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A Multi-Band Asymmetric Stepped-Slot Antenna for DCS, PCS, WiMAX, 4G, and WLAN Applications

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***Abstract*- A multi-band stepped-slot antenna, fed by modified 50 Ω coplanar waveguide (CPW) transmission line is described and implemented. The designed antenna effectively supports digital communication systems (DCS 1.71-1.88GHz), personal communication systems (PCS 1.85-1.99 GHz), worldwide interoperability for microwave access (WiMAX 3.30-3.80GHz), fourth generation (4G 3.40-4.2 GHz) mobile communication system, and wireless local area network (WLAN 5.15-5.35 GHz). In order to cover the aforementioned valuable bands, in the first step rectangular slots are subtracted symmetrically from the radiating patch. Besides, stair-shaped rectangular slots are etched at the radiator edges. Also, to operate at DCS and PCS systems, dual-section CPW feed line with different widths is designed. Actually antenna is designed by using quasi-fractal methods, to cover frequency ranges of 1.64-1.99 GHz, 3.35-4.3 GHz and 4.8-5.4 GHz (for |S11|< -10 dB). The antenna size is 75.2 × 38.54 × 1.6 mm3 and it is etched on FR4 substrate. The antenna development steps are presented and discussed in detail. Moreover investigation of important design parameters is performed. The designed multi-band antenna has respectable results such high gain in center of each operating band and considerable efficiency of 90%, 85% and 86% in 1.85, 4 and 5GHz respectively. Also omni-directional patterns and acceptable group delay are obtained. Measurement data are presented to validate the numerical outcomes. All of these prominent features make this antenna, worthwhile for multi-band applications.**

***Index Terms*-** DCS, dual-part CPW feed line, 4G, Multi-band antenna, PCS, stepped-slot, WiMAX, WLAN

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I. INTRODUCTION

In recent years, many multi-band antennas have been emphasized to reduce interference. To satisfy this goal, allocate specific frequency bands have been developed to support different applications. The most well-known bands are wireless local area network (WLAN), worldwide interoperability for microwave access (WiMAX), long-term evolution-advanced (LTEA), and so on. Several multi-band antennas were deigned to work at different separate bands [1-5]. In [1], a dual-band antenna was obtained by L-shaped and E-shaped radiating elements. The L- and E-elements were used to support higher and lower band of the WLAN systems respectively. Another dual-band antenna was reported in [2] with rectangular radiator and trapezoid conductor on ground plane. The antenna covers frequency ranges from 2.01 to 4.27 GHz for the WLAN applications and 5.06 to 6.79 GHz for Wi-MAX systems. A tri-band antenna was applied for WLAN and Wi-MAX applications in [3]. A rectangular patch antenna with pre-fractal Koch-like was presented in [4] for Galileo and Wi-MAX quad-band operation. A compact multi-band antenna with Loop-Inverted F construction has been reported in [5].

Nowadays, the focus is on low profile and ease on fabrication antennas [6-8]. Accordingly, so many methods have been proposed to response multi-band demands. For example, a self-complementary antenna for dual-band WLAN applications consisting of a pie-shaped radiating patch, was proposed in [9], which operates at frequencies of centered at 2.45 GHz and 5.5 GHz. The design of three-dimensional (3-D) slot loop antenna is described in [10] to covers 1.64-4.24 GHz and 4.55-6.21 GHz for mobile terminals. A triangle-shape antenna fed by coplanar waveguide (CPW) acquired in [11]. In [12], [13] and [14] fractal-shape structures were designed for multi-band systems. Furthermore, inverted-F shapes show good performance for multi-band applications which are implemented in [15], [16] and [17].

