Antenna Design for LMX5251, LMX5252, LMX9814, and LMX9820

1.0 Introduction

This application note is intended for designers using the LMX5251 or LMX5252 Bluetooth® radio chips or LMX9814 or LMX9820 Bluetooth modules. Antenna design for various applications is described along with theory, matching circuit description, suppliers and examples.

Any structure that is resonant at 2.45 GHz with bandwidth more than 100 MHz and efficiency >50% can be considered a Bluetooth antenna. Therefore, a countless variety of antennas can be used, and they are application-specific. Some common types are:

- *Wire Monopole*—This consists of a simple wire soldered at one end from which it is fed against a ground plane. It is trimmed to be resonant at 2.45 GHz and provides good performance and high efficiency. The disadvantage of this antenna is that it is not low profile because it projects above the PCB.

- *PIFA*—The Printed Inverted F Antenna is like a monopole printed on a PCB, but it has a ground point and feed point along the main resonant structure.

- *Helix*—Similar to the wire monopole, except that it is coiled around a central core (usually air) making the physical dimensions smaller. It provides excellent performance, but projects above the PCB.

- *Ceramic*—Surface mount dielectric antennas are the smallest types of antennas available, because they are printed on a high-dk ceramic slab, which makes the electric field concentrated allowing the antenna to be made small while keeping a high resonant frequency.

This application note only describes PIFA and ceramic antennas because they are the most common, low-profile, smallest, and inexpensive types available.

2.0 Theory

Printed and surface-mount antennas have certain common properties. Area around and beneath the radiating element must be kept copper-free. The ground plane must be placed on one side of the radiating element. Bandwidth is >100 MHz with VSWR <2.5 and efficiency >60%.

The antenna will detune if any object is placed close to it (in its near field). This has an effect of pulling the frequency, which must be retuned to 2.45 GHz.

An oscillating or constantly accelerating charge is critical in producing propagating waves. A static or non-accelerating charge will result in a non-propagating electric field. But this is not the only condition for radiation. For example, consider a printed $\lambda g/4$ element on microstrip, as shown in Figure 1.
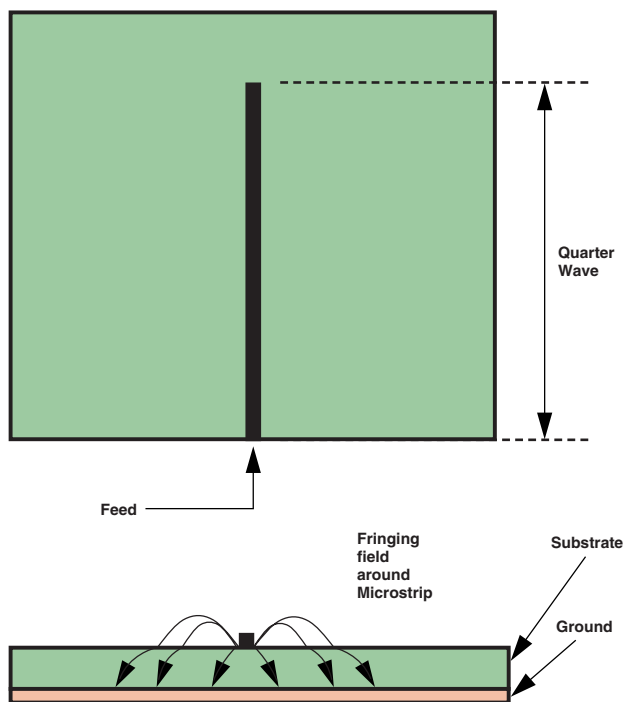

Figure 1. Fringing Field With Full Ground Plane

The fringing field around the microstrip due to the ground plane directly underneath the substrate will be confined to a small area. If a network analyzer is connected to the feed point, it would indicate a high VSWR and narrow bandwidth. This means very little radiation is being emitted from the microstrip element.

To increase the radiation emission and achieve greater bandwidth, the ground plane must be moved away from the microstrip element which makes the fringing field cover more distance, as shown in Figure 2. But it should be noted that if the ground plane is moved too far, then the fringing field stops altogether, and there is no radiation. Therefore, the position and size of the ground plane is vital in the design of a good radiator.
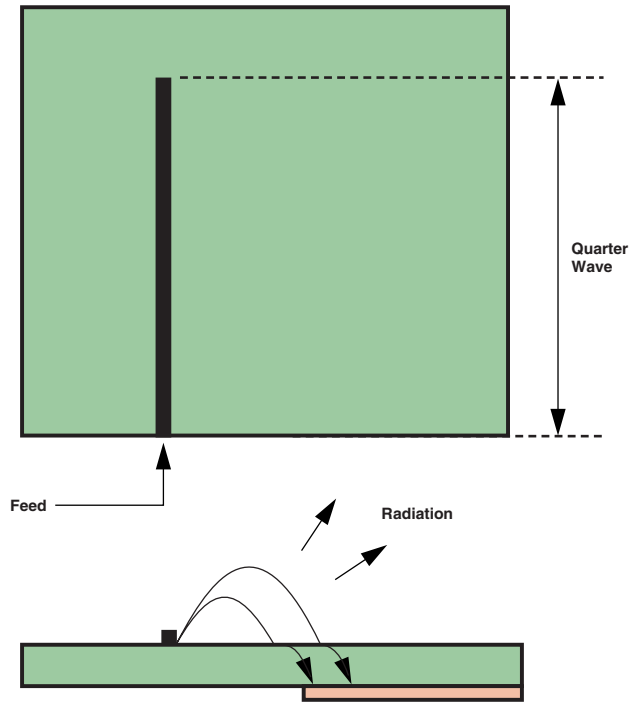

Figure 2. Fringing Field With Partial Ground Plane

The antenna could be imagined as an impedance transformer, transforming the impedance of a microstrip line (50Ω) to that of free space (377Ω), which allows the power to be transferred from a guided wave to a free-space wave.

The radiation pattern from such antennas in which the physical size is much smaller then wavelength ($L << \lambda$) is almost symmetrical in all directions, as shown in Figure 3. The pattern can be controlled only when L is similar or greater than λ.
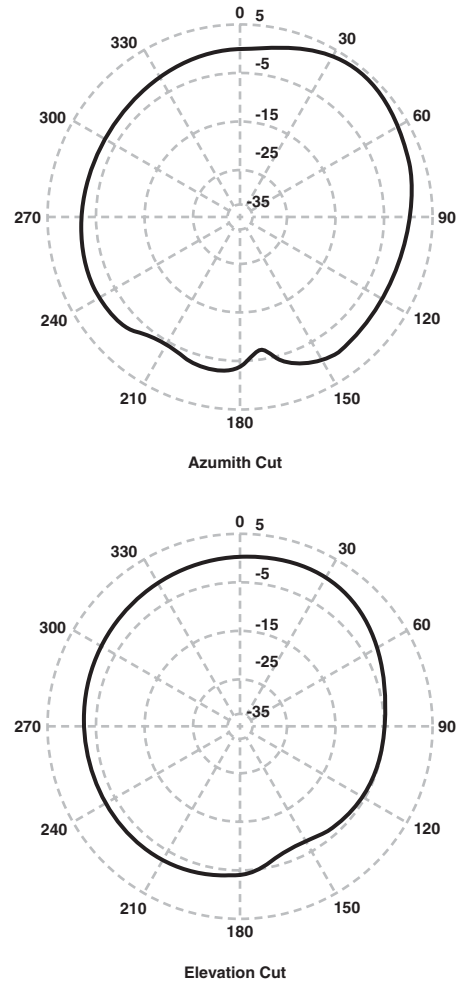

