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Frequency Reconfigurable Antenna Controlled by Multi-Reed Switches

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***Abstract*—A frequency reconfigurable patch antenna using reed switches to connect the patch with the ground plane is proposed. Compared with other voltage-controlled switches like MEMS and PIN diodes, reed switches are controlled by a magnetic field which can penetrate the ground plane easily. In this way, the control circuit can be placed beneath the ground plane to avoid its impacts on the radiation performance of the antenna. Twenty-four reed switches are used to increase the reconfigurability of the antenna and to show the feasibility of our concept when multiple control circuits are used simultaneously. The presented antenna can be reconfigured to operate in the frequency range from 0.3 to 3 GHz, covering for a large number of communication services. Three operating modes of the antenna (with resonance frequencies at 0.8, 2, and 2.85 GHz, respectively) are presented to illustrate the feasibility of this method. The measured matching and radiation characteristics of the fabricated antenna prototype agree well with the simulations.**

***Index Terms*—Frequency reconfigurable, multi-reed switches, patch antenna.**

I. Introduction

DUE to the rapid development of wireless communication services, reconfigurable antennas (RAs) are required to reduce the number of antennas and to increase the flexibility of wireless devices. The properties of an RA can be controlled in a desirable manner by placing RF switches. In recent years, several papers have been published on the frequency reconfigurable antenna (FRA) using RF MEMS, PIN diodes, and varactor diodes [1]–[3].

One problem for these voltage-controlled switches is that the dc-bias control lines may have an adverse effect on the antenna performance. The effect of bias lines and relevant electronics can be neglected when a single switch is used to achieve an FRA with limited functionality [4]. However, in order to cover a wider frequency band, more switches are needed in the FRA; thus, the effect of multiple control circuits should be taken into account as the number of switches increases. Some methods have already been proposed to alleviate this effect and to reduce the number of bias lines. For example, in [5], the PIN diodes are biased from the back side of the substrate through vias. In [6], a symmetrical layout of the switches is designed to counteract the influence on the antenna performance. However, only the peripheral patches could be connected to the bias lines. Reported concepts limit the design freedom of the FRA inevitably.

In our previous work [7], [8], the reed switch controlled by a magnetic field was used in an RA to verify its feasibility as an RF switch. As the magnetic field can penetrate the ground plane easily, the control lines and associated electronics could be located beneath the ground plane, so they do not affect the performance of the antenna. In this letter, we use this idea to investigate a wideband RA that uses 24 reed switches to connect the microstrip patch to the ground plane at several locations. We will not only show that the use of multiple reed switches increases the reconfigurability of the antenna, but we will also show that a good performance can be obtained in case of multiple control circuits. In our concept, the reed switches are located between the patch and ground plane, minimizing parastics. This is different from the concept presented in [9], where the switches are located beneath the ground plane. Potential applications of our concept include reconfigurable multiband base stations for wireless communication and tunable antennas for hyperthermia [10].

II. Design of the Proposed Antenna

A. Antenna Design

The geometry and dimensions of the proposed coaxial-fed microstrip antenna are depicted in Fig. 1 and Table I, respectively. The rectangular patch is printed on the top side of the FR-4 substrate (relative permittivity 4.4 and loss tangent 0.02) with thickness 1.5 mm and size 220×150 mm^2. The air gap from the top layer to the ground plane (size 280×210 mm^2) is $H = 5$ mm and is supported by four nylon pillars. The length of the patch is $L = 200$ mm, resulting in a resonance frequency around 750 MHz for the patch antenna without switches. The configuration of Fig. 1 uses 24 reed switches, each of which can connect the patch to the ground plane. The reed switches used in this design have a length of 4 mm [11]. The position of each switch is indicated by the numbers $1 \ldots 24$ in Fig. 1. The lead wire of each reed switch plunges through the ground plane and is enclosed by the associated 500-turn coil. Each coil is fixed by a thin wooden board, which is mounted on the bottom side of the ground plane [see Fig. 2(b)]. The leads of the reed switches are positioned at the center of the coils in order to maximize the magnetic field. The magnetic field that is provided by the actuation coils can penetrate the metal ground plane to turn each switch ON or OFF. The control circuit of each switch

