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Reconfigurable antenna structure for RFID system applications using varactor-loading technique

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Abstract

A novel method is presented for electrically tuning the frequency of a compact radio-frequency identification (RFID) tag antenna. A tuning circuit, comprising a radio frequency (RF) switch and discrete passive components, was completely integrated into the antenna element, which is thus free of DC wires. The low-profile printed antennas were fabricated together with the layouts of the DC control circuits and other RF/baseband circuit footprints. A surface-mounted varactor was applied as a frequency-tuning element at the proper places of the meandered slots in the compact antenna. Prototype designs showed that the in-band frequency (return loss < 10 dB) was tunable from 2.4 GHz to 2.8 GHz when the bias voltage varied from 4 V to 7 V. The impact of the tuning circuit on the antenna's return loss and radiation pattern were experimentally studied through comparison with the performance of a reference antenna not incorporating the tuning circuit. The proposed frequency tuning concept can be extended to more complex compact structures as well as other types of antennas to give enhanced electrical performance.

Key Words: *RFID, Active antenna, frequency tuning, reconfigurable dipole antenna*

1. Introduction

In recent years, wireless communication and personal area network technology has grown quickly, especially radio-frequency identification (RFID). RFID technology consists of a variety of technologies including the integrated circuit technique, computer technique, identification technique, and communication technique. This working band of RFID technology covers 100-500 KHz in the low band range, 13.56 MHz in the high band range, and a microwave band range including 860-960 MHz and 2.45 GHz [1]. RFID is a rapidly developing technology that uses radio frequency (RF) signals for automatic identification of objects. RFID finds many applications in various areas such as asset identification and retail item management. In RFID systems, the most important

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performance is the maximum read range at which the RFID reader can detect the backscattered signal from the tag. The read range is sensitive to the tag orientation, the material on which the tag is placed, and the propagation environment [2]. It is the antenna that determines the performance of a tag stuck to a specific object. Therefore, the antenna must be designed and optimized for materials to be attached to it and for a range of locations for these materials. The tag antenna should be small in size, low in profile, and inexpensive to manufacture. The tag antenna with broadband is also needed to minimize the effect of frequency shift on the read range, depending on the materials to which it is attached. Compact dipoles or folded dipoles printed on film are being widely studied to comply with these requirements.

A RFID tag is an antenna combined with a microchip in a compact package. Selection of the designed tag antenna with good characteristics for the ultra-high frequency (UHF) and microwave RFID system is a very important project. Dipole-type and patch-type designed antennas allow for RFID tag antenna main use and a modified flexible shape for personal customization. The compact dipole antenna for the RFID tag is a good candidate owing to its omnidirectional radiation pattern, simple structure, low cost, and ease of construction. Conventionally, the design shape of the compact antenna from printed microstrip lines, such as folded shapes, meander shapes, and slot-coupled shapes, have attracted increasing attention due to their low profile, reduced size, and resonance frequency for operating bands [3,4]. However, a fractal shape of technology has been used to create wide-band or multiband antennas. Several fractal geometries have been introduced for antenna application with varying degrees of success in improving antenna characteristics [5]. Some of these geometries have been particularly useful in reducing the size of the antenna. These are low-profile antennas with moderate gains and they can be operative at multiple frequency bands. The proposed antenna of this study is presented and explored in 4 stages with the rectangular fractal self-similar rule of shape and metal meander patch, and it could be applied to the dipole antenna. A wide band characteristic with the fractal improves the narrow band of the printed compact antenna for RFID application.

In the present study, a model is proposed to analyze the radiation and return loss characteristics of a varactor-loaded compact RFID antenna. Three identical varactor diodes are integrated on the proper places and edges of a compact antenna. The fringing capacitance introduced at the radiating edge is changed with the change in the bias voltage, resulting in a change in the electrical length of the patch and thus its resonant frequency. The resonance of the compact antenna is therefore electronically controlled by the reverse bias of the varactor diode.

The analysis of the varactor-loaded compact RFID antenna and radiating-edge gap-coupled parasitic elements is based on circuit theory. The details of the entire investigation are given in the following sections.