Azimith Cut

Elevation Cut

Figure 3. Antenna Radiation Pattern

Input return loss when viewed on a network analyzer looks like that shown in Figure 4, with the full band covered with VSWR < 2. This gives very good matching into the antenna, however in real conditions when the antenna is detuned due to handling or placement of components close to it, a VSWR of 3 to 4 is typical.
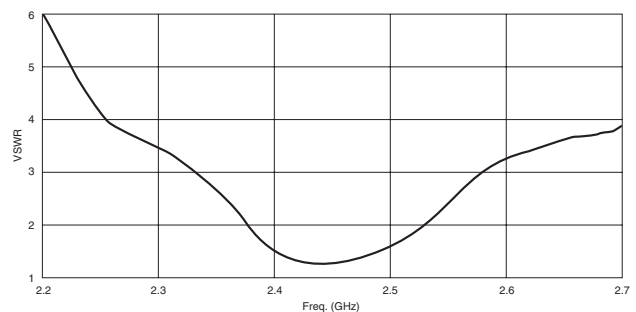

Figure 4. Return Loss

3.0 Layout

3.1 PIFA ANTENNA

The typical length of a 2.45-GHz resonant printed antenna is 20 to 25 mm, depending on the thickness of the substrate and dielectric constant. Copper clearance is required around the radiating element which is fed from a point along it, as shown in Figure 5. The position of the feed can be used to control the input impedance into the antenna. The ground plane required on one side of the antenna is approximately 20 mm wide. If it were any smaller, it will start to reduce the bandwidth at the input. Good design practice is to have a three-element matching network going into the feed, to give some additional tuning ability if required. To obtain the exact dimensions of the design, input impedance and bandwidth would have to be simulated over the frequency band using an antenna simulation package. Alternatively an antenna manufacturer can be contacted that has the capability to make such a design.
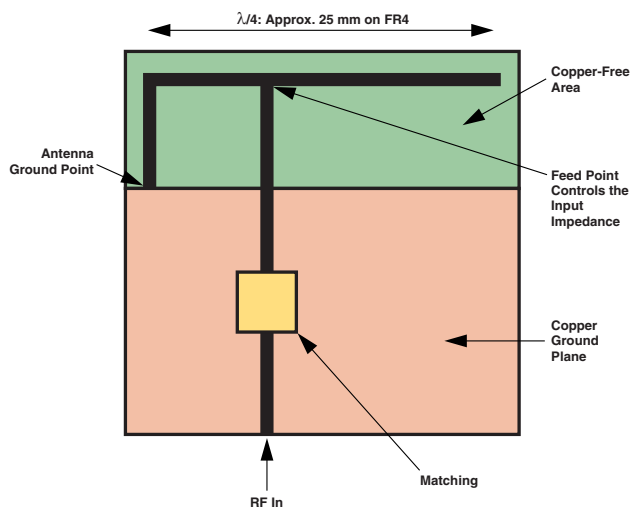
The PIFA is placed on the edge of the motherboard PCB, as shown in Figure 6. The area around the corner is kept copper-free, and any components such as the shielding that come close to the PIFA may pull its frequency. This can be retuned by milling the end of the radiating element. The LMX5251/LMX5252 and its surrounding components do not need shielding unless they are very close to the radiating element.
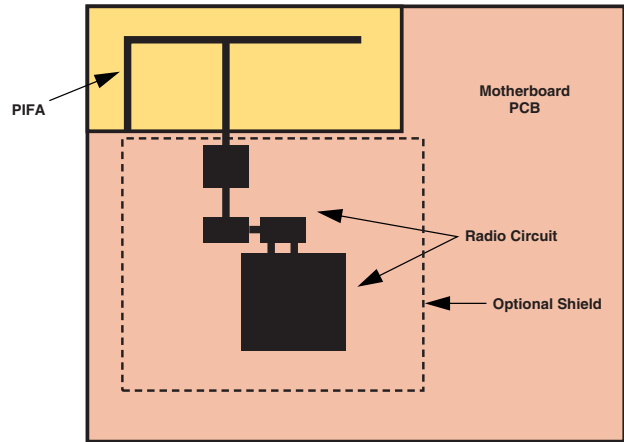

Figure 6. PIFA Antenna Placement

Figure 5. Printed Inverted-F Antenna (PIFA)

3.2 CERAMIC DIELECTRIC ANTENNA

A ceramic dielectric antenna is smaller than a PIFA or any other PCB antenna because the active element is wound around a high-dk ceramic slab, which concentrates the electric field. As with a PIFA, a copper-cleared area and a ground plane are required, as shown in Figure 7. A smaller ground plane can be used, at the expense of bandwidth and efficiency.
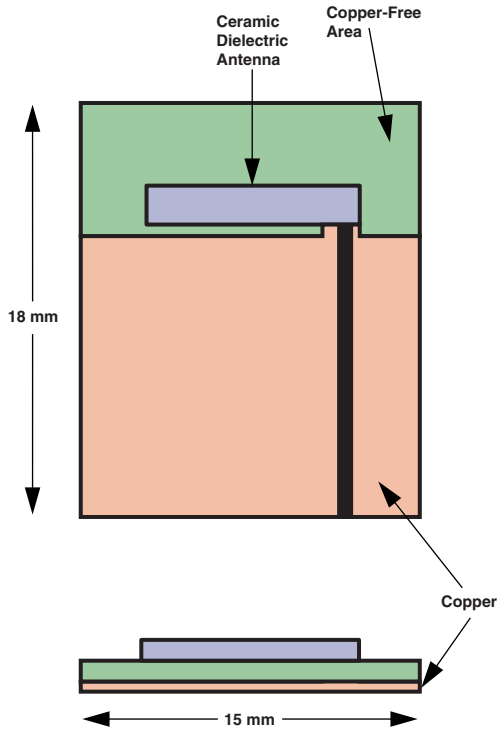

Figure 7. Ceramic Dielectric Antenna Placement

An example antenna from Mitsubishi with details of the ceramic element dimensions is shown in Figure 8.
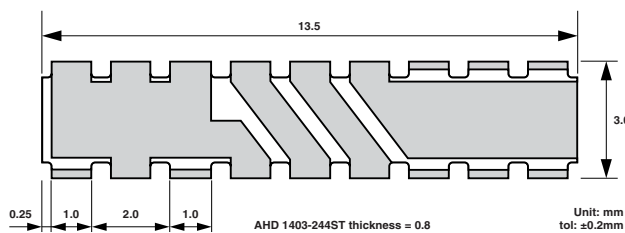

Figure 8. Typical Chip Dimensions

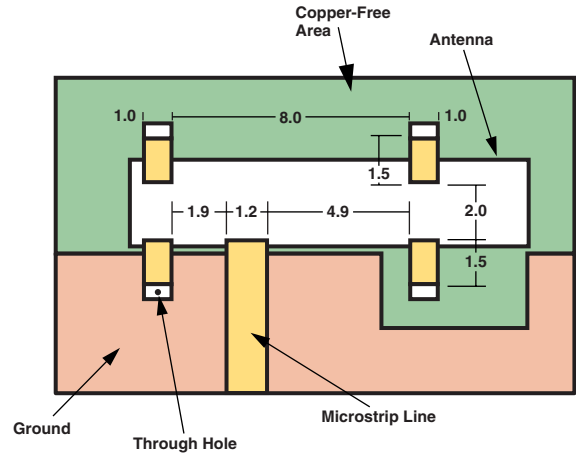The land pattern required for mounting on the PCB is shown in Figure 9.

