NEAR-FIELD UHF RFID READER ANTENNA DESIGN

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SUMMARY

The objective of this work is to design near-field UHF RFID reader antennas with wide coverage areas and long detection distances. The design challenge lies in creating reader antennas that are electrically large yet capable of providing strong and even field distribution within its interrogation zone. In this thesis, three designs of near-field UHF reader antenna, namely, a top-to-bottom coupled segmented loop antenna, a side-by-side coupled segmented loop antenna, and a loop antenna with phase shifters are proposed.

The top-to-bottom coupled segmented loop antenna is presented for near-field UHF RFID applications. The proposed antenna, with an overall size of $175 \times 180 \times 0.5$ mm$^3$, is shown to achieve a large interrogation zone of $160 \times 160$ mm$^2$. Using segmented lines, the current along the proposed antenna is kept in phase even though the perimeter of the loop is of two operating wavelengths. The proposed segmented loop antenna is shown to generate strong and even magnetic field distribution in the near-field zone over a frequency band of 840–960 MHz (13.3%). Good impedance matching is observed over the frequency band of 840–1270 MHz (40.8%). The proposed antenna, compared to a commercial near-field UHF RFID reader antenna, extends the detection range by 2.5 times. It achieves a 100% reading rate at a tag reading distance of 60 mm within a given interrogation zone.

The side-by-side coupled segmented loop antenna is introduced to incorporate the segmented structure on a single surface of substrate for the ease of fabrication. Single directed current is coupled through the segmented structure of the electrically large antenna to provide strong and even magnetic near-field distribution. The proposed antenna has the overall size of $175 \times 180 \times 0.5$ mm$^3$. It achieves a large interrogation
zone of $160 \times 160$ mm$^2$. Although the proposed antenna has an electrical size of 1.88 times the operating wavelength, it affords strong and even magnetic field distribution in the near-field zone over a frequency band of 840–960 MHz (13.3%). The proposed antenna prototype achieves good impedance matching over 820–1050 MHz (24.6%). It provides a 100% reading rate for a detection range of 36 mm. This is a 1.5 times increase in the detection distance compared to that of a commercial near-field UHF RFID reader antenna.

A loop antenna with phase shifters is proposed for near-field UHF RFID applications. Phase shifters are introduced to provide a 180° phase shift to the phase-inversed current. With that, the current flowing along the loop antenna is kept in a single direction. The proposed antenna is shown to exhibit strong and even magnetic field distribution in the near-field zone over a frequency band of 900–930 MHz (3.3%), despite its large physical size of $208 \times 143 \times 0.5$ mm$^3$. The antenna is shown to provide a large interrogation zone of $110 \times 110$ mm$^2$. Good impedance matching is achieved over 730–940 MHz (25.1%). The proposed antenna prototype, compared with a conventional loop antenna with similar interrogation zone, is shown to double the detection distance. It affords an 80% reading rate for a detection range up to 24 mm.
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### LIST OF SYMBOLS AND ABBREVIATIONS

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<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tr>
<td>CP</td>
<td>Circular Polarization</td>
</tr>
<tr>
<td>dB</td>
<td>Decibels</td>
</tr>
<tr>
<td>HF</td>
<td>High Frequency</td>
</tr>
<tr>
<td>ID</td>
<td>Identification</td>
</tr>
<tr>
<td>LF</td>
<td>Low Frequency</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RFID</td>
<td>Radio Frequency Identification</td>
</tr>
<tr>
<td>SMA</td>
<td>Sub-miniature A Connector</td>
</tr>
<tr>
<td>UHF</td>
<td>Ultra High Frequency</td>
</tr>
<tr>
<td>VNA</td>
<td>Vector Network Analyzer</td>
</tr>
<tr>
<td>$C$</td>
<td>Capacitance</td>
</tr>
<tr>
<td>$E$</td>
<td>Electric field</td>
</tr>
<tr>
<td>$H$</td>
<td>Magnetic field</td>
</tr>
<tr>
<td>$H_z$</td>
<td>Magnetic field in $z$-direction</td>
</tr>
<tr>
<td>$L$</td>
<td>Inductance</td>
</tr>
<tr>
<td>$x$</td>
<td>Rectangular coordinate</td>
</tr>
<tr>
<td>$y$</td>
<td>Rectangular coordinate</td>
</tr>
<tr>
<td>$z$</td>
<td>Rectangular coordinate</td>
</tr>
<tr>
<td>$\varepsilon_r$</td>
<td>Relative permittivity</td>
</tr>
<tr>
<td>$\tan\delta$</td>
<td>Loss tangent</td>
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<tr>
<td>$S_{21}$</td>
<td>Transmission function of a transmitting/receiving antenna pair</td>
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CHAPTER 1 : INTRODUCTION

This introductory chapter presents an overview of this thesis. It serves as the prelude for the chapters following this. It highlights the background information of the near-field UHF RFID reader antenna, the objective and the motivation of the research. It ends with the outline of the thesis.

1.1 Background

Radio frequency identification (RFID), which was developed around World War II, is a technology that provides wireless identification and tracking capability [1], [2]. RFID systems employ semiconductor-based wireless technology to identify and track objects. Such systems enable us to simultaneously read or write multiple tags and activate remote sensing devices based on their unique IDs [3].

Generally, the RFID systems at the low frequency (LF, 125−134 KHz) and the high frequency (HF, 13.56 MHz) bands are based on the inductive coupling to provide power transfer and data transmission between a reader antenna and a tag while the RFID systems at the ultra-high frequency (UHF, 840−960 MHz) and the microwave (2.4 GHz and 5.8 GHz) bands are based on the propagation of electromagnetic waves to transfer the information between a reader and a tag [4]. Currently, the near-field ultra-high frequency (UHF) RFID technology receives a lot of attention due to its promising opportunities in item-level RFID applications such as item-level tracking of sensitive products, pharmaceutical logistics, transports, medical products and bio-sensing applications [5]–[16].
One of the challenges in near-field UHF RFID applications is the design of reader antennas with large coverage areas and longer detection distances. Conventional solid-line loops have been used as reader antennas in the low frequency (LF) and the high frequency (HF) RFID systems for many years [3]. Usually, electrically small loops (i.e. the perimeter of a loop antenna $C < \lambda/2\pi$, where $\lambda$ is the operating wavelength) are capable of producing strong and uniform magnetic field in the region near the antenna. However, UHF RFID applications require a reader antenna with a large coverage (for example, $150 \times 150$ mm$^2$). The loop antenna which offers such a large interrogation zone is no longer electrically small. The conventional solid-line loop with a perimeter comparable to one operating wavelength cannot produce even magnetic field distribution in the near-field zone of the antenna because the current distribution along the loop experiences phase-inversion and current nulls. The magnetic field is relatively weak in certain regions of the interrogation zone, which degrades the reliability of the RFID tag detection.

1.2 Objective

The objective of this thesis is to design near-field UHF RFID reader antennas. The antennas designed are capable of providing wide coverage areas and long detection distances in the near-field zone of the antennas.

1.3 Research Motivation

Loop antennas are normally used as reader antennas in the LF and the HF RFID systems [17]. When a loop antenna is less than half-a-wavelength at its operating frequency, it provides strong and even magnetic field distribution in the direction
perpendicular to the surface of the loop [18]–[21]. Such characteristic is desirable for the RFID tagging systems. This is because when the loop is of the length less than 0.5 $\lambda$, current flows in a single direction. Such current flow produces magnetic fields which are added in the center region of the loop antenna. As a result, the magnetic field distribution at the space enclosed by the loop is strong and even. The tags located in this area will be effectively detected. However, when the operating frequency of the antenna rises to the UHF band, the antenna physical size greatly decreases. This reduction of area limits the number of tags to be detected at a single read.

If the electrical size of the conventional loop antenna at the UHF band were to be enlarged, the loop antenna cannot produce uniform magnetic field as the current flowing in the loop features nulls and phase-inversion along the circumference. As a result, the antenna produces relatively weak magnetic field in certain regions of the antenna and this affects the tag detection.

Therefore, the design challenge of the near-field UHF RFID reader antenna lies in creating an electrically large reader antenna with strong and uniform magnetic near-field distribution in the interrogation region.

1.4 Thesis Overview

In the thesis, three designs of near-field UHF RFID reader antenna are proposed. The configuration of each design is given. It is followed by the explanation in the principle of the proposed antenna operation. Then, the antenna design guidelines are stated. The parametric study is performed on the proposed antenna. After that, the proposed antenna is being prototyped. The measurement of the antenna prototype is
conducted to verify the design. After that, comparison between the proposed antennas is given. At last, concluding remarks of the proposed antenna are provided.

1.5 Thesis Outline

The thesis consists six chapters. Chapter 1 provides a brief introduction of the near-field UHF RFID antenna. The research objective, research motivation, thesis overview and thesis outline are presented under this chapter.

In Chapter 2, the literature review on the near-field UHF RFID antenna is conducted. The aspects reviewed are the field regions of the antenna, the advantages of the near-field UHF over the traditional HF RFID systems, the near-field UHF RFID systems, and the near-field UHF RFID reader antenna designs.

In Chapter 3, a top-to-bottom coupled segmented loop antenna is introduced. The antenna configuration is presented. The principle of the antenna operation is discussed. Design procedures of the top-to-bottom coupled segmented loop antenna are stated and the explanation on methods of interpreting the performance of the near-field antenna is given. A parametric study performed on such antennas is disclosed and measurement results of the antenna prototype are presented. Concluding remarks on the top-to-bottom coupled segmented loop antenna are given.

In Chapter 4, a side-by-side coupled segmented loop antenna is proposed. The antenna configuration is provided. The principle of the antenna operation is presented. After that, design procedures of the side-by-side coupled segmented loop antenna are stated. The performance of the segmented antenna is analyzed. A parametric study performed on the antenna is presented and measurement of the antenna prototype is conducted to verify the design. The performance of the top-to-bottom coupled and the
side-by-side coupled segmented loop antenna is compared. Concluding remarks on the side-by-side coupled segmented loop antenna are provided.

In Chapter 5, a loop antenna with phase shifters is introduced. The antenna configuration is presented, the principle of the antenna operation and the procedures of the antenna design are provided. The explanation on methods of interpreting the performance of the near-field antenna is given. A parametric study is performed on the proposed antennas and the antenna prototypes are measured. Comparisons between the loop antenna with phase shifters and the segmented antennas proposed in Chapter 3 and 4 are made. Concluding remarks on the loop antenna with phase shifters are given.

In Chapter 6, the important results presented in the previous chapters are summarized, the conclusion on this work is given, and suggestions for future work are provided.
CHAPTER 2 : LITERATURE REVIEW

Literature review was conducted with the purposes of obtaining theoretical background needed in the research topic and gaining the current techniques and applications involved in the research topic. In this chapter, the aspects reviewed are the field regions of the antenna, the operation of the near-field RFID systems, advantages of the near-field UHF over HF RFID systems, design challenges of the near-field UHF RFID antenna, and the designs of the near-field UHF RFID reader antenna.

2.1 Antenna Field Regions

The space around an antenna can be divided into two main regions: the far-field region and the near-field region, depending on the nature of the electromagnetic field produced by the antenna. Although no abrupt changes in the field configurations are noted between the boundaries, there exist distinct differences among these regions \([22]–[28]\). The near-field region can be further divided into two sections, namely, the reactive near-field region and the radiating near-field region. Fig. 2.1 shows the field regions for an electrically small and an electrically large antenna.

![Antenna field regions](image)

Fig. 2.1. Antenna field regions: (a) electrically small antenna and (b) electrically large antenna.
2.1.1 Reactive Near-field Region

The reactive near-field region is the immediate surrounding space enclosing the antenna. In the reactive near-field region, the energy is stored in the electric and the magnetic fields but not radiated. This energy is exchanged between the signal source and the fields. In near-field region, the ratio of the quasi-static magnetic and electric is no longer $377\,\Omega$. Either the electric (E) field or the magnetic (H) field can be the dominant component of the energy. For an electric dipole, the E-field components dominate. For a magnetic dipole, or a loop, the H-field components dominate.

For electrically small antennas, wherein the maximum antenna dimension is small compared to an operating wavelength $\lambda$, the reactive near-field boundary is given by:

$$ r = \frac{\lambda}{2\pi} \quad (1) $$

For electrically large antennas, the reactive near-field boundary is described by:

$$ r = 0.62 \sqrt[3]{\frac{D^3}{\lambda}} \quad (2) $$

where $D$ is the largest dimension of the antenna.

2.1.2 Radiating Near-field Region

In the radiating near-field region, the angular field distribution is dependent on the distance from the antenna. The energy is radiated as well as exchanged between the source and a reactive near field. In this region, the amplitude pattern of the antenna begins to smooth and forms lobes. If the antenna is electrically small, this field region may not exist. For the electrically large antennas, the boundary of the region is defined by
\[ 0.62 \sqrt{\frac{D^3}{\lambda}} \leq r \leq \frac{2D^3}{\lambda} \quad (3) \]

2.1.3 Far-field Region

In the far-field region, electric and magnetic fields propagate outward as an electromagnetic wave and are perpendicular to each other and to the direction of propagation. The angular field distribution does not depend on the distance from the antenna. The fields are uniquely related to each other via the free space impedance (377 Ω). In far-field region, EM wave decays as \(1/r\). The amplitude pattern at this region is well formed, usually consisting of major and minor lobes. If the antenna has a maximum overall dimension \(D\), the inner boundary of far-field region is given by

\[ r = \frac{2D^3}{\lambda} \quad (4) \]

2.2 Operation in Near-field RFID Systems

In the passive RFID system, power is transferred from reader to tag. The tag, upon receiving the energy from the RFID reader, is being induced and transfer energy back to the reader with required information needed by the reader [29].

In near-field, the quasi static and the inductive components are the main components of the electromagnetic field. The electric field is decoupled from the magnetic field. For a loop antenna, the magnetic field dominates in the near-field zone. For a dipole antenna, the electric field dominates the near field zone. The dominant field in the near-field zone is used as the coupling mechanism for the RFID system. The RFID system with loop antenna uses inductive coupling while the RFID system with dipole antenna adopts capacitive coupling for transfer of information in the near field zone [3].
In the inductive coupling, as illustrated in Fig 2.2, a loop antenna from the RFID reader produces strong magnetic field in the near field region. The varying magnetic field, upon reaching the near-field tag, creates alternating voltage across the RFID tag. The RFID tag, consists of a loop antenna with inductance $L$, and capacitors with capacitance $C$ (forming $LC$ circuit), produces large alternating current at the resonant frequency [30]. The alternating current will then produces magnetic field that propagates to the reader. Meanwhile, the chip of the tag antenna, which is of variable load impedance, will vary the impedance to encode information on the magnetic field which is then propagated back to the reader.

For the capacitive coupling, a dipole antenna is adopted. The charge distribution across the dipole reader antenna provides electric fields to be coupled to the dipole tag antenna. The tag antenna, upon receiving the varying electric field, will then generate an electric field propagating back to the RFID reader.

In the near-field RFID system, the inductive coupling is widely being used. Unlike the electric field, the magnetic field is less susceptible to the absorption when it propagates through a medium with high magnetic permeability. It is suitable for operation in the close proximity of metals and liquids. In contrast, the capacitive coupling systems are hardly used in practical applications as the energy is stored in electric field and it is severely affected by objects with high dielectric permittivity and loss [31]–[34].

Fig. 2.2. Inductive coupling mechanism of near-field RFID [3].
2.3 HF and Near-field UHF RFID Systems

The high frequency (HF) band ranges from 3 to 30 MHz. The HF RFID system uses the frequency of 13.56 MHz. It normally adopts near-field magnetic coupling for item-level tagging and seldom uses far-field as communication mode [3]. HF tags are often found on library books, transportation tickets, garments and pharmaceutical products [7].

Ultra high frequency (UHF) accommodates the frequency band from 300 MHz to 1 GHz. The UHF RFID adopts 840 to 960 MHz to cover the bands allocated by different countries [4]. The UHF RFID works in both the near-field and the far-field. In the near-field UHF RFID systems, one can apply the magnetic (inductive) coupling or the electric (capacitive) coupling to achieve information transfer between a reader and a transponder [5]. In the far-field UHF RFID, information is transferred using electromagnetic (EM) wave. In the far field, the polarization of the EM wave is a factor that needs to be taken into account in order to achieve better efficiency in transmission and reception [5]. The ability of UHF RFID systems to work in the near-field and the far-field has made them possible to cover all types of RFID application from item-level tagging to pallet-level tagging [35]. This has inspired the researchers and engineers to explore the possibilities in applying the near-field UHF RFID systems.

Table 2.1 Advantages of near-field UHF over traditional HF RFID systems

<table>
<thead>
<tr>
<th>Near-field UHF</th>
<th>HF</th>
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<tbody>
<tr>
<td><strong>On the design of the tag antenna:</strong></td>
<td><strong>On the design of the tag antenna:</strong></td>
</tr>
<tr>
<td>• Tags can be constructed by single loop without any cross-over (bridge). The complexity of antenna</td>
<td>• Multiple loops are needed for tag antenna designs to achieve correct operating frequency. Cross-over is</td>
</tr>
</tbody>
</table>
On the interference between the tags:
- Tags can be placed very close with one another, with less interference, while accurate reading can still be achieved [36].

On the interference between the tags:
- Larger separation (compared to that of the near-field UHF) may be needed in order to have accurate reading, as interference between the tags is more severe [36].

On the data transfer rate of the RFID systems:
- Information is transferred between the tags and the reader at a higher data rate [36].

On the data transfer rate of the RFID systems:
- Information is transferred between the tags and the reader at a lower data rate compared to that of the near-field UHF RFID system [36].

Table 2.1 shows the advantages of the near-field UHF when compared to the traditional HF RFID systems. It is noticed that the near-field UHF systems require tags with small size and simple structure. The near-field UHF RFID is less susceptible to interference and tags can be placed closer to one and another while achieving accurate reading performance. Such systems provide a higher data transfer rate as compared with the HF RFID systems. As such, the near-field UHF RFID systems receive a lot of attention due to the promising opportunities in item-level RFID applications such as item-level tracking of sensitive products, pharmaceutical logistics, transports, medical products, and bio-sensing applications [5]–[16]. Such advantages spur the investigation in the design of near-field UHF RFID reader antennas to provide efficient tag detection to the RFID systems.
2.4 Overview of Near-field UHF RFID Systems

The basic concept of the near-field UHF RFID is to make the UHF RFID systems work in short distances and on different objects as reliably as that of the LF/HF RFID [4]. Similar to the LF/HF RFID systems, the coupling between the near-field UHF RFID reader antenna and the tags can be either magnetic (inductive) or electric (capacitive) [29]. Inductive coupling systems are preferred as such system is less affected by object which is of high permittivity such as metal or liquid as discussed in Section 2.3.

An excellent overview of the near-field UHF RFID can be found in [37], wherein several approaches of implementing near-field UHF RFID systems have been described. The near-field UHF RFID system can be configured using existing reader modules, reader antennas and tags. However, such system has limited performance. To achieve the best performance, a near-field UHF RFID system must adopt reader antennas and tags that are specially designed for near-field applications. This has spurred the investigation in the design of near-field UHF RFID reader antennas to provide efficient tag detection to the near-field RFID system.

From [38], it is noted that the tangential and the radial electric/magnetic field components in the near-field region of an antenna can contribute to the coupling between the reader antenna and the tag in the RFID system. In an inductively coupling RFID system, the magnetic components dominate the coupling. If the tag antenna is small, the magnetic field created by the reader antenna is not perturbed by the tag [38], [39]. The coupling coefficient is thus proportional to [38], [39]:

\[ C \propto f^2 N_{\text{tag}}^2 S_{\text{tag}}^2 B^2 \alpha \] \hspace{1cm} (5)
where $f$ is the operating frequency, $N_{tag}$ is the number of turns in tag antenna coil, $S_{tag}$ is the cross-section area of the coil, $B$ is the magnetic field density at the tag location created by the reader antenna, and $\alpha$ is the antenna misalignment loss. Formula (5) indicates that the coupling of a specific near-field RFID tag is dependent on the magnetic field generated by the RFID reader antenna. An antenna that can produce strong and even magnetic field in an interrogation zone will enhance the detection accuracy as well as the system reliability and is thus more desirable in the near-field UHF RFID system.

### 2.5 Near-field UHF RFID Reader Antenna

#### 2.5.1 Design Considerations of Near-field UHF RFID Reader Antenna

**Close detection range**

The near-field reader antenna, when connected to the near-field RFID systems, should provide good detection capability within a near-field distance [40]. The performance of the near-field reader antenna can be determined by obtaining the maximum distance of the antenna with a predetermined reading rate (e.g. the maximum distance from the antenna to achieve an 80% of tag reading rate).

**Even field distribution in the coverage area without null area**

In near-field RFID systems, RFID tags are randomly distributed over the interrogation region of the reader antenna. To ensure that tags can be detected effectively everywhere within the interrogation zone, a reader antenna with even field distribution is required. Even field distribution is important for ensuring 100% tag reading rate. With
that, the reliability of the antenna is enhanced. The near field reader antenna should provide even field across a wide coverage without null area at the near field distance.

**Physical attribute of the antenna**

The design the reader antenna should be low profile in nature, in order for it to fit in shelves [17], under conveyor belts [41], or be made portable for the item-level tagging [42].