Among multiple types of techniques, cutting slots on ground plane and radiator is one of the most favorable methods to researchers. Slots are used in many various shapes. A novel U-slot and inverted-U antenna with a size of 50 × 80 mm^2 that could be used for Wi-MAX, HIPERLAN/2, and radar communication systems is discussed in [18]. Other U-shape slot antennas are presented in [19], [20] and [21]. With the use of three L-shape slots, an antenna with the overall size of 16 × 30 mm^2, can provide tri-band operation, for WiMAX and WLAN applications [22]. Also in [23], a printed circular disc monopole antenna with frequency range of 4.74 to 9.58 GHz is investigated. The L-shape slot was added on ground plane to cover 2.68 to 3.28 GHz. Two reconfigurable slot antennas are presented in [24] and [25]. In [24], a tapered rectangular slot antenna is suggested. The antenna has capability to switch between ultra-wide, triple- and dual-bands, by activating T-shape and C-shape resonators. In [25], multi-band performance is achieved by loading trapezoidal slot in the radiating monopole and rectangular slots in the ground plane. A bow-tie slot antenna with tri-band operation was presented. A compact bow-tie antenna with circular slots was presented for WiMAX and WIFI applications in [26]. A multi-band slot-loaded dipole antenna for WLAN and LTE-A applications was designed in [27]. In [28], a Y-slot antenna with a size of $0.08\lambda_o \times 0.384\lambda_o$ is presented for WLAN and LTEA systems. Meanwhile, different strips slot loaded on rectangle ground plane to find out a dual-band antenna operating in the frequency bands of 4.8 to 6.5 GHz, and 7.8 to 8.4 GHz. In [29], a T-shaped antenna with an inverted T-shaped stub and two E-shaped stubs is proposed. However, the bandwidth for global positioning system (GPS) is about 1.575-1.665 GHz, for WiMAX applications is 3.27-3.97 GHz and for WLAN systems is 2.4-2.545 GHz and 5.17-5.93 GHz. A cavity-backed annular ring slot SIW antenna with multi-band multi-mode characteristics was introduced in [30]. In [31], a triple-band CPW-fed antenna (1.575 GHz, 2.4-2.485 GHz and 5.15-5.85 GHz) with integrated H-shape slot on the radiator is proposed where used for GPS and WIFI systems. An open-slot antenna consists of parallel rectangular slots on ground plane is presented in [32]. A T-shaped slot has been designed at frequency bands of 2.4-2.9 GHz, 3.7-5.2 GHz, and 5.7-6 GHz [33]. In [34], a handset antenna using slots on ground plane was presented. Also, some fractal slot antennas for multi-band applications have been presented in [35-8].

In this paper, to support digital communication systems (DCS), personal communication systems (PCS), WiMAX, WLAN and forth generation (4G) mobile communication systems, a simple stepped-slot antenna is designed and the obtained results are discussed in details. The novelty of the proposed structure lies in its simple structure and multi-band operation with satisfactory radiation characteristics. Several techniques are used to achieve desirable frequency- and time-domain performance. In order to operate at 1.71-1.88 GHz and 1.85-1.99 GHz for DCS and PCS systems, modified dual-part 50Ω CPW feed line with different widths is designed. By integrating quasi-fractal slots on rectangular radiating patch, triple band characteristics are established. Besides, optimized stair-shaped slots are created on two edges of the patch to enable the antenna to cover tree band cantered at 1.85, 3.75 and 5.25 GHz with reflection coefficient less than -10 dB. Prototypes of the multi-band antenna are constructed on FR4 substrate with size of $75.2 \times 38.54 \times 1.6$ mm^3 and measured. The frequency and time domain results are presented to investigate the antenna behaviour in all frequency bands. Simulation and experimental results are presented and compared. The agreement between simulation and test results reveals the antenna is dealing with multi-band applications.

