A Novel Planar Microstrip Antenna Design for UHF RFID

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Master's Thesis Defense

19th July 2006

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Publications

- Accepted - “ Novel Planar Microstrip Antenna for UHF RFID.” The 4th International Conference on Computing, Communications and Control Technologies, 21st -23rd July 2006, Orlando, USA
- Submitted - “High Performance Planar Microstrip Antenna for UHF RFID.” IEE Electronic letters, 2006
- Several US patents pending

Presentation Overview

- **Introduction**
- **Background**
  - Universe of RFID – Need, history, implementation, and standards
  - Passive UHF RFID – characteristics, and limitations
  - Basics of microstrip antenna design
  - Existing microstrip RFID designs
- **Planar Microstrip Antenna – Implementation**
  - Approach – Balanced feed mechanism
  - Design considerations and design evolution
- **Results**
- **Future work**
- **Conclusions**

Introduction

- Auto–ID (automatic identification) technology enables identification and tracking of assets and goods
- RFID (Radio frequency identification) – an implementation of Auto–ID
- Most passive UHF (ultra high frequency) RFID tags – printed dipoles or some variation of printed dipole
- ‘Metal-water’ problem - dipoles suffer performance degradation when placed near conductors, e.g. metals, and high dielectric materials like water

Introduction

- Microstrip antennas – a potential solution to the metal-water problem
- The traditional microstrip antenna require cross-layered structures
- Commercially expensive – large manufacturing complexity and hence cost

Research question

- Can a microstrip antenna that is completely planar be constructed?

Auto–ID technology - The need for RFID

- ❑ Barcodes, Lasers
  - ❑ Low data storage
  - ❑ Need LOS with the interrogator
- ❑ Voice recognition, and Biometrics
  - ❑ Need human intervention
- ❑ RFID
  - ❑ Operates without a LOS
  - ❑ Can store large amounts of user data using integrated circuit technology

History of RFID

- 1939
  - ❑ Identify friend or foe (IFF) was a tag and track technique used by the British allies to identify airplanes [5]
- 1960 - 70
  - ❑ Military applications like equipment and personnel tracking [4]
- 1980 - 90
  - ❑ Industrial goods needed counterfeit protection, shrinkage protection and tracking through the several stages in the supply chain
- 2003 - 04
  - ❑ Passive UHF RFID systems increasingly being employed in distribution and supply chains like Wal-mart and Tesco [3]
- 2004 - 05
  - ❑ Government agencies including US-DOD and FDA have issued recommendations requiring suppliers to use RFID on their products [6] [7]

Implementation of RFID

- **RFID tag-reader system – three major components**
  - ❑ reader or interrogator - radio transceiver connected to Tx and Rx antennas
  - ❑ tag or transponder - tuned antenna, and stored data
  - ❑ host computer - program the reader, and store information received
- **Types of RFID – based on how data is stored**
  - ❑ Without IC – Unique patterns printed on tag material surface. E.g., Surface acoustic wave RFID (SAW RFID)
  - ❑ With IC – The IC contains all the data. E.g., Passive UHF RFID

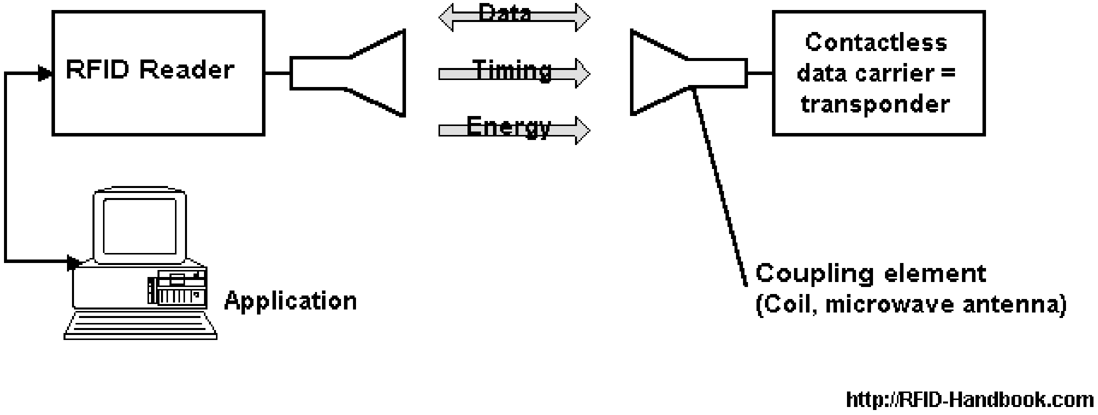


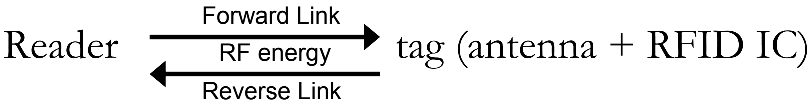
Figure 2.1: RFID system block representation (RFID handbook [8])

Implementation of RFID (contd..)

- **Further classifications of RFID with IC**
  - Based on principle of operation
    - Near field - magnetic field induction between the reader and tag. Commonly operated in LF and MF bands
    - Far field - uses backscattering. Commonly operated in UHF and microwave frequency bands
  - Based on IC functionality [15]
    - Class 0, Class 1 and Class 2 - passive tags
    - Class 3 - semi–passive, have battery source to operate internal circuitry
    - Class 4 and Class 5 - active

Passive UHF RFID

- Electromagnetic wave propagation for data communication


Reader

tag (antenna + RFID IC)

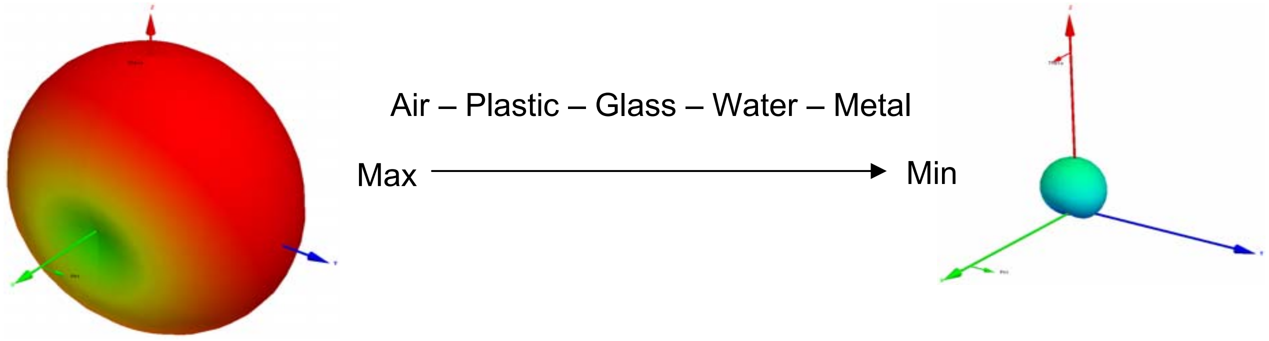
- Common implementation - simple dipole or some variation of it e.g., dual dipole, folded dipole
- Tag acts as receiver and scatterer; impedance modulation by the RFID IC changes the scattering characteristics of tag enabling tag-reader communication
- Tag performance
  - Radiation characteristics – antenna length is odd multiples of λ/2
  - Power transfer - antenna impedance is conjugate match of RFID IC impedance
  - External factors – multipath, properties of materials to which tag is attached
- Friis equations - determines power received from reader to the tag

$$P_r = pq\frac{P_t G_t G_r \lambda^2}{(4\pi r)^2}$$

P_r = power received from reader antenna to the tag antenna.
r = reader to tag distance The
P_t = reader transmitted power by
G_t = reader gain, G_r = tag gain
p = polarization mismatch, q = impedance mismatch

Performance limitations

- Material characteristics affect critical antenna properties
  - ❑ High dielectric and lossy materials e.g., water - detune the tag and reduce radiation efficiency
  - ❑ Metals - causes large increase in antenna radiation resistance, prevent efficient power transfer
  - ❑ Plastics and foams - detune the antenna by changing substrate properties



Air – Plastic – Glass – Water – Metal

Max → Min

Figure 2: Qualitative performance degradation of a UHF dipole when placed on different materials.

