A Coplanar Reconfigurable Folded Slot Antenna Without Bias Network for WLAN Applications

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***Abstract*—The design of a reconfigurable single folded slot antenna is shown. Metal strips are used in the slot to manipulate the ground size around the slot, which yields to changing the slot's perimeter and thus changing the resonant frequency of the antenna. The design of a single folded slot antenna is first illustrated. Later, the design is modified to be reconfigurable. The resonant frequencies for the reconfigurable design are chosen to be applicable with the WLAN applications. The antenna design, simulation, and measurements are described. The simulated results both for the return loss and maximum gain agree with the measurements. The antenna has similar radiation patterns in both bands. The advantage of this design is that the length of the bias lines does not affect the antenna performance, thus making its design, feeding, and matching an extremely simple and low-cost procedure for antenna designers.**

***Index Terms*—Folded single slot antenna, p–i–n diodes, reconfigurable antennas.**

I. Introduction

THE design of reconfigurable antennas has received a lot of attention in the past years [1]–[3]. Reconfigurable antennas are useful for wireless applications, which require an efficient use of the electromagnetic spectrum and low interference between adjacent channels [4], [5]. This type of antenna provides wideband tuning range achievable without deteriorating the antenna return loss, gain, and radiation pattern. Such kind of deterioration is typical of miniaturized antennas.

Electromechanical or electrical switches such as RF MEMS, p–i–n diodes, and varactors have been used for reconfigurable antennas design. Reconfigurable antennas with integrated [6] and packaged [7] RF MEMS have been achieved. Although RF MEMS for specific antenna designs can be used without bias lines [8], and even though they exhibit high Q [4], [9] and low loss, they require expensive equipment and increased fabrication time and cost. In contrast, reconfigurable antennas with p–i–n diodes and/or varactors are simpler to fabricate. However, p–i–n diodes require an appropriate forward bias to reduce the effect of forward bias resistance that affects the reconfigurable antenna response [4]. In antennas loaded with varactors, the tuning linearity depends strongly on the varactor characteristics. The use of p–i–n diodes and varactors in reconfigurable antennas has been described in the literature [1], [5], [10].

Reconfigurable slot antennas have also been achieved [4], [10], where p–i–n diodes and varactors alter the slot length to change the antenna resonant frequency. These designs were fed from the bottom layer using a microstip line and were matched by choosing appropriate dimensions for the feeding line and its position with respect to the slot. Folded single slot antennas have four times less input impedance than slots and thus can be easily matched to 50 Ω. They are fed by a coplanar waveguide (CPW) line and are used in different applications due to their low cost, ease of fabrication, and wider-than-microstrip-antennas bandwidth [11]. Also, since they consist of a larger metal surface than their dual equivalent printed dipole, the conductor loss is smaller, making the antenna more efficient. Their design is described in [11], and their finite-difference time domain (FDTD) analysis in [12]. Dual-band designs are shown in [13]. In this work, a frequency reconfigurable folded slot antenna is designed, fabricated, and measured for the first time.

The coplanar reconfigurable folded slot antenna demonstrated in this letter uses commercial low-cost p–i–n diodes to alter its resonant frequency by changing the perimeter length of the slot. The design procedure will be described analytically. In addition, the effect of the forward resistance on the antenna's performance is investigated. A significant advantage of this antenna design is that it does not require dc bias circuits and blocking capacitor chips. Therefore, the design is simplified and the fabrication cost is significantly reduced. The measured results are compared to the simulated ones, and they are in a very good agreement.

II. Folded Slot Antenna Design

A. Single Folded Slot Antenna Design

The design of single and double folded slot antennas is demonstrated in [11]. The slot's perimeter C of a resonant single folded slot antenna with respect to free-space wavelength λ_0 at the resonant frequency is [11]

$$C/\lambda_0 \approx C_0/\sqrt{(\varepsilon_r+1)/2} \tag{1}$$

where $C = 2\cdot(L_{\rm s}+b+W_{\rm a}-W_{\rm b})$ as shown in Fig. 1, C_0 is the value of C/λ_0 for $\varepsilon_{\rm r}=1$ [11], and $\varepsilon_{\rm r}$ is the substrate permittivity. The constant C_0 was found with a commercial method of moments (MoM) code, and it equals 0.93 for $L_{\rm s}/b = 0.019$. Preliminary design dimensions are shown in Table I(a). These dimensions are used to achieve the first resonance at 5.775 GHz.

