Design of a Novel Split-Bowtie Slotted Multi-Resonant Antenna

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***Abstract*—This article demonstrates a novel design of a split-bowtie slotted multi-resonant antenna. The design process was inspired from previous research of integrating a slot of a similar profile to the outer boundary of a rectangular patch antenna. The followed approach presents steps of proposed antenna evolution, which starts with a bowtie-shape slotted antenna and a coaxial feed to a final design with a split-bowtie-shaped slot, and a double transmission line feed. Polar dimensions of the outer boundary (radii and angle) and slot profiles together with the dimensions of the feed, whether coaxial or transmission line, were considered as parameters for optimization. Four antennas were accordingly studied, which led to the final split-bowtie-shaped antenna IV. These designs were performed utilizing a special simulation package called "CST Microwave Suite" that included the optimizer "Genetic Algorithm". The final design offers 4 simultaneous bands from a single split-bowtie-shaped slot; a big advantage of unnecessary integration of a set of complicated slots on front and ground planes. Further, the antenna finds applications in mobile GSM and LTE bands 900/1800 MHz and 2.1 GHz, together with the satellite communications band 1.25 GHz. It is therefore simple, non-reconfigurable, easy to fabricate, designed on a single copper layer, with a low cost FR4 substrate and a plane copper ground.**

***Index Terms*—Split-bowtie-shaped slot, multi-resonant, double-slotted, GSM 900/1800, LTE 2.1, GPS 1.25**

I. Introduction

Multi resonant antennas have received much interest from researchers and users of various wireless applications with benefits of size compactness and reduced cost. While microstrip antennas can be etched in different shapes and sizes, bowtie antennas can be designed to serve narrow and ultra-band frequency ranges. Bowtie antennas have been extensively applied in radar [1]–[3] and mobile base-stations [4]. Some researchers [5] studied its robust characteristics over the frequency range (3 GHz to 11 GHz). Others [6] studied the effect of changing the angle on the return loss and the radiation patterns. They concluded that "doubling the angle to 80° had no effect on return loss but on a narrower half power beam-width (HPBW) in the radiation pattern." Rounding [7] the side edges of the bowtie antenna, on the other hand, "improved the return loss, the input impedance and the stability of radiation patterns."

On a different front, "changing the position of certain slit configurations on various parts of the antenna arms" was studied [8] and was found to "produce resonances at around 3 GHz, 5 GHz and 7 GHz frequencies." Inserting "circular and polygon shaped slots on the bowtie arms" were introduced [9] in a new antenna with "multi-resonant bands" that could be utilized for many wireless applications. By "etching slots of different lengths in a bowtie patch," the authors in [10] were able to introduce "bent monopoles that produced various operating frequencies." As the lengths of the introduced multiple bent monopoles met the quarter wavelength resonance condition, they successfully produced a slotted bowtie antenna with three bands; "300 MHz within the 2GHz to 3 GHz range, 300 MHz within the 3 GHz to 4 GHz range, and 600 MHz within the 5 GHz to 6 GHz range."

More recently, the authors in [11] proposed a novel triple-band dipole antenna, where slots were etched on the bowtie patch. Accordingly, "three bent dipoles with different lengths that corresponded to different operating frequencies were formed." The proposed antenna produced three bandwidths; "270 MHz in the 2.3 GHz to 2.7 GHz range, 910 MHz in the 3.1GHz to 4.1 GHz range and 1.25 GHz in the 4.5 GHz to 6.00 GHz range, with a satisfactory reflection coefficient of less than -10 dB." The authors in [12] presented a multiband reconfigurable bowtie slot antenna using switchable pairs of slots. The proposed approach is based on "the integration of two pairs of slots on the two sides of the antenna to create new bands." The properties of the bowtie antenna have been used to design a "reconfigurable frequency antenna with a high realized gain, operating in the WiFi, WiMAX, and WLAN with four operating modes, one in single band, two in dual band and one in triple band."

Kavith [13] investigated the design and performance of "Sierpinski Fractal Bowtie antenna to obtain multiband behavior." The evaluation of "Sierpinski fractal antenna was made up to two iterations." The overall dimension of Sierpinski fractal antenna was 110x70 mm^2.The final design was able to operate at frequencies "1.4 GHz, 3.5 GHz, 4.6 GHz and 7.4 GHz with gains of 6.4 dB, 9.2 dB, 6.7 dB and 9.1 dB respectively." Kumar *et al*. [14] investigated a "bowtie antenna on FR4 substrate (40 mm × 58 mm × 1.5 mm) with a modified symmetric split ring resonator (SRR) that was implemented beneath the substrate, as meta-material loading, which consisted of two circles and three circles." Each circle was broken into four quarter circles by four rods. The effect of "the modified symmetric SRR locations and consequent geometry" was analyzed. In both configurations, 4 bands

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between 3.3 GHz and 7.1 GHz were produced. With the two proposed circles, a fifth band at 1.6 GHz was claimed with a return loss just below the -10 dB margin.

