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Electro-Geometrical Analysis of Transversal V-Fold Patch Antenna

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ABSTRACT- This paper investigates an original concept of electro-geometrical analysis of flexible microstrip antenna. The research work is focused on the analysis of the innovative effect of "V"- shape folding on the resonance frequency and input impedance of microstrip patch antenna. The V-folded antenna is assumed to behave as an arm constituted by horizontal and tilted members which are geometrically characterized by the folding angle, *a*. The folding is characterized by the angle between the horizontal plane and the folded part of the patch antenna printed on a Kapton flexible substrate. The initially flat-configured planar antenna was designed to operate at about 2.45 GHz. The innovative design method of the V-shape folded flexible antenna is explained. Full wave electromagnetic simulations of different geometrical states of the flexible antenna were performed in the frequency range from 1 GHz to 5 GHz. Exceptional results of tilted surface radiating part of flexible patch antenna were found with a positive folding angle from $a_{min}=0°$ to $a_{max}=45°$. It was understood for the first time in the area of antenna engineering that the resonance frequency is fluctuating according to typical sine damping in the function of the V-folding angle variation. The folded angle effect, which has never been understood before is discussed. In addition to the angle effect, the input resistance and input reactance of the V-folded flexible patch antenna is also plotted.

Keywords: V-folding; flexible antenna; microstrip patch antenna; design method; resonance frequency; input impedance.

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1. INTRODUCTION

THE twenty-first-century normal life is hard to imagine without electronic technology. In difference to the last century, we assist the big trend of mobile electronic integration everywhere which should operate every time today. Wireless electronic products able to operate more ubiquitously in many areas as smart textiles, smart carts and smart wearable devices such as a smartwatch, and so on … were developed. To satisfy such needs, the manufacturing industries introduced mobile electronics based on embedded IoT technology [1]. Such technology is designed with innovative wireless microwave circuits expected for different applications such as IoT and ISM bands [2].

Behind the spectacular technological progress, wireless communication engineers are facing more and more different challenges. For example, the adequate design of electronic mobile devices must be developed according to the geometrical shape and geometrical deformation of their support object. The flexible electronic printed circuit boards (PCBs) [3-4] can be the unique solution to overcome such technical bottlenecks. The flexible PCBs are expected to be the solution suitable for IoT communication objects with arbitrary geometrical shapes. One of the key electronic functions of the communication system behind is the antenna. For this reason, nowadays, the antenna system implemented in flexible electronic technology [5-6] becomes more and more an attractive research topic for antenna designers. This paper has analyzed a state of art flexible antenna design.

To guarantee wireless communication quality, high-performance antennas are necessary for the modern system [7-

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8]. But the most practical and most integrable topologies of antenna which are successfully approved for several applications as satellite and defense remains the microstrip patch structure [10-12]. However, deeper investigations on design, simulation and test methods as proposed in [13-23] are still needed in the function of different configurations of patch antenna applications. The microstrip antenna theory constitutes the basic step of the design step [13-14]. In addition, a good understanding is needed for the enhancement of patch antenna performance as the bandwidth [1cross-polarizationtion [16] and efficiency [17]. For example, different design aspects of patch antenna feeding were studied [18-21]. Feeding methods of patch antennas with microstrip lines [18-19] and probes [20] were proposed. For the case of contact difficulties, alternative feeding methods with series-parallel and coupled slots [21] were also introduced. Some recent research works [22] on the patch antenna were focused on the design methods itself to win on the compactness and bandwidth for example by playing on innovative optimization methods. The design of an arbitrary shaped microstrip patch antenna was also proposed [23]. But in the present study, our main focus is much more on the design of patch antenna with the typical geometrically deformable shape. As stated previously, the standard l solution for antenna integration on geometrical deformable devices is to use flexible and non-rigid microstrip antennas [24-25]. Actually, the metallic radiation part of patch antennas [10-25] is traditionally based on flexible metallic material. The novelty of recent ones is the use of flexible substrates [25]. So far, few research works [24-34] are available in the literature on the study of flexible microstrip antenna. A Compact perylene-coated flexible antenna for WLAN and upper-band UWB applications is introduced in [26]. Compared to what was done on the flat-configured ones. Many promising applications were expected for flexible antennas such as UHF RFID [27], UHF textiles [28-29], and even for telemedicine communication terminals [30]. Some design, simulation, and testing of flexible microstrip antennas are proposed in [31-33]. But many studies are still needed for the prediction of the characteristics of flexible microstrip antennas. Recently, a dual-band dual-polarized CPW-fed monopole antenna was designed [34] and paper bending [39] resembles the process we worked. The design of the CPW flexible antenna [34] is performed with the possibility to operate with discrete frequency reconfigurability. Many scholars working on the improvement of directivity, gain, and bandwidth [41-42] as basic parameters of a patch antenna, even with different shapes [43] despite the progressive different studies on the flexible antenna, so far, no research work is available in the literature about the V-folding effect on the planar antenna.