2. RFID system overview with theoretical considerations

2.1. Antenna equations

The communication in passive UHF and microwave RFID systems is based on backscattering: the reader transmits energy, commands, and data to the tag, which then responds by backscattering its identification data back to the reader, as depicted in Figure 1a. RFID tags consist of an antenna and a microchip, and the tags get all of their energy for functioning from the electromagnetic radiation emitted by the reader through a rectifier, a voltage multiplier, and a voltage modulator inside the microchip. The tag sends the information back to the reader by switching between 2 states: the first is matched to the antenna and the second is strongly mismatched [5]. Signals received by the RFID reader antenna both forward and reverse communications. RFID also normally uses simple modulations such as amplitude-shift keying, phase-shift keying, and frequency-shift keying.

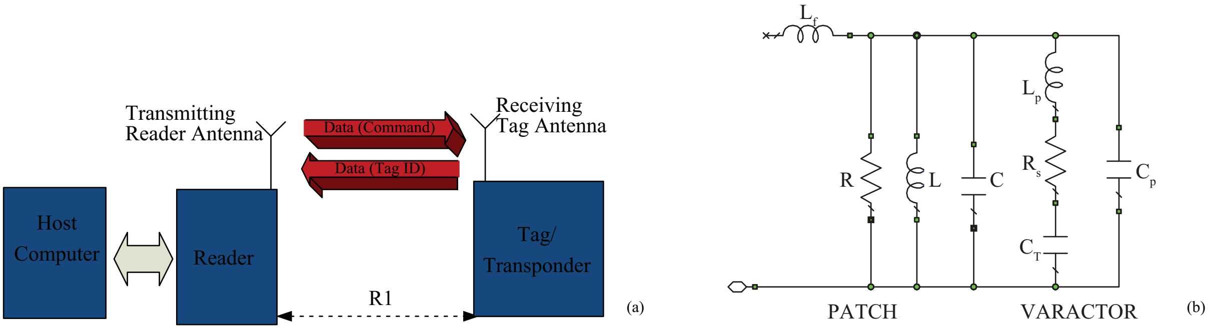

Figure 1. a. Generic backscattered RFID system. b. Equivalent circuit of varactor-loaded microstrip antenna.

The RF forward communication can be represented as shown in Figure 1a, a block diagram of a typical RFID system.

The power density at distance $R1$ from the transmitting antenna in the direction (θ_{trans}, ϕ_{trans}) is:

$$W_{trans} = \frac{P_{trans}G_{trans}(\theta_{trans}, \phi_{trans})}{4\pi R_1^2} \tag{1}$$

where P_{trans} is the input power of the transmitting antenna and G_{trans} is the gain of the transmitting reader antenna. $P_{trans}G_{trans}$ is called the reader-transmitted equivalent isotropic radiated power (EIRP). The power received by the RFID tag antenna is expressed by the following antenna formula [5]:

$$P_{tag} = W_{trans}G_{tag}(\theta_{tag}, \phi_{tag})\frac{\lambda^2}{4\pi}\left|\rho'_{trans}.\rho'_{tag}\right|^2 \quad . \tag{2}$$

The surface waves that flow on the antenna get excited and travel along the dielectric substrate. When these waves reach the edges of the substrate, they are reflected, scattered, and diffracted, causing a reduction in gain and an increase in end-fire radiation and cross-polar levels. This also increases the cross-coupling between the array elements. The excitation of surface waves is a function of ε_r and h. The power loss in the surface waves increases with an increase in the normalized thickness, h/λ_0, of the substrate. The loss due to surface waves can be neglected when h satisfies the below criterion [6].

$$\frac{h}{\lambda_0} \leq \frac{0.3}{2\pi\sqrt{\varepsilon_r}} \tag{3}$$

2.2. Varactor-loaded active compact antenna

The equivalent circuit of a rectangular microstrip antenna is a parallel combination of resistance R, inductance L, and capacitor C. According to the modal expansion cavity model, the values of R, L, and C are given as below [7].

$$C = \frac{\varepsilon_0\varepsilon_e l\omega}{2h}\cos^{-2}(\pi d/l) \tag{4}$$

$$L = \frac{1}{\omega^2 C} \tag{5}$$

$$R = \frac{Q_r}{\omega C} \tag{6}$$

$$Q_r = \frac{C\sqrt{\varepsilon_r}}{4fh} \tag{7}$$

Here, c is velocity of light, d is the feed-point location, $\omega = 2\pi f_r$, fr is the design frequency, Qr is the radiation quality factor, and ε_e is the effective permittivity of the medium. The varactor diode when reverse-biased is shown in Figure 1b, in which L_p and C_p represent the parasitic inductance and capacitance associated with the mounting and packaging of the device. R_s is the spreading resistance associated with the finite thickness of the epitaxial layer as well as the ohmic contact of the diode, and C_T is the bias-dependent capacitance, which is used to obtain the tunable resonance frequency in the microstrip antenna [8,9].