Idris *et al*. [15] investigated a multiband and wideband frequency reconfigurable. A "strapline, in the middle of a slotted bowtie antenna was achieved for wideband configuration, whereas two additional slotted arms were integrated for multiband configuration." As a result, the antenna operated, through switches, at multiband mode (1.7 GHz and 2.6 GHz) and wideband mode (3.5 GHz to 9.0 GHz) simultaneously. Ghaffar *et al*. [16] presented a "frequency reconfigurable triangular (half bowtie) antenna with compact size to cover sub 6 GHz." Two slots were included in the design to get multiband response while "two pin diodes were added to get dual-band and tri-band mode." By "changing the states of pin diode, resonance in the sub 6 GHz band (2.5 GHz, 3.5 GHz, and 3.7-4.2 GHz) was achieved." When both diodes were on, it resonated at "2.18-2.36 GHz, 2.68-3.32GHz, and 3.75 GHz to 4.50 GHz." When both diodes were off, the resonance frequency was "2.25 GHz to 2.58 GHz, and 3.5 GHz to 4.46 GHz."

Dhanaraj *et al.* [17] proposed a Bowtie antenna that was integrated with a "metamaterial reflector array." "Electrically coupled split-ring resonator (ECSRR) unit cells were accordingly designed and analyzed of different geometrical shapes with negative permeability and negative permittivity." The 5 to 6 periodical ECSRR unit cell embedded with modified Bowtie antenna were fabricated on FR4 epoxy substrate (1.6 mm). The "metamaterial embedded bowtie antenna" achieved a maximum gain of 11.08 dBi and a 50% broadband resonance at 5.5 GHz. Two more narrow bands at 4.2 GHz and 6.6 GHz were achieved. Roy *et al.* [18] proposed an antenna that consisted of a "self-complementary vacant cross dipole on a circular patch" where the "front and back side dipole, together made a bow-tie configuration." There were "two equilateral triangle shapes with an internal circle inside the vacant dipole", one in front side and the other on the back side. A coaxial feed was constructed in the back side. The antenna was printed on 1.6 mm thick FR4 substrate with a relative permittivity of 4.4 and the total square shaped region measured 154 mm × 160 mm. The antenna resonated at "0.89 GHz, 1.83 GHz, 2.18 GHz and 2.45 GHz."

Ramalakshmi *et al*. [19] presented a new approach to design a "miniaturized, multiband bowtie fractal antenna by employing a rectangular slotted Sierpinski fractal geometry corresponding to many wireless communication applications." The antenna was evaluated for 2 iterations and the final proposed antenna gave a "frequency coverage of (0.1 GHz to 0.2 GHz), (3.4 GHz to 3.45 GHz), (5.6 GHz to 5.85 GHz), (8.4 GHz to 9.0 GHz), (10.67 GHz to 11.1 GHz), (11.2 GHz to 12.00 GHz) bands for L, S, C, and X band applications with appropriate return loss and VSWR values." The gain was calculated as "0.529 dB at 0.2 GHz and 5.074 dB at 3.5 GHz". Dayo *et al*. [20] investigated a "new compact high gain and multiband bowtie slot antenna with miniaturized triangular shaped metallic ground plane." The antenna was realized on the low-cost FR4 epoxy thick substrate. High gain of "6.3 dBi, 5.72 dBi, 3.64 dBi, 2.89 dBi and 2.58 dBi are achieved at 17.5 GHz, 15.5 GHz, 2.86 GHz, 6.72 GHz and 10.66 GHz resonances." The antenna was proposed as a favorable candidate for the advanced heterogeneous wireless communication applications.