For this reason, we would like to propose a research activity on this question by starting pedagogically with the most elementary aspect. The present paper developed a numerically full-wave electro-geometrical analysis of the V-folding effect on the patch antenna resonance frequency and input impedance, the paper proposal is organized into three sections as follows:

Section 2 focused on the design methodology. A novel method of elementary folding of the microstrip patch antenna is described. The concept of folding in a "V" geometrical shape is studied by controlling the angle of a tilted arm of the patch compared to the horizontal one.

Section 3 is the discussion on the original electro-geometrical analysis of computed results on the antenna resonance frequency and also the input impedance in the function of the tilted-horizontal arms of the folded antenna. A proof-of-concept (POC) of a microstrip patch antenna printed on a flexible Kapton substrate will be described. And *section 4* ends the paper with a conclusion.

2. DESIGN OF V-FOLDING PATCH ANTENNA

The present section explains how the patch antenna is geometrically designed to reproduce the V-shape bending. The choice of the antenna design parameters in function of the desired operating frequency is justified. The parameters of the electro-geometrical analysis are defined.

2.1 Design Description

This introductive subsection is focused on the design aspect. For a basic understanding of the V-folding effect, we propose the POC constituted by one of the most popular antenna topologies. The POC design will be described in the following paragraph.

2.1.1 Microstrip Patch Antenna Design

Figure 1 recalls the profile view of the microstrip line structure. This microstrip structure is essentially composed of a dielectric substrate assumed with relative permittivity, ε_r, and having a thickness, *h*.

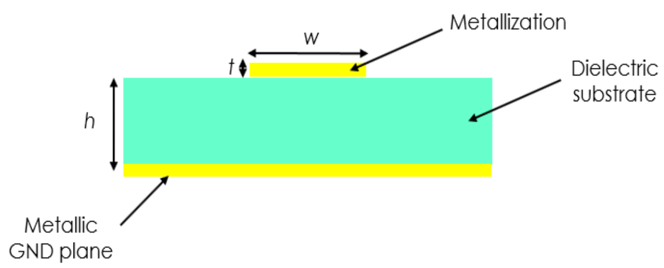

Figure 1: Face view of the microstrip line

In the present case of study, we can denote the effective permittivity as ε_{reff}. The top and bottom sides are striped with conductive metallization. The top strip line is defined geometrically with width, *w*, and thickness, *t*. We use the Hammerstad-Jensen microstrip line theory [35-36] to model electrically the structure.

Figure 2 depicts the top view of the patch antenna which is designed in the 3-D environment of the CST MWS®. The overall structure is defined with overall width and length, D_x, and D_y, respectively. The metallic surface of the radiating part of the patch antenna is defined as width and length, d_x, and d_y, respectively. The antenna is fed by a coaxial structure and connected to a transition microstrip line.

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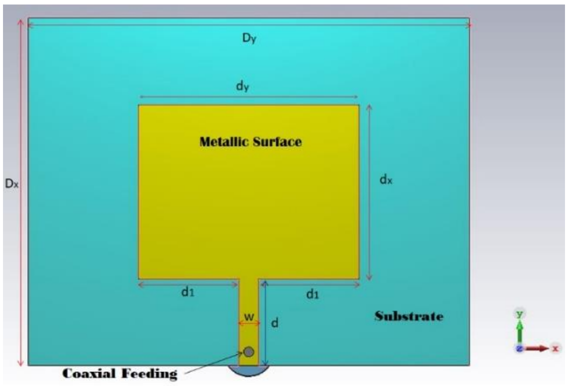

