The Analysis of a Reconfigurable Antenna With a Rotating Feed Using Graph Models

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***Abstract*—This letter investigates a new reconfigurable antenna technique based on the rotation of a slot. The surface currents are redistributed for each slot position. The antenna is simulated, fabricated, and tested. The return loss frequency tuning matches the simulated data. The antenna radiation pattern remains unchanged for different slot positions. Finally, the process for automatic rotation and control of the slot is investigated using graph models.**

***Index Terms*—Graph models, microstrip antennas, reconfigurable antennas.**

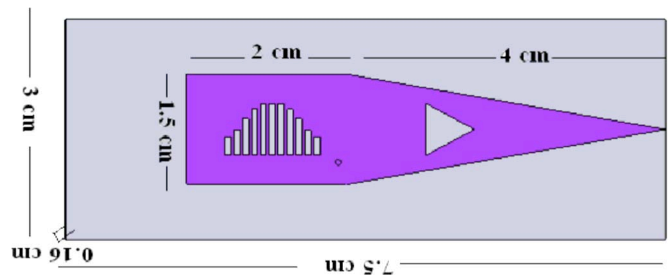

Fig. 1. Antenna structure in [7] and [8] with initial slot position.

I. Introduction

MANY techniques have been used to reconfigure an antenna. An antenna can have a reconfigurable frequency behavior, a reconfigurable radiation pattern, a reconfigurable polarization, or several of these properties joined together. Most of the techniques used to achieve reconfigurability resort to electronic components such as switches, diodes, or tunable capacitors.

In [1], variable capacitors are used to connect different wires constituting a grid antenna leading into a frequency-tuned antenna. In [2], the length of a dipole is adjusted by switches leading also into a frequency agile antenna. A reconfigurable radiation pattern is achieved in [3] by feeding similarly oriented antennas on four faces of a cube. Polarization reconfigurability is achieved in [4] by incorporating diodes on slots in different configurations leading to a switch between right-hand circular polarization (RHCP) and left-hand circular polarization (LHCP). The spiral shape of a patch with the length controlled by different switches is used in [5] to achieve polarization and return loss reconfigurability.

In this letter, a new technique is used to achieve a reconfigurable frequency behavior. This technique employs rotating slots to obtain an indirect feed rotation. The desired reconfigurability property and the antenna structure are defined first. Then, *graph modeling* [6] of the antenna is used as a tool to understand its structure and investigate its optimality. The antenna is then simulated and fabricated, and measurements are provided to prove the validity of the new approach.

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II. Antenna Structure and Properties

The antenna we propose here is the one in [7] and [8]. The basic structure of the antenna, shown in Fig. 1, consists of three different layers. The lower layer, which constitutes the ground plane, covers the entire substrate (3 cm width and 7.5 cm length). The middle substrate has a dielectric constant of $\varepsilon_r = 3.9$ and a height of 0.16 cm. The upper layer, which is the patch, consists of a rectangle of 1.5 cm $\times$ 2 cm joined with an isosceles triangle ($\mathrm{base} = 1.5$ cm and height $\mathrm{h} = 4$ cm). Inside the rectangular patch, 10 rectangular slots that follow a Chebychev distribution around a center rectangular slot, were inserted. Furthermore, inside the triangular patch, a triangular slot of $\mathrm{base} = 0.75$ cm and of height 0.6062 cm is inserted. The antenna is fed through a 50-Ω SMA connector where the feeding position is optimized for the original slot position.

The patch is composed of a rectangular part joined with a triangular part. The resultant shape with the Chebychev slots improves the multiband property of the entire antenna, and the triangular slot fine-tunes these resonances to some desired frequencies as detailed in [7] and [8]. A comparison between the surface current distribution on the antenna structure with and without the slots is shown in Fig. 2. The multiresonance operation of this antenna is shown in the return loss plot of Fig. 3 and in the zero-reactance crossing of the antenna input impedance in Fig. 4. Fig. 5 shows the three-dimensional (3-D) radiation pattern of the antenna at 4.6 GHz. The simulations were done using Ansoft's HFSS V11.