3. Tag antenna structure

This study was simulated on an FR4 substrate with relative permittivity of 4.6, width of 1.6 mm, and dimensions of 103 × 33 mm^2. The fractal dipole antenna has a rectangular fractal shape. The antenna consists of a loop for feeding and a meandered dipole, which are coupled inductively. The proposed miniaturized RFID tag antenna is shown in Figure 2. The structure incorporates an antenna element, feeding and short circuit pins, and 3 RF varactor diodes, as illustrated.

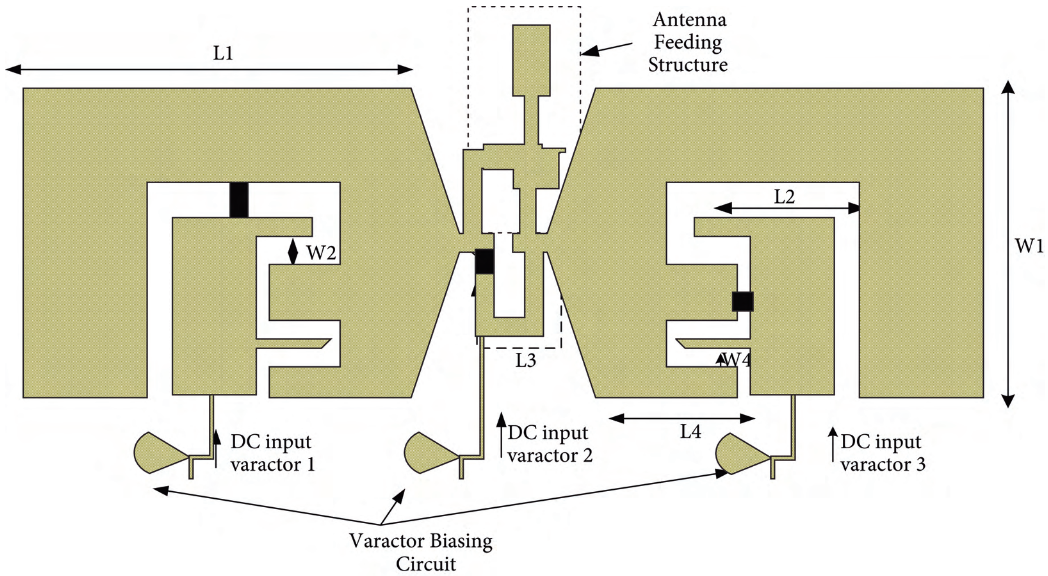

Figure 2. Schematic of the proposed varactor-loaded antenna for RFID tag.

The fractal dipole antenna has a rectangular compact shape and a pair of meander patches with a metal length of 23 mm and a width of 1 mm; there is an end gap distance of 2 mm between the meander patch end and the feed microstrip line. The optimal dimensions of the proposed antenna are W_1 = 33 mm, L_1 = 41.5 mm, W_2 = 3 mm, W_3 = 2 mm, L_2 = 9.3 mm, L_3 = 23 mm, and L_4 = 15.2 mm. The dimensions of the antenna were first studied with AWR Microwave Office simulation electromagnetic software and then verified by the experiment. Details of the proposed antenna and results of the prototypes are discussed below. To observe the tag's response for the proposed tag antenna shown in Figure 2, the antenna's performances were measured using the measurement system shown in Figure 3.

