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RESEARCH PAPER

A high-gain inkjet-printed UWB LPDA antenna on paper substrate

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An ultra-wideband (UWB) log-periodic dipole array (LPDA) antenna inkjet-printed on a 0.5 mm thick photo paper substrate is presented. The overall size of the LPDA antenna is 130 × 60 mm². The LPDA antenna exhibits stable input-impedance characteristics and a consistent end-fire radiation pattern over the whole operating band of 2.2–11 GHz. Fulfilling the need of high-gain flexible antennas for UWB, a highly directive measured gain of 9.5 dBi on a paper substrate makes it an excellent candidate for flexible wireless devices.

Keywords: UWB, Log-periodic dipole array, Paper substrate, Inkjet printing

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I. INTRODUCTION

Ultra-wideband (UWB) is a mainstream wireless communication standard with advantages of having lower power consumption and high data rate transmission within 3.1–10.6 GHz frequency spectrum. UWB antennas require both low signal-loss and stable radiation characteristics within their wide frequency bands. Recent UWB applications have focused on sensor data collection, point-to-point wireless communication as well as aerospace applications [1]. Such large-scale systems require the underlying sub-components to be extremely low cost. Therefore, recent research has focused on identifying alternative manufacturing methods such as inkjet printing as well as organic substrates such as paper and textiles. Organic substrates provide unique advantage of being cheaper, flexible, lighter, and environment friendly as compared with conventional substrates such as FR-4 and Rogers. Furthermore, the advances in nano-particle ink have brought its conductivities close to that of metals such as copper. The conductive ink coupled with the inkjet printing processes, means that the devices can be fabricated in lesser time and at a much lower cost. Moreover, complex and time-consuming fabrication processes involving chemicals, masking, and etching are eliminated.

First inkjet-printed antennas on paper substrate appeared in literature around 2009. These antennas were designed for different discrete sensors that were integrated with RFID [2, 3] and mostly operate at ultra-high frequency (UHF) bands with narrow bandwidths and low gains. More recently, there has been an increase in inkjet-printed antennas, but still very few have addressed UWB applications. For instance, an inkjet-printed UWB patch antenna with omnidirectional radiation pattern is presented in [4] with a peak gain of 5.5 dBi. Similarly, Cook and Shamim [5] present a UWB Vivaldi antenna with an average gain of about 5 dBi. The gain is quite low in the lower range of UWB frequencies.

This paper presents a fully characterized inkjet-printed high-gain UWB log-periodic dipole array (LPDA) antenna on the paper substrate with a gain of 9.5 dBi and a compact size of 130 × 60 mm². This LPDA design provides comparatively higher gain among the paper-based inkjet-printed UWB antennas published so far. In Table 1, a comparison of recent flexible and non-flexible wideband/UWB antennas with the proposed flexible LPDA design is given. The gain of paper-based antennas is more or comparable with FR4-based LPDA antennas with extra benefits of flexibility and cost reduction. The novelty is to demonstrate, designing and printing of flexible UWB antenna with sufficiently high gain on paper substrate.

II. ANTENNA DESIGN

The layout of the proposed LPDA antenna is shown in Fig. 1. A standard LPDA antenna consists of a series of dipole elements arranged along the antenna axis on the center feed-line. The length of the dipoles and their relative spacing dictate the resonance frequencies within the operating bandwidth of the LPDA. The proposed inkjet-printed LPDA antenna follows the same configuration as log-periodic wire antennas. Therefore, the standard design procedure for LPDAs proposed by Carrel [9] is adopted. The design goals for the LPDA are directivity and operating bandwidth, while the design parameters are the scaling factor τ and the spacing factor σ.

An average directivity of 10 dBi and a bandwidth of 2–11 GHz are targeted. By applying Carrel design curves, the calculated values of τ and σ are 0.865 and 0.17, respectively. The

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Table 1. Comparison between recently published flexible & non-flexible UWB antennas.

