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Broadband and Compact Design Variations of Z-Shaped Printed Slot Microstrip Antenna

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ABSTRACT: In this research work, a Z-shaped printed slot microstrip antenna with variations in feed location has been presented to realize broadband and compact antenna. The Z-shaped slot has been realized by placing two right angle triangle shaped patches in opposite directions inside rectangular shaped slot. Further by aligning the microstrip line as feed along the length and width of Z-shaped slot, the broadband and compact antenna respectively has been realized. The antenna is fabricated using an FR4 substrate having electrical dimension of $0.48\lambda_0 \times 0.4\lambda_0$. The antenna offers 407 MHz (27%) measured impedance bandwidth for broadband and 22% of reduction in size for compact configurations. The parametric analysis, equivalent circuit analysis, and temperature as an environmental testing parameter of proposed designs are presented and validated in this paper.

1. INTRODUCTION

Enormous growth in wireless communication demands antennas which offer broadband response with reduction in antenna dimensions. The advantages of microstrip antennas such as low profile, easy fabrication, and light weight make them preferable in wireless communication applications. However, one major limitation of microstrip antenna (MSA) is narrow impedance bandwidth. The bandwidth of the MSA can be enhanced by increasing the thickness and lowering the dielectric constant of substrate. In the ultra-high frequency (UHF) range, lowering dielectric constant realizes large size MSA. Also, the thickness should be greater than $0.06\lambda_0$ to realize broadband antenna. Therefore, in the UHF band it is a crucial task to design a broadband MSA smaller in size. Cutting of slots, stacking, and multiple gap coupled patches are the techniques to realize broadband MSAs [1]. However, stacking and gap coupled techniques increase the overall size of antennas.

Printed slot antennas are gaining popularity due to their enormous design potential. These antennas are in low profile, economical, and easy to interface with radio frequency (RF) circuitry. The researchers are prominently working on the development of various shape slot antennas [2–11]. A properly stepped size shape compact slot antenna for ultra wideband (UWB) application has been reported in [2]. The combination of modified circular ring and U-shaped slots for dual band wireless applications has been presented to achieve 14.1% and 6.4% impedance bandwidths for GSM and Wi-MAX applications, respectively [3]. An extended length based square ring shaped printed slot antenna with circular polarization for C and Ku band applications has been reported in [4]. The reported antenna offers the gains of 3.2 and 3.4 dBic for dual band applications. A rhombus-shaped slot resulting from 45° rotation of rectangular ring for UWB application using a 1.6 mm thick FR4 substrate has been proposed in [5]. The proposed design claims a compact size of $19 \times 21\,\text{mm}^2$ compared with reported literature. In [6], a circularly polarized printed slot antenna having a square ring shaped slot with an arc shaped strip has been presented for UHF RFID application. In the presented antenna design, the feed line has been modified into deformed bent to achieve broadband response. The effective use of 45° rotated slots and parasitic patch has been demonstrated in [7] to realize a dual frequency wideband antenna with reduction in size. The reported design of antenna exhibits dual band response having impedance bandwidths of 3.7 GHz and 4.4 GHz. It has been revealed in [8] that, by modifying and tuning the stub, the impedance bandwidth can be extended. The reported antenna has been formed using a diamond shaped tuning stub with square ring shaped slot rotated by an angle of 45°. The antenna exhibits the broad impedance bandwidth of 123%. A voltage standing wave ratio (VSWR) bandwidth of 136% has been realized by placing two parasitic half circular patches alongside microstrip line feed, and a diagonal square ring shaped slot has been etched at the bottom in [9]. A fractal shaped slot based printed slot antenna for bandwidth enhancement has been reported in [10]. By optimizing the fractal shape iterations, the impedance bandwidth has been enhanced. In [11], a rectangular slot with a small isosceles triangular slot has been presented for bandwidth enhancement for Wi-MAX application. The reported antenna exhibits the VSWR bandwidth of 3.97 GHz. Authors of this paper have presented a Z-shaped antenna using a flexible foam substrate for UHF ISM band application. The reported antenna exhibits 5 MHz bandwidth with 8 dBi gain [12]. The reported designs in the literature commonly use wireless application bands such as Wi-MAX or WLAN. However, realizing the broadband response in UHF band of frequencies is a

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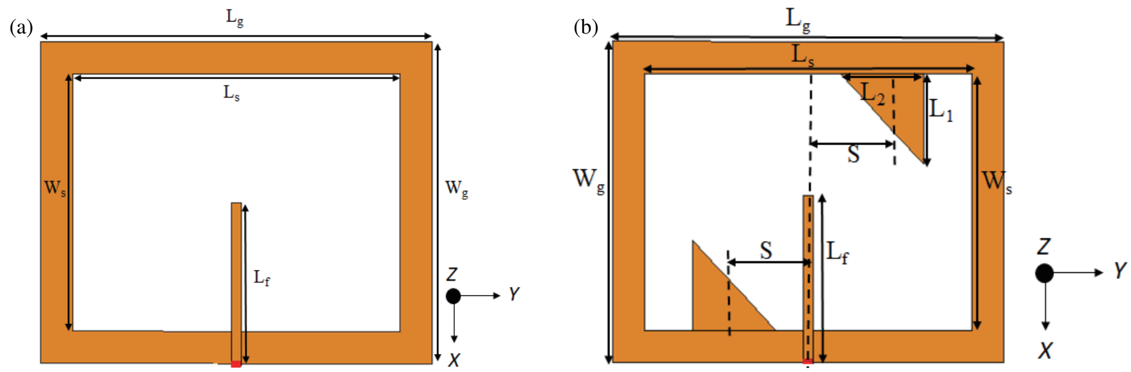

FIGURE 1. Geometry of Z-shaped printed slot antenna (a) without triangular patch (b) with triangular patch.