**Object at proximity of antenna**

The reader antenna designed should function well with the existence of objects with different size, RF properties, or material compositions at the proximity of the antenna [34], [44]. The tag that is attached around metal or liquid should be effectively detected by the reader antenna adopting magnetic field in the detection mechanism of the RFID system.

### 2.5.2 Near-field UHF RFID Reader Antenna Design Challenge

Loop antennas are usually used as reader antennas in the HF RFID systems. When the loop antenna is less than half-a-wavelength at the operating frequency, it will provide strong and even magnetic field distribution which is perpendicular to the surface of the loop [18]–[21]. Such characteristic is desirable for the RFID tagging system. Fig. 2.3 shows the current distribution of half wavelength loop antennas at the HF frequency, 13.56 MHz and at the UHF frequency, 915 MHz. The results are simulated using the IE3D software package [45]. When a loop antenna is with the length less than 0.5 λ,
current flows in a single direction. Such current flow will produce magnetic fields which are added in the center region of the loop antenna. As a result, the magnetic field distribution in the region surrounded by the loop antenna is strong and even, as illustrated in Fig. 2.4. The tags located in this area will be effectively detected. However, when the operating frequency of the antenna rises to the UHF band, the physical size of the antenna greatly decreases, from $2.7 \times 2.7 \text{ m}^2$ (HF band, 13.56 MHz) to $41 \times 41 \text{ mm}^2$ (UHF band, 915 MHz). The reduction of area causes the number of tags to be detected at a single read to be reduced.

Fig. 2.3. Simulated current distribution of a half wavelength loop at different frequencies (a) HF band, 13.56 MHz and (b) UHF band, 915 MHz [45].

Fig. 2.4. Simulated 2-D magnetic field distribution of a half wavelength loop ($z = 0.5 \text{ mm}$) at different frequencies: (a) HF band, 13.56 MHz and (b) UHF band, 915 MHz [45].
If the electrical size of the conventional loop antenna at the UHF band were to be enlarged, from 0.5 $\lambda$ (41 $\times$ 41 mm$^2$) to 2 $\lambda$ (164 $\times$ 164 mm$^2$), the loop antenna cannot produce uniform magnetic field as the current flowing in the loop features current nulls and phase-inversion along the circumference [18]–[21]. As a result, the antenna produces relatively weak magnetic field in certain regions of the antenna and this affects the tag detection as exhibited in Fig. 2.5.

Therefore, the design challenge of the near-field UHF RFID reader antenna lies in creating an electrically large reader antenna with strong and uniform magnetic field distribution in the interrogation region.

2.5.3 Prior Arts

Frank [46] had proposed a spiral antenna (Fig. 2.6), with the area of 400 $\times$ 300 mm$^2$ that is 20 mm above the ground plane as a near-field UHF RFID reader antenna. The operating frequency is in the UHF region, 900 MHz. The antenna designed is
claimed to have uniform strong near field in vicinity of the antenna. The antenna is claimed to be able to read over an area of $200 \times 200 \text{ mm}^2$. In the simulation results, the electric field variation is within 5dB along a horizontal direction at a height of 50 mm, as exhibited in Fig. 2.7. However, electrical (E) field components dominate in the near-field of such antenna and they are easily affected by surrounding objects which are of high permittivity and loss such as metal and liquid.

Fig. 2.6. Spiral antenna for near field application [46].

Fig. 2.7. Simulated electric field of the antenna across a horizontal line at a height of 50 mm across the antenna [46].
Liu and Hilegass [41] designed a three-patch antenna to detect boxes going through a conveyor belt. The antenna is able to provide circularly polarized (CP) far-field radiation and near-field radiation. The antenna, having the overall size of $28 \times 20 \times 0.8$ inches cube, is designed using the PCB of 0.26 inches thick with the permittivity of 1.13. Both reader antennas are designed to function at the frequency of 915 MHz. The authors stated that by changing the CP direction of the far-field antenna, near-field design can be achieved (Fig. 2.8). The characteristic of the near-field design is that the far-field gain is reduced and the near-field electric strength distribution can be controlled so that the reader is only able to read the box above the antenna while not able to read the adjacent box (Fig. 2.9). The design, however, is an array design and switching control is needed to control the near-field distribution across the arrays of antenna. In this design, the E-field components dominate in the near-field of such antenna and thus are easily affected by surrounding objects with high permittivity and loss such as metal and liquid.

![Fig. 2.8. (a) 3-patch antenna for RFID operation (a) far-field operation (b) near-field operation][41]
Dobkin et al. [47] proposed a segmented magnetic antenna for a near-field UHF RFID reader antenna. The loop antenna is separated by capacitors of 1.2 pF (Fig. 2.10). The capacitors, together with the inductances introduced on the segmented lines, create resonant structures. As a result, current on the segmented antenna can be kept in a single direction. However, the impedance matching bandwidth of the antenna is narrow (890–930 MHz or 4.4%) in nature and the introduction of electronic components on antenna
consumes the energy provided by the source. Besides that, the size of the antenna is not sufficiently large (the antenna only has a diameter of 50 mm).

Fig. 2.10. The proposed segmented antenna with capacitors (a) the real model and (b) the equivalent circuit [47].

A broken loop antenna [48] is patented by Oliver, for the Impinj Inc. US company. The antenna operates at the UHF bands. The antenna consists of three broken loops. The antenna is claimed to work in both the near-field and the far-field regions.
CHAPTER 3 : TOP-TO-BOTTOM COUPLED SEGMENTED LOOP ANTENNA

In this chapter, the top-to-bottom coupled segmented loop antenna is proposed. First, the antenna configuration is presented. This is followed by the discussion of the principle of antenna operation. After that, design procedures of the top-to-bottom coupled segmented loop antenna are stated. Then, the performance of the segmented antenna is analyzed. A parametric study is performed on the proposed antenna. Measurement of the antenna prototype is conducted to verify the design. At last, concluding remarks on the top-to-bottom coupled segmented loop antenna is provided.

3.1 Antenna Configuration

Fig. 3.1 shows the scheme of the proposed top-to-bottom coupled segmented loop antenna. A Cartesian coordinate system is oriented in such a position that the upper surface of the substrate lies in the $x$-$y$ plane. The center of the square segmented loop is located at the origin of the coordinate system.

The segmented loop antenna is made up of two dashed-line loops. Each of the line loops is symmetrically structured with respect to the $y$-axis. The dashed-lines are printed on the top and the bottom of a substrate as shown in Fig. 3.1. The dashed-line on the top of the substrate loop is composed of several line sections with the same length, $L_{\text{top}}$, except for the first two sections, each with the length of $L_{\text{top0}}$. These first two line segments are connected to the parallel feed lines for the purpose of impedance matching.
The dashed-line loop on the top of the substrate is indicated with the line width, $W$, and the spacing between the adjacent line-sections is indicated with the space width, $S_{\text{top}}$.

The dashed-line loop on the bottom of the substrate, on the other hand, is open ended. Each segmented strip on the outer loop is of equal length, $L_{\text{bot}}$. The line width of the outer loop is indicated with the line width, $W$, and each line section is separated with the space width, $S_{\text{bot}}$, except for the first and the last section of the outer loop at the bottom of the antenna, which are separated with a larger space width, $S_{\text{bot0}}$.

These two loops are separated by a distance, $H$. Besides that, these two dashed-line loops are positioned in such a way that the broken points of the dashed-lines printed on the top layer are located around the middle points of the dashed-lines printed on the bottom layer, and vice versa. The internal area $(a \times a)$ of the dashed-line loops is indicated as the interrogation zone with a perimeter of $4a$.

The antenna is fed by a pair of parallel strip line with a strip width of $W_f$. A matching circuit can be used to achieve required antenna impedance matching over a specific frequency range.

The size of the antenna is determined by the perimeter of the segmented loop antenna. It should be noted that the impedance matching circuits are not considered in determining the perimeter of the antenna.

The antenna is printed on both the top and bottom of a substrate with a relative permittivity, $\varepsilon_r$, a substrate thickness $H$, and a loss tangent of $\tan\delta$ as exhibited in Fig. 3.1(c). The 3D view of the antenna is provided in Fig. 3.1(d).
(a)

(b)

(c)
Fig. 3.1. Configuration of the proposed top-to-bottom coupled segmented loop antenna: (a) top layer (b) bottom layer, (c) side view and (d) 3D view.
3.2 Principle of Operation

The near-field distribution of a loop antenna can be first studied by observing the current distribution on the particular antenna. Fig. 3.2 shows the comparison of simulated current distribution between the conventional solid line loop antenna and the proposed top-to-bottom coupled segmented loop antenna. Each of the antennas has the size of $2\lambda$, where $\lambda$ is the corresponding free space wavelength at the operation frequency of 915 MHz.

For a conventional loop, as current moves along the antenna, current phase will be accumulated. The accumulation of current phase is due to the impedance imposed when the current is forced to move around the antenna. As the current moves around $0.5\lambda$ on the antenna, current null will occur. The direction of current flow changes in every $0.5\lambda$ along the loop. Fig. 3.2(a) exhibits the current distribution of a square solid loop antenna with an electrical size of $2\lambda$. Due to the fact that each side of the square loop is about $0.5\lambda$, current flows in opposite direction in adjacent sides of the loop. The magnetic fields in produced in the $z$-axis, $H_z$, by these currents cancel one and another. As a result, the field intensity of the antenna is thus very weak in the center portion of the antenna, as exhibited in Fig. 3.3(a). This situation is not desired in the near-field RFID reader antennas as RFID tags located at the center portion of the antenna cannot be effectively detected.

The problem encountered in the electrically large conventional loop antenna can be resolved using segmented structures. Since the strips on the antennas are not physically connected, current flows from one strip to another (between top and bottom layer) through coupling. The segmented structure has a unique characteristic: it is capable
of providing a very small phase delay when the current flows through the adjacent sections. As a result, the current is kept flowing in a single direction along the proposed segmented loop antenna. The magnitude of the current is also being maintained at an almost equal value even though the loop is electrically large (> 0.5 λ). The magnetic fields produced in the z-direction are thus being added up. The antenna hence exhibits strong and even distribution over the interrogation zone (Fig. 3.3(b)). Such magnetic field distribution is preferred for the near-field UHF RFID application as the tags can be effectively detected even though the size of the antenna is comparable with its operating wavelength.

Fig. 3.2. Simulated current distribution at 915 MHz: (a) conventional solid line loop antenna and (b) top-to-bottom coupled segmented loop antenna [45].
Fig. 3.3. Simulated 2-D magnetic field distribution at 915 MHz (z = 0.5 mm): (a) conventional solid line loop antenna and (b) top-to-bottom coupled segmented loop antenna [45].

3.3 Design Procedure

For a specific design with the required interrogation zone, \( a \), and the required operating frequency, \( f_0 \), the other geometrical parameters of the segmented antenna can be determined by the following procedures:

- Length of the excited line sections of the top layer dashed-line loop, \( L_{\text{top}0} \)

From the excitation point of view, the segmented loop antenna can simply be considered as a loaded dipole antenna with an arm length of \( L_{\text{top}0} \). To ensure that current flow on the dipole is in a single direction, a total dipole length (\( 2L_{\text{top}0} \)) of less than 0.5 \( \lambda \) should be used [18]–[20]. In this case, each \( L_{\text{top}0} \) must be less than 0.25 \( \lambda \). As current flows through the loop by coupling, loading effect should be considered when designing the antenna. In this example, a shorter \( L_{\text{top}0} \), with the electrical length of 0.15 \( \lambda \) is used.

- Length of the line sections of the top layer dashed-line loop, \( L_{\text{top}} \)
Based on the perimeter of the interrogation zone \((4a)\), the number of the line sections \((N)\), the width of the line sections \((W)\), the spacing between the adjacent line sections \((S_{\text{top}})\) at the top layer, and the spacing between the first two line sections \((S_0)\), the length of the top layer dashed-line sections \((L_{\text{top}})\) can be calculated by

\[
L_{\text{top}} = \frac{4a + 8W - 2L_{\text{top}0} - S_0 - (N + 1)S_{\text{top}}}{N} \tag{6}
\]

- Length of the line sections of the bottom layer dashed-line loop, \(L_{\text{bot}}\)

The bottom layer dashed-line loop is composed of \(N+1\) line sections with the length of \(L_{\text{bot}}\). Similarly, the length of the dashed-line sections can be calculated by

\[
L_{\text{bot}} = \frac{4a + 8W - S_{\text{bot}0} - NS_{\text{bot}}}{N + 1} \tag{7}
\]

where the spacing between the adjacent line sections \((S_{\text{bot}})\) at the top layer, and the spacing of the first and last line section at the bottom of the loop \((S_{\text{bot}0})\). Here, the \(S_{\text{bot}0}\) is fixed at 0.15 \(\lambda\) to provide effective coupling between the top layer dashed-line and bottom layer dashed-line.

It is suggested that the separation parameters, namely \(S_{\text{top}}\), \(S_{\text{bot}}\), and \(S_0\), should be electrically small to ensure proper coupling between the coupled segmented lines.

A matching network comprising simple stubs can be adopted to match the antenna to the 50-\(\Omega\) feed line over the desired frequencies.

### 3.4 Interpretation of Performance

The characteristics of the top-to-bottom coupled segmented loop antenna are first studied by simulation in terms of the antenna current distribution and the antenna magnetic near-field distribution. A top-to-bottom coupled segmented loop antenna
operating at $f_0 = 915$ MHz is designed. The detailed geometrical parameters of the antenna design are: $a = 154$ mm, $N = 12$, $W = 2$ mm, $H = 1$ mm, $L_{\text{top}} = 47$ mm, $S_0 = 1.3$ mm, $L_{\text{top}} = 47$ mm, $S_{\text{top}} = 1$ mm, $L_{\text{bot}} = 47$ mm, $S_{\text{bot0}} = 49.3$ mm and $S_{\text{bot}} = 1$ mm. The antenna is designed in free space and without any substrate. The feeding source is placed directly across the excitation line sections of the top layer dashed-line loop.

The segmented antenna offers an interrogation zone of $164 \times 164$ mm$^2$, or $0.5 \times 0.5 \lambda^2$ at 915 MHz. For comparison, the results of a conventional solid line loop antenna are also exhibited. Figs. 3.2 and 3.3 in the previous section (Section 3.2) compare the simulated current and the 2-D magnetic field distributions between the conventional solid line loop antenna and the segmented loop antenna at 915 MHz.

The 2-D magnetic field distribution illustrated in Fig. 3.3 provides a very good visual observation of the magnetic near-field distribution of the antenna. However, it is difficult to give a quantitative measure of the magnetic field intensity from such plots. To better quantify the magnetic field intensity, the magnetic field distribution of the antenna in the $z$-direction is being plotted along the $x$- and $y$-axes, as exhibited in Fig. 3.4.

The magnetic field intensity shown in Fig. 3.4 is extracted from the simulated 2-D magnetic field distribution in Fig. 3.3. It is observed that the magnetic field distributions are symmetrical with respect to the $y$-axis ($x = 0$ mm) for both the antennas (Fig. 3.4 (a)). Furthermore, the magnetic field features a strong magnitude in the regions very close to the loop lines ($x = -84$ mm) and decreases when the observation point is moved away from the lines.

Fig. 3.4(a) shows the comparison of magnetic field distribution between the segmented loop and the conventional solid line loop along the $x$-axis. The segmented
loop antenna offers desired magnetic field distribution with a variation of 20 dB over the entire interrogation zone (-84 mm ≤ x ≤ 84 mm) and a variation of 0.5 dB over a major portion of the interrogation zone (-60 mm ≤ x ≤ 60 mm). The solid line loop antenna, however, in Fig. 3.4(a), is not able to generate even magnetic field over the interrogation area. There exist a variation of 41 dB over the range of -84 mm ≤ x ≤ 84 mm and a variation of 20 dB over -60 mm ≤ x ≤ 60 mm.

Fig. 3.4(b) shows the magnetic field distribution along y-axis. The segmented loop antenna offers a much better magnetic field distribution than that of the solid line loop antenna. A maximum magnetic field variation of 60 dB is observed for the solid loop antenna along the y-axis while only a maximum magnetic field variation 29 dB is observed for segmented loop antenna over the range of -72 mm ≤ x ≤ 72 mm. In the range of -60 mm ≤ x ≤ 60 mm, the variation of magnetic field for solid line loop antenna is 36 dB while the variation of magnetic field for the segmented loop is 5 dB.

In addition, it is observed that the magnetic filed distribution along the y-axis is slightly asymmetrical to the x-axis. This is resulted from the asymmetric antenna geometry structure as well as the radiation and the attenuation caused by the coupled lines.
Fig. 3.4. Magnetic field distribution of the top-to-bottom coupled segmented loop antenna and the conventional solid line loop antenna (at 915 MHz, $z = 0.5$ mm): (a) $x$-axis variation, and (b) $y$-axis variation.
Fig. 3.5 shows the $x$- and $y$- axes magnetic field distribution of the segmented loop antenna at the frequencies of 700, 840, 915, 960, and 1050 MHz. The segmented antenna achieves even magnetic field distribution with little variation over the frequency range of 840–960 MHz. Such characteristic is desirable for RFID applications. When the operating frequency is shifted down to a lower frequency, such as at 700 MHz, or shifted up to a higher frequency, such as 1050 MHz, the evenness of the magnetic field distribution degrades.

At 700 MHz, the current flows in single direction along the loop. However, the magnitude of the current features a large variation (Fig. 3.6). It is observed that the current flowing on the segmented line sections located near to the feeding port is much stronger than the current flowing at the top portion of the antenna. This causes the magnetic field at the upper portion of the proposed antenna to be weaker than that at the lower portion, as exhibited in Fig. 3.7. At 700 MHz, the segmented lines are electrically short. As a result, current cannot be effectively coupled throughout the segmented loop. Such situation will in turn create asymmetrical current distribution on the antenna and produce uneven field distribution across the interrogation zone of the antenna.

At 1050 MHz, the current flowing along the loop (Fig. 3.6) exhibits phase inversion and there are obvious current nulls on the loop. As a result, the magnetic field distribution shown in Fig. 3.7 features weak field intensity in the center portion of the antenna.

It is clear that the magnetic filed distribution along the $x$- and $y$- axes demonstrate the variation of the magnetic field density produced by the antenna. For brevity, the
current distribution and the 2-D magnetic field distribution of the antennas are not exhibited thereafter, only the $x$- and $y$- axes magnetic field distributions are provided.

Fig. 3.5. Magnetic field distribution of the top-to-bottom coupled segmented loop antenna at different frequencies ($L_{\text{top}} = 47$ mm, $L_{\text{bot}} = 47$ mm, $z = 0.5$ mm): (a) $x$-axis variation and (b) $y$-axis variation.
Fig. 3.6. Simulated current distribution of the top-to-bottom coupled segmented loop antenna ($L_{\text{top}} = 47 \text{ mm}, L_{\text{bot}} = 47 \text{ mm}, z = 0.5 \text{ mm}$) at 700, 915, 960 and 1250 MHz.

Fig. 3.7. Simulated 2-D magnetic field distribution of the top-to-bottom coupled segmented loop antenna ($L_{\text{top}} = 47 \text{ mm}, L_{\text{bot}} = 47 \text{ mm}, z = 0.5 \text{ mm}$) at 700, 915, 960 and 1250 MHz.
3.5 Parametric Study

A parametric study of the top-to-bottom coupled segmented loop near-field antenna is conducted to find out the effect of changes in the antenna geometric parameters on the antenna performance. The studies are conducted using the IE3D software package [45]. The parameters under study include the length of the coupling strips, $L_{\text{top}}$ and $L_{\text{bot}}$, the size of the segmented loop antenna, substrate permittivity used on the antenna, $\varepsilon_r$, the separation between two coupled strips, $H$, the width of the strip, $W$, and the gaps between the similar coupling strips, $S_{\text{top}}$ and $S_{\text{bot}}$. To better understand the influence of the parameters on the antenna performance, only one parameter is varied at a time, while the others are kept unaltered unless specified.

3.5.1 Length of Coupling Strips, $L_{\text{top}}$ and $L_{\text{bot}}$

This study is carried out to determine the effect of the variation in length of coupling strips, $L_{\text{top}}$ and $L_{\text{bot}}$, on the performance of the top-to-bottom coupled segmented loop antenna. By keeping the overall length of the antenna at 656 mm ($2\lambda$) and the main radiating length of the antenna, $L_{\text{top0}}$, at 47 mm, the length of top layer dashed coupling strip, $L_{\text{top}}$ is varied from 40.2 to 143 mm while the length of bottom layer dashed coupling strip, $L_{\text{bot}}$ is varied from 40.6 to 123.8 mm correspondingly to observe the effect of variation in coupling strips length on the impedance matching and the magnetic near-field distribution in $z$-direction ($H_z$) of the segmented antenna.

Fig. 3.8 shows the effect of the variation in the length of the coupling strips, $L_{\text{top}}$ and $L_{\text{bot}}$, on the impedance matching of the proposed antenna. By decreasing the length of the coupling strips, the resonant frequency shifts toward a higher frequency. Segmented antenna with the length of coupling strip $L_{\text{top}}$ of 149 mm and $L_{\text{bot}}$ of 163 mm has the first
resonant at 380 MHz. As the length of the segmented antenna is being decreased to $L_{\text{top}}$ of 40.2 mm and $L_{\text{bot}}$ of 40.6 mm, the antenna has its first resonant frequency shifted up to 1000 MHz.