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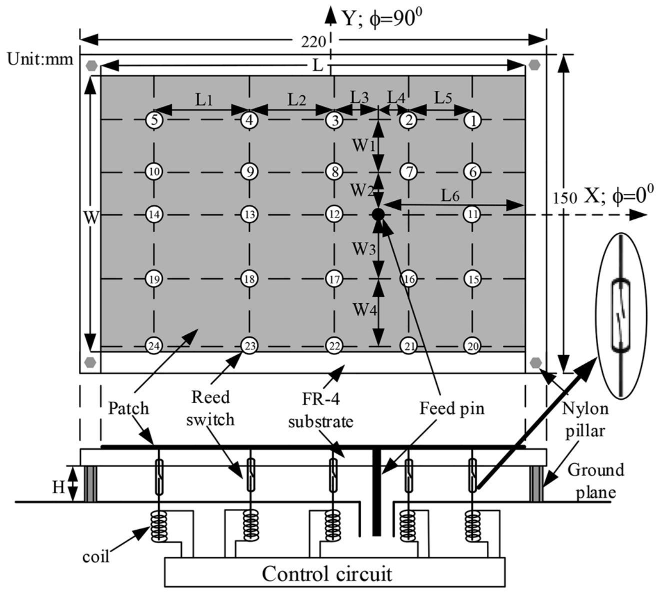

Fig. 1. Top view and side view of the proposed antenna (a spherical (r, θ, ϕ) coordinate system is used).

TABLE I
DETAILED DIMENSIONS OF THE ANTENNA (UNIT: mm)

L	L_1	L_2	L_3	L_4	L_5
200	45	40	20	15	30
W	W_1	W_2	W_3	W_4	L_6
130	25	20	30	32.5	70

is also below the ground plane; thus, it will not affect the radiation characteristics of the antenna. In the simulation using CST MWS [12], the reed switch is modeled based on its state. When the switch is OFF, it exhibits a capacitance of 0.1 pF, which can be regarded as an open circuit in the frequency range of interest. In case the switch is ON, it acts as a short circuit with a low series resistance of 0.2Ω. To guarantee the accuracy of the simulated results, we added these lumped components to the simplified equivalent model [8] of the reed switch.

B. Principle of Reconfiguration

Since the reed switches operate in a binary state ("ON" or "OFF"), they provide the antenna with 2^{24} states totally. By selectively connecting and disconnecting the different states of the reed switches, various modes of operation with various current distributions can be achieved in the patch. Each arrangement of the switches alters the fields in the cavity below the patch in such a way that the resonance frequency can be increased or decreased as compared with its default unloaded resonance frequency. For example, a quarter-wave shorted microstrip antenna is realized when switch 5, 10, 14, 19, and 24 are in the ON state and all other switches in the OFF state. The distribution of location of the switches is based on two principles. The first one is the use of asymmetric topology. In this way, any duplicate cases are avoided [9]. Second, the distribution of the switches is much denser near the feed point [13]. Assuming the feed point to be the origin, the distance between adjacent switches in both directions becomes larger and larger. Therefore, in Table I, $W_1 > W_2$; $W_4 > W_3$; $L_1 > L_2 > L_3$; $L_5 > L_4$. Considering

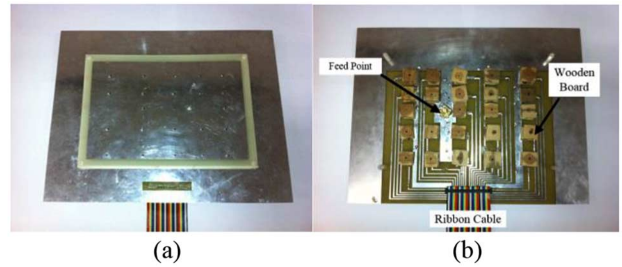

Fig. 2. Fabricated prototype of the antenna: (a) top view and (b) bottom view.