- Achieve uniform performance – electrically separate antenna from the material it is attached to

Microstrip Antennas

- **Consist of**
  - Dielectric substrate
  - Conducting planes – ground plane, Antenna plane

- Radiate primarily due to fringing fields between the patch edge and the ground plane - quasi-TEM mode

- **Most common models**
  - Transmission line model [29,10]
  - Cavity model [11,12]

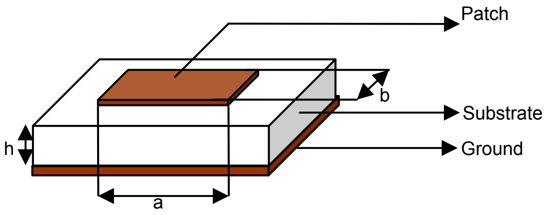


Figure 3: Basic rectangular microstrip patch antenna.

- **Feed mechanisms**
  - Directly connected to patch - e.g., microstrip line, coaxial probe [12,13]
  - Coupled to patch – e.g., aperture coupling, proximity feed [13]

Single feed line excited with reference to ground

Existing Microstrip RFID Designs

- Inverted-F antenna (IFA) [14] basis for most of these designs
  - ❑ Quarterwavelength patch terminated at on end with shorting wall or pins connecting to ground
- Wire-type planar IFA [1, 2]
  - ❑ Fed with a wire connected to the ground plane
  - ❑ RFID IC imbedded vertically between the ground plane and patch

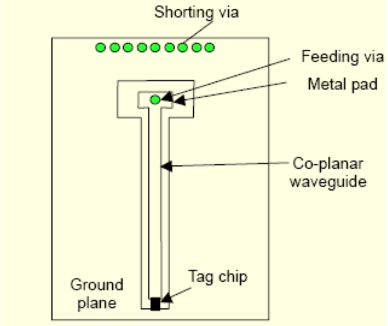


Figure 4: Chip attached to PIFA RFID tag [2].

- Slotted planar IFA [16]
  - ❑ Continuous metal wall extending half way through substrate
  - ❑ RFID is surface mounted using a 'U- shaped' slot
- **Manufacturing complexity significant – increases cost**

Planar Microstrip Antenna

- **Single unbalanced feed** – cross-layered, complex, costly
- **Balanced feed** - two unbalanced microstrip transmission lines 180º out of phase with each other
  - Odd mode symmetry – creates virtual ground along line of symmetry, eliminates reference to ground
  - Shunt shorting stubs provide impedance matching
  - Antenna, feed, matching network lie on same plane - completely planar, low complexity, cost

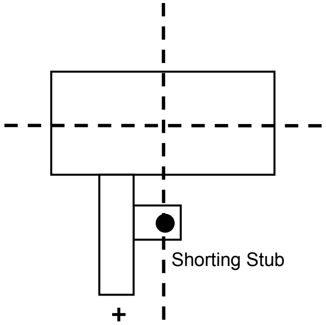


Figure 5: Single microstripline unbalanced feed with shorting stub

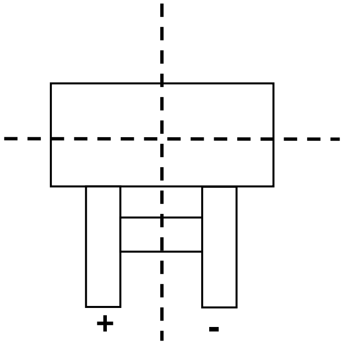


Figure 6: Dual microstripline differential feed with shorting stub

Odd mode analysis

- Current and voltage distribution along a transmission line

$$I(x) = I_o \sin\left(\frac{2\pi x}{\lambda}\right) e^{jw}$$

where I_o is the current at $x = 0$

and x the distance in terms of λ

$$V(x) = V_o \cos\left(\frac{2\pi x}{\lambda}\right) e^{jw}$$

where V_o is the voltage at $x = 0$

$$Z(x) = \left(\frac{V(x)}{I(x)}\right)$$

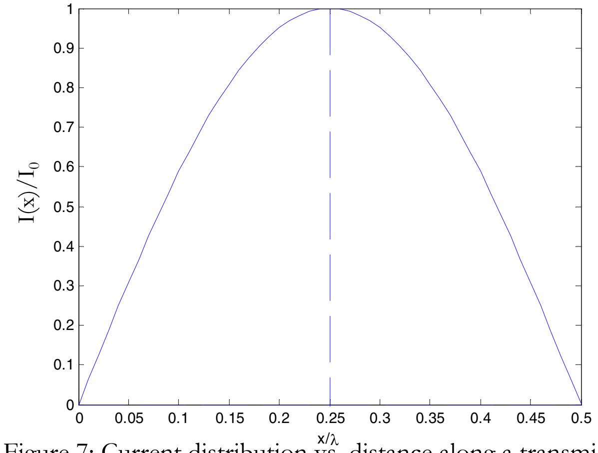


Figure 7: Current distribution vs. distance along a transmission line section

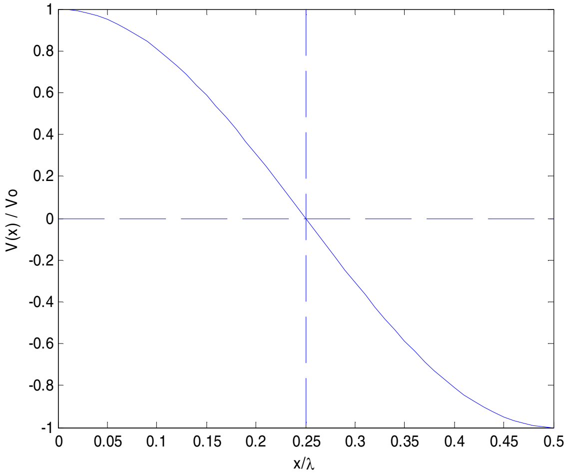


Figure 8: Voltage distribution vs. distance along a transmission line section

Odd mode analysis (cont…)

- Rectangular patch antenna - circuit symmetry

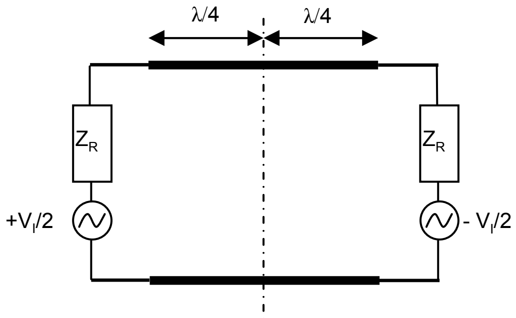


Figure 9: Circuit model of a rectangular microstrip patch with plane of symmetry.