![Graph](image)

Fig. 3.8. Effect of the variation in the coupling strips length, $L_{\text{top}}$ and $L_{\text{bot}}$, on the impedance matching of the top-to-bottom coupled segmented loop antenna.

Besides that, for an antenna with a fixed size of $2\lambda$ at 915 MHz, the magnetic near-field density around the area of the antenna differs when the coupling strip lengths are being varied (Fig. 3.9). It is observed that the antenna provides even magnetic near-field distribution at the first resonant frequency of the antenna. Segmented antenna with coupling strip length of $L_{\text{top}} = 47$ mm and $L_{\text{bot}} = 47$ mm provides the most even magnetic field distribution at 915 MHz.
Fig. 3.9. Effect of the variation in the coupling strips length, $L_{\text{top}}$ and $L_{\text{bot}}$, on the magnetic near-field distribution of the top-to-bottom coupled segmented loop antenna at 915 MHz ($z = 0.5$ mm) along (a) $x$-axis, and (b) $y$-axis.
Figs. 3.10 to 3.13 show the magnetic field distribution \((H_z)\) of the segmented loop antenna for different coupling strip length at different frequency along the \(x\)- and \(y\)-axes. It is observed that the operating frequency at which the proposed antenna generates the strongest and the most even magnetic field distribution is strongly dependent on the electrical length of the segmented line section. Table 3.1 lists the \(f_0\) and the corresponding \(L_{\text{top}}\) and \(L_{\text{bot}}\), for all the antennas. It can be found that, to have the even magnetic field distribution at the near-field of the reader antenna, the optimum length of the coupling strips length \(L_{\text{top}}\) and \(L_{\text{bot}}\), are about 0.13 to 0.18 \(\lambda\), where \(\lambda\) is the operating wavelength of the antenna.

Of all the cases in the study, it should be noted that the graphs of impedance matching are used to discuss the effect of changing in antenna parameters on its resonant frequency. At the first resonant frequency, current flows in a single direction along the antenna. As a result, even field distribution is achieved. From Fig. 3.8, it is obvious that, at the resonant frequencies, the antenna may not match well with the 50-\(\Omega\) system. Such antenna, when directly connected to the RFID system, has the potential of damaging the system. This problem can be solved by adding impedance matching network between the antenna and the feeding lines without affecting on the field distribution of the antenna.

Table 3.1 Relationship between operating frequency and length of segmented line section of the top-to-bottom coupled segmented loop antenna.

<table>
<thead>
<tr>
<th>(L_{\text{top}}, L_{\text{bot}}) (mm)</th>
<th>(f_0) (MHz)</th>
<th>Length ((\lambda))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L_{\text{top}} = 143) mm, (L_{\text{bot}} = 123.8) mm</td>
<td>380</td>
<td>(\theta_{\text{top}} = 0.181, \ \theta_{\text{bot}} = 0.156)</td>
</tr>
<tr>
<td>(L_{\text{top}} = 71) mm, (L_{\text{bot}} = 68.3) mm</td>
<td>650</td>
<td>(\theta_{\text{top}} = 0.153, \ \theta_{\text{bot}} = 0.147)</td>
</tr>
<tr>
<td>(L_{\text{top}} = 47) mm, (L_{\text{bot}} = 47) mm</td>
<td>915</td>
<td>(\theta_{\text{top}} = 0.143, \ \theta_{\text{bot}} = 0.143)</td>
</tr>
<tr>
<td>(L_{\text{top}} = 40.2) mm, (L_{\text{bot}} = 40.8) mm</td>
<td>1000</td>
<td>(\theta_{\text{top}} = 0.134, \ \theta_{\text{bot}} = 0.136)</td>
</tr>
</tbody>
</table>
Fig. 3.10. Magnetic field distribution of the top-to-bottom coupled segmented loop antenna at different frequencies ($L_{\text{top}} = 143$ mm and $L_{\text{bot}} = 123.8$ mm, $z = 0.5$ mm): (a) $x$-axis variation, and (b) $y$-axis variation.
Fig. 3.11. Magnetic field distribution of the top-to-bottom coupled segmented loop antenna at different frequencies ($L_{\text{top}} = 71$ mm and $L_{\text{bot}} = 68.3$ mm, $z = 0.5$ mm): (a) $x$-axis variation, and (b) $y$-axis variation
Fig. 3.12. Magnetic field distribution of the top-to-bottom coupled segmented loop antenna at different frequencies ($L_{\text{top}} = 47$ mm and $L_{\text{bot}} = 47$ mm, $z = 0.5$ mm): (a) $x$-axis variation, and (b) $y$-axis variation
Fig. 3.13. Magnetic field distribution of the top-to-bottom coupled segmented loop antenna at different frequencies ($L_{top} = 40.2$ mm and $L_{bot} = 40.8$ mm, $z = 0.5$ mm): (a) $x$-axis variation, and (b) $y$-axis variation
3.5.2 Overall Size of Antenna

This study aims to determine the influence of the size of the top-to-bottom coupled segmented loop antenna on the impedance matching and the near-field magnetic distribution. The length of the coupling element, \( L_{\text{top}} \) and \( L_{\text{bot}} \) is both fixed at 47 mm. The length of the fed element \( L_{\text{bot}0} \) is also fixed at 47 mm. The size of the antenna is varied by adding additional coupling elements to increase the size of the antenna from 0.59 \( \lambda \) to 2.07 \( \lambda \) (Fig. 3.14). Fig. 3.15 exhibits the magnetic field distribution of the antennas at 915 MHz. It is observed that all the antennas generate even magnetic field distribution with little variation along \( x \)-axis in the major portion of the interrogation zone. Besides that, magnetic field intensity of the antenna decreases as the size increases. The magnetic field shows a larger variation along \( y \)-axis.

![Fig. 3.14. Top-to-bottom coupled segmented loop antenna with different sizes (a) 0.59 \( \lambda \), (b) 1.02 \( \lambda \), (c) 2.00 \( \lambda \), (d) 2.49 \( \lambda \), and (e) 3.07 \( \lambda \) [45].](image)

Fig. 3.15. Magnetic field distribution of the top-to-bottom coupled segmented loop antennas with different sizes (at 915 MHz, $z = 0.5$ mm): (a) $x$-axis variation and (b) $y$-axis variation.

Fig. 3.16 shows the magnetic field distribution along $z$-axis. It is found that a smaller segmented loop antenna generates a stronger magnetic field in the region near the
antenna and features a faster reduction as the distance $z$ increases. A larger segmented loop antenna, on the other hand, generates a weaker magnetic field in the region near the antenna but features a slower reduction as the distance $z$ increases. This characteristic is similar to that of the conventional loop antenna.

![Magnetic field distribution of the top-to-bottom coupled segmented loop antennas with different sizes along $z$-axis at 915 MHz.](image)

**Fig. 3.16.** Magnetic field distribution of the top-to-bottom coupled segmented loop antennas with different sizes along $z$-axis at 915 MHz.

### 3.5.3 Substrate Permittivity, $\varepsilon_r$

In practical design, it is convenient and cost efficient to print the antenna onto a substrate which is of specific dielectric constant ($\varepsilon_r$) and thickness ($H$). The occurrence of the substrate will affect the coupling between the segmented line sections and thus will alter the operating frequency of the antenna. This study aims to examine the effect of substrate on the performances of the top-to-bottom coupled segmented loop antenna. In
In this study, four typical substrates, namely the RT5880 ($\varepsilon_r = 2.2$, $\tan\delta = 0.0009$), the RO4003 ($\varepsilon_r = 3.38$, $\tan\delta = 0.0027$), the FR4 ($\varepsilon_r = 4.4$, $\tan\delta = 0.02$), and the RO3010 ($\varepsilon_r = 10.2$, $\tan\delta = 0.0023$), with the same thickness, $H$, of 0.508 mm are used. The antenna dimensions are similar to those mentioned in Section 3.4. It is found that, when the antenna is placed on different substrate, the impedance matching of the antenna changes, as exhibited in Fig. 3.17. It is observed that as the effective permittivity of the substrate increases, the resonant frequency of the antenna shifts to a lower frequency.

![Graph](image)

**Fig. 3.17.** Effect of the variation in the substrate dielectric constant, $\varepsilon_r$, on the impedance matching of the top-to-bottom coupled segmented loop antenna.

**Fig. 3.18** illustrates the magnetic field distribution of the proposed antenna printed onto different substrates at 915 MHz. It is observed that the field distribution tends to be uneven with the occurrence of the substrate. Larger dielectric constant results a larger field variation.
Fig. 3.18. Effect of the variation in the substrate dielectric constant on the magnetic field distribution of the top-to-bottom coupled segmented loop antenna (at 915 MHz, $z = 0.5$ mm) along (a) $x$-axis, and (b) $y$-axis.
It is found that the introduction of substrates decreases the resonant frequency. The antenna provides even near-field when at its first resonant frequency. Other than 915 MHz in free space ($\varepsilon_r = 1$), the corresponding operating frequencies where antenna magnetic field distribution remains even for different substrates are 640 MHz (with $\varepsilon_r = 2.2$), 540 MHz (with $\varepsilon_r = 3.38$), 480 MHz (with $\varepsilon_r = 4.4$), and 330 MHz (with $\varepsilon_r = 10.2$), respectively, as exhibited in Figs 3.19 to Fig. 3.22. It implies that the substrate with higher dielectric lowers the antenna operating frequency.
Fig. 3.19. Magnetic field distribution of the top-to-bottom coupled segmented loop antenna at different frequencies (RT 5880, $\varepsilon_r = 2.2$, $\tan\delta = 0.0009$, $z = 0.5$ mm): (a) $x$-axis variation, and (b) $y$-axis variation.
Fig. 3.20. Magnetic field distribution of the top-to-bottom coupled segmented loop antenna at different frequencies (RO 4003, $\varepsilon_r = 3.38$, tan$\delta = 0.0023$, $z = 0.5$ mm): (a) $x$-axis variation, and (b) $y$-axis variation.
Fig. 3.21. Magnetic field distribution of the top-to-bottom coupled segmented loop antenna at different frequencies (FR4, $\varepsilon_r = 4.4$, $\tan\delta = 0.02$, $z = 0.5$ mm): (a) $x$-axis variation, and (b) $y$-axis variation.

(a)

(b)
3.5.4 Separation between Upper and Lower Coupling Strips, $H$

This study is performed to determine the effect of separation between the upper and lower coupling strips, $H$, on the impedance matching and the near-field distribution of the antenna. The separation distance is varied from 0.1, 0.5, 1.0, to 1.5 mm.

Fig. 3.23 shows the changes in the antenna resonant frequency with varying separations between the upper and lower coupling strips, $H$. It should be noted that this parametric study is done in free space. It is observed that as the separation distance between the strips decreases, the resonant frequency of the antenna is significantly shifted down to a lower frequency. Fig. 3.24 compares the magnetic field distribution of the antennas with different separation distance at 915 MHz. It is found that the optimum
separation distance is 0.5 mm for the segmented antenna to maintain an even field distribution at 915 MHz.

Fig. 3.23. Effect of the variation in the separation between the upper and lower coupling strips, $H$ on the impedance matching of the top-to-bottom coupled segmented loop antenna.
Fig. 3.24. Effect of the variation in the separation between the upper and lower coupling strips, $H$ on the magnetic field distribution of the top-to-bottom coupled segmented loop antenna (at 915 MHz, $z = 0.5$ mm) along (a) $x$-axis, and (b) $y$-axis.
The magnetic field distribution of the top-to-bottom coupled segmented antenna with separation distance $H$ of 0.1, 0.5, 1.0, 1.5, and 2.0 mm is in Figs. 3.25 to 3.28. It is found that the magnetic field distribution of the antenna changes with the variation in the separation distance. As the separation of the strips increases, the frequency of the antenna which corresponds to the evenness magnetic field too increases.
Fig. 3.25. Magnetic field distribution of the top-to-bottom coupled segmented loop antenna at different frequencies ($H = 0.1 \text{ mm, } z = 0.5 \text{ mm}$): (a) $x$-axis variation, and (b) $y$-axis variation.
Fig. 3.26. Magnetic field distribution of the top-to-bottom coupled segmented loop antenna at different frequencies ($H = 0.5 \text{ mm}, z = 0.5 \text{ mm}$): (a) $x$-axis variation, and (b) $y$-axis variation.
Fig. 3.27. Magnetic field distribution of the top-to-bottom coupled segmented loop antenna at different frequencies ($H = 1.0 \, \text{mm}, \, z = 0.5 \, \text{mm}$): (a) $x$-axis variation, and (b) $y$-axis variation.
3.5.5 Strip Width, $W$

The width of the strip, $W$, for both top and bottom dashed-line, is varied from 0.5, 1.0, 2.0, to 4.0 mm to observe the effect it imposes on the performances of the segmented antenna. It should be noted that the variation in the width size causes the variation in the antenna size. However, the interrogation area ($a \times a$) of the antenna remains unchanged for all the cases for fair comparison. Fig. 3.29 exhibits the effect of varying widths on the impedance matching of the segmented antenna. It is observed that the resonant frequency of the top-to-bottom coupled segmented loop antenna shifts left to a lower frequency as the strip width increases.
Fig. 3.29. Effect of the variation in the strip width, $W$, on the impedance matching of the top-to-bottom coupled segmented loop antenna.

Fig. 3.30 compares the magnetic field distribution of the antennas with different widths at 915 MHz. It is found an optimum separation distance of 2.0 mm is required for the segmented antenna to maintain an even magnetic field distribution at 915 MHz.
Fig. 3.30. Effect of the variation in the strip width, $W$, on the magnetic field distribution of the top-to-bottom coupled segmented loop antenna at (915 MHz, $z = 0.5$ mm) along (a) $x$-axis, and (b) $y$-axis.
Figs. 3.31 to 3.34 show the magnetic field distribution for width of the segmented loop on different operating frequencies of the antenna. It is found that the frequency which corresponds to the evenness near-field distribution is around the first resonant frequency of the top-to-bottom coupled segmented loop antenna. As the width of the strip antenna decreases, the frequency of the antenna which corresponds to the evenness magnetic field increases.
Fig. 3.31. Magnetic field distribution of the top-to-bottom coupled segmented loop antenna at different frequencies ($W = 0.5 \text{ mm}$, $z = 0.5 \text{ mm}$): (a) $x$-axis variation, and (b) $y$-axis variation.
Fig. 3.32. Magnetic field distribution of the top-to-bottom coupled segmented loop antenna at different frequencies ($W = 1.0 \text{ mm}, z = 0.5 \text{ mm}$): (a) $x$-axis variation, and (b) $y$-axis variation.
Fig. 3.33. Magnetic field distribution of the top-to-bottom coupled segmented loop antenna at different frequencies ($W = 2.0 \text{ mm}, z = 0.5 \text{ mm}$): (a) $x$-axis variation, and (b) $y$-axis variation.
Fig. 3.34. Magnetic field distribution of the top-to-bottom coupled segmented loop antenna at different frequencies ($W = 4.0 \text{ mm}$, $z = 0.5 \text{ mm}$): (a) $x$-axis variation, and (b) $y$-axis variation.

3.5.6 Gaps between Coupling Strips, $S_{\text{top}}$ and $S_{\text{bot}}$

The gaps between the coupling strips of the same layer, $S_{\text{top}}$ and $S_{\text{bot}}$, are varied from 0.5, 1.0, 2.0, to 4.0 mm to observe the effect of such variation on the performances of the segmented antenna. It should be noted that the change in the gap distance alters the coupling strip lengths, $L_{\text{top}}$ and $L_{\text{bot}}$. However, the change in $L_{\text{top}}$ and $L_{\text{bot}}$ is electrically small and does not impose great influence on the performances of the antenna. As the gaps of the coupling strips in the same layer increase, the resonant frequency of the antenna shifts to the right, to a higher frequency. Such situation is illustrated in Fig. 3.35. However, the influence of the gaps on the magnetic field distribution, $H_z$, is insignificant as exhibited in Fig. 3.36. Therefore, the gaps between the coupling strips, $S_{\text{top}}$ and $S_{\text{bot}}$,
can be used to tune the impedance matching without affecting the magnetic near-field performance of the segmented antenna.

Fig. 3.35. Effect of the variation in the gaps between the coupling strips of the same layer, \( S_{\text{top}} \) and \( S_{\text{bot}} \), on the impedance matching of the top-to-bottom coupled segmented loop antenna.
Fig. 3.36. Effect of the variation in the gaps between the coupling strip of the same layer, $S_{\text{top}}$ and $S_{\text{bot}}$, on the magnetic near-field distribution of the top-to-bottom coupled segmented loop antenna at 915 MHz ($z = 0.5$ mm) along (a) $x$-axis, and (b) $y$-axis.

3.5.7 Conclusion on Parametric Study

Parameters that influence the performances most in the top-to-bottom coupled segmented loop antenna are the length of the coupling strips $L_{\text{top}}$ and $L_{\text{bot}}$, the substrate permittivity used on the antenna, $\varepsilon$, the separation between the upper and lower coupling strips, $H$, and the width of the coupling strips, $W$. All these parameters cause significant changes in the resonant frequency of the antenna and affect the near-field distribution of antenna.

The gaps between the coupling strips of the same layer, $S_{\text{top}}$ and $S_{\text{bot}}$, however, show effect on the resonant frequency of the antenna and do not significantly alter the magnetic field distribution of the antenna. Such parameter can be used for tuning the
impedance matching when the influential parameters of the antenna are being set. It should be noted that the parameter should be electrically small to maintain the proper coupling between the lines.

For the size of the proposed antenna, a smaller antenna generates stronger magnetic field intensity over limited interrogation zone. The larger antenna produces weaker magnetic field intensity but it offers a bigger interrogation zone. Therefore, there exists a trade-off between the interrogation zone and the reading range when it comes to designing such type of antenna.

3.6 Antenna Implementation, Results and Discussion

The top-to-bottom coupled segmented loop antenna can be printed onto any substrate and be optimized at specific operating frequency by selecting the proper parameters. In this section, an antenna prototype is printed onto a FR4 substrate. The FR4 substrate is with a permittivity of $\varepsilon_r = 4.4$, a loss tangent of $\tan \delta = 0.02$, and a thickness of $H = 0.508 \text{ mm}$. The antenna is designed at the operating frequency of 915 MHz. The antenna prototype is with an overall size of $175 \times 180 \text{ mm}^2$ ($0.53 \times 0.55 \lambda^2$) with a perimeter of $2.16 \lambda$. It offers an interrogation zone of $160 \times 160 \text{ mm}^2$ ($0.50 \times 0.50 \lambda^2$). The proposed segmented antenna is fed by a parallel strip line printed on the opposite sides of the substrate. The upper/bottom parallel strips are connected to the inner/outer conductors of an SMA connector, respectively. A matching network comprising stubs is adopted to match the antenna to the 50-Ω feed line. The detailed dimensions of the antenna prototype are exhibited in Fig. 3.37(a). The photograph of the antenna prototype is provided in Fig. 3.37(b). A conventional solid-line loop antenna of the same interrogation zone is prototyped for comparison as illustrated in Fig. 3.37(c).
Fig. 3.37. Configuration of the loop antenna prototypes using FR4 substrate: (a) detailed dimensions of the top-to-bottom coupled segmented loop antenna prototype, (b) photo of the top-to-bottom coupled segmented loop antenna prototype, and (c) photo of the solid loop antenna with similar interrogation zone.

3.6.1 Impedance Matching Measurement

Using the Agilent E5230A vector network analyzer (VNA), the impedance match of the antenna is measured. Fig. 3.38 exhibits the measured return loss. The bandwidth for 10 dB return loss covers the frequency range of 840–1270 MHz (40.8%). Compared to the simulation, good agreement is achieved. However, there are slight discrepancy
between the measured and the simulated return losses. This is due to the differences between the antenna feeding methods adopted in the simulation and the measurement. In simulation, the antenna is directly fed by a pair of differential ports. In measurement, the antenna is connected to a feeding cable, which is unbalanced and further connected to the VNA. It is difficult to simulate such cable in the IE3D simulation system. Therefore, the simulated and measured impedance matching is slightly different across the frequency range.

![Graph of measured vs simulated return loss](image)

Fig. 3.38. Measured and simulated return loss of the top-to-bottom coupled segmented loop antenna prototype.

### 3.6.2 Magnetic Field Distribution Measurement

The magnetic field distribution is measured using the E5230A VNA and the Langer EMV-Technik RF-R 3-2 near-field probe [49]. The antenna and the near-field probe are connected to Port 1 and Port 2 of the VNA, respectively. The relatively magnetic field intensity is quantified by $|S_{21}|$. The near-field magnetic field probe is
placed on the surface of the antenna prototype, and is moved along the $x$- and $y$- axes separately with an interval of 5 mm. No calibration of the probe is required in the measurement since what we concern here is the relatively field distribution, not the absolute magnitude of the magnetic field. Figs. 3.39, 3.40, and 3.41 show the simulated and measured magnetic field intensity at 840, 915, and 960 MHz, along $x$- and $y$- axes. It should be noted that the simulated magnetic field density ($H_z$) is of unit A/m (dB) and the measured field intensity is in the form of $|S_{21}|$, which is dimensionless. For fair comparison, both results at the origin ($x = 0$, $y = 0$) are being normalized. The trend of both the results is observed. Of all the cases, good agreement is observed between measured and simulated relative magnetic distribution.

