtained by the commercial electromagnetic simulation tool, the FEM-based software HFSS by ANSOFT.**

***Index Terms*—Genetic algorithms, microstrip antennas, multiple band antennas, multiport circuits.**

I. Introduction

RECENT advances in wireless communications systems, such as GSM and DCS in Europe, PCS in America, wireless local area networks (WLAN), wireless local loops (WLL), future broadband 3G systems and etc., have instigated a flurry of interest in microstrip antennas. This is mainly due to the unique features of microstrip antennas; which are, namely, low in profile, compact in structure, light in weight, conformable to nonplanar surfaces, easy and inexpensive for mass production, and well suited for integration with feeding networks and microwave devices, especially with the modern monolithic microwave integrated circuit technology. In addition, from the applications point of view, the microstrip antennas can be designed to perform any function that other antenna structures can perform, such as, circularly polarized radiation, multiband operations, etc. Since most wireless communications systems co-exist in the same geographic area, one handset needs to cover some of these services, which requires multimode or at least dual-mode operation. For example, since services from GSM900 and GSM1800 have been provided in Europe over the same regions for the same customers, dual-band mobile phones covering both frequency bands have become necessity for the expansion of the systems. Therefore, it is of paramount importance to devise a computationally efficient approach to design dual or multiband microstrip antennas that also satisfy other specifications like input voltage standing wave radio (VSWR) over each band. In this paper, an efficient algorithm based on the cavity model and a genetic optimization algorithm is developed to design multiband microstrip antennas with shorting strips or slots. This approach is very versatile and efficient, that is, one can optimize any set of characteristics of the antenna with the optimization of the number and locations of the shorting strips or slots.

Recent studies on microstrip antennas have primarily concentrated on the improvement of bandwidth and on the design of multifunction operations [1]–[9]. As a result, almost 100% bandwidth in terms of VSWR, and dual-band operations for GSM900 and GSM1800+WLAN services have been successfully accomplished and demonstrated [1], [6]. Along with this revived interest on the applications of microstrip antennas, development of efficient and accurate simulation tools to help analyze and design such antennas has gained some interest as well. For the simulations of printed antennas, there have been three major approaches, namely, the transmission line model, the cavity model and the full-wave techniques, ordered according to increasing accuracy [10]. Among these, the cavity model has a special place for providing physical intuition on the electrical characteristics and radiation mechanism of microstrip antennas, in addition to better accuracy as compared to the transmission line model, and better computational efficiency as compared to the full-wave approaches [11]–[13]. Therefore, the cavity model is often used to design the first trial antenna, and then the fine-tuning is performed with a full-wave approach, like HFSS by ANSOFT. Since the cavity model is numerically quite efficient and capable of handling variety of microstrip antennas with shorting pins and slots, when it is coupled with a suitable optimization algorithm, the combination would be a very efficient and effective design tool, at least during the initial phase of the design. During this study, a genetic algorithm was chosen as the suitable optimization tool that would be coupled with the cavity model. This choice was motivated

Manuscript received September 28, 2001; revised April 28, 2002.

O. Ozgun was with the Electrical and Electronics Engineering Department, Bilkent University, Bilkent 06533, Ankara, Turkey. She is now with The Scientific and Technical Research Council of Turkey (TÜBİTAK)-National Research Institute of Electronics & Cryptology (UEKAE), 06100 Ankara, Turkey.

S. Mutlu was with the Bilkent University, Electrical and Electronics Engineering Department, Bilkent 06533, Ankara, Turkey. She is now with Basari Company, 06070 Ankara, Turkey.

M. I. Aksun was with the Electrical and Electronics Engineering Department, Koc University, Sariyer 80910, Istanbul, Turkey. He is now with the Electrical and Electronics Engineering Department, Bilkent University, Bilkent 06533, Ankara, Turkey.

L. Alatan is with the Electrical and Electronics Engineering Department, Middle East Technical University, 06531 Ankara, Turkey.

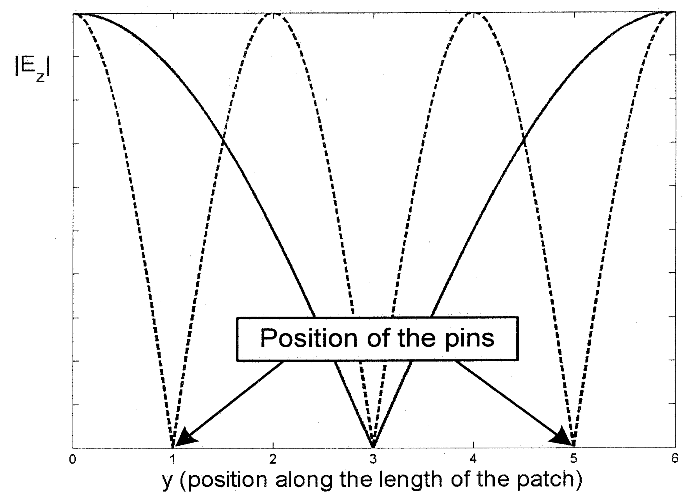
Digital Object Identifier 10.1109/TAP.2003.814732

by the earlier study of the optimization algorithms applied to microstrip antennas, in conjunction with a full-wave simulation tool [14], where it was concluded that the genetic optimization algorithms with binary encoding are quite suitable for problems with discrete choices of the optimization parameters.

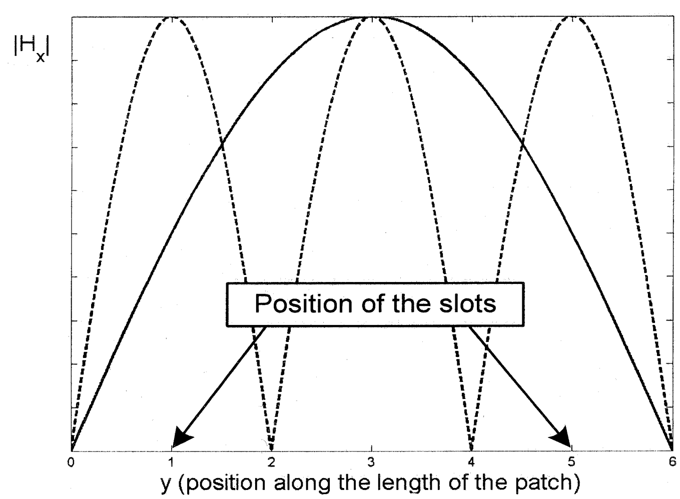
The idea of using a single patch in dual-frequency operation was first proposed and developed by Derneryd [15], where a single disc-shaped patch was connected to a complex impedance matching network, resulting in two narrowly spaced frequency bands. Since then, a variety of single-patch, dual-band microstrip antennas have been proposed and designed, some of which use patches loaded with shorting pins [16]–[18], some others use patches with slots [19]–[22], and patches with more than one port [6], [8]. In addition, there are some other approaches to achieve the dual-band operation: triangular microstrip antenna with a V-shaped slot loading [23]; circular microstrip antenna with an open-ring slot [24]; stacked quarter wavelength rectangular patch elements [25]; and drum-shaped patches [26] are just the few of these examples available in the literature.