III. Reconfigurable Antenna Design

We want to achieve an antenna with reconfigurable resonant frequencies and without the use of switches. For each surface

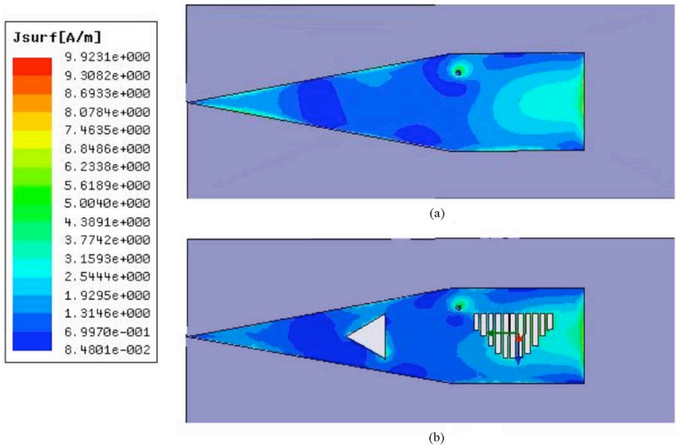

Fig. 2. Surface current distribution at 4.66 GHz on the antenna structure (a) without slots and (b) with Slots.

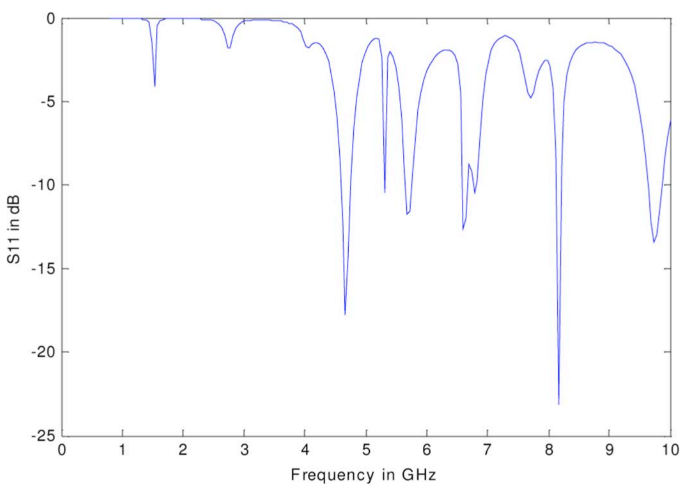

Fig. 3. Antenna return loss in dB at initial slot position.

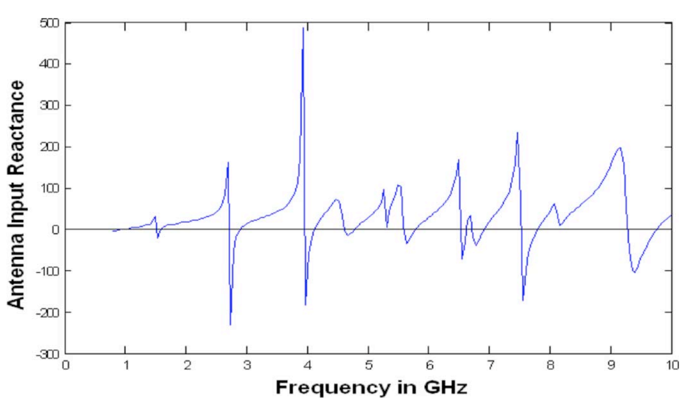

Fig. 4. Antenna input reactance as a function of frequency at the initial slot position.