Other structures than bowtie antennas were reported that utilized metamaterial technology to excite multiband frequencies. These consist of "Split Ring Resonators" (SRRs) [21] to produce "negative permeability which help to improve performance parameters such as bandwidth and miniaturization of microwave antennas." Selvi *et al*. [22] reported a "CPW-fed SRR metamaterial-inspired antenna" for multiband operation. The five circular rings contributed to resonance at "2.20 GHz, 2.88 GHz, 3.54 GHz, 4.27 GHz, 5.51 GHz and 6.55 GHz" respectively. Al-Tumah *et al*. [23] proposed a "novel double annular-ring microstrip antenna", split into six sectors to achieve multiband operation with high gain and impedance bandwidth. The gaps on the "driven and parasitic patches" excited resonant frequencies that were located in the "Ku-, K-, and Ka-bands, centered at 13.10 GHz, 20.72 GHz, 25.00 GHz, and 28.85 GHz," respectively, thus making the antenna capable of these multiband applications. Christydass *et al*. [24] proposed a structure that achieved multiband operation by "engraving 2 Complementary Split Ring Resonators (CSRRs) and a C-Shaped slot". In addition, "2 Split Ring Resonators (SRRs) were printed on the adjacent sides of the radiating element." The proposed structure operated at "2.25 GHz, 3.86 GHz, 4.60 GHz, 5.64 GHz, 5.86 GHz, 6.94 GHz, 7.48 GHz, and 9.47 GHz."

In the present work, a baseline bowtie antenna, with no slots, and three more antennas, with a "bowtie-shaped" slot and a "split-bowtie-shaped slot etched on the bowtie patch", are designed and analyzed. Three of the designs are tested with a coaxial transmission line, fed into one of the arms. The final antenna is fed with a transmission line network that, in turn feeds the two arms. The remainder of the paper is organized as follows: Section two reviews design equations and considerations of bowtie antennas. Section three describes the antenna designs and their optimization. Section four presents the results of return loss and radiation patterns. Section five is a conclusion.

II. Bowtie Antenna Design Considerations

The conventional way to design a microstrip bowtie antenna, as shown schematically in Fig. 1, is to identify its geometrical parameters using an approximate mathematical equation [25]. Equation (1) shows that the resonant frequency, f_r depends on W, W_c, L and S, as shown in Fig. 1, which determine the dimensions and shape of the antenna.

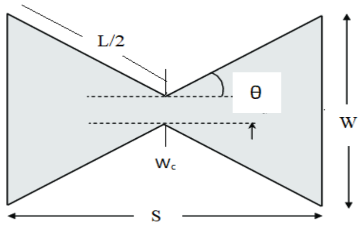


Fig. 1. Schematic diagram showing the layout of a microstrip bowtie antenna.

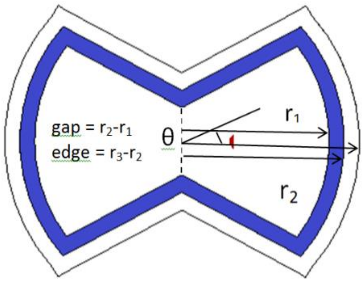


Fig. 2. Schematic diagram of a "slotted bowtie antenna".

$$f_r = 1.152 \frac{c}{L^2 \sqrt{\varepsilon_{\text{eff}}}} \left(\frac{(W + 2\Delta L) + (S + 2\Delta L)}{(W + 2\Delta L) + (W_c + 2\Delta L)} \right) \quad (1)$$

The parameters ΔL and ε_{eff} in (1) are defined as

$$\Delta L = \frac{0.412h(\varepsilon_{\text{eff}} + 0.3)}{(\varepsilon_{\text{eff}} - 0.258)} \left(\frac{\frac{W + W_c}{2h} + 0.262}{\frac{W + W_c}{2h} + 0.813} \right) \quad (2)$$

$$\varepsilon_{\text{eff}} = \left(\frac{\varepsilon_r + 1}{2} \right) + \left(\frac{\varepsilon_r - 1}{2} \right) \left(\frac{24h}{W + W_c} + 1 \right)^{-1/2} \quad (3)$$

The rounded bowtie antenna, shown in Fig. 2, is closely related to the conventional triangular one that is presented in Fig. 1. The effect of rounding the edges relatively flattens the impedance frequency response with respect to a regular bowtie antenna. Reflections from rounded edges occur simultaneously with a consequence of a more stable performance. The thought of "incorporating slots, similar in shape to the bowtie antenna, for producing multiband resonance was inspired by a previous work on a double U-slot rectangular patch antenna [26]." In that work, the authors had a prior knowledge of what the final antenna design would look like. The aims set for the present research, were to investigate several slot and feed designs, and study the effect of each design variation on multi-resonant frequency performance. A bowtie antenna with no slots was proposed as a baseline; its performance will be compared with the rest of the antenna designs. In this section, the conventional equations generally characterize an approximate design of a basic bowtie antenna with straight edges and no slots. Appropriate curving of the edges of the antenna arms, and modification of the slot design, were allowed by simulation and optimization, using the "CST Studio Suite" [27] software. The designs were built on the experience developed in the computation and modeling of the slots in [26], as well as the optimization applied by the CST software simulation.