Figure 9. Typical Chip PCB Footprint

The ceramic dielectric antenna behaves similarly to a PIFA, in that it can be detuned, has a symmetrical radiation pattern, and has an efficiency of approximately 70%.
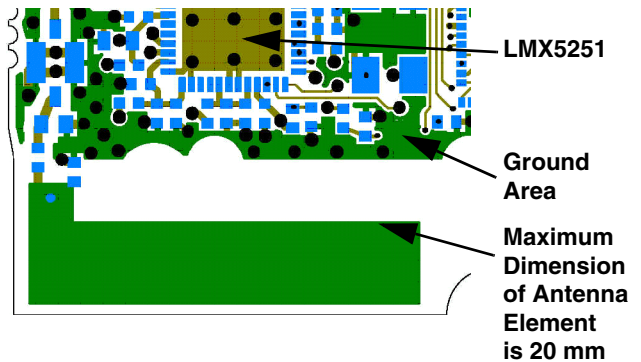
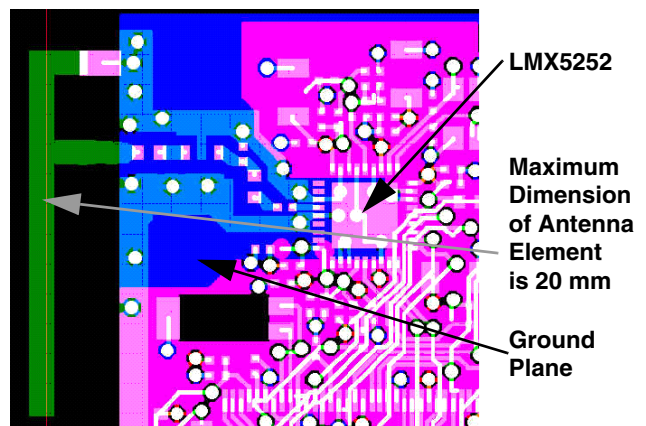## 3.3 EXAMPLES OF 2.4-GHZ PIFA ANTENNAS

Figure 10. LMX5251 PIFA Antenna

Figure 11. LMX5252 PIFA Antenna

3.4 LMX9814/LMX9820 ANTENNAS

The LMX9814 and LMX9820 are packaged as shielded LTCC modules, approximately 14 × 10 mm in size. The design of its antenna is very similar to that of the LMX5251/LMX5252, but the shielding makes two differences. First, the metal shield protects the components in the module from the electric field of the antenna, so it is possible to place the LMX9814/LMX9820 much closer to the antenna element. Second, the shielding also acts as a ground plane, so less unpopulated ground area is required around the radiating element.

In the example using a ceramic dielectric antenna shown in Figure 12, the module is placed close to the radiating element. The electric field from the antenna couples to the surface of the shielded enclosure producing propagating radiation. If the shield is well-grounded, there will be no adverse effects on the components inside.
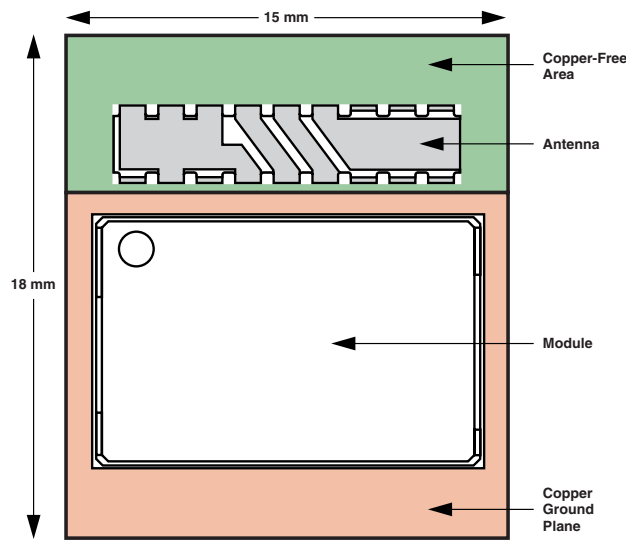

Figure 12. LMX9814/LMX9820 Antenna

4.0 Matching

Purchased antennas, such as surface-mount ceramic dielectric antennas, will be matched to 50Ω input impedance with return loss <-7dB over 100 MHz bandwidth, centered at 2.45 GHz. However, this is only as measured on the manufacturers test board, in free space. Taking this antenna and putting it on the application PCB, in which the ground-plane layout may be different or there may be detuning components such as filters placed nearby, will pull the resonant frequency of the antenna away from 2.45 GHz. The antenna therefore needs matching to the correct frequency. This can be achieved by means of a three-element PI network, placed at the input to the antenna. Usually a capacitor pair and an inductor, or an inductor pair and a capacitor, will give sufficient tuning ability.

There are three steps to matching:

1. The network analyzer must be calibrated accurately with the electrical delay removed.
2. An impedance measurement from 2.300 to 2.600 GHz of the return loss and a Smith-Chart plot.
3. Matching by placing capacitors and/or inductors onto the PCB to see how the impedance is changed.

4.1 NETWORK ANALYZER CALIBRATION

The network analyzer should be calibrated for S11, one-port only measurements using the open, short, and load standard provided. A flat line should be obtained when the standards are removed as shown in Figure 13.
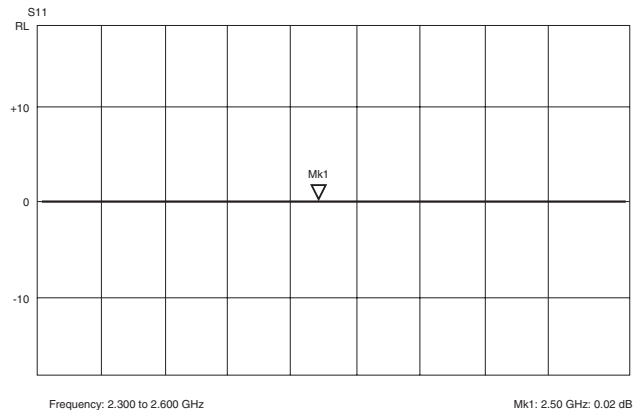