TABLE 1. Geometry of Z-shaped printed slot antenna.

Parameter	L_g	W_g	L_s	W_s	L_1	L_2	S	L_f
Dimension (mm)	122	100	102	80	28	26	23	52

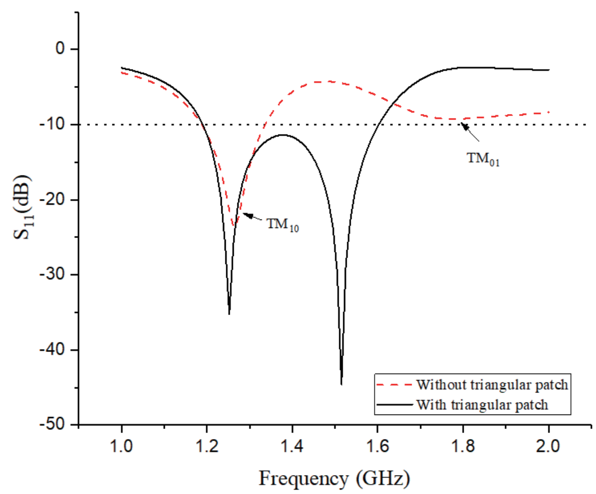

FIGURE 2. Return loss of Z-shaped printed slot antenna with and without triangular patches.

challenging task and the motivation behind the proposed work.

In the proposed research work, two design variations of a unique Z-shaped printed slot antenna are presented. Reduction in the higher order modes of slot antenna due to enhancement of electrical length is the novelty of Z-shaped slot. In this research work, the variation of a microstrip feed line along the length and width of a Z-shaped slot realizes broadband and compact designs, respectively.

2. ANTENNA GEOMETRY AND DESIGN OF Z-SHAPED PRINTED SLOT ANTENNA FOR BROADBAND RESPONSE

Figure 1 depicts the geometry of the Z-shaped printed slot antenna where the microstrip feed line is placed along the length of rectangular slot. As given in Fig. 1(a), the dimensions of rectangular slot length L_s and width W_s are estimated at the 1.2 GHz centre frequency using the equations given in [1]. The microstrip line as feed is placed on the top of the substrate, and the slot is etched at the bottom side. Two right angle triangle patches having dimensions L_1 and L_2 are placed in the opposite sides of rectangular slot length to realize the Z-shaped slot structure as shown in Fig. 1(b). The location S of right angle triangular patches with respect to the center of slot has been optimized to achieve broadband response. The width W_f of microstrip feed line is selected as 3 mm to match with 50 Ω impedance. An FR4 substrate having thickness $h = 1.6$ mm and dielectric constant $\varepsilon_r = 4.3$ is used to design, simulate, and fabricate this antenna. A method of moments (MoM) based CAD Feko [13] antenna simulator is used to simulate the proposed design of antenna. The overall dimensions of the Z-shaped printed slot antenna is given in Table 1.

Figure 2 depicts the return loss characteristics of the printed Z-shaped slot antenna with and without triangular patches. The rectangular slot antenna resonates at fundamental TM_{10} mode

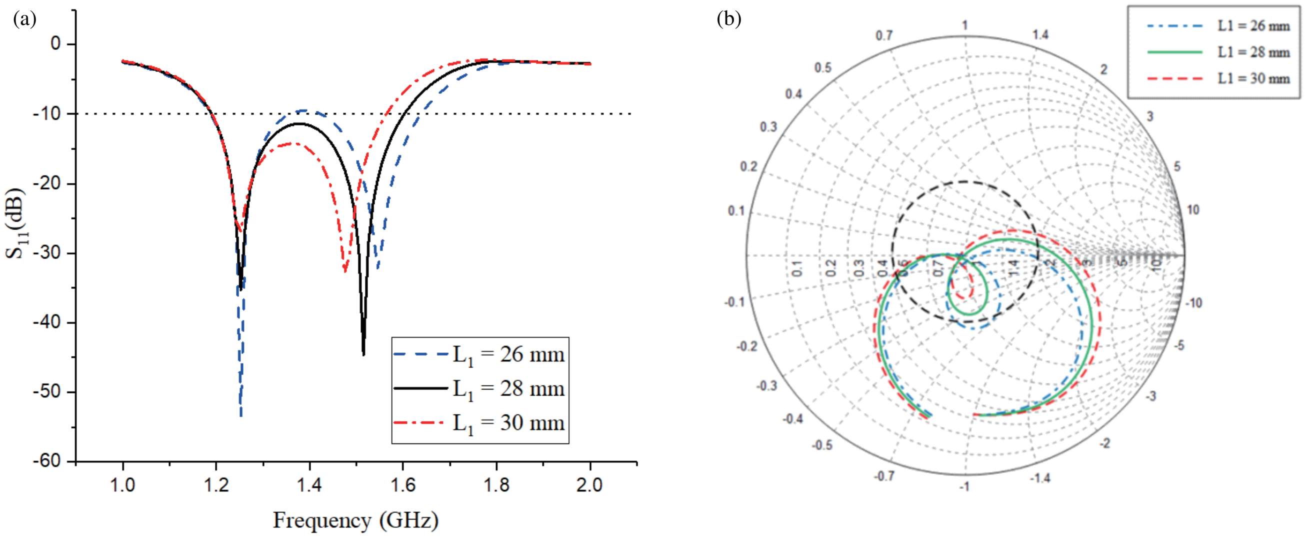

FIGURE 3. Effect of variation of L_1 on (a) return loss (b) impedance.

having 1.2 GHz frequency. The antenna also exhibits TM_{01} mode with poor impedance matching around 1.8 GHz. With properly designed right angle triangular patches, the Z-shaped slot has been realized. These patches are responsible to lower the TM_{01} mode frequency, merging with fundamental TM_{10} mode and realizing broadband response. The detailed analysis of the variation of physical parameters on the return loss characteristics of proposed antenna to achieve broadband response has been presented further.

