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Diode loaded slot –patch antenna design and analysis for 2.4 GHz transceiver application

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In this paper, diode loaded slot -patch antenna is presented and the effects on the bandwidth (BW) and efficiency are investigated. A single diode-loaded slot patch antenna gives 2.4 GHz frequency operation with broadband radiation. In this study, the design consists of a rectangular microstrip antenna with a parallel slot loaded close to the radiating edge of the patch and three meandering narrow slits embedded on the antenna surface. Two antenna layouts are designed, for different coverage areas: a reference antenna having 4.95 dBi directivity and a diode loaded antenna with 5.36 dBi directivity. A slot-patch operating at 2.4 GHz having 1.2% BW has been utilized as a reference antenna. The slot-patch antenna has been designed using *CST* microwave studio and implemented. The proposed slot-patch radiation pattern is better than without diode loading radiation pattern. In addition, it has been shown that diode compensation significantly improves the matching level. Theoretical, simulation, and measurement results are in a good agreement. Slot-patch antenna design can be used for RF receiver-transmitter systems.

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Keywords: Slot antenna, Schottky diode, matching, Wireless local-area network (WLAN)

1. Introduction

Slot patch antenna is one of the important elements in the RF system for receiving or transmitting systems. In addition, active antenna has active devices and is employed on the passive antenna elements to improve antenna performances. The active integrated antenna indicates more specifically that the passive antenna elements and the active circuitry are integrated on the same substrate [1]. In conventional wireless or radar systems, the antenna and circuit have been considered as separate subsystems. There have been several major developments in the last decade or so which have led to the current increase in the importance of diode-antenna integration [1–6]. Circuit combining quickly becomes inefficient due to high losses in suitable transmission media. These difficulties have led to much activity in active antennas and some papers emphasize the importance of this topic [7, 8, 10].

Active and passive microstrip antennas are designed as which is one of the most important blocks of the 2.4 GHz ISM band transceiver wireless communication systems. In wireless transmitter or receiver systems, size and efficiency are key factors to take consideration. High efficiency circuits are designed for use in portable components in these systems. The transmitter lossless can be reduced by using the matching circuits [2, 3]. In this article, we discuss the active slot-patch antenna structure [11, 12].

Several interesting approaches to change the resonant frequency of a microstrip antenna are available in literature. In the dual-frequency stacked circular disc microstrip antenna [4], the upper resonance is mechanically tunable by adjusting the air gap width between the substrate and the ground plane. Slot antennas are common for frequency tuning because their resonant frequency can be changed easily with lumped capacitors (or varactors), inductors or switches [7-8]. Microstrip slot loaded antennas are easy integration with microwave integrated circuit. Integration with a diode device can be realized because of the structure of the microstrip is also similar to the circuit board and the easiness to create a matching network for any microwave devices [10].

Active elements equivalent circuit model is used to minimize imaginary part of impedance by changing the dc value. Generally, the resonance of antennas, such as dipole antennas, monopole antennas, loop antennas, slot antennas and microstrip antennas, is determined by the effective length of the radiator. The effective length of an antenna plays an important role in determining the operating frequency. In this case, frequency reconfiguration can be achieved by controlling the effective length of an antenna. There are a few methods of controlling mechanisms. The effective length of an antenna can be changed by adding or removing part of the length by using electronic switches. Nowadays, electronic switches, such as Schottky diodes, FETs and RF MEMS are commonly used for switching. Although RF MEMS have many advantages, Schottky diode is favorable to many researchers as it has acceptable performance, low cost and ease of fabrication. For instance, in [13], Schottky diodes are placed on the fractal dipole antenna to produce tunable frequency bands. A similar approach for slot antenna is also reported in [14]. The usage of RF MEMS to achieve frequency tuning has been reported in [15, 16]. Another way to change the resonant frequency is by using variable reactive loading (typically capacitance) such as varactor diodes. It allows smooth frequency changes with the changes of capacitance value. The disadvantage of using varactor diodes is the limited frequency range switching. An H-shaped antenna with frequency selectivity using varactor diode has been presented in [17]. Similar approach has also been reported in [18]. Structural or mechanical changes can also be used to deliver larger frequency shifts. The main challenge of using this method lies in the physical design which is the size of the antenna and the actuation mechanism including its maintenance. These types of antennas have been reported in [19].