- Odd mode

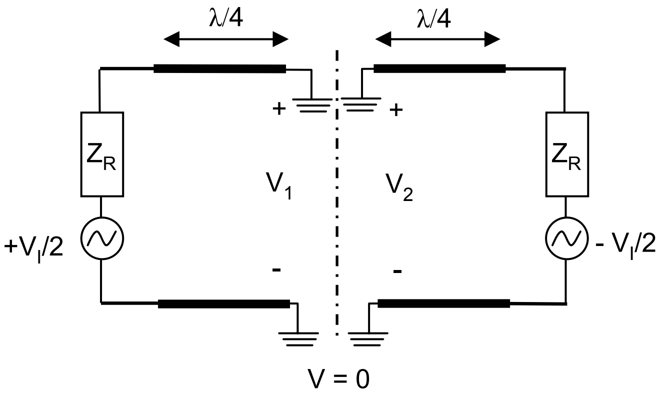


Figure 10: Odd mode symmetry circuit model.

- Even mode

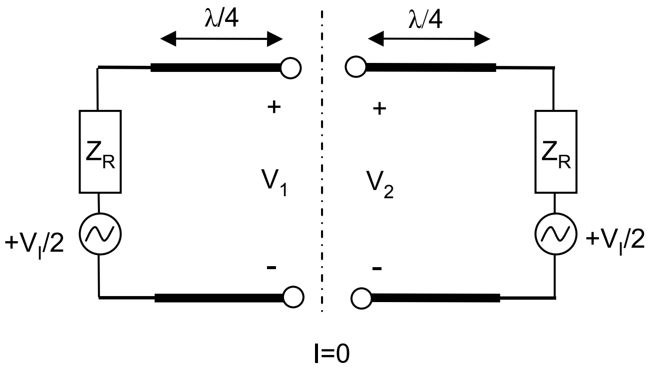


Figure 11: Even mode symmetry circuit model.

Odd mode analysis (cont…)

- Introduce two ports P_1 and P_2
- Patch impedance = parallel combination of a short circuit transformed by l_2 and Z_R transformed by l_1
- Impedance at P_1 = patch impedance transformed by sections of feed transmission line and shorting stub
- A completely planar microstrip antenna of desired input impedance can be designed using the balanced feed with shorting stub matching network

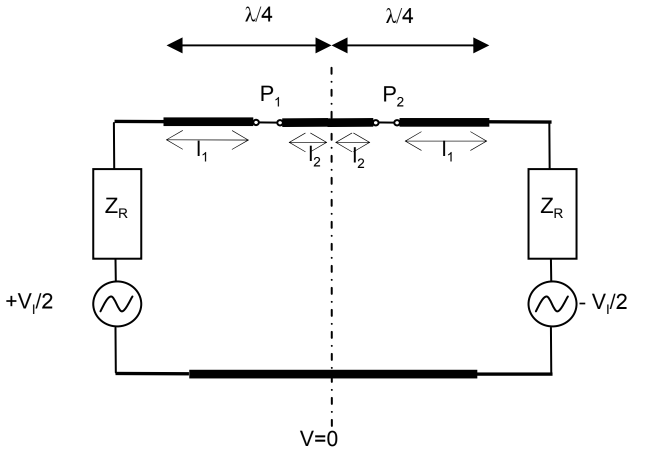


Figure 12: Odd mode circuit symmetry model of microstrip patch antenna with two ports.

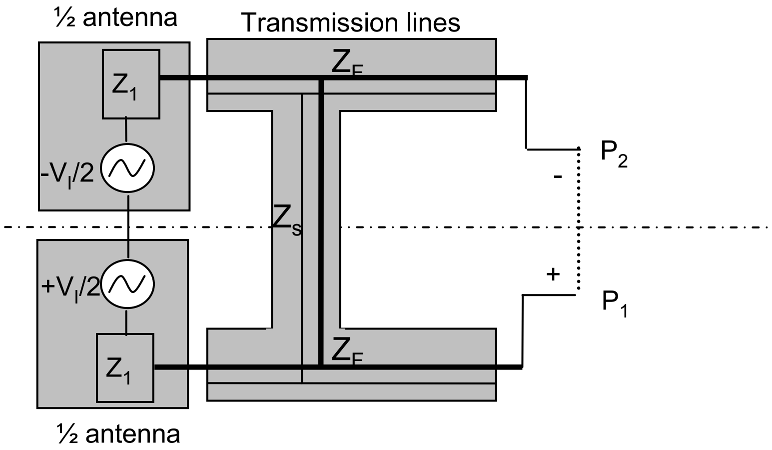


Figure 13: Circuit model of microstrip patch antenna with two ports.

Characterization of materials

- Tag construction requires
  - Substrate - High density polyethylene (HDPE) or polypropylene (PP)
  - metal - (copper)
  - RFID IC - EPC Class 1 Gen 1 or EPC Class 1 Gen 2

- Substrate
  - Thickness (h) ~ 62 mils measured using vernier calipers
  - Dielectric constant (ε_r)
  - Loss tangent (tan δ)

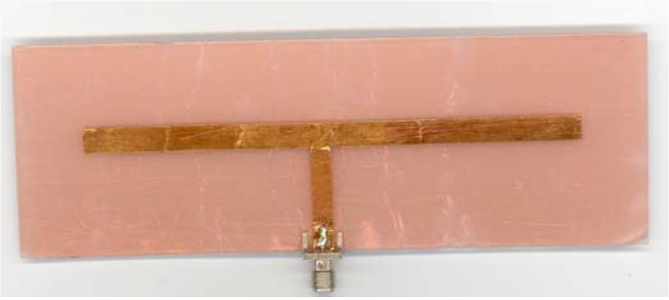


Figure 14: Experimental microstrip patch to determine substrate properties.

- Experimental procedure
  - Design a test resonant patch based on assumed values
  - $\varepsilon_r = 2.25$ and $\tan\delta = 0.001$
  - Measured S_{11} and estimate the actual values of ε_r and tan δ

Substrate Properties

- Effective dielectric constant

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-1/2}$$

Where h = height of substrate and W = width of the patch

- If W = 10mm, ε_{eff} is = 1.7334

- Effective wavelength at 882 MHz

$$\lambda_{eff} = \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}} = 25.6625cm$$

- Resonant length (taking fringing fields into account)

$$\lambda_{eff} * 0.49 = 12.5746cm$$

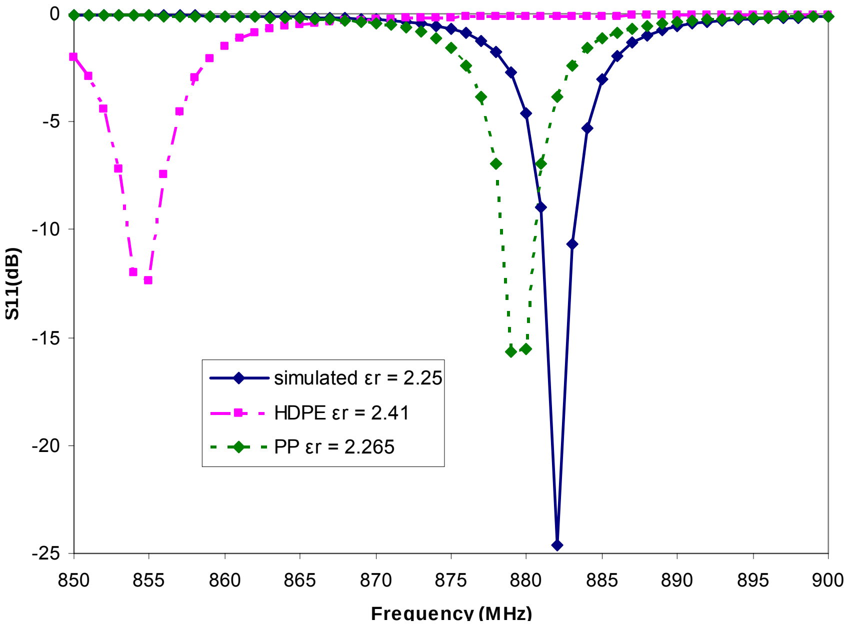


Figure 15: Refection coefficient vs. frequency for simulated and measured values of ε_r.