The simulated input impedance $(Z_{\rm in})$ is shown in Fig. 2. The resonance occurs at 5.775 GHz as expected, and the input resistance is high, in the order of 500 Ω. This impedance must be

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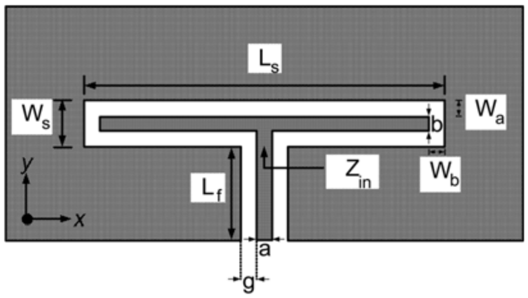

Fig. 1. Schematic of the CPW-fed single folded slot antenna. The shadowed (gray) areas represent metal areas.

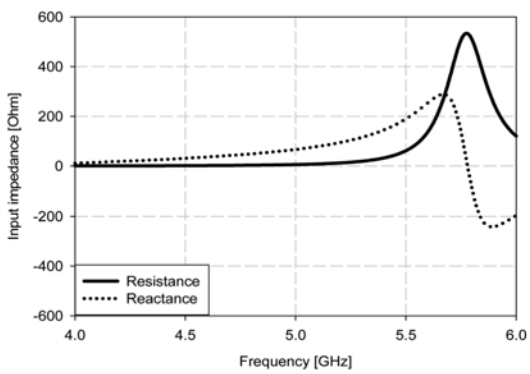

Fig. 2. Simulated input impedance of the initial folded slot antenna design. The resonance occurs at 5.775 GHz.

TABLE I
(a) Initial Dimensions of the Folded Slot Antenna.
(b) Final Dimensions of the Folded Slot Antenna

(a)

Initial Dimensions (in mm)			
L_s	17.86	L_f	0
W_s	0.55	a	0.1
W_a	0.1	b	0.35
W_b	0.1	g	0.1

(b)

Final Dimensions (in mm)			
L_s	19.21	L_f	18.5
W_s	2.75	a	2.5
W_a	2.05	b	0.35
W_b	0.675	g	0.21

reduced to match the antenna at its center frequency. Adding n additional slots reduces the input resistance by the factor $1/n^2$ [12]. However, this increases the complexity and cost of fabrication. Another technique to reduce the input resistance to any desired value is manipulating the dimension W_a until 50 Ω is achieved [13]. Here, W_a was found to be 2.05 mm, and the simulated Z_in for the slot antenna with the modified W_a is shown in Fig. 3.

The simulated input impedance is first found by deembedding exactly at the slot terminals as shown in Fig. 1. The CPW feed-line is studied next since the return loss is measured at its end where the SMA connector is connected. It is desired to extend the dimension L_f away from the slot terminals to mitigate the effect of the SMA connector on the return loss and radiation pattern measurements. Hence, the CPW characteristic impedance should be close to the input impedance and close to 50 Ω (that of the feeding cable here) to retain the good match. The dimension g is changed to 0.21 mm due to the fabrication limitations, and a is designed to be 2.5 mm. In addition, the feeding line's length is chosen to be $\lambda_\mathrm{g}/2$ at 5.775 GHz, while the dimension W_b is tuned to achieve the optimum results of the return loss. Table I(b) shows also the final design dimensions. The simulated return loss of the final design is shown in Fig. 4, and it includes the feeding CPW line effect.

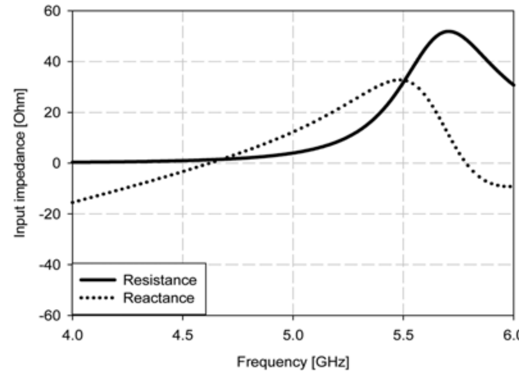

Fig. 3. Simulated input impedance of the modified folded slot antenna design after changing the dimension W_a. The input resistance is 50 Ω at 5.775 GHz. The reactance is zero at the same frequency.