II. ANTENNA DESIGN

The geometry of the proposed multi-band antenna is shown in Fig. 1. This figure shows all final effective dimensions. The antenna with the size of $75.2 \times 38.54 \times 1.6$ mm^3 is printed on FR4 substrate with permittivity 4.4 and loss tangent of 0.02. The numerical simulations were performed via full-wave Ansoft HFSS simulator package. A modified CPW transmission line, which consists of two sections with different widths, is used for feeding the antenna. Moreover, to investigate multi-band operation, asymmetric quasi-fractal slots along with stair-shaped slots are etched on rectangular radiating patch. Development stages of the antenna structure and corresponding simulated reflection coefficient curves are illustrated in Figs. 2 and 3, respectively. The procedure of the antenna design begins with rectangular patch and simple feed line with 50 Ω impedance (Antenna 1). In the second step, by using a modified dual-section CPW feed line (Antenna 2), the first resonance frequency of the antenna is shifted from 2.6 to 1.7 GHz (Fig. 3). Fig. 3 indicates that Antenna 2 can operate at 1.71-1.88 GHz and 1.85-1.99 GHz for DCS and PCS systems, respectively. Subsequently, by applying quasi-fractal slots on the radiator (Antenna 3), the antenna matching is considerably improved over 3-5 GHz frequency range. In the fourth step, two arms of the slotted radiator are truncated (Antenna 4) and as shown in Fig. 3, the second resonant frequency of the structure is occurred at 4 GHz. Next, two small rectangular strips are added just in the middle section of the patch (Antenna 5). As illustrated in Fig. 3, this technique causes tri-band operation of the antenna. In the next stage, staircase-like slots are utilized at the corners of the patch (Antenna 6) and consequently the first resonance frequency is shifted from 1.4 to 1.7 GHz. In the final step, a vertical strip is added to the right side of the radiator. It is seen in Fig. 3 that the proposed antenna can cover frequency ranges of 1.64-1.99 GHz, 3.35-4.3 GHz, and 4.8-5.4 GHz (for $|S_{11}| < -10$ dB). The numerical analysis and geometry refinement of the proposed antenna are performed by using Ansoft HFSS, a full-wave electromagnetic simulator package which is based on the finite element method. The geometrical parameters of the proposed antenna are presented in Table I.

The simulated reflection coefficient curves of the antenna for different key parameters are shown in Fig. 4. Through numerous simulations it was found that the parameters b, Lf, and S are three prominent geometrical parameters of the proposed antenna. From Fig. 4(a), it can be concluded that by decreasing the first section feed line length Lf to 13.5 mm, the lower band edge frequency of the second band increases, also reflection coefficient in third band deteriorates, as Lf is increasing from 14.5 to 15.5 mm. This parameter has considerable influence on WiMAX (3.30-3.80GHz) and 4G (3.40-4.2 GHz) bands. As it can be seen, the optimum value of Lf for most efficient multi-band coverage is 14.5 mm. The influence of variation of rectangular slot length b on impedance bandwidth of the antenna is presented in Fig. 4(b). Results of this Fig. show that this parameter affects the mid frequencies of the antenna bandwidth. The optimum value of b for supporting WiMAX (3.30-3.80GHz) and 4G (3.40-4.2 GHz) bands, is 9.27 mm while the first (DCS 1.71-1.88GHz and PCS 1.85-1.99 GHz) and the third (WLAN 5.15-5.35 GHz) bands are nearly not changed. Besides, it is observed from Fig. 4(c) that the second band which covers WiMAX and 4G applications is significantly affected by variation of S. This parameter has slight effect on the first and third bands.

Table I. Geometrical parameters of the antenna (units: mm)

parameter	**w1**	**L1**	**W2**	**L2**	**L3**	**L4**	**L5**	**Lf**	**Lt**	**wf**	**wt**	**ws1**
value	38.54	75.20	3854	34.07	39.75	36.37	32.57	14.5	21.88	3.50	0.94	25.92
parameter	**ws2**	**ws3**	**ws4**	**Su**	**S1**	**S2**	**S3**	**S**	**SL**	**g1**	**b**	
value	11.11	3.50	5.82	13.61	3.55	3.55	3.50	5.95	13.61	0.35	9.75	

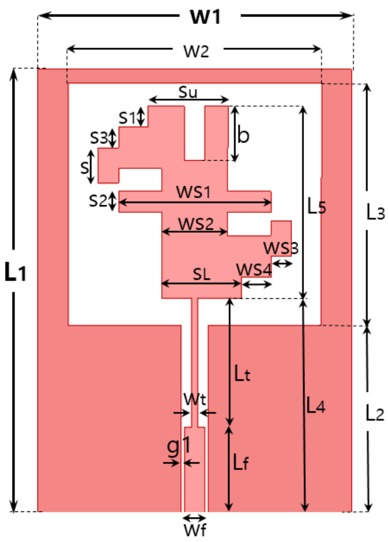

Fig. 1. Antenna geometry and design parameters.