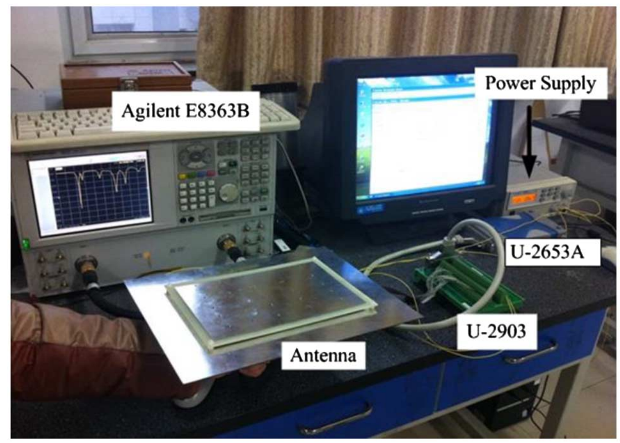

Fig. 3. Setup for measurement of the antenna.

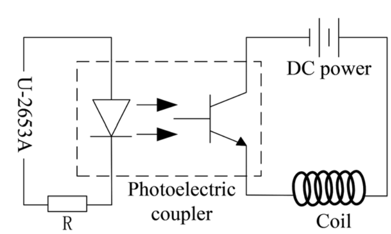

Fig. 4. Equivalent control circuit of a single reed switch.

the size of the feed and wooden board, which are at the bottom of the ground plane in Fig. 2(b), the minimum distance should be 20 mm.

C. Control Circuit for the Reed Switch

Fig. 2 shows the top- and side view of the fabricated prototype. The bonding wires in Fig. 2(b) near the switches are connected to the outer control circuit by a ribbon cable. The control circuit comprises the Agilent U-2653A (64 output USB modular digital I/O), dc power, photoelectric couplers, and some basic electronic devices. The setup for measurement of the antenna including the entire control circuit is shown in Fig. 3. To further explain the control mechanism of the antenna, Fig. 4 shows the equivalent control circuit of a single reed switch. The photoelectric coupler is used to isolate the input and output signals. When one of the control switches of the Agilent U-2653A is closed, the related coil is energized by a 0.1 A dc current, which produces the required magnetic field to turn on the reed switch. The dc current consumption can be reduced further by using miniature permanent magnets. When a magnet is placed below the coils, the current can be decreased to 0.02 A [14]. By using this circuit, the switch state can be easily controlled through the PC.

TABLE II
STATES OF REED SWITCHES IN THESE THREE FREQUENCIES ("0"–OFF, "1"–ON)

Switch / Case	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Case 1	0	1	0	0	0	1	1	0	1	1	1	0	0	0	0	0	1	1	1	0	0	0	1	1
Case 2	0	1	1	1	1	0	0	1	0	0	0	0	0	1	0	0	1	0	1	0	1	0	1	0
Case 3	0	0	0	1	1	0	1	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1	1	0

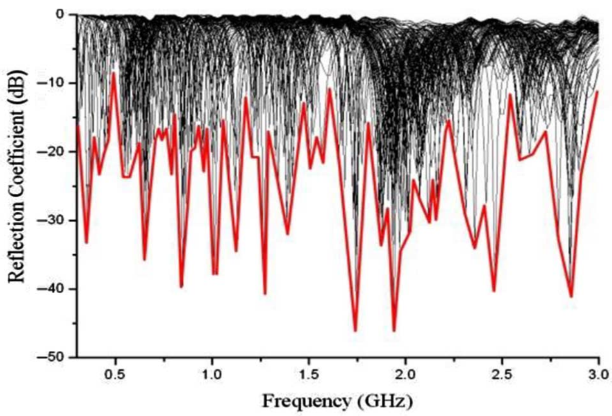

Fig. 5. Measured reflection coefficient of 400 configurations.