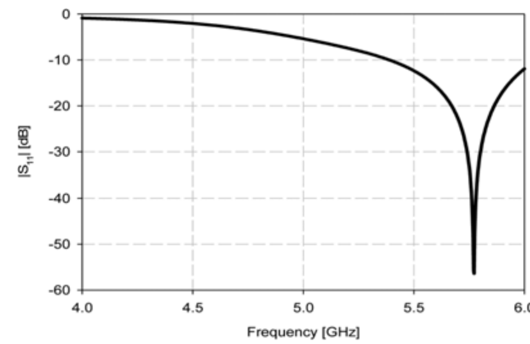

Fig. 4. Simulated return loss of the folded slot antenna with the dimensions shown in Table I(b). The CPW line's effect is considered in these results.

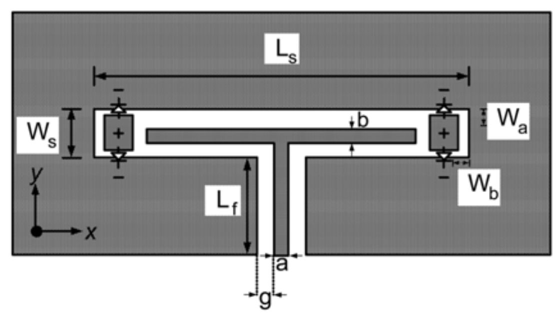

Fig. 5. Schematic of the reconfigurable folded slot antenna. The connection between the metallic strip and the ground plane is controlled by the diode's state. The dimensions are as in Table I(b), except for L_s, which is 21.22 mm.

B. Reconfigurable Single Folded Slot Antenna Design

The described folded single slot antenna can be made reconfigurable by controlling its resonant frequency through a change in the perimeter of the slot. Fig. 5 depicts the schematic of the reconfigurable folded slot antenna. The design is similar to the previous. However, the dimension L_s is extended to 21.22 mm to achieve a first resonance at 5.25 GHz. Metallic strips are then inserted in the slot and are attached to the ground plane using p–i–n diodes. The diodes manipulate the slot's perimeter by connecting or disconnecting the metallic strips. When the diodes are biased, the metallic strips are connected to the ground plane

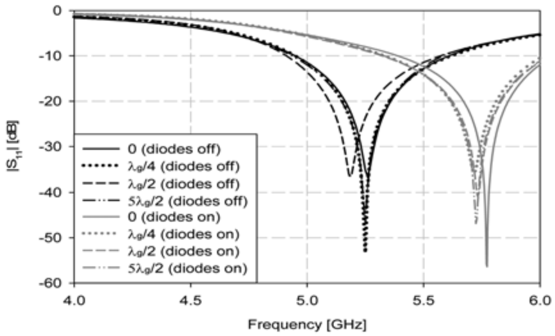

Fig. 6. Return loss of the reconfigurable antenna at both bands for various dc bias lines. The length of the bias lines, with respect to the guided wavelength at 5.25 GHz, practically does not affect the resonant frequency of the antenna at both bands.

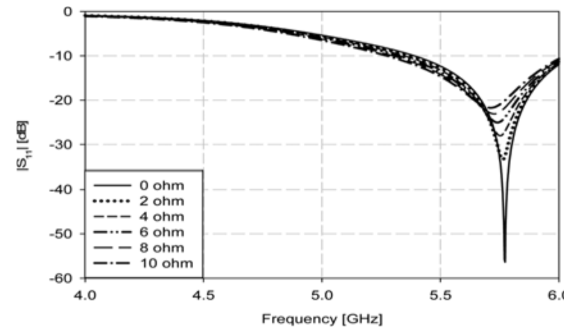

Fig. 7. Simulated return loss of the presented design at 5.775 GHz for different forward resistance values of the p–i–n diodes. The resistance deteriorates the return loss and slightly shifts the resonant frequency.