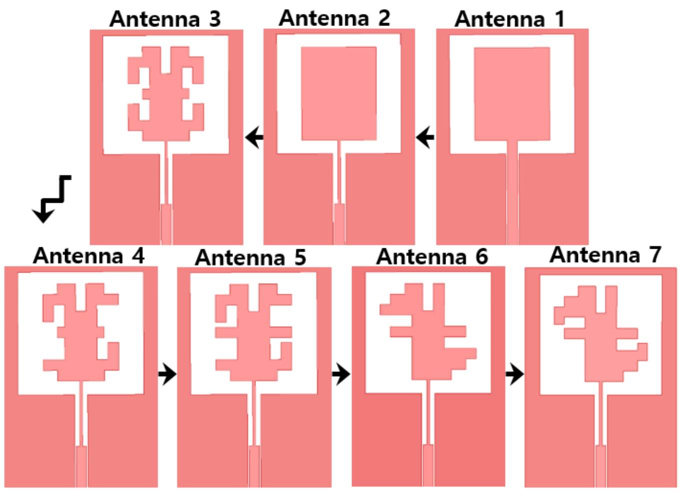

Fig. 2. Design evolution of the proposed multi-band antenna.

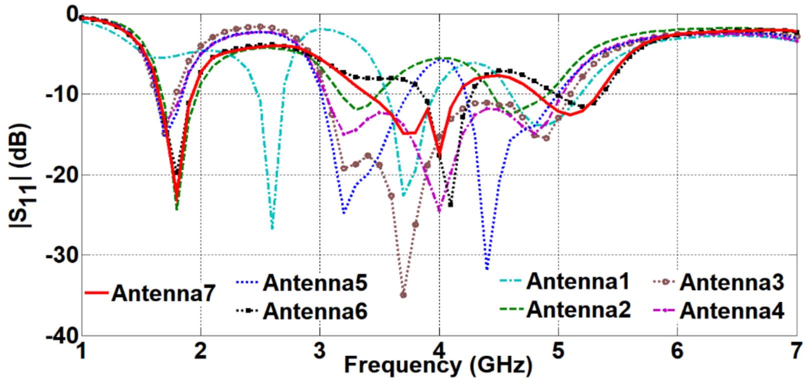

Fig. 3. Simulated reflection coefficient curves of the antennas corresponding to Fig. 2.

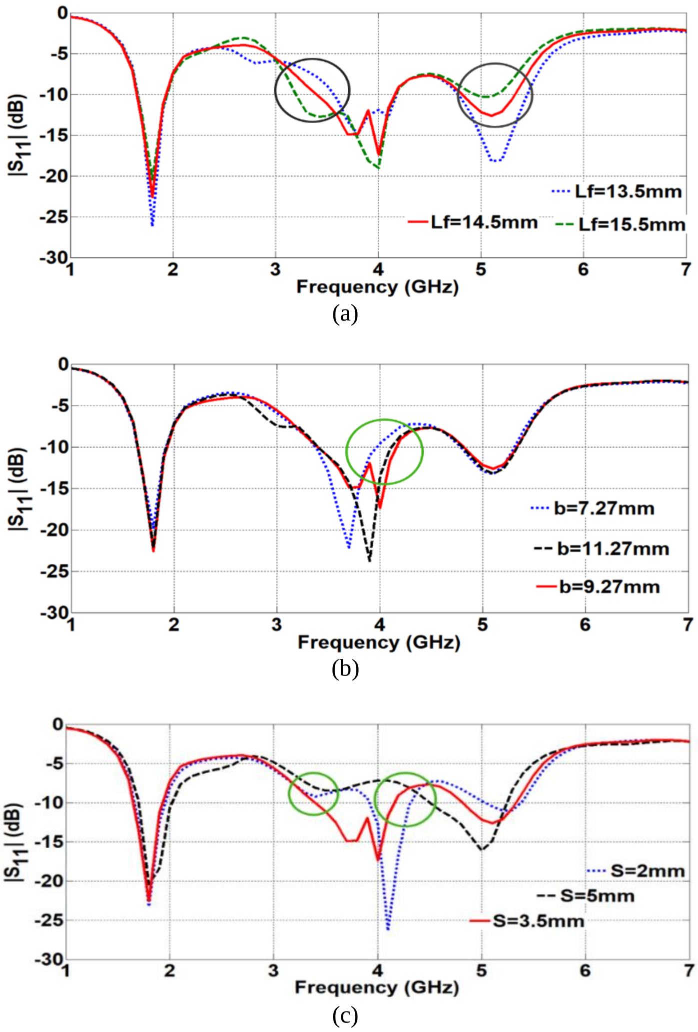

Fig. 4. Reflection coefficient for different values of (a) Lf, (b) b, and (d) S.