Figure 2: Top View of Patch Antenna Design with CST MWS®

2.1.2 Analytical Approach and Numerical Computation

To perform the numerical analysis, full-wave simulation will be performed in the following section. The frequency domain simulation is provided by the S-parameters. Acting as a one-port circuit, we can consider the main parameter, S_{11}. We remind that for the case of a patch antenna implemented in a classical flat configuration, based on the microstrip patch antenna theory, the resonance frequency versus the geometrical parameters is ideally given by:

$$f_r = \frac{c\sqrt{2}}{d_x\sqrt{1+\varepsilon_{reff}}} \quad (1)$$

By definition, the input impedance is expressed as:

$$Z_{in}(j\omega) = R_{in}(\omega) + jX_{in}(\omega) \quad (2)$$

With input resistance and input reactance, $R_{in}(\omega)$ and$X_{in}(\omega)$ by denoting the angular frequency variable, ω. The antenna input impedance can be determined from the reflection parameter, S_{11}, via the following S-to-Z transform equation:

$$Z_{in}(j\omega) = \frac{R_0[1+S_{11}(j\omega)]}{1-S_{11}(j\omega)} \quad (3)$$

With R_0 is the reference impedance which is equal to 50 Ω.

2.2 Geometrical Description of V-folded Flexible Microstrip Patch Antenna

The originality and the difficulty of the study is the consideration of the antenna deformation. To do this, we would like to point out the difference between the classical research works [10-23] on rigid planar antenna shown in *figure 3(a)*. The main challenge of the present study is to consider the uncommon cases of the flexible patch antenna. In other words, the substrate is assumed to be flexible with a degree of freedom of folding. The geometry of the considered V-folding of the flexible patch microstrip antenna is illustrated in *figure 3(b)*.

The present V-folded design is specified geometrically with the transversal axis parallel to the GND plane. We choose this axis along the transition between the feeding microstrip line [18-19] and the radiation surface plane of the patch.

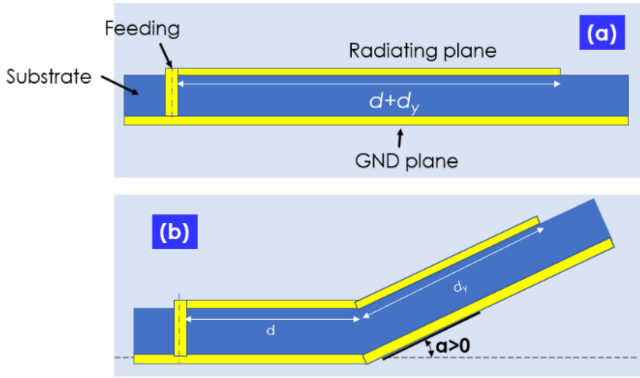

Figure 3: Profile view of (a) flat and (b) V-folded geometry of flexible patch antenna introduced in figure 2

2.3 Methodology of the Electro-Geometrical Performance Analysis

Figure 4 indicates the methodology of the electro-geometrical analysis of a V-folded flexible patch antenna. It must begin with the expected antenna specifications. Then, the flexible substrate characteristics as the relative permittivity, the loss tangent, the metallization parameters, and the geometrical sizes should be defined.

The microstrip circuit design physical parameters can be calculated based on the TL theory [35-36]. One particularly important effort which is done in the first time in the present study is the V-shape design of the folded patch antenna. We use in this study the 3-D EM commercial tool, CST MWS®, [37] to perform this design. Then, based on the MATLAB [37] post-processing, the analyses and interpretation of the results constitute the final steps of the study.

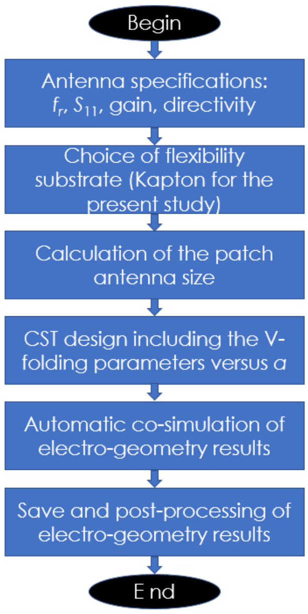

Figure 4: Workflow illustrating the methodology of the V-folded effect electro-geometrical analysis

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To show the practical application of his novel concept a case study of V fold antenna is discussed in forgoing section.

3. POC DESIGN OF V-FOLDED MICROSTRIP ANTENNA

The present section is focused on the applicative study of the POC design of a V-folded flexible microstrip patch antenna.

