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Bendable UHF RFID tag antenna for retail garments using non-uniform meandered lines

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Abstract

A bendable UHF RFID tag antenna using non-uniform meandered lines for retail garments in the textile industry is presented. Based on an earlier UHF RFID tag antenna using nonuniform meandered lines, the proposed tag is fully bendable and aimed to be embedded in retail garments for long-life cycles. As a result, a relatively low cost, wide band, compactness and good conjugate matching with good dipole-like read range is presented. Results showed an antenna with a wide bandwidth of 900MHz and a long read range of 10.1m making the UHF RFID tag antenna using non-uniform meandered lines a potential candidate for retail garments in bendable applications of the textile industry. Simulations are corroborated by measurements and are in fairly agreement.

KEYWORDS:

Cloth tag, Internet of Things, UHF-RFID, Wide-band, Inventory management, flexible tag.

1 | INTRODUCTION

In recent years, Radio-Frequency Identification (RFID) systems operating at Ultra-High Frequency (UHF) have been significantly adopted for identification and tracking in applications such as human monitoring, health-care, library and inventory management, and Internet of Things (IoT). For UHF RFID systems, various frequency bands are assigned worldwide, i.e., 866-869 MHz for Europe, 865-868 MHz for New Zealand and India, 908.5-914 MHz for Korea, 902-928 MHz for USA, and 940-943 MHz for China [1]. Typically, the RFID system consists of a reader and a tag comprising a chip and an antenna. The tag chip is powered through the antenna by signals originating from the reader and sends back the chip unique code information using the back-scattering principle[2]. Several design approaches have already been discussed for impedance matching and size reduction of RFID tags, which include T-Matching [3], inductively coupled loop [4], and meander line antennas(MLA). For instance, the inductive coupling technique improves impedance matching of a tag antenna with little effect on the radiation efficiency [5]. Similarly, the T-matching technique [6] achieves a broadband matching, reduced size, and improved efficiency. Furthermore, a meander line(ML) [7] is an attractive technique to design a reduced size antennas. Similarly, in [7] a uniform and non-uniform meander line techniques are studied for size reduction and gain enhancement. Furthermore, in [8], a non-uniform technique led to improved impedance matching and bandwidth enhancement. Still, they require improved efficiency with associated read range.

In the literature, various RFID tag designs have also been reported [**?**, **?**, **?**] on host objects such as metal, glass, and wooden, but requires customization for multi-platform in a compact form. Some multilayered structures are also reported in [**?**]. Specifically, stretchable tags are proposed in [9, 10, 11] which achieve 10.6m reading range in original form, and after 100 stretches reading range decrease from 10m to 7m. Similarly, a graphene based passive UHF RFID textile tag is proposed in [9] for pasting on cloths and foam objects, however, reporting low reading range of 3.2m, and a embroidered flexible tag in [10]

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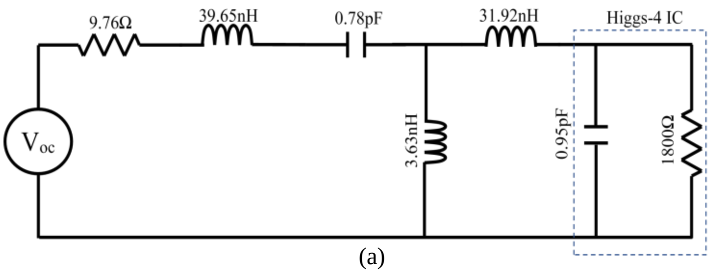
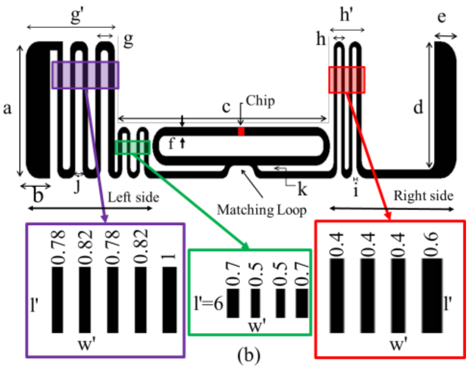
with longer reading range. The design is not optimized to consider the effect of AMS and magnetic locks on the tags. Therefore, not suitable for inventory cloth tags. In this paper, to comply with the expectations immediately described, a bendable UHF RFID tag antenna using non-uniform meandered lines for retail garments in the textile industry is presented and compared to an earlier design [[12]] (made on FR4). The relatively low cost tag is wide band, compact and with good conjugate matching with good read range. The remaining of the paper is organized as follows, Section 2 shows the proposed bendable UHF RFID tag antenna, Section 3 the analysis and results and Section 4 the concluding remarks.

