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THE INVESTIGATION OF EMBEDDED SYSTEM ELECTROMAGNETIC RADIATION BY USING AUTOMATIC NEAR-FIELD MEASUREMENTS

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ABSTRACT

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Electromagnetic interference (EMI) is increasingly becoming a major topic of concern in the electronic world. In the meanwhile, equipment designers need to do more with electromagnetic incompatibility than just make the systems operate. Electronic devices must be implemented to work in the real world without polluting the environment and to make standardized tests to comply with government electromagnetic compatibility regulations. Hence, the major design objective should be electromagnetic compatibility. The main purpose of this thesis is to investigate electromagnetic interference of different embedded system by using near-field probes.

The main equipment used are an EMC scanner and an anechoic chamber (Bilog antenna) for measuring the EMI of different self-made loop antennas. This thesis aims to show how the electronic products easily break the limit level if there are some design faults. The main attention is to design a loop antenna and measure it with far-field and near-field probes and to investigate electromagnetic radiation at a certain point and frequency.

The test is completed in far-field in which it is very difficult for the designers to spot the origin of interference. Comparatively, near-field measurements spot the radiation area. The near-field probes are used to complete the measurements in near-field which are very small in size. To get a specific result, smaller probes were used, since they locate a particular source of RF fields. According to the measurement results of this thesis, the near-field probe is the more efficient way of finding the interference.

Keywords: Electromagnetic Interference, EMC Scanner, Near-Field Probes

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ABBREVIATIONS AND SYMBOLS

Abbreviations

dB	Decibel
EMC	Electromagnetic compatibility
EMI	Electromagnetic interference
EMP	Electromagnetic pulse
EMR	Electromagnetic radiation
ESD	Electrostatic discharge
IC	Integrated circuit
miniVNA	mini VECTOR NETWORK ANALYSER
MKS	Meter Kilogram Second
PC	Personal Computer
PCB	Printed Circuit Board
RF	Radio Frequency

Symbols

A	Area (m^2)
c	Speed of light (m/s)
E	Electric field (V/m)
f	Frequency (1/s)
I_{cm}	Common mode current (A)
I_{dm}	Differential mode current (A)
mm	millimeter
r	Radius (m)
V	Voltage
V_{cm}	Common mode Voltage (V)
%	Percentage

Greek

θ	Angle
π	Pi

λ   Wavelength (m)

1 INTRODUCTION

The introduction is divided into three parts: purpose of the thesis, overview structure of the thesis and methodology.

1.1 Purpose of the Thesis

The purpose of this thesis is to investigate embedded system electromagnetic radiation by using automatic near-field measurements. Near-field are areas of the electromagnetic field around an object. The near-field measurements are made of a small antenna, which are cheap and with them it is simple to investigate electromagnetic radiation. Probes are connected to a spectrum analyzer for frequency-domain measurement. This provides a fast and accurate method for determining radiation source.

The advantage of near-field is that the measurements are completed indoor without any external problems of electromagnetic disturbance, climate condition and safety issues. The near-field measurements provide a complete characterization of radiation source.

1.2 Methodology

During this project, the following tools and methods were used to collect and generate the data:

- PADS Logic: A program to design a schematic of the PCB
- PADS Layout: A program used for component pin design of the PCB
- Anechoic chamber: A room which has an absorber in its wall, ceiling and floor to absorb the incident energy that is simulate in free space.
- EMC Scanner Model RSE321: This machine is used to investigate electromagnetic radiation from the PCB by using near field probes.
- A room where Electronic Printed Circuit Board is Manufactured
- EMC Room: used to investigate electromagnetic radiation from the PCB in far field by using BILOG antenna.

