Planar Artificial Transmission Lines Loading for Miniturization of RFID Printed Quasi-Yagi Antenna

Parviz Hajizadeh, H. R. Hassani, and Seyed Hassan Sedighy

***Abstract*—A compact omnidirectional printed quasi-Yagi antenna for RFID reader application is presented. To reduce the size of the antenna, the radiating elements of the quasi-Yagi antenna are replaced by artificial transmission lines (ATLs). The proposed antenna that operates at 915 MHz has a substrate size of 52×77 mm^2, which shows more than 76.24% size reduction in comparison to the previously reported compact Yagi antenna. At the center frequency, the antenna has an input impedance of $46.66 - j4.27\ \Omega$, radiation efficiency of 98.2%, and a gain of 1.84 dBi. The experimental data are in good agreement with the simulation results.**

***Index Terms*—Artificial transmission line (ATL), RFID antenna, Yagi.**

I. Introduction

In RECENT years, there has been a rapid growth in the development of RFID systems for use in various industrial fields. For RFID systems operating at LF and HF frequencies, information and power transmission are generally based on the coupling inductance, while for UHF and microwave frequencies, the communication between the reader and the tag is based on the electromagnetic wave propagation. The two most important parts of an RFID system are the transponder (antenna) and the reader. When designing the reader, a compact-size antenna is of paramount importance [1]–[3].

An extensive research and development has been done to improve the antennas for the RFID applications. A compact dual linearly polarized aperture-coupled microstrip patch antenna array system has been introduced in [4] for such applications. A printed Yagi antenna has been introduced in [5] to increase the gain and the front-to-back ratio of the tag's antenna and extend the reading range. Printed loop antenna for near-field RFID readers is another option that has been introduced in [6]. There are a few articles that use printed dipole as RFID antennas.

Most of these reported antennas occupy a large substrate surface area, and a challenging problem for the designers is to reduce the size of the overall antenna. For this purpose, the folded printed dipole antenna with two radiating arms and a shorting strip is proposed in [7]. Each radiating arm is bent into a G-shape to obtain a compact size. Also, the step impedance transmission lines have been used in [8] to make the dipole antenna even more compact. Efficient planar left-handed antenna working in the zero-order mode is another way to reduce the dimensions of the antenna. This approach takes advantage of the left-handed topology to achieve well-matched input impedance values and a miniaturized antenna, with improved performances with respect to the conventional left-handed loading [9]. The meander-line approach has been used in [10] and [11] to design compact RFID tag antennas. Such antennas have inductive input impedance that can be complex-conjugate-matched with the tag chips and, as such, are more suitable for tag antennas. However, due to the real part of the input impedance being low, these antennas have low efficiencies.

Recently, we used a planar artificial transmission line loading with single-layer printed circuit broad fabrication process for miniaturization of a quasi-Yagi antenna [12]. Here, this technique is considered in more detail and discussion. In this method, a compact omnidirectional printed quasi-Yagi antenna loaded by artificial transmission line (ATL) structure has been introduced to reduce the overall dimension of the printed antenna suitable for RFID applications. In the proposed antenna, a new microstrip artificial transmission line that is based on the ATL given in [13] has been used for loading the radiating arms of the quasi-Yagi antenna. This new artificial transmission line composed of microstrip quasi-lumped elements and their discontinuities is able to synthesize transmission lines with a wide range of characteristic impedances and electrical lengths and may therefore significantly reduce the required physical lengths of both high- and low-impedance lines. Since the proposed antenna has an impedance of $46.66 - j4.27\ \Omega$, it is more suitable for reader antennas, and because of its excellent efficiency, it can give a great read range in comparison to previous work. The proposed antenna is fabricated and tested, and results are compared to those of the simulation. Simulated results are obtained through the commercially available software package HFSS.

II. Artificial Transmission Line

A simple antenna suitable for RFID application is the printed dipole antenna. The physical length of each arm of a dipole antenna is approximately $\lambda_g/4$, and the electrical length is 90°. In most RFID applications, this length is very large, especially in the UHF zone. Generally, this is considered as a big drawback. To overcome this obstacle, an ATL structure is proposed here.