2.1. Parametric Analysis of Physical Parameters for Broadband Response

The right angle triangular patches having dimensions as L_1, L_2 and the separation with respect to center S have been varied by keeping other parameters unchanged. This analytical study helped to understand the effective use of higher order modes to realize broad impedance bandwidth. The effects of variation of length L_1 on return loss and impedance characteristics are depicted in Figs. 3(a) and Figs. 3(b), respectively.

The vertical length L_1 has been varied from 26 mm to 30 mm. For the length 26 mm dual band response having bandwidths of 168 MHz and 212 MHz is observed and presented in Figs. 3(a). Better impedance matching with bandwidth of 372 MHz has been obtained for the length of 30 mm. However, broadband response with impedance bandwidth of 411 MHz has been realized for the length $L_1 = 28$ mm. This is because of the Z-shaped slot which enhances the electrical length of the surface current. The higher order mode of the proposed antenna lowers and merges with the fundamental mode. This phenomenon can be verified by studying the impedance plot as depicted in Figs. 3(b). The coupling between the fundamental and higher order modes is better for lengths 28 mm and 30 mm. For the 26 mm length the coupling is strong; however, it moves out of the VSWR = 2 circle. The parametric analysis has been carried out on variation of horizontal length L_2 and distance S. The length L_2 and the distance from center of antenna S have been varied, and their effects on return loss and impedance characteristics have been observed. It has been noted that no significant effect on variation of L_2 and space between the center of antenna and triangular patch S on bandwidth has been observed, and it remains constant at 411 MHz. These variations of L_2 and S and its effect on bandwidth is presented in Figs. 4 (a) and (b) respectively.

Figures 5(a) and (b) present radiation characteristics at 1.25 GHz and 1.51 GHz, respectively. The radiations of proposed antenna are in broadside directions over the bandwidth with maximum gain of 2.03 dBi in both E-plane and H-plane. The cross polarizations level at both frequencies is below -16 dB in both planes.

The surface current analysis has been carried out and depicted in Figs. 6(a) and (b) for 1.25 GHz and 1.51 GHz, respectively. The orientation of current is found the same for both the frequencies, therefore realizing the broadside radiations at both the frequencies. It can also be noted that, due to the presence of right angle triangular patches inside the rectangular slot, the electrical length of the surface current increases, and therefore it lowers the higher order mode frequency, achieving broadband response.

3. ANTENNA GEOMETRY AND COMPACT DESIGN OF ZSSHAPED PRINTED SLOT ANTENNA

The orientation of microstrip feed line plays a vital role in the design of slot based microstrip antennas. It has been noted that by changing the location of microstrip feed line a compact slot antenna can be realized. As presented in Figs. 7, the feed line is aligned to the width of the rectangular slot. This change in the feed line increases the electrical length of surface current across the Z-shaped slot and shifts the resonating frequency towards lower side, and hence the compact printed slot MSA can be designed.

The return loss characteristics of the Z-shaped compact MSA with and without Z-shaped slot is compared and presented in Figs. 8. The antenna resonating frequency with Z-shaped slot

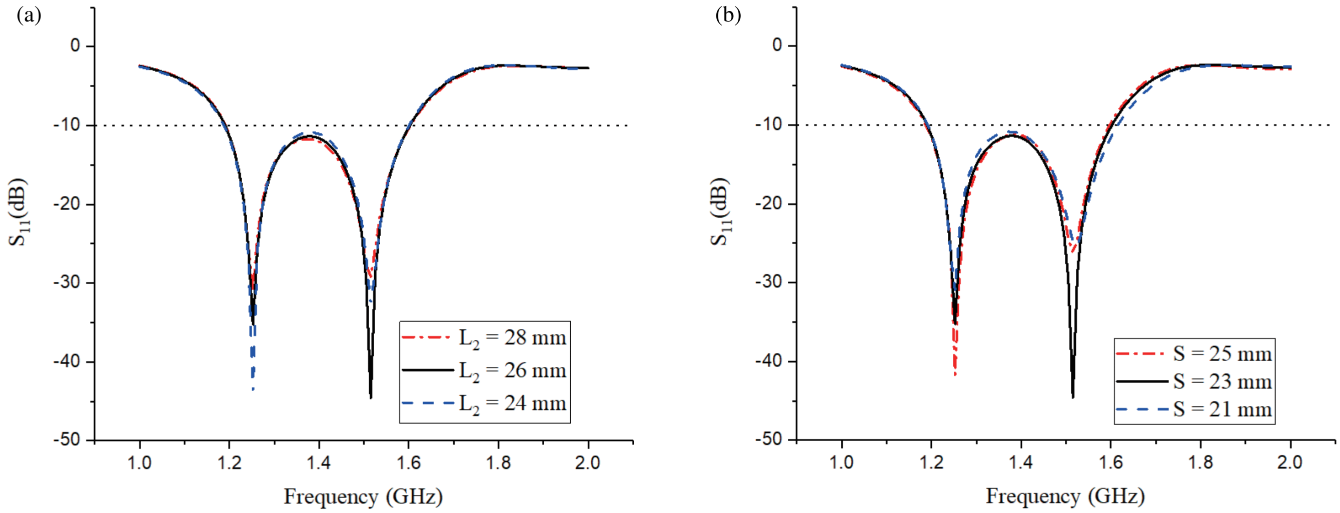

FIGURE 4. Effect of variation of (a) L_2 and (b) S on return loss.