![Graph](a)
Fig. 3.39. Measured and simulated magnetic field distribution of the top-to-bottom coupled segmented loop antenna prototype (at 840 MHz, $z = 0.5$ mm): (a) $x$-axis variation and (b) $y$-axis variation.
Fig. 3.40. Measured and simulated magnetic field distribution of the top-to-bottom coupled segmented loop antenna prototype (at 915 MHz, $z = 0.5$ mm): (a) $x$-axis variation and (b) $y$-axis variation.
Fig. 3.41. Measured and simulated magnetic field distribution of the top-to-bottom coupled segmented loop antenna prototype (at 960 MHz, $z = 0.5$ mm): (a) $x$-axis variation and (b) $y$-axis variation.

### 3.6.3 Reading Range Test

The antenna prototype is used as a reader antenna in a near-field UHF RFID system to verify its performance on the near-field tag detection range. As shown in Fig. 3.42, the antenna prototype is connected to the Impinj Speedway reader (865–956 MHz, with 30-dBm output) [50] to detect the Impinj near-field button type tags. The tags are of the model J21 and each of them is 9 mm in diameter [51]. 25 tags are positioned symmetrically on a Styrofoam disc with a diameter of 160 mm. The number of the detected tags are recorded when the Styrofoam disc is positioned above/below the antenna prototype at different distances. To ensure the reliability of the read range test, the tags attached to the Styrofoam disc are randomly placed, and an average of five measurements is recorded at each reading distance from the antenna.
Fig. 3.42. Reading rate experiment set-up for the top-to-bottom coupled segmented loop antenna.

Fig. 3.43. Measured reading rate against distance of the top-to-bottom coupled segmented loop antenna and the solid line loop antenna with the similar interrogation zone.

Fig. 3.43 shows the reading rate against the tag detection distance. In addition, the result of the tag reading distance of a conventional solid line loop antenna is illustrated in the same figure for comparison. The solid line loop antenna prototype has the identical
perimeter as the proposed antenna. It provides an interrogation zone of $160 \times 160 \text{ mm}^2$. Both the antenna prototypes offer bi-directional reading. The segmented loop antenna prototype exhibits superior performance over the conventional solid loop antenna. It achieves a 100% reading rate with a distance up to 24 mm. The conventional solid line loop antenna prototype, however, offers only a reading rate of 40% when the tags are placed at the surface ($d = 0 \text{ mm}$) of the antenna.

3.6.4 Uni-directional Antenna Prototype

In some RFID applications, uni-directional detection is desired. The most common method of making a loop-like antenna uni-directional is to apply a metal plate or reflector at one side of the antenna [18]. Fig. 3.44 demonstrates a uni-directional segmented loop antenna. The antenna prototype is positioned above a copper plate with a certain distance, $g$, using Styrofoam. The copper plate measures $300 \times 300 \text{ mm}^2$ or $0.9 \times 0.9 \lambda^2$, where $\lambda$ is the operating wavelength at 915 MHz in free space.

![Uni-directional top-to-bottom coupled segmented loop antenna prototype.](image)
The return loss of the uni-directional antenna prototypes is measured, at each distance $g$. The results are exhibited in Fig. 3.45. It is observed that, when the metal plate is placed very close to the antenna (i.e. $g = 10$ and $20$ mm), the antenna impedance matching is severely degraded. When the metal plate is of sufficient distance away from the metal plate (i.e. $g = 40$ and $50$ mm), the impedance matching is less affected. The impedance matching for 10 dB return loss can be achieved over a wide frequency band 840–1200 MHz.

Fig. 3.45. Measured return loss of the uni-directional top-to-bottom coupled segmented loop antenna prototype with different separation distances, $g$.

Fig. 3.46 exhibits the reading rate of a uni-directional top-to-bottom segmented loop antenna prototype. A copper plate with the dimensions of $300 \times 300$ mm$^2$ is placed 40 mm away from the antenna. The distance for 100% tag reading is enhanced to 60 mm,
which is 2.5 times of that of the original segmented loop antenna prototype without metal plate.

In addition, the result of a commercial near-field UHF antenna, the Impinj Brickyard near-field RFID antenna is exhibited in Fig. 3.46 for comparison. The Impinj Brickyard near-field antenna has the model number of CS-777 and offers a circular interrogation zone with a diameter of 160 mm [52]. The proposed uni-directional segmented loop antenna achieves a 100% reading rate distance of 2.5 times of that of the commercial antenna. The uni-directional segmented loop antenna is capable of providing the 100% reading rate distance up to 60 mm. The commercial antenna, in contrast, can only provide the 100% reading rate distance up to 24 mm.

Fig. 3.46. Measured reading rate against detection distance for the uni-directional top-to-bottom segmented loop antenna and the Impinj CS-777 near-field antenna.
3.6.5 Verification of Antenna Coverage Area

It is essential to find out the coverage area of the proposed antenna. The antenna coverage area is defined as the maximum area where a 100% reading rate is obtained when the near-field RFID tags are placed at a near-field distance ($d = 0$ mm) of the antenna. It should be noted that the metal plate reflector is not included in this experiment.

As shown in Fig. 3.47, the RFID tags are distributed randomly within different investigation areas, from $220 \times 220$ mm$^2$ (with a total of 90 tags), $200 \times 200$ mm$^2$ (with a total of 60 tags), $180 \times 180$ mm$^2$ (with a total of 50 tags), and $160 \times 160$ mm$^2$ (with a total of 35 tags). The reading rate is then being obtained with the procedure similar to section 3.6.3.

Fig. 3.47. Near-field RFID tags distributed randomly within different investigation area: (a) $220 \times 220$ mm$^2$, (b) $200 \times 200$ mm$^2$, (c) $180 \times 180$ mm$^2$, and (d) $160 \times 160$ mm$^2$
Fig. 3.48 shows the reading rate against detection range of RFID tags which are placed within different coverage areas. At a distance $d = 0$ mm, when the tags are located within an area larger than that of the antenna, a 100% tag reading rate could not be achieved. A 100% tag reading rate is only achieved when all the tags are located within the area bounded by antenna ($160 \times 160$ mm$^2$).

Fig. 3.48. Measured reading rate against distance for the top-to-bottom coupled segmented loop antenna prototype with different investigation zones.

Therefore, it can be verified that the prototype of the top-to-bottom coupled segmented loop antenna is able to provide a coverage area of $160 \times 160$ mm$^2$. This area can be used as the interrogation area ($a \times a$) when one would like to design such antenna.
3.7 Concluding Remarks

A top-to-bottom coupled segmented loop antenna is proposed in this chapter. The segmented structures are able to provide a very small phase delay to the current flowing through them. As a result, the current along the segmented lines is kept in phase. This causes the current to flow in a single direction along the proposed segmented loop antenna even though the loop is electrically large (> 0.5 $\lambda$). The proposed segmented antenna has an overall size of $175 \times 180 \times 0.5$ mm$^3$. It achieves a large interrogation zone of $160 \times 160$ mm$^2$. The proposed electrically large segmented loop antenna has demonstrated the capability of producing strong magnetic field with relatively uniform near-field distribution over a frequency band of 840–960 MHz (13.3%). Such characteristics are desirable for the near-field UHF RFID systems.

The proposed antenna prototype has shown significant improvement by achieving a maximum reading rate of 100%. The conventional loop antenna prototype with similar interrogation zone, in comparison, only affords a maximum reading rate of 40%. The proposed antenna, compared to a commercial near-field UHF RFID reader antenna, extends the detection range by 2.5 times and achieves a 100% reading rate at a tag reading distance of 60 mm within a given interrogation zone.

From the parametric studies done, the length of the coupling strips $L_{\text{top}}$ and $L_{\text{bot}}$, the separation between the upper and lower coupling strips, $H$, and the width of the coupling strips, $W$. The substrate properties have been found to have severe effects on antenna performance and therefore have to be considered in practical design.
The top-to-bottom coupled segmented loop antenna proposed in Chapter 3 is shown to provide strong and even near-field distribution even though the antenna is larger than one operating wavelength. However, the segmented strips are printed on the top and the bottom of a substrate. This double layer structure is complex from the fabrication point of view. Therefore, methods have been tried to design the segmented loop antenna on a single layer.

In this chapter, the side-by-side coupled segmented loop antenna is introduced. The structure of the segmented antenna is designed on a single layer for the ease of fabrication. First, the antenna configuration is presented. Then, the principle of the antenna operation is discussed. After that, design procedures of the side-by-side coupled segmented loop antenna are stated. This is followed by the explanation on methods of interpreting the performance of the near-field antenna. A parametric study performed on such antennas is disclosed and measurement results of the antenna prototype are presented. Then, the performance of the top-to-bottom coupled and the side-by-side coupled segmented antenna is compared. At last, concluding remarks on the side-by-side coupled segmented loop antenna is given.

### 4.1 Antenna Configuration

The proposed scheme of side-by-side coupled segmented loop antenna is exhibited in Fig. 4.1. A Cartesian coordinate system is chosen in such a way that the
upper surface of the substrate lies in the $x$-$y$ plane. The origin of the coordinate system is chosen at the center of the square segmented loop.

The segmented loop antenna comprises two dashed-line loops which are symmetrically structured with respect to the $y$-axis. The inner dashed-line loop is composed of several line sections with the same length, $L_{\text{in}}$, except for the first two sections, each with the length of $L_{\text{in0}}$. These first two line segments are connected to the parallel feed line. As shown in Fig. 4.1(a), the inner dashed-line loop is indicated with the line width, $W$, and the spacing between the adjacent line-sections is indicated with space width, $S_{\text{in}}$. The outer dashed-line loop, on the other hand, is open ended. The line sections on the outer loop are all of the similar length, $L_{\text{out}}$. The line width of the outer loop is indicated with the line width, $W$, and each line section is separated with the space width, $S_{\text{out}}$, except for the first and last section of the outer loop at the bottom of the antenna, which are separated with a larger space width, $S_{\text{out0}}$. The inner dashed-line loop and outer dashed-line loop are separated with the gap space, $S$. These two dashed-line loops are positioned in such a way that the broken points of the inner loops are located around the middle points of the dashed-line sections of the outer loop separately, and vice versa. The internal area ($a \times a$) of the inner dashed-line loop is indicated as the interrogation zone with a perimeter of $4a$.

The size of the antenna is determined by the perimeter of the segmented loop antenna. It should be noted that the impedance matching circuits are not considered in determining the perimeter of the antenna.

To feed the proposed segmented antenna, a pair of parallel strip line with a strip width of $W_f$ is used. Impedance of the antenna can be matched to the 50-$\Omega$ system using
appropriate matching circuit. Unlike the top-to-bottom coupled segmented antenna, the antenna is printed on a single layer of the substrate with the relative permittivity, \( \varepsilon_r \), substrate thickness \( H \), and the loss tangent of \( \tan \delta \), as shown in Fig. 4.1(b).

![Configuration of the proposed side-by-side coupled segmented loop antenna: (a) top view and (b) side view.](image)

**Fig. 4.1.** Configuration of the proposed side-by-side coupled segmented loop antenna: (a) top view and (b) side view.

## 4.2 Principle of Operation

The principle of the side-by-side coupled segmented loop antenna operation is similar to that discussed in Section 3.2. For a conventional loop antenna with total
electrical length larger than 0.5 λ where λ corresponds to the free space operating wavelength, current phase inversion will occur along the loop. As a result, the current flowing on the loop antenna will not be in a single direction. This causes the magnetic field distribution in the z-direction ($H_z$) on the loop to be cancelled. Hence, field nulls will be featured in the area of the loop, as shown in Fig 4.3(a). Such occurrence is not desirable in UHF near-field reader antenna.

The segmented structures are able to provide a very small phase delay to the current flowing through them. As a result, the current along the segmented lines is kept in phase. This causes the current to flow in a single direction along the proposed segmented loop antenna even though the loop is electrically large (> 0.5 λ). The magnetic fields produced in the z-direction are thus being added up. The antenna thus exhibits strong and even field distribution over the interrogation zone (Fig. 4.3(b)).

Fig. 4.2. Simulated current distribution at 915 MHz: (a) conventional solid line loop antenna and (b) side-by-side coupled segmented loop antenna [45].
4.3 Design Procedure

First, the required interrogation zone, $a$, and the required operating frequency, $f_0$ are set. The other geometrical parameters of the segmented antenna can be determined by the following procedures:

- Length of the excited line sections of the inner dashed-line loop, $L_{in0}$

From the excitation point of view, the segmented loop antenna can simply be considered as a loaded dipole antenna with an arm length of $L_{in0}$. To ensure that current flow on the dipole is in a single direction, a total dipole length ($2L_{in0}$) of less than 0.5 $\lambda$ should be used [18]–[20]. As such, each $L_{in0}$ must be less than 0.25 $\lambda$. Generally, $L_{in0} = 0.2 \lambda$ is adequate, where $\lambda$ corresponds to the wavelength at the operating frequency.

- Length of the line sections of the inner dashed-line loop, $L_{in}$

Based on the perimeter of the interrogation zone ($4a$), the number of the line sections ($N$), the width of the line sections ($W$), the spacing between the adjacent line sections in the
inner segmented loop \((S_{\text{in}})\), and the spacing between the first two line sections \((S_0)\) the length of the inner dashed-line sections can be calculated by

\[
L_{\text{in}} = \frac{4a + 8W - 2L_{\text{in}0} - S_0 - (N + 1)S_{\text{in}}}{N} \tag{8}
\]

- Length of the line sections of the outer dashed-line loop, \(L_{\text{out}}\)

The outer dashed-line loop is composed of \(N+1\) line section with length of \(L_{\text{out}}\). Similarly, the length of the dashed-line sections can be calculated by

\[
L_{\text{out}} = \frac{4a + 16W + 8S - NS_{\text{out}} - S_{\text{out}0}}{N + 1} \tag{9}
\]

where \(S\) is the spacing between the dashed-line loops and \(S_{\text{out}}\) is the spacing between the adjacent line sections in the outer segmented loop. Here, the \(S_{\text{out}0}\) is fixed at 0.17 \(\lambda\) to provide effective coupling between the inner dashed-line and outer-dashed line.

It is suggested that the separation parameters, namely \(S_{\text{in}}, S_{\text{out}}, S_0\) and \(S\), should be electrical small to ensure the proper coupling between the coupled segmented lines.

A matching network comprising simple stubs can be adopted to match the antenna to the 50-\(\Omega\) feed line at the desired frequencies.

### 4.4 Interpretation of Performance

To interpret the performance of the side-by-side coupled segmented loop antenna, the simulated current distribution along the loop and the simulated magnetic field distribution near the antenna are first obtained. In this section, a side-by-side coupled segmented loop antenna operating at 915 MHz is designed. The detailed geometrical parameters of the antenna design are: \(a = 154\ \text{mm}, N = 7, W = 2\ \text{mm}, S = 1, L_{\text{in}0} = 68.8\ \text{mm}, S_0 = 1.3\ \text{mm}, L_{\text{in}} = 69.3\ \text{mm}, L_{\text{in}} = 1\ \text{mm}, L_{\text{out}} = 174.1\ \text{mm}, S_{\text{out}0} = 55.9\ \text{mm}, \) and \(S_{\text{out}} = \)
1 mm. The antenna is designed in free space without any substrate. The feeding source is placed directly across the excitation line sections of the inner dashed-line loop. All the simulations are performed using the IE3D software, which is based on the Method of Moments [45].

The segmented antenna has an interrogation zone of $154 \times 154 \text{ mm}^2$ or $0.47 \times 0.47 \lambda^2$ at 915 MHz. For comparison, the results of a conventional solid line loop antenna are also exhibited. The square solid line loop has the same size as the inner dashed-line loop and thus offers the similar interrogation zone. Figs. 4.2 and 4.3 in Section 4.2 compare the simulated current and 2-D magnetic field distributions between the conventional solid line loop antenna and the segmented loop antenna at 915 MHz.

The 2-D magnetic field distribution illustrated in Fig. 4.3 provides a very good visual observation of the magnetic near-field distribution of the antenna. However, it is difficult to give a quantitative measure of the magnetic field intensity from such plots. Fig. 4.4 exhibits the magnetic field distribution along $x$- and $y$-axes, which allows us to quantify the field variation in a more convenient and accurate way.

In Fig. 4.4(a), it is observed that the magnetic field distributions are symmetrical with respect to the $y$-axis ($x = 0$ mm) for both the antennas. The magnetic field features a stronger magnitude in the regions very close to the loop lines and experiences a fast reduction when it moves towards the center region of the proposed antenna. Fig. 4.4(a) shows the magnetic field distribution of the segmented loop and the conventional solid line loop along the $x$-axis. The segmented loop antenna offers desired magnetic field distribution with a variation of 12 dB over the entire interrogation zone ($-77 \text{ mm} \leq x \leq 77$ mm) and a variation of 0.5 dB over the major portion of the interrogation zone ($-60 \text{ mm} \leq \lambda^2$ at 915 MHz. For comparison, the results of a conventional solid line loop antenna are also exhibited. The square solid line loop has the same size as the inner dashed-line loop and thus offers the similar interrogation zone. Figs. 4.2 and 4.3 in Section 4.2 compare the simulated current and 2-D magnetic field distributions between the conventional solid line loop antenna and the segmented loop antenna at 915 MHz.

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\( x \leq 60 \text{ mm} \). In addition, a sharp field reduction is observed over the intervals of \((-80 \text{ mm} \leq x \leq 79 \text{ mm})\) and \((79 \text{ mm} \leq x \leq 80 \text{ mm})\). These are the intervals located in between the inner and outer dashed-line loops. As the current flowing through both the inner and outer coupled line is of the same direction, magnetic fields produced at the area between the coupled lines cancel each other. As a result, total magnetic field in the \( z \)-direction, \( H_z \), at such area experiences a sharp drop. The solid line loop antenna, in contrast, is not able to generate even magnetic field over the interrogation area. There exist variation of 38 dB over the range of \(-72 \text{ mm} \leq x \leq 72 \text{ mm} \) and variation of 20 dB for \(-60 \text{ mm} \leq x \leq 60 \text{ mm} \).

Fig. 4.5(b) exhibits the magnetic field distribution along the \( y \)-axis. The segmented loop antenna offers a much better magnetic field distribution than that of the solid line loop antenna. The maximum magnetic field variation is 50 dB for the solid loop antenna and 27 dB for the segmented loop antenna over the range of \(-72 \text{ mm} \leq x \leq 72 \text{ mm} \). In the range of \(-60 \text{ mm} \leq x \leq 60 \text{ mm} \), the variation of magnetic field for the solid line loop antenna is 22 dB while the variation of magnetic field for the segmented loop is 9 dB. In addition, it is observed that the magnetic field distribution along the \( y \)-axis is slightly asymmetrical to the \( x \)-axis. This is due to the asymmetric antenna geometry as well as the attenuation and the radiation caused by the coupled lines.
Fig. 4.4. Magnetic field distribution of the side-by-side coupled segmented loop antenna and the conventional solid line loop antenna (at 915 MHz, $z = 0.5 \text{ mm}$): (a) $x$-axis variation, and (b) $y$-axis variation.

The magnetic field distribution of the segmented loop antenna, along the $x$- and $y$-axes, at the frequencies of 700, 840, 915, 960, and 1250 MHz is exhibited in Fig. 4.5. Even magnetic field distribution with little variation is observed over the frequency range of 840–960 MHz. Such field distribution is desirable for RFID applications. When the
operating frequency is shifted down to a lower frequency, such as 700 MHz, or shifted up to a higher frequency, such as 1250 MHz, the evenness of the magnetic field distribution degrades. In the study of current distribution, it is found that at 700 MHz, the current along the loop is still flowing in a single direction. However, the magnitude of the current experiences a large variation when it travels around the proposed segmented loop (Fig. 4.6). It is observed that the current flowing on the segmented line sections located near to the feeding port is much stronger than the current flowing at the upper portion of the antenna. This causes the magnetic field at the upper portion of the segmented antenna to be weaker than those at the lower portion, as exhibited in Fig. 4.7. The asymmetrical current distribution is attributed to the weak coupling between the segmented lines as these segmented lines are electrically short at lower frequencies.

At 1250 MHz, the current flowing along the loop as shown in Fig. 4.6 exhibits phase inversion and there are obvious current nulls on the loop. As a result, the magnetic field distribution shown in Fig. 4.7 features weak field intensity in the center portion of the antenna.
Fig. 4.5. Magnetic field distribution of the side-by-side coupled segmented loop antenna at different frequencies ($L_{in} = 74.1$ mm, $L_{out} = 69.3$ mm, $z = 0.5$ mm): (a) $x$-axis variation and (b) $y$-axis variation.
Fig. 4.6. Simulated current distribution of the side-by-side coupled segmented loop antenna ($L_{in} = 74.1$ mm, $L_{out} = 69.3$ mm, $z = 0.5$ mm) at frequencies 700, 915, 960, and 1250 MHz.