Material	Simulated resonance	Measured resonance	Measured ε_r	Measured tanδ
HDPE	882 MHz	855 MHz	**2.41**	**0.0035**
PP	882 MHz	879 MHz	**2.265**	**0.0012**

Table 1: Measured substrate properties.

RFID IC Properties

- RFID IC
  - ❑ Direct attach – high degree of precision
  - ❑ Strap attach- RFID IC connected to two mounting pads with a thin superstrate, connected to antenna with conductive adhesive

Figure 16: RFID IC in strap form

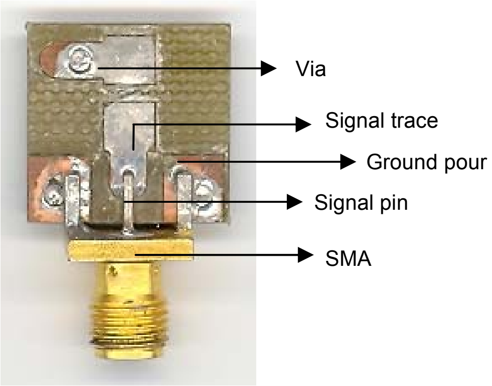


Figure 17: RFID strap impedance measurement board.

- ❑ Experimental procedure to measure strap impedance
  - Test board designed and calibrated to take conductive epoxy into account
  - Mount strap and measure S_{11}
  - $Z_{IC} \sim 10 - j150\ \Omega$ for EPC class I Gen 1 straps
  - $Z_{IC} \sim 35 - j110\ \Omega$ for EPC class I Gen 2 straps

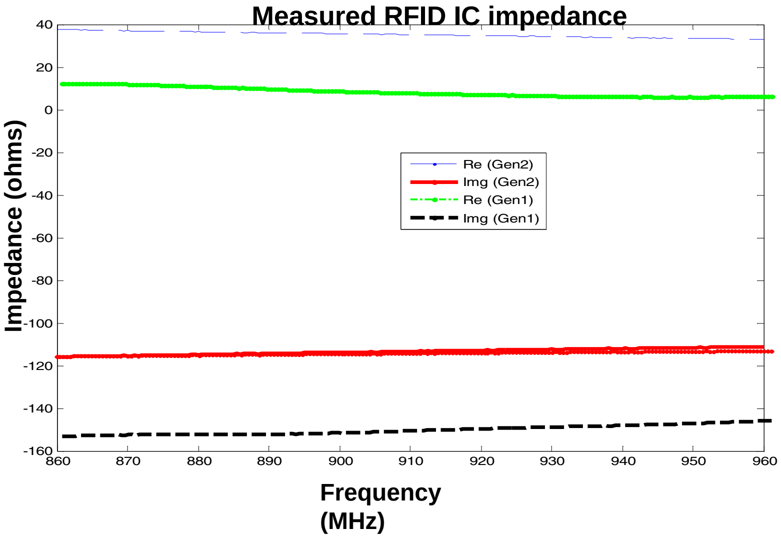


Figure 18: Measured RFID IC impedance for EPC class 1 Gen 1 and Gen2.

Design Parameters

- Antenna parameters
  - Substrate properties
  - Length and width of the rectangular patch
  - Microstrip feed transmission line characteristics
- Matching network parameters
  - Shorting stub characteristics
  - Position of stub with respect to the patch antenna.

Antenna Design Parameters

Parameter	Description
L	Length of rectangular patch
W	Width of rectangular patch
ε_r	Dielectric of substrate
h	Height of substrate

Parameter	Description
$\tan \delta$	Loss tangent of substrate
l_F	Length of balanced feed transmission line
w_F	Width of balanced feed transmission line
offset	Distance of the feed line from the radiating edge

Table 2: Notations used for antenna parameters.

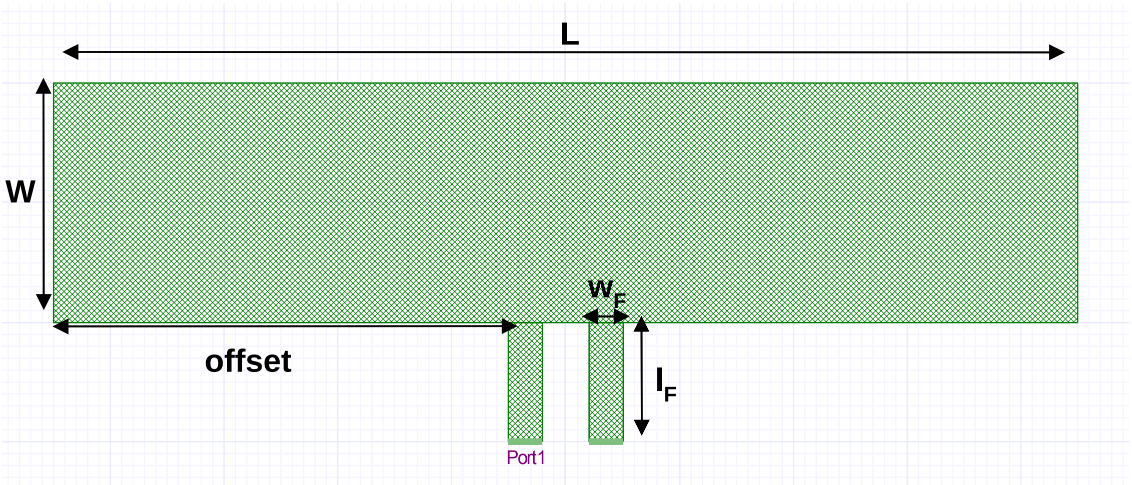


Figure 19: Rectangular patch antenna with balanced feed transmission lines - top view.

Antenna Parameters
Dielectric constant and loss tangent

- **ε_r affects the fringing fields and resonant length**
  - ❑ low values of ε_r → increased fringing fields → greater radiated power
  - ❑ higher ε_r → smaller resonant length → large Q
- **tan δ affects antenna Q-factor**
  - ❑ Large tan δ → small Q → greater 3dB bandwidth
  - ❑ Large tan δ → low radiation efficiency → low peak gain
- **W/h affects radiating resistance and Q-factor**
  - ❑ thicker substrate → reduced radiation resistance → greater bandwidth
  - ❑ thicker substrate → increased weight and cost
- We choose HDPE – Low cost, easy to work with, consistent properties

  PP samples showed inconsistencies in substrate properties

Antenna Parameters

- Rectangular patch = transmission line
  - Patch width affects characteristic impedance, radiation resistance, and antenna aperture
  - Patch length affects resonant frequency
- Feed line characteristics
  - Feed line length transforms patch impedance

    Longer l_F → greater inductive reactance
  - w_F determines feed line characteristic impedance

    Small w_F → greater inductive reactance
  - Small offset → large patch impedance
  - Offset changes electrical length of antenna