Figure 13. Return Loss, No Connection

Before soldering the semi-rigid cable to the PCB, it is connected to the end of the network analyzer cable, and the electrical delay is adjusted with the end of the semi-rigid cable shorted. Use a short cable attachment (less than 5 cm), otherwise the electrical delay will be too long. Electrical delay is adjusted until it is measuring a perfect short on the Smith Chart as shown in Figure 14.
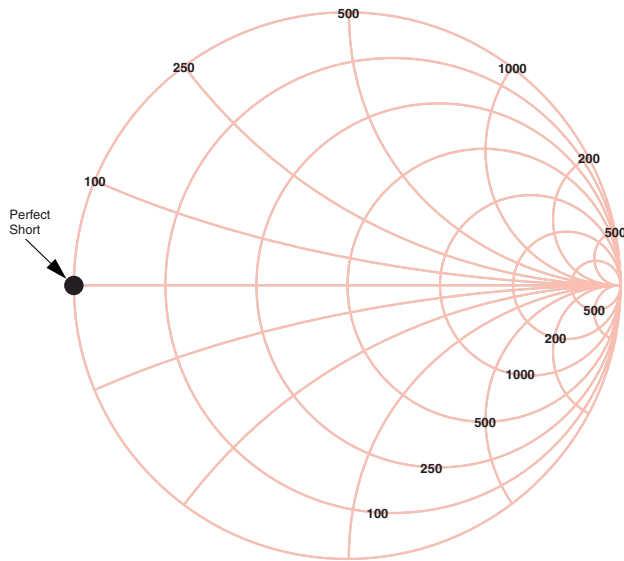

Figure 14. Smith Chart, Perfect Short

4.2 MEASUREMENT

Attach the semi-rigid cable to the PCB and ground it at a point close to the end of the cable. When measuring the input impedance of the antenna, it is important to have the setup on a wooden or non-detuning surface and to keep your hands away from the setup, otherwise the measurement will be incorrect. An example of a typical return loss measurement is shown in Figure 15.
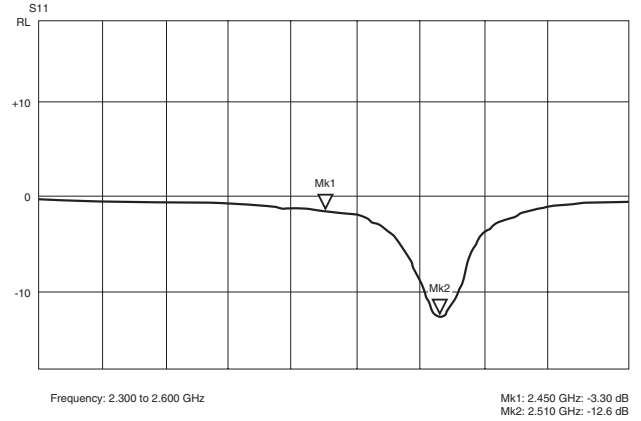

Frequency: 2.300 to 2.600 GHz

Mk1: 2.450 GHz: -3.30 dB
Mk2: 2.510 GHz: -12.6 dB

Figure 15. Return Loss, Antenna Connected

In this example, the resonant frequency of the antenna is 60 MHz too high. At the desired frequency, the return loss is only -3.3 dB.
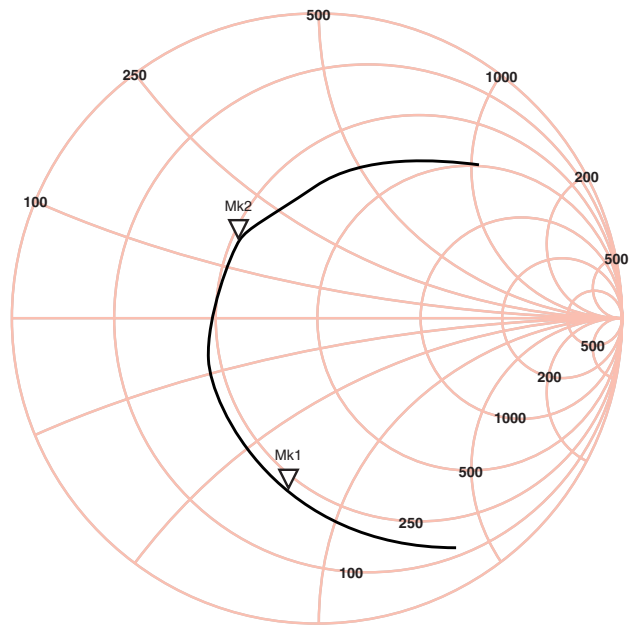

Figure 16. Smith Chart, Antenna Connected

4.3 TUNING THE IMPEDANCE

After taking an accurate measurement of the input impedance, it can be tweaked using the matching components on the three-element PI network. Marker 1 impedance has to be transformed to 50Ω, as shown in Figure 17.
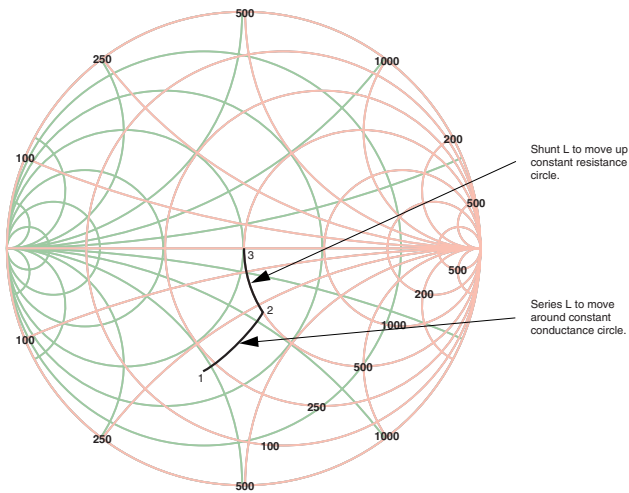

Figure 17. Impedance Transformation

Starting from the impedance point that needs to be matched (point 1), add a 1.8-nH series inductor to move from point 1 to 2. A shunt inductor will transform the impedance at point 2 to the center of the chart, which is the normalized 50Ω impedance point. The matching network is shown in Figure 18.
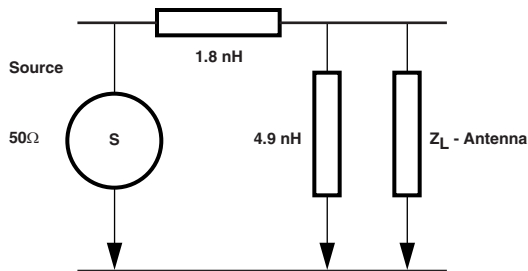

Figure 18. Impedance Matching Network

This is only a theoretical matching circuit. In reality, the inductors have parasitic resistance and capacitance, so the impedance will not be transformed as cleanly as shown on the Smith Chart. Also, the exact values shown above may not be available in a standard kit. Some trial and error is required to get the exact match required.

4.4 PI-NETWORK MATCHING

A popular type of matching network is the PI-network, consisting of two shunt components with one series component in the middle. This provides flexibility for retuning a detuned antenna. Even though only two components are normally used for matching the load to the source, it allows putting the shunt component either before or after the series component.