1.3 Overview Structure of Thesis

This thesis consists of eight separate tasks which started with an introduction about the purpose, overall structure of the thesis and methodology. Afterwards, chapter 2 and chapter 3 include the theory of the thesis. Chapter 2 contains electromagnetic compatibility which explains about the aspects, history of the thesis as well as the importance of electromagnetic compatibility. Then, chapter 3 includes electromagnetic radiation which describes about the electromagnetic spectrum, digital circuit radiation and PCB. Digital circuit radiation consists of two parts with the description of differential mode radiation and common mode radiation. The fourth chapter illustrates the practical part of the thesis with near field measurements by EMC scanner. It gives a short description about the EMC scanner and anechoic chamber in which the measurements are completed. Likewise, the fifth chapter gives an introduction to how to implement a PCB board. Moreover, chapter six contains the testing and result of the project. And finally, chapter seven includes a conclusion of the thesis.

2   ELECTROMAGNETIC COMPATIBILITY

EMC provides an ability for an electronic product to work compatibly with its environment without any interferences. EMC deals with the problems of electronic devices which generate electromagnetic disturbances. Communication, computation, automation and other purposes make the widespread use of electronic circuits necessary for various circuits to function in close proximity to each other and these circuits often affect each other adversely. (EMI) Electromagnetic interference has become a major problem for circuit designers. The large number of electronic devices in common use is partly responsible for this trend. The use of integrated circuits and large scale integration has reduced the size of electronic equipment. /14, 3/

An electronic system which can function compatibly with other electronic systems and do not produce or is susceptible to interference is known to be electromagnetically compatible with its environment. If a system satisfies the following three criteria, then it is electromagnetically compatible:

- If a system does not cause interference with other systems.
- If a system does not cause interference with itself.
- If a system is not susceptible to emissions from other systems.

Also, the device must meet legal requirements in all countries of the world before it is placed on the market. /15, 2/

2.1   Aspects of EMC

There are three aspects of EMC: generation, transmission and reception of electromagnetic energy. The basic framework of EMC design is shown in Figure 1 below:
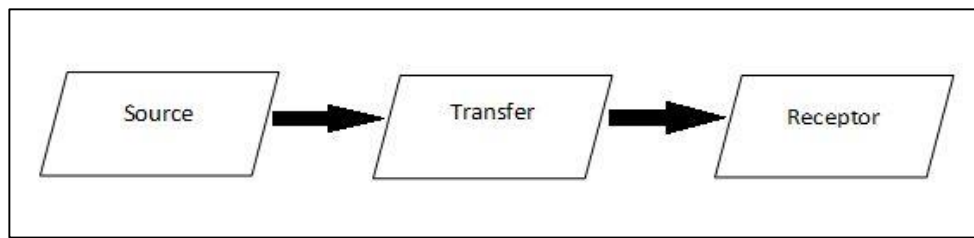
Figure 1. EMC coupling problem /15/

In Figure 1, it is illustrated that a source produces emission and a transfer transfers the emission energy to a receptor where it is processed resulting in either wanted or unwanted manners. Here, if the receptor acts in an unwanted manner, then interference occurs and with unplanned coupling modes, transfer of electromagnetic energy occurs. Unwanted manner of the receptor establishes interference. So, the processing of received energy by the receptor decides whether there will be interference. But it is difficult to determine that a signal incident on a receptor will cause interference in that receptor. It is clear that the source or receptor may act in an intended manner or unintended manner and also may behave in both manners. This depends on the transferring path as well as the type of source or receptor. There are three ways to prevent interference which should be considered while solving the EMC problems:

- If the emission is suppressed at its source.
- If the transferring path is as inefficient as possible.
- If the receptor is less susceptible to the emission. /15, 3-4/

Some other aspects of EMC are: electrostatic discharge (ESD), electromagnetic pulse (EMP), lightning, TEMPEST.