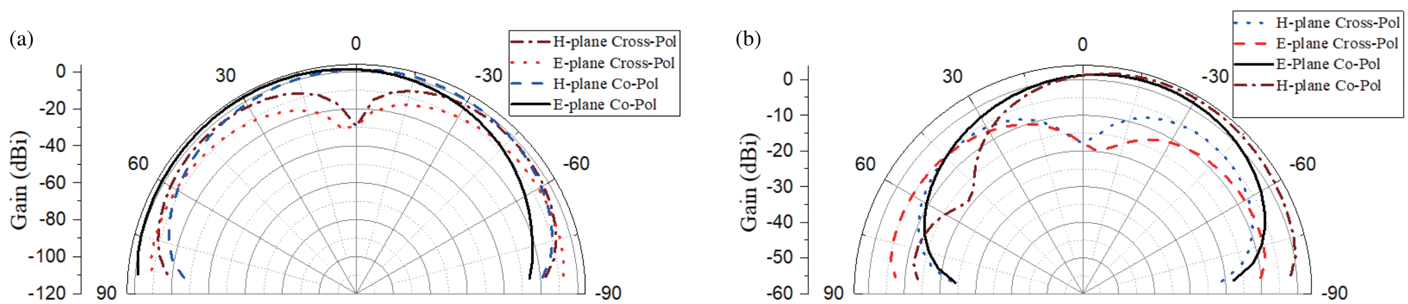

FIGURE 5. Radiation pattern (a) 1.25 GHz (b) 1.51 GHz.

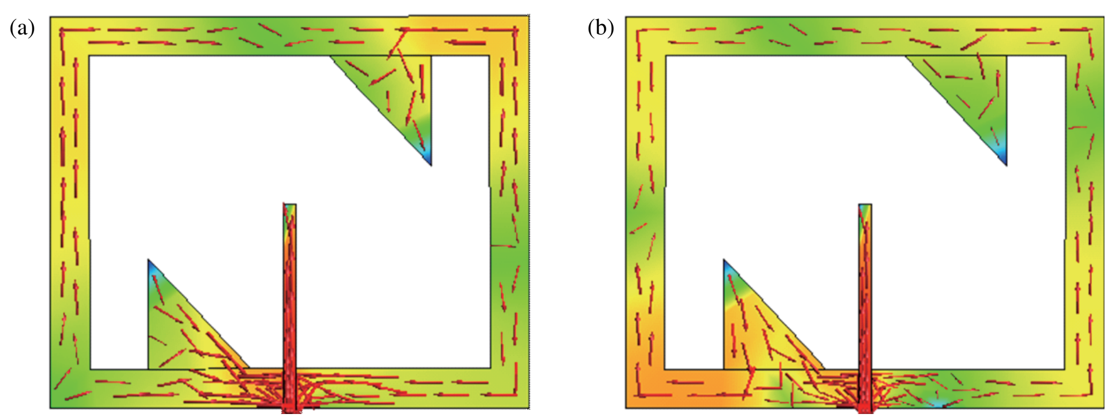

FIGURE 6. Surface current (a) 1.25 GHz (b) 1.51 GHz.

shifts towards lower side. The antenna resonates at 942 MHz with the impedance bandwidth of 152 MHz covering GSM 900 wireless band. The 22% reduction of size has been achieved by changing the feed line orientation. To study the effect of dimensions of antenna geometry parameters, the parametric analysis has been carried out and presented in the next section.

3.1. Parametric Analysis of Physical Parameters for Compact Response

The parametric analysis has been carried out on the right angle triangular dimensions L_1 and L_2. The length L_1 has been varied from 30 mm to 34 mm, and its effect on return loss is depicted in Fig. 9(a). It is observed that the increase in length L_1 enhances the electrical length of surface current. This ef-

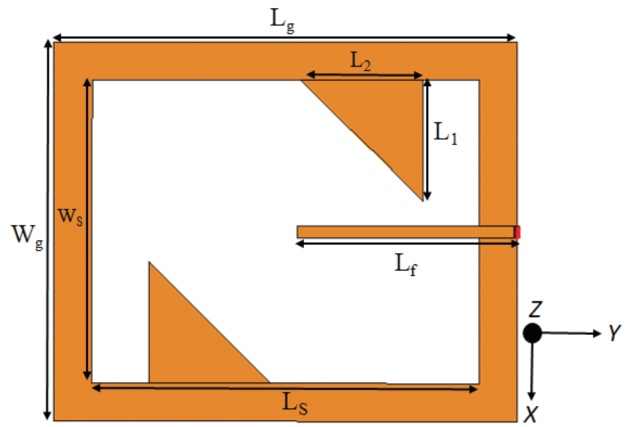

FIGURE 7. Antenna geometry of compact Z-shaped MSA.