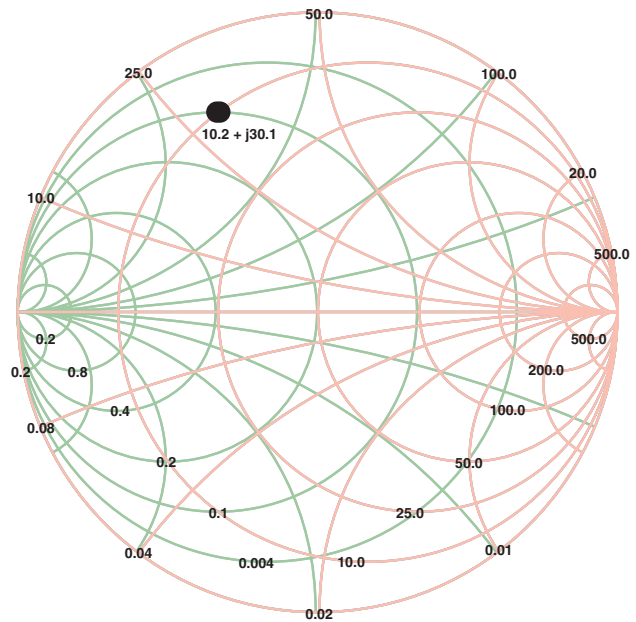For example, consider the data point on the Smith Chart: (10.2 + j30.1)Ω shown in Figure 19.

Figure 19. Single Frequency Data Point

There are two methods for matching to the load. The first technique is to move around a constant resistance circle from position 1 to 2 by adding a series capacitance and then from 2 to 3 around a constant conductance circle by adding a shunt capacitance, as shown in Figure 20.
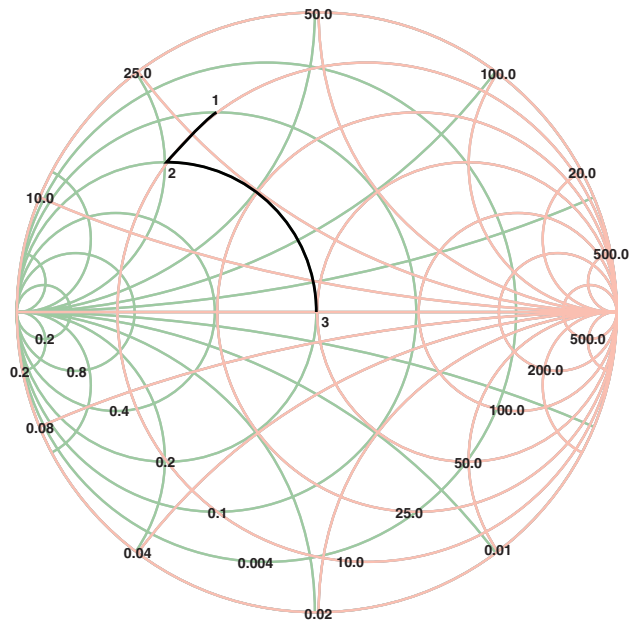

Figure 20. After Resistance-Conductance Tuning

The second technique is to move around the conductance circle and then the resistance circle by adding a shunt and series capacitance respectively, as shown in Figure 21.
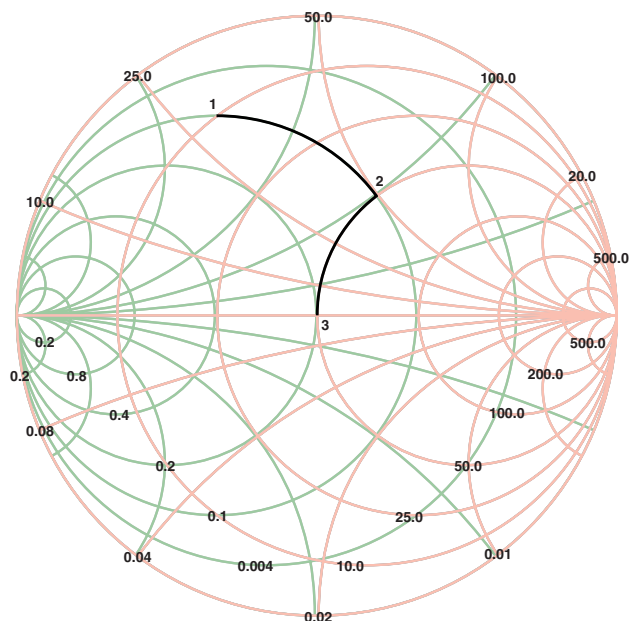

Figure 21. After Conductance-Resistance Tuning

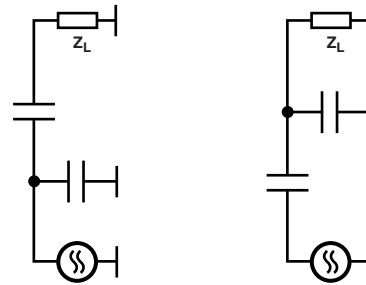The matching networks for the two methods are shown in Figure 22.

Figure 22. Two Possible Matching Networks

To allow both types of matching, a PI-pad must be used with the redundant gap bridged using a zero-Ω link.

However, so far we have only matched a single-point frequency to 50Ω. In the case of a real passive device such as an antenna, the entire Bluetooth band has to be matched as closely as possible to 50Ω. At least three frequency points have to be matched, as shown in Figure 23.
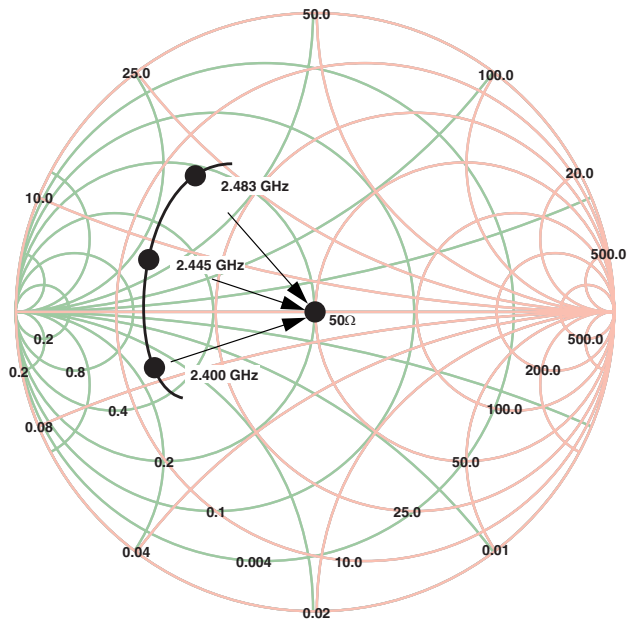

Figure 23. Broadband Match

The difficulty with making a broadband match to one frequency point is that the other two will go even further out! For example, 2.483 GHz can be brought closer to 50Ω by adding a shunt capacitor, but the 2.400 GHz point will move around the conductance circle creating an even larger mismatch at lower frequencies. A compromise must be found that will suit the entire band. This normally involves using simulation software such as HP-ADS (advanced design systems). If this is not possible, then a lot of manual tweaking is needed concentrating on the center frequency point.