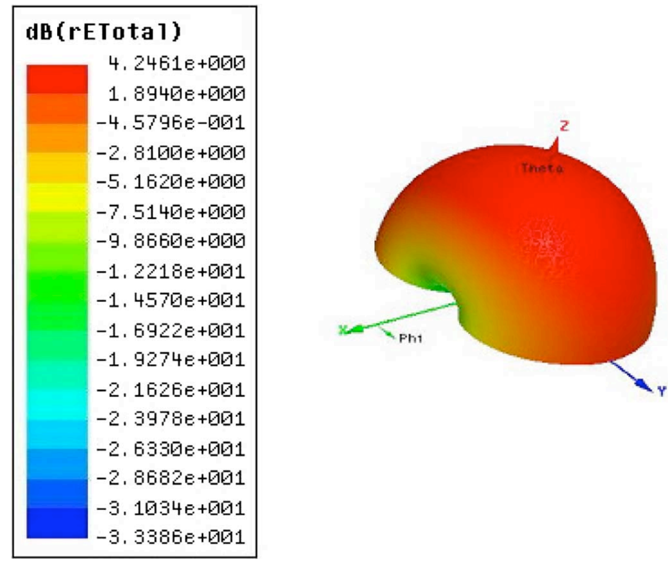

Fig. 5. Antenna 3-D radiation pattern at 4.6 GHz when slot is at the initial slot position.

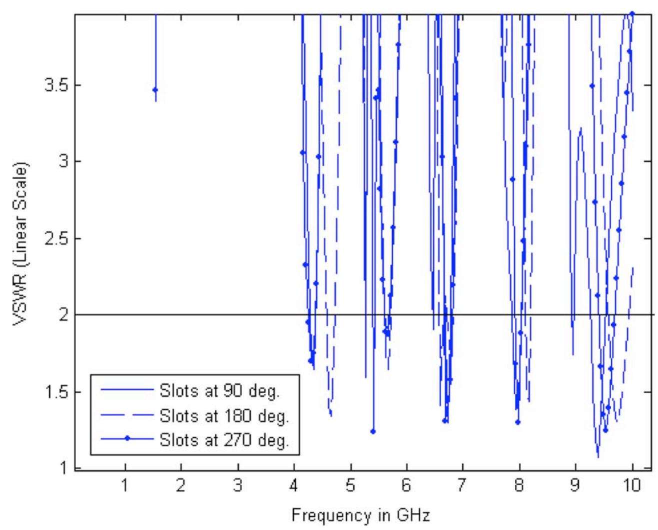

Fig. 6. VSWR for three different slots positions.

current distribution, the antenna exhibits a set of resonant frequencies. The alteration of the surface current distribution will result in a reconfigurable resonance antenna. The reconfiguration technique investigated here makes use of a slot rotation. Since the Chebychev slots boost the antenna's multiband property, their rotation will change the surface current distribution on the patch of the antenna and will constitute an indirect feed rotation. The slot rotation changes the reactive loading imposed by the presence of the slots in the structure. Fig. 6 shows the simulated voltage standing wave ratio (VSWR) for three different slot positions illustrating the structure's resonance tuning. Fig. 6 shows that this resonance tuning is clearer for frequencies higher than 4 GHz. New resonances are created, as well as shifts in bandwidths and changes in amplitudes.

The fabricated antenna is shown in Fig. 7 and represents the last prototype fabricated. A small cylinder was removed from the body of the antenna and then reattached with a manual handle. The removal of the cylinder has to start from the bottom of the antenna (ground plane) reaching to the top (the patch), leaving a small copper extension from the body of the patch around the cavity, constantly touching the circle holding the slots at all time, as shown in Fig. 8. It is important to keep the connection between the circle holding the slots and the rest of the patch at all slots position so that the surface currents have a

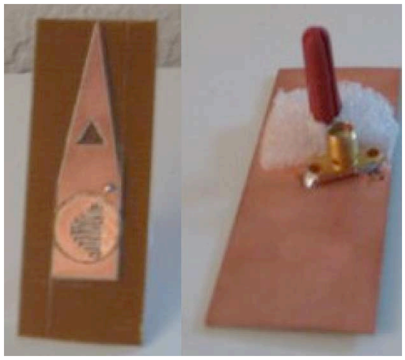

Fig. 7. Front and back view of the fabricated prototype.

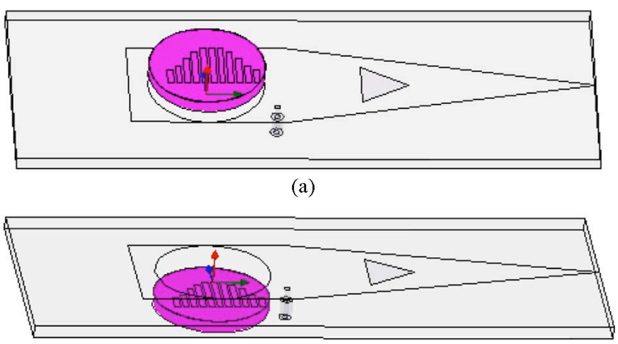

Fig. 8. (a) The removal of the cylinder holding the Chebychev slots. (b) The reinsertion of the cylinder holding the Chebychev slots through the cavity to the extended copper.