Considering that microstrip antennas are resonant structures and can resonate at many discrete frequencies, they are bound to operate more than one frequency by nature. However, the dual-frequency operation with just a single patch antenna is mostly useful if the antenna over both frequency bands of interest has similar radiation patterns, polarizations and input impedance characteristics. Therefore, in the design of dual-band microstrip antennas, one needs to decide on the useful modes of resonance satisfying these constraints. For example, if an antenna is to be designed for linear polarization on the same direction over both frequency bands, then the two lowest useful modes of resonance are (0,1) and (0,3) modes according to the cavity model. Furthermore, since the frequencies associated with these modes are fixed (the ratio of the frequencies of the modes is 3), they need to be tuned according to the specification of the required bands of frequencies. In this respect, shorting pins (or strips) located between the patch and the ground plane and slots in the patch geometry play very important roles in tuning the modal frequencies to the desired frequencies. By properly placing the shorting pins under the patch or slots in the patch, the ratio of the frequencies corresponding to the lowest useful cavity modes, namely (0,1) and (0,3), can be adjusted to any value less than 3. Note, that a shorting pin placed at the nodal lines of (0,3) mode does not affect the resonant frequency of (0,3) mode significantly, but increases the resonant frequency of (0,1) mode, by forcing the electric field to be zero at the position of the shorting pin as seen in Fig. 1(a). Similarly, when a slot is placed on the patch where the magnetic field of (0,3) mode is maximum, the radiation from the slot results in a perturbation of the field distribution that gives rise to a decrease in the operating frequency of (0,3) mode [Fig. 1(b)].

Brief review of the cavity model in conjunction with the multiport analysis for a microstrip antenna with shorting strips and slots is provided in Section II. Then, the design process of microstrip antennas with strips and slots via the genetic optimization algorithm is discussed in Section III, where some examples and discussions on the proposed algorithm for the design of multifrequency antennas are also included. In addition, the electrical characteristics of the designed antennas, as obtained by the multiport analysis, are compared to those obtained experimentally and to those obtained by the full-wave method, HFSS by ANSOFT. This is followed by the conclusion in Section IV.



(a)



(b)

Fig. 1. Cavity modes of the patch antenna (solid line: (0,1) mode, dashed line: (0,3) mode).

II. Cavity Model With Shorting Pins and Slots

The cavity model was first proposed in 1979 for probe-fed microstrip antennas [11]. Since then, the method has been further improved to predict the input impedance of microstrip antennas with multiple strips or slots, and to cover microstrip antennas fed by slots in the ground plane [17], [19], [27]. The major restriction of the cavity model is on the thickness of the substrate, which is supposed to be not more than a few hundredths of a wavelength. This is mainly because the model assumes that neither field components nor the source can be a function of the vertical coordinate under the patch. As a result of this assumption, the electric field has only z component, while the magnetic field has only x and y components in the region bounded by the microstrip patch and the ground plane, Fig. 2. In addition, using the fact that the electric current density on the microstrip

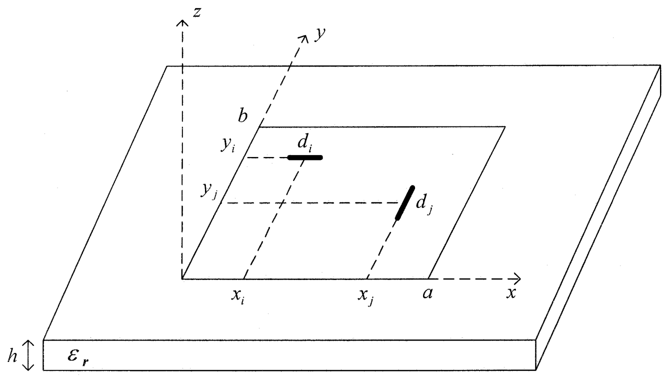


Fig. 2. Geometry of a microstrip antenna with one x-directed probe feed and one y-directed shorting pin.

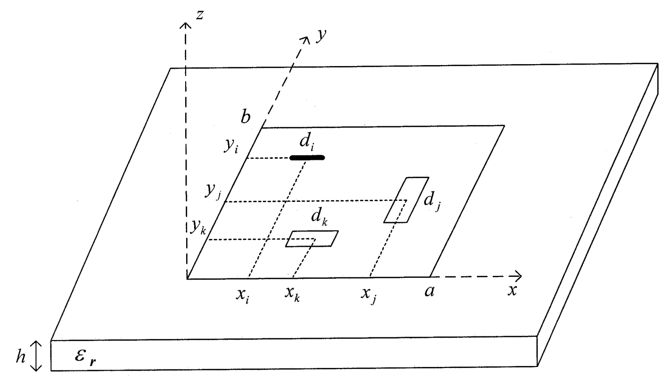


Fig. 3. Geometry of a microstrip antenna with one probe feed and two slots.

patch has no normal component along the edge of the patch, the tangential magnetic field is assumed to be negligible not just at the edges of the patch but all the way down to the ground plane. Therefore, the region between the patch and the ground plane can be surrounded by perfect magnetic conductor (PMC) wall that would not significantly alter the original field distribution under the patch, and hence forms a cavity. Consequently, once the cavity is formed as the model of the patch antenna, the fields in the cavity and subsequently other electrical characteristics can be easily obtained by the well-known solution of the cavity.