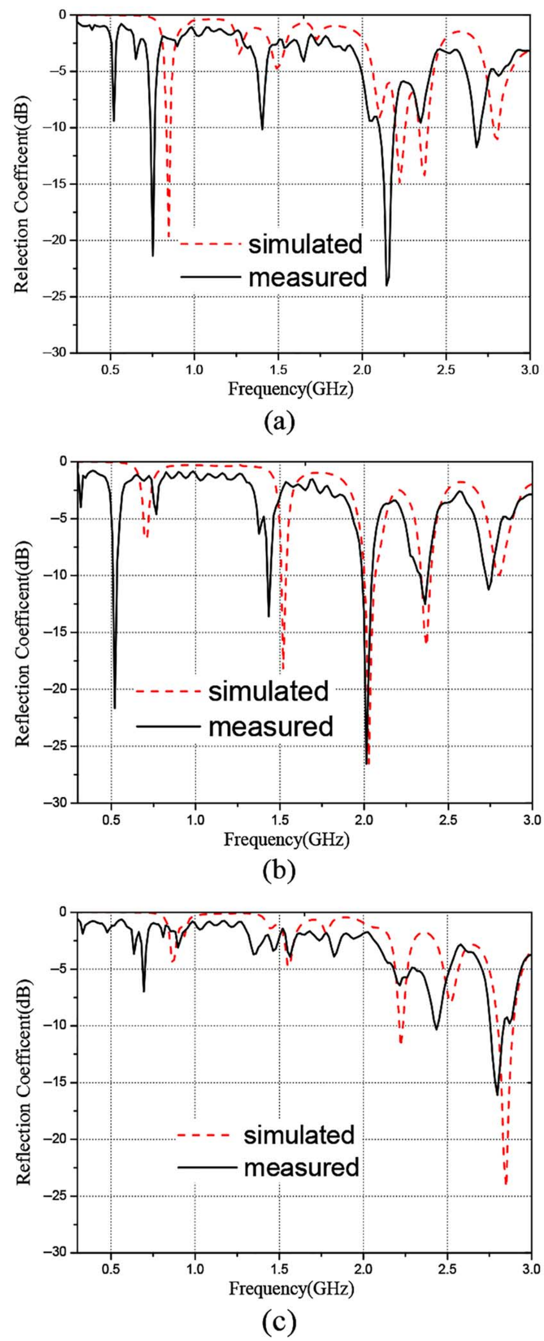

Fig. 6. Reflection coefficient in (a) case 1, (b) case 2, (c) case 3 (resonate at 0.8, 2, and 2.85 GHz, respectively).

III. RESULTS AND DISCUSSION

Each switch has two states, "ON" or "OFF", and the 24 switches can provide 2^{24} different combinations to reconfigure the antenna. Obviously, it is impossible to carry out all the simulations because it will cost too much time. For this reason, we used only 100 unique binary sequences, which are generated randomly, each of which comprises 24 bits, to represent 100 different configurations of the antenna. According to every binary sequence, we set the states of the 24 switches by a PC when measuring the antenna. The first set of 100 measurements is then plotted and analyzed. Clearly, gaps remain in the whole band. Then, another set of 100 binary sequences is created and measured. It turned out that we need about 400 binary sequences to get a good coverage over the frequency band from 0.3 to 3 GHz. A lookup table was created that can be used to find the optimal state for a particular frequency of operation. The superposition of these results for the input reflection coefficient, as well as the overall envelope curve, is plotted in Fig. 5. It can be easily observed that the envelope of the reflection coefficient (red curve) is less than −10 dB over the frequency band from 0.3 to 3 GHz, which means that this antenna can work well at any arbitrary frequency within this band by virtue of reconfiguration of the binary control sequence of the reed switches. A better result should be expected if more samples are taken into account.

We have investigated three specific cases in which the antenna can be configured in more detail, that is, at 0.8, 2, and 2.85 GHz (case 1, case 2, and case 3, respectively). Table II lists the states of the 24 reed switches in these three cases. The digit "0" corresponds to the "OFF" state, and digit "1" to the "ON" state. The simulated and measured reflection coefficients of the proposed antenna operating at these three specific frequencies are plotted in Fig. 6. In case 1, the impedance bandwidth of the antenna with reflection coefficient below −10 dB is 30 MHz (3.7%), from 0.79 to 0.82 GHz. For the other two cases, the bandwidth is 50 MHz (2.5%) at 2 GHz and 120 MHz (4.2%) at 2.85 GHz, respectively. The agreement between simulations