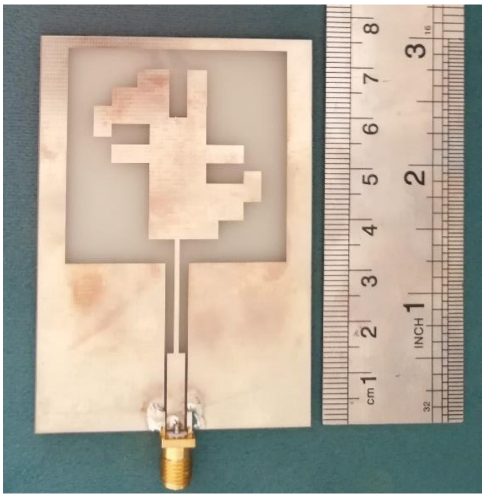

Fig. 5. Photograph of the fabricated prototype.

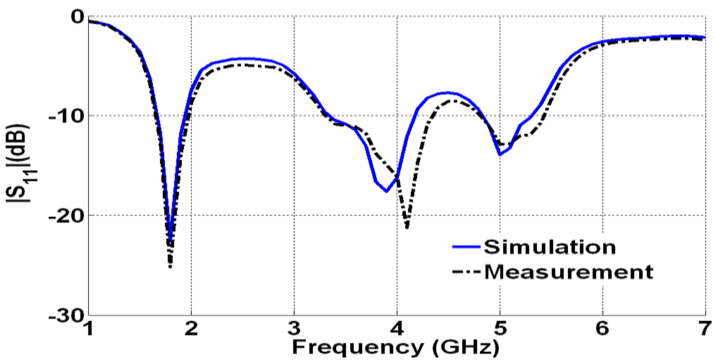

Fig. 6. Variation of reflection coefficient of the proposed antenna versus frequency.

III. EXPERIMENTAL VERIFICATION

To demonstrate the validity of numerical results obtained by Ansoft HFSS, the antenna was fabricated and measured. Fig. 5 shows photograph of the antenna prototype. This section, gives a comparison between experimental and numerical results of the multi-band antenna. The experimental results such as reflection coefficient, radiation patterns, gain, and radiation efficiency are reported. Also, the time domain performance of the antenna is investigated. The outcomes exhibit that the experimental and numerical results are considerably matched. As seen in Fig. 6, both measured and simulated reflection coefficient curves show that the antenna has multi bandwidth operation which can cover 1.64 to 1.99 GHz, 3.35 to 4.3 GHz, and 4.8 to 5.4 GHz. The slight discrepancy at 3.5-4.8 GHz range may be due to measurement errors and test equipment. Far-field co- and cross-polar radiation patterns in both E- and H-plane are also measured and compared at the centre frequency of each band namely 1.8, 3.9 and 5.1 GHz and presented in Fig. 7. The radiation patterns in E- and H-plane are bi-directional and almost omni-directional, respectively.