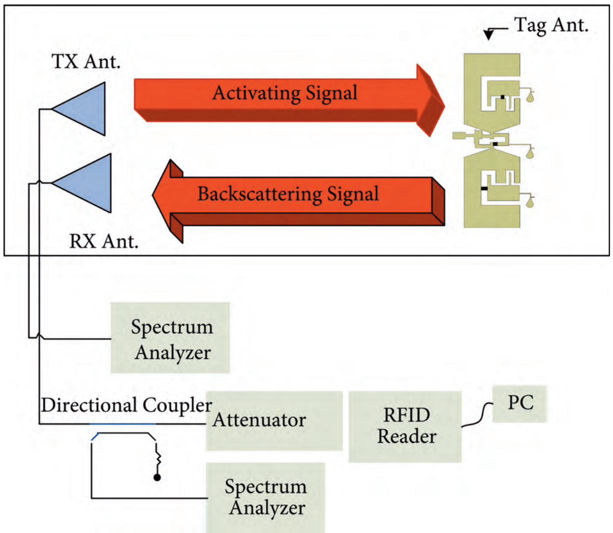

Figure 3. Measurement setup.

Moreover, various positions of varactor diodes on the proposed antenna were studied in order to enhance the performance of the system by making it reconfigurable. Effects of different combinations of ON-OFF conditions at proper DC biasing voltages on the return loss were observed and analyzed. A low-impedance, quarter-wavelength, open-circuited, radial shunt stub to an RF short circuit was used for varactor DC biasing circuit. The advantages of this type of stub are that it creates low impedance to the ground at a precise point, and its physical length is shorter than the equivalent transmission line.

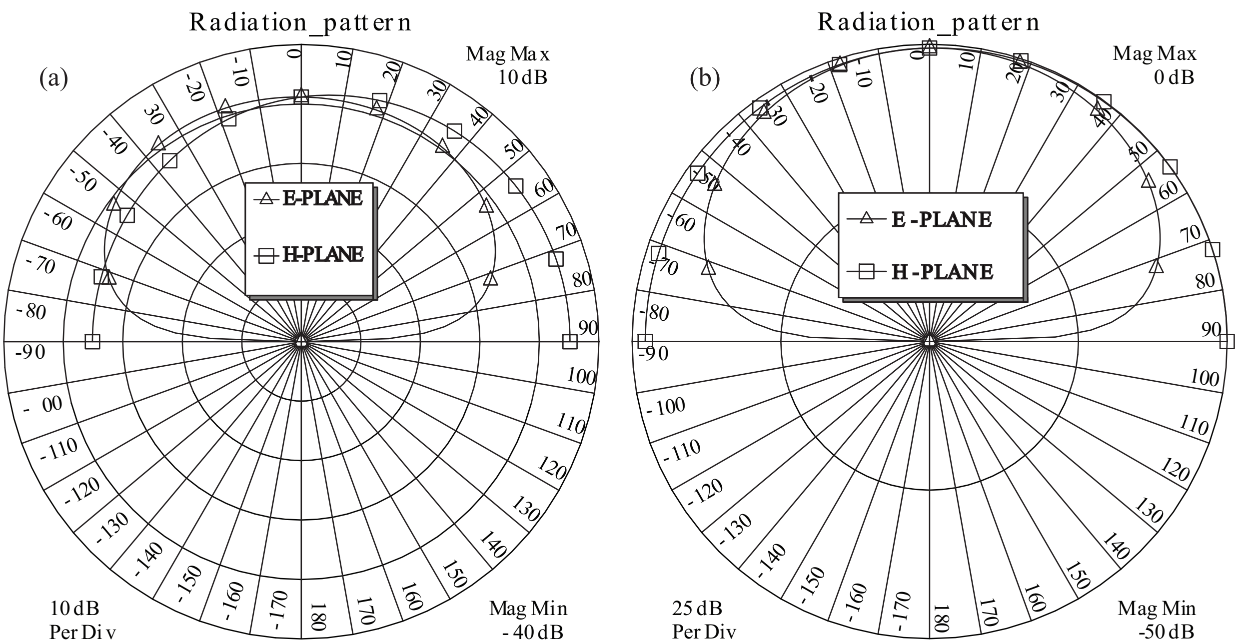

Figure 4. Radiation pattern comparisons of proposed antenna: a) radiation patterns of proposed antenna with all varactors OFF at 2.4 GHz, b) radiation patterns of proposed antenna with all varactors ON at 2.4 GHz.

The performance was measured in terms of the tag antenna's response, impedance bandwidth, and radiation pattern. Based on the backscattering method, the measurement of the tag antenna was carried out in a clean room. The total measurement system included a transmitting and receiving system. The transmitting system consists of a RFID reader (MR3002A) [10] and reader antenna, and it transmits a wake-up signal to the tag antenna. The receiving system consists of a receiving antenna and a spectrum analyzer, and it detects a backscattering signal power from the tag antenna.