3.1 Expected Antenna Specifications

The study is based on the flexible microstrip patch antenna design and simulation with 3-D EM full wave computation with CST MWS® commercial tool [37]. The CST® design of the V-folded flexible microstrip patch antenna will be described. Then, the computed results will be discussed in order to state the electro-geometrical analysis conclusion.

The investigation of the flexible antenna design method by taking into account the geometrical constraint is developed in the present section. As the objective of the study, we are proposing to design a flat microstrip patch antenna with radiation frequency equal to f_r=2.25 GHz and standardly input matched with S_{11}=-10 dB. Once the specifications are chosen, the different sizes as the physical widths and lengths of each metallic conductor element are determined from the synthesis equations of microstrip patch antenna corresponding to flat antenna theory [13]. The design was made following the methodology explained earlier in *figure 4*.

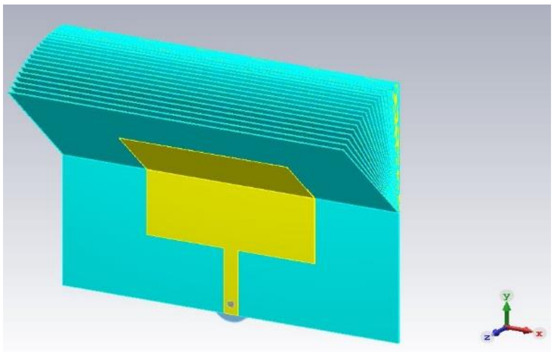
3.2 Description of the Different Steps of the Introduced V-Folded Patch Antenna

Figure 5(a) depicts the 3-D design perspective view of the folded antenna with different values of angle, *a*. It is constituted by a flat arm (assumed to be fixed) from the excitation port and the folded arm tilted compared to the horizontal planed. The profile views of *figure 5(b)* highlight the different geometrical positions of the tilted arm. In this configuration, the folded part is along the half-vertical plane of the patch antenna length. This 3-D structure of the microstrip patch antenna was designed in the CST MWS® environment.

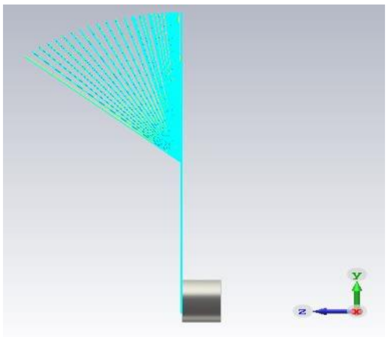
The geometrical design of the structure was challengingly based on the combination of:

- The flat part is the combination of box elements of dielectric and metallic materials. This part of the flexible microstrip patch antenna contains the excitation wave port represented by a coaxial connector with internal and external diameters, d_i= 4mm and d_e= 0.8 mm. The metallic part of the coaxial connector with a vertical revolutionary axis is in copper and the insulating material is in the air feeding the input transition microstrip line with a 1 W maximal power source.

- The folded part is a combination of the same box material properties, but the tilted position is controlled with angle, *a*. The interconnection between the tilted and flat parts is designed based on any material which supports Folding.



(a)



(b)

Figure 5: CST MWS® design of flexible patch antenna POC: (a) perspective and (b) profile views

3.3 Design Parameters and Choice of the Materials

The preliminary thing necessary to design a folded element is the availability of a flexible substrate. The choice of substrate susceptible to operate in the expected radiation frequency band is particularly important. In the present study, we choose the Kapton substrate because readily available and most usable with less cost. This substrate is constituted by dielectric and flexible material [31-33] with presents the main characteristics, relative permittivity, and the loss tangent shown in *table 1*. The conductor metallization is in Copper (Cu) which is characterized by its conductivity.

Table 1: Physical and Geometrical Parameters of the Designed Flexible Patch Antenna

Components	Description	Parameter	Value
Substrate	Material	Kapton	-
	Relative permittivity	ε_r	3.5
	Loss tangent	tan(δ)	0.003
	Thickness	h	0.13 mm
Metallization conductor	Material	Copper (Cu)	-
	Thickness	t	0.017 mm
	Conductivity	σ	58 MS/m
Patch	Length	D_x	56.5 mm
	Width	D_y	69.6 mm
	Length	d_x	28.25 mm
	Width	d_y	34.8 mm
	Width	d_l	15.9 mm
	Length	d	14.125 mm
	Width	w	3 mm

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The bottom part of *table 1* is addressed the geometrical sizes of the antenna after the simulation of the structure with these design parameters, we get the results discussed in the next section.