Fig. 4.7. Simulated 2-D magnetic field distribution of the side-by-side segmented loop antenna ($L_{in} = 74.1$ mm, $L_{out} = 69.3$ mm, $z = 0.5$ mm) at frequencies 700, 915, 960 and 1250 MHz.
4.5 Parametric Study

A parametric study is conducted to provide more information about the effects of geometric parameters on the performance of the side-by-side coupled segmented loop antenna. The studies are conducted using the IE3D software package [45]. The parameters under study include the length of the coupling strips, $L_{in}$ and $L_{out}$, the size of the segmented loop antenna, substrate permittivity used on the antenna, $\varepsilon_r$, substrate thickness, $H$, the separation between two coupled strips, $S$, the width of the strip, $W$, the extension of the first coupled strip, $\Delta l$, the gaps between the similar coupling strips, $S_{in}$ and $S_{out}$. To better understand the influence of the parameters on the antenna performance, only one parameter is varied at a time, while the others are kept unaltered unless specified.
4.5.1 Length of Coupling Strips, $L_{\text{in}}$ and $L_{\text{out}}$

![Diagram showing dimensions of the side-by-side coupled segmented loop antenna with different coupling strip lengths, $L_{\text{in}}$ and $L_{\text{out}}$.](image)

Fig. 4.8. Dimensions of the side-by-side coupled segmented loop antenna with different coupling strip lengths, $L_{\text{in}}$ and $L_{\text{out}}$. (a) $L_{\text{in}} = 149$ mm, $L_{\text{out}} = 163$ mm. (b) $L_{\text{in}} = 99.2$ mm $L_{\text{out}} = 97.4$ mm. (c) $L_{\text{in}} = 74.1$ mm $L_{\text{out}} = 69.3$ mm. (d) $L_{\text{in}} = 59.1$ mm $L_{\text{out}} = 53.7$ mm [45].

This study aims to find out the effect of the length of coupling strips, $L_{\text{in}}$ and $L_{\text{out}}$, on the performances of the side-by-side segmented antenna. By keeping the size of the antenna at 656 mm (2 $\lambda$) and the main radiating length of the antenna, $L_{\text{in0}}$, at 138.9 mm, the length of inner-dashed coupling strip, $L_{\text{in}}$ is varied from 59.1 to 163 mm while the length of outer-dashed coupling strip, $L_{\text{out}}$ is varied from 53.7 to 163 mm correspondingly (as shown in Fig. 4.8) to observe the effect of such changes on the impedance matching and the magnetic near-field distribution in $z$-direction ($H_z$) of the proposed segmented antenna. Fig. 4.9 shows the effect of the variation in length of the coupling strips, $L_{\text{in}}$ and
The length of the coupling strips, \( L_{\text{in}} \) and \( L_{\text{out}} \), has significant impact on the impedance matching of the antenna. By decreasing the length of the coupling strips, the resonant frequency shifts toward a higher frequency. Segmented antenna with the length of coupling strip \( L_{\text{in}} \) of 143 mm and \( L_{\text{out}} \) of 163 mm has the first resonant at 530 MHz. As the length of the segmented antenna is being decreased to \( L_{\text{in}} \) of 59.1 mm and \( L_{\text{out}} \) of 53.7 mm, the antenna’s first resonant frequency is shifted up to 930 MHz.

Fig. 4.9 shows the effect of the variation in the length of the coupling strips, \( L_{\text{in}} \) and \( L_{\text{out}} \), on the impedance matching of the antenna. By decreasing the length of the coupling strips, the resonant frequency shifts toward a higher frequency. Segmented antenna with the length of coupling strip \( L_{\text{in}} \) of 143 mm and \( L_{\text{out}} \) of 163 mm has the first resonant at 530 MHz. As the length of the segmented antenna is being decreased to \( L_{\text{in}} \) of 59.1 mm and \( L_{\text{out}} \) of 53.7 mm, the antenna’s first resonant frequency is shifted up to 930 MHz.

Fig. 4.9. Effect of the variation in the coupling strips length, \( L_{\text{in}} \) and \( L_{\text{out}} \), on the impedance matching of the side-by-side coupled segmented loop antenna.
Fig. 4.10. Effect of the variation in the coupling strip lengths, $L_{in}$ and $L_{out}$, on the magnetic near-field distribution of the side-by-side coupled segmented loop antenna at 915 MHz ($z = 0.5$ mm) along (a) $x$-axis, and (b) $y$-axis.
Besides that, for an antenna size with a fixed size of $2 \lambda$, the magnetic near-field density ($H_z$) around the area of the antenna differs when the coupling strip length is being varied (Fig. 4.10). It is observed that the antenna provides even magnetic near-field distribution at the first resonant frequency of the antenna. Figs. 4.11 to 4.14 show the magnetic field distribution ($H_z$) of the segmented loop antenna for different coupling strip length at different frequencies. It is observed that the frequency for antenna to exhibit strong and even field distribution is dependent on the electrical length of the segmented line section.

Table 4.1 lists the $f_0$ and the corresponding $L_{in}$ and $L_{out}$ for all the antennas. It is found that, to have the even field magnetic field distribution at the near-field of the reader antenna, the optimum length of the coupling strips length $L_{in}$ and $L_{out}$ are about 0.17 to 0.28 $\lambda$, where $\lambda$ is the operating wavelength.

Of all the cases in the study, it should be noted that the graphs of impedance matching are used to discuss the effect of changing in antenna parameters on its resonant frequency. At the first resonant frequency, current flows in a single direction along the antenna. As a result, even field distribution is achieved. From Fig. 4.9, it is obvious that, at the resonant frequencies, the antenna may not match well with the 50-$\Omega$ system. Such antenna, when directly connected to the RFID system, has the potential of damaging the system. This problem can be solved by adding impedance matching network between the antenna and the feeding lines without affecting on the field distribution of the antenna.
Table 4.1 Relationship between operating frequency and length of segmented line section of the side-by-side coupled segmented loop antenna

<table>
<thead>
<tr>
<th>( L_{in}, L_{out} ) (mm)</th>
<th>( f_0 ) (MHz)</th>
<th>Length (( \lambda ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_{in} = 163 \text{ mm}, \ L_{out} = 149 \text{ mm} )</td>
<td>530</td>
<td>( \theta_{in} = 0.26, \ \theta_{out} = 0.28 )</td>
</tr>
<tr>
<td>( L_{in} = 99.2 \text{ mm}, \ L_{out} = 97.4 \text{ mm} )</td>
<td>730</td>
<td>( \theta_{in} = 0.241, \ \theta_{out} = 0.237 )</td>
</tr>
<tr>
<td>( L_{in} = 74.1 \text{ mm}, \ L_{out} = 69.3 \text{ mm} )</td>
<td>915</td>
<td>( \theta_{in} = 0.226, \ \theta_{out} = 0.211 )</td>
</tr>
<tr>
<td>( L_{in} = 59.1 \text{ mm}, \ L_{out} = 53.7 \text{ mm} )</td>
<td>930</td>
<td>( \theta_{in} = 0.183, \ \theta_{out} = 0.167 )</td>
</tr>
</tbody>
</table>
Fig. 4.11. Magnetic field distribution of the side-by-side coupled segmented loop antenna at different frequencies ($L_{in} = 163$ mm, $L_{out} = 149$ mm, $z = 0.5$ mm): (a) $x$-axis variation, and (b) $y$-axis variation.
Fig. 4.12. Magnetic field distribution of the side-by-side coupled segmented loop antenna at different frequencies ($L_{\text{in}} = 99.2$ mm, $L_{\text{out}} = 97.4$ mm, $z = 0.5$ mm): (a) $x$-axis variation, and (b) $y$-axis variation.
Fig. 4.13. Magnetic field distribution of the side-by-side coupled segmented loop antenna at different frequencies ($L_{in} = 74.1$ mm, $L_{out} = 69.3$ mm, $z = 0.5$ mm): (a) $x$-axis variation, and (b) $y$-axis variation.
Fig. 4.14. Magnetic field distribution of the side-by-side coupled segmented loop antenna at different frequencies ($L_{\text{in}} = 59.1$ mm, $L_{\text{out}} = 53.7$ mm, $z = 0.5$ mm): (a) $x$-axis variation, and (b) $y$-axis variation.

### 4.5.2 Overall Size of Antenna

Fig. 4.15 shows the different sizes of the side-by-side coupled segmented loop antenna. The length of the coupling element, $L_{\text{in}}$ and $L_{\text{out}}$ is fixed at 67.1 mm and 59.3 mm respectively and the length of the fed element $L_{\text{out0}}$ is fixed at 137.6 mm. The size of the antenna is varied by adding additional coupling elements to increase the perimeter of the interrogation area ($4a$) from 0.81 $\lambda$ to 2.95 $\lambda$ (where $\lambda$ is the free space wavelength at 915 MHz). Fig. 4.16 exhibits the magnetic field distribution of the antennas ($z = 0.5$ mm) at 915 MHz. It is observed that all the antennas generate even magnetic field distribution with little variation along $x$-axis in the major portion of the interrogation zone. Besides that, magnetic field intensity of the antenna decreases as the size increases. The magnetic field shows a larger variation along the $y$-axis.
Fig. 4.15. Side-by-side coupled segmented loop antenna with different perimeters (a) 0.93 \( \lambda \), (b) 1.57 \( \lambda \), (c) 2.00 \( \lambda \), (d) 2.43 \( \lambda \), and (e) 3.07 \( \lambda \) [45].
Fig. 4.16. Magnetic field distribution of the side-by-side coupled segmented loop antennas with different sizes (at 915 MHz, $z = 0.5$ mm): (a) $x$-axis variation and (b) $y$-axis variation.
The magnetic field distribution of the proposed antenna along z-axis is exhibited in Fig. 4.17. Similar to the conventional solid line loop antenna, the smaller segmented loop antenna generates a stronger magnetic field in the region near the antenna and features a faster reduction as the distance increases. In practical application, there is a trade-off between the interrogation zone and the reading range. Smaller antenna generates stronger magnetic field intensity over smaller interrogation zone and limited tag reading distance. The larger antenna produces weaker magnetic field intensity but offers a larger interrogation zone and further tag reading distance.

![Graph showing magnetic field distribution](image)

**Fig. 4.17.** Magnetic field distribution of the side-by-side coupled segmented loop antennas with different sizes along z-axis at 915 MHz.

### 4.5.3 Substrate Permittivity, $\varepsilon_r$

This parametric study is done to examine the effect of substrate on the performances of the side-by-side coupled segmented loop antenna. The effects of four typical substrates, which are the RT5880 ($\varepsilon_r = 2.2$, $\tan\delta = 0.0009$), the RO4003 ($\varepsilon_r = 3.38$, $\tan\delta = 0.0027$), the FR4 ($\varepsilon_r = 4.4$, $\tan\delta = 0.02$), and the RO3010 ($\varepsilon_r = 10.2$, $\tan\delta = 0.0023$),
with the same thickness, \( H \), of 0.508 mm, are investigated. The antenna dimensions provided in Section 4.4 are used in this study. It is found that when the antenna is being placed on different substrate, the impedance matching of the antenna changes, as exhibited in Fig. 4.18. It is observed that as the effective permittivity of the substrate increases, the resonant frequency of the antenna shifts to a lower frequency.

Fig. 4.18. Effect of the variation in the substrate dielectric constant, \( \varepsilon_r \), on the impedance matching of the side-by-side coupled segmented loop antenna.

Fig. 4.19 shows the magnetic field distribution for the proposed antenna printed onto different substrates at the frequency of 915 MHz. It is observed that the field distribution tends to be uneven with the occurrence of the substrate. Larger dielectric constant results in larger field variation across the interrogation area of the antenna.
The antenna provides even near-field when its operating frequency is located near the first resonant frequency of the antenna. Other than 915 MHz in free space ($\varepsilon_r = 1$), the corresponding operating frequencies where antenna magnetic field density remains evenly distributed for different substrates are 780 MHz (with $\varepsilon_r = 2.2$), 740 MHz (with $\varepsilon_r = 3.38$), 700 MHz (with $\varepsilon_r = 4.4$), and 580 MHz (with $\varepsilon_r = 10.2$), respectively, as exhibited in Fig. 4.19.
in Figs 4.20 to Fig. 4.23. It is observed that the substrate with higher dielectric constant lowers operating frequency of the antenna.

Fig. 4.20. Magnetic field distribution of the side-by-side coupled segmented loop antenna at different frequencies (RT 5880, $\varepsilon_r = 2.2$, $\tan \delta = 0.0009$, $z = 0.5$ mm): (a) $x$-axis variation, and (b) $y$-axis variation.
Fig. 4.21. Magnetic field distribution of the side-by-side coupled segmented loop antenna at different frequencies (RO 4003, $\varepsilon_r = 3.38$, $\tan\delta = 0.0023$, $z = 0.5$ mm): (a) $x$-axis variation, and (b) $y$-axis variation.
Fig. 4.22. Magnetic field distribution of the side-by-side coupled segmented loop antenna at different frequencies (FR4, $\varepsilon_r = 4.4, \tan\delta = 0.02, z = 0.5$ mm): (a) $x$-axis variation, and (b) $y$-axis variation.
Fig. 4.23. Magnetic field distribution of the side-by-side coupled segmented loop antenna at different frequencies (RO 4003, $\varepsilon_r = 10.2$, tan$\delta = 0.0027$, $z = 0.5$ mm): (a) $x$-axis variation, and (b) $y$-axis variation.
4.5.4 Substrate Thickness, $H$

This parametric study aims to determine the effect of substrate thickness, $H$, on the impedance matching and the magnetic near-field distribution of the antenna. This study is carried out using the substrate of FR4 with the relative permittivity of $\varepsilon_r = 4.4$ and with the similar antenna dimensions to those in Section 4.4. The thickness of the substrate, however, is varied from 0.508 mm (20 mils), 0.8128 mm (32 mils) to 1.524 mm (60 mils).

Fig. 4.24 shows the changes of the resonant frequency of the antenna with the variation of the FR4 thickness. It is observed that as the thickness of the substrate increases, the resonant frequency of the antenna shifts down. Fig. 4.25 compares the magnetic field distribution of the antennas on the FR4 substrate with different thicknesses. It is found that thicker substrate causes weaker magnetic field and larger magnetic field variation in the interrogation zone of the antenna.

![Graph showing the effect of substrate thickness on impedance matching](image-url)

Fig. 4.24. Effect of the variation of the substrate thickness, $H$, on the impedance matching of the side-by-side coupled segmented loop antenna.
Fig. 4.25. Effect of the variation of the substrate thickness on the magnetic field distribution of the side-by-side coupled segmented loop antenna (at 915 MHz, $z = 0.5$ mm) along (a) $x$-axis, and (b) $y$-axis.

Similar to increasing the dielectric constant, the increase of the dielectric thickness raises the effective dielectric constant. This causes the operating frequency of
the antenna to be shifted down. The corresponding operating frequencies are moved down to 700, 660, and 610 MHz for the 0.508 mm (20mils), 0.8128 mm (32mils), and 1.524 mm (60mils) FR4 substrate, respectively, as exhibited in Figs. 4.26 to 4.28.

![Graph](image_url)

(a)

![Graph](image_url)

(b)

Fig. 4.26. Magnetic field distribution of the side-by-side coupled segmented loop antenna at different frequencies (FR4, \( H = 0.508 \) mm, \( z = 0.5 \) mm): (a) \( x \)-axis variation, and (b) \( y \)-axis variation.
Fig. 4.27. Magnetic field distribution of the side-by-side coupled segmented loop antenna at different frequencies (FR4, $H = 0.8128$ mm, $z = 0.5$ mm): (a) $x$-axis variation, and (b) $y$-axis variation.
Fig. 4.28. Magnetic field distribution of the side-by-side coupled segmented loop antenna at different frequencies (FR4, $H = 1.524$ mm, $z = 0.5$ mm): (a) $x$-axis variation, and (b) $y$-axis variation.
4.5.5 Spacing between Coupled Strips, $S$

The spacing between the coupled strips, i.e. the spacing between the inner dashed line and outer dashed line, $S$, is varied from 0.1, 0.5, 1.0, 1.5, to 2 mm as shown in Fig. 4.29 to observe the effect of such changes on the impedance matching and the magnetic near-field distribution of the proposed antenna. It should be noted that the increase in coupled strip spacing causes an increase in the size of the antenna. However, the interrogation zone of the antenna remains unchanged. As exhibited in Fig. 4.29, the resonant frequency of the antenna shifts up to a higher frequency when the separation between the two adjacent coupling strips increases.

![Fig. 4.29. Effect of the variation in the spacing between coupled strip, $S$, on the impedance matching of the side-by-side coupled segmented loop antenna.](image)

Generally, at 915 MHz, the magnetic field density around the antenna too increases with the increase of the separation, $S$ as exhibited in Fig. 4.30. However, when the separation, $S$ is too large ($S = 2.0$ mm), the magnetic field density of the antenna
decreases. This is because current cannot be efficiently coupled between the coupling strips. Therefore, an optimum separation, $S$ of 1.0 mm is chosen to provide a high magnetic field intensity while maintaining even field distribution of the antenna.

![Graph](image-url)

Fig. 4.30. Effect of the variation in the separation between two adjacent coupling strips, $S$, on the magnetic near-field distribution of the side-by-side coupled segmented loop antenna at 915 MHz ($z = 0.5$ mm) along (a) $x$-axis, and (b) $y$-axis.
4.5.6 Strip Width, $W$

The width of the strip, $W$, for both inner and outer dashed-line, is varied from 0.5, 1.0, 2.0, to 4.0 mm. It should be noted an increase of strip width causes an increase in antenna size. However, the interrogation area of the antenna remains unchanged for all the cases for fair comparison. Fig. 4.31 exhibits the effect of varying the width of the strip, $W$, on the impedance matching of the proposed segmented antenna. It is observed that the resonant frequency of the segmented antenna shifts left to a lower frequency as the strip width increases.

![Graph showing the effect of varying strip width on impedance matching](image)

Fig. 4.31. Effect of the variation in the strip width, $W$, on the impedance matching of the side-by-side coupled segmented loop antenna.

From Fig. 4.32, it is observed that, generally, the magnetic field distribution is higher when the width of the antenna is smaller. However, the smaller width of strip causes the overall distribution of the magnetic field to be uneven when being compared to that of the larger width strip. Therefore, it is observed that the field density maintains strong and evenly distributed when the strip width is 2 mm.
Fig. 4.32. Effect of the variation in the strip width, $W$, on the magnetic near-field distribution of the side-by-side coupled segmented loop antenna at 915 MHz ($z = 0.5$ mm). (a) $x$-axis variation, and (b) $y$-axis variation.
4.5.7 Extension of First Coupled Line, $\Delta l$

The length of the first coupled line is extended in both positive and negative direction to observe the effect of such changes on the performances of the segmented antenna (Fig. 4.33). From Fig. 4.34, it is found that the positive extension of coupled line will shift the resonant frequency of the antenna leftward. However, the near-field distribution is hardly altered from the extension of the first coupled line (Fig. 4.35). Therefore, the extension can be applied in tuning the impedance match at the operating frequency without affecting the near-field performance of the segmented antenna.

Fig. 4.33. Extension of the first coupled line, $\Delta l$
Fig. 4.34. Effect of the variation in the extension of the first coupled line, $\Delta l$, on the impedance matching of the side-by-side coupled segmented loop antenna.
Fig. 4.35. Effect of the variation in the extension of the first coupled line, $\Delta l$, on the magnetic near-field distribution of the side-by-side coupled segmented loop antenna at 915 MHz ($z = 0.5$ mm) along (a) $x$-axis, and (b) $y$-axis.

4.5.8 Gaps between Series of Coupling Strip, $S_{in}$ and $S_{out}$

The gaps between the series coupling strip, $S_{in}$ and $S_{out}$, as exhibited in Fig. 4.36, are varied from 0.5, 1.0, 2.0, to 4.0 mm to observe the effect of such changes on the performances of the segmented antenna. It should be noted that changes of gaps alter the coupling strip lengths, $L_{in}$ and $L_{out}$. However, the changes in $L_{in}$ and $L_{out}$ are electrically small and do not affect the performances of the antenna. As the gaps between the series coupling strips increase, the resonant frequency of the antenna shifts to the right, to a higher frequency. This is clearly illustrated in Fig. 4.37. However, the influence of the gaps on the magnetic field distribution, $H_z$, is insignificant (Fig. 4.38). Therefore, the
gaps between the series coupling strips, $S_{in}$ and $S_{out}$, can be used to tune the impedance matching without affecting the magnetic near-field performance of the segmented antenna.

Fig. 4.36. Gaps between the series coupling strip, $S_{in}$ and $S_{out}$
Fig. 4.37. Effect of the variation in the gaps between the similar coupling strip, $S_{in}$ and $S_{out}$, on the impedance matching of the side-by-side coupled segmented loop antenna.
Fig. 4.38. Effect of the variation in the gaps between the series of coupling strip, \( S_{in} \) and \( S_{out} \), on the magnetic near-field distribution of the side-by-side coupled segmented loop antenna at 915 MHz. (a) \( x \)-axis variation, and (b) \( y \)-axis variation.

4.5.9 Conclusion on Parametric Study

From the parametric study, it is found that the parameters that influence performances of the side-by-side coupled segmented loop antenna most are the length of the coupling strips \( L_{in} \) and \( L_{out} \), the substrate permittivity used on the antenna, \( \varepsilon_r \), and the substrate thickness, \( H \). All of these parameters cause significant changes in the resonant frequency and the magnetic near-field distribution of the proposed antenna.