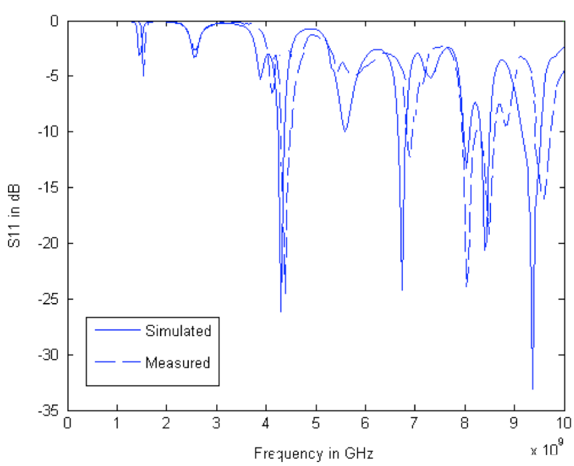

Fig. 9. Comparison between simulated and measured S11 for slots at 90°.

continuous flow. The knob is manually rotated in the fabricated prototype. We propose the automation of the rotation mechanism in Section IV. Fig. 9 shows the matching between the return loss for the fabricated and the simulated antenna when the Chebychev slots are at 90°. Fig. 10 shows the simulated radiation patterns for different slot positions and different plane cuts at 1.6 and 4.29 GHz. The measured return loss tuning for different slot positions is shown in Fig. 11. We note that the rotation from 0° to 90° shifts the resonances to higher frequencies, while the rotation from 90° to 180° shifts these resonances back to lower frequencies as shown in Fig. 11.

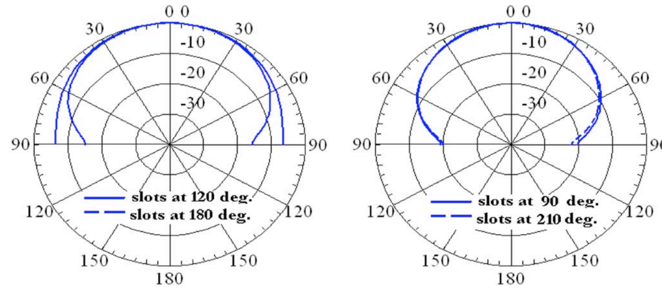

Fig. 10. Radiation pattern for different slots positions. (a) Phi $= 90°$ cut at 1.6 GHz. (b) Phi $= 0°$ cut at 4.29 GHz.

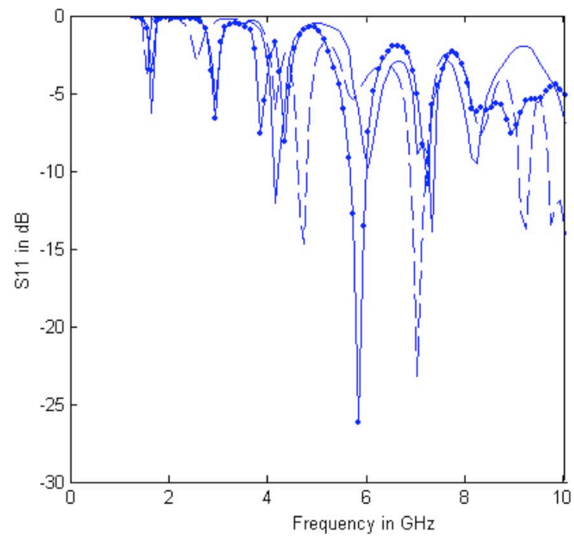

Fig. 11. Comparison between measured results for different slot positions.

IV. Rotation Process Control

Automating the slot rotation process increases its accuracy. Several commercial rotary switches can be used to automatically rotate the slot. Rotary switches can also be customized for this design and implemented through a field programmable gate array (FPGA) to control the rotation of the slots on the antenna.