4. COMPUTED RESULTS OF V-FOLDED MICROSTRIP PATCH ANTENNA

In the present section, the computed results of the folded patch antenna are introduced. As indicated in our design methodology of workflow shown in *figure 4*, the last part of the folded antenna investigation is the EM full wave computation and the data result post-processing. Then, the numerical computed data were analyzed with MATLAB® programming.

4.1 Assignments of Simulation Parameters

The numerical simulation parameter specifications of the proposed innovative electro-geometrical analysis of flexible antenna must be performed in the following steps:

STEP 1: The overall geometrical parameters including the range of the angle change must be defined. In the present study, we choose the minimum value to be equal to a_{min}=0°, and the maximum value is set to a_{max}=45°. The main challenge of this design is the choice of the intermediate value of this angle. We have chosen some increasing set values as {0°, 1°, …, 45°}. It is very important to underline that with CST MWS® the minimal value of the angle after 0 is 1°. So, we do not have the possibility to assign angle *a* with an absolute value lower than 1°.

STEP 2: Basic Folding processes can be done in many ways by choosing the combined antenna structure and choosing any shape (cylindrical, cone, rectangle, *etc*) to bend/fold by opting for Bend Layer Stack up in the bending process options.

STEP 3: This step consists in choosing the type of simulation. We have considered the S-parameter simulations which run for each value of *a* defined previously. It means that the simulations of the flexible antenna shown in *figure 5* were performed in an S-parameter regime.

STEP 4: This step consists in choosing the solver. The 3-D EM computations were carried out in full wave by using the FIT solver. The simulation parameters were chosen based on the transient option with the transient solver of CST MWS®. For the present study, the minimal and maximal frequencies are f_{min}=1 GHz and f_{max}=5 GHz under 1001 sampling frequencies, respectively.

4.2 Computed S-Parameter Electro-Geometric Cartography

Following the previously described design and simulation steps, we obtained particularly interesting results from our folded antenna illustrating very new findings about the electro-geometrical behavior. The performed S-parameter simulations of the V-folded patch antenna were simulated based on the parameters of *table 2*.

Table 2: Simulation Parameters

Designation	Parameter	Value
Frequency	f_{min}	1 GHz
	f_{max}	5 GHz
	Δf	1 MHz
Angle	a_{min}	0°
	a_{max}	45°
Solver	Time Domain Solver of CST MWS®	Accuracy (-40 dB)
Computation time duration	-	6 minutes

We obtain the electro-geometrical cartography of the reflection parameter displayed in *figure 6*. This electro-geometrical mapping is based on the couple of variable frequency-angle (*f*,*a*). A very interesting phenomenon of the reflection parameter behavior is observed in different frequency zones. To analyze this result, we considered the frequency positioning of the minimal value of the reflection parameter, S_{11}. To generate the present results, we can emphasize that the EM full wave computations were performed during six minutes for the electro-geometrical parameters set in the previous table.

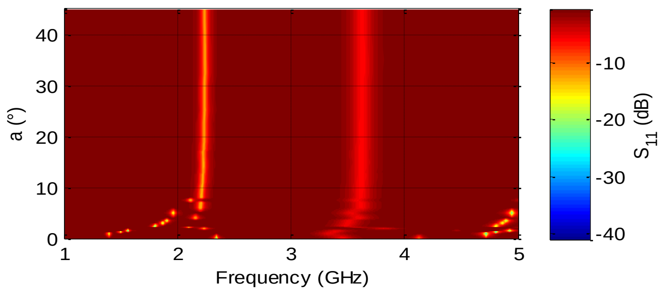

Figure 6: Electro-geometric cartography of S11 from V-folded antenna POC shown in Figure 5

From this 2-D mapping, the resonance frequency versus angle will be investigated in the following section.

5. ANALYSIS OF ANTENNA RESONANCE FREQUENCY VERSUS FOLDING ANGLE

To analyze the electro-geometrical aspect, we proposed an innovative approach based on the resonance frequency. The following subsections will describe the obtained results.