A. Multiple Shorting Strips

With the use of the above stated assumptions on the field directions and variations, and the boundary conditions of the cavity, the electric field E_{zi} anywhere under the patch can be obtained, for a 1 Amp. uniform probe current located at a point (x_i, y_i), as [19]

$$E_{zi} = j\omega\mu \sum_m \sum_n \frac{\psi_{mn}(x,y)\psi_{mn}(x_i,y_i)}{k^2 - k_{mn}^2} \times \mathrm{sinc}\left(\frac{m\pi d_i}{2a}\right) \tag{1}$$

where

$$\psi_{mn}(x,y) = \alpha_{mn}\cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right)$$
$$\alpha_{mn} = \sqrt{\frac{\varepsilon_{om}\varepsilon_{on}}{ab}} \quad \varepsilon_{om,on} = \begin{cases} 1 & m,n=0 \\ 2 & m,n\neq 0 \end{cases}$$

k_{mn} is the eigenvalue of the (m,n) mode, $k^2 = k_0^2\varepsilon_r(1 - j/Q)$, Q is the quality factor of the cavity, and $(a,\, b)$ and d_i are the effective dimensions of the patch and effective width of the feeding strip extended laterally in *x* direction, respectively. Since the electric field is constant along *z* direction, the voltage created by ith source at any point under the patch can simply be written as $V_i = -hE_{zi}$. Hence, the self and mutual impedances, Z_{ii} and Z_{ij}, for the *z* polarized uniform current densities on any two strips, as shown in Fig. 2, can be calculated by averaging the voltage generated by the jth source over the extend of the ith shorting strip (V_{ij}). The shorting strips could be extended laterally either in the same direction or in perpendicular directions and the mutual impedances are obtained as

$$\begin{aligned} Z_{ij} &= \frac{V_{ij}}{I_i} = V_{ij} = -\frac{h}{d_i}\int_{\mathrm{over} d_i} E_{zj}|_{y=y_i}\, dx \\ &= -j\omega\mu h \sum_m\sum_n \frac{\psi_{mn}(x_i,y_i)\psi_{mn}(x_j,y_j)}{k^2-k_{mn}^2} \\ &\quad\times \left\{ \begin{matrix} \mathrm{sinc}\left(\frac{m\pi d_i}{2a}\right) \\ \mathrm{sinc}\left(\frac{n\pi d_i}{2b}\right) \end{matrix} \right\} \left\{ \begin{matrix} \mathrm{sinc}\left(\frac{m\pi d_j}{2a}\right) \\ \mathrm{sinc}\left(\frac{n\pi d_j}{2b}\right) \end{matrix} \right\} \end{aligned} \tag{2}$$

where the upper and lower expressions in each curly bracket are for the lateral extensions of *x* and *y* directions, respectively, for the strips, i and j. Since the main goal of the multiport analysis is to get the effect of the shorting strips on the input impedance, there is no need to assign the feeding probe *a priori*, that is, any strip can be the feeding probe or shorting strip. For an N-port microstrip antenna, the input impedance seen at port-i can be calculated by assigning zero voltage (short circuit) to all ports except the ith port. In this case, the port currents are related to each other in the following form:

$$\overline{\overline{Z}}_{-i,-i}\bar{I}_{-i} = -\overline{Z}_{-i}^T I_i \Rightarrow \bar{I}_{-i} = -\overline{\overline{Z}}_{-i,-i}^{-1}\overline{Z}_{-i}^T I_i \tag{3}$$

where $\overline{\overline{Z}}_{-i,-i}$ is the impedance matrix from which ith row and ith column have been extracted, $\overline{Z}_{-i}$ is the ith row of the impedance matrix, $\bar{I}_{-i}$ and $\overline{V}_{-i}$ are the port current and voltage vectors, respectively, all with the ith entries are extracted. Superscript -1 and T denote the inverse and transpose operators, respectively. By using (3), the input impedance seen at port-i is obtained as

$$\begin{aligned} Z_{\mathrm{in}}(\mathrm{at\,port} - i) &= \left.\frac{V_i}{I_i}\right|_{V_j=0, j\neq i} = \frac{Z_{ii}I_i + \overline{Z}_{-i}\bar{I}_{-i}}{I_i} \\ &= Z_{ii} - \overline{Z}_{-i}\overline{\overline{Z}}_{-i,-i}^{-1}\overline{Z}_{-i}^T \end{aligned} \tag{4}$$

B. Multiple Slots

For the sake of illustration, a patch with two perpendicularly oriented slots with the lengths of d_j and d_k and a vertical strip with the width of d_i is demonstrated in Fig. 3. Note, that only very narrow slots are considered in this work, and all the lengths of the slots are effective lengths, which are slightly smaller than the physical lengths [27].

For the application of the multiport analysis to such geometries, slots need to be defined as additional ports, across which voltage sources would be suitable to define. Therefore, since both a vertical strip as the feed and slots exist, the matrix that characterizes the system is not a pure impedance matrix any more, as in the case of multiple shorting strips. For example, the matrix and its entries for the system depicted in Fig. 3. are given as follows:

$$\begin{bmatrix} V_i \\ I_j \\ I_k \end{bmatrix} = \begin{bmatrix} Z_{ii} & h_{ij}^V & h_{ik}^V \\ h_{ji}^I & Y_{jj} & Y_{jk} \\ h_{ki}^I & Y_{kj} & Y_{kk} \end{bmatrix} \begin{bmatrix} I_i \\ V_j \\ V_k \end{bmatrix} \tag{5}$$

where the matrix is of a hybrid type, mixed with impedance Z, admittance Y, current gain h^I and voltage gain h^V parameters. Since there is only one vertical strip, which is used for feeding, in this example and throughout this study, only Z_{ii} exists in this formulation. However, this approach can be easily extended to multiple vertical strips and slots together, for which case the characterization matrix would be formed by block matrices of $\overline{\overline{Z}}_{11}$, $\overline{\overline{H}}_{12}^V$, $\overline{\overline{H}}_{21}^I$, and $\overline{\overline{Y}}_{22}$. Referring back to the example given in Fig. 3, the parameter Z_{ii} has already been introduced in (2); the others can be obtained easily from the following definitions:

$$\begin{aligned} h_{ij(k)}^V &= V_i|_{V_{j(k)}=1V,\ \text{port}-\text{i:open},\ \text{port}-\text{k(j):short}} \\ &= -\frac{h}{d_i} \int\limits_{\text{over } d_i} E_{zj(k)}|_{y=y_i} dx \end{aligned} \tag{6}$$

$$\begin{aligned} h_{j(k)i}^I &= I_{j(k)}|_{I_i=1A,\text{port}-\text{j and }-\text{k:short}} \\ &= \int\limits_{\text{over } d_{j(k)}} H_{y(x)i}|_{\substack{x=x_j \\ (y=y_k)}} dy(dx) \end{aligned} \tag{7}$$