4. Experimental results

At the operating frequency, the radiation patterns of the proposed slot antenna were calculated to compare antenna performances while all varactors were OFF and ON, as depicted in Figures 4a and Figure 4b. There was an apparent improvement in the radiation pattern with the varactor-loading effect.

To verify the effects of the varactors, the antenna was simulated with bias lines of different DC bias voltage values; the resonance-shifting changes are illustrated in Figures 5a-5c. There is good agreement between the

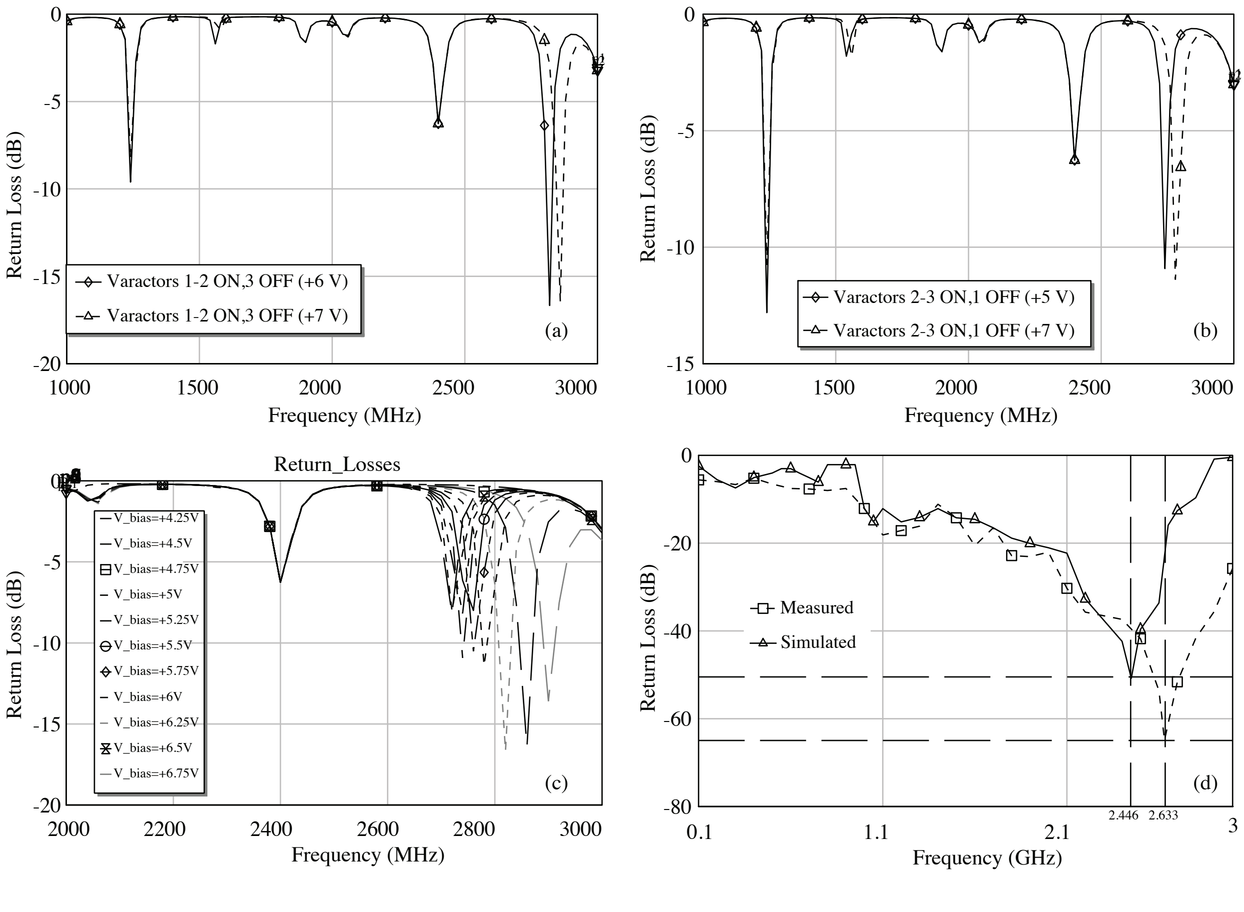

Figure 5. Effects of varactor-loading technique on return loss performance of proposed antenna: a) simulated return loss of varactor-loaded proposed antenna (varactors 1 and 2 ON, 3 OFF, V = +6 V; varactors 1 and 2 ON, 3 OFF, V = +7 V), b) simulated return loss of varactor-loaded proposed antenna (varactors 2 and 3 ON, 1 OFF, V = +5 V; varactors 2 and 3 ON, 1 OFF, V = +7 V), c) return loss of the proposed antenna at ISM band for various DC bias voltage while all varactors are ON, d) comparison of measured and simulated return loss of proposed antenna while all varactors are ON.