5.1 Basic Approach Resonance Frequency Analysis

The antenna parameter variation is referenced with the change of resonance frequency, f_r. To identify this frequency, MATLAB® calculations were performed by sweeping the value of *a* from a_{min} to a_{max} and then we solve the following equation:

$$\begin{cases} \omega_r = 2\pi f_r \\ |S_{11}(j\omega_r)| = min|S_{11}(j\omega)| \end{cases} \quad (4)$$

The two local minimums of S_{11} are localized for each value corresponding to the frequency band of the antenna radiation.

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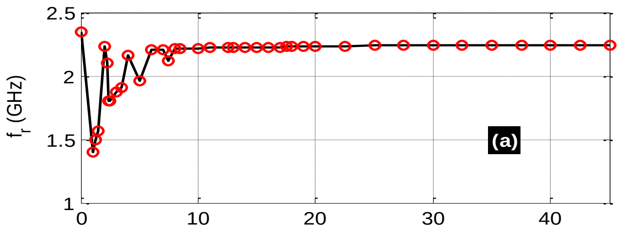
The two-frequency bands should correspond to two different radiation modes of the antenna as TE_{mn} and TM_{mn} with m and n being positive integers. The electro-geometrical analysis of the results can be interpreted based on the physical width and physical lengths of the patch antennas. Doing this, the resonance frequencies of these modes should respect the equation:

$$f_r(m,n) = \frac{c}{2}\sqrt{\left(\frac{m}{d_x}\right)^2 + \left(\frac{n}{d_y}\right)^2} \quad (5)$$

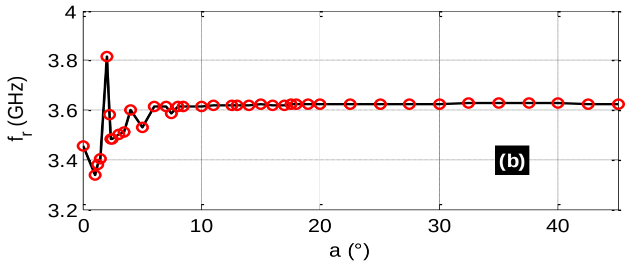
After calculations, we obtain the two radiation and resonance frequencies which will be interpreted in the following paragraph.

5.2 Resonance Frequencies in the Function of Folding Angle

Figure 7(a) and *figure 7(b)* plot the variation of the V-folded antenna proposed in *figure 4*. A very singular phenomenon of resonance frequency variation is observed here. It can be seen that significant fluctuation of the two resonance frequencies is observed when a is lower than 10°. In the first frequency band, the amplitude of the variation is more than 1.3 GHz. However, the second frequency band the variation is lowed than 0.3 GHz.



(a)



(b)

Figure 7: Results of (a) 1st and (b) 2nd resonance frequencies folding angle

Table 3 summarizes the asymptotic resonance frequencies. These are standard modes without any excitation.

Table 3: Resonance frequencies in the identified two-bands

Parameters	1st band	2nd band
Modes	TE (m=1, n=0)	TM (m=1, n=1)
f_m	f_1=2.24 GHz	f_2=3.62 GHz

The analysis of the input impedance associated with the resonance frequency versus electro-geometrical will be described in the following subsection.

5.3 Input Resistance and Reactance versus Folding Angle

Figure 8 depict the electro-geometrical cartographies of the input resistance, reactance, and impedance of the folded antenna versus the couple (f, a). *Figure 9* and *figure 10* presents the corresponding input resistance and reactance deduced from the cartographies at the identified resonance frequencies given previously in *figure 7*. The resonance frequency keeps on moving for every slight beginning [40]. From these components, we have the total input impedance defined in *equation (2)* presents the magnitude plotted in *figure 11*. Once again, *figure 10(a)* shows that the reactance trends converge to -24 Ω when the angle is higher than 15°. Moreover, we can see in *figure 11(a)* and *figure 11(b)* that the input impedance magnitude is varying between 43 Ω and 58 Ω. And for the 2nd band, the input impedance is changing between 33 Ω and 39 Ω, respectively.