$$\begin{aligned} Y_{jj(kk)} &= I_{j(k)}|_{V_{j(k)}=1V,\text{port}-\text{i:open},\ \text{port}-\text{k(j):short}} \\ &= -\int\int\int \overline{M}_{j(k)}^* \cdot \overline{H}_{j(k)} dv \end{aligned} \tag{8}$$

$$\begin{aligned} Y_{jk(kj)} &= I_{j(k)}|_{V_{k(j)}=1V,\text{port}-\text{i:open},\ \text{port}-\text{j(k):short}} \\ &= \int\limits_{\text{over } d_{j(k)}} H_{yk(xj)}|_{\substack{x=x_j \\ (y=y_k)}} dy(dx) \end{aligned} \tag{9}$$

where $\overline{M}_{j(k)}$ denotes the magnetic volume current density at the slot j(k) and the volume below it down to the ground plane, and the field components are defined with the two subscripts: the first defines the polarization of the field; and the second defines the port that was generated from. Note that slots are modeled as uniform magnetic current densities, not only at the surface where slots reside but also in the volume just below it down to the ground plane [19], [27]. The reason for the extension of the magnetic current at the slot into the volume below is that, as it was mentioned in the introduction, source models used in the cavity model must be independent of the coordinate perpendicular to the patch in the substrate.

Once the matrix representation of the patch with a feed and slots is obtained, the input impedance seen by the probe feed can be obtained in terms of the load admittances Y_j and Y_k across the slot terminals at port-j and port-k, respectively [28]. By using the port relations at slot terminals ($I_{j(k)} = Y_{j(k)} V_{j(k)}$), the input impedance seen by the probe feed at port-i is found as

$$\begin{aligned} Z_{\text{in}} = Z_{ii} - &\left(h_{ij}^V - \frac{h_{ik}^V Y_{kj}}{Y_j + Y_{kk}} \right) \\ &\times \left(\frac{h_{ji}^I - \frac{Y_{jk} h_{ki}^I}{Y_k + Y_{kk}}}{Y_j + Y_{jj} - \frac{Y_{jk} Y_{kj}}{Y_k + Y_{kk}}} \right) - \frac{h_{ik}^V h_{ki}^I}{Y_k + Y_{kk}} \end{aligned} \tag{10}$$

For the sake of completeness, the definition of the input impedance of a slot with given dimensions is given in Appendix A.

In summary, the multiport analysis of a microstrip antenna with some shorting pins and/or slots is performed by following these steps: 1) vertical strips (shorting or feeding) and slots are considered as the ports of an N-port network; 2) voltage and current sources are assigned to the slots and vertical strips, respectively; 3) independent parameters of the ports (voltage and current for strips and slots, respectively) are written in terms of the dependent parameters (current and voltage for strips and slots, respectively); 4) circuit parameters, like impedance, admittance, current gain and voltage gain, are obtained by short-circuiting some slots and by open-circuiting some strips; and finally 5) the input impedance at the feed port is obtained in terms of the circuit parameters, and hence the effects of the slots or strips on the input impedance are quantitatively obtained.

III. Results and Discussion

After having introduced and reviewed the cavity model and multiport analysis of microstrip antennas with shorting strips and slots, these approaches have been combined with a robust optimization algorithm, the genetic algorithm. Since the genetic algorithm has been well studied and reviewed in the literature [31]–[33], it is not repeated here in detail. Instead, the steps of the algorithm are provided for being able to discuss the parameters used in the optimization algorithm. The first step is to code the parameters of the optimization as finite length strings (chromosomes), then to generate a population of these strings, which will be multiple starting points as contrary to a single initial point in gradient based optimization algorithms. Therefore, this approach increases the probability of finding the global optimum by searching the whole parameter space in parallel. The next step is to evaluate the cost function at each member of the population and to assign some fitness value. Then, the genetic algorithm employs some probabilistic transition rules (randomized operators) to guide the search for optimum, which are reproduction, crossover and mutation.

A. Multiple strips

In this study, the genetic optimization algorithm was first used to find the appropriate locations and widths of the shorting strips in a microstrip patch antenna to match the input impedances to 50 Ω at both low and high frequencies and to satisfy a desired frequency ratio f_h/f_l, where f_h and f_l denote the high and low frequencies, respectively, for a dual-band operation. For the optimization, the feed location, its width and orientation, the number of shorting strips, their orientations and the desired frequency ratio are used as known and fixed parameters, while the

x and y coordinates, and the width of each shorting strip are used as the optimization parameters. So, the objective function is written as

$$f_{\text{obj}} = 100 - \sqrt{\left(f_{\text{ratio}} - \frac{f_h}{f_l}\right)^2 + (Z_l - 50)^2 + (Z_h - 50)^2} \tag{11}$$

where $f_{\text{ratio}} = f_h/f_l$ is the desired frequency ratio, Z_l and Z_h are the input impedances at f_l and f_h, respectively, and 100 is just a positive number determined empirically to make f_{obj} maximum at the point of optimization.

For the presentation of the algorithm discussed so far in this paper, two microstrip antennas with some shorting strips have been designed for dual-band operation via the genetic optimization algorithm. The first example is an air-filled antenna and its fixed parameters are as follows: $a = 8$ cm, $b = 10$ cm, $h = 0.6$ cm, $\sigma = 10^5$ mho/cm, $\tan\delta = 10^{-5}$, the position of the feed, $(x_f,\ y_f) = (4\ \text{cm},\ 0\ \text{cm})$, the width of the feed, $d_f = 0.5$ cm and the lateral extension of the feed is in x direction.

The genetic algorithm has five internal properties: chromosome length, population size, generation number, crossover probability, and mutation probability. Since each variable parameter, real or integer, is transformed into a binary string with the length defined by the precision required for that variable, the chromosome length is the length of the member in the population, that is, the length of the binary string combined for all variables. For the study of these two antennas, the chromosome length is chosen as 25 chromosomes per unknown parameter, so that the total length of each chromosome (or a member in the population) for a patch with N shorting strips is $3N \times 25$, 3 being the number of the variable parameters for each strip. The crossover probability and mutation probability used are 0.65 and 0.008, respectively, and two-point crossover is applied in each trial. The population size and generation number determine the speed and efficiency of the genetic algorithm. The optimization parameters and results for the air-filled antenna with at most two shorting strips for different population sizes and generation numbers are given in Table I, where $(x_{s1},\ y_{s1})$ and $(x_{s2},\ y_{s2})$ denote the coordinates of the first and second strips, respectively, d_{s1} and d_{s2} are the widths of the strips, while P and G are the population size and the generation number, respectively, and f_{ratio} is the desired frequency ratio. To guide the search algorithm, the limits of the x and y coordinates of the shorting strips are determined by the patch dimensions, while the strip widths are varied in the range of 0.1–1.5 cm. Case-1 corresponds to the patch with one shorting strip extended laterally in x direction, case-2 and case-3 correspond to the patches with two shorting strips: the former has both strips extended in *x* direction, the latter has one extended in *x* direction and the other extended in *y* direction.