Graph modeling the antenna structure with rotating slots helps us create a cost- and time-effective algorithm that can be used to program the FPGA controlling the rotation process. Graph models are explained and detailed in [6]. In [9], the authors have proved that graphs can be used to model reconfigurable antennas. There are several possible mappings to model reconfigurable antennas with graphs. We map our graph so that its vertices correspond to the antenna's different angles of rotation as shown in Fig. 12. The edges connecting these vertices are undirected, and they represent the rotation process between two angles. The edges are undirected since the rotation process is reversible.

The cyclic flow of the graph is due to the fact that the graph is modeling the rotation process controlled by rotary switches. The mode of operation of rotary switches ensures a sequential rotation. For example, if A1 represents 0°, A2 represents 30°, and A3 represents 60°. The rotation from 0° to 60° is represented by edges connecting A1 (0°) to A2 (30°) and A2 (30°)

$$A = \begin{bmatrix} 0 & T(A_1 \rightarrow A_2) & T(A_1 \rightarrow A_3) & T(A_1 \rightarrow A_4) \\ T(A_2 \rightarrow A_1) & 0 & T(A_2 \rightarrow A_3) & T(A_2 \rightarrow A_4) \\ T(A_3 \rightarrow A_1) & T(A_3 \rightarrow A_2) & 0 & T(A_3 \rightarrow A_4) \\ T(A_4 \rightarrow A_1) & T(A_4 \rightarrow A_2) & T(A_4 \rightarrow A_3) & 0 \end{bmatrix}$$

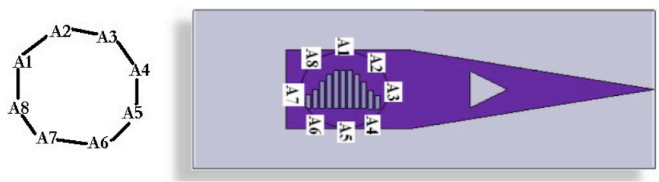

Fig. 12. All possible configurations represented by all possible edges.

to A3 (60°). The edges in the graph are weighted. The weights represent costs or benefits that need to be minimized or maximized. In our model, the weights represent the time of rotation from one angle into another, and they are calculated according to

$$w_{ij} = T(A_i \rightarrow A_j). \tag{1}$$

The weight of a path is defined as the sum of the weights of its constituent edges. The direction of rotation of the slots will be chosen according to the direction of the shortest path to move from one position into another. The shortest path in a weighted graph corresponds to the least sum of weights in a particular path. In a reconfigurable antenna design, a shorter path in the graph may mean a shorter current flow in the antenna and thus a certain resonance associated with it. A longer path in the graph may denote a lower frequency in the antenna than the shorter path.

The graph modeling of this antenna with all possible edges is shown in Fig. 12. The weight w_{ij} represent the time it takes to switch from angle i into angle j.

In the case where this antenna is implemented on a time-sensitive platform like a satellite, arriving at the desired position with the shortest time possible, regardless of the system constraints, is very important. Finding the shortest path for each possible scenario is a major requirement. In complicated reconfigurable antennas that may result in large graphs with more complicated structures, employing standard graph algorithms such as Dijkstra's shortest path algorithm may be necessary; whereas in simpler models, an exhaustive search for the shortest paths is sufficient, even when the cost of the rotation is not proportional to the rotation angle. Example: In a particular system, going from 0° to 30° might be more costly than going from 0° to 230°. Dijkstra's algorithm [6] can be used to program an FPGA to control the rotation of the slots through a rotary switch. The adjacency matrix A showing all the graph weights calculated according to (1) is shown at the top of the page. This matrix represents only four rotation processes. It can be evaluated numerically. However, the exact numerical values depend on the fabricated system.

V. Conclusion

In this letter, we have investigated a new technique that achieves antenna frequency resonance reconfigurability. The technique is based on rotating slots following a Chebychev distribution. The rotation of these slots redistributes the surface currents leading to reconfigurability. The antenna was graph modeled, and the shortest paths were investigated. An algorithm was introduced to program an FPGA that can control the rotation of the slots by always choosing the fastest and the shortest paths.

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