Fig. 2 shows a schematic diagram of a "slotted bowtie antenna." A "bowtie-shaped" slot design is introduced with an aim to produce "multiple resonant frequencies." To enable this, the side edges of the patch and the slot were allowed to be curved. All the slotted antennas studied in this paper had four optimization parameters, namely r_1, r_2, r_3 and the angle θ.

Initially, the feed was a single coaxial one, placed on the antenna horizontal axis and on one arm of the antenna. The final double-slotted antenna was designed with a transmission feed line as in [6], but with a thin gap introduced in the middle which is inset into the patch, reaching opposite to the slot mouths. This allows simultaneous excitation of the two arms of the antenna. The dimensions of the double feed line were optimized to match a 50 ohm feed. A "1.6 mm FR4 dielectric of ε_r = 4.4" layer, measuring 100 mm × 100 mm was chosen for the design.

The resonant frequencies are described as in [28]:

$$f_r = \frac{ck_{mn}}{2\pi\sqrt{\varepsilon_r}} = \frac{2c\sqrt{m^2 + mn + n^2}}{3a\sqrt{\varepsilon_r}} \quad (4)$$

where "f_r is the resonant frequency, k_{mn} is the missing mode, m and n are the number of modes, c is the velocity of light in free space, and $a = L/2$ is the side length of the bowtie antenna".

Equation (4) assumes that the antenna is enclosed by a "prefect magnetic wall." A number of modifications were suggested in [28] for the more realistic case where the antenna was not enclosed by such a "perfect magnetic wall." An expression for a_{eff} has been arrived for the resonant frequency of the dominant TM_{10} mode. This is shown in (5) to (7):

$$f_{10} = \frac{2c}{3a\sqrt{\varepsilon_r}} \quad (5)$$

The side length is accordingly expressed as

$$a = \frac{2c}{3f_r\sqrt{\varepsilon_r}} \quad (6)$$

The effective value of the side length is expressed as

$$a_{\text{eff}} = a + \frac{h}{\sqrt{\varepsilon_r}} \quad (7)$$

The effective dielectric constant is expressed as

$$\varepsilon_{\text{eff}} = \left(\frac{\varepsilon_r + 1}{2} \right) + \left(\frac{\varepsilon_r - 1}{4\sqrt{1 + (12h/a)}} \right) \quad (8)$$

Hence the antenna wavelength is calculated as

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{\text{eff}}}} \quad (9)$$

III. Antenna Designs and Optimization

This section describes the progressive approach used in the design of the bowtie antennas studied. Multiband bowtie antennas were investigated with and without "bowtie-shaped" slots on both arms of the antenna. Several designs, as shown in Fig. 3 to Fig. 6, were studied before reaching the final design. An FR4 substrate (ε_r= 4.4) of 110 mm × 50 mm × 1.6 mm was initially considered for the designs. Antenna I, shown in Fig. 3, was a baseline bowtie antenna, without slots and with a coaxial feed, located on the antenna's horizontal axis.

Antenna II, shown in Fig. 4, was a slotted version of the baseline antenna. Antenna III, shown in Fig. 5, was modified to have a “split-bowtie-shaped” slot. Antenna IV, shown in Fig. 6, was designed with a “split-bowtie-shaped” slot and a double transmission line feed.

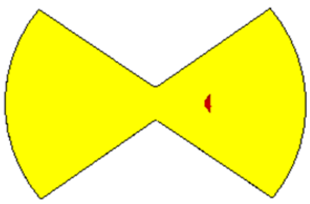


Fig. 3. Antenna I with an off-center coaxial feed.

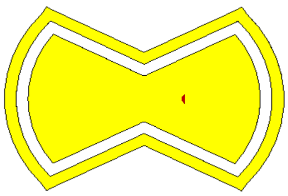


Fig. 4. Antenna II with an additional “bowtie-shaped” slot.

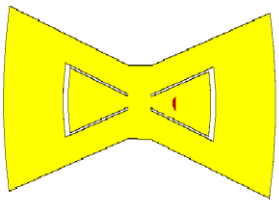


Fig. 5. Antenna III with a “split-bowtie-shaped” slot.

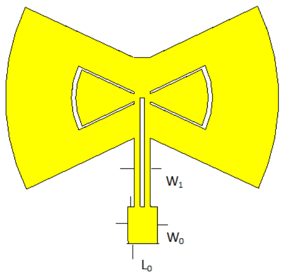


Fig. 6. Antenna IV with a “split- bowtie-shaped” slot and “double-line feed”.