First, the input impedance of the detuned antenna is measured using a network analyzer and saved as an S-parameters block, i.e. frequency points vs. impedance points across the Bluetooth band. This can then be entered into ADS along with the PI network, as shown in Figure 24.
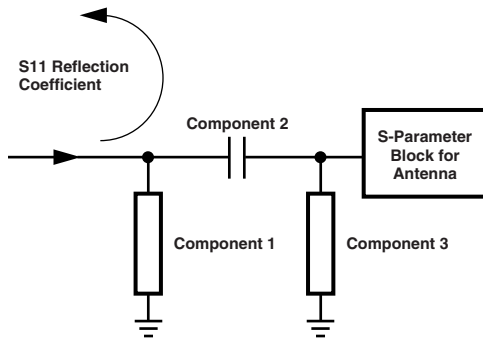

Figure 24. PI Network

To make the model more realistic, it is more effective to use real components with added parasitics rather than just pure inductance and capacitance. The models for the components with the parasitics are shown in Figure 25.
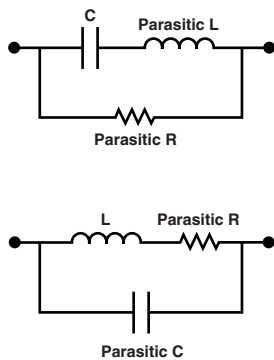

Figure 25. Component Models

Data for the parasitic values can be obtained from the component manufacturer.

Starting with the best possible values used to match 2.445 GHz, the model is entered into ADS, and an optimization procedure is set up to reduce S11 as much as possible in iterative steps from 2.400 to 2.483 GHz. The simulation finely tweaks the PI-pad component values and measures S11. If it is lower, then the components are tweaked again in the same direction until the best optimized solution is found.

The same procedure can be used for larger matching networks or even active networks, which may yield better results. However larger circuits will have higher insertion loss due to the parasitic resistance present within the components.

4.5 MATCHING TO A NON-50Ω ACTIVE SOURCE/LOAD IMPEDANCE

If the source and load impedances are both non-50Ω, then they can be matched in much the same way as a 50Ω impedance as shown in Figure 26.
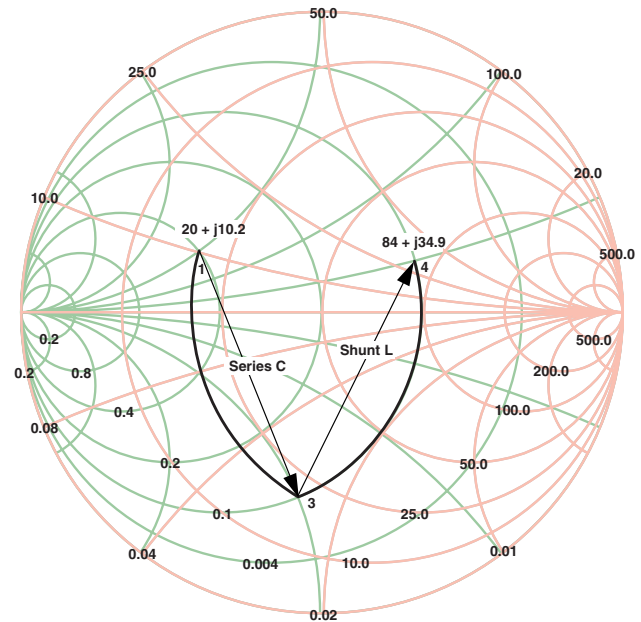

Figure 26. Matching to Non-50Ω Impedance

In this example the load is at 20 + j10 and the source at 84 + j35. A series capacitance and shunt inductance is required to transform the load impedance to that of the source.

Because these are non-50Ω, they can lie anywhere on the Smith Chart and must be measured using a vector network analyzer (VNA) to determine their exact value.

Measuring the input impedance of a receiver or passive antenna is simple. A calibrated VNA will display the value on its screen. However, when measuring the output impedance of a power amplifier or transmitter, this technique cannot be used because the power being transmitted will completely disrupt the VNA reading. The technique of conjugate matching using a variable load must be used.

In Figure 27, a variable load and attenuator can provide any desired load impedance to the PA. Therefore, it can influence its output power which is measured using the power meter attached to the coupled port of the directional coupler. When a perfect conjugate match is applied to the output of the PA, the power measured on the power meter will be at its maximum, which signifies the best power transfer conditions.
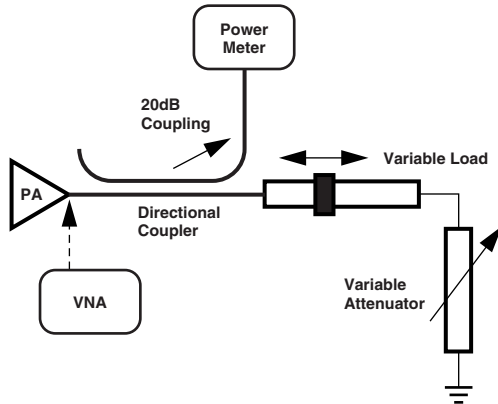

Figure 27. Setup for Determining Output Impedance

When best power transfer is achieved, the variable load and attenuator are fixed so that their impedance cannot be changed. The PA is detached from the directional coupler and a VNA attached to the input of the directional coupler to measure the input impedance at this point. The measured impedance is the conjugate of the output impedance of the PA, or if the impedance measured on the VNA is $R + jX$ then the output impedance of the PA will be $R - jX$ by definition.

Definition: the term *conjugate match* means that if in one direction from a junction the impedance is $R + jX$, then in the opposite direction the impedance will be $R - jX$. The condition for maximum power absorption by a load, in which the impedance seen looking toward the load at a point in a transmission line is the complex conjugate of that seen looking toward the source.

5.0 Antenna Vendors

Table 1 lists vendors for off-the-shelf antenna products and custom designs.

Table 1. Antenna Vendors

Vendor	Products	Contact Information
gigaAnt	Small ceramic chips and larger surface-mount antennas suitable for mobile phones, headsets and laptops, printers, etc. For example, 3030A5839-01 Leftside, 3030A5887-01 Rightside.	gigaAnt Ideon Science & Technology Park S-223 70 Lund Sweden Phone:+46 46 286 41 77 Web: www.gigaant.com E-mail: info@gigaant.com
Mitsubishi Materials	Small ceramic chips for surface-mount. Suitable for mobile applications	Mitsubishi Materials Corporation Advanced Products Strategic Company Sales Group, Electronic Components 1-297, Kitabukuro-cho, Omiya-ku Saitama-city, Saitama, 330-8508 Japan Phone: +81 48 641 5991 Fax: +81 48 641 5562 Web: www.mmc.co.jp E-mail: devsales@mmc.co.jp
Tyco Electronics	Large high-gain printed antennas for applications such as access points. Small ceramic chips for surface-mount. Suitable for mobile applications	Tyco Antenna Products/Rangestar 350 Metro Park Rochester, NY 14623 USA Phone: (585) 272-3103 Fax: (585) 272-3110 Web: www.rangestar.com
Centurion	PCB surface-mount antennas for various applications.	Centurion Wireless Technologies PO Box 82846 Lincoln, NE 68501 USA Phone: (402) 467-4491 Fax: (402) 467-4528 Web: www.centurion.com E-mail: sales@centurion.com
Murata	PCB surface-mount antennas For example, M1 series ANCM12G45SAA072 or W1 series ANCW12G45SAA110TT1.	Murata International Sales Dept. 3-29-12 Shibuya, Shibuya-ku Tokyo 150-0002 Japan Phone: +81 3 5469 6123 Fax: +81 3 5469 6155 Web: www.murata.com E-mail: intl@murata.co.jp

6.0 Comparison Summary

Table 2 compares the features of different antenna types.