Ref. No.	Antenna	Average gain (dBi)	Substrate	Loss tangent	Band (GHz)
[5]	Vivaldi (95 × 80 mm²)	5	Commercial photo paper ($\varepsilon_r = 3$)	0.02	3.1–10.6
[6]	LPDA (130 × 100 mm²)	5.2	FR-4 ($\varepsilon_r = 4.5$)	0.02	1.1–13.8
[7]	LPDA (56.92 × 16.56 mm²)	7.4	Arlon AD250 ($\varepsilon_r = 2.5$)	0.0013	4–18
[8]	LPDA (117.15 × 38.9 mm²)	6.85	Arlon AD450 ($\varepsilon_r = 4.5$)	0.0035	3–6
(Our design)	LPDA (130 × 60 mm²)	9.5	Commercial photo paper ($\varepsilon_r = 3$)	0.02	3.1–10.6

Table 2. Optimized values of the design parameters.

Operating bandwidth (B)	Bandwidth of the active region (B_{AR})	Scaling factor (τ)	Spacing factor (σ)	Antenna aperture angle (α)	No. of dipole elements (N)
5.5	1.80	0.865	0.17	11.22	16

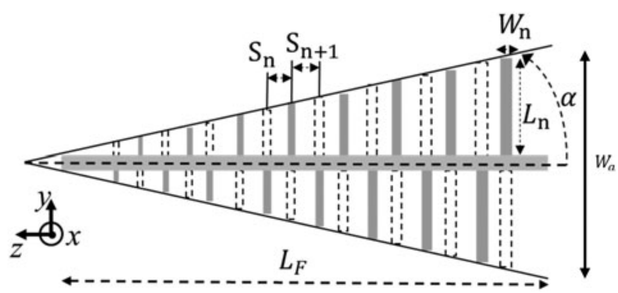

Fig. 1. Layout of the proposed paper-based LPDA antenna, $L_F = 130$, $W_a = 60$ mm.

number of elements of the proposed LPDA antenna is then calculated by,

$$N = 1 + \frac{\ln(B.\ B_{AR})}{\ln(1/\tau)}, \quad (1)$$

where "B" is the operating bandwidth and B_{AR} is the bandwidth of the active region. The value of B for the proposed design is

$$B = \frac{f_{max}}{f_{min}} = \frac{11}{2} = 5.5,$$

$$\alpha = \arctan\left(\frac{1-\tau}{4\sigma}\right) = \arctan\left(\frac{1-0.865}{4 \times 0.17}\right) = 11.22,$$

$$B_{AR} = 1.1 + 7.7.(1-\tau)^2.\cot\alpha = 1.80,$$

where "α" is the log-periodic antenna aperture angle (see Fig. 1). Using the above values in equation (1), the number of dipole elements is $N = 16.84$. Since the value of N must be an integer therefore 16 elements are utilized in the design. The optimized values of all the design parameters are summarized in Table 2.

The paper substrate used for inkjet-printing has relative permittivity $\varepsilon_r = 3$ and loss tangent tan $\delta = 0.02$. The optimized dipole length L_n and width W_n is 25 and 4.82 mm, respectively, and are determined for the lower frequency of 2 GHz through full-wave simulation in CST Microwave Studio. The lengths, widths and spacing for the other

Table 3. Dimensions of the 16 dipole elements of the LPDA antenna.

Dipole	L_n (mm)	W_n (mm)	S_n (mm)
1	25.0	4.82	
2	22.0	4.29	16.05
3	19.4	3.81	14.2
4	17.1	3.39	12.7
5	15.0	3.02	11.32
6	13.2	2.69	10.08
7	11.6	2.39	8.97
8	10.1	2.13	7.99
9	8.79	1.89	7.11
10	7.64	1.68	6.33
11	6.61	1.50	5.64
12	5.70	1.33	5.03
13	4.88	1.19	4.48
14	4.16	1.05	3.99
15	3.54	0.94	3.56
16	2.94	0.83	3.18

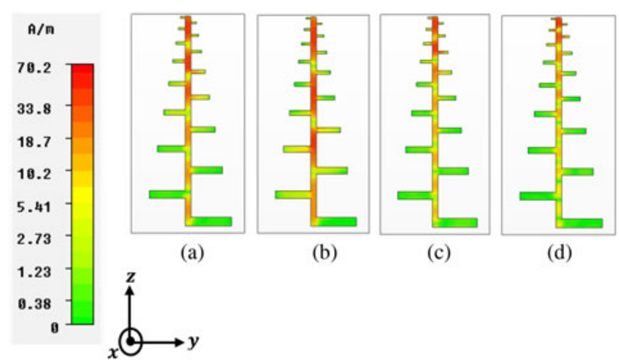

Fig. 2. Surface current density: (a) 3 GHz, (b) 5 GHz, (c) 7 GHz, (d) 10 GHz.