For the optimization of the antenna designs, “CST Studio Suite” [27] provides “automatic optimization routines for antennas and electromagnetic systems. It contains several optimization algorithms.” A well-known optimizer is “Genetic Algorithm” which finds an optimal solution by utilizing an evolutionary approach. “It generates genes in a population and then refines them through multiple generations with random gene mutation.” By selecting “the fittest sets of parameters at each generation, the algorithm converges to a global optimum.” All antennas were optimized, using the “Genetic Algorithm” available on the “CST software tool”. The optimization parameters shown in Fig. 2 were varied within reasonable ranges and for multiple optimization runs to achieve the required four resonance bands. The antenna designs I and II (shown in Fig. 3 and Fig. 4, respectively) did not produce more than two resonance bands each, as will be shown in the results section. The optimized parameters r_1, r_2, r_3 and θ for Antenna III (shown in Fig. 5) resulted in three resonance bands.

Possible design approaches for obtaining the four resonance bands were either to change the feed to a double transmission line feed, to affect simultaneous excitation of the two antenna arms, or to build another split-bowtie-shaped slot inside the original slot, re-optimize all associated dimensions and test for a fourth resonant band. It was decided to follow the first approach, as it looked less complicated and more promising. The extra parameters required for the transmission-line feed were the sizes of the lower transmission line, W_0 and L_0, and the width of the upper transmission line, W_1. The width of the splitting gap, in the middle of the transmission line feed, was kept constant at 1 mm. The input impedance at all feeding ports was optimized to 50 Ω.

The parameters (r_1, r_2, r_3 and θ), shown in Fig. 2, (D_1, D_2, X_0 and Y_0) of the coaxial feed, and (W_0, L_0 and L_1) of the transmission line feed were subjected to the optimization process. Tables I and II show the design range for each parameter and the obtained optimized value. The optimization was simultaneously conducted on all parameters in each antenna. In regard to the antenna coaxial feed, only X_0 of the feed coordinates (X_0, Y_0) on the bowtie right arm of Fig. 5 was optimized, while Y_0 was kept constant at zero value. The split gap width of the transmission feed in Fig. 6, on the other hand, was kept constant at 1mm. The goals were set at producing four resonance frequency bands, centered at “900 MHz, 1800 MHz, 1.25 GHz and 2.1 GHz, with a return loss that is clearly lower than −10 dB.”

TABLE I: DESIGN AND OPTIMIZED PARAMETERS OF ANTENNA III (X_0, Y_0 ARE THE FEED COORDINATES, D_1, D_2 ARE THE INNER AND OUTER DIMENSIONS OF THE COAXIAL FEED, RESPECTIVELY)

Parameter	Design value (mm)	Min (mm)	Max (mm)	Optimized (mm)
r_1	20	18	22	20.22
r_2	21	18	24	23.14
r_3	55	54	58	57.53
θ	15°	10°	20°	13.95°
d_1	1	0.5	1.5	0.95
d_2	5	4	6	5.82
x_0	0	0	20	16.03
y_0	0	0	0	0

TABLE II: DESIGN AND OPTIMIZED PARAMETERS OF ANTENNA IV (W_O, L_O AND W_1 ARE THE LOWER AND UPPER PARAMETERS OF THE TRANSMISSION LINE FEED DIMENSIONS)

Parameter	Design value (mm)	Min (mm)	Max (mm)	Optimized (mm)
r_1	20	18	23	22.53
r_2	25	23	27	25.64
r_3	50	48	53	52.91
θ	25°	20°	30°	25.28°
W_o	10	8	12	9.98
L_o	10	8	13	12.68
w_1	2	1	3	2.71

IV. RESULTS

This section contains results obtained for the return loss and radiation patterns of antenna designs I-IV when using the optimized parameters obtained from the CST Studio software.

A. Return Loss

Fig. 7 to Fig. 10 show the return loss versus frequency for optimized Antenna I to Antenna IV, respectively.

Antenna I produced two resonances at "700 MHz and 2.1 GHz," as shown in Fig. 7. Fig. 8 shows the effect of introducing a "bowtie-shaped" slot, in Antenna II, by down-shifting the higher frequency to 1.8 GHz. Several attempts were made to produce more than two resonant frequencies utilizing the 4 optimization parameters; r_1, r_2, r_3 and θ, as demonstrated in Fig. 2. Fig. 9 shows the effect of introducing a "split-bowtie-shaped" slot on producing three resonance frequencies. The third resonance frequency emerged, "at 1.4 GHz with a -8 dB return loss level, while the higher frequency shifted up from 1.8 GHz to 2.1 GHz." A transmission line feed, whose width and length were optimized, except for the fixed middle-gap, was introduced in Antenna IV to divide the signal power between the "split-bowtie-shaped" slot, as shown in Fig. 6. Fig. 10 resulted in four resonance frequencies; "1 GHz, 1.25 GHz, 1.8 GHz and 2.1 GHz, which were below the -10 dB return loss level".