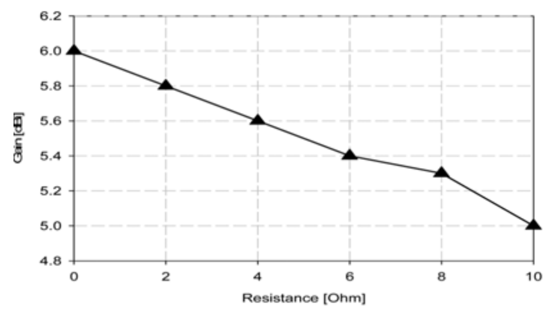

Fig. 8. Simulated gain response of the presented design with respect to different values of the forward bias resistance at 5.775 GHz. The gain deteriorates as resistance values increase.

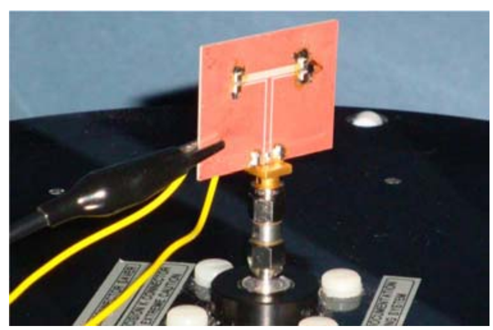

Fig. 9. The fabricated antenna during measurements. The diodes are biased from the back side of the substrate through vias (made only for illustration purposes). The dc ground is connected to the CPW ground.

and become part of it. Thus, the perimeter of the slot is reduced, and the antenna resonates at $f_{\rm on} = 5.775$ GHz. In contrast, the slot's perimeter is extended when the diodes are unbiased. This forces the antenna to resonate at the lower frequency $f_{\rm off}$, which here was chosen to be 5.25 GHz.

The reconfigurable folded slot antenna design is achieved by connecting and disconnecting the metallic strips to the ground plane using p–i–n diodes. The p–i–n diodes are biased using bias lines that are connected to the metallic strips. When the diodes are not biased, the dc bias lines attach neither to the antenna's RF part nor to the ground. Therefore, the lines do not shift the resonant frequency $(f_{\rm off})$. On the other hand, when the diodes are biased, the lines become part of the antenna ground and slightly increase the ground plane size, thus having a negligible effect on the resonant frequency $(f_{\rm on})$. As a result, this type of antenna does not require the design of a dc bias circuit to nullify the effect of bias lines at the resonant frequencies, and the lines can be made with any length. Such a bias circuit is often inevitable in conventional reconfigurable antennas. To verify the previous concept, the antenna was simulated with bias lines of different lengths, and the simulated return loss is shown in Fig. 6. In the realized antenna, the diodes were biased from the substrate's backside through vias. The vias are not necessary and were made only to keep the front side as clear as possible for illustration purposes. The results show that there is practically no effect of the length of the dc bias lines on the resonant frequency for both states of the diodes. Thus, the design of dc bias circuit is not required. The p–i–n diodes exhibit a small forward resistance when forward-biased, which affects antenna return loss and gain. Fig. 7 shows the effect of the forward resistance on the return loss response. As the resistance increases, the return loss degrades and the resonant frequency slightly decreases. The simulated gain at 5.775 GHz for various forward resistances is shown in Fig. 8. As the resistance increases, it reduces the maximum achievable gain. A 1-dB gain drop happens as the resistance increases from 0 (ideally) to 10 Ω.

III. Measurements and Results Discussion

The antenna was fabricated on a RO4003C substrate with 32 mils thickness, relative dielectric permittivity of 3.55, and loss tangent of 0.0027. The ground size is 1575×1180 mils^2. Fig. 9 shows the fabricated antenna during measurements. The diodes are biased from the back side of the antenna through vias made inside the metallic strips and substrate. Each metallic strip is connected to a biasing cable. Each bias line is connected to a 1.3-KΩ resistor for diode, and vector network analyzer (VNA) protection and was made 90 cm long ($\sim 22\lambda_{\rm g}$ at 5.25 GHz). A Keithley-2400 SourceMeter was used to bias the diodes. The forward dc voltage is set to 15 V, which results in a diode resistance less than 1 Ω. The measurements were carried out using an 8753ES VNA. The measured and simulated results of the return loss and maximum gain are compared in Figs. 10 and 11, respectively. The results agree very well with the previous design discussion and the simulations.