While walking across a nylon carpet, rubber-soled shoes can cause a buildup of static charge on the body. Likewise, if an electronic device, such as a keyboard is touched, then static charge may be transferred to the device, and an arc is created between the finger tips and the device. This may cause permanent destruction of the device such as integrated circuit chips which can result in system malfunction. This is called ESD. /15, 7/

After the first nuclear detonation in the mid-1940s, it was found that the semiconductor devices in the electronic systems, which were used to monitor the effects of the blast were destroyed and that was caused by an intense electromagnetic wave created by the charge separation and movement within the detonation. This results, bad communication and data processing facilities in military communities which is against the effect of EMP. /15, 7/

Lightning is also an aspects of EMC. Lightning occurs frequently and it affects the electronic systems. During lightning, the lightning channel carries more than 50,000 ampere of current which can combine to electronic systems either by direct radiation or by combining to the commercial power system and then conducted into the device via ac power cord. /15, 7-8/

It is challenging for the military to get rid of the problem called TEMPEST. Electronic devices such as monitors and other machines emit electromagnetic radiation during normal use but with the help of correct tools such as antennas and receiver, one can intercept those emissions from faraway location and then replay the information that was captured. This is how TEMPEST works. It is possible to determine what is being typed on an electronic device by monitoring its electromagnetic emissions. There are also other cases of direct interference of radiated emissions from which the content of the communications or data can be determined. These are some of the problems related to EMC but there are also several different problems where only the context of the problem changes. /15, 9/

2.2 History of EMC

In the late 1800s and 1901, Marconi demonstrated his experiment for interference and its correction. He provided the first transatlantic transmission using an array of copper wires and at that time the only receptors of significance were radio receivers which were few and widely separated, so that the correction of an interference problem was comparatively simple. Around 1920, radio interference began to appear in various technical journals and the radio receivers and antennas were somewhat simple and prone to interference either from external sources or from inside as with

self-induced oscillations. And around 1930, this radio interference appear as a major problem from electrical device like electric motors, railroads and signs.

During World War II, electronics devices such as radios, navigation devices and radar are mostly used which results interference on aircraft. During that time, the density of the electronics was less than it is today, so these EMI problems can be easily corrected by moving cables away from noise emission sources. Still, the interference problem increased with the inventions of high-density electronic components such as bipolar transistor in 1950s, the integrated circuit (IC) in 1960s and the microprocessor chip in 1970s.

In the early 1960s vacuum tubes were used as switching elements in digital computers which required more power consumption. In the 1970s IC, integrated circuits allowed to construct computers which required less power and physical space but towards the end of the 1970s analog signal processing were started to be replaced by digital signal processing which meant that the density of electronics was increasing rapidly. As a result, EMI problems began to increase. /15, 10-11/

By the early 1995, the UK Department of Health had issued guidelines where the use of cordless, cellular and mobile phones were banned within certain areas in hospitals due to their electromagnetic field, which interfere with medical equipment and life-support machines. The Department of Health was forced to issue the guidelines after a number of reported cases, where medical equipment has been reset or stopped working, caused by the interferences from cellular phones. /8/

2.3 Why electromagnetic compatibility is important?

EMI is a very serious environmental pollution which affects minor to major ranges of electronic systems. EMI causes electrical and electronic malfunctions, can avoid the proper use of radio frequency spectrum, can produce flammable or other hazardous atmospheres, and may even have a direct effects on human tissue. The danger of EMI is controlled by accepting the practices of EMC. EMC helps equipment or a system to be self-compatible and be capable of tolerating a specified degree of interference. It helps not to generate more than its requirement. Due to these EMI problems, EMC is becoming more important. /6, 20, 11-14/

3 ELECTROMAGNETIC RADIATION

This chapter describes the electromagnetic radiation and digital circuit radiation which explains about the different modes of radiations in electrical and electronic devices.