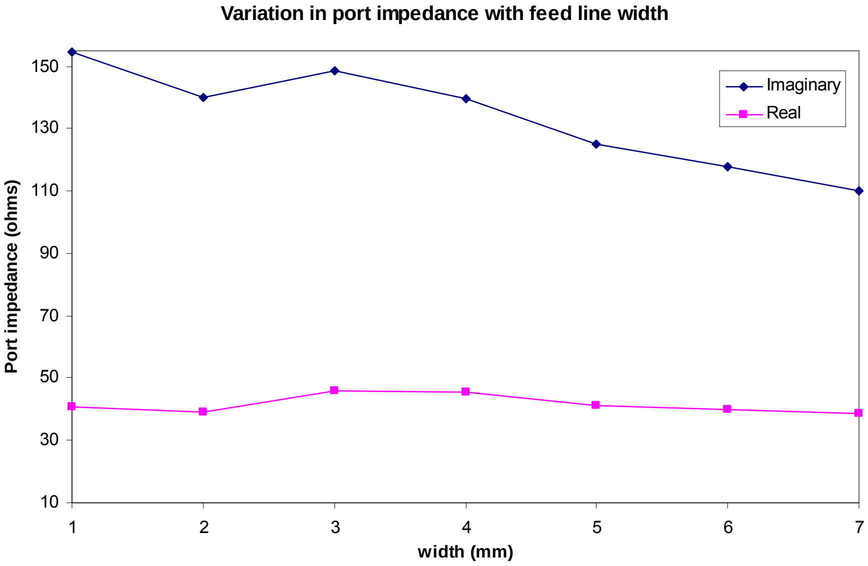


Figure 20: Variation in port impedance with feed line width.

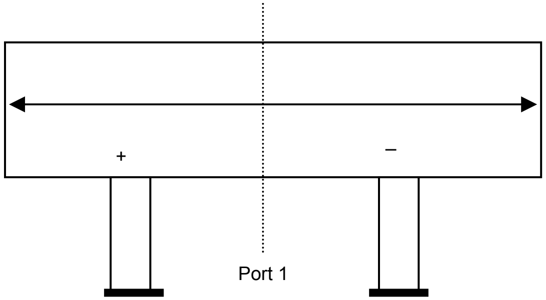


Figure 21: Total electrical length of a balanced feed microstrip antenna.

Effects of Feed Line Length

- Changing the offset or length of the feed line changes the effective electrical length of the antenna
  - Increasing offset reduces input port impedance; reduces electrical length and antenna resonates at higher frequency.
  - Lengthening the feed line adds reactive impedance and also increases the total electrical
  - The effects are minor and easy to compensate by adjusting L

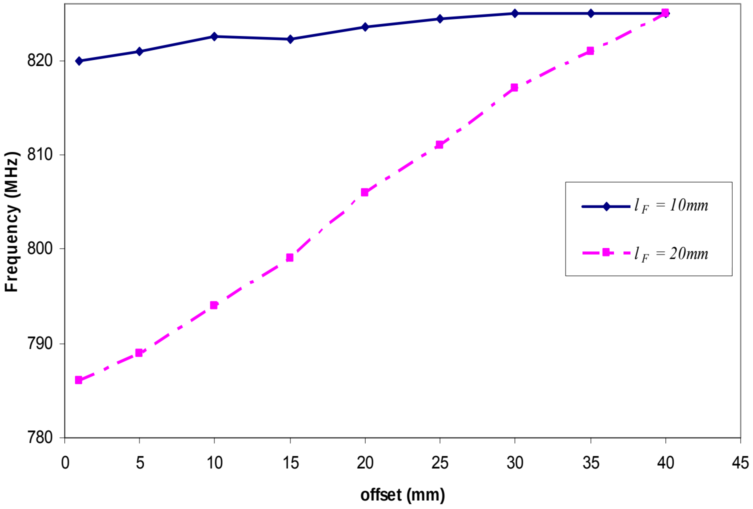


Figure 22: Change in simulated resonant frequency with offset.

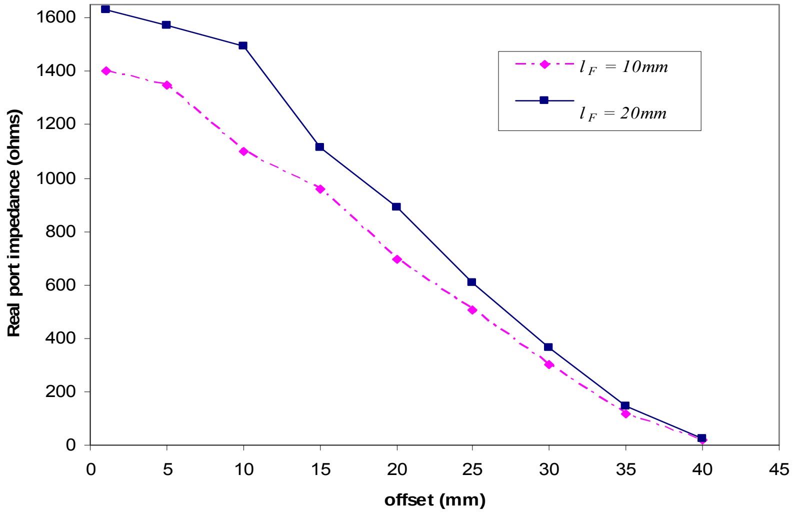


Figure 23: Change in simualted resistive input impedance with offset.

Matching Network Parameters

- RFID IC impedance is highly capacitive; the conjugate match is predominantly inductive
- Microstrip antenna, at resonance, the resistive impedance peaks; the reactive impedance becomes zero
- Shorting stubs add a reactive component in parallel to the patch impedance
- Simulated input impedance shows larger variance without shorting stub

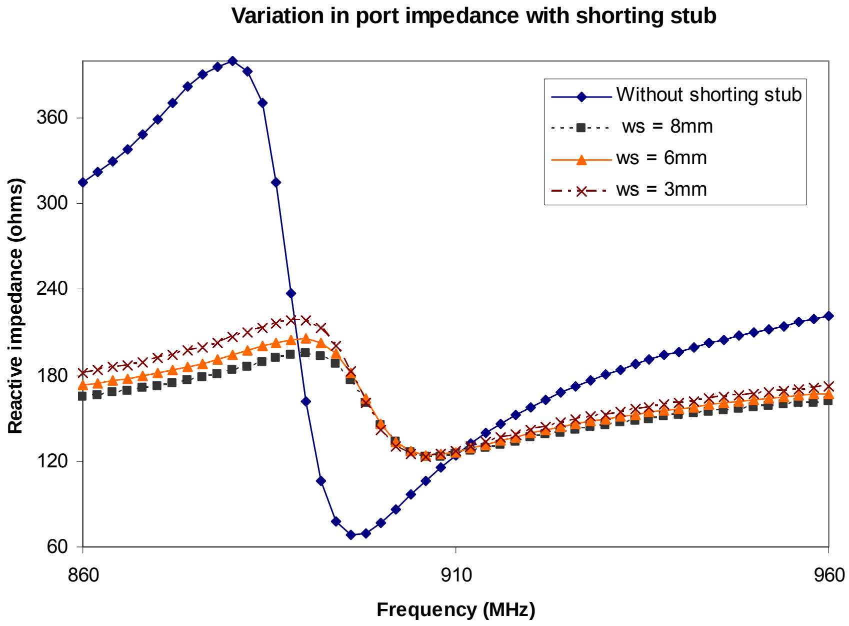


Figure 24: Variation in simulated input port impedance with and without shorting stub.