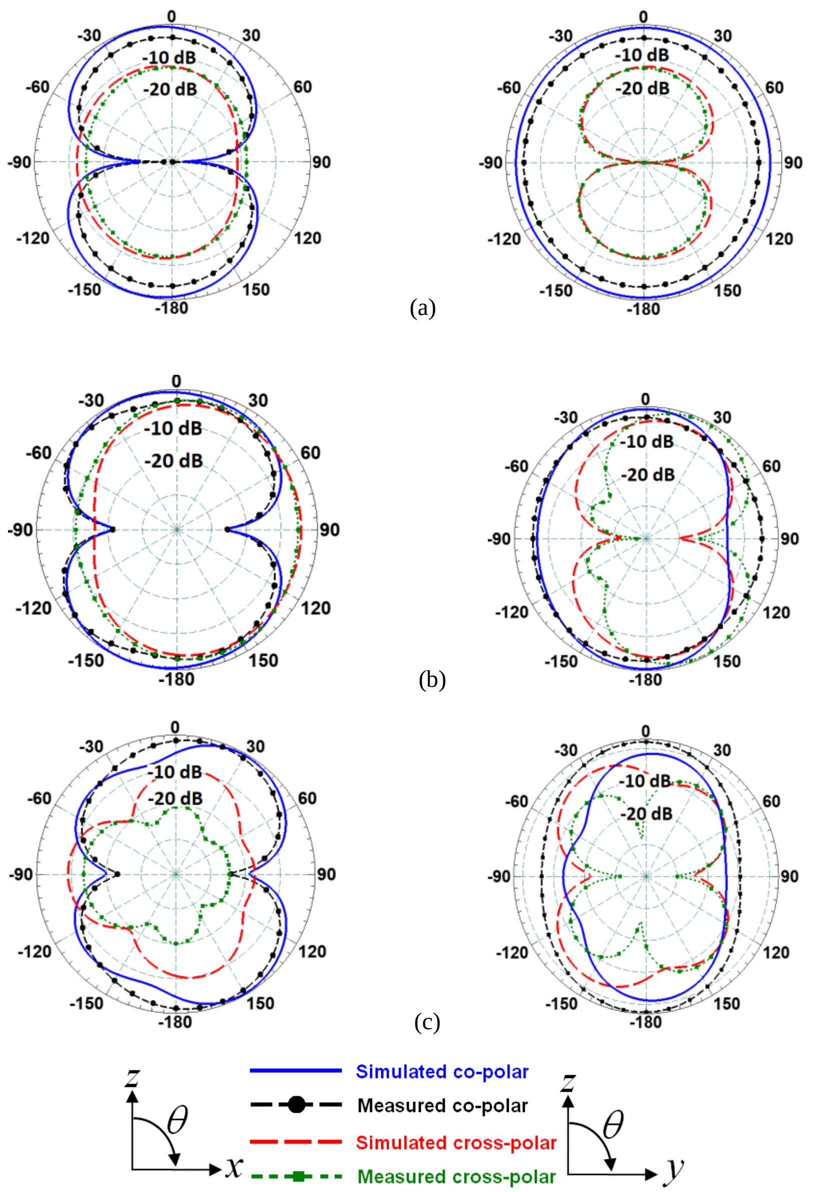

Fig. 7. Measured E(y-z)-plane and H(x-z)-plane radiation patterns of the proposed multi-band antenna at (a) 1.8 GHz, (b) 3.9 GHz , and (c) 5.1 GHz (left: H-plane, right: E-plane).

The increase in cross-polarization level is due to the excitation of hybrid current distribution on the antenna radiator at high frequencies. However, it is acceptable in three bands. Fig. 8 plots the numerical and experimental gain curves of the proposed antenna versus frequency. The measured gain at 1.8, 4, and 5 GHz is 1.2, 2.5, and 4.5 dBi, respectively. Good agreement between simulated and measured values is observed. The simulated and calculated (from measured data) efficiency diagrams of the antenna are presented in Fig. 9. The fabricated antenna features 90%, 85%, and 86% radiation efficiency at 1.8, 4, and 5 GHz, respectively. By considering lossy FR4 substrate with loss tangent of 0.02 and thickness of 1.6 mm, the antenna radiation efficiency is reasonable within the all bands of operation.

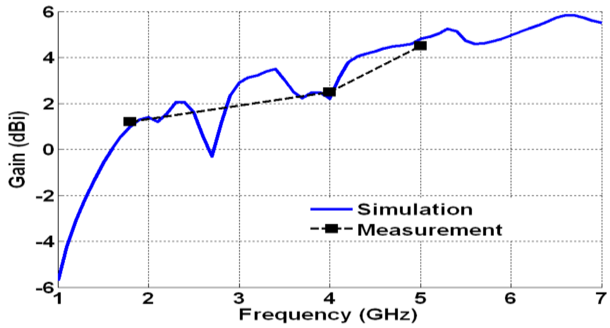

Fig. 8. Simulated and measured peak gain curves of the proposed antenna versus frequency.