The miniaturization of passive microwave components by means of ATL structures has drawn more and more attention recently [13]. To reduce the physical length of a microstrip line

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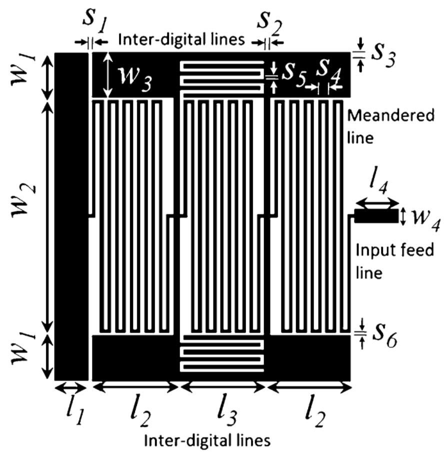


Fig. 1. Structure of the proposed unit-cell printed artificial transmission line.

while maintaining exactly the same electrical length as the conventional counterpart, a planar ATL can be incorporated. The planar artificial transmission line is composed of quasi-lumped elements that can be replaced by standard discontinuous lines such as meandered and interdigital lines. To the knowledge of the present authors, up until now, the ATL structures reported in the literature have been used to reduce the size of microwave components. In this letter, we use the ATL structure to reduce the size of the required printed antenna for the RFID applications.

The ATL structure can be applied to the arms of a simple printed dipole antenna. However, to be able to apply this, the width of the arms should be large enough in order for the ATLs to be included. Thus, first a hypothetical rectangular patch can replace the open-ended transmission line of each dipole arm. Then, the ATL is incorporated within each of the two patches.

The hypothetical patch is designed to operate at the required frequency of 915 MHz. The equivalent lumped element model of the patch antenna is a parallel LC circuit. The equivalent lumped element model can be turned into an easily realizable printed ATL structure.

The characteristic impedance of a transmission line is the square root of the equivalent inductance over equivalent capacitance, and also its guided wavenumber is the square root of the equivalent inductance times the capacitance. By increasing the equivalent inductance and capacitance, the guided wavenumber can be increased efficiently to achieve the required electrical length with unchanged characteristic impedance for the line. Thus, the propagation constant can be controlled in an ATL structure, leading to reduced antenna size.

Fig. 1 shows the structure of the proposed ATL structure (with discontinuities on one side, and a finite ground on the other side of the substrate) replacing the patch in each arm of the original dipole antenna. The structure is fed through a printed transmission line followed by the meander line that is terminated in a narrow rectangular patch. This wide patch provides better radiation efficiency for the cell. Two narrow rectangular patches are also placed on the top and bottom part of the cell in which interdigital lines are created.

Fig. 2 presents the equivalent lumped-element model of the structure in Fig. 1. The relevant inductances and capacitances,

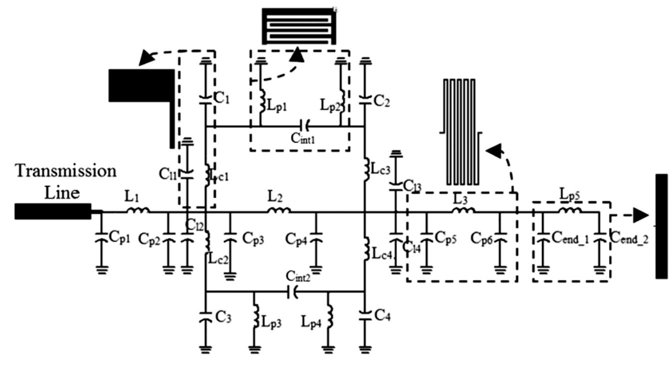


Fig. 2. Equivalent lumped circuit of a single arm of the patch dipole antenna.

TABLE I
ELEMENT VALUES OF THE EQUIVALENT CIRCUIT MODEL OF FIG. 2.
VALUES ARE IN pF AND nH

C_{p1}	4.51	C_1	0.37	C_{l3}	0.37	L_1	13.4	L_{p4}	7.45
C_{p2}	4.51	C_2	0.37	C_{l4}	0.37	L_2	13.4	L_{p5}	0.94
C_{p3}	4.51	C_3	0.37	C_{int1}	2.59	L_3	13.4	L_{c1}	4.8
C_{p4}	4.51	C_4	0.37	C_{int2}	2.59	L_{p1}	7.45	L_{c2}	4.8
C_{p5}	4.51	C_{l1}	0.37	$C_{end\text{-}1}$	1.55	L_{p2}	7.45	L_{c3}	4.8
C_{p6}	4.51	C_{l2}	0.37	$C_{end\text{-}2}$	1.55	L_{p3}	7.45	L_{c4}	4.8

tabulated in Table I, can be obtained through simulation via HFSS package. The relationship between the parameters of the equivalent characteristic impedance, guided wavenumber, inductances, and capacitances of a cell can be described as