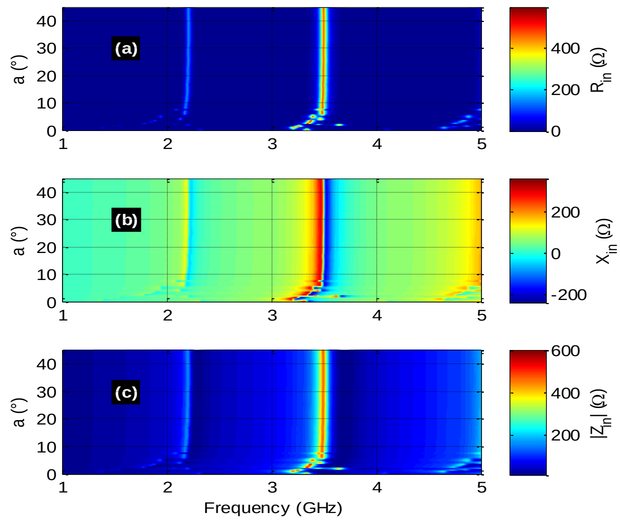


Figure 8: Electro-geometric cartography of input (a) resistance, (b) reactance and (c) impedance of the V-folded flexible antenna

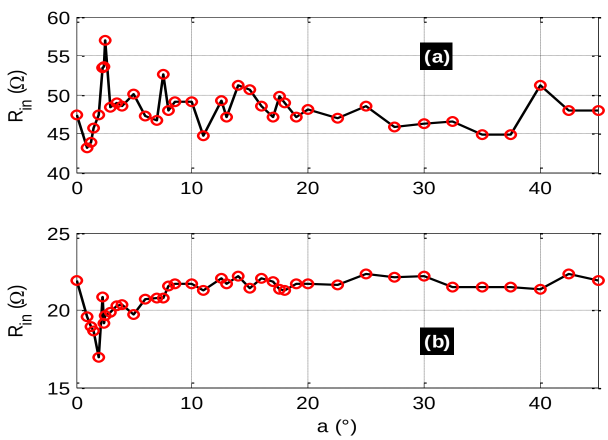


Figure 9: Input resistance in (a) 1st and (b) 2nd band versus angle.

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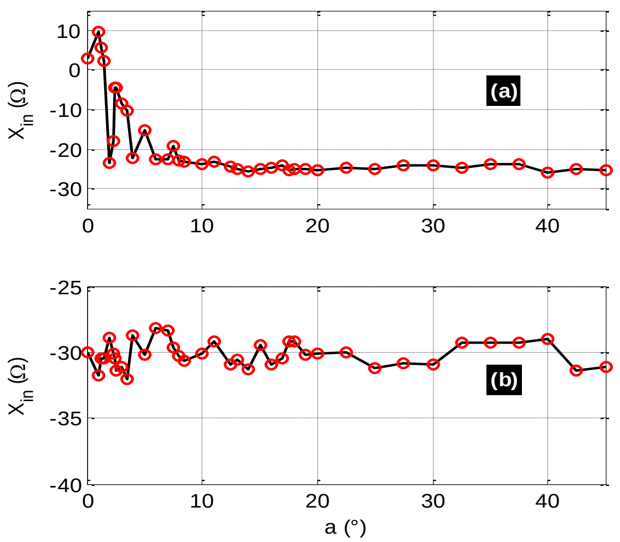

Figure 10: Input reactance in (a) 1st and (b) 2nd band versus angle

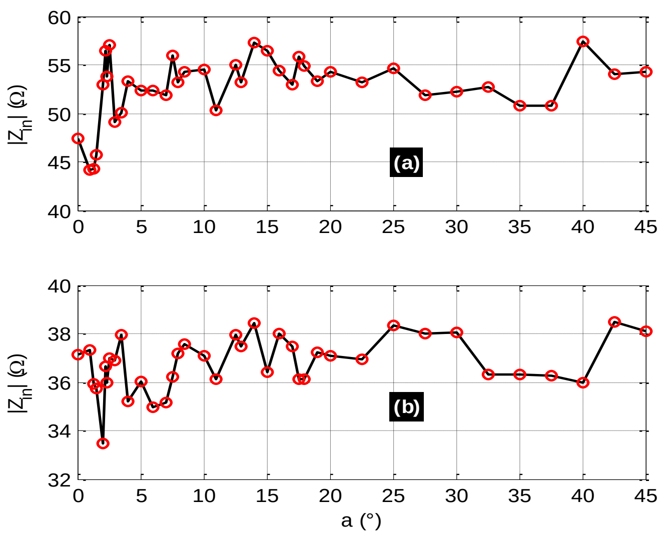

Figure 11: Input impedance in (a) 1st and (b) 2nd band versus angle

5.4 Interpretation from the Electro-Geometrical Analysis

Table 4 and *table 5* summarize the values of radiating and resonance frequencies, input impedance, and also the reflection coefficients in the 1st and 2nd frequency bands of the modes discussed previously. We can see in the last column of *table 4* that the flexible antenna is still matched better than -10 dB in the 1st band event the folding angle is increasing up to 45°.