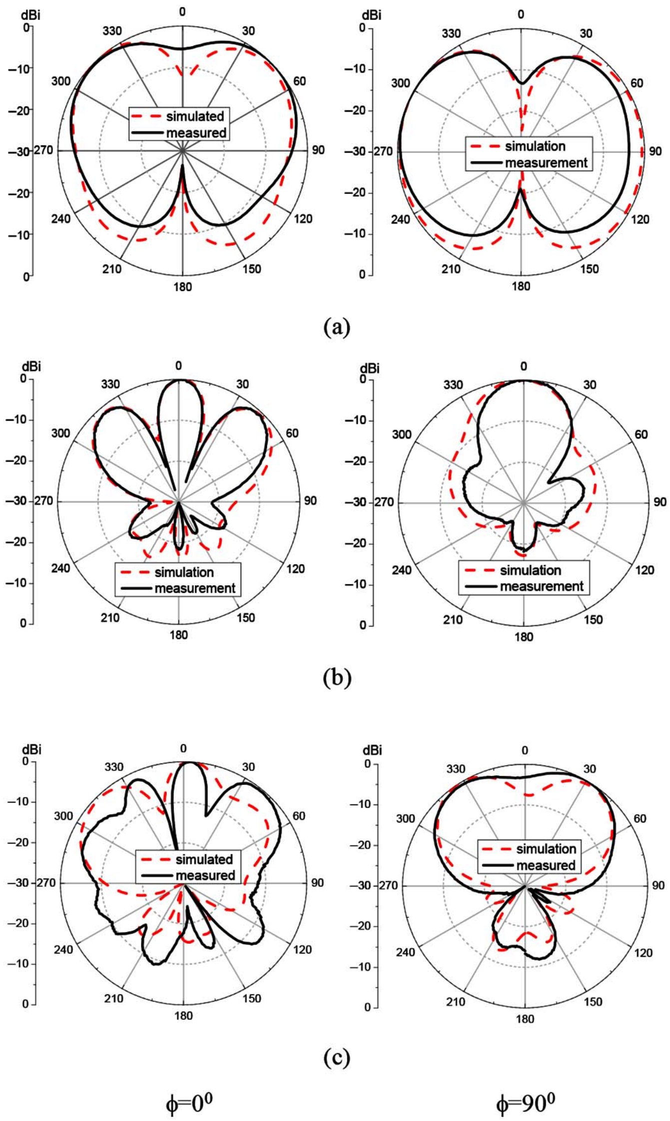

Fig. 7. Normalized radiation patterns at (a) 0.8, (b) 2, and (c) 2.85 GHz.

TABLE III
SIMULATED PEAK GAIN IN BOTH PLANES (UNIT: dBi)

Frequency / Plane	0.8 GHz	2 GHz	2.85 GHz
x-z	2.8	7.7	1.07
y-z	2	7.9	5.7

and measurements is good; however, some discrepancy can be observed that may be caused by additional parasitic effects of the switches and by the fabrication errors. In a practical realization, the lookup table can be used to select the proper settings for a specific frequency.

The antenna radiation patterns were measured in a far-field anechoic chamber at 0.8, 2, and 2.85 GHz, respectively. Fig. 7 shows the simulated and measured normalized radiation patterns in the $\phi = 0^\circ$ plane and the $\phi = 90^\circ$ plane at the three specific frequencies. The simulated peak gain at these three frequencies in both planes is provided in Table III. As the switches connect the patch to the ground plane, the current on the patch can flow to the ground plane, so the back lobes are emerged. It is observed that the patterns in the $\phi = 0^\circ$ plane deviate from a normal patch antenna pattern at higher frequencies. At higher frequencies, the electrical size of the patch is relative large, resulting in a more complex radiation pattern. In a practical application with non-line-of-sight (NLOS) type of propagation, this might not be so relevant. Note that the patterns in both planes are not totally symmetrical, even in $\phi = 90^\circ$ planes, and this can be attributed to the asymmetrical distribution of the reed switches which are turned on.

IV. CONCLUSION

The proposed antenna with 24 reed switches connecting the patch and the ground plane is frequency reconfigurable in a wide frequency range suitable to accommodate future applications, like tunable hyperthermia. The complex control circuit of the reed switches do not affect the radiation performance of the antenna. Using these switches, the reconfigurable antenna can get rid of the limitation of bias lines, and the designers have more freedom to explore the reconfigurable capacity of this antenna. The antenna can be reconfigured to operate at any frequency within the band from 0.3 to 3 GHz by turning ON or OFF these reed switches. Further research may aim to decrease the number of switches without reducing the tuning range.

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