Parameters like the separation between two coupled strips, \( S \), the width of the strip, \( W \), the extension of the first coupled strip, \( \Delta l \), and the gaps between the coupling strips, \( S_{in} \) and \( S_{out} \), affect the impedance matching of the antenna, but do not alter the magnetic field distribution of the antenna significantly. Such parameters can be used for tuning the impedance match of the proposed antenna when the influential parameters of
the antenna are being set. These parameters should be electrically small to maintain the proper coupling between the coupled lines.

For the comment on the size of the proposed antenna, smaller antenna generates stronger magnetic field intensity over limited interrogation zone. The larger antenna produces weaker magnetic field intensity but offers a bigger interrogation zone. Therefore, there exists a trade-off between the interrogation zone and the reading range when it comes to designing such type of antenna.

### 4.6 Antenna Implementation, Results and Discussion

For practical implementation, the side-by-side coupled segmented loop antenna can be printed onto any substrate and optimized at specific operating frequency by selecting the proper parameters. In this section, an antenna prototype printed on a FR4 substrate with a relative permittivity, $\varepsilon_r$ of 4.4, a loss tangent, $\tan\delta$ of 0.02, and a thickness, $H$ of 0.508 mm is demonstrated. The antenna is designed at the center frequency of 915MHz. The segmented loop antenna is with an overall size of $175 \times 180$ mm$^2$. It offers an interrogation area of $154 \times 154$ mm$^2$. The internal perimeter of the antenna is 616 mm, which is of $1.88\lambda$ at 915 MHz.

As shown in Fig. 4.39(a), the antenna is fed by two parallel strip lines which are printed on the opposite sides of the substrate. The upper/bottom parallel strips are connected to the inner/outer conductors of an SMA connector, respectively. A matching network comprised of simple stubs was adopted to match the antenna to the 50-Ω feed line. The matching network here is similar to that of the top-to-bottom coupled segmented antenna (Section 3.6) for fair performance comparison in the later section (Section 4.7). In practice, however, a matching network that is on a single layer (top
layer) can be designed. The detailed dimensions of the antenna prototype are exhibited in Fig. 4.39(a) and the photograph of the antenna prototype is provided in Fig. 4.39(b). A conventional solid-line loop antenna of the same interrogation zone, as illustrated in Fig. 4.39(c), is also prototyped for comparison.

Fig. 4.39. Configuration of the loop antenna prototypes using FR4 substrate: (a) detailed dimensions of the side-by-side coupled segmented loop antenna prototype, (b) photo of the side-by-side coupled segmented loop antenna prototype, and (c) photo of the solid-line loop antenna.
4.6.1 Impedance Matching Measurement

The impedance matching measurement of the antenna is carried out with the Agilent E5230A vector network analyzer (VNA). Fig. 4.40 exhibits the measured return loss. The bandwidth for 10 dB return loss covers the frequency range of 820–1050 MHz (24.6%). Compared to the simulation, good agreement is achieved. However, there are slight discrepancy between the measured and the simulated return losses. This is due to the differences between the antenna feeding methods adopted in the simulation and the measurement. In simulation, the antenna is directly fed by a pair of differential ports. In measurement, the antenna is connected to a feeding cable, which is unbalanced and further connected to the VNA. It is difficult to simulate such cable in the IE3D simulation system. Therefore, the simulated and measured impedance matching is slightly different across the frequency range.

Fig. 4.40. Measured and simulated impedance matching of the side-by-side coupled segmented loop antenna prototype.
4.6.2 Magnetic Field Distribution Measurement

Using the E5230A VNA and the Langer EMV-Technik RF-R 3-2 near-field probe [49], the magnetic field distribution of the proposed antenna is measured. The antenna and the near-field probe are connected to Port 1 and Port 2 of the VNA, respectively. The relatively magnetic field intensity is quantified by $|S_{21}|$. The near-field magnetic field probe is placed on the surface of the antenna prototype, and is moved along the $x$- and $y$-axes separately with an interval of 5 mm. The calibration of the probe is not required in the measurement since what we concern here is the relative field distribution, not the absolute magnitude of the magnetic field. Figs. 4.41, 4.42, and 4.43 show the simulated and measured magnetic field intensity at 840, 915, and 960 MHz, along $x$- and $y$- axes. It should be noted that the simulated magnetic field density ($H_z$) is of unit A/m (dB) and the measured field intensity is in the form of $|S_{21}|$, which is dimensionless. For fair comparison, both results at the origin ($x = 0, y = 0$) are normalized. The trend of both the results is observed. Of all the cases, good agreement is observed between measured and simulated relative magnetic distribution.
Fig. 4.41. Measured and simulated magnetic field distribution of the side-by-side coupled segmented loop antenna prototype (at 840 MHz, $z = 0.5$ mm): (a) $x$-axis variation and (b) $y$-axis variation.
Fig. 4.42. Measured and simulated magnetic field distribution of the side-by-side coupled segmented loop antenna prototype (at 915 MHz, $z = 0.5$ mm): (a) $x$-axis variation and (b) $y$-axis variation.
Fig. 4.43. Measured and simulated magnetic field distribution of the side-by-side coupled segmented loop antenna prototype (at 960 MHz, $z = 0.5$ mm): (a) $x$-axis variation and (b) $y$-axis variation.
4.6.3 Reading Range Test

For the reading range test, the antenna prototype is applied as a reader antenna in a near-field UHF RFID system. As shown in Fig. 4.44, the antenna prototype is connected to the Impinj Speedway reader (865–956 MHz, 30-dBm output) [50] to detect Impinj button type tags. The tags are of the model J21 and each of them is 9 mm in diameter [51]. 25 tags are positioned symmetrically on a Styrofoam disc with a diameter of 160 mm. The number of the detected tags are recorded when the Styrofoam disc is positioned above/below the antenna prototype at different distances. To ensure the reliability of the read range test, the tags attached to the Styrofoam disc are randomly placed, and an average of five measurements is recorded at each reading distance from the antenna.

Fig. 4.44. Reading range experiment set up for the side-by-side coupled segmented loop antenna.
Fig. 4.45. Measured reading rate against distance of the side-by-side coupled segmented loop antenna and the solid line loop antenna with a similar interrogation zone.

Fig. 4.45 shows the reading rate against the tag detection distance. The result of the tag reading distance of a conventional solid line loop antenna is also illustrated in the same figure for comparison. It should be noted that the solid line loop antenna has the identical dimensions of the inner dashed-line loop of the proposed antenna. Both the proposed segmented loop antenna and the conventional solid line loop antenna offer bidirectional reading. The segmented loop antenna exhibits superior performance over the conventional solid loop antenna. It achieves a 100% reading rate with a distance up to 24 mm, while the conventional solid line loop antenna offers only a reading rate of 45% even though the tags are placed on the surface ($d = 0$ mm) of the antenna.
4.6.4 Uni-directional Antenna Prototype

Uni-directional detection is preferred in some RFID applications. The most common method in making a loop-like antenna uni-directional is to apply a metal plate or reflector at one side of the antenna [18]. Fig. 4.46 demonstrates a uni-directional segmented loop antenna. The antenna prototype is positioned above a copper plate with a certain distance, \( g \). Styrofoam is used to create such separation distance. The copper plate is with a size of \( 300 \times 300 \text{ mm}^2 \) or \( 0.9 \times 0.9 \lambda^2 \), where \( \lambda \) is the antenna free space operating wavelength at 915 MHz.

![Uni-directional side-by-side coupled segmented loop antenna prototype.](image)

Fig. 4.46. Uni-directional side-by-side coupled segmented loop antenna prototype.

Fig. 4.47 shows the measured return loss of the uni-directional antenna prototypes at each distance \( g \). It is observed that the metal plate degrades the impedance matching of the uni-directional antenna especially when it is placed at a very close distance to the antenna (i.e. \( g = 10 \) and 20 mm). When the metal plate is of sufficient distance away from the metal plate (i.e. \( g = 40 \) and 50 mm), the impedance matching is less affected. The impedance matching for 10 dB return loss can be achieved at a certain frequency range, 820–1000 MHz. However, the impedance matching bandwidth in such situation is reduced.
<table>
<thead>
<tr>
<th>Frequency, MHz</th>
<th>without copper plate</th>
<th>( g = 10 ) mm</th>
<th>( g = 20 ) mm</th>
<th>( g = 40 ) mm</th>
<th>( g = 50 ) mm</th>
</tr>
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<tr>
<td>600</td>
<td>25</td>
<td>20</td>
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</table>

Fig. 4.47. Measured return loss of the uni-directional side-by-side coupled segmented loop antenna prototype with different separation distances, \( g \).

The reading rate of a uni-directional side-by-side coupled segmented loop antenna prototype with a copper plate \((300 \times 300 \text{ mm}^2)\) placed 40 mm away from the antenna is exhibited in Fig. 4.48. The distance for 100% tag reading is enhanced to 36 mm, which is 1.5 times of that of the original segmented loop antenna prototype without metal plate.

In addition, the result of a commercial near-field UHF antenna, the Impinj Brickyard near-field RFID antenna, with the model number of CS-777, and with the circular interrogation zone of a diameter of 160 mm [52] is exhibited in Fig. 4.48 for comparison. It is observed that the proposed uni-directional segmented loop antenna achieves a 100% reading rate up to 36 mm. The commercial antenna, however, can only provide the 100% reading rate distance up to 24 mm. The proposed uni-directional segmented loop antenna is able to achieve 1.5 times tag reading distance than that of the commercial antenna.
4.6.5 Verification of Antenna Coverage Area

It is essential to find out the coverage area of the proposed antenna. The antenna coverage area is defined as the maximum area where a 100% reading rate is obtained when the near-field RFID tags are placed at a near-field distance \((d = 0 \text{ mm})\) of the antenna. It should be noted that the metal plate reflector is not included in this experiment.

In Fig. 4.49, the RFID tags are distributed randomly within different investigation areas, from \(220 \times 220 \text{ mm}^2\) (with a total of 90 tags), \(200 \times 200 \text{ mm}^2\) (with a total of 60 tags), \(180 \times 180 \text{ mm}^2\) (with a total of 50 tags), and \(160 \times 160 \text{ mm}^2\) (with a total of 35 tags). The reading rate is then being obtained with the procedure similar to that in Section 4.6.3.
Fig. 4.49. Near-field RFID tags distributed randomly within different investigation area: (a) $220 \times 220 \text{ mm}^2$, (b) $200 \times 200 \text{ mm}^2$, (c) $180 \times 180 \text{ mm}^2$, and (d) $160 \times 160 \text{ mm}^2$

Fig. 4.50 shows the results of the reading rate of RFID tags placed within different coverage area. It is observed that when the tags are located within an area larger than that of the antenna, 100% tag reading rate could not be achieved even if the tags are placed on the surface of the antenna ($d = 0 \text{ mm}$). When the RFID are located within the area bounded by the antenna, which is $160 \times 160 \text{ mm}^2$, all the tags can be accurately detected by the RFID system.
Fig. 4.50. Measured reading rate against distance for the side-by-side coupled segmented loop antenna prototype with different investigation zones.

Therefore, it can be verified that the prototype of the side-by-side coupled segmented loop antenna is able to provide a coverage area of $160 \times 160$ mm$^2$. This area can be referred as the interrogation area ($a \times a$) for the proposed antenna.

4.7 Comparison of Top-to-bottom and Side-by-side Coupled Segmented Loop Antenna

The reading rate of the loop antenna with top-to-bottom and the side-by-side coupled segmented loop antennas are being compared. For fair comparison, both the antennas are of similar size ($164 \times 164$ mm$^2$ or $0.5 \times 0.5 \lambda^2$, with $\lambda$ corresponds to the operating wavelength at 915 MHz). Both the antenna adopts the similar matching stub too.
Fig. 4.51. Measured reading rate against distance for the top-to-bottom coupled segmented antenna and the side-by-side coupled segmented loop antenna.

It can be observed that both the antennas offer bi-directional reading. They achieve a 100% reading rate with a distance up to 24 mm, as illustrated in Fig. 4.51. At near-field intervals $-60 \text{ mm} \leq d \leq -36 \text{ mm}$ and $36 \text{ mm} \leq d \leq 60 \text{ mm}$, the top-to-bottom coupled segmented antenna offers a higher reading rate compared to that of the side-by-side coupled segmented antenna. The reading rate of the top-to-bottom coupled antenna, however, drops at a faster rate when the reading distance, $d$, is larger than 60 mm. This can be concluded that the top-to-bottom coupled segmented antenna offers a higher field density at the near-field zone but the field density drops at a faster rate when being compared to that of the side-by-side coupled segmented antenna.
4.8 Concluding Remarks

A side-by-side coupled segmented loop antenna is proposed in this chapter. The proposed antenna is designed on a single layer for ease of fabrication. The segmented structures are able to provide a very small phase delay to the current flowing through them. As a result, the current along the segmented lines is kept in phase. This causes the current to flow in a single direction along the proposed segmented loop antenna even though the loop is electrically large (> 0.5 λ). The proposed antenna has an overall size of 175 × 180 × 0.5 mm³. It achieves a large interrogation zone of 160 × 160 mm². The proposed segmented loop antenna has demonstrated the capability of producing strong magnetic field with relatively uniform field distribution over a frequency band of 840–960 MHz (13.3%) in the near-field region of the antenna even though the perimeter of the antenna is comparable to the wavelength. With such characteristics, it is suitable for near-field RFID UHF reader.

The proposed antenna prototype has shown significant improvement by achieving a maximum reading rate of 100%. The conventional loop antenna prototype with similar interrogation zone, in contrast, is only able to offer a maximum reading rate of 40%. The proposed antenna, compared to a commercial near-field UHF RFID reader antenna, extends the detection range by 1.5 times and achieves a 100% reading rate at a tag reading distance of 36 mm within a given interrogation zone.

From the parametric studies done, it is found that the length of the segmented line section determines the operating frequency at which the antenna produces even magnetic
field distribution. The substrate properties are found to have the severe effects on antenna performance and therefore have to be considered in practical design.¹

¹For the side-by-side coupled segmented loop antenna, an electronic letter with the title of “Segmented Loop Antenna for UHF Near-Field RFID Applications” has been published in the IEE Electronics Letters in July 2009 [53]. A conference paper with the title of “UHF Near-field RFID Reader Antenna” has been accepted for the December 2009 Asia Pacific Microwave Conference (APMC2009) [54]. Besides that, a full paper with the title of “A Broadband Near-field UHF RFID Antenna” has been submitted to the IEEE Transactions on Antennas and Propagation in July 2009 [55].
CHAPTER 5 : LOOP ANTENNA WITH PHASE SHIFTERS

The top-to-bottom coupled segmented antenna proposed in Chapter 3 and the side-by-side coupled segmented antenna proposed in Chapter 4 are found to provide strong and even near-field distribution for the application as UHF near-field reader antennas with electrical sizes larger than one operating wavelength. However, both the structures have large numbers of tuning parameters for the current to be effectively coupled to the entire antenna for even near-field distribution. In this chapter, loop antenna with less tuning parameters yet with a simple operating principle is proposed. The antenna is also capable of providing strong and even field distribution with an electrical size larger than one operating wavelength.

The loop antenna with phase shifters is investigated in this chapter. First, the antenna configuration is presented. Then, the principle of the antenna operation is discussed. After that, procedures of the antenna design are stated. This is followed by the interpretation of the performance of the near-field antenna. A parametric study is performed and the antenna prototypes are measured. After that, comparisons between the loop antenna with phase shifters and the segmented antennas proposed in Chapter 3 and 4 are provided. At last, concluding remarks on the loop antenna with phase shifters are given.

5.1 Antenna Configuration

Fig. 5.1 shows the scheme of the loop antenna with phase shifters. A Cartesian coordinate system is oriented in such a position that the upper surface of the substrate lies
in the $x$-$y$ plane and the center of the square loop antenna is at the origin of the coordinate system.

Unlike the segmented antennas proposed in Chapter 3 and 4, the loop antenna with phase shifters is composed of a solid loop line. The antenna is printed on top of a substrate, as shown in Fig. 5.1.

The antenna is generally a square loop. Each side of the loop is of length $L_1$. At each corner of the loop, there is an excess loop line, which is of length of $L_2$. The loop is with the total length of $L_{\text{tot}}$. The width of the loop is indicated by the line width, $W$. The internal area ($a \times a$) of the proposed antenna is indicated as the interrogation zone with a perimeter of $4a$.

The antenna is fed by a pair of parallel strip lines with a strip width of $W_f$. A matching circuit can be used to achieve required antenna impedance matching over a specific frequency range. The antenna is printed on the top of a substrate with the relative permittivity, $\varepsilon_r$, substrate thickness, $H$, and the loss tangent, $\tan\delta$, as exhibited in Fig. 5.1(b).

The size of the antenna is determined by the perimeter of the loop antenna. It should be noted that the impedance matching circuits and the phase shifters are not considered in determining the perimeter of the antenna.
The shape of the excess loop lines can be varied to reduce the space occupied by the antenna, with the same interrogation area, as shown in Fig. 5.2.
5.2 Principle Operation

To study the near-field distribution of the loop antenna, current distribution of the antenna is first observed. Fig. 5.3 shows the comparison of simulated current distribution between the conventional solid line loop antenna and the loop antenna with phase shifters, each with the total length of $2 \lambda$, at 915 MHz.

As current moves along the conventional solid loop antenna, current phase will be accumulated. The accumulation of current phase is due to the impedance imposed when the current is forced to move around the antenna. Current null will occur when it moves around $0.5 \lambda$ of the solid loop line. Direction of the current flow changes when the current moves further than $0.5 \lambda$ on the solid line. Fig. 5.3(a) exhibits the current distribution of the square solid loop antenna with the electrical size of $2 \lambda$. Due to the fact that each side of the square loop is about $0.5 \lambda$ in length, current flows in opposite direction in adjacent
sides of the loop. The magnetic fields in produced in the z-axis, $H_z$, by these currents cancel each other and is thus very weak in the center portion of the antenna, as exhibited in Fig. 5.4(a). This situation is not desired in the near-field RFID reader antennas as RFID tags located at the center portion of the antenna cannot be effectively detected.

The problem encountered in the electrically large conventional loop antenna can be resolved using the loop antenna with phase shifters. At each corner of the square loop of the proposed antenna, there is an excess loop line. These loop lines can be tuned in such a way that the current with the opposite direction (relevant to that on the loop) is kept in them. Therefore, the excess loop line can be treated as a 180° current phase shifter. With four phase shifters (for an antenna with interrogation perimeter of 2 $\lambda$), the current along the proposed loop antenna can be made flowing in a single direction along the antenna (Fig. 5.3(b)) even though the loop is electrically large (> 0.5 $\lambda$). The magnetic fields produced in the z-direction are thus being added up and exhibits even distribution over the interrogation zone (Fig. 5.4(b)). Such magnetic field distribution is preferred for the near-field UHF RFID application as the tags can be effectively detected even though the size of the antenna is larger than one operating wavelength.
Fig. 5.3. Simulated current distribution at 915 MHz: (a) conventional solid line loop antenna and (b) loop antenna with phase shifters [45].
Fig. 5.4. Simulated 2-D magnetic field distribution at 915 MHz (z = 0.5 mm): (a) conventional solid line loop antenna and (b) loop antenna with phase shifters [45].

5.3 Design Procedure

For a specific design with the required interrogation zone, a, and the required operating frequency, \( f_0 \), the other geometrical parameters of the loop antenna with phase shifters can be determined by the following procedures:

- Length of each side of the square loop, \( L_1 \)

For the proposed antenna with the total perimeter of interrogation area less than 2 \( \lambda \), the length at each side of the loop, \( L_1 \), should be less than half an operating wavelength (\( L_1 \leq 0.5 \lambda \)). This is because direction of current changes in every half-a-wavelength. If one would like to design a loop that is longer than 2 \( \lambda \), one should be reminded that a phase shifter should be introduced in every 0.5 \( \lambda \) distance along the loop to ensure that current
flows in a single direction. In our example, the length at each side of the loop is set at 0.45 $\lambda$.

- Length of each of the excess loop line/phase shifter, $L_2$

The length of each excess loop line/phase shifter, $L_2$, should be more than 0.5 $\lambda$ ($L_2 \geq 0.5 \lambda$), to keep opposite flow of current from entering to the loop antenna. As such, strong and even near-field distribution could be obtained.

It is suggested that the separation between the two feeding lines, $S_0$, the feeding strip width, $W_f$, and the loop width, $W$ should be electrically small so that the antenna performance will not be affected.

A matching network comprising simple stubs can be adopted to match the antenna to the 50-$\Omega$ feed line at the desired frequencies.

### 5.4 Interpretation of Performance

In this section, a loop with four phase shifters operating at 915 MHz is designed. The detailed geometrical parameters of the antenna design are: $a = 144$ mm, $W = 2$ mm, $S_0 = 2$ mm, $L_1 = 142$ mm, and $L_2 = 168$ mm. The antenna is designed in free space without any substrate. The feeding source is placed directly across the end of the loop. All the simulations are performed using the IE3D software [45].

In addition, the loop antenna with phase shifters offers an interrogation zone of $144 \times 144$ mm$^2$ or $0.44 \times 0.44 \lambda^2$ at 915 MHz. For comparison, the results of a conventional solid line loop antenna are also exhibited. The square solid line loop has the same size as proposed antenna and thus offers the similar interrogation zone.
To quantify the magnetic field distribution of the antenna in a more convenient way, the magnetic field intensity is plotted along the $x$- and $y$-axes of the antenna as shown in Fig. 5.5.