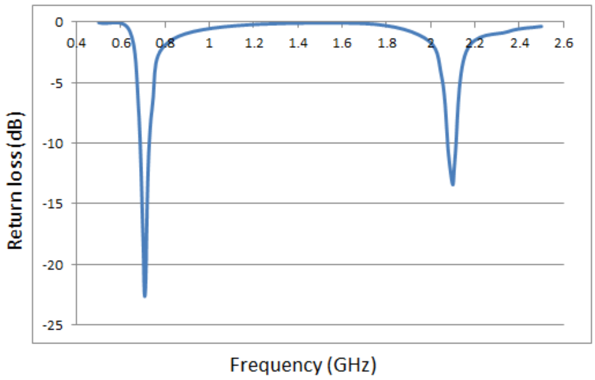


Fig. 7. Return loss versus frequency of antenna I.

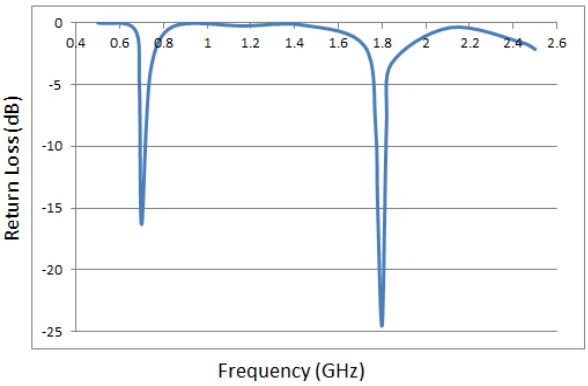


Fig. 8. Return loss versus frequency of antenna II.

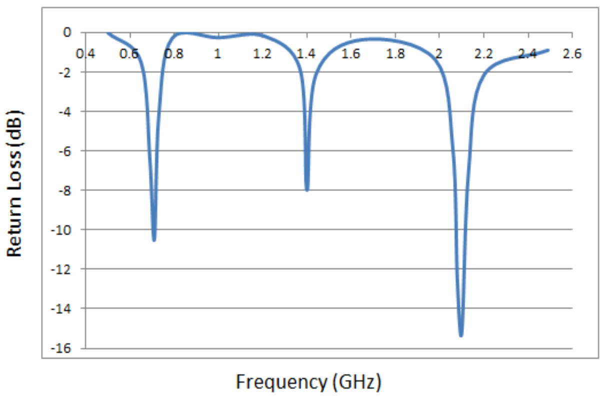


Fig. 9. Return loss versus frequency of antenna III.

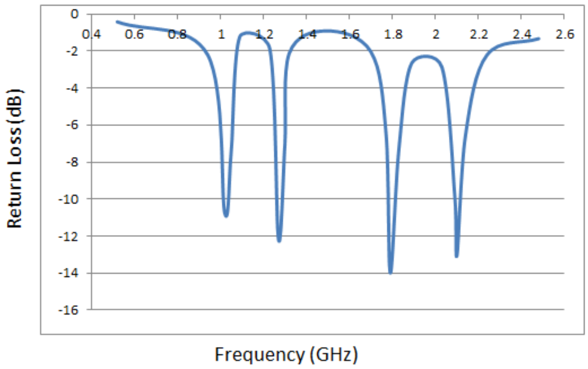


Fig. 10. Return loss versus frequency of antenna IV.

B. Radiation Patterns

Fig. 11 to Fig. 14 show the E-plane and H-plane radiation pattern of the four optimized Antenna I to Antenna IV, at their dominant resonant frequency bands.

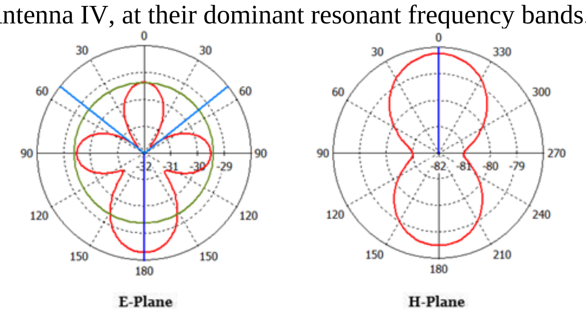


Fig. 11. Radiation pattern of antenna I at 700 MHz frequency.