3.1 Electromagnetic radiation

In order to understand about the effects of electromagnetic disturbance, the familiarity with the concept of electromagnetic radiation (EMR) is needed. EMR is a wave which travels by oscillating electric and magnetic disturbance. The electric and magnetic fields are perpendicular to each other and the combined wave moves right angle to both electric and magnetic oscillating fields. The distance of these oscillations is defined as wavelength (λ). The number of oscillations per second is called frequency (f). These two concepts can be better observed in Figure 2.
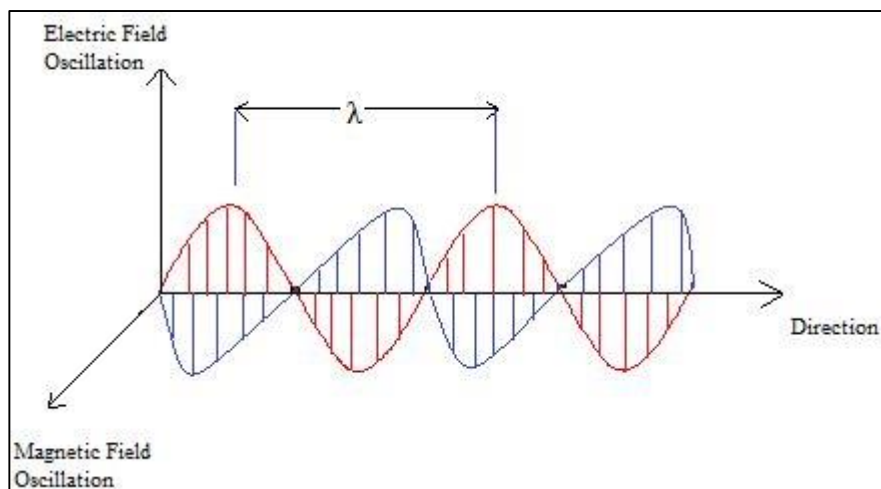
Figure 2. Electromagnetic Wave /3/

Some general properties of all electromagnetic radiation:

- Other types of waves such as sound need a medium to travel through but EMR can travel through an empty space.
- The speed of light (c) is always a constant. (c: 2.99792458×10^8 m/s)
- Wavelengths are measured between the distances of oscillation which is usually denoted as λ.

In general, wavelength and frequency are closely related to each other. As a wave's wavelength increases, the frequency decreases and vice versa. "*When the energy level increases, the electromagnetic energy is released. As a result, the energy level increases and wavelength and frequency decrease. Electromagnetic energy travels in waves. Therefore, electromagnetic radiation is grouped into categories based on its wavelength or frequency into the electromagnetic spectrum.*" The human eye can detect EMR with a frequency between 790 terahertz (400 nanometer) and 400 terahertz (700 nanometer) as a visible light. Figure 3 shows the different classifications of EMR in electromagnetic spectrum such as: radio waves, microwave, infrared waves, ultraviolet radiation, visible lights, X-rays and gamma rays. The spectrum of frequencies of EMR spreads from very low values over the range of radio waves, television waves and microwaves to visible light and beyond to the extensively higher values of ultraviolet light, x rays and gamma rays.
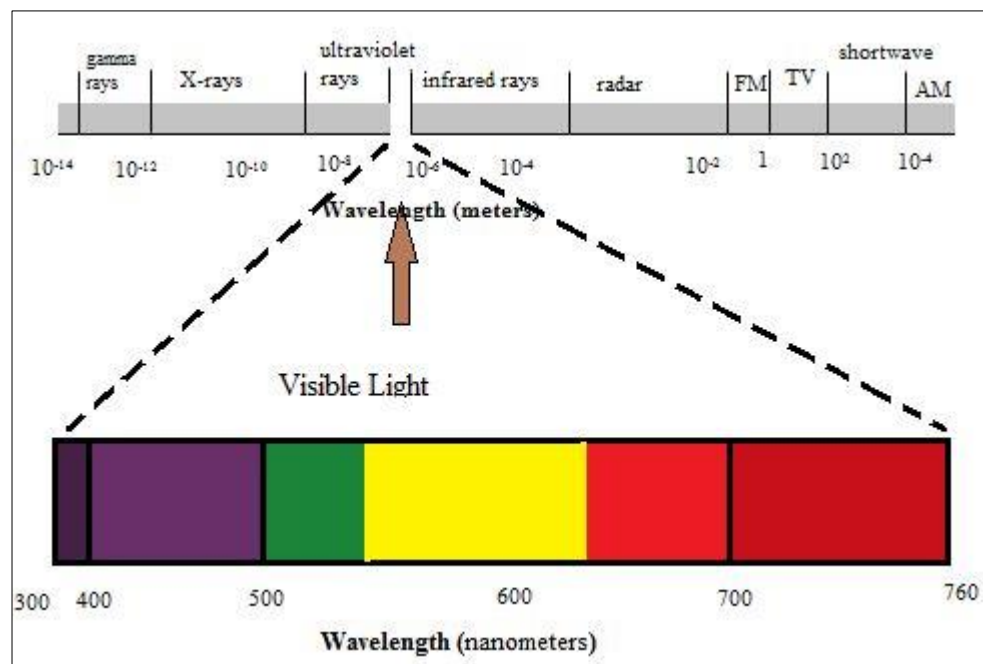
Figure 3. Electromagnetic Spectrum /11/