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dipoles are computed by:

$$\tau = \frac{L_{n+1}}{L_n} = \frac{W_{n+1}}{W_n} = \frac{S_{n+1}}{S_n}. \qquad (2)$$

Table 3 shows the dimensions of all the dipole elements. The spacings between the dipoles are computed using aperture angle α.

The current distribution gives an insight into the physical behavior of the antenna at various frequencies as shown in Fig. 2. It is seen that the current at 3 GHz is concentrated along the feed line. As the frequency is increased from 5 to 7 GHz, the current starts to concentrate in the smaller dipole elements thus making the antenna highly directional. At 10 GHz, majority of the surface currents are accumulated along the narrow end of the LPDA making it more directional at higher frequencies.

III. FABRICATION AND MEASURED RESULTS

The fabricated antenna is displayed in Fig. 3. This LPDA is inkjet-printed using a Diamatix DMP-2831 printer and UT Dots silver nano-particle ink [10–12]. The inkjet printing technology has become quite mature over the last 6–8 years providing better printing resolutions as well as repeatable structures [4, 5, 10–12]. In addition, the nano-particle inks offer suitable conductivities and viscosity for accurate jetting through the printer cartridges and nozzles. A typical antenna fabrication involves selection of the right droplet size, drop spacing, and number of layers. It is important to note that few calibration structures (straight lines, etc.) are printed before printing of the actual antenna. Once the calibration is achieved, repeatable printing is easily achieved. A final step after inkjet printing is called sintering which can be done through conventional heating or laser heating. This is done to evaporate the solvent mixed in the nano-particle ink hence improving the conductivity of the traces. The sintering process is also found to be repeatable offering same conductivity each time. In our design, we used commercial photo paper as a dielectric substrate. However, various other flexible polymers such as Kapton and polyethylene

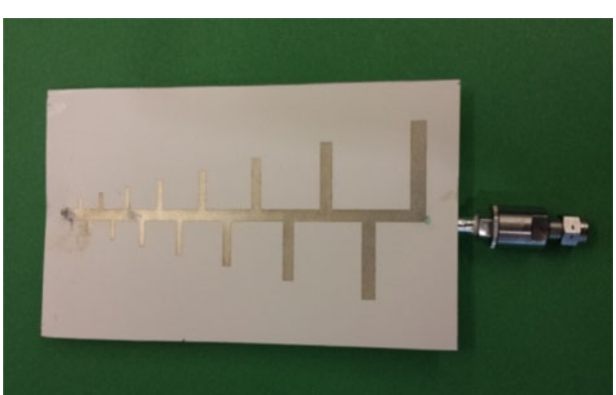

Fig. 3. Fabricated prototype (130 × 60 mm^2) of LPDA with infinite balun feed.

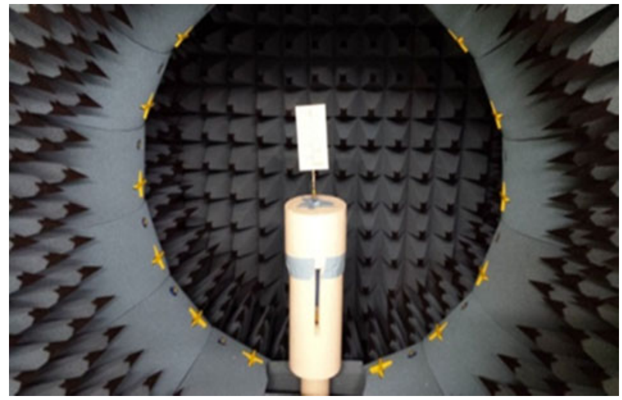

Fig. 4. Antenna measurement setup.

terephtalate (PET) have also been used to demonstrate flexible antennas, sensors, and electronics [4, 5, 10–12]. However, paper substrate is better than the others due to its lowest cost and porous nature. The latter property is critical because the nano-particle ink tends to flow on smooth plastic substrates and it is very challenging to obtain accurate dimensions of the required structures.