simulated and measured return loss results shown in Figure 5d. The transmission parameter of the proposed antenna was measured, as shown in Figure 6, while all varactors were OFF.

When varactors 1 and 2 are ON and varactor 3 is OFF, the resonance is at 2.57 GHz for DC voltage +6 V. The antenna covers the frequency ranges of the ISM band within at least a 3-dB impedance bandwidth. Under the same conditions, the resonance is at 2.59 GHz for DC voltage +7 V. The measured return losses of these conditions are illustrated in Figure 7.

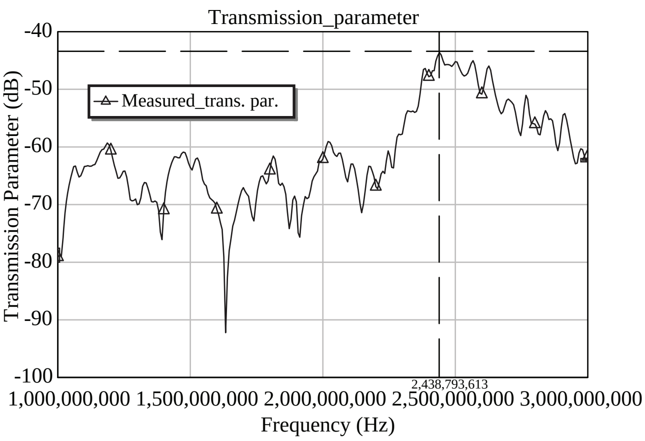

Figure 6. Measured transmission parameter of proposed antenna (all varactors OFF).

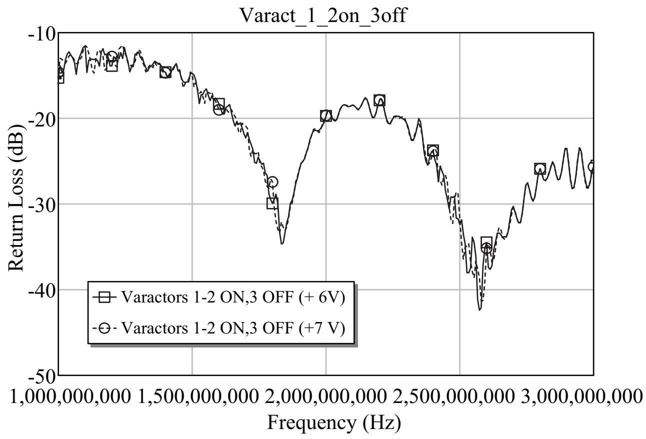

Figure 7. Measured return loss (RL) of varactor-loaded proposed antenna (varactors 1 and 2 ON, 3 OFF, RL = –42.42 dB at 2.57 GHz, V = +6 V; varactors 1 and 2 ON, 3 OFF, RL = –41.27 dB at 2.59 GHz, V = +7 V).

When varactors 2 and 3 are ON and varactor 1 is OFF, the resonance is at 2.57 GHz for DC voltage +5 V. Under the same conditions, the resonance is at 2.58 GHz for DC voltage +7 V. The measured return losses of these conditions are illustrated in Figure 8.