Table 2. Antenna Comparison

Antenna Type	Performance	Profile	Cost	Physical Size
Stub helix or monopole	Good bandwidth and efficiency, does not require matching network.	**High:** Projects from the side of the PCB	High	2.4 GHz antenna is approximately 15 mm long, but projects. Does not need ground plane to function.
Surface-mount ceramic chip	Reasonable performance on $\lambda g/4$. Small bandwidth and reduced efficiency. Can become detuned during handling	**Low:** Can be machine mounted during assembly, no more than 0.5 mm thick	Medium	Element for 2.4 GHz is approximately 12 mm long, but needs ground area and clearance around active region.
Printed inverted-F or other printed types	Reasonable performance on $\lambda g/4$. Small bandwidth and reduced efficiency. Can become detuned during handling	**Lowest:** Printed on PCB	Low	Element for 2.4 GHz is approximately 25 mm long, but needs ground area and clearance around active region.

7.0 Points for Consideration

- Many types of antennas are available.
- Antenna type is chosen to fit the application.
- Larger antennas generally have better performance than smaller ones.
- Ground plane is always required with printed or ceramic antennas.
- Cannot put metal objects such as crystals close to antenna without causing detuning.
- The case of a phone or other device will also detune the antenna, so some tuning adjustment ability is needed.
- Matching elements have parasitic values that affect their quality; this is not possible to simulate using simple simulation software. Some trail and error is therefore required when performing the match or a sophisticated simulation tool must be used.
- The LMX9814/LMX9820 shielding will act as the ground plane for the antenna if placed correctly.
- The LMX5251/LMX5252 radio chip must be shielded from the strong electric field only if it is placed close to the radiating element. Shielding will improve performance but is not always required.

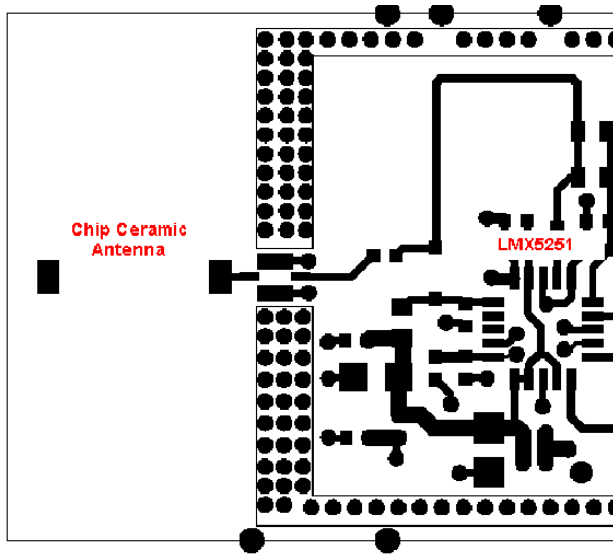## 8.0 Examples of Antennas Used With LMX5251/LMX5252

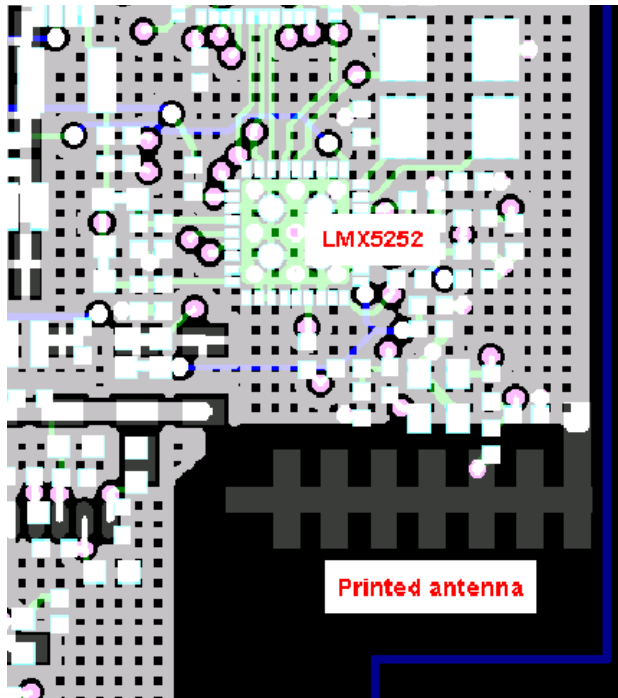**Figure 28. Ceramic Chip Antenna for Industrial Remote Control with External PA**

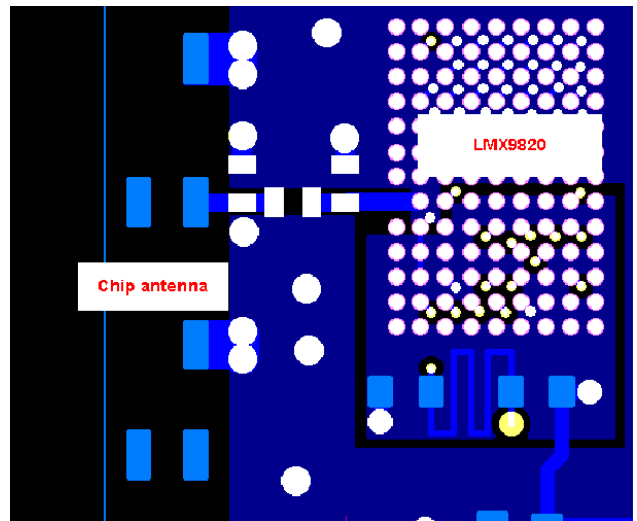**Figure 29. Printed Antenna—Monopole Yagi-Array for Off-Board Navigation Using GPS**

Figure 30. Ceramic Chip Antenna for Intelligent Remote Access for Car Lock
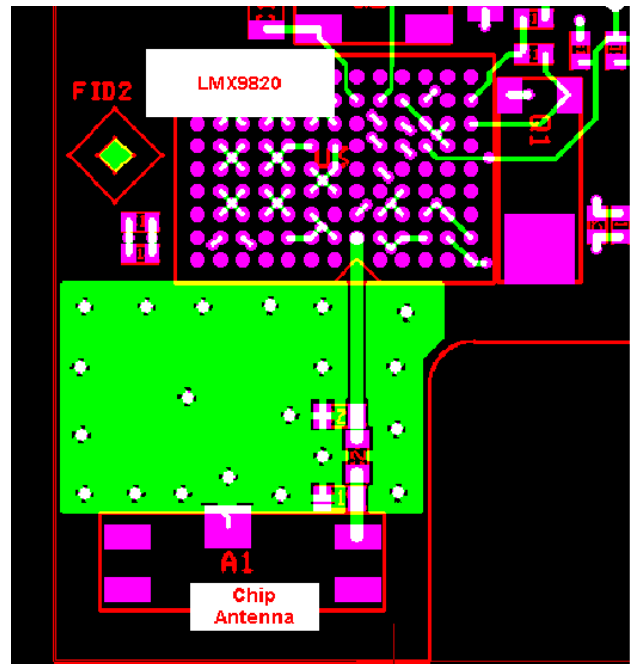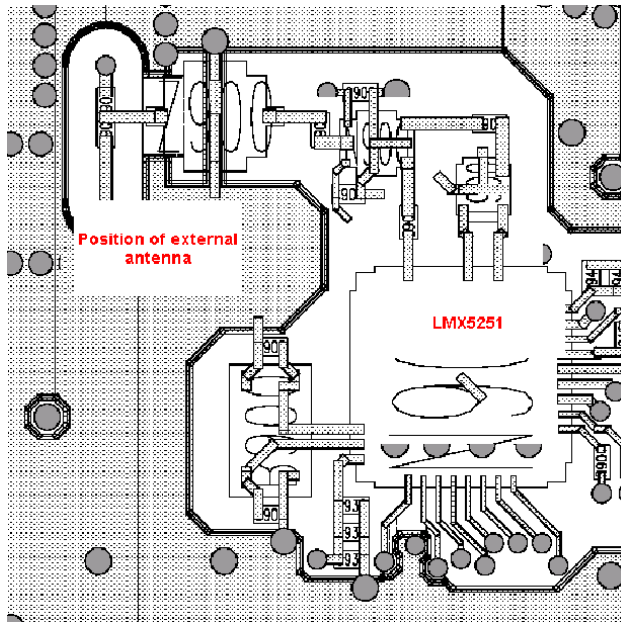