In order to obtain accurate on-paper dimensions for our design, an optimized drop diameter of 25 μm and a drop spacing of 30 μm are chosen. Each side of the LPDA is printed on a separate 0.25 mm-thick photo paper and then glued together to achieve a total substrate thickness of 0.5 mm. The printed antenna is heat-sintered at 80 °C for

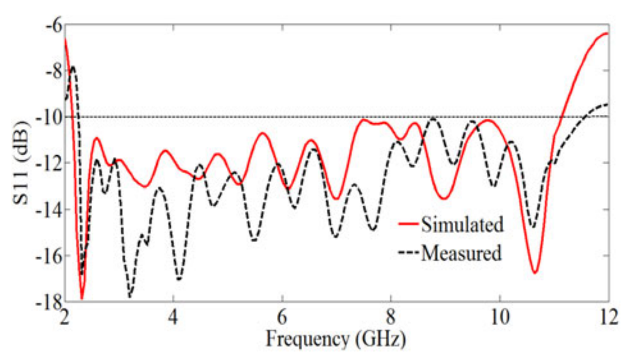

Fig. 5. Measured and simulated S_{11} for the LPDA.

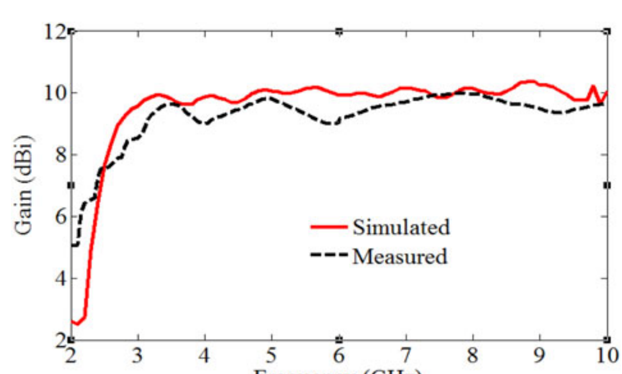

Fig. 6. Measured and simulated gain (IEEE) for the fabricated LPDA.

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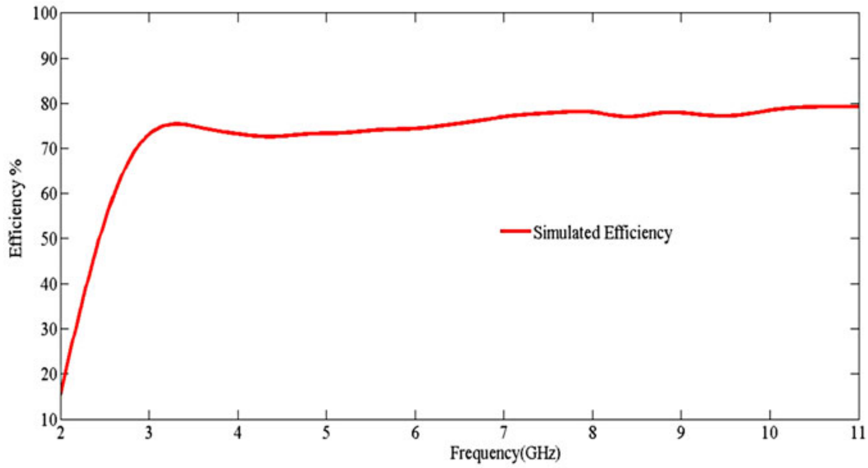

Fig. 7. Simulated radiation efficiency of the LPDA.