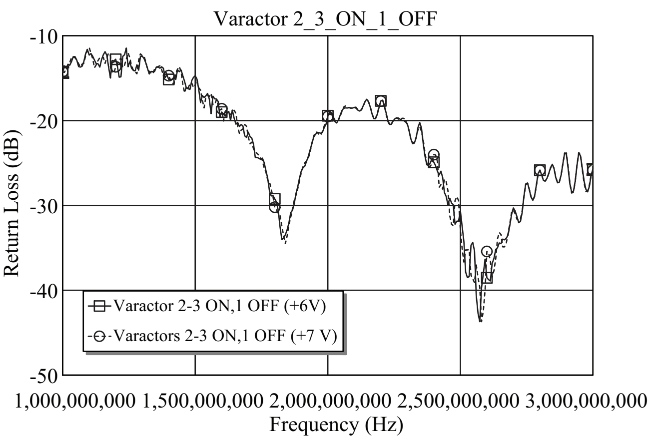

Figure 8. The measured return loss (RL) of varactor-loaded proposed antenna (varactors 2-3 ON, 1 OFF, RL = –43.70 dB at 2.57 GHz, V = +5 V; varactors 2 and 3 ON, 1 OFF, RL = –43.70 dB at 2.58 GHz, V = +7 V).

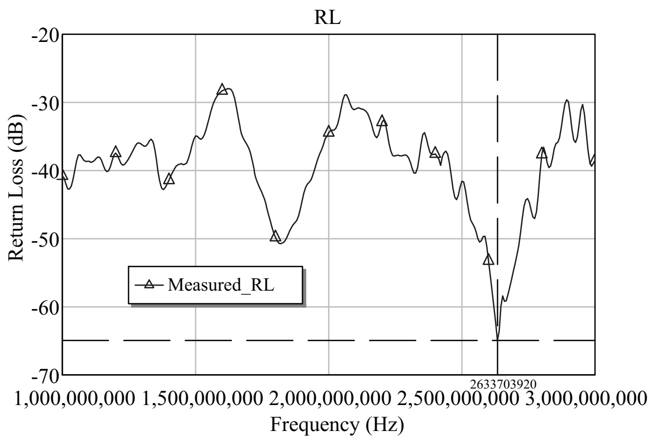

Figure 9. The measured return loss of proposed antenna without varactors (impedance bandwidth of 260 MHz).

Figure 9 shows the measured return loss of the proposed dipole tag antenna with a gap-coupled-shaped radiator without using varactors. The results of the measurement show that the proposed dipole tag antenna provides an operation frequency bandwidth of approximately 260 MHz, ranging from 2.48 GHz to 2.74 GHz. Obviously, the proposed design has sufficient bandwidth to meet the requirement of the ISM band's RFID applications.

The ON and OFF conditions for the varactors were obtained using +5 V, +6 V, +7 V, and 0 V (with a 20 mA forward current), respectively, to create the forward and reverse bias for the diode. The tag's response to the proposed antenna and reference antenna are illustrated in Figures 10 and Figure 11, respectively.

Table. Proposed antenna performance parameters.

Configuration		Resonance measured		Simulation
ε_r, h (mm)	f_r (GHz)	S_{11} (dB)	Tag's response	HPBW & gain (f_r)
4.6, 1.6	2.63 BW	–64.92	–65.56 dB	81
	(12%)		(@ 2.42 GHz)	(4.125 dB)

As a comparison between our proposed antenna and the reference antenna on a RFID tag, the tag antenna response on an MR3820A 2.45 GHz active RFID tag, shown in Figure 12, is illustrated in Figure 11.

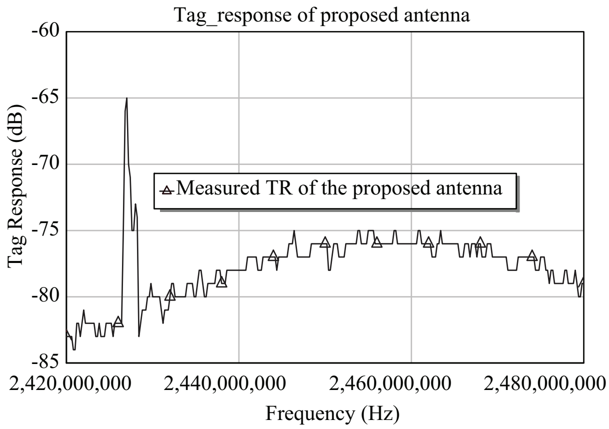

Figure 10. The measured tag's response (TR) with proposed antenna (all varactors OFF at 2.427 GHz, $W_1 = 33$ mm, $L_1 = 41.5$ mm, $W_2 = 3$ mm, $W_3 = 2$ mm, $L_2 = 9.3$ mm, $L_3 = 23$ mm, $L_4 = 15.2$ mm).