Electromagnetic spectrum refers to the complete distribution of EMR according to the frequency or wavelength. All electromagnetic waves travel with the same velocity in a vacuum at the speed of light which is 2.99792458×10^8 meters per second. The complete distribution covers a wide range of frequencies and wavelengths

and it consists of many sub ranges which are differently named based on their differences in behavior in emission, transmission and absorption and this commonly referred to electromagnetic spectrum. The entire electromagnetic spectrum includes all waves from the lowest to the highest frequency. /3/

In 1865 James Clerk Maxwell introduced that light is a wave with both electric and magnetic components. So, it is a form of electromagnetic radiation. When light is focused on a prism, then the light rays with different wavelengths bent by different amounts and it is changed into band or spectrum of different colors. Only a small portion of the total electromagnetic spectrum can be seen by human eyes. Electromagnetic radiation which has a high frequency has a short wavelength and with a low frequency has a long wavelength. /17, 74-75/

3.2 Digital Circuit Radiation

It is difficult and complicated to design a complex digital logic as it is more complicated to control the emission from it. It is very important to meet the required tests such as EMC test in bringing electronic products to the market. From the start, emission control should be treated as a design problem and it should receive the necessary engineering resources throughout the design process. This topic represents the radiated emission and outlines the parameters on which radiation depends and also gives a method to figure out the radiated emissions as a function of the electrical characteristics of the signals and the physical characteristics of the system. And, after finding the parameter which affect radiation, it is easier to minimize the emissions and to develop new techniques. /13, 464-465/

There are two types of radiations which occur in digital electronics: differential mode or common mode. Differential mode radiation proceeds from current flowing around loops made by the conductors of the circuit which is normal process of the circuit and these loops perform like a small loop antenna that radiate magnetic fields predominately. During the design process, the loop size and area should be controlled to decrease the radiation. Differential mode radiation is easier to control than common mode radiation. /13, 464-465/

Common mode radiation takes place due to the undesired voltage losses in the conductors and it is the result of unwanted inductance, capacitance and resistance in the circuit. It is generated by wires or I/O cables. These I/O cables radiated electric fields. During the design process, it is necessary to provide methods for controlling the common mode emission problem. Because of these reasons, common mode radiation is more difficult to understand and control. /13, 464-465/