For the first antenna, with the optimized positions and widths of the shorting strips given in Table I, the simulation results are provided in Table II. To assess the accuracy of the simulation technique used in conjunction with the optimization algorithm, the results of a full-wave approach, namely HFSS, are also provided. It is observed from Table II that the resonant frequencies and the reflection coefficients for both low and high bands agree very well with those predicted by HFSS.

TABLE I
OPTIMIZATION PARAMETERS AND RESULTS FOR THE AIR-FILLED ANTENNA (DIMENSIONS IN CENTIMETERS)

Case	P	G	f_{ratio}	Strip	x_{s1}	y_{s1}	d_{s1}	x_{s2}	y_{s2}	d_{s2}
1	200	200	2.24	1	4.99	3.73	1.43	-	-	-
2	150	150	2.24	2	5.15	4.35	0.36	2.13	3.01	1.24
3	10^3	100	2.24	2	5.05	3.76	1.25	4.94	3.65	1.13

TABLE II
SIMULATION RESULTS FOR THE AIR-FILLED ANTENNA

Model	Case	f_l(GHz)	$\|\Gamma in\|_l$	f_h(GHz)	$\|\Gamma in\|_h$	f_h/f_l
Multi-port	1	1.7	0.041	3.95	0.008	2.32
	2	1.74	0.032	4.05	0.017	2.33
	3	1.74	0.041	4.11	0.002	2.36
HFSS	1	1.68	0.217	3.96	0.110	2.36
	2	1.74	0.090	4.05	0.169	2.33
	3	1.71	0.157	4.00	0.070	2.34

TABLE III
RESONANT FREQUENCIES AND REFLECTION COEFFICIENTS FOR THE DIELECTRIC-FILLED ANTENNA

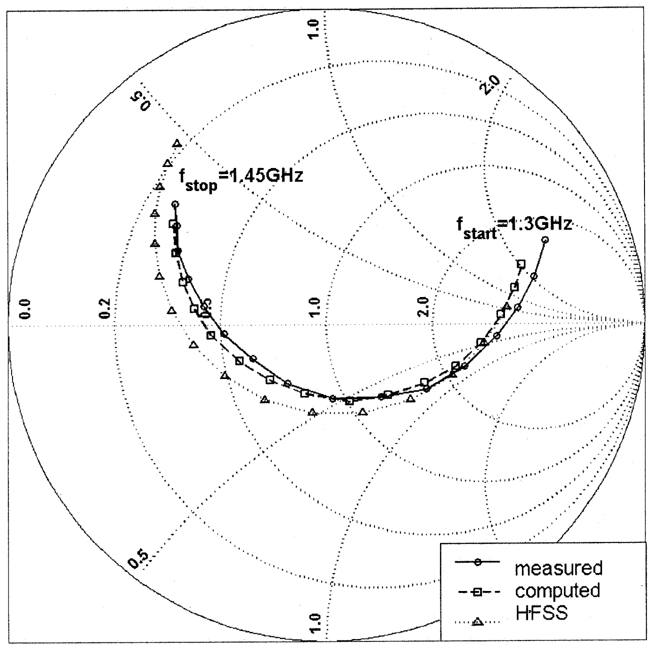
Case	f_l (GHz)	$\|\Gamma in_l\|$	f_h(GHz)	$\|\Gamma in_h\|$	f_h/f_l
Multi-port	1.55	0.085	3.78	0.560	2.44
HFSS	1.568	0.030	3.76	0.441	2.40

TABLE IV
OPTIMIZATION PARAMETERS AND RESULTS FOR $f_h/f_l = 2.7$

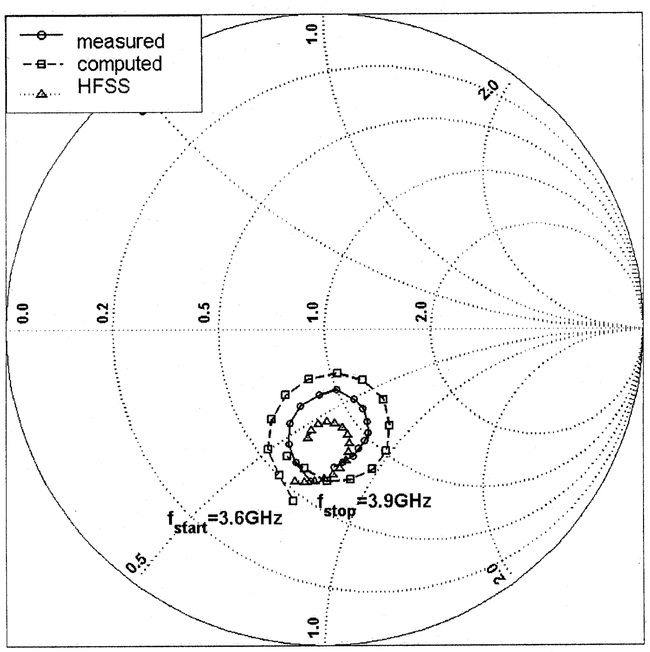
	Multi-port			HFSS			
	f_h/f_l	f_l (GHz)	f_h (GHz)	f_h/f_l	f_l (GHz)	f_h (GHz)	Output (in cm)
1 slot: d_1 & (x_1, y_1)	2.76	1.37	3.78	2.72	1.35	3.66	d_1=1.1395 at (3.664, 5.287)
2 slots: d_1 & (x_1, y_1), d_2 & (x_2, y_2)	2.69	1.38	3.72	2.73	1.35	3.67	d_1=1.3936 at (3.735, 5.148) d_2=0.1397 at (4.023,4.459)
3 slots: d_1 & (x_1, y_1), d_2 & (x_2, y_2), d_3 & (x_3, y_3)	2.65	1.38	3.65	2.73	1.35	3.66	d_1=1.7179 at (1.385, 3.210) d_2=0.1397 at (4.168, 4.733) d_3=0.1148 at (1.564, 1.352)

The second antenna was designed to demonstrate the applicability of the proposed algorithm for microstrip antennas over a dielectric material ($\varepsilon_r = 4.7$), for which the fixed parameters are: $a = 5$ cm, $b = 6$ cm, $h = 0.16$ cm, $\sigma = 10^6$ mho/cm, $\tan\delta = 5 \times 10^{-4}$, $(x_f,\ y_f) = (2.5\ \text{cm},\ 1.8\ \text{cm})$, $d_f = 1$ cm. For dual frequency operation, this antenna was designed with one shorting strip located at $x_s = 2.5$ cm, $y_s = 1.0$ cm, and with a width of $d_s = 1.5$ cm, extending in *x* direction laterally. The low and the high resonance frequencies together with the reflection coefficients at resonance are presented and compared in Table III.