Effect of Finite Ground Plane

- Ansoft Designer simulation software assumes infinite ground and substrate for microstrip designs
- Finite substrate and ground plane affect radiation pattern and resonant frequency
  - ❑ Finite ground and substrate have some fringing fields that lie in free space causing the patch to resonate lower than with infinite substrate and ground planes
  - ❑ Dielectric test board with different ground planes extensions used measure S11 and hence the resonant frequency
  - ❑ 1.5 cm extended ground approximates infinite plane

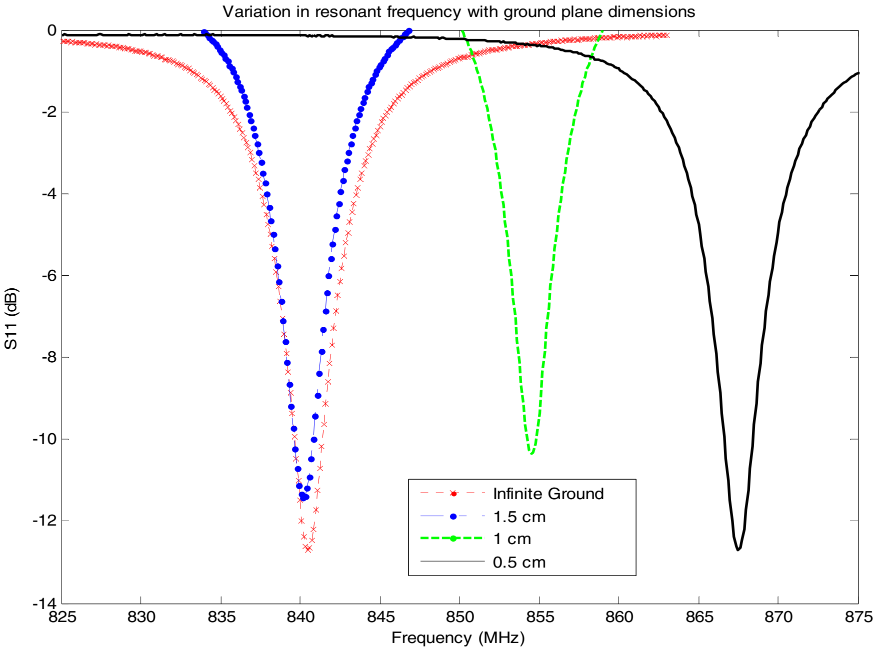


Fig 24: Variation is mesured resonant frquency with different finite ground plane extensions.

Initial Design Parameters

- Based on the previous analyses the initial parameters for the microstrip patch antenna with balanced feed are selected as shown

Parameter	Value (units)
ε_r	2.41
tan δ	0.0035
h	62 mils (1.575)mm
L	106.6 mm
W	35 mm
Extended ground plane	1.5 cm

Table 3: Initial design parameter values for microstrip antenna with balanced feed.

Design Evolution

- Design goals
    - Achieve peak performance at 915 MHz
    - Return loss less than -10db throughout the Federal Communications Commission (FCC) bandwidth for RFID operations
    - Small form-factor
- A stage-wise implementation procedure is adopted to arrive at the optimum values for the design parameters
    - Single patch antenna with dual stub matching network – based on initial design parameter values, all widths are kept constant
    - Single patch antenna with single stub matching network – based on dual stub design parameter values, all parameters are varied to achieve optimum performance

Single Patch Antenna with Dual Stub Matching Network

- Adjust the patch and feed line lengths to make the antenna resonate at the desired frequency.
- Since the offset and resonant lengths are inter-dependent, determining the feed point is non-trivial.
- The offset values varied relative to length of the patch. Any change in the resonant frequency compensated by changing length of patch
- Desired port impedance = 10+j150Ω
- Shorting stubs used to tune the reactive impedance

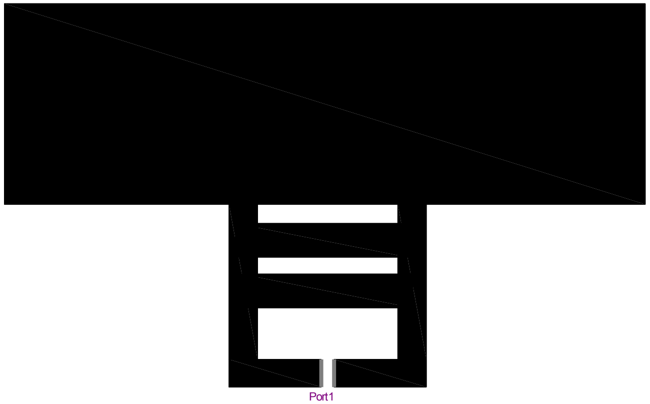


Figure 25: Simulation model of the single patch dual stub matching network deign – top view.

Parameter	Value (units)
ε_r	2.41
tan δ	0.0035
h	62 mils
L	**110 mm**
W	35mm
Extended ground plane	1.5cm

Parameter	Value (units)
l_F	**35 mm**
w_F	2 mm
offset	**L/2.89** mm
w_s	2 mm
l_s	**12.5 mm**

Table 4 : Single patch dual stub matching network design values.

Single Patch Antenna with Single Stub Matching Network

- Second stage of design evolution
- Design criteria - minimize the matching network area without affecting the performance
- Line widths are also varied
- The dual stub matching network is replaced by a single shorting stub of 1mm width
- Narrow meandered feed lines add to the reactive impedance and reduce the area
- Narrow feed lines result in greater characteristic impedance, consequently greater input impedance, the offset value is increased to compensate
- Desired port impedance = 35 + j110Ω (i.e., conjugate of EPC Class 1 Gen 2 strap impedance

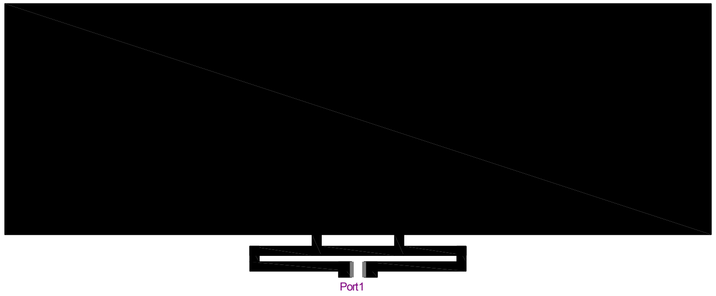


Figure 26: Simulation model of the single patch single stub matching network deign – top view.