3.2.1 Differential mode radiation

In most electronic products, the fundamental sources are currents flowing in the circuits (oscillators or impulsive sources, buses like high speed serial data bus) that are attached on a PCBs. Like in Figure 4, some of the energy is radiated from the PCB, which can be showed as a small loop antenna carrying the disturbance current. Differential mode radiations are connected from the power supply to the low frequency switching noise. /19, 235-239/
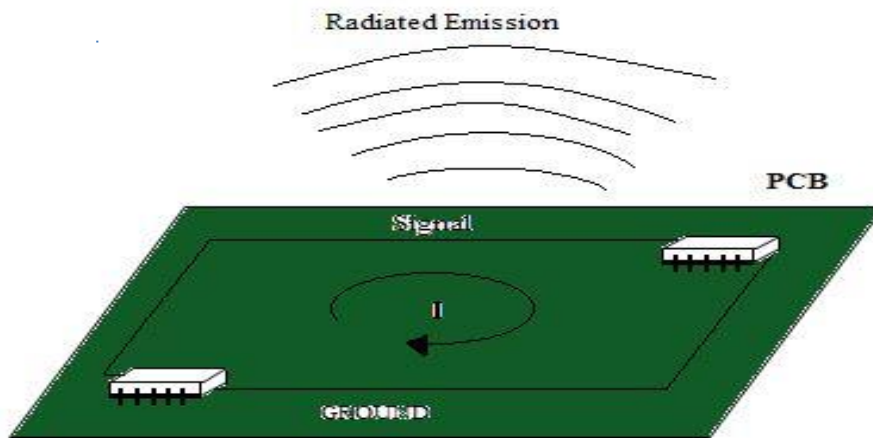
Figure 4. PCB with Differential mode radiation /19, 235/

Differential mode radiation can be displayed as a small loop antenna which is embedded in a PCB. So, for the small loop antenna in far field, the magnitude of the electric field (E) can be measured in free space at distance r with area A, carrying current I_{dm} equal to

$$E = 131.6 \times 10^{-16} (f^2 A I_{dm}) \left(\frac{I}{r}\right) \sin \theta, \qquad \text{Equation 1}$$

Where E is in V/m, f is in Hz, A is in square meters, I_{dm} is in amperes, r is in meters and θ is the angle between the observation point and a perpendicular to the plane of the loop. In a small loop, the current is all over in phase where the perimeter is less than one quarter wavelength $\left(\frac{1}{\lambda}\right)$ but for larger loops, the current is not all in phase so from the total emission, instead of adding some current it may be subtracted. /13, 465-466/

In the free space, a small loop antenna pattern is a torus (doughnut shape) as shown in Figure 5. From the sides of the loop, there is maximum radiation which then results in the plane of the loop and no radiation occurs in the direction perpendicular to the plane of the loop. A receiving antenna will detect the maximum emission which is in the same direction to the plane of the loop. /13, 466/
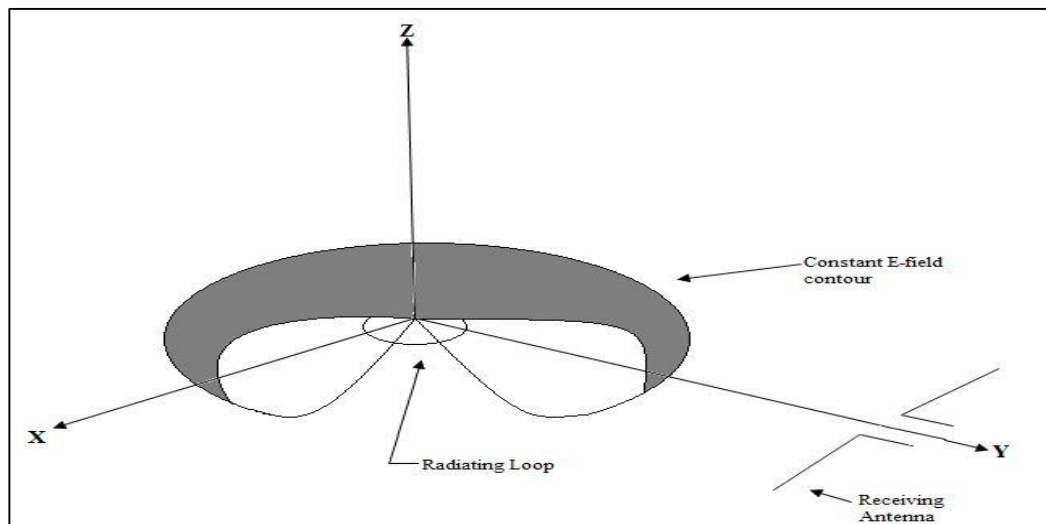
Figure 5. A small loop antenna radiation pattern in free-space. /13, 466/