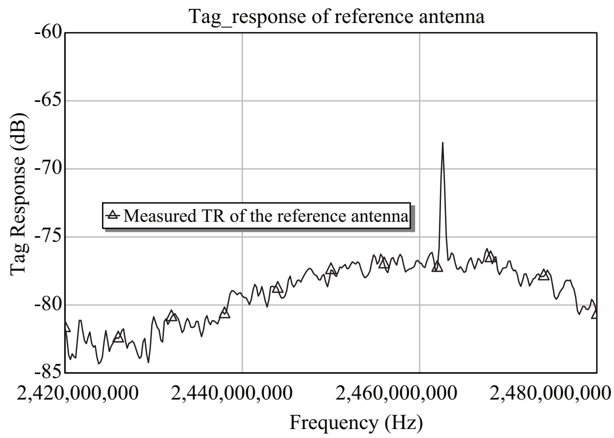

Figure 11. Measured tag's response (TR) of reference antenna on MR3820A at 2.46 GHz.

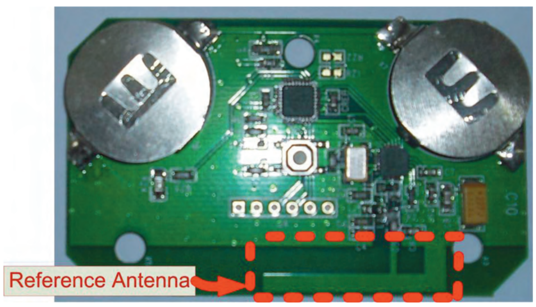

Figure 12. MR3820A 2.45 GHz active RFID tag.

In our application, the tag microchip has an input impedance of 85.0-j103.0 Ω [11]. In order to achieve the ideal impedance matching, the geometry of the feeding lines was designed to match the impedance and make a 180° phase shift. The input impedance of our tag antenna is illustrated in Figure 13.

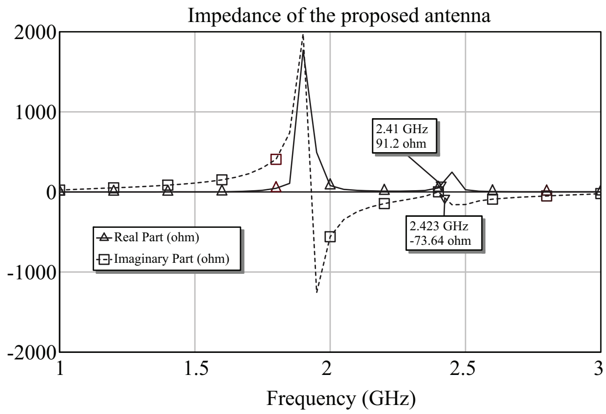

Figure 13. Simulated input impedance of proposed antenna (all varactors ON).

5. Conclusion

A compact dipole antenna was developed and could achieve a wide bandwidth and effective radiation pattern across the entire operating band. From the investigation of the RFID tag antennas, it was found that the feed structure and the compactness had a strong effect on the antenna's operating bandwidth and radiation pattern. Simulation and measurement results showed that by choosing a fractal shape and a metal meander patch and tuning their dimensions, the operating bandwidth was 12% and stable radiation patterns could be obtained. The tag antenna response was measured as –65.56 dB at the 2.42 GHz ISM band while the reference antenna response was measured as –68.07 dB at 2.46 GHz. In addition, a novel frequency tuning method for compact dipole antennas was proposed and validated through practical measurements. In this method, the tuning circuit is built into the antenna element by using discrete reactive passive components to form separate paths for the RF signal and the DC voltage, the latter being used to control the state of the active component. The DC voltage is applied to the antenna with the RF signal, and the tuning circuit is completely integrated. The effectiveness of the tuning method was demonstrated with a double-feed dipole antenna tuned with a RF varactor diode switch to operate in the ISM frequency band.

Furthermore, good simultaneous matching was observed at the ISM band for the entire range of bias voltages, low levels of cross-polarized radiation were observed, and the radiation patterns of the band remained practically unchanged as the DC bias voltage was changed. RF microelectromechanical system components or RF varactors may be used to further improve the electrical performance and functionality of the antennas.

A Rohde & Schwarz FSH6 Spectrum Analyzer was used for scattering parameter measurements and the tag's responses were measured with Auburn Technology's P-20A 3 GHz RF Probe.

Acknowledgments

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