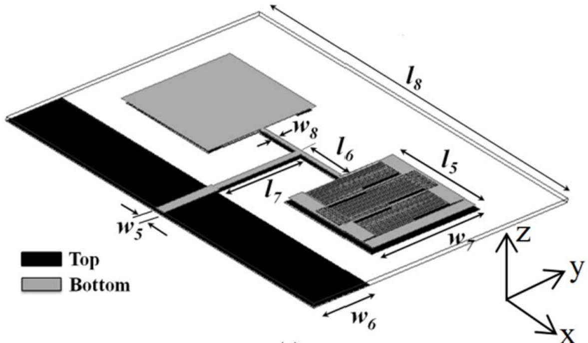
$$Z_{0,\mathrm{ATL}} = \sqrt{\frac{L_{\mathrm{ATL}}}{C_{\mathrm{ATL}}}} \tag{1}$$

$$\beta_{\mathrm{g,ATL}} = \omega\sqrt{L_{\mathrm{ATL}} \cdot C_{\mathrm{ATL}}} \tag{2}$$

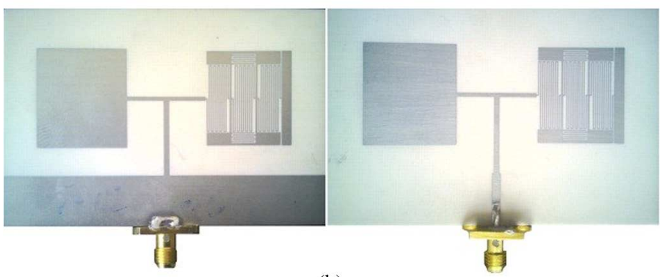
where

$$\begin{aligned} L_{\mathrm{ATL}} &= L_1+(L_{c1}+L_{p1})\,\|(L_{c2}+L_{p3})+L_2+(L_{c3}+L_{p2})\| \\ &\quad \times (L_{c4}+L_{p4})+L_3+L_{p5} \qquad (3) \\ C_{\mathrm{ATL}} &= C_{p1}+C_{p2}+C_{p3}+C_{p4}+C_{p5}+C_{p6}+C_{l1}+C_{l2} \\ &\quad +C_{l3}+C_{l4}+C_1+C_2+C_3+C_4+C_{\mathrm{int\_1}} \\ &\quad +C_{\mathrm{int\_2}}+C_{\mathrm{end\_1}}+C_{\mathrm{end\_2}}. \qquad (4) \end{aligned}$$

Referring to the equivalent circuit shown in Fig. 2, L_1, L_2, and L_3 represent meandered-line inductances. The C_1–C_4 capacitances are realized by patches that are placed at the corners of the cell. The $C_{\mathrm{int}-1}$ and $C_{\mathrm{int}-2}$ are two interdigital capacitors in the top and bottom of the ATL structure, and C_{end} is the capacitance related to the termination patch. The other lumped elements are due to parasitic effects between the segments. For a given characteristic impedance and guided wavenumber of a printed line, the ATL structure can be designed. By proportionally increasing the unit-cell total inductance and capacitance of the lumped circuit model while keeping the ratio of the two terms unchanged, the characteristic impedance (Z_{c}) and guided wavenumber (β_{g}) of the unit cell of an artificial transmission line can be obtained from (1)–(4) while keeping the overall length of the ATL structure much lower than the original printed line. The amount of reduction also depends on the efficiency required for the structure.



(a)



(b)

Fig. 3. (a) Structure of the proposed antenna with ATL. (b) Fabricated antenna, top and bottom planes.

TABLE II
DIMENSION COMPARISON BETWEEN PROPOSED ANTENNA AND SOME REFERENCES

Antenna type	Dimension (mm^3)	Dimension in λ_g	Compaction
Introduced in [2]	100× 100×1.6	0.568×0.568	100.00%
Introduced in [4]	100×100×6	0.511×0.511	80.94%
Introduced in [3]	90×90×1	0.5×0.5	77.5%
Proposed in this paper	52×77×0.8	0.296×0.296	23.76%

III. ANTENNA DESIGN AND CONFIGURATION

The proposed quasi-Yagi antenna suitable for the RFID application is shown in Fig. 3. For a simple balanced feed, the two radiating arms consisting of ATL cells are connected to a microstrip feedline. To have the phase reversal between the two arms, as required for the dipole, the two ATL structures are placed in reverse. A truncated ground acting as a reflector for the antenna structure is also placed at the bottom of the board.