Parameter	Value (units)
ε_r	2.41
tanδ	0.0035
h	62 mils
L	**106.8 mm**
W	**35mm**
Extended ground plane	1.5cm

Parameter	Value (units)
$\mathbf{l_F}$	**22 mm**
$\mathbf{w_F}$	**1 mm**
offset	**L/2.29 mm**
$\mathbf{w_s}$	**1mm**
$\mathbf{l_s}$	**5.5 mm**

Table 5 : Single patch dual stub matching network design values

Simulated Results

- Performance characteristics
  - ❑ Dual stub
  - ❑ Max Gain = 0db at 917
  - ❑ 3dB BW = 8.2MHz
  - ❑ Form-factor = 110 x 67 mm; the matching network with the balanced feed = 37 x 33 mm
  - ❑ Single stub
  - ❑ Max Gain = -1.15db at 915MHz
  - ❑ 3dB BW = 8.2MHz
  - ❑ Form-factor = 106 x 41.5 mm; the matching network with the balanced feed = 34 x 6.5mm
- Both antenna designs have less than -10db return loss for EPC Class 1 Gen 1 impedance over FCC RFID bandwidth

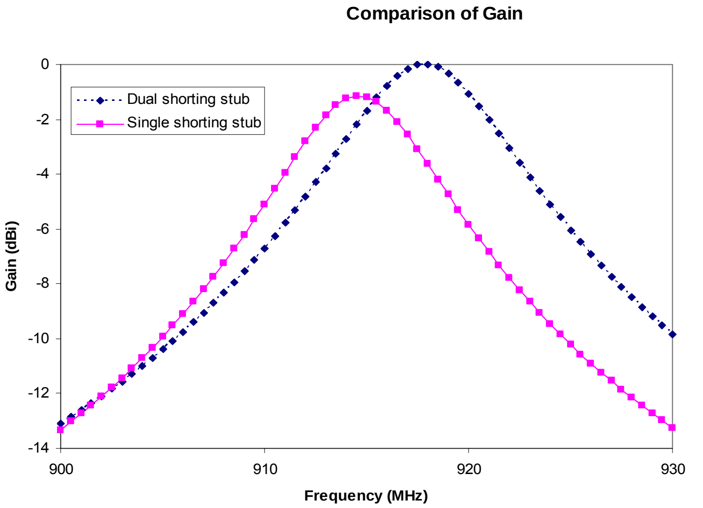


Figure 27: Comparision of simulated gains for different matching networks.

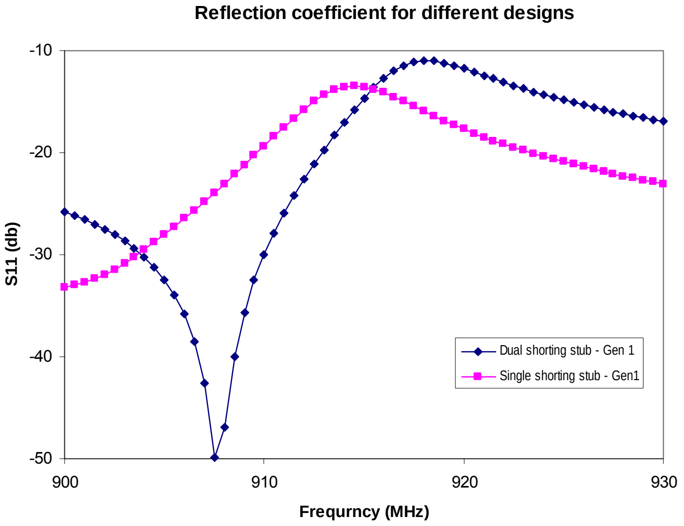


Figure 28 : Comparision of simulated reflction coefficient for different matching networks.

Optimization Issues

- The criteria for optimization of the microstrip RFID antenna performance are
  - **Maximize power transfer** – both designs have -10dB impedance BW throughout the desired frequency band
  - **Maximum peak performance** - matching to very low real impedance (i.e. 10 – 35Ω) causes high current densities resulting in larger Ohmic losses [32] and reduced gain. Tradeoff between the input port impedance at resonance and the gain.
  - The port impedance is maximized until the threshold of -10dB return loss is maintained resulting in good power transfer while maximizing gain
  - **Minimize substrate thickness**
  - **Achieve maximum bandwidth**
  - **Minimize form – factor**
- The design prototypes presented in this section are sub-optimal realizations in terms of bandwidth and form-factor

Measured Results

- Prototype fabrication

1. Firstly the substrate is cut to the required size (i.e. antenna dimensions and additional 1.5 cm of extended ground plane).
2. Substrate covered with a self adhering copper layer on both sides.
3. The Ansoft Designer model is cut out on one side of the substrate while the other serves as the ground plane.
4. RFID IC with the strap is then attached to the antenna using conductive silver epoxy

Figure 29: Planar microstrip antenna with balanced feed mechanism – Prototype.

Measured Results (cont..)

- Validation and performance measurement involves measuring the antenna input impedance and gain over the given bandwidth
- Balanced to unbalanced measurement – use a **balun** or use **odd mode symmetry**, the input impedance measured at only one of the two balanced feed lines is equal to ½ the overall input port impedance
- Feeding the patch with a single balanced feed will change current distribution and therefore the far field pattern.
- The device has both odd and even modes
- Even mode contribution to far field not significant
- Therefore we use single unbalanced feed for measurements

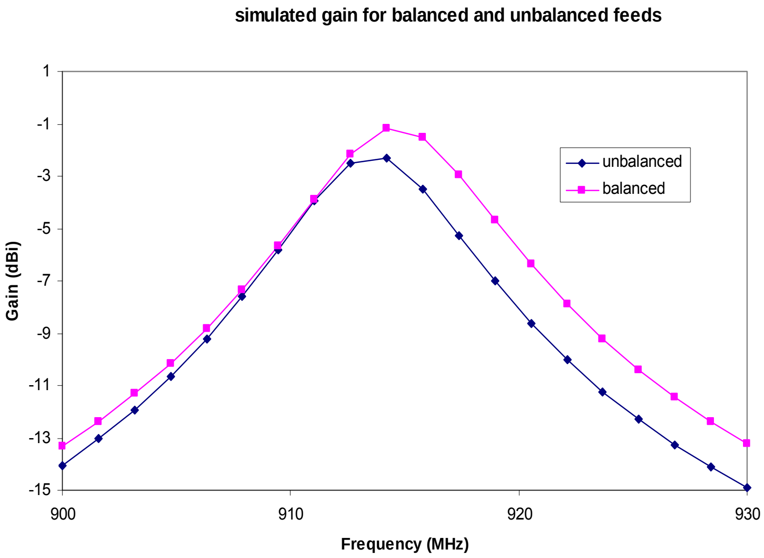


Figure 30: Effect of balanced and unbalanced feed mechanisms on antenna gain.

Figure 31: Measurement prototype with single unbalanced feed connected to a SMA connector.

Measured Impedance

- Results show that there is good agreement between simulated and measured impedance values
- The lower resistance values are measured slightly below zero
- Both simulated and measured peaks occur at almost the same frequency and are of equal in magnitude
- Validates our estimates of dielectric constant and loss tangent
- The Q-factor of the antenna is as expected
- The experimental method used for characterization of substrate materials is therefore accurate

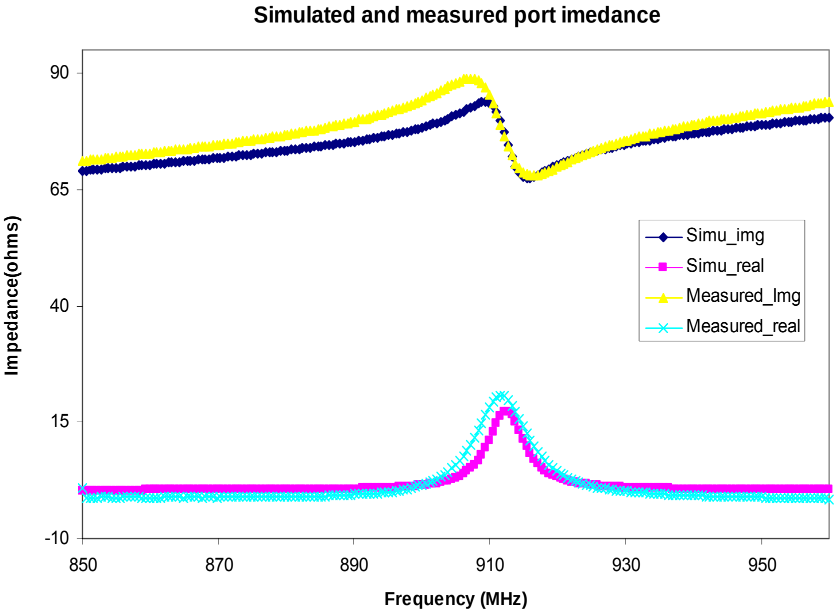


Figure 32: Simulated and measured prototype antenna input impedance with single feed excitation.