2. Antenna design and equivalent circuit with active device

The proposed antenna is described in this section. Diode loaded antenna applications include control of the resonance frequency [1], control of the input matching conditions [2], and phase control in injection-locked oscillators [3, 4] and this letter describes return loss control. The radiating patch was designed using transmission line calculations [15, 16] to operate at 2.4 GHz. The antenna is printed on FR4-glass epoxy substrate of thickness h = 1.6 mm and dielectric constant ε_r =4.6. This paper presents a 2.4 GHz slot patch antenna design comprising diode directly connected to a high gain slot-patch antenna on the same substrate as shown in Fig. 1. A rectangular slot-patch antenna having a size (L, W) = (37.5, 56) mm fed by a 50 Ω characteristic impedance. Feeding microstrip line having dimension (Lf5o, Wf5o) = (4, 5.75 mm) was designed for 2.4 GHz. U-shaped gap is located on the rectangular microstrip antenna. The length of the gap, *Ls* = 40 mm and slot width *Ws* = 2.5 mm active element which is used diode is located *x=28* mm and *y=11* mm coordinates referring to antenna's center. Ground plane and the substrate have a width of *Wg* = 40 mm and a length of *Lg* = 40 mm. Diode biasing is obtained by etching 0.3 mm width slots in the ground plane parallel to the slit line.

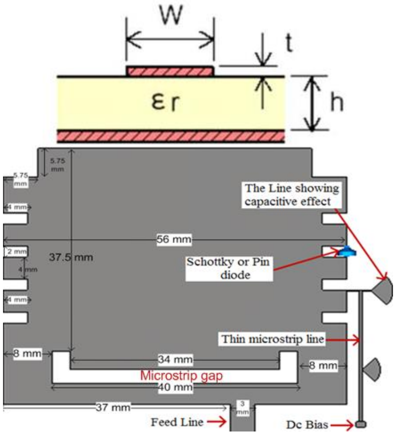


Fig. 1. Geometry of the proposed slot- patch antenna (FR4-glass epoxy: h=1.6 mm, ε_r *=4.6, and* $\tan\delta$ *=0.0016).*

Low impedance λ/4 open stub microstrip line is used for DC bias circuit that is well isolated from the antenna. The length of the slot affects the resonance frequency but has only a small effect on the return loss. As the slot length increases, the resonant frequency decreases as reported in [17, 18]. Therefore, altering the length of the coupling slot will shift the resonant frequency. The proposed prototypes have different slot lengths (*Ls*) and the same slot width (*Ws*) of 1 mm. Schottky diodes are inserted across the slot for effectively change its length. Bias isolation is produced by narrow slots in the ground plane as discussed in Section 2. The slits provide a path for the DC current.

2.1. Loaded antenna

When a diode is integrated with a radiating patch, it provides a variable capacitive reactance at the point of its location, thereby changing the resonance frequency of the patch. Fig. 2 is shown that schematic diagram of active patch antenna model and equivalent transmission line model.

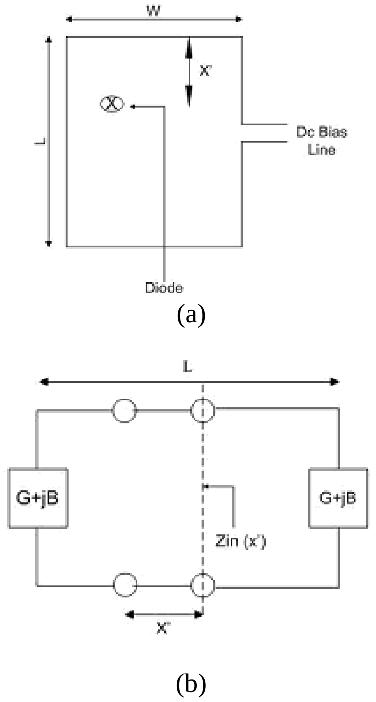


Fig. 2. (a) Schematic diagram of active antenna (b) Equivalent transmission line model.