The initial dimensions of the ATL cell are calculated through (1)–(4) to have a 0.1-λ_g electrical length (for 60% length reduction) at 915 MHz with 50 Ω characteristic impedance. As mentioned before, such size reduction ensures a good antenna efficiency. The HFSS simulation software is used for tuning the value of parameters to match the antenna input impedance at 915 MHz with the reduced length 0.1 λ_g. The RO4003 substrate with thickness of 0.8 mm and ε_r of 3.35 is used. Through optimization, the proposed antenna design parameters are the following: $w1 = 3.2$, $w2 = 9.5$, $w3 = 9.7$, $w4 = 0.93$, $w5 = 1.8$, $w6 = 12$, $w7 = 23.5$, $w8 = 1.25$, $S1 = 0.2$, $S2 = 0.4$, $S3 = 0.25$, $S4 = 0.3$, $S5 = 0.25$, $S6 = 0.25$, $l1 = 2.3$, $l2 = 5.9$, $l3 = 5.9$, $l4 = 6.1$, $l5 = 21$, $l6 = 8.29$, $l7 = 11.5$ (all dimensions are in millimeters). The size of the required substrate is 52×77 mm^2, which is 23.76% of the previously reported Yagi antenna designs. A prototype of the antenna is fabricated and shown in Fig. 3(b). In Table II, the proposed antenna is compared to some other RFID antennas obtainable in the literature. It can be seen that the proposed antenna has a very compact dimension compared to the others.

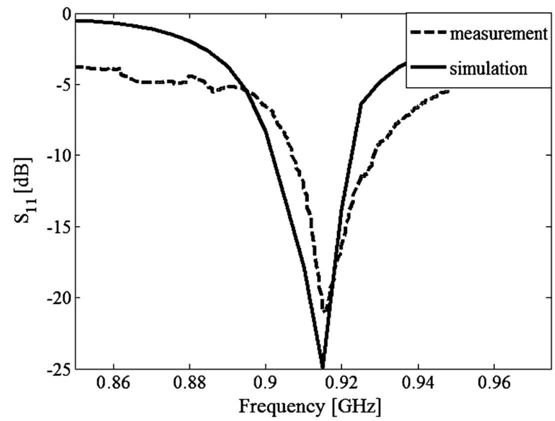
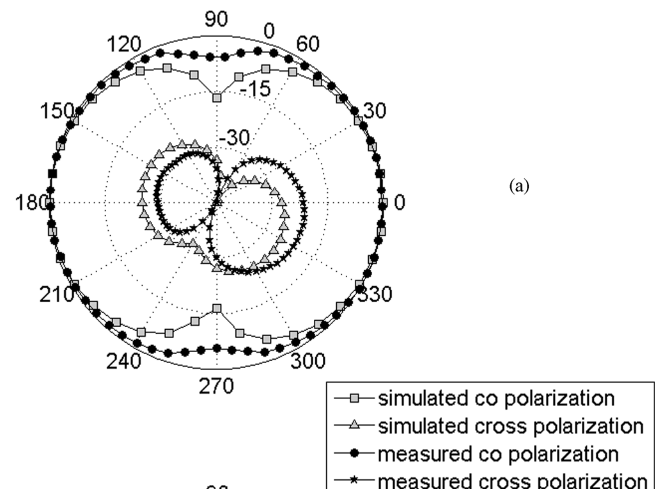
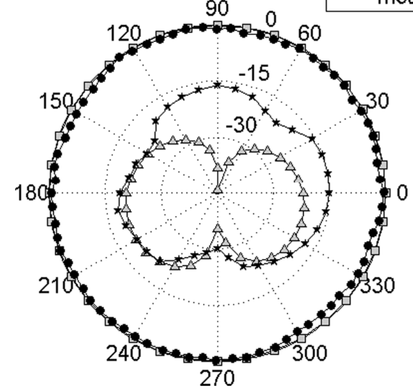


Fig. 4. Measured and simulated reflection coefficient of the proposed RFID antenna.



(a)



(b)

Fig. 5. Simulated and measured co- and cross polarization of the proposed antenna at 915 MHz. (a) E-plane ($\varphi = 90^\circ$). (b) H-plane ($\varphi = 0^\circ$).