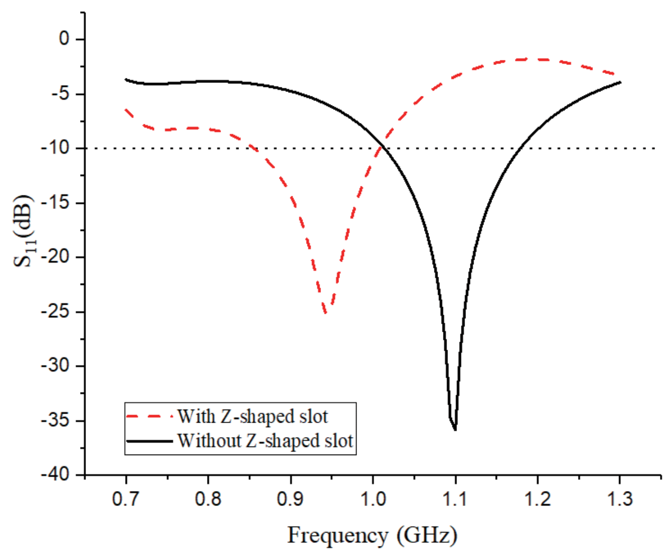

FIGURE 8. Comparison of return loss characteristics with and without Z-shaped slot.

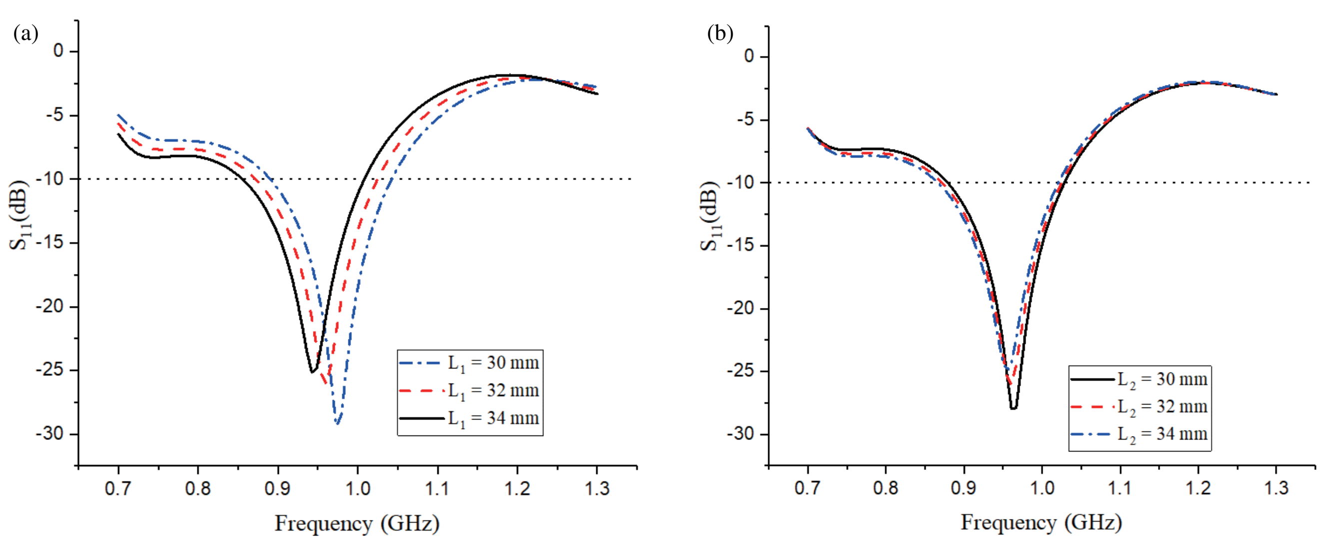

FIGURE 9. Effect of variation of (a) L_1 and (b) L_2 on return loss.

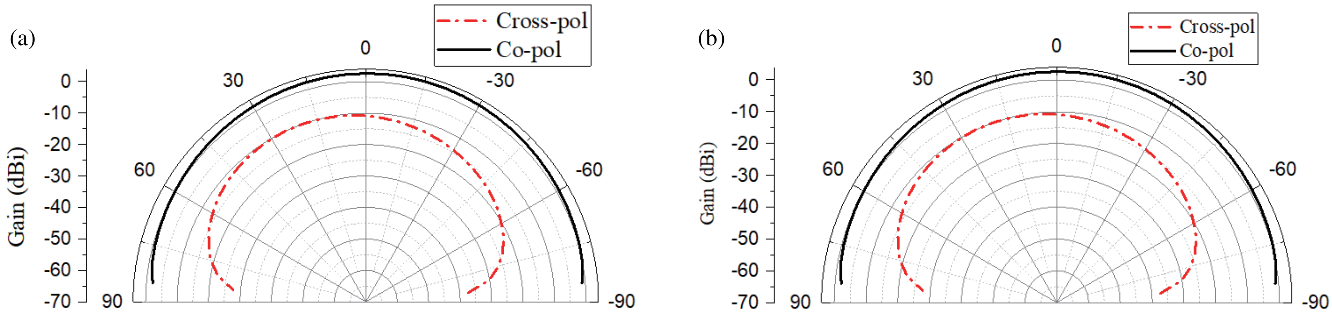

FIGURE 10. Radiation pattern at 942 MHz (a) E-plane (b) H-plane.