2 | DESIGN AND FABRICATION

The equivalent circuit model [13] of the tag antenna is calculated and shown in Fig.1 (a). The analytical design process begins



(a)



(b)

Dimension (mm)	a	b	c	d	e	f	g	h	i	j	k
Earlier design	16	4.3	33.0	13	3.2	1	2.8	1.7	0.5	1.2	0.7
Proposed tag	16	4.5	33.2	13	3.2	0.5	2.8	1.3	0.5	1.2	0.7

(c)

FIGURE 1 (a) Equivalent circuit model (b) layout (c) parameters of the proposed tag.

with calculation of the equivalent circuit model parameters defined in Fig. 1 (a). The tag is matched with an EPC global Class-1 2nd generation Higgs-4 chip [14] having input impedance 20.55-j191.45Ω and a parallel equivalent resistance R_c=1800Ω and capacitance C_c=0.95pF at 866 MHz. The procedure to find equivalent circuit parameters is as follows. The quality factor of the proposed tag antenna was targeted for Q_a=23. The radiation resistance of the antenna is calculated as,

$$R_a = 80(\frac{\pi \beta l}{\lambda_0})^2 = 9.76\Omega \tag{1}$$

where, β=0.575, length of antenna l=6.7cm, and λ_0=34.64cm at 866MHz. We target to achieve at-least 20dB return loss at 866MHz, which is equivalent to a reflection coefficient Γ=0.1. Therefore, the scaled resistance

$$R_n = \frac{(\Gamma + 1) \times R_a}{(1 - \Gamma)} = 18.79\Omega \tag{2}$$

and the maximum power transfer efficiency

$$\alpha = \sqrt{\frac{R_n}{R_c}} = 0.1022 \tag{3}$$

are calculated. Let the operating angular frequency ω_0 be at 866MHz. Using C_c, an equivalent of series and parallel inductors

$$L_{eq} = L_1 + L_2 = \frac{1}{\omega_0^2 \times C_c} = 35.55nH \tag{4}$$

is calculated. Since

$$\alpha = \frac{L_2}{L_1 + L_2} \tag{5}$$

the matching inductances are found as L_1=31.92nH and L_2=3.63nH. Using the series inductance defined as

$$L_{se} = \frac{L_1 \times L_2}{L_1 + L_2} = 3.26nH \tag{6}$$

the proposed antenna inductance

$$L_a = \sqrt{\frac{L_{se}^2 + (\frac{2R_aQ_a}{\omega_0})^2 - L_{se}}{2}} = 39.65 \tag{7}$$

is calculated as L_a=39.65nH. The resonating frequency f_r of the proposed antenna prior the matching network is found by

$$f_r = \frac{Q_aR_a}{2\pi L_a} = 900MHz \tag{8}$$

and the antenna capacitance.

$$C_a = \frac{1}{2\pi f_a Q_a R_a} = 0.78pF \tag{9}$$

Following the same procedure, the equivalent circuit of the earlier antenna is found with parameters compared to those of the proposed tag in Fig.1 (c). The proposed tag is then simulated using commercial electromagnetic software Ansys HFSS. Whereas the earlier design was made on a single-sided PCB of FR4 substrate having ϵ_r=4.4, tanδ=0.02, and thickness 1.54mm with copper deposition of 20 microns, the bendable tag was made on a single-sided polyimide substrate having ϵ_r=3.5, tanδ=0.008, and thickness 0.05mm with copper deposition of 10 microns. As with [12], a meander-line technique [15] is used to increase the electrical length of the antenna and using non-uniform lines (track width and length) with smooth corners. The tag antenna was matched with an EPC global Class 1 2nd generation Higgs-4 chip [14] having input impedance 21.55-j191.45Ω at 866 MHz and capable for operation in the frequency range 830-960 MHz. Therefore, the input impedance of the antenna was conjugately matched with the tag chip impedance, and the matching loop of the proposed design conveniently tailored. The simulated parameters of the resulting design presented in Fig.1 (b) are listed in Fig.1 (c) and compared to those of the earlier design. The performance of the proposed tag antenna is evaluated next.