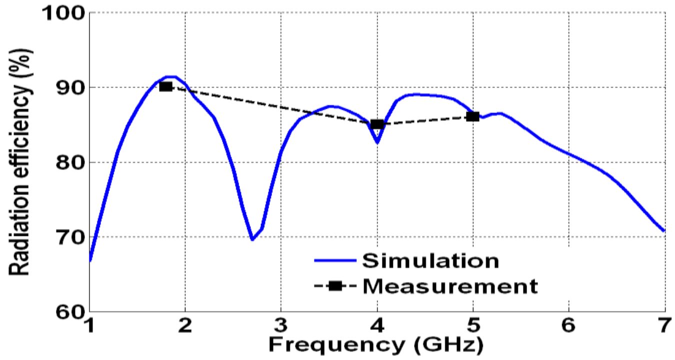

Fig. 9. Radiation efficiency curves of the proposed antenna versus frequency.

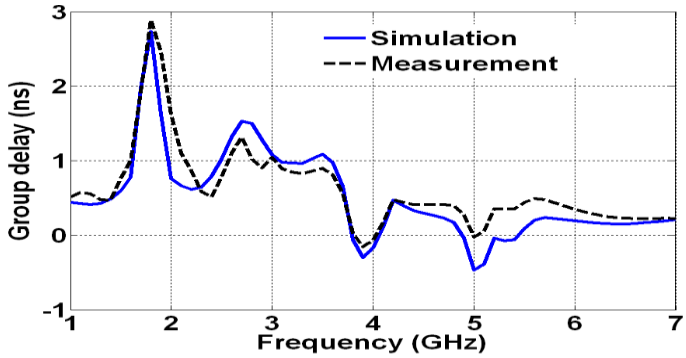

Fig. 10. Group delay versus frequency of proposed antenna for face to face configuration.

Along with frequency-domain analysis, time-domain performance should also be analyzed to guaranty that the unwanted distortion is minimized. In this work, to analyze the time-domain characteristic of the antenna, group delay parameter is investigated. This time-domain characteristic determines the signal distortion which an antenna adds to its input signal. Notice that the signal distortion reduces signal-to-noise ratio and increases bit error rate in communication systems. In order to provide desirable time-domain behavior in a typical UWB system, constant group delay is required over the entire working band [39], [40]. Fig. 10 presents the experimental and numerical group delay curves of the antenna for face-to-face configuration. To investigate the group delay, the distance between the receiving and transmitting antennas was selected as 100 cm. As shown in Fig. 10, the total variation of the measured group delay is limited to less than 3 ns over the whole working bands. The results indicate that the fabricated multi-band antenna has an acceptable time domain characteristic [41], [42]. Although not shown, similar results for side-by-side case were obtained.

IV. CONCLUSION

A multi-band stepped-slot antenna, fed by modified CPW transmission line has been proposed. The antenna effectively covers the operating bandwidths of the implicational and modern wireless communication systems included, DCS, PCS, 4G, WLAN and WiMAX. In order to operate at 1.71-1.88 GHz and 1.85-1.99 GHz for DCS and PCS systems, modified dual-part 50Ω CPW feed line with different widths is designed. Furthermore, by etching quasi-fractal and stair-shaped slots on the radiating patch and adding optimized adjusting strips to the radiator, working bands of WiMAX (3.30–3.80 GHz), 4G (3.40-4.20 GHz), and WLAN (5.15-5.35 GHz) systems, are also provided. The antenna size is $75.2 \times 38.54 \times 1.6$ mm^3 and it is etched on FR4 substrate. The antenna development stages are presented and discussed in detail. Moreover investigation of important design parameters is performed. The designed multi-band antenna has respectable results such high gain at the centre of each operating band and considerable efficiency of 90%, 85% and 86% in 1.85, 4 and 5 GHz, respectively. Also omni-directional patterns and acceptable group delay are obtained. Measurement data are presented to validate the numerical outcomes. Reasonable agreement between simulated and measured results is observed. This outstanding antenna is a proper choice to be used in multi-band systems.

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