From the designs of these two dual-band antennas, a total of four cases, it is observed that the antennas designed by the genetic optimization algorithm with the multiport analysis agree with the specifications, as confirmed by the results of a rigorous

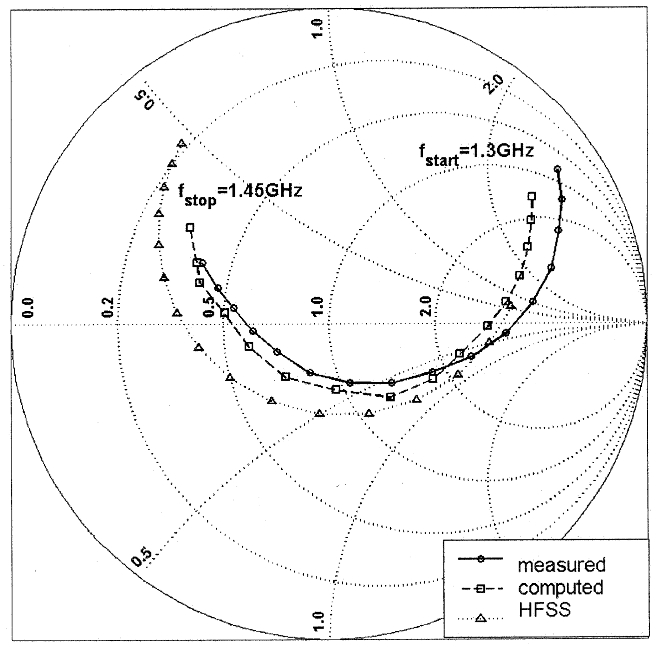


(a)

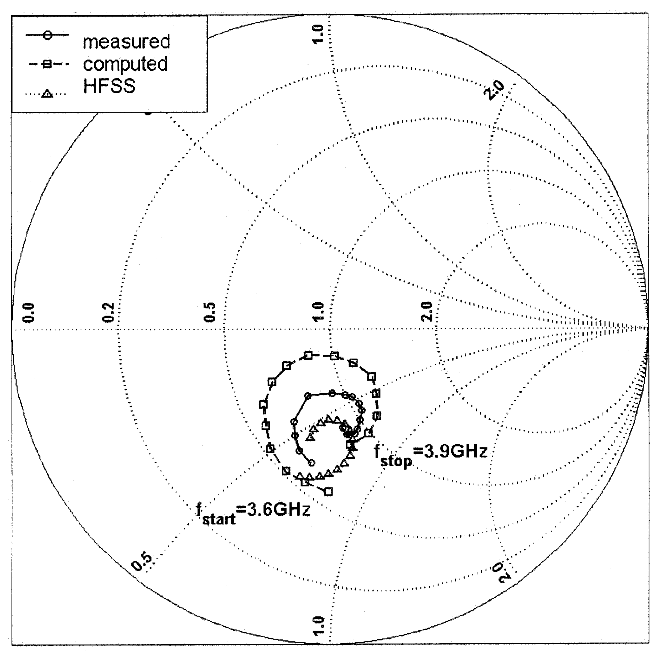


(b)

Fig. 4. Measured and computed impedance loci of the first patch antenna in Table IV: (a) low band and (b) high band.



(a)



(b)

Fig. 5. Measured and computed impedance loci of the second patch antenna in Table IV: (a) low band and (b) high band.

full-wave method, HFSS. This observation suggests that the algorithm presented here can make an efficient and accurate CAD tool, at least for the initial design of dual-band microstrip antennas with multiple shoring strips. Another point worth noting is that, during the design iterations, the strip locations tend to converge to the nodal E field lines of the third cavity mode, as expected.

B. Multiple Slots

The proposed design algorithm for microstrip antennas, which is the multiport analysis in conjunction with the cavity model and genetic optimization algorithm, is further tested on microstrip antennas with slots etched in the patch, with a view of designing dual-band antennas. For this study, a rectangular patch antenna (made of bronze) fed by a vertical strip is designed with the following fixed parameters: $a = 8.0$ cm, $b = 10$ cm, $h = 0.6$ cm, $\varepsilon_r = 1.0$, $\tan\delta = 10^{-5}$, $\sigma = 10^6$ S/m, $(x_f,\ y_f) = (4.0\text{ cm},\ 3.0\text{ cm})$, and $d_f = 1.0$ cm. As in the case of the patch antenna with shorting strips, the goal of the optimization is again to find the appropriate coordinates and length of the slots used, to satisfy the specifications on the frequency ratio and on the input impedance over the high and low frequency bands. So, using the objective function defined in (11), *x* and *y* coordinates, and the length of each slot are optimized. It is worth mentioning that the cavity model is applicable to patch antennas with narrow slots, therefore the width of each slot is fixed to 0.15 cm. For the optimization algorithm, the chromosome length, crossover and mutation probabilities are set to 20 (for each optimization parameter), 0.65 and 0.008, respectively. Also, two-point crossover is used in each process.

The frequency ratio is set to 2.7, and optimizations are performed for different numbers of *x* oriented slots. In each optimization with different number of slots, the population size and generation number are fixed to 1000 and 200, respectively. The optimization results are summarized in Table IV, where the first column gives the number of *x* oriented slots, and the last column gives the optimized positions and lengths of the slots. For all the cases studied here, the specifications on the frequency ratio and the input impedances have been very well satisfied. To verify the optimization results, the first and second optimized antennas in Table IV were realized and tested experimentally. Then, the input impedances obtained from the multiport analysis in conjunction with the cavity model, from measurements and from HFSS are compared over both low and high bands as shown in Figs. 4 and 5.

It is observed from Table IV that the design algorithm presented in this paper provides positions and lengths of the slots quite accurately for the design of dual-band microstrip antennas. The input impedance loci presented in Figs. 4 and 5 imply that the multiport method proposed in this paper performs well, as far as the accuracy is concerned.