Measured Gain

- The gain of the prototype is measured in two different ways
  - Using network analyzer with two prototypes

$$G_r = \left[\left| S_{21} \right|^2 \frac{(4\pi r)^2}{\lambda^2} \right]^{1/2}$$

  - Using RFID reader
    - Vary reader transmit power and frequency

Transmitted power = min turn on power.

Transmit antenna gain = 6dBi circular polarization

Received power = 6.5μW, r = 15 feet

- Tag performance does not follow measured gain, there are also significant differences between measured and simulated antenna gain

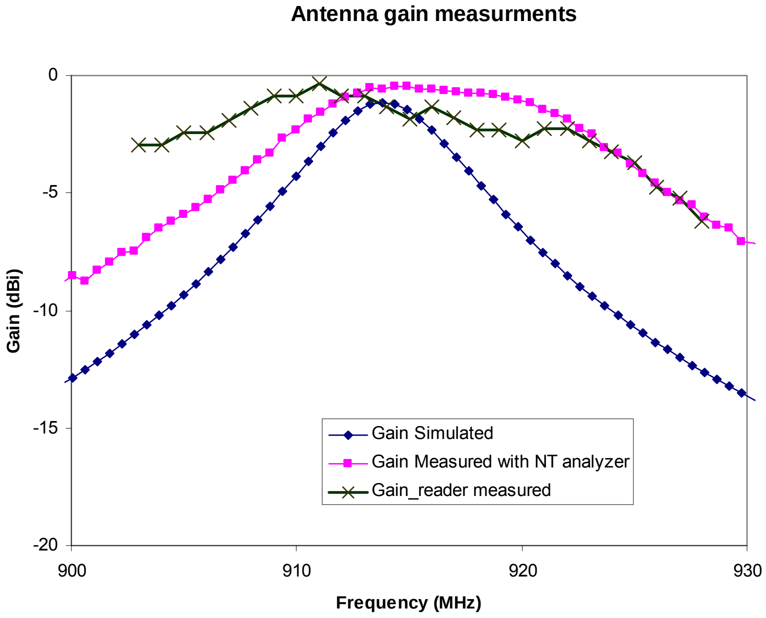


Figure 33 Simulated and measured prototype antenna gain characteristics.

Method	Peak Gain (dBi)	3dB bandwidth (MHz)
Simulated	-1.25	10.3
Measured with network analyzer	-0.48	15.8
Measured with RFID reader	-0.33	20.6

Table 6: Performance characteristics of prototype antenna for different measurement techniques.

Comparisons

- Prototype compared with commercial tags
  - free space
  - on metal with cardboard separation
  - directly on metal
  - on plastic container with water
- Comparison metric – read distance
- Most commercial tags use 4-5 mm thick substrates
- The comparisons show that the prototype tag has superior performance in free space as well as near metal and water compared to other tags

Figure 34: Commercial tags

Tag	Standard	Distance (in ft)			
		Free space	On metal with 6mm cardboard	Directly on metal	Water in plastic container
Avery metal tag	EPC 0+	12	7	7	5
Avery Triflex	EPC 0+	32	4	0	1
Symbol RFX3000	EPC 0	12	3	2	2
Prototype	EPC Gen 2	32	32	32	32

Table 7: Performance comparison between prototype and other commercially available tags.

* *All tags were tested in the same environment with SAMsys MP9320 v2.8 reader and circularly polarized UHF antenna.*

Future Work

- The balanced feed matching network microstrip antenna - potential solution to the metal-water problem of RFID
  - The results however show that the single patch single shorting stub design is limited in its performance by narrow gain bandwidth
  - Constraint to keep the microstrip RFID tag low profile and cost effective, eliminates the possibility of making use of traditional broadband
- The scope of future work
  - Exploring planar mechanisms that allow increase the gain bandwidth
  - Reduce the form factor
  - Thoroughly investigate the effects of planar balanced feed mechanism on the microstrip patch
  - Develop more rigorous test procedures

Preliminary investigation

- Dual patch construction with different feed mechanisms
  - Direct balanced feed
  - Inductively coupled feed
  - Combined inductive and direct feed
- Moderate increase in form factor
- Greater bandwidth

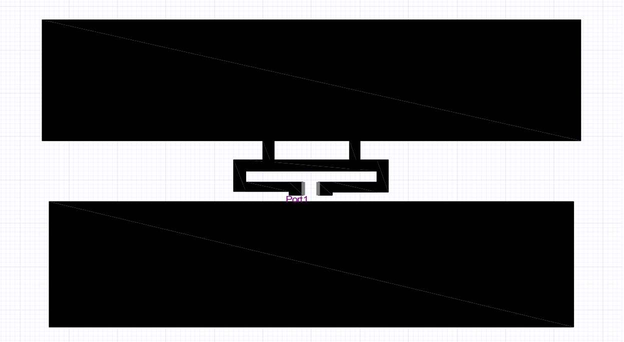


Figure 35: Simulation model for dual patch combined feed broadband design.

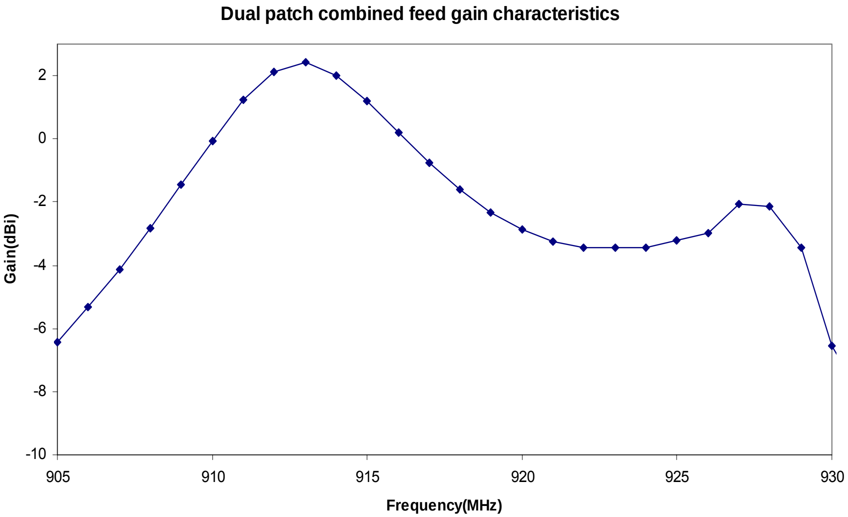


Figure 36: Simulated gain vs frequency – Combined feed.

Conclusions

- We have successfully demonstrated that a completely planar microstrip antenna construction is possible
- Balanced feed microstrip antenna
  - Theory - Odd mode analysis
  - Advantages
    - High performance irrespective of material attached to
    - Reduced manufacturing complexity and therefore cost
  - Disadvantages
    - Narrow bandwidth
    - Large form-factor
  - Further exploration of multi- resonant designs for broadband applications

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Thank you