The magnetic field intensity shown in Fig. 5.5 is extracted from the simulated 2-D magnetic field distribution in Fig. 5.4. It is observed that the magnetic field distributions are symmetrical with respect to the $y$-axis ($x = 0$ mm) for both the antennas (Fig. 5.5 (a)). Furthermore, the magnetic field features stronger magnitude in the regions very close to the loop lines and experiences a fast reduction when the observation point is moved towards the center of the antenna.

Fig. 5.5(a) shows the comparison of magnetic field distribution between the loop proposed antenna and the conventional solid line loop along the $x$-axis. The proposed antenna offers desired magnetic field distribution with a variation of 25 dB over the entire interrogation zone (-72 mm $\leq x \leq$ 72 mm) and a variation of 7 dB over the major portion of the interrogation zone (-60 mm $\leq x \leq$ 60 mm). In addition, a sharp field reduction is observed over the intervals of (-74 mm $\leq x \leq$ -72 mm) and (72 mm $\leq x \leq$ 74 mm). These are the intervals located on the loop strip. As the current flowing on the line of the loop is of the same direction, weak magnetic fields are produced on the loop lines. As a result, total magnetic field in the $z$-direction, $H_z$, at such an area experiences a sharp drop. The solid line loop antenna, however, in Fig. 5.5(a), is not able to generate even magnetic field over the interrogation area. There exist variation of 38 dB over the range of -72 mm $\leq x \leq$ 72 mm and variation of 18 dB for -60 mm $\leq x \leq$ 60 mm.

Fig. 5.5(b) exhibits the magnetic field distribution along $y$-axis. The loop antenna with phase shifters antenna offers a much better magnetic field distribution than that of
the solid line loop antenna. The maximum magnetic field variation is 45 dB for the solid loop antenna and 27 dB for the loop antenna with phase shifters antenna over the range of $-72 \text{ mm} \leq x \leq 72 \text{ mm}$. In the interval of $-60 \text{ mm} \leq x \leq 60 \text{ mm}$, the variation of magnetic field for the solid line loop antenna is 24 dB while the variation of magnetic field for the loop antenna with phase shifters is 8 dB.
Fig. 5.5. Magnetic field distribution of the loop antenna with phase shifters and the conventional loop antenna without phase shifter (at 915 MHz, $z = 0.5$ mm): (a) $x$-axis variation, and (b) $y$-axis variation.

Fig. 5.6 shows the $x$- and $y$-axes magnetic field distribution of the loop antenna with phase shifters antenna at the frequencies of 700, 900, 915, 930, and 1250 MHz. It is shown that the loop antenna with phase shifters achieves even magnetic field distribution with little variation over the frequency range of 900–930 MHz, which is desirable for RFID applications. When the operating frequency shifts down to a lower frequency, such as 700 MHz, or shifts up to a higher frequency, such as 1250 MHz, the evenness of the magnetic field distribution degrades. This is due to the fact that the excess loop line at the corner of the antenna is electrically shorter (for operating frequency at 700 MHz) or electrically longer (for operating frequency at 1250 MHz). As shown in Fig. 5.7, the current along the loop is no longer in a single direction. This causes the magnetic field
distribution to be uneven and nulls appear in the interrogation zone of the proposed antenna (Fig. 5.8).

![Graph](image)

**Fig. 5.6.** Magnetic field distribution of the loop antenna with phase shifters at different frequencies ($L_1 = 142$ mm, $L_2 = 168$ mm, $z = 0.5$ mm): (a) $x$-axis variation and (b) $y$-axis variation.
Fig. 5.7. Simulated current distribution of the loop antenna with phase shifters \((L_1 = 142 \text{ mm}, L_2 = 168 \text{ mm}, z = 0.5 \text{ mm})\) at different frequencies: (a) 700 and (b) 1250 MHz [45].

Fig. 5.8. Simulated 2-D magnetic field distribution of the loop antenna with phase shifters \((L_1 = 142 \text{ mm}, L_2 = 168 \text{ mm}, z = 0.5 \text{ mm})\) at different frequencies: (a) 700 and (b) 1250 MHz [45].
5.5 Parametric Study

A parametric study is conducted to provide information about the effect of geometric parameters on the performance of the loop antenna with phase shifters. The study is conducted using the IE3D software package [45]. The parameters under study include the length of the phase shifter, \( L_2 \), length of each side of the square loop, \( L_1 \), substrate permittivity used on the antenna, \( \varepsilon_r \), substrate thickness, \( H \), and the width of the loop, \( W \). To better understand the influence of the parameters on the antenna performance, only one parameter is varied at a time, while the others are kept unaltered unless specified.

5.5.1 Length of Phase Shifter, \( L_2 \)

This study aims to determine the effect of the length of the excess loop line/phase shifter, \( L_2 \), on the magnetic near-field distribution of the proposed antenna. By keeping the length of each side of the square loop constant, \( L_1 = 148 \text{ mm or } 0.45 \lambda \), where \( \lambda \) is the operating wavelength at 915 MHz in free space, the length of the phase shifter, \( L_2 \), is varied from 131 mm (0.4 \( \lambda \)), 147 mm (0.45 \( \lambda \)), 164 mm (0.5 \( \lambda \)) to 180 mm (0.55 \( \lambda \)).

Fig. 5.9 shows the magnetic distribution of the proposed antenna with different lengths of phase shifter. To provide strong and even field distribution within the interrogation zone, the length of each of phase shifter, \( L_2 \), should be around 147 mm (0.5 \( \lambda \)). When the length of the phase shifter is electrically shorter (0.4 and 0.45 \( \lambda \)) or electrically longer (0.55 \( \lambda \)), the current on the loop will not be solely in a single direction. This causes the magnetic field distribution on the antenna to be weak and uneven.
Fig. 5.9. Effect of the variation in the length of the phase shifters, $L_2$, on the magnetic near-field distribution on the loop antenna with phase shifters at 915 MHz along (a) $x$-axis and (b) $y$-axis.
5.5.2 Length of Each Side of Square Loop, $L_1$

This study aims to find out the effect of the length of each side of the square loop, $L_1$, on the performance of the proposed antenna. By keeping the total length of the proposed antenna, $L_{\text{tot}}$ at 1246 mm ($3.88 \lambda$, where $\lambda$ is the free space operating wavelength at 915 MHz), the length of each side of the square loop, $L_1$, is varied from 98 mm ($0.3 \lambda$), 131 mm ($0.4 \lambda$), 147 mm ($0.45 \lambda$), 164 mm ($0.5 \lambda$) to 197 mm ($0.6 \lambda$) to observe its effect on the magnetic near-field distribution in $z$-direction ($H_z$) of the proposed antenna. It should be noted that the variation in the length of $L_1$ changes the length of phase shifters and affects the interrogation zone of the antenna. Smaller $L_1$ provides a smaller interrogation zone. This is depicted in Fig. 5.10.
Fig. 5.10. Proposed loop antenna with phase shifters with different $L_1$ (a) 0.3 $\lambda$, (b) 0.4 $\lambda$, (c) 0.45 $\lambda$, (d) 0.5 $\lambda$, and (e) 0.6 $\lambda$ [45].

From Fig. 5.11, it is found that, the optimum length for $L_1$ is 0.45 $\lambda$. With $L_1$ = 0.45 $\lambda$, the magnetic field of the antenna is strong and even throughout the interrogation zone. It is also observed that smaller size antennas (with $L_1$ = 0.3 and 0.4 $\lambda$) do not
guarantee high and even magnetic field distribution despite their smaller interrogation zone. This result opposes the results appeared in Chapter 3 (Section 3.5.2, Fig. 3.15) and Chapter 4 (Section 4.5.2, Fig. 4.16). This is because the magnitude of the current flowing through the smaller antennas (with $L_1 = 0.3$ and $0.4 \lambda$) is relatively smaller and thus the magnetic field produce at the interrogation regions are weaker as being compared with that of the proposed antenna with $L_1 = 0.45 \lambda$. Proposed antennas with longer $L_1$ ($L_1 = 0.5$ and $0.6 \lambda$) too produce weaker magnetic field distribution in the interrogation zones. This is because the current on the square loops is not in a single direction. Hence, field nulls appear in the interrogation zones.
Fig. 5.11. Magnetic field distribution of the loop antenna with phase shifters with different lengths of $L_1$ (at 915 MHz, $z = 0.5$ mm): (a) $x$-axis variation and (b) $y$-axis variation.

### 5.5.3 Substrate Permittivity, $\varepsilon_r$

To examine the effect of substrate on the performances of the loop antenna with phase shifters, four typical substrates, namely the RT5880 ($\varepsilon_r = 2.2$, $\tan\delta = 0.0009$), the RO4003 ($\varepsilon_r = 3.38$, $\tan\delta = 0.0027$), the FR4 ($\varepsilon_r = 4.4$, $\tan\delta = 0.02$), and the RO3010 ($\varepsilon_r = 10.2$, $\tan\delta = 0.0023$), with the same thickness, $H$, of 0.508 mm are used. The antenna dimensions are similar to those in Section 5.4. It is found that, when the proposed antenna is placed on different substrate, the impedance matching of the antenna changes as exhibited in Fig. 5.12. It is observed that as the effective permittivity of the substrate increases, the resonant frequency of the antenna is shifted down to a lower frequency.
Fig. 5.12. Effect of the substrate dielectric constant, $\varepsilon_r$, on the impedance matching of the loop antenna with phase shifters.

Fig. 5.13 illustrates the magnetic field distribution for the proposed antenna printed onto different substrates at 915 MHz. It is observed that the field distribution tends to be uneven with the occurrence of the substrate. Larger dielectric constant results in larger field variation.

Of all the cases in the study, it should be noted that the graphs of impedance matching are used to discuss the effect of changing in antenna parameters on its resonant frequency. At the first resonant frequency, current flows in a single direction along the antenna. As a result, even field distribution is achieved. From Fig. 5.12, it is obvious that, at the resonant frequencies, the antenna may not match well with the 50-$\Omega$ system. Such antenna, when directly connected to the RFID system, has the potential of damaging the system. This problem can be solved by adding impedance matching network between the antenna and the feeding lines without affecting on the field distribution of the antenna.
Fig. 5.13. Effect of the variation in the substrate dielectric constant on the magnetic field distribution of the loop antenna with phase shifters at (915 MHz, z = 0.5 mm) along (a) x-axis, and (b) y-axis.
The adding of the substrate decreases the resonant frequency. The proposed antenna provides even magnetic near-field distribution around the resonant frequency. Other than 915 MHz in free space ($\varepsilon_r = 1$), the corresponding operating frequencies where antenna magnetic field distribution remains even for different substrates are 865 MHz (with $\varepsilon_r = 2.2$), 780 MHz (with $\varepsilon_r = 3.38$), 740 MHz (with $\varepsilon_r = 4.4$), and 600 MHz (with $\varepsilon_r = 10.2$), respectively as exhibited in Figs. 5.14 to 5.17. It implies that the substrate with higher dielectric constant shifts down the antenna operating frequency.
Fig. 5.14. Magnetic field distribution of the loop antenna with phase shifters at different frequencies (RT 5880, $\varepsilon_r = 2.2$, $\tan\delta = 0.0009$, $z = 0.5$ mm): (a) $x$-axis variation, and (b) $y$-axis variation.

(a)

(b)
$\varepsilon_r = 3.38$, RO4003

Fig. 5.15. Magnetic field distribution of the loop antenna with phase shifters at different frequencies (RO 4003, $\varepsilon_r = 3.38$, tan$\delta = 0.0023$, $z = 0.5$ mm): (a) x-axis variation, and (b) y-axis variation.

$\varepsilon_r = 4.4$, FR4
Fig. 5.16. Magnetic field distribution of the loop antenna with phase shifters at different frequencies (FR4, $\varepsilon_r = 4.4$, $\tan\delta = 0.02$, $z = 0.5$ mm): (a) $x$-axis variation, and (b) $y$-axis variation.
5.5.4 Substrate Thickness, $H$

This study is conducted using the FR4 substrate with the relative permittivity, $\varepsilon_r$, of 4.4, the loss tangent, $\tan\delta$, of 0.02, and with the antenna dimensions mentioned in Section 5.4. The thickness of the substrate, $H$, however, is varied from 0.508 mm (20 mils), 0.8128 mm (32 mils) to 1.524 mm (60 mils) to observe the effect such variation on the impedance matching and the magnetic near-field distribution of the proposed antenna.

Fig. 5.18 shows the changes of the resonant frequency of the antenna with the variation of the FR4 thickness. It is observed that as the thickness of the substrate increases, the resonant frequency of the antenna shifts to a lower frequency. Fig. 5.19 compares the magnetic field distribution of the antennas on the FR4 substrate with
different thicknesses at 915 MHz. It is found that the thicker the substrate causes larger magnetic field variation in the interrogation zone of the antenna.

Fig. 5.18. Effect of the variation of the substrate thickness, \( H \), on the impedance matching of the loop antenna with phase shifters.
Similar to increasing the dielectric constant, the increase of the dielectric thickness also raises the effective dielectric constant. This causes the operating frequency to be shifted down. The corresponding operating frequencies move down to 720 MHz, 700 MHz, and 640 MHz for the 0.508 mm (20mils), 0.8128 mm (32mils), and 1.524 mm (60mils) FR4 substrates, respectively, as exhibited in Figs. 5.20 to Fig. 5.22.

Fig. 5.19. Effect of the variation of the substrate thickness on the magnetic field distribution of the loop antenna with phase shifters (at 915 MHz, $z = 0.5$ mm) along (a) $x$-axis, and (b) $y$-axis.
Fig. 5.20. Magnetic field distribution of the loop antenna with phase shifters at different frequencies (FR4, $H = 0.508$ mm, $z = 0.5$ mm): (a) $x$-axis variation, and (b) $y$-axis variation.
Fig. 5.21. Magnetic field distribution of the loop antenna with phase shifters at different frequencies (FR4, $H = 0.8128$ mm, $z = 0.5$ mm): (a) $x$-axis variation, and (b) $y$-axis variation.
Fig. 5.22. Magnetic field distribution of the loop antenna with phase shifters at different frequencies (FR4, $H = 1.524$ mm, $z = 0.5$ mm): (a) $x$-axis variation, and (b) $y$-axis variation.
5.5.5 Width of Loop Line, $W$

The width of the loop line, $W$, is varied from 0.5, 1.0, 2.0, to 4.0 mm. It should be noted that the increase in width of the loop line increases the size of the antenna. However, the interrogation area of the antenna remains unchanged for all the cases for fair comparison. Fig. 5.23 exhibits the effect of varying the width of the strip, $W$, on the impedance matching of the proposed antenna. It is observed that the resonant frequency of the remains unchanged as the width is varied. However, the return loss of the antenna improves as the line width increases.

![Graph of Return loss vs Frequency for different widths](image)

Fig. 5.23. Effect of the variation in the strip width, $W$, on the impedance matching of the loop antenna with phase shifters.

From Fig. 5.24, it is observed that the near-field distribution is hardly altered from the increase of loop line width, $W$. Therefore, the loop line width can be applied in improving the impedance matching without affecting the near-field performance of the loop antenna with phase shifters.
Fig. 5.24. Effect of the variation in the strip width, $W$, on the magnetic near-field distribution on the loop antenna with phase shifters (at 915 MHz, $z = 0.5$ mm) along (a) $x$-axis, and (b) $y$-axis.
5.5.6 Conclusion on Parametric Study

From the parametric study, it is found that the parameters that influence performance of the loop antenna with phase shifters include the length of each side of the square loop, $L_1$, the length of each phase shifter, $L_2$, the substrate permittivity used on the antenna, $\varepsilon_r$, and the substrate thickness, $H$. All of these parameters cause significant change in the magnetic near-field distribution of antenna.

Since the magnetic field distribution ($H_z$) is generally governed by the current distribution on the antenna, the above mentioned parameters have to be carefully optimized to ensure that current flowing along the square loop is kept in a single direction. From the parametric study, it is found that for a proposed antenna with a desired interrogation parameter of about $2\lambda$ operating in free space and with the operating frequency of 915 MHz, four phase shifters are needed. The total length of the loop line is found to be around $3.8\lambda$. The length of each side of the square loop, $L_1$ is found to be $0.45\lambda$, and the length of each phase shifter is found to be around $0.5\lambda$.

The width of the loop line, $W$, on the other hand, shows slight effect on the resonant frequency of the antenna and does not severely affect the magnetic field distribution of the antenna. Therefore, it can be used for impedance matching purpose when the influential parameters of the antenna are being set.

5.6 Antenna Implementation, Results and Discussion

The loop antenna with phase shifters is prototyped on the FR4 substrate ($\varepsilon_r = 4.4$, $\tan\delta = 0.02$, thickness $H = 0.508$ mm). The antenna is designed at the center frequency of 915 MHz. To reduce the space occupied by the antenna, the phase shifters on the proposed antenna is bended, as illustrated in Fig. 5.25. Optimization on each phase shifter
is done to ensure that current flowing through the square loop is kept in a single direction for strong and even magnetic field distribution. The loop antenna with phase shifters is with an overall size of $208 \times 143 \text{ mm}^2$. It offers an interrogation area of $112 \times 112 \text{ mm}^2$ $(0.34 \times 0.34 \lambda^2)$. The internal perimeter of the antenna is 448 mm, which is of $1.34 \lambda$ at 915 MHz. As shown in Fig. 5.25(a), the antenna is fed by two parallel strip lines which are printed on the opposite side of the substrate. The upper/bottom parallel strips are connected to the inner/outer conductors of an SMA connector, respectively. A matching network comprised of simple stubs is adopted to match the antenna to the 50-$\Omega$ feed line. The detailed configuration and dimensions of the antenna prototype are exhibited in Fig. 5.25(a) and the photograph of the antenna prototype is provided in Fig. 5.25(b). A conventional solid-line loop antenna of the same interrogation zone, as illustrated in Fig. 5.25(c), is prototyped for comparison.
Fig. 5.25. Configuration of the loop antenna prototypes using FR4 substrate: (a) detailed dimensions loop antenna with phase shifters prototype, (b) photo of the loop antenna with phase shifters prototype, and (c) photo of the solid loop antenna of similar interrogation zone.
5.6.1 Impedance Matching Measurement

The impedance matching measurement of the antenna is carried out with the Agilent E5230A vector network analyzer (VNA). Fig. 5.26 exhibits the simulated and measured impedance matching of the loop antenna with phase shifters prototype. The bandwidth for 10 dB return loss covers the frequency range of 730–940 MHz (25.1%). Good impedance matching is observed across the required frequency band of 900–930 MHz where the antenna prototype provides strong and even magnetic near-field distribution. However, there are slight discrepancy between the measured and the simulated return losses. This is due to the differences between the antenna feeding methods adopted in the simulation and the measurement. In simulation, the antenna is directly fed by a pair of differential ports. In measurement, the antenna is connected to a feeding cable, which is unbalanced and further connected to the VNA. It is difficult to simulate such cable in the IE3D simulation system. Therefore, the simulated and measured impedance matching is slightly different across the frequency range.

Fig. 5.26. Simulated and measured impedance matching of the loop antenna with phase shifters prototype.
5.6.2 Magnetic Field Distribution Measurement

The magnetic field distribution is measured using the E5230A VNA and the Langer EMV-Technik RF-R 3-2 near-field probe [49]. The antenna and the near-field probe are connected to Port 1 and Port 2 of the VNA, respectively. The relatively magnetic field intensity is quantified by $|S_{21}|$. The near-field magnetic field probe is placed on the surface of the antenna prototype, and is moved along the $x$- and $y$-axes separately with an interval of 5 mm. Calibration of the probe is not required in the measurement since what we concern here is the relative field distribution, not the absolute magnitude of the magnetic field. Figs. 5.27, 5.28, and 5.29 show the simulated and measured magnetic field intensity at 840, 915, and 960 MHz along $x$- and $y$-axes. It should be noted that the simulated magnetic field density ($H_z$) is of unit A/m (dB) and the measured field intensity is in the form of $|S_{21}|$, which is dimensionless. For comparison, both results at the origin ($x = 0$, $y = 0$) are being normalized. The trend of both the results is observed. Of all the cases, good agreement is observed between simulated and measured relative magnetic distribution.
Fig. 5.27. Simulated and measured magnetic field distribution of the loop antenna with phase shifters prototype (at 840 MHz, $z = 0.5$ mm): (a) $x$-axis variation and (b) $y$-axis variation.
Fig. 5.28. Simulated and measured magnetic field distribution of the loop antenna with phase shifters prototype (at 915 MHz, $z = 0.5$ mm): (a) $x$-axis variation and (b) $y$-axis variation.
Fig. 5.29. Simulated and measured magnetic field distribution of the loop antenna with phase shifters prototype (at 960 MHz, \( z = 0.5 \) mm): (a) \( x \)-axis variation and (b) \( y \)-axis variation.
5.6.3 Reading Range Test

To verify the tag detection performance of the antenna prototype, the antenna prototype is used as a reader antenna in a near-field UHF RFID system to detect the UHF near-field tags. As shown in Fig. 5.30, the antenna prototype is connected to the Impinj Speedway reader (865–956 MHz, 30-dBm output) [50] to detect Impinj button type tags. The tags are of the model J21 and each of them is 9 mm in diameter [51]. 25 tags were positioned on a Styrofoam with the dimensions 120 × 120 mm². The number of the detected tags are recorded when the Styrofoam disc is positioned above/below the antenna prototype at different distances. To ensure the reliability of the read range test, the tags attached to the Styrofoam disc were randomly placed, and an average of five measurements was recorded at each reading distance from the antenna.