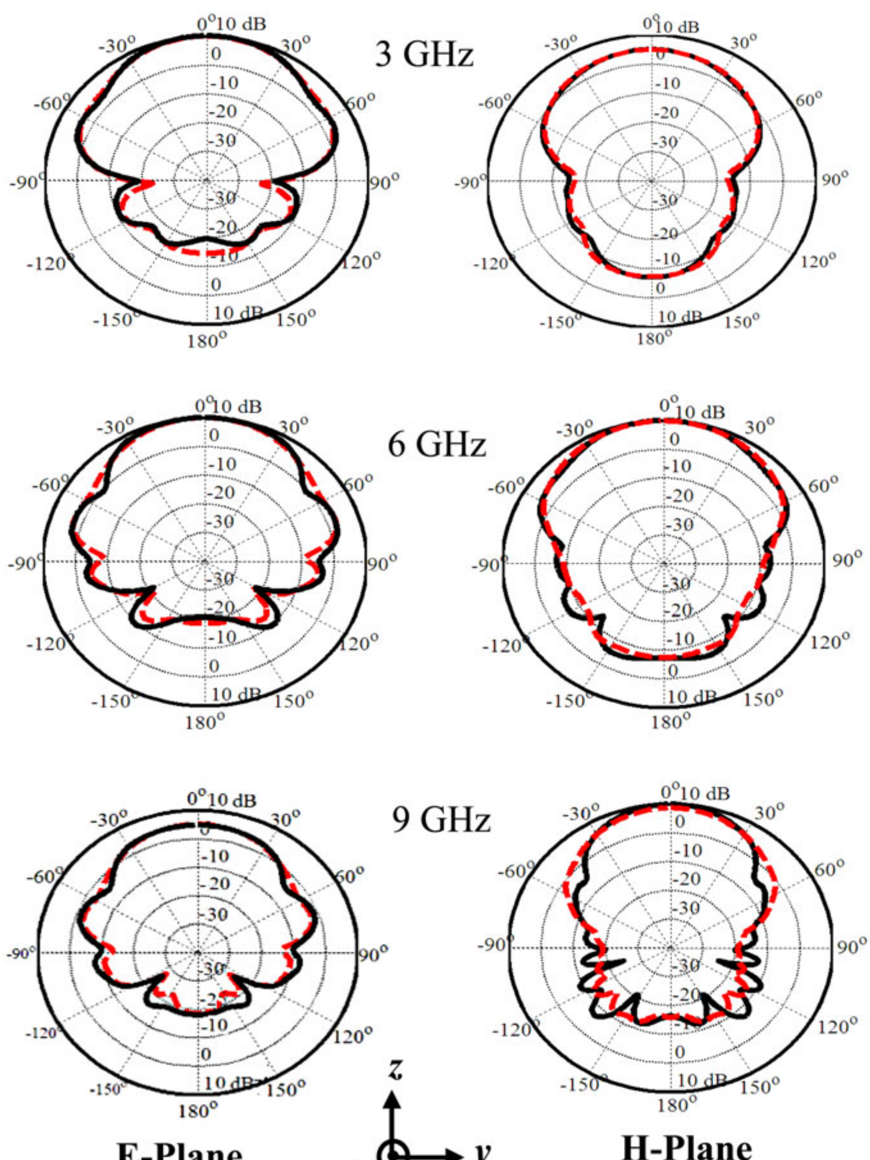

Fig. 8. Simulated (-------) and measured (_____) radiation patterns at different frequencies.

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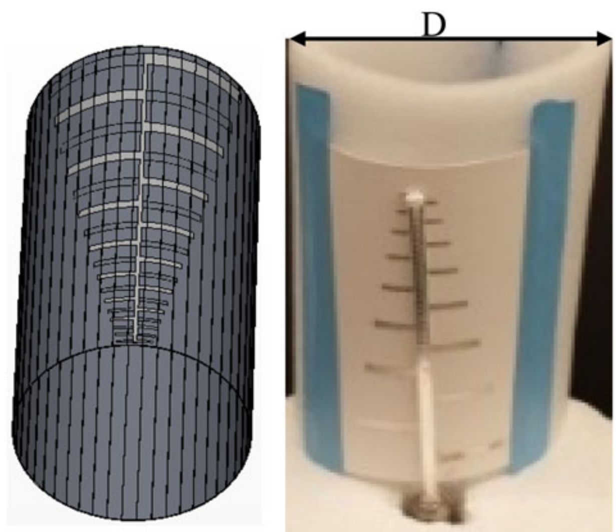

Fig. 9. LPDA in bent configuration.

15 min achieving a subsequent ink conductivity of 6×10^6 S/m [10–12]. The antenna is fed using a coaxial cable; the outer conductor of the coaxial cable is connected to the bottom layer of the line while the inner conductor is connected to the top side via a through-hole in the paper substrate using conductive epoxy. The overall size of the LPDA is 130×60 mm^2.