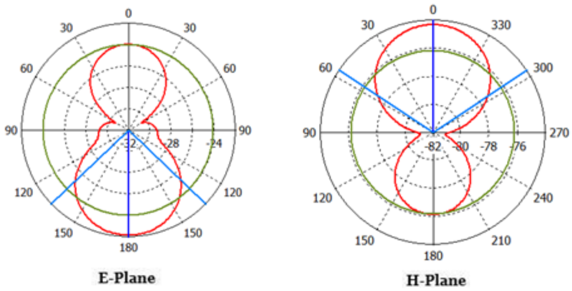


Fig. 12. Radiation pattern of antenna II at 1.8 GHz frequency.

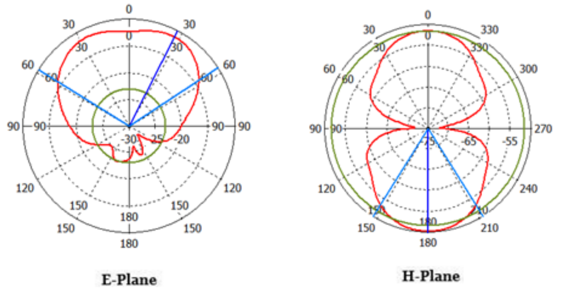


Fig. 13. Radiation pattern of antenna III at 2.1 GHz frequency.

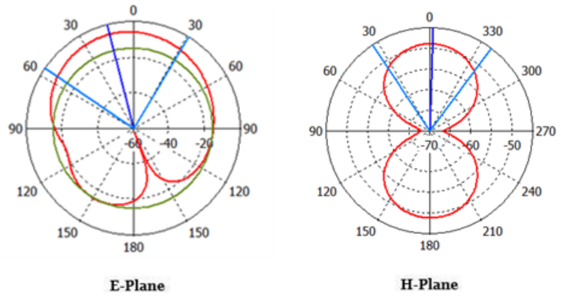
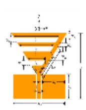
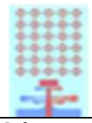
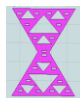


Fig. 14. Radiation pattern of antenna IV at 1.8 GHz frequency.

In general, for a patch in the *xy* plane, where the *E* vector points in the *y* direction of the *xyz* Cartesian coordinate system, then as angle φ is varied while angle θ is kept constant at 0^0, the *E*-plane (i.e. the *yz*-plane) radiation pattern can be produced. On the other hand, as θ is varied while φ is kept constant at 0^0, the H-plane (i.e. *xz*-plane) radiation pattern can be produced. The *E*-plane and *H*-plane radiation patterns for Antenna I to Antenna IV were obtained at the center resonance frequencies; 700 MHz, 1.8 GHz, 2.1 GHz and 1.8 GHz, respectively.

Fig. 11 and Fig. 12 show fairly similar radiation pattern trends, at 700 MHz and 1.8 GHz frequencies. Most notably, Fig. 13 and Fig. 14 had fairly similar radiation patterns at 2.1 GHz and 1.8 GHz frequencies, respectively. However, the radiation pattern of Antenna IV in Fig. 14, appeared to be more directional with a BW= 90° in the E-plane pattern, compared to antenna III with a BW= 120°. The H-plane patterns in Fig. 13 and Fig. 14 had comparatively a similar directivity with a BW= 60°.

TABLE III: COMPARATIVE ANALYSIS OF VARIOUS MULTIBAND SLOTTED BOWTIE ANTENNAS

Y. Tawk *et al.* [9]	M.T. Wu *et al.* [10]	C.Y. Shuai *et al.* [11]	P. Dhanaraj *et al.* [17]	S. Roy *et al.* [18]	G.Ramalak. *et al.* [19]	O.W.Ata *et al.*
Tri-band bowtie antenna with polygon and circular slots	Tri-band trapezia slotted bowtie monopole antenna	Tri-band bent dipole-slotted bowtie antenna	Meta-material embedded bowtie antenna with electrically coupled split ring resonator	Bowtie cross dipole with diagonally equilateral triangle with circles inside	Hex-band 2-itertion rectangular slotted Sierpinski Fractal Bowtie antenna	Quad-band bowtie-shaped slotted antenna
						