3 | PARAMETRIC ANALYSIS AND SIMULATED RESULTS

For the study, a parametric analysis was first performed. 9 cases of uniform meander line are considered, and results given in Table 1 . Similarly, 9 cases are considered for non-uniform meander line in Table 1 . To compare the performance of the tag using uniform and non-uniform meander lines, τ, gain and read range of the tag are evaluated. τ is the propagation coefficient between the antenna and the chip showing a better value for the non-uniform case and because the gain of the tag in this case is increased, the reading range is also improved; this is a 10% to 55% increase compared to the uniform meandered line version. The simulated parametric analysis of the symmetric and non symmetric tags are shown in Fig. 2 (a) for the g'=2 and h'=2.

TABLE 1 Parametric analysis of the tag with uniform and non-uniform meandered lines

			Uniform meander lines			Non-uniform meander lines		
S.N.	No. of turns of element g'	No. of turns of element h'	τ	Gain dBi	Read Range (m)	τ	Gain dBi	Read Range (m)
1	1	0	0.2252	-1.5	4.13	0.2420	-0.5	4.81
2	2	0	0.2801	-0.5	5.18	0.3039	0.0	5.71
3	3	0	0.2908	-0.4	5.33	0.3297	0.1	6.02
4	1	1	0.3290	-0.4	5.67	0.3844	0.2	6.57
5	1	2	0.4192	0	6.71	0.6522	0.8	9.18
6	2	1	0.3861	-0.2	6.29	0.5350	0.8	8.31
7	2	2	0.5383	0.4	7.96	0.8042	0.8	10.19
8	3	0	0.4365	0.3	7.09	0.5655	0.6	8.35
9	3	2	0.5826	0.7	8.57	0.8213	0.9	10.4

For symmetric meandered lines, the first case is observed with g'=1 and h'=0, It means one meander line exists in left side and no meander line exists in right side, and similarly, the second case shows g'=2 and h'=0 It means only two meander line exists in the left side of the tag. The proposed tag is now simulated and results subsequently detailed. Fig. 2 (c) shows the impedance responses of the chip, the equivalent circuit and the proposed tag. From the results at 866MHz with similar impedance response to that of the equivalent circuit which was originally targeted for a return loss>20dB at 866MHz. Since the Higgs-4 chip operates in the frequency range 830-960 MHz, the proposed tag covers the entire universal passive UHF RFID band. The simulated current distribution of the proposed tag at 866 MHz is depicted in Fig. 2 (b). The simulated peak gain of the tag was 1.1dBi. Compared to the earlier design (gain 1.2dBi) this is an insignificant impact on performance.

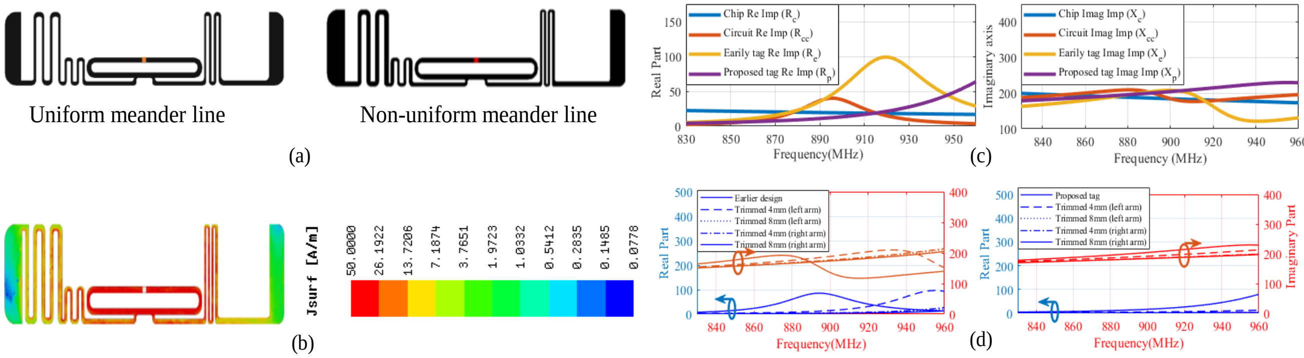


FIGURE 2 Simulated results of the proposed tag.