The measured resonant frequency for the OFF state is 5.14 GHz, and the simulated is 5.25 GHz (a 2.1% shift). This small discrepancy between the measured and simulated results is due to the parasitic effects of the packaged diodes that could not be considered in the simulations since data about them were not available. The measured resonant frequency for the ON state

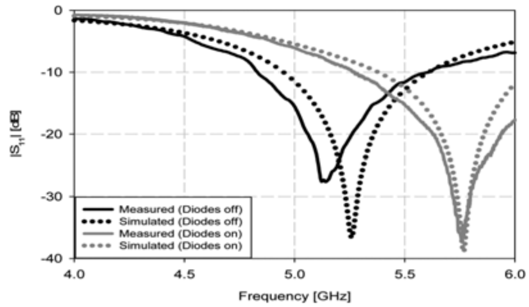

Fig. 10. Measured and simulated return loss response of the reconfigurable folded slot antenna. Measured results are very close to simulated ones. The effect of the dc bias cables is negligible.

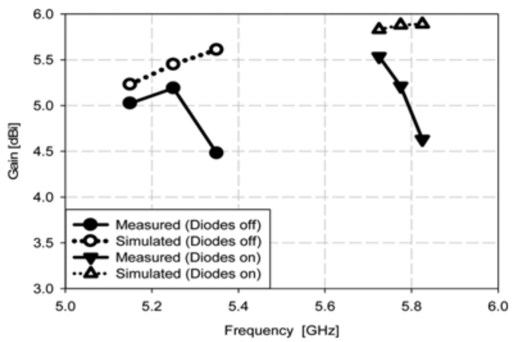

Fig. 11. Measured and simulated maximum gain of the reconfigurable folded slot antenna. The gain response does not change with the reconfigurability, and it exhibits similar values in both bands.

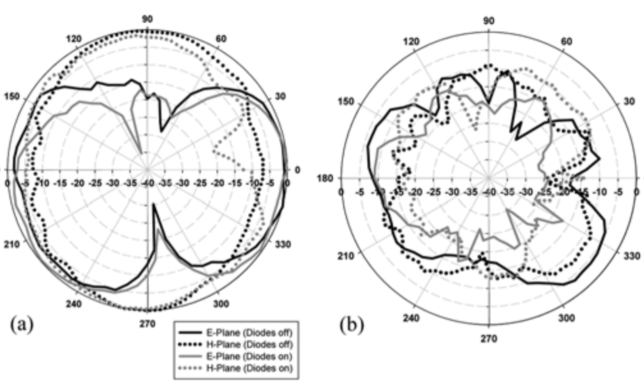

Fig. 12. Measured normalized E- and H-plane radiation pattern at 5.25 (diodes OFF) and 5.775 GHz (diodes ON): (a) co-pol radiation patterns, and (b) cross-pol radiation patterns.

is 5.75 GHz, which is very close to the simulated 5.775-GHz resonant frequency (0.43% shift). This result is closer, and it was expected because the diodes act as short circuits and their volumetric parasitic effect is minimized, reducing the discrepancy between measured and simulated results. Fig. 11 shows the simulated and measured gain at both bands. The measured maximum gain is approximately 5.2 dBi at 5.25 GHz and 5.6 dBi at 5.775 GHz. The measured results are close to the simulated ones.

The measured normalized E- and H-plane radiation patterns at both resonant frequencies and for both p–i–n diode states are shown in Fig. 12. A dual-polarized, 2–18-GHz wideband horn antenna was used to perform the measurements in the custom-built anechoic chamber at SDSM&T. The patterns are very similar at both bands as desired and as dictated by the antenna reconfigurability scheme. The H-planes are almost omnidirectional, while the E-planes have two nulls at each band. Further measurements showed the cross-pol gain to be slightly more than -10 dBi at some angles, most likely due to the long dc bias wires, which may reflect part of the incident radiation coming from the measurement device.

IV. Conclusion

The design of reconfigurable coplanar single folded slot antennas was presented for the first time. p–i–n diodes were used to alter the perimeter of the slot achieving frequency reconfigurability. Using an innovative bias methodology, it was shown that the resonant frequency of this antenna (as well as of any similar design of the same type) is not affected by the dc bias lines' length, eliminating the need for a dc bias circuit. This simplifies the design procedure and significantly reduces design time and cost. A prototype was fabricated using standard printed circuit board (PCB) technology and measured. The measured and simulated results were very close to each other, validating the proposed concept.

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