Diode location is most significant for input impedance.

$$Z_{in}(x') = \frac{1}{2G}\left[\cos^2(\beta x') + \frac{G^2+B^2}{Y_0^2}\sin^2(\beta x') - \frac{B}{Y_0}\sin(2\beta x')\right] \qquad (1)$$

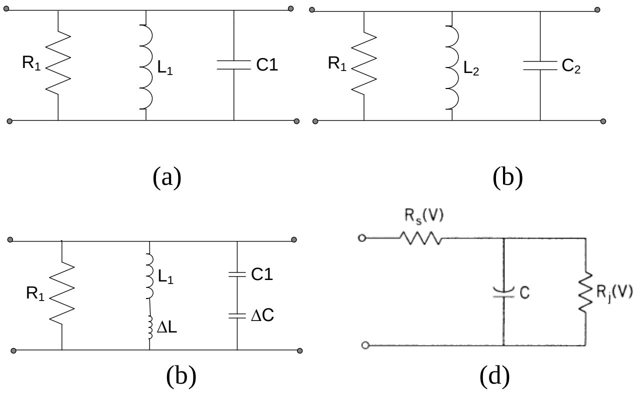
where β is the propagation constant of the microstrip line, Y_0 is the characteristic admittance of the microstrip line, G and B is the total antenna conductance and the radiating edge susceptance, respectively. Equation (1) can be further simplified for practical case of $G/Y_0 << 1$ and $B/Y_0 <<1$ to equation (2) [5].

$$Z_{in}(x') = \frac{\cos^2(\beta x')}{2G} \tag{2}$$

Equivalent circuit characterization of the active device is of crucial importance to active patch antenna simulation. Full performance prediction can only be achieved using both linear and nonlinear device characterization. In particular for oscillator analysis, where accurate frequency and power level are required, for amplifier linearity analysis, and for mixer or return loss level action, nonlinear models are required [3]. The radiation efficiency is depending on the geometry. Commonly utilized reactively loaded impedance matching method is a successful technique since the impedance variations are the dominant bandwidth limiting factor [9].

Active diode elements can be placed directly on the substrate material. DC power supply is necessary to operate this circuit. However, the microwave signals which is flowing on the antenna must not lost on the supply lines. So, they selected a very high impedance of the supply lines. In active circuits, if dc power supply is affecting to other elements, dc supply lines must be isolated from microwave input and output signals or it is used dc blocking capacitors to protect circuit's elements. According to cavity-model theory, a microstrip patch antenna can be modeled as a parallel LCR circuit. The current flows from the feeding point to the top and bottom edges of the patch. The electric and magnetic-field discontinuities occur across the notch. The effect of the notch will be both capacitive and inductive.

The equivalent circuit corresponding to this current flowing on the patch is shown in Fig. 3.



(a) (b)

(b) (d)

Fig. 3. (a) Equivalent circuit of the rectangular microstrip patch antenna (b) Corresponding to the current flowing around the notch (c) Simplified circuit (d) Diode equivalent model.

In the notched microstrip patch antenna, two resonant circuits are coupled together and form a dual resonant circuit for dual-band as shown in Fig. 4. Here, both the inductive and capacitive coupling have been considered.