3.1 | Robustness and bending performance of the proposed tag

Since the cloth tags for inventory applications are reused several times, they are likely to get damaged. It may reduce the reading range due to change in the tag's performance. To analyze this, the robustness of the proposed tag is evaluated and compared to that of the earlier design. The robustness is measured from a hypothesis the original dimensions of the tag arms (right and left) are damaged by trimming the arms (conductive elements b and e) substantially. Fig. 2 (d); the earlier design response is also included. Similar performance can be observed between designs. The robustness of the tag antenna (trimming of its arms)

TABLE 2 Trimming and bending performance of the tag antenna arms.

		Earlier tag		Proposed tag				Earlier tag		Proposed tag	
S.N.	Left arm (mm)	Return Loss (dB)	Read Range (m)	Return Loss (dB)	Read Range (m)	S.N.	Right arm (mm)	Return Loss (dB)	Read Range (m)	Return Loss (dB)	Read Range (m)
1	00	41	10.8	28	10.40	1	00	41	10.8	28	10.40
2	01	38	10.6	27	9.90	2	01	41	10.7	27	9.50
3	02	32	10.0	26	9.10	3	02	34	10.4	26	9.40
4	03	29	9.60	26	9.00	4	03	29	10.2	26	8.70
5	04	25	9.46	26	8.50	5	04	22	8.70	25	7.90
6	05	25	9.33	26	8.00	6	05	23	7.20	25	7.00
7	06	24	9.22	25	7.30	7	06	23	6.80	24	6.70
8	07	24	7.67	25	7.00	8	07	23	6.54	25	6.60
9	08	23	7.12	25	6.70	9	08	22	6.60	24	6.40
10	09	23	6.92	24	6.50	10	09	23	6.60	24	6.50

Bending angle(degree)	15°	30°	45°	75°	95°	130°	190°
Read Range(m)	10.4	10.33	10.3	10.3	10.24	9.74	8.13

regarding the simulated read range is given in Table 2 , which shows a relatively good robustness tolerance and similar results of the proposed tag as compared to the earlier design; that is only 0.4m reduced read range compared to the earlier design. Therefore, validating the robustness of the proposed tag against accidental damage. Yet, because of the nature of the proposed tag made of copper etched on polyimide this is expected to last long-life cycles on garments. Unlike the earlier design, the proposed tag antenna is aimed to be bendable with a tolerance that can allow direct attach to garments. The tag was simulated for its maximum reading range when the tag was bent with a certain degree of con-formality. The resulting performance is presented in Table 2 for various arching angles projected by the tag length at the center of a cylinder. The tag in its original (flat) shape achieved a 10.4m reading range with a minor variation of 0.16m when curved up-to 95°. For a very high degree of bending (192°), the read range (8.13m) seemed reasonably good to regard the tag antenna as bendable.

4 | EXPERIMENTAL RESULTS

The fabricated prototype is shown in Fig. 3 (a). The following setup, shown in Fig. 3 (b), was used for the measurements. Essentially, it uses a 6dBi circularly polarized reader antenna connected to a RFID reader module with maximum output power adjusted to 25dBm and was tested for two different frequency bands of RFID: ETSI (865-868 MHz) and FCC (902-928MHz). The tag attached to a cloth was initially placed at a far distance and moved slowly closer to the RFID reader until it was read; this found accurate read range of the tag. The simulated and measured read patterns of the tag measured at 866 MHz are shown