IV. RESULTS

The measured and simulated reflection coefficient of the proposed antenna is shown in Fig. 4. From these results, it

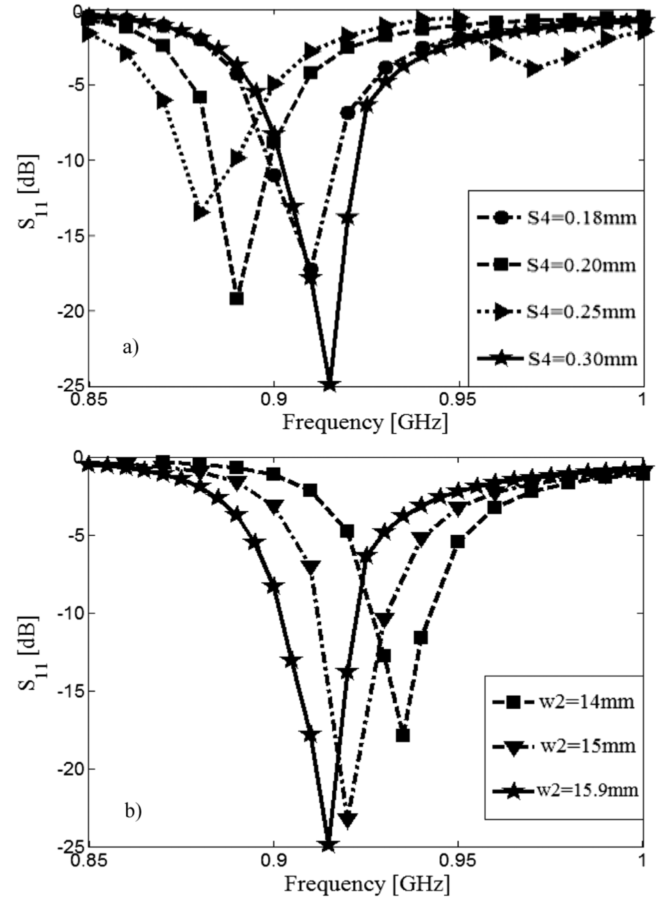


Fig. 6. Simulated reflection coefficient of antenna for various design parameters. *(top)* $S4$. *(bottom)* $w2$.

can be seen that the antenna resonates at 915 MHz, and good impedance match is achieved. The measured and simulated co- and cross polarization of the E- and H-plane patterns of the proposed antenna are shown in Fig. 5 at 915 MHz. As can be seen, the antenna has an omnidirectional pattern in the elevation direction (H-plane), and overall, the cross-polarization level is about 15 dB below the copolarization level. These features make the antenna useful for RFID application.

In addition, the effect of each of the parameters in the ATL cell shown in Fig. 1 can be studied through simulation. As an example, the effects of $S4$ and $w2$ that are related to the meander-line inductors are demonstrated in Fig. 6. By decreasing $S4$ from 0.3 to 0.18 mm, the overall length of the meandered line decreases, leading to reduced total inductance. This change in the total inductance of the cell reduces the L_{ATL} of (3) and thus shifts the resonance frequency. Similarly, reducing the value of $w2$ shifts the resonance frequency upward.

Other parameters of the proposed ATL structure have also been investigated. For example, by increasing $w1$, the overall area of the corner patches increases leading to increased total capacitance. The parameter $l4$ is used for adequate adjustment of the phase. By increasing $S1$, the parasitic capacitance of the meandered line increases, and this leads to enlarged total capacitance.

In practical situations, it is usual to place such an antenna within some protective covers. It can be shown that if dielectric protective covers are placed on both sides of the proposed antenna, the resonant frequency of the antenna shifts downward, while its pattern changes insignificantly.

V. Conclusion

A new ATL structure has been proposed to compact the arms of a quasi-Yagi antenna suitable for RFID readers. The presence of the ATL structure results in reduction of the quasi-Yagi antenna arm's length from the conventional value of 0.25 λ_{g} to present 0.1 λ_{g}. The overall antenna dimension is 52×77 mm^2, which shows more than 76.24% size reduction in comparison to the previously reported Yagi antenna. The antenna has an omnidirectional pattern, a gain of 1.86 dB, a radiation efficiency of 98.2%, and an input impedance of 46.66 $-$j4.27.

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