Figure 31. Ceramic Chip Antenna for Distance Meter

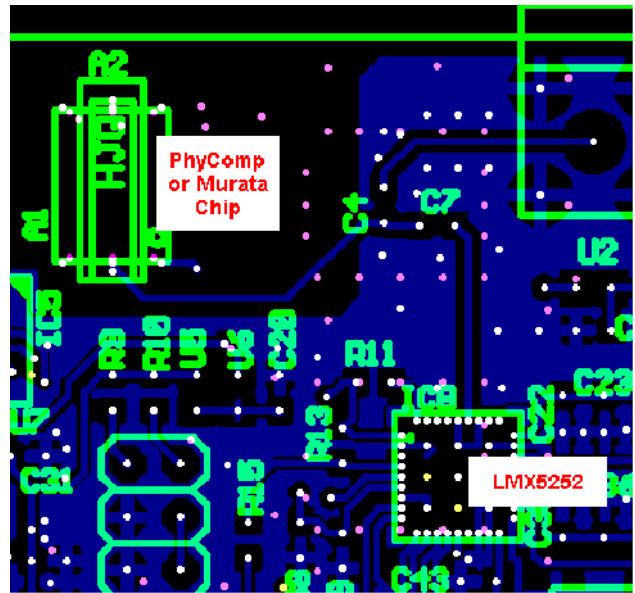**Figure 32. External Antenna—Helix or Monopole for Automotive Integrated Hands-Free Kit**

Figure 34. Surface-Mount Chip Antenna (Phycomp AN-2700 or Murata ANCM12G) for Automotive Hands-Free Kit
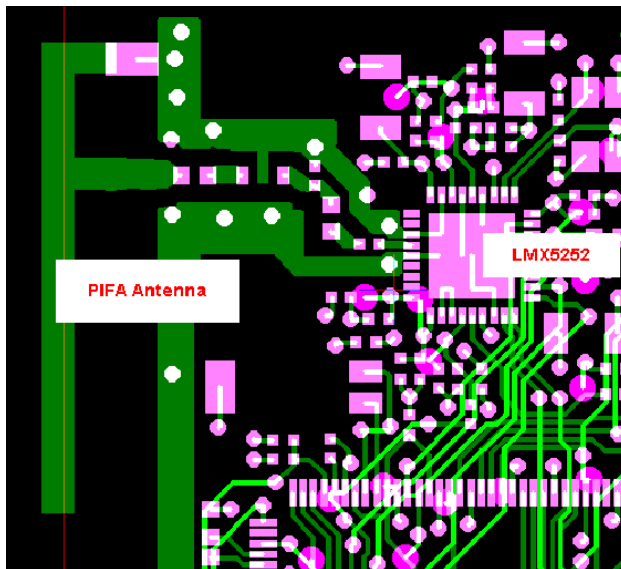
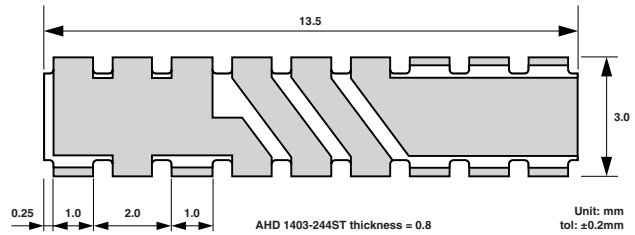**Figure 33. Printed PIFA Antenna for Automotive Hands-Free Kit**

Figure 35. Surface-Mount Chip Antenna (Mitsubishi Materials AHD 1403) for Electronic Whiteboard

9.0 Popular Antenna Types

Ceramic chip antennas (Mitsubishi, gigaAnt) are the most popular types being used in Bluetooth products. These cost about 40 cents/unit.
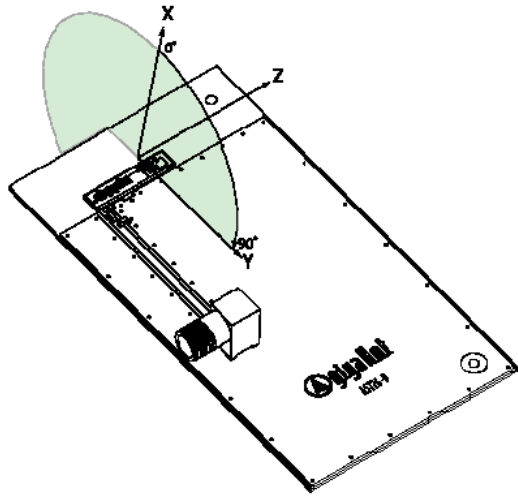

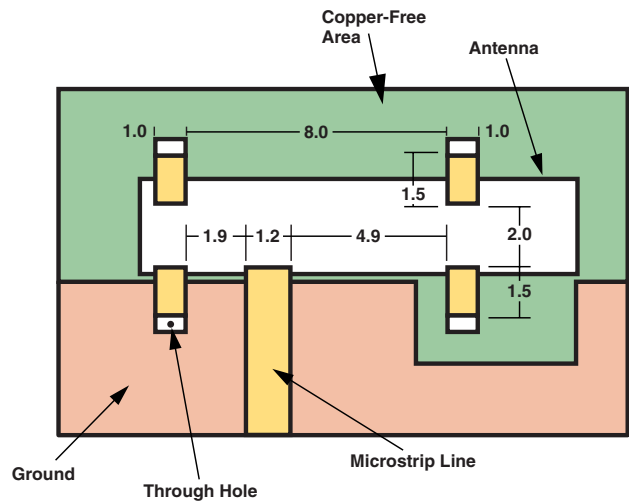**Figure 36. gigaAnt Rufa 2.4 GHz SMD Antenna**

Figure 37. Mitsubishi AHD1403 Surface-Mount Antenna

The second most popular type is the PIFA. These have the lowest cost because they consist of a PCB trace, but are larger and more design-intensive.

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