IV. Conclusion

Dual-frequency operation of rectangular patch antennas with shorting strips and slots has been investigated via the cavity model in conjunction with the multiport theory. By combining this approach with the genetic optimization algorithm, an efficient and accurate design tool was proposed for dual-band microstrip antennas using multiple vertical strips or slots. For the examples provided in this study, the frequency ratio of the high-band and low-band frequencies, and the input impedances over these bands were used as the specifications, while the coordinates and dimensions of the strips or slots were the optimization parameters. The antennas so designed have been realized, and dual-band operation was verified experimentally as well as by simulation of the antennas rigorously via HFSS by Ansoft. It is observed that the theoretical results agree well with the experimental results. Therefore, this approach can be safely proposed as an efficient CAD tool for dual-band microstrip antennas that would use slots or vertical strips, at least for the initial design of the antennas.

Appendix A
Impedance of a Slot

The impedance of a slot in an infinite ground plane can be approximately obtained by the impedance of a short dipole via well-known Babinet's principle [29], [30]

$$Z_{\text{slot}} \cdot Z_{\text{dipole}} = \frac{\eta^2}{4} \tag{A.1}$$

where η is the intrinsic impedance of the free space, and the dipole is assumed to be the complement of the slot. Since the input impedance of a short dipole can be modeled as a series connection of radiation resistance, ohmic resistance, inductance, and capacitance, which are expressed as follows [30]:

$$R_r = \frac{80\pi^2}{I_0^2 \lambda^2} \left(\int_{-1}^{l} I(z) dz \right)^2 \tag{A.2}$$

where I_0 is the magnitude of the current distribution, and l is the half-length of the dipole

$$R_o = \frac{2I}{2\pi \mathrm{w}} \underbrace{\left(\frac{\omega\mu_o}{2\sigma}\right)^{\frac{1}{2}}}_{\text{surface resistance}} \tag{A.3}$$

$$L_d = \frac{1}{|I_o|^2} \int_{o}^{l} \underbrace{\left(\frac{\mu_o}{\pi}\right) \ln\left(\frac{2z}{\mathrm{w}}\right)}_{L(z)\text{: Inductance per unit length}} \times |I(z)|^2 \, dz \tag{A.4}$$

$$C_d = \int_{\frac{s}{2}}^{l} \underbrace{\frac{\pi\varepsilon_0}{\ln\left(\frac{2z}{\mathrm{w}}\right)}}_{C(z)\text{: Capacitance per unit length}} dz \tag{A.5}$$

where s is the half of the gap provided for the voltage source, and w is the radius of the dipole, i.e., 2_{w} is the width of the slot. Hence, the input impedance of the short dipole is obtained as

$$Z_{\text{dipole}} = R_r + R_o + j\omega L_d + \frac{1}{j\omega C_d}. \tag{A.6}$$

References

[1] N. Herscovici, "A wide-band single-layer patch antenna," *IEEE Trans. Antennas Propagat.*, vol. 46, pp. 471–474, Apr. 1998.

[2] ——, "New considerations in the design of microstrip antennas," *IEEE Trans. Antennas Propagat.*, vol. 46, pp. 807–812, June 1998.

[3] J.-Y.Jia-Yi Sze and K.-L.Kin-Lu Wong, "Slotted rectangular microstrip antenna for bandwidth enhancement," *IEEE Trans. Antennas Propagat.*, vol. 48, pp. 1149–1152, Aug. 2000.

[4] K. L. Wong and J. Y. Jan, "Broadband circular microstrip antenna with embedded reactive loading," *Electron. Lett.*, vol. 34, pp. 1804–1805, 1998.

[5] J. R. James and G. Andrasic, "Multifunction printed antennas," in *Advances in Microstrip and Printed Antennas*, K. F. Lee and W. Chen, Eds. New York: Wiley, 1997.

[6] J. F. Zurcher, A. Skrivervik, O. Staub, and S. Vaccaro, "A compact dual-port dual-frequency printed antenna with high decoupling," *Microw. Opt. Technol. Lett.*, vol. 19, pp. 131–137, Oct. 1998.

[7] M. Kijima, Y. Ebine, and Y. Yamada, "Development of a dual-frequency base station antenna for cellular mobile radios," *IEICE Trans. Commun.*, vol. E82-B, pp. 636–643, Apr. 4, 1999.

[8] J. F. Zürcher, Q. Xu, A. Skrivervik, and J. R. Mosig, "Dual-frequency, dual-polarization four port printed planar antenna," *Microw. Opt. Technol. Lett.*, vol. 23, pp. 75–78, Oct. 20, 1999.

[9] G. S. Binoy, C. K. Aanandan, P. Mohanan, K. Vasudevan, and K. G. Nair, "Single-feed dual-frequency dual-polarized slotted square microstrip antenna," *Microw. Opt. Technol. Lett.*, vol. 25, pp. 395–397, June 20, 2000.

[10] D. M. Pozar and J. R. James, "A review of CAD for microstrip antennas and arrays," in *Microstrip Antennas: The Analysis and Design of Microstrip Antennas and Arrays*, D. M. Pozar and D. H. Schaubert, Eds. New York: IEEE Press, 1995.

[11] Y. T. Lo, D. Solomon, and W. F. Richards, "Theory and experiment on microstrip antennas," *IEEE Trans. Antennas Propagat.*, vol. AP-27, pp. 137–145, Mar. 1979.