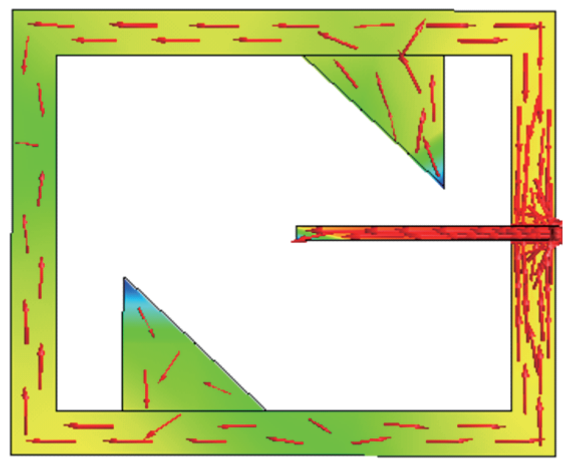

FIGURE 11. Surface current at 942 MHz.

fect shifts the resonating frequency to lower side, and hence the reduction in size has been realized. The optimum results has been obtained for $L_1 = 34$ mm, and the proposed design of antenna is tuned to desired GSM 900 wireless communication band. The variation of length L_2 has been simulated. The length L_2 is varied from 30 mm to 34 mm. However, no significant change in the resonant frequencies and bandwidth is observed. The variation of L_2 and its effect on return loss are presented in Figs. 9(b).

Figure 10 depicts radiation pattern for the compact design of the Z-shaped printed MSA at 942 MHz. The peak gain of 2.63 dBi at resonating frequency is obtained. The radiations are in broadside direction, and cross polarization is below -10 dB in both E- and H-planes. Figs. 11 presents the surface current at 942 MHz. It is seen that the feed line is along the width of Z-shaped slot which enhances the electrical length of current. The electrical length of current is increased because of length of the slot and right angle triangles embedded inside the slot. This results in shifting of resonant frequency to lower side.

4. EQUIVALENT CIRCUIT AND EXPERIMENTAL RESULT VALIDATION

The theoretical analysis of proposed Z-shaped printed slot antenna has been carried out. The rectangular slot having dimensions L_s and W_s is considered to estimate the values of equivalent inductance and capacitance using Eqs. (1)–(3) [14].

$$C_1 = \frac{\varepsilon_0 \varepsilon_r L_S W_S}{2h} \tag{1}$$

$$L_1 = \frac{1}{C_1 \omega_0^2} \tag{2}$$

$$R_1 = \frac{Q}{\omega_0 C_1} \tag{3}$$

Where Q is the quality factor and given by [14].

$$Q = \frac{c\sqrt{\varepsilon_r}}{4 f_r h} \tag{4}$$

Similarly, the equivalent inductance and capacitance of right angle triangular patches are computed using equations (1)–(3). The estimated values of inductance and capacitance for slot and right angle triangular patch are $L_1 = 0.18$ nH, $C_1 = 97$ pF, $L_2 = 0.9$ nH, and $C_2 = 8.66$ pF, respectively. The microstrip feed line is modelled by its transmission line equivalent circuit indicating two series inductance L_{ML} and a shunt capacitor C_{ML}. When the antenna is excited by the RF source, this feed line radiates. This radiated field by feed line coupled with the rectangular slot which resonates at desired resonating frequency. This proves that there exists a fringing capacitance between the Z-shaped slot and microstrip feed line which is given

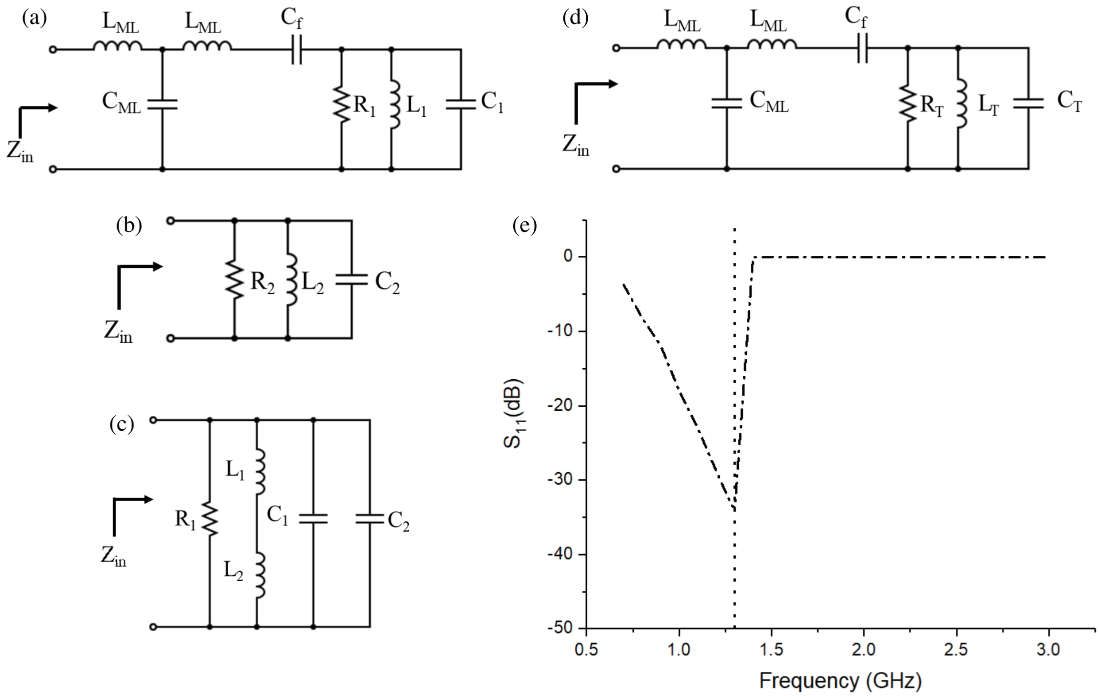

FIGURE 12. Equivalent circuit (a) rectangular slot, (b) right angle triangular patch (c) series and parallel combination (d) Z-shaped printed slot, (e) simulated return loss of equivalent circuit.