Antenna measurements in both straight and bended forms is performed in an 18 GHz Satimo-Star-Lab anechoic chamber, as shown in Fig. 4. The simulated and measured reflection coefficient and gain are shown in Figs 5 and 6, respectively. The measured return loss is in general agreement within the complete UWB band. The slight deviation is attributed to the manual gluing process which has two consequences. Firstly, the two dipole arms are minutely misaligned and secondly the discontinuity in the dielectric due to air gaps occurs between the two layers of paper. The gain is measured using a broadband Horn as a reference antenna. The proposed antenna has a peak gain of 9.5 dBi with slight degradation at the lower-frequency band.

The simulated radiation efficiency is given in Fig. 7. It is about 80% for the whole UWB band. The radiation efficiency does not include the reflection losses that are represented by the reflection efficiency in terms of S_{11}. In Fig. 8, the measured radiation patterns in both E and H planes at frequencies of 3, 6, and 9 GHz are shown. The end-fire radiation patterns with side lobe levels (SLLs) well below -21 dB are achieved.

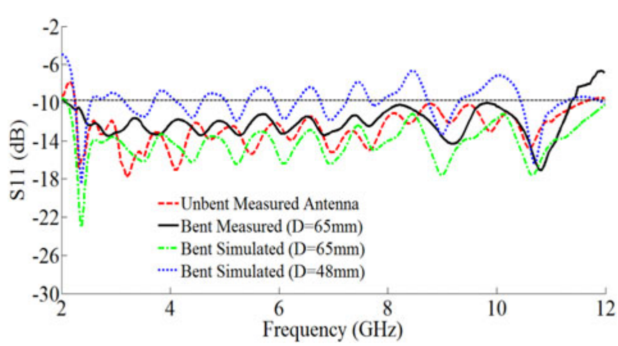

Fig. 10. Measured and simulated S_{11} in bending state.

IV. BENDING ANALYSIS

As the antenna is intended for flexible wireless devices, its performance under bent conditions is also validated. For this purpose, the antenna is placed on a cylindrical surface with a diameter "D" of 65 mm as shown in Fig. 9. The bending analysis is only done in horizontal direction; in vertical direction the bending analysis is not possible due to non-flexible coaxial feed.

Figure 10 depicts the antenna reflection coefficient in bent and unbent forms. Other than a slight mismatch at 11 GHz, no major shift is observed and can be attributed to change in the antenna electrical length in the bent stage. To show the antenna ability to perform in extreme bending conditions, simulated S_{11} with 48 mm diameter cylinder is also given in Fig. 10. The choice of the radii was made due to the cylinders available in the laboratory on which the antenna could be mounted. However, these values also indicate the limit at which the antenna can be bent. At the upper limit of 65 mm, slight changes in the return loss and radiation pattern begins to occur, as shown in Figs 10 and 12. While 48 mm is the lowest limit after which further bending results in distortion and deviation in radiation properties taking the performance below the required acceptable level.

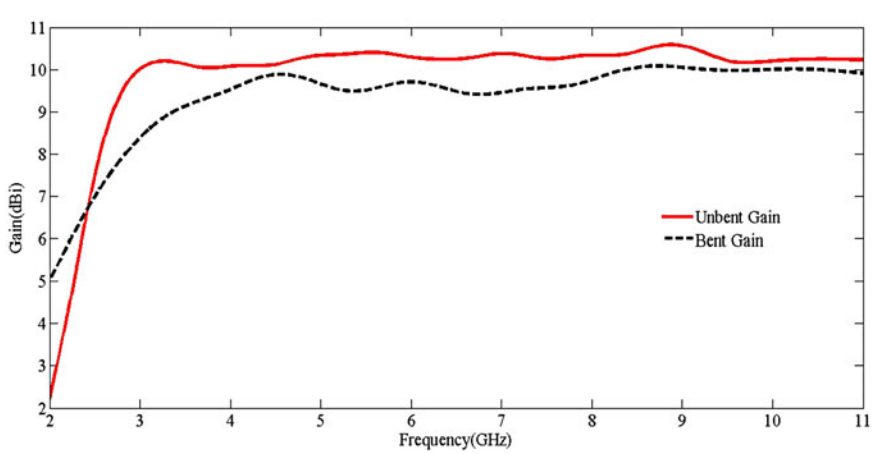

Fig. 11. Simulated gain in unbent and bent ($R = 68$ mm) condition.