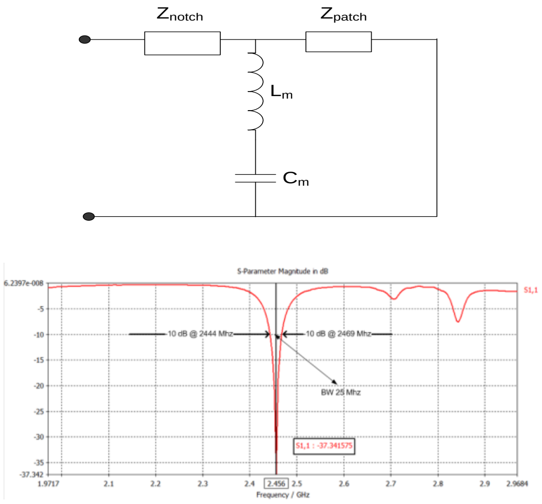


Fig. 4. Equivalent Circuit of the Notched Microstrip Patch Antenna.

The coupling coefficient between these two resonators is given by;

$$C_p = \frac{1}{\sqrt{Q_1 \cdot Q_2}} \tag{3}$$

where Q_1 is the quality factor of the resonant circuit due to normal current, given by

$$Q_1 = \frac{\omega L_1}{R_1} \tag{4}$$

and Q_2 is the quality factor of the resonant circuit due to the notch effect given by

$$Q_2 = \frac{\omega L_2}{R_1} \tag{5}$$

mutual inductance between the two resonant circuit is L_m and mutual capacitance between the two resonant circuit is C_m :

$$L_m = \frac{C_p^2(L_1+L_2)+\sqrt{C_p^2(L_1+L_2)^2+4\cdot C_p^2(1-C_p^2)\cdot L_1L_2}}{2(1-C_p^2)} \tag{6}$$

$$C_m = \frac{-(C_1+C_2)+\sqrt{(C_1+C_2)^2-4\cdot C_1C_2\cdot(1-C_p^{-2})}}{2} \tag{7}$$

Then the input impedance of the notched rectangular microstrip patch antenna can be computed from the simplified circuit shown in Fig. 4 as follows:

$$Z_{in} = Z_{notch} + \frac{(Z_{patch}.Z_{in})}{(Z_{patch} + Z_{in})} \tag{8}$$

$$Z_{in} = jwL_m + \frac{1}{jwC_m} \tag{9}$$

Using equation (17) the reflection coefficient, can be computed as follows:

$$\Gamma = \frac{Z_0 - Z_{in}}{Z_0 + Z_{in}} \tag{10}$$

The equations for radiation patterns of ***E*** and ***H*** planes of the microstrip antenna:

$$E(\theta) = \frac{-jk_0WVe^{-jk_0r}}{\pi r}\cos(kh\cos\theta)\frac{\sin\left(\frac{k_0W}{2}\sin\theta\sin\phi\right)}{\frac{k_0W}{2}\sin\theta\sin\phi}\cos\left(\frac{k_0L}{2}\sin\theta\sin\phi\right)\cos\phi$$
$$(0 \le \theta \le \pi/2) \tag{11}$$

$$E(\phi) = \frac{-jk_0WVe^{-jk_0r}}{\pi r}\cos(kh\cos\theta)\frac{\sin\left(\frac{k_0W}{2}\sin\theta\sin\phi\right)}{\frac{k_0W}{2}\sin\theta\sin\phi}\cos\left(\frac{k_0L}{2}\sin\theta\sin\phi\right)\cos\phi\sin\phi$$
$$(0 \le \theta \le \pi/2) \tag{12}$$

where $k_0 = 2\pi/\lambda_0$. The active element is used to examine the effect of diode.

2.2. Results

In this paper, BAS70, BAS83, BA592, BB721 diodes were used and C-V curve of diodes were taken as reference. Slot loaded patch antenna performances strongly depend on the device and its location.

Table 1 shows that the capacity for response to the voltage of diodes. These characteristics are affected to the antenna performances (RL, Zin, BW and SWR etc.). However, location of diode is affected radiation pattern. For the board 1.635 mm thick FR4-glass epoxy material ε_r=4.6 and $\tan\delta$=0.0016 metalized on two sides with 35 µm thick copper was used. BA592, BAS70 and BAS83 are more effective than BB721 on the patch antenna.

Table 1. Different diodes C-V values.