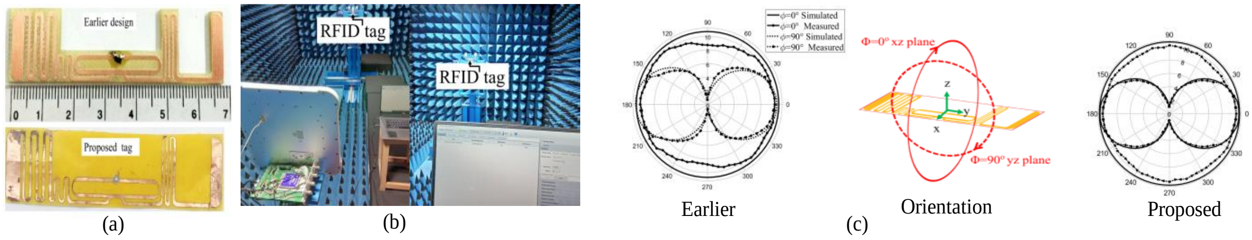


FIGURE 3 Fabricated prototypes and measured results of earlier design and the proposed design.

in Fig. 3 (c); earlier design response is also shown. Dipole-like radiation pattern is observed with omnidirectionality in $\Phi = 0°$ plane. To corroborate the measured results, the read range of the tag is calculated theoretically with Friss equation [17]

$$r = \frac{\lambda}{4\pi}\sqrt{\frac{P_t G_t G_r \tau}{P_{th}}} \tag{10}$$

where λ is wavelength, $P_t = 25$dBm and $G_t = 6$dBi are power transmitted and gain of the reader antenna, respectively. G_r is gain of tag antenna, $P_{th} = -20.5$dBm is the chip sensitivity,

$$\tau = \frac{4R_c R_a}{|Z_c + Z_a|^2}, 0 \leq \tau \leq 1 \tag{11}$$

is the power transmission coefficient, $Z_c = R_c - jX_c$ and $Z_a = R_a + jX_a$ are the chip and the antenna impedance's, respectively. The theoretical reading range of the proposed tag is calculated as 10.4m and 10m respectively for the 866MHz and 915MHz central frequencies. That is a lower 0.4m and 0.2m respectively compared to the earlier design.

The measured maximum read range (at the foresight direction, Fig. 3 (c)) of the proposed design compared to the earlier is summarized in Table 3 . The measured results indicate that the read range of the proposed rigid tag is 10.2m and 9.8m

TABLE 3 Measured read range and trimming data of the proposed tag.

Tags	Size(mm×mm)	Theoretical read range (m)		Measured read range (m)	
		ETSI band	FCC band	ETSI band	FCC band
Earlier design	16×67	10.8	10.2	10.2	9.8
Proposed design	16×67	10.4	10.0	10.1	9.7

S.N.	Trimming Left arm (mm)	Earlier design Read Range (m)	Proposed design Read Range (m)	Trimming Right arm (mm)	Earlier design Read Range (m)	Proposed design Read Range (m)
1	00	10.2	10.1	00	10.2	10.1
2	03	9.0	8.0	03	9.0	8.0
3	06	8.0	7.0	06	6.5	6.5
4	09	6.5	6.0	09	5.5	5.7

as compared to 6.1m and 5.9m of the commercial tag in ETSI and FCC bands, respectively. The read range of the proposed flexible tag is measured as 10.1m (9.7m) in ETSI (FCC) band. Moreover, the proposed tags are smaller in size compared to the commercial tag by 11%. To validate the robustness of the proposed tag experimentally, the read range for several trimmings of the tag antenna arms is measured results agree simulated results (Table 2) and show a relatively good robustness tolerance for the proposed design. Compared to the earlier design only compromises 0.1m-0.5m read range what validates the bendable proposed tag for textile applications. Yet, because of the nature of the proposed tag made of copper etched on polyimide this is expected to last long-life cycles on garments.

5 | CONCLUSION

In this paper, a bendable UHF RFID tag antenna using non-uniform meandered lines for retail garments in the textile industry has been presented. Based on an earlier UHF RFID tag antenna using nonuniform meandered lines, the proposed tag was shown to be fully bendable while embedded in retail garments for long-life cycles. As a result, a relatively low cost, wide band, compactness and good conjugate matching with good dipole-like read range was shown. Results showed an antenna with a wide bandwidth of 900MHz and a long read range of 10.1m making the UHF RFID tag antenna using non-uniform meandered lines a potential candidate for retail garments in bendable applications of the textile industry.

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