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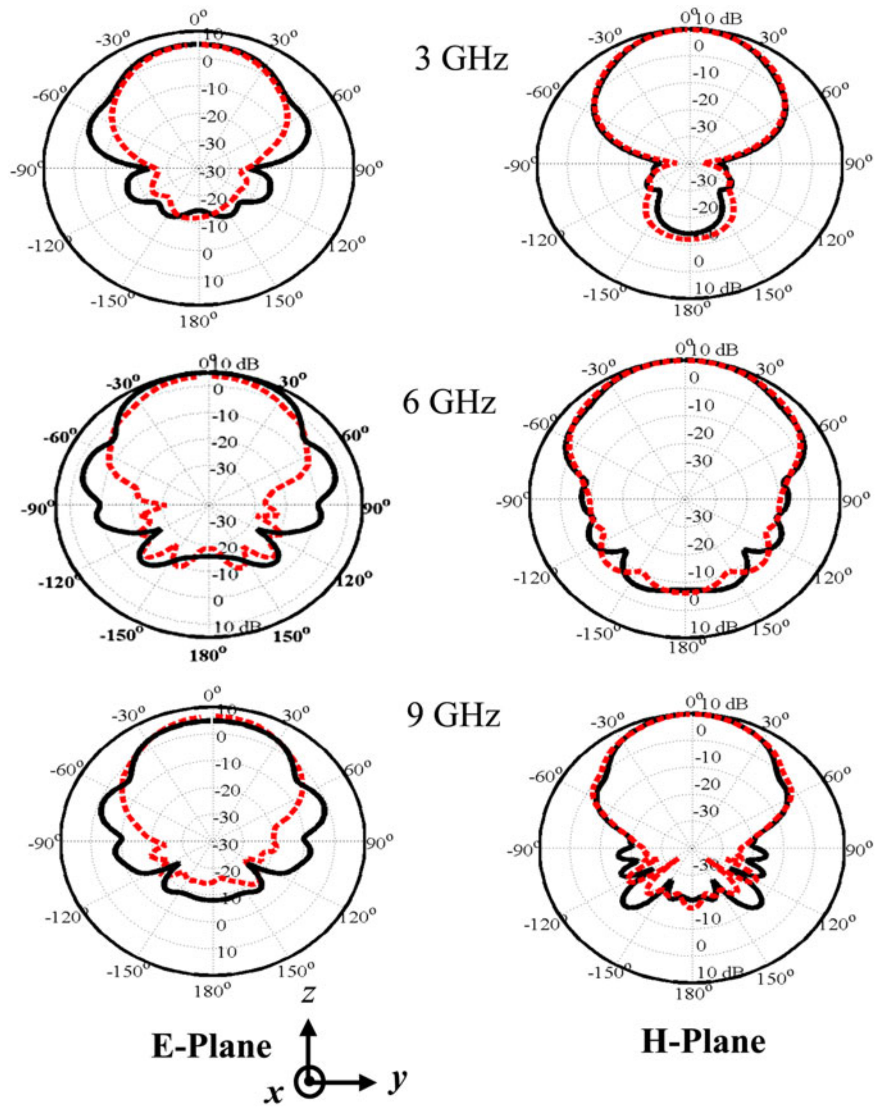

Fig. 12. Measured radiation patterns in bent (-------) and unbent (_____) configurations.

The simulated gain for bent and unbent conditions is also compared in Fig. 11 showing a good match. The radiation patterns of the antenna are also measured in bent configuration and then compared with the unbent patterns as shown in Fig. 12. No significant change is observed in the radiation patterns and the antenna maintains its radiation characteristics after repeated testing, making it suitable for highly directive UWB antennas in flexible wireless devices.

V. CONCLUSION

This paper presents a fully characterized UWB LPDA antenna in 2.2–11 GHz frequency band with the highest reported on-paper gain of 9.5 dBi. The antenna is well matched in its complete band of operation with minimal gain variation. It also shows a consistent end-fire radiation pattern with low SLLs in both bent and unbent form. The compact, lightweight, and flexible design of the antenna makes it a potential candidate for many wireless communication devices.

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