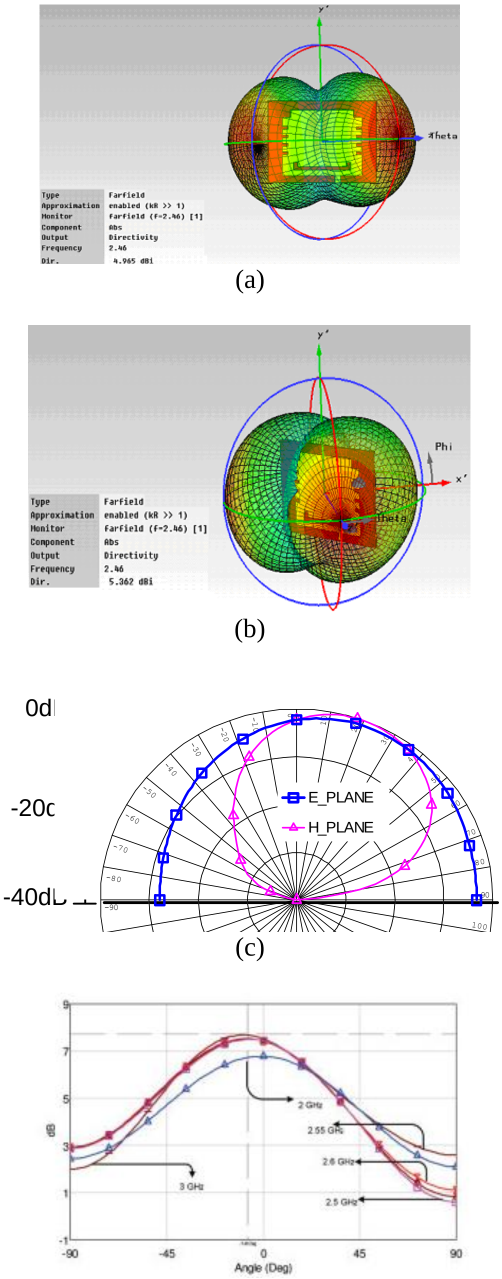
BAS70 Schottky diode	C (pF)	0.28	0.3	0.31	0.33	0.35	0.38	0.39	0.41	0.5	0.65	0.8	1.1	1.25
	V (v)	45	40	35	30	25	20	15	10	5	3	2	1	0
BAS83 Schottky Barrier Diode	C (pF)	0.5	0.5	0.5	0.52	0.6	0.65	0.72	0.77	0.9	1.1	1.3	1.5	1.8
	V (v)	60	50	45	30	15	10	7.5	5	4	3	2	1	0
BA592 Silicon RF Switching Diode	C (pF)	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.65	0.7	0.71	0.78	0.85	1.1
	V (v)	40	35	30	25	20	15	10	5	4	3	2	1	0
BB721 *Silicon Epitaxial* ***Planar*** Diode	C (pF)	1.8	2	2.2	2.4	2.5	4.8	7.8	8.4	10	12	14	15	17
	V (v)	40	35	30	25	20	10	7.5	5	4	3	2	1.5	1

Table 2 is summarized simulation result of the slot loaded antenna. Each state corresponds to operation in a specific frequency band of operation. The better results (*R.L.,G*) are obtained with BA592 and The S_{11} and input impedance (*@ fr*) are obtained *37.34 dB* and *54 + j6.4* respectively. The radiation pattern is not distorted in 2–3 GHz frequencies. Active diodes and slits position on the x and y axes are placed on the most appropriate points.

Table 2. Antenna performance simulation result for different diodes.

Diode	***Frequency***	***RL***	***BW***	***D***
BAS70	2.456 GHz	-31.06 dB	76 Mhz	5.313 dBi
BAS83	2.456 GHz	-35.38 dB	74 Mhz	5.359 dBi
BA592	2.456 GHz	-37.34 dB	75 Mhz	5.362 dBi
BB721	2.456 GHz	-27.49 dB	75 Mhz	5.305 dBi

CST Microwave Studio was used to simulate the antenna performances. The 3-D presentation of radiation pattern is shown in Fig. 5 and clearly seen that active slot loaded antenna performances are much better than the reference antenna. Especially, good gain and beam shape results have been obtained in diode loading condition in E-plane pattern, which is near the resonance frequency [Fig.5].