The reading rate against the reading distance is shown in Fig. 5.31. The result of a conventional solid line loop antenna is illustrated in the same figure for comparison. The solid line loop antenna has the same size as the loop antenna with phase shifters prototype. It has the interrogation zone of 112 × 112 mm². Both the antenna prototypes
offer bi-directional reading. The loop antenna with phase shifters exhibits superior performance over the conventional solid loop antenna. It achieves an 80% reading rate with a distance up to 24 mm, while the conventional solid line loop antenna achieves an 80% reading rate only with a distance up to 10 mm.

![Graph showing reading rate against distance for proposed loop antenna with phase shifters and solid line loop antenna.]

Fig. 5.31. Measured reading rate against distance of the loop antenna with phase shifters prototype and the conventional solid line loop antenna prototype with similar interrogation zone.

### 5.6.4 Uni-directional Antenna Prototype

Some RFID applications prefer uni-directional detection. The most common method in making a loop-like antenna uni-directional is to apply a metal plate reflector at one side of the antenna [18]. Fig. 5.32 demonstrates a uni-directional loop antenna with phase shifters. The antenna prototype is positioned above a copper plate (300 × 300 mm²) with a certain distance, g. To create such separation, Styrofoam is used.
Fig. 5.32. Prototype of uni-directional loop antenna with phase shifters.

The return loss of the uni-directional antenna prototypes is measured at each distance $g$. The results are exhibited in Fig. 5.33. It is observed that the metal plate severely affects the antenna impedance matching when it is placed at a very close distance to the antenna (i.e. $g = 10$ and $20$ mm). When the metal plate is of sufficient distance away from the metal plate (i.e. $g = 40$ and $50$ mm), it does not affect the impedance matching of the antenna significantly. The $10$ dB return loss can be achieved at a frequency range of $720$–$940$ MHz.

Fig. 5.33. Measured return loss of the uni-directional loop antenna with phase shifters prototype with different separation distance, $g$. 
Fig. 5.34 exhibits the reading rate of a uni-directional loop antenna with phase shifters prototype when a copper plate with the dimensions of 300 × 300 mm² is placed 50 mm away from the antenna. In this chapter, the reading rate of the proposed uni-directional antenna is not compared with that of the commercial antenna, the Impinj brickyard near-field RFID antenna, as the size of the proposed antenna prototype is not comparable with the Impinj’s antenna. Instead, the reading rate of the proposed antenna is being compared with that of the uni-directional conventional solid line loop with similar interrogation zone as displayed in Fig. 5.25 in the earlier section (Section 5.6). It is observed that the proposed loop antenna with phase shifters achieves an 80% reading rate of up to 60 mm, which is three times of that of the conventional loop antenna.

Fig. 5.34. Measured reading rate of the proposed uni-directional loop antenna with phase shifters prototype and the uni-directional conventional loop antenna prototype with along distance \( d \).
5.6.5 Verification of Antenna Coverage Area

To find out the coverage area of the loop antenna with phase shifters, this experiment is performed. Antenna coverage area is defined as the maximum area where a 100% reading rate is achieved when the near-field RFID tags are placed at a near-field distance ($d = 0 \text{ mm}$) of the antenna. It should be noted that the metal plate is not included in this experiment.

In Fig. 5.35, the RFID tags are distributed randomly within different investigation areas, from $170 \times 170 \text{ mm}^2$ (with a total of 60 tags), $150 \times 150 \text{ mm}^2$ (with a total of 50 tags), $130 \times 130 \text{ mm}^2$ (with a total of 40 tags), to $110 \times 110 \text{ mm}^2$ (with a total of 35 tags). The reading rate is obtained with the procedure similar to that explained in Section 5.6.3.

Fig. 5.35. Near-field RFID tags distributed randomly within different investigation area: (a) $170 \times 170 \text{ mm}^2$, (b) $150 \times 150 \text{ mm}^2$, (c) $130 \times 130 \text{ mm}^2$, and (d) $110 \times 110 \text{ mm}^2$
Fig. 5.36 shows the results of the reading rate of RFID tags placed within different coverage area. It is observed that, at the distance $d = 0$ mm, when the tags are located within an area larger than that of the antenna, 100% tag reading rate could not be achieved. It is when the tags are located within the area bounded by antenna, in this case $110 \times 110$ mm$^2$, all the tags are accurately detected by the RFID system.

Therefore, it can be shown that the prototype of the loop antenna with phase shifters is capable of providing a coverage area of $110 \times 110$ mm$^2$. This area can be referred as the interrogation area $(a \times a)$ for the proposed antenna.

**5.7 Comparison between Loop Antenna with Phase Shifters and Segmented Loop Antennas**

The loop antenna with phase shifters introduced in this chapter is being compared with the segmented antennas introduced in Chapter 3 and 4.
5.7.1 Operating Bandwidth of Proposed Antennas

Figs. 5.37, 5.38, and 5.39 display the simulated magnetic field distribution ($H_z$) of the loop antenna with phase shifters, side-by-side coupled segmented loop antenna, and the top-to-bottom coupled segmented loop antenna at 840, 915, 930, and 960 MHz along the $x$- and $y$- axes. These frequencies are the operating frequencies of the UHF RFID systems. The graphs are of the same scale for the ease of comparison. It should be noted that the three antennas are of the same size of $164 \times 164 \text{ mm}^2$. It can be observed that the side-by-side coupled segmented antenna (Fig. 5.38) and top-to-bottom coupled segmented antenna (Fig. 5.39) provides even and strong magnetic near-field distribution in the major portion of the interrogation zone ($-60 \text{ mm} \leq x \leq 60 \text{ mm}$ and $-60 \text{ mm} \leq y \leq 60 \text{ mm}$) within the frequency band of 840–960 MHz. The magnetic field variation is within 5 dB along the $x$-axis and within 10 dB along the $y$-axis for both the antenna. This is not the case for the loop antenna with phase shifters. The antenna only provides strong and even field distribution along the $x$- and $y$- axes within at the frequencies of 915 and 930 MHz. At 840 and 960 MHz, there exist field nulls in the interrogation zone of the antenna. This affects the detection reliability of the antenna when it is applied as a reader near-field antenna. It can be concluded that the loop antenna with phase shifters offers a narrower operating bandwidth (900–930 MHz) for strong and even field RFID tags detection when it is compared with that of the side-by-side coupled segmented loop antenna (840–960 MHz) and that of the top-to-bottom coupled segmented loop antenna (840–960 MHz). The difference is due to the principle of operation of the antennas. Phase shifters incorporated on a loop antenna is narrow band in nature. Segmented loops, on the other hand, are able to keep the current in phase along the loop over a wider bandwidth.
Fig. 5.37. Simulated magnetic field distribution of the loop antenna with phase shifters at different frequencies: (a) $x$-axis variation and (b) $y$-axis variation.
Fig. 5.38. Simulated magnetic field distribution of the side-by-side coupled segmented loop antenna at different frequencies: (a) $x$-axis variation and (b) $y$-axis variation.
Fig. 5.39. Simulated magnetic field distribution of the top-to-bottom coupled segmented loop antenna at different frequencies: (a) $x$-axis variation and (b) $y$-axis variation.
5.7.2 Tag Reading Rate Comparison

The reading rate of the loop antenna with phase shifters and the segmented antennas are being compared. For comparison, these three antennas are designed to have a similar interrogation zone \((112 \times 112 \text{ mm}^2)\) and tag reading rate are shown in Fig. 5.40.

![Fig. 5.40. Measured reading rate against distance for the loop antenna with phase shifters as well as the side-by-side and the top-to-bottom coupled loop segmented antenna.](image)

It is observed that the three antennas offer bi-directional reading. The reading rate of the loop antenna with phase shifters is comparable to that of the side-by-side coupled segmented loop antenna up till a distance, \(d\), of 60 mm. From \(d = 60\) mm onwards, the reading rate of the loop antenna with phase shifters drops at a faster rate compared with that of the segmented antennas. It can be concluded that the performance of the loop antenna with phase shifters at the near-field distance is comparable to the segmented antennas. However, after the near-field distance, the field of the loop antenna with phase shifters drops at a faster rate when compared to that of the segmented antennas.
5.7.3 Space Occupied by Proposed Antennas

Fig. 5.41. Fabrication prototypes of the proposed antennas of similar interrogation zone (112 × 112 mm²): (a) the loop antenna with phase shifters, (b) the side-by-side coupled segmented loop antenna, and (c) the top-to-bottom coupled segmented loop antenna.

Fig 5.41 shows the prototype of the proposed antennas. With the similar interrogation zone of 112 × 112 mm², the loop antenna with phase shifters occupies the largest space with the overall size of 208 × 143 mm². The top-to-bottom segmented antenna, on the other hand, occupies the smallest space, with an overall size of 126 × 132 mm². This is because the additional space is allocated to the phase shifters of the antenna. Therefore, when comes into designing the reader antennas with size constraint, such factor should be factored into consideration.
5.8 Concluding Remarks

A loop antenna with phase shifters is proposed in this chapter. Phase shifters are introduced to the conventional solid loop antenna to provide a 180° phase shift to the phase-inversed current so that the current flowing along the loop antenna is kept in a single direction. As a result, the magnetic fields produced in the z-direction are thus being added up and exhibits strong and even magnetic field distribution over the interrogation zone of the electrically large antenna over a frequency band of 900–930 MHz (3.3%). The proposed prototype, with dimensions $208 \times 143 \times 0.5 \text{ mm}^3$, provides an interrogation zone of $110 \times 110 \text{ mm}^2$. It is suitable to be used as near-field RFID UHF reader antenna. Compared with the segmented antennas proposed in Chapter 3 and 4, the loop antenna with phase shifters has less tuning parameters. It has a simpler operating principle.

From the performed parametric study, it is found that the length of each side of the square loop, $L_1$, the length of phase shifter, $L_2$, the substrate permittivity used on the antenna, $\varepsilon_r$, and the substrate thickness, $H$ affects the magnetic distribution of the antenna most. For a proposed antenna with a desired interrogation parameter of about $2 \lambda$ operating in free space and with the operating frequency of 915 MHz, the total length of the loop line is found to be around $3.8 \lambda$. The length of each side of the square loop, $L_1$ is with the electrical length of $0.45 \lambda$, and the length of each phase shifter, $L_2$, is with the electrical length of $0.5 \lambda$.

The proposed antenna prototype has shown significant improvement by achieving a maximum reading rate of 100% when compared with the conventional loop antenna prototype with similar interrogation zone (with only a maximum reading rate of 96%). The antenna prototype doubles the detection distance up to 24 mm for an 80% reading.
rate over a similar coverage when it is compared to that of the conventional solid loop antenna prototype with a similar interrogation zone.
CHAPTER 6 : CONCLUSION

In this chapter, the summary of important results is given. Conclusions on the thesis work are given. Then, suggestions for future work are provided.

6.1 Summary of Important Results

Table 6.1 Comparison of novelty or design features of the proposed antennas

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Proposed Antenna</th>
<th>Novelty / Design Features</th>
</tr>
</thead>
</table>
| 3       | Top-to-bottom coupled segmented loop antenna | • Incorporates segmented line structures that keep the current flowing in the electrically large loop in phase  
         |                   | • Produces strong and even magnetic near-field distribution with a large electrical size of 2\( \lambda \)  
         |                   | • Printed on two substrate layers |
| 4       | Side-by-side coupled segmented loop antenna | • Incorporates segmented line structures that keep the current flowing in the electrically large loop in phase  
         |                   | • Produces strong and even magnetic near-field distribution with a large electrical size of 1.88\( \lambda \)  
         |                   | • Printed on a single substrate layer |
| 5       | Loop antenna with phase shifters | • Incorporates phase shifters that provide a 180° phase shift to the phase-inversed current flowing through the loop antenna  
         |                   | • Produces strong and even magnetic near-field distribution with a large electrical size of 1.4\( \lambda \)  
         |                   | • Printed on a single substrate layer |

Table 6.1 compares the novelty or design features of the three proposed antennas. The top-to-bottom coupled segmented loop antenna is comprised of segmented line structures on two substrate layers. The segmented line structures are capable of keeping the current flowing on the electrically large loop in phase. As a result, the antenna, despite being electrically large (2\( \lambda \)), is capable of producing strong and even magnetic near-field distribution. The side-by-side coupled segmented loop antenna adopts the segmented line structures on a single layer of substrate to reduce the complexity of the
fabrication. The side-by-side coupled segmented structures, similar to the top-to-bottom coupled segmented structures, are capable of keeping the current distribution along the loop in phase even though the perimeter of the loop is of $1.88 \lambda$. As a result, the antenna generates strong and even magnetic field distribution in the near-field zone. The loop antenna with phase shifters uses phase shifters to provide a 180° phase shift to phase-inversed current so that the current flowing along the loop is kept in a single direction even though the loop is electrically large. Compared to the proposed segmented antennas, the loop antenna with phase shifters has simpler operating principle and less tuning parameters. The antenna is capable of providing strong and even magnetic near-field distribution over an interrogation zone with a perimeter of $1.4 \lambda$. Such characteristics are desired for near-field UHF RFID reader antennas.

<table>
<thead>
<tr>
<th>Performance</th>
<th>Top-to-bottom coupled segmented loop antenna</th>
<th>Side-by-side coupled segmented loop antenna</th>
<th>Loop antenna with phase shifters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impedance Bandwidth</td>
<td>840–1270 MHz (40.8%)</td>
<td>820–1050 MHz (24.6%)</td>
<td>730–940 MHz (25.1%)</td>
</tr>
<tr>
<td>Bandwidth of even magnetic field distribution over interrogation zone</td>
<td>840–960 MHz (13.3%)</td>
<td>840–960 MHz (13.3%)</td>
<td>900–930 MHz (3.3%)</td>
</tr>
<tr>
<td>Interrogation area with 100% read rate at near-field</td>
<td>160 ×160 mm$^2$ (0.5 × 0.5 $\lambda^2$)</td>
<td>160 ×160 mm$^2$ (0.5 × 0.5 $\lambda^2$)</td>
<td>110 × 110 mm$^2$ (0.34 × 0.34 $\lambda^2$)</td>
</tr>
<tr>
<td>80% tag reading distance (compared with that of the conventional loop antenna of similar interrogation zone)</td>
<td>60 mm (0 mm)</td>
<td>40 mm (0 mm)</td>
<td>24 mm (10 mm)</td>
</tr>
<tr>
<td>80% tag reading distance (compared with that of the conventional loop antenna of similar interrogation zone)</td>
<td>60 mm (0 mm)</td>
<td>40 mm (0 mm)</td>
<td>24 mm (10 mm)</td>
</tr>
</tbody>
</table>
Table 6.2 compares the important performances of the three antenna designs. It is observed that all the three antennas provide a sufficiently large impedance bandwidth. It should be noted that the impedance bandwidth can be controlled using matching stubs or circuits. The bandwidth of even magnetic field distribution over the interrogation zone, on the other hand, is dependent on the working principle of the antenna. It is found that the segmented antennas in Chapters 3 and 4 support a wider bandwidth (840–960 MHz) as being compared to that of the loop antenna with phase shifters (900–930 MHz). In such bandwidth, the variation of magnetic field distribution in the interrogation zone is less 10 dB. Such bandwidth is important for reliable near-field UHF RFID reader antenna.

In the verification of interrogation zone of the near-field antennas, it is observed that the interrogation zone of the proposed antennas is actually the area bounded by the strip of the antenna. The perimeter of the interrogation zone of all the proposed antennas is larger than $1\lambda$. The top-to-bottom coupled segmented loop antenna has shown to afford an interrogation zone of $160 \times 160 \text{ mm}^2 (0.5 \times 0.5 \lambda^2)$. The side-by-side coupled segmented loop antenna has provided an interrogation zone of $160 \times 160 \text{ mm}^2 (0.5 \times 0.5 \lambda^2)$. The loop antenna with phase shifters affords an interrogation zone of $110 \times 110 \text{ mm}^2 (0.34 \times 0.34 \lambda^2)$.

For the comparison of tag reading rate at the surface ($d = 0 \text{ mm}$), it is found that all three proposed antennas achieve a 100% reading rate. The respective solid loop antenna with the similar interrogation zone, however, is not able to provide a 100% reading rate. Even though the physical size of the proposed antennas is electrically large,
the proposed antennas are capable of providing strong and even magnetic near-field distribution for reliable RFID tagging.

Last but not least, for the comparison of an 80% tag reading distance of the proposed antennas, it is found that all the proposed antennas provides superior performance in the 80% tag reading distance when compared with their respective solid loop antenna with the similar interrogation area.

6.2 Conclusion

In conclusion, three designs of near-field UHF RFID reader antenna, namely the top-to-bottom coupled segmented loop antenna, the side-by-side coupled segmented loop antenna, and the loop antenna with phase shifters, have been presented in this work. The design challenge of the near-field UHF RFID reader antenna lies in creating an electrically large reader antenna with strong and uniform magnetic field distribution in the interrogation region.

The proposed antennas have shown to provide wide coverage areas. The top-to-bottom coupled segmented loop antenna has shown to afford a coverage area of $160 \times 160 \, \text{mm}^2$ ($0.5 \times 0.5 \, \lambda^2$). The side-by-side coupled segmented loop antenna has shown to provide a coverage area of $160 \times 160 \, \text{mm}^2$ ($0.5 \times 0.5 \, \lambda^2$). The loop antenna with phase shifters has shown to afford a coverage area of $110 \times 110 \, \text{mm}^2$ ($0.34 \times 0.34 \, \lambda^2$). The perimeter of the interrogation zone of each proposed antenna is several times larger than one antenna operating wavelength.

The proposed antennas have shown to provide longer tagging distances. The top-to-bottom coupled segmented loop antenna has achieved the 80% reading distance of 60 mm. The side-by-side coupled segmented loop antenna has shown to afford the 80%
reading distance of 40 mm. The loop antenna with phase shifters has achieved the 80% reading distance of 24 mm. Compared with the respective solid loop antennas with similar interrogation zone, the proposed antennas have shown significant improvement in tag reading distance. Compared to a commercial near-field UHF RFID reader antenna, the top-to-bottom coupled segmented loop antenna prototype has improved the detection range by 2.5 times with a 100% reading rate for a distance of 60 mm. The side-by-side coupled segmented loop antenna prototype, on the other hand, has increased the reading distance by 1.5 times. It has shown to achieve a 100% reading rate for a detection range of 36 mm.

Although the proposed antennas are electrically large, they have shown to provide strong and even field distribution over the operating bandwidth. The variation of the magnetic distribution of the antennas within the bandwidth is less than 10 dB. The top-to-bottom coupled and the side-by-side coupled segmented antenna have shown to afford strong and even field distribution over 840–960 MHz, while the loop antenna with phase shifters has shown to provide strong and even field distribution over 900–930 MHz. Such characteristics are desirable for near-field UHF RFID reader antennas.

Controlling the current flow along the loop is essential for providing strong and even magnetic near-field within the bounded zone of the antenna. The current flowing along the loop should be in a single direction. It is because single direction current flow on the loop produces magnetic fields which are added in the center region of the loop antenna. As a result, the magnetic field distribution at the space enclosed by the loop is strong and even. The tags located in this area will be effectively detected. When the size of the loop antenna is larger than half the operating wavelength, different techniques can
be applied to control the current flow on the antenna. The segmented structures are capable of providing a very small phase delay to the current flowing through them. As a result, the current along the segmented lines is kept in phase. This causes the current to flow in a single direction along the proposed segmented loop antenna even though the loop is electrically large (> 0.5 λ). A phase shifter, on the other hand, is capable of providing a 180° phase shift to the phase-inversed current so that the current flow along the antenna is kept in a single direction even though the solid loop is electrically large.

Parametric studies have been performed to provide design guidelines for the realization of the proposed antennas. From the parametric studies, it is found that some parameters have directly affected the near-field distribution of the antenna while some have shown insignificant influence on the field distribution but have shown to help in providing a better impedance matching to the 50-Ω system.

6.3 Suggestions for Future Work

The objective in the thesis has been achieved. For the continuation in this research direction, recommendations for future work are proposed.

The shape of the near-field UHF RFID reader antenna can be further explored from this study. In the thesis, square loop antennas are proposed. Various shape of antenna (such as circular loop, polygonal loop, and etc.) can be further studied to provide strong and even field distribution in the near-field zone.

In the thesis, the largest electrical size of the proposed near-field antenna is 2 λ. Further work can be dedicated to producing near-field antenna with the electrical size larger than 2 λ yet having strong and even field distribution over the interrogation region.
The segmented structure and the phase shifters are introduced to control the current flow on the electrically large loop antenna. New techniques can be further explored to achieve the similar objective so as to produce a high reliability near-field UHF RFID reader antenna.

This research focuses on producing near-field UHF RFID reader antenna. Techniques can be applied to incorporate the far-field detection characteristics in the near-field antenna so that a UHF reader antenna capable of detecting both near-field and far-field tags can be created.
REFERENCES


[45] IE3D version 14, “Zeland Software Incorporation,” Fremont, Calif, USA.


LIST OF PUBLICATIONS