Table 4: Resonance frequency, input impedance, and reflection coefficient versus folding angle in the 1st band

a	f_r (GHz)	R_{in} (Ω)	X_{in} (Ω)	S_{11} (dB)
0.0	2.34	47.33	2.74	-28.11
1.0	1.40	43.13	9.58	-17.99
1.3	1.50	43.86	5.70	-21.00
1.5	1.56	45.73	2.18	-26.01
2.0	2.24	47.43	-23.56	-12.53
2.3	2.10	53.49	-17.95	-15.18
2.4	1.80	53.57	-4.38	-25.27
2.5	1.80	56.93	-4.36	-22.33
3.0	1.87	48.40	-8.40	-21.25
3.5	1.91	48.97	-10.19	-19.75
4.0	2.16	48.48	-22.17	-13.14
5.0	1.96	50.13	-15.27	-16.43
6.0	2.20	47.21	-22.49	-12.87
7.0	2.21	46.74	-22.50	-12.81
7.5	2.12	52.54	-19.33	-14.57
8.0	2.21	47.97	-22.90	-12.82
8.5	2.21	49.06	-23.22	-12.83
10.0	2.22	49.03	-23.73	-12.65
11.0	2.22	44.66	-23.21	-12.24
13.0	2.23	47.08	-24.88	-12.04
14.0	2.23	51.25	-25.51	-12.23
20.0	2.24	48.06	-25.26	-12.03
30.0	2.24	46.25	-24.20	-12.15
45.0	2.24	47.92	-25.41	-11.97

However, as reported in *table 5*, this reflection coefficient is worst and always higher than -6 dB in the second band.

Table 5: Resonance frequency, input impedance, and reflection coefficient versus folding angle in the 2nd band

a	f_r (GHz)	R_{in} (Ω)	X_{in} (Ω)	S_{11} (dB)
0.0	3.46	21.93	-29.97	-5.56
1.0	3.34	19.61	-31.77	-4.81
1.3	3.38	18.92	-30.52	-4.76
1.5	3.40	18.67	-30.45	-4.71
2.0	3.82	16.93	-28.87	-4.40
2.3	3.58	20.84	-30.12	-5.28
2.4	3.48	19.14	-30.44	-4.82
2.5	3.48	19.62	-31.35	-4.85
3.0	3.50	19.85	-31.08	-4.94
3.5	3.51	20.29	-32.07	-4.95
4.0	3.60	20.39	-28.71	-5.31
5.0	3.53	19.70	-30.18	-4.99
6.0	3.62	20.69	-28.19	-5.44
7.0	3.62	20.80	-28.35	-5.46
7.5	3.58	20.76	-29.65	-5.31
8.0	3.62	21.56	-30.30	-5.44
8.5	3.62	21.71	-30.63	-5.44
10.0	3.62	21.67	-30.08	-5.49
11.0	3.62	21.25	-29.23	-5.47
13.0	3.62	21.67	-30.59	-5.43
14.0	3.62	22.21	-31.34	-5.48
20.0	3.62	21.67	-30.07	-5.49
30.0	3.62	22.17	-30.95	-5.51
45.0	3.62	21.92	-31.16	-5.43

6. CONCLUSION

An innovative study of the V-folding effect on the patch antenna resonance and matching is developed. After the recall of the classical flat antenna, the innovative design method of the V-folded microstrip patch antenna is proposed. The influence of the V-folding on the patch antenna resonance is illustrated with numerical computation based on a 3-D EM computation tool. An original aspect of the resonance frequency variation with 2.24 GHz and 3.24 GHz asymptotic values is observed in the function of the folding angle.

The observed behavior can also be explained by the influence on the TE and TM radiating modes of the antenna. Emphatically, the resonances were identified analytically based on the antenna EM cavity modeling. Therefore, the associated propagative modes were identified. The input impedance variation is also fluctuating around an asymptotic value.

In the continuation of the present work, the experimental investigation including radiation pattern, gain, directivity, and efficiency is in progress. In addition, the negative angle and more complex folding effects are being studied further.

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