(a)

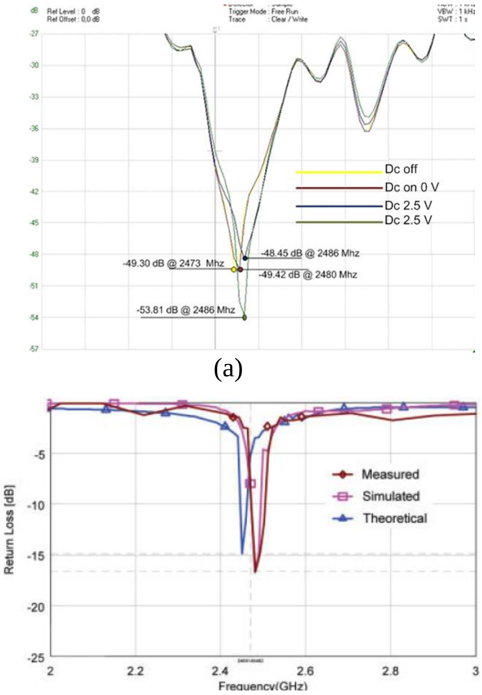
(b)

(c)

(d)

Fig. 5. (a) Diode loaded antenna pattern (b) Reference antenna pattern (c) Simulated radiation pattern of the microstrip patch antenna (d)Pattern performance for different frequencies (ε_r *= 4.7 h=1.6mm,* $\tan\delta$ *=0.019).*

The simulated radiation patterns are shown in Fig. 6 in the E-and H-planes, respectively.



(a)

(b)

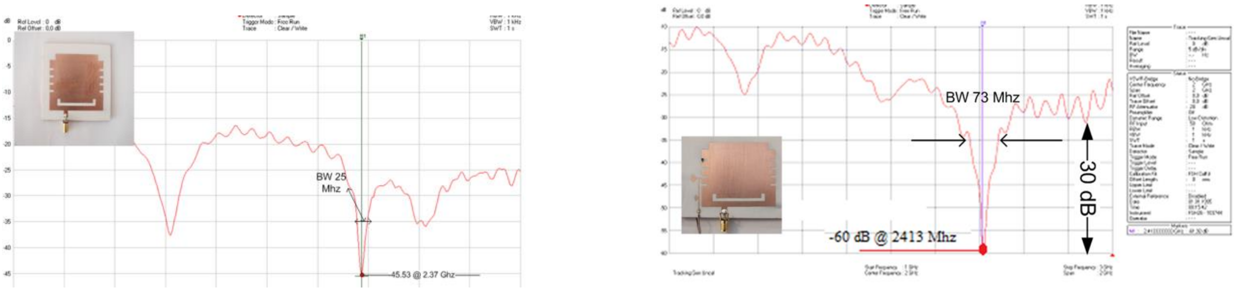
Fig. 6. (a) Measured return loss for various Dc levels (b) $|S_{11}|$ *parameter.*