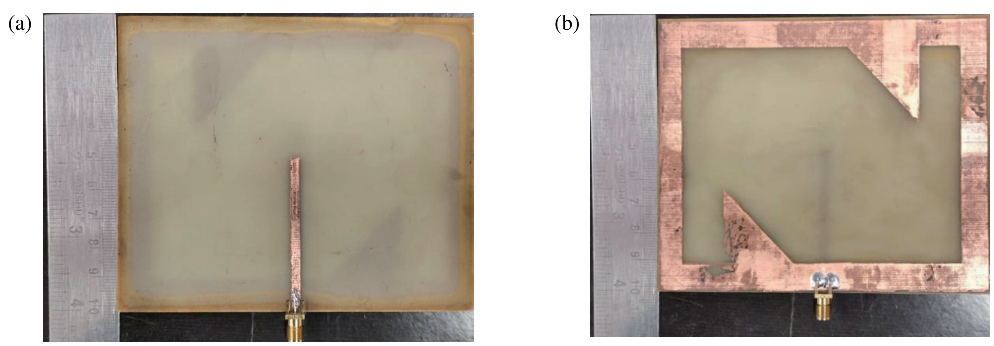

FIGURE 13. Photographs of fabricated prototype for broadband design (a) top side (b) bottom side.

by Eqs. (5), (6) [14].

$$2C_f = \sqrt{\frac{\varepsilon_r}{c.Z_0}} - C_P \tag{5}$$

$$C_P = \varepsilon_0 \varepsilon_r \frac{W_f}{h} \tag{6}$$

The estimated value of this fringing capacitance is 71.38 pF. Further, when Z-shaped slot radiates, it lowers the higher order mode of slot antenna, merges it with fundamental mode, and realizes the increased bandwidth. This phenomenon can be modelled by considering series inductances L_1 and L_2 and parallel capacitances C_1 and C_2 of rectangular slot and right angle triangular patches, respectively. The values of series inductance L_T and parallel capacitance C_T are computed as 1.08 nH and 105 pF, respectively. The combination of series inductance and parallel capacitance exhibits the theoretical bandwidth of 472 MHz which is in considerable agreement with the simulated and measured bandwidths of 411 MHz and 407 MHz, respectively. The development of equivalent circuit is depicted in Figs. 12(a)–(d), and its simulated response of reflection characteristics using ADS software is presented in Fig. 12(e).

It is noted from Fig. 12(e) that the return loss characteristics of proposed Z-shaped printed slot antenna and equivalent circuit are in good agreement. The proposed designs of broadband and compact Z-shaped printed slot antennas have been simulated and fabricated using an economical FR4 substrate with optimized dimensions. The fabricated antenna is tested using Obzor VNA. Photographs of the fabricated prototype are depicted in Figs. 13(a), (b) and Figs. 14(a), (b) for broadband and compact designs variation, respectively. A photograph of experimental setup is presented in Figs. 15.

The measured impedance bandwidths for broadband and compact designs are 407 MHz and 149 MHz compared to simu-

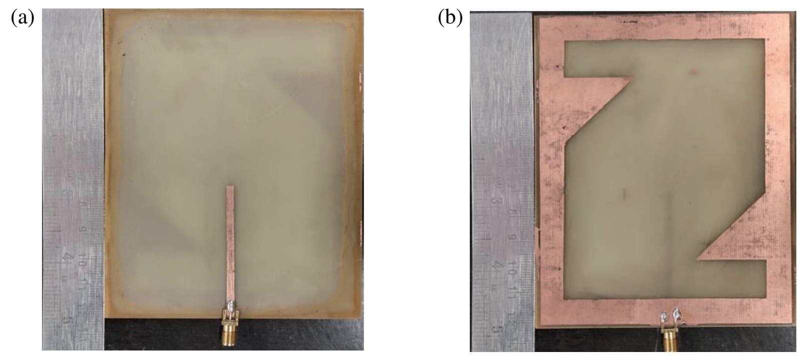

FIGURE 14. Photographs of fabricated prototype for compact design (a) top side (b) bottom side.

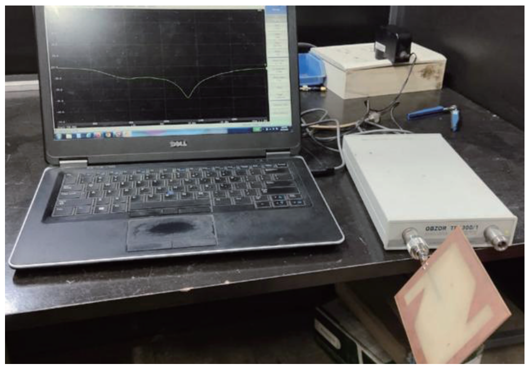

FIGURE 15. Photograph of experimental set up.