[12] W. F. Richards, Y. T. Lo, and D. D. Harrison, "An improved theory for microstrip antennas and applications," *IEEE Trans. Antennas Propagat.*, vol. 29, pp. 38–46, Jan. 1981.
[13] W. F.William F. Richards, "Microstrip antennas," in *Antenna Handbook*, Y. T. Lo and S. W. Lee, Eds. New York: Van Nostrand Reinhold, 1993.
[14] L. Alatan, M. I. Aksun, K. Leblebicioglu, and M. T. Birand, "Use of computationally efficient method of moments in the optimization of printed antennas," *IEEE Trans. Antennas Propagat.*, vol. 47, pp. 725–732, Apr. 1999.
[15] A. G. Derneryd, "Microstrip disc antenna covers multiple frequencies," *Microw. J.*, pp. 77–79, May 1978.
[16] D. H. Shaubert, F. G. Garrar, A. Sindoris, and S. T. Hayes, "Microstrip antennas with frequency agility and polarization diversity," *IEEE Trans. Antennas Propagat.*, vol. 29, pp. 118–123, Jan. 1981.
[17] W. F. Richards and Y. T. Lo, "Theoretical and experimental investigation of a microstrip radiator with multiple lumped linear loads," *Electromagn.*, vol. 3, no. 3–4, pp. 371–385, July–Dec. 1983.
[18] S. C. Pan and K. L. Wand, "Dual frequency triangular microstrip antenna with shorting pin," *IEEE Trans. Antennas Propagat.*, vol. 45, pp. 1889–1891, Dec. 1997.
[19] B. F. Wang and Y. T. Lo, "Microstrip antennas for dual-frequency operation," *IEEE Trans. Antennas Propagat.*, vol. 32, pp. 938–943, Sept. 1984.
[20] Y. M. M. Antar, A. I. Ittipiboon, and A. K. Bhattacharyya, "A dual frequency antenna using a single patch and an inclined slot," *Microw. Opt. Technol. Lett.*, vol. 8, pp. 309–311, Apr. 20, 1995.
[21] J. H. Lu, "Dual-frequency operation of a single-feed rectangular microstrip antenna with a pair of comb-shaped slots," *Microw. Opt. Technol. Lett.*, vol. 23, pp. 183–186, Nov. 5, 1999.
[22] ——, "Slot-loaded rectangular microstrip antenna for dual-frequency operation," *Microw. Opt. Technol. Lett.*, vol. 24, pp. 234–237, Feb., 20 2000.
[23] K.-L.Kin-Lu Wong, M.-C.Mon-Chun Pan, and W.-H.Wen-Hsiu Hsu, "Single-feed dual-frequency triangular microstrip antenna with a V-shaped slot," *Microw. Opt. Technol. Lett.*, vol. 20, pp. 133–134, Jan. 20, 1999.
[24] J. Y. Jan and K. L. Wong, "Single-feed dual-frequency circular microstrip antenna with an open-ring slot," *Microw. Opt. Technol. Lett.*, vol. 22, no. 3, pp. 157–159, Aug. 1999.
[25] L.Lakhdar Zaid, G.Georges Kossiavas, J.-Y.Jean-Yves Dauvignac, J.Josiane Cazajous, and A.Albert Papiernik, "Dual-frequency and broad-band antennas with stacked quarter wavelength elements," *IEEE Trans. Antennas Propagat.*, vol. 47, pp. 654–660, Apr. 1999.
[26] S. O. Kundukulam, M.Manju Paulson, C. K. Aanandan, P. Mohanan, and K. Vasudevan, "Dual-band dual-polarized compact microstrip antenna," *Microw. Opt. Technol. Lett.*, vol. 25, pp. 328–330, June 5, 2000.
[27] M. I. Aksun, S. L. Chuang, and Y. T. Lo, "On slot-coupled microstrip antennas and their applications to CP operation—theory and experiment," *IEEE Trans. Antennas Propagat.*, vol. AP-38, pp. 1224–1230, Aug. 1990.
[28] P. K. Park and C. T. Tai, "Receiving antennas," in *Antenna Handbook*, Y. T. Lo and S. W. Lee, Eds. New York: Van Nostrand Reinhold, 1993.
[29] R. F. Harrington, *Time-Harmonic Electromagnetic Fields*. New York: McGraw-Hill, 1961.
[30] M. Kominami, D. M. Pozar, and D. H. Schaubert, "Dipole and slot elements and arrays on semi-infinite substrates," *IEEE Trans. Antennas Propagat.*, vol. AP-33, no. 6, pp. 600–607, June 1985.
[31] D. E. Goldberg, *Genetic Algorithms in Search, Optimization, and Machine Learning*. Reading, MA: Addison-Wesley, 1989.
[32] F. J. Ares-Pena, J. A. Rodriguez-Gonzalez, E. Villaneuva-Lopez, and S. R. Rengarajan, "Genetic algorithms in the design and optimization of antenna array patterns," *IEEE Trans. Antennas Propagat.*, vol. 47, p. 506, Mar. 1999.
[33] J. M. Johnson and Y. Rahmat-Samii, "Genetic algorithms and method of moments (GA/MOM) for the design of integrated antennas," *IEEE Trans. Antennas Propagat.*, vol. 47, p. 1606, Oct. 1999.

Ozlem Ozgun was born in Turkey on July 8, 1976. She received the B.S. and M.S. degrees in electrical engineering from Bilkent University, Ankara, Turkey, in 1998 and 2001, respectively.

Currently, she is a Research Scientist at The Scientific and Technical Research Council of Turkey (TÜBİTAK)–National Research Institute of Electronics & Cryptology (UEKAE), Ankara. Her research interests include numerical electromagnetics, electromagnetic propagation and scattering, microstrip antennas and microwave theory.

Selma Mutlu was born in Turkey on January 22, 1975. She received the B.S. and M.S. degrees in electrical engineering from Bilkent University, Ankara, Turkey, in 1998 and 2001, respectively.

Currently, she is a Software Developer at Basari Company, Ankara. Her research interests include numerical electromagnetics, microstrip antennas and microwave theory.

M. I. Aksun (M'92–SM'99) received the B.S. and M.S. degrees in electrical and electronics engineering at the Middle East Technical University, Ankara, Turkey, in 1981 and 1983, respectively, and the Ph.D. degree in electrical and computer engineering at the University of Illinois at Urbana-Champaign, in 1990.

From 1990 to 1992, he was a Postdoctoral Pellow in the Electromagnetic Communication Laboratory at the University of Illinois at Urbana-Champaign. From 1992 to 2001, he was on the faculty of the Department of Electrical and Electronics Engineering at Bilkent University, Ankara, Turkey, where he was a Professor since 1999. In 2001, he joined the Department of Electrical and Electronics Engineering at Koc University, Istanbul, Turkey, as a Professor. His research interests include numerical methods for electromagnetics, microstrip antennas, indoor and outdoor propagation models, and microwave and millimeter-wave integrated circuits.

Lale Alatan (S'91–M'97) received the B.S., M.S., and Ph.D. degrees in electrical engineering from the Middle East Technical University (METU), Ankara, Turkey, in 1990, 1993, and 1997, respectively.

From 1997 to 1998, she was a Postdoctoral Fellow in the Electrical and Computer Engineering Department at Carnegie Mellon University, Pittsburgh, PA, and from 1998 to 1999, in the Electrical and Computer Engineering Department at the New Jersey Institute of Technology, Newark. Currently, she is an Assistant Professor with the Electrical and Electronics Engineering Department at METU. Her research interests include numerical analysis of printed structures, microstrip antennas, phased arrays, and optimization techniques.