3. Experimental results

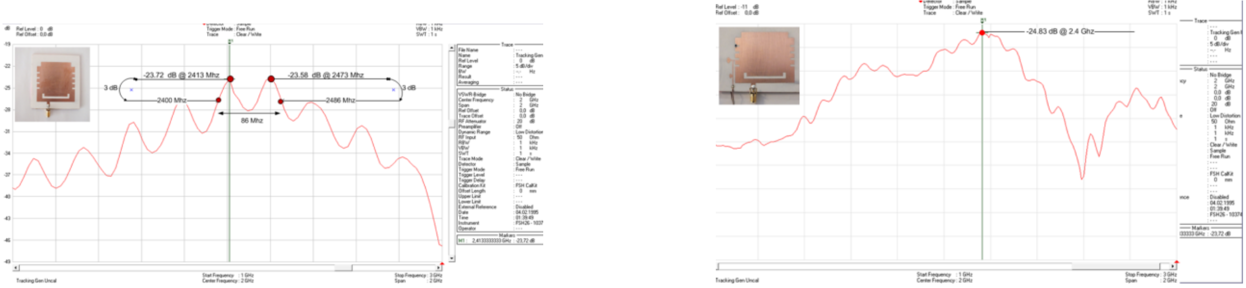
Microstrip slot loaded antenna has the potential to be a better candidate for return loss control configuration because it offers wide frequency range tuning and the conveniences of tuning the resonant frequency with switches of diodes across the slot. A combination of ***Schottky*** diode is used in [20] where a reconfigurable slot antenna is capable to 2.4 GHz frequency band. The antenna is capable to switch between two modes which are the standard and half-slot mode. The standard mode operates when the ***Schottky*** diode is switched on and $|S_{11}|$ and resonance frequency is changed with DC biasing in this case.

In this section, the simulated and measured reflection coefficients and radiation patterns are presented and compared with and without diodes. $|S_{11}|$ parameters and equivalent impedance are changing with DC biasing because of the BA592 diode capacity. As shown in Fig. 6, $|S_{11}|$ is -53.81 dB and *fr* is 2486 MHz at 5V and $|S_{11}|$ was obtained -49.42 at 2480 MHz with 0.5V .

The impedance bandwidth of the antenna is enhanced from 25 MHz for copper antenna to 73 MHz for slot and diode loaded antenna. Both passive and active antenna return loss were obtained by using Rohde & Schwarz FSH3 Handheld Spectrum Analyzer as shown in Fig. 7. With this geometry, by positioning switches in the slot, impedance control can be achieved. Schottky diodes are positioned in the slot in order to obtain reconfiguration. Due to the different radiation patterns obtained at the higher and lower frequency bands, a diode is placed top-slit the antenna to produce directional radiation pattern at the frequency bands. Schottky diode S-parameter representative is used in the measurement.



(a) Passive (S_{11}) (b) Diode loaded (S_{11})



(c) Passive (S_{21}) (d) Diode Loaded (S_{21})

Fig. 7. Measured results.

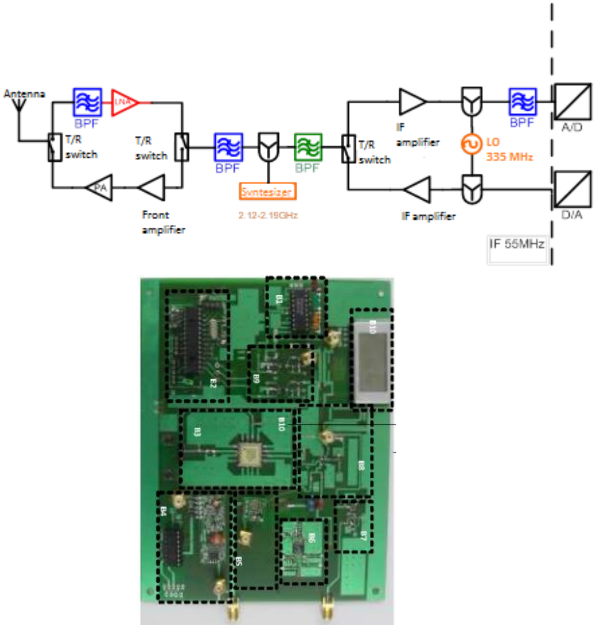
The differences between the simulated and measured results are occurred due to the Schottky diode parasitic effects. It is observed that the slot loaded patch antenna shows a stable radiation pattern over the frequency range of 2–2.5 GHz. Simulated and measured performance results summarized in Table 3.

Table 3. Performance comparison simulated and measured performance of antennas.