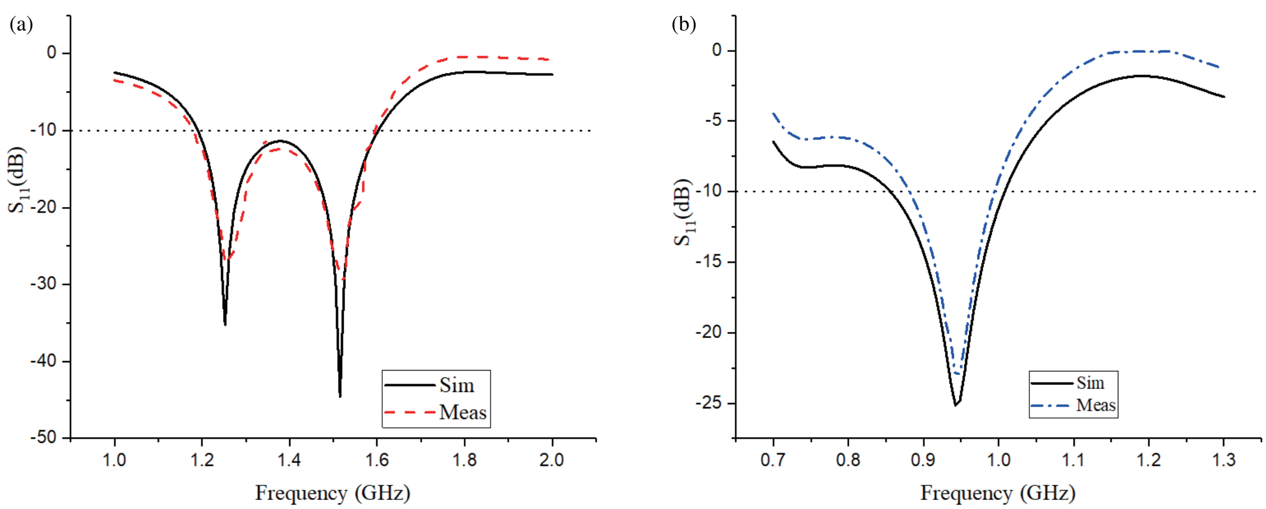

FIGURE 16. Comparison of simulated and measured return loss, (a) broadband design, (b) compact design.

TABLE 2. Comparison of proposed antenna with previous antenna designs.

Ref. No.	Thickness (mm)	Size (mm)	Slot type	Gain (dBi)	Polarization
[2]	1.27	17 × 8	Stepped	3.36	Linear
[3]	1.6	48 × 48	Modified circular ring	–	Linear
[5]	1.6	19 × 21	Rhombus	0.84–1.76	Linear
[6]	0.8	70 × 70	Square	2.85–0.45	Circular
[8]	1	28 × 28	Rotated square	1.5–5	Linear
This work	1.6	122 × 100	Z-shaped	2.63	Linear

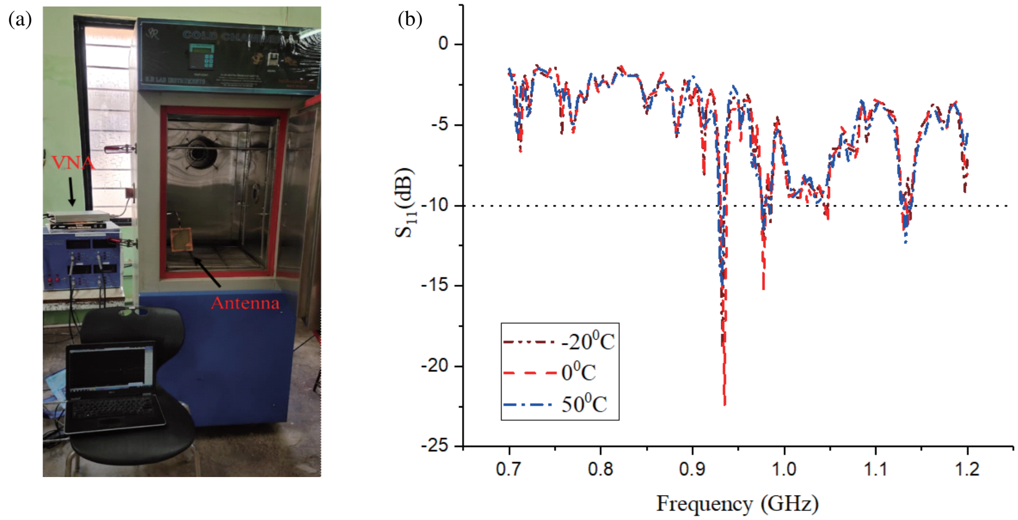

FIGURE 17. (a) Photograph of experimental setup for temperature testing, (b) return loss characteristics at temperature variations.

lated bandwidths of 411 MHz and 152 MHz, respectively. The measured and simulated results are obtained in close agreement with each other. The comparison of simulated and measured return losses for broadband and compact design are presented in Figs. 16(a)–(b).

The fabricated antenna has also been tested under varying temperature conditions of $-20°$C, 0°C, and 50°C to study the practical relevance of proposed antenna design. The fabricated prototype has been placed inside the cold and hot chambers and the temperature has been set at $-20°$C, 0°C, and 50°C, respectively. The return loss characteristics of proposed design have been measured at aforementioned temperatures. It has been observed that the resonance frequency remains unchanged; however, the impedance bandwidth has been reduced. The experimental setup and the obtained return loss characteristics of different temperature conditions are presented in Figs. 17(a) and (b).

Further, the proposed design of antenna has been compared in terms of thickness, size, slot type, gain, and polarization with previously reported antenna designs in literature and illustrated in Table 2.

5. CONCLUSION

The variations in design of Z-shaped printed slot antenna by shifting the microstrip feed line to realize broadband and compact antenna are presented in this paper. The right angle triangular patches have been embedded inside the rectangular slot to realize Z-shaped slot structure. The higher order mode of proposed design is used to realize broadband response. The antenna offers 27% of measured impedance bandwidth for broadband configuration and 12.79% impedance bandwidth for compact configuration. Also, the change in feed location achieves reduction in size by 22% for compact Z-shaped slot antenna configuration. The simulated and optimized antenna structure has been fabricated and tested. The simulated and measured results are compared and found in good agreement. The return loss of equivalent circuit model matches reasonably with simulation results. The low and high temperature testing validates proposed design more viable.

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