Substrate: RO3006 (*h*=1.27mm) ε_r= 6.15	Substrate: FR4 (*h*=0.8mm) ε_r= 4.2	Substrate: FR4 (*h*=0.8mm) ε_r= 4.2	Substrate: FR4 (*h*=1.6 mm) ε_r= 4.4	Substrate: FR4 (*h*=1.6 mm) ε_r= 4.4	Substrate: FR4 (*h*=1.6 mm) ε_r= 4.4	Substrate: FR4 (*h*=1.6 mm) ε_r= 4.4
Dimensions: 50×50mm (etched on both copper layers)	Dimensions: 100×60mm (etched on single copper layer)	Dimensions: 82.5×70mm (etched on both copper layers)	Dimensions: 44×65 mm (etched on both copper layers)	Dimensions: 154×160 mm (etched on both copper layers)	Dimensions: 50×50mm (etched on single copper layer)	Dimensions: 110×50mm (etched on single copper layer)
Feed: CPW 50 Ω TX feed	Feed: CPW TX line feed	Feed: 50 Ω line & wide band microtrip to coplanar stripline (CPS) transition as a balun	Feed: Coaxial feed	Feed: Coaxial feed	Feed: Coaxial probe feed	Feed: Double-line 50 Ω TX feed with a 1 mm gap in the middle
Resonance bands: 2.4 GHz, 3.5 GHz, 5.3 GHz	Resonance bands: 2.5 GHz, 3.5 GHz, 5.5 GHz	Resonance bands: 2.5 GHz, 3.5 GHz, 5.0 GHz	Resonance bands: 4.2 GHz 5.5 GHz (50%) 6.6 GHz	Resonance bands: 0.89 GHz, 1.83 GHz, 2.18 GHz 2.45 GHz	Resonance bands: 0.2 GHz, 3.5 GHz, 6.3 GHz, 8.6 GHz, 10.9 GHz, 11.7 GHz,	Resonance bands: 900 MHz / 1800 MHz 1.25 GHz, 2.1 GHz
Max Gain : Low band 1.8 dB Mid band 1.5 dB High band 4.5 dB	Max Gain: Low band: 3.93 dB Mid band: 3.56 dB High band: 3 75 dB	Max Gain: Low band 2.4 dB Mid band: 3.5 dB High band: 4.2 dB	Max gain: 11.08 dB at 5.5 GHz	Max gain: 3.9 dB @0.89 GHz 4.4 dB @ 1.83, 2.18 GHz 4.8 dB @ 2.45 GHz	Max Gain: 0.529 dB 5.074 dB 4.518 dB 5.335 dB 9.18 dB 21.17 dB	Max Gain: GSM: 3.5 dB / 4.4 dB GPS: 3.9 dB LTE: 5.1 dB
Application: Wi-F, WiMAX LTE	Application: WLAN, WiMAX	Application: WLAN, WiMAX, LTE	Application: 5G Communication networks	Application: GSM 900/1800 3G, Wi_Fi	Application: L, S, C, and X bands	Application: GSM 900/1800, LTE, GPS

V. COMPARATIVE ANALYSIS

Table III compares seven different multiband slotted bowtie antennas. Our antenna offers a simple, low cost, low profile design, on a single copper layer and merits over the rest that it has 4 bands, instead of 3 bands, with a relatively high gain at relatively lower bands; GSM 1800 and LTE 2.1. In addition, the combination of GSM, LTE and GPS bands in a single antenna makes it a versatile one for mobile and satellite radio applications. It has relatively most compact patch dimensions, after the fractal and meta-material embedded antennas, considering the low frequencies of its quad bands.

VI. CONCLUSION

A novel split-bowtie slotted multi-resonant antenna was designed and tested. The design is simple, low-cost and low-profile. Towards the final design, four antennas with different bowtie slot patterns and feeds were accordingly designed and developed. Antenna IV with a "split- bowtie-shaped" slot and double-line feed had the best performance, resulting in four resonant frequencies at 0.9 GHz, 1.25 GHz, 1.8 GHz, and 2.1 GHz. As far as radiation patterns, antenna IV had relatively the highest directivity with a half power bandwidth of 90° in the E-plane and 60° in the H-plane. It merits over the compared bowtie antennas in the published literature, as the simplest self-profile slotted quad band antenna design. With a single split-bowtie-shaped slot, having a similar profile to the antenna outer boundary that is simple, non-reconfigurable, easy to fabricate and does not involve further designs or deformations on the ground plane, while suitable to GSM 900/1800, LTE 2.1 and GPS 1.25 band applications, the novel antenna has a potential for extra bands if a second or more split-bowtie-shaped slots are carefully added and optimized inside the original slot.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

O.W. Ata conducted the research, analyzed the data and wrote the paper. M.I. Jawadeh executed the simulation of the antennas on CST Microwave Suite. Both authors had reviewed and approved the final version.

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