Parameters	**U-shape Slot Loaded Antenna *-Passive-***	**U-shape Slot Loaded Antenna *-BAS592-***	**U-shape Slot Loaded Antenna BAS 83**	**U-shape Slot Loaded Antenna BAS 70**
Return Loss @ fr	Sim. -31.5 dB Meas -36.8 dB	Sim. -37.5 dB Meas -47.8 dB	Sim. -35 dB Meas -42 dB	Sim. -31.5 dB Meas -42.8 dB
Input Impedance @ fr	Meas. 49.5-j6.5	Meas. 49.64-j8.9	Sim. 48-j4	Meas. 49-j4.5
Gain @ fr	Sim. 4.95 dB	Sim. 5.36 dB	Sim. 5.35 dB	Sim. 5.31 dB
Beam Width HPBW (@ -3dB)	Sim. 50	Sim. 45 °	Sim. 40.3 °	Sim. 50
Bandwidth (@ -3dB)	% 1.1 Meas. %1.6 Sim.	%3.01 Meas. % 3.5 Sim.	%3 Meas. % 4 Sim.	%4.2 Meas. % 6 Sim.
VSWR (Sim.)@ fr	1.2 Meas.	1.12 Meas.	1.25 Meas.	1.1 Meas.
Resonance Freq. (GHz)	2.35 Meas. 2.42 Sim	2.43 Meas. 2.44 Sim	2.45 Meas. 2.42 Sim.	2.4 Meas. 2.42 Sim
Group Delay Variations	<6.5ns	<6.5ns	<6.2ns	<6.5ns
Construction	FR4/ Engineering foams, Copper	FR4/ Engineering foams, Copper	FR4/ Engineering foams, Copper	FR4/ Engineering foams, Copper
Connector	SMA-Female	SMA-Female	SMA-Female	SMA-Female
Dimesions Weight	37.5mm x 56 mm x 1.16 mm Brackets 3.6 g			

The impedance of slot loaded antenna is obtained as 49.64-j8.9 Ω at 2.4 GHz. The Return loss was observed 60 dB at 2.41 GHz for diode loaded antenna. However, return loss was observed 45.53 dB at a 2.37 GHz for passive antenna as shown in Fig.7. Transmission performance (S_{21}) results are very close to each other for passive and active antennas. FPV542 model system was used as image and sound transmitter in order to analyze the proposed antenna performances.

In the first analysis, FPV542 transmitter was performed as reference antenna and then active slot loaded antenna was replaced with the reference antenna. Proposed loaded antenna has been used as the input of the receiver. Image quality can be understood the RSSI output of the receiver (Fig. 8).



Prototype Transceiver
(a)

Reference (RSSI)
(b)

Diode Loaded (RSSI)
(c)

Fig. 8. Measuremet results using FPV542 modules.

The measured and simulated results are tabulated in Table 2 and 3 where good correlation has been obtained between the measured and simulated results. A small shift on the resonant frequency is due to the fabrication tolerances. There are some classical techniques for the increasing the matching level and radiation pattern in according to loading point of the antenna [6]. For matching, low impedance λ/4 open stub microstrip line was used in proposed antenna model. It is obvious that successful results are obtained in diode slot loaded patch antenna. In summarly, when the BA592 diode is used as a reactive load, the BW of 3.15 % and maximum gain of 5.36 dBi have been obtained with a small amount of shift in the resonant frequency. Rohde & Schwarz FSH6 Spectrum Analyzer has been used for the measurements.

4. Conclusion

In this article, the effects of the active diode loading on the *BW* and efficiency of a slot patch antenna have been investigated. The performance parameters of the designed slot-patch antenna with and without diode loading networks have been compared using CST. Good radiation patterns were obtained in all states of diodes position. The technique of embedding diode loading crossing the slot loaded patch antenna to produce good return loss response and gain has been presented and discussed. The measurement results show that utilizing the *RL*, *BW* have been increased to 47.82 dB, 73MHz and the better radiation pattern has been obtained in E and H planes. The results show that utilizing the Schottky diode-matching as the compensation circuit, return loss level has been increased and the best transmission performance has been obtained. The proposed system can be find in mobile communication applications.

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