Whenever the loop perimeter rises more than one quarter wavelength and becomes equal to wavelength, then radiation pattern rotates by 90°, so that the maximum radiation occurs perpendicular to the plane of the loop. As a result, for a large loop antenna, maximum radiation occurs perpendicular to the plane of the loop as shown in Figure 5, whereas for a small loop antenna, maximum radiation occurs in the plane of the loop. The above Equation 1 can be also applied to any planar loop although it was derived for a circular loop. The magnitude and radiation pattern is not responsive to the shape of the loop but it always depend on its area. So, there is

an equal amount of radiation in all small loops having same area even though their shape differs. /13, 466-467/

The first term of Equation 1 is a constant which handles the properties of the media (free space). The second term explains the characteristics of the loop (radiation source). The third term characterizes the decay of the field as it moves away from the source. And finally, the last term is the angle off which accounts for the angular orientation of the measuring point regarding a perpendicular to the plane of the loop. /13, 467/

However, most EMC radiation measurements from electronic products are made in an open area with a ground plane, which provides a reflective surface. But Equation 1 is applied only for a small loop with no reflecting surfaces which is situated in free space. This reflective ground plane can rise up the measured emission as much as 6 dB so Equation 1 must be multiplied by 6 dB. And, for correcting the ground reflection in an open area, it is assumed that the observation is made at a distance r in the plane of the loop ($\theta = 90°$), thus Equation 1 can be rewritten as

$$E = 263 \times 10^{-16}(f^2 A I_{dm})\left(\frac{1}{r}\right), \qquad \text{Equation 2}$$

Here, the maximum electric field radiation vary with the current level I_{dm}, the loop area A, and the square of the frequency f.

And for a 3 meter measuring distance r, Equation 2 can be rewritten as

$$E = 87.6 \times 10^{-16}(f^2 A I_{dm}), \qquad \text{Equation 3}$$

In summary, differential mode emission can be controlled. /13, 467/

Some of the primary ways to control differential mode radiation are as follows:

Reduce Loop Area
To design a systems that meet legal requirements for radiated emission, loop areas must be kept very small. Reducing the loop area should be done early in the design to minimize the area surrounded by current flow in which signal leads and their

associated ground-return leads close together. In such conditions, Equation 2 can be used for predicting the radiated emission. /13, 468/

Reduce Current Level

To find the radiation, it is necessary to known the current but the current is rarely known accurately, therefore it must be measured or estimated. The current depends on the load impedance of the circuit that terminates the loop and also the source impedance of the circuit that drives the loop. Loop current can be measured with a wide-brand current probe which may require cutting the signal trace and adding a long wire in series with the trace, just to clip the current probe. /13, 468/
Beside these above process, there are also some other techniques for reducing the differential mode radiation from a product.

Board Layout

Differential mode emission can be controlled with the layout of the PCB. When laying out a PCB to control radiation, it is necessary to minimize the loop areas formed by the signal traces. It is very difficult to control the area of the loops made by all the signal and transient power supply currents. Those loops with highest frequency and where the signal is periodic (that is, it has the same wave shape all the time) must be investigated individually which are called critical loops but other noncritical loops can be controlled by using good PCB layout practices. In this case, periodicity is very important. A loop of a certain area can radiate so much energy if it carries a certain amount of current and if all that energy is at one frequency then the amplitude will be high at each frequency but if the energy is spread over the frequency spectrum then the energy at any one frequency will be much lower. Due to the highest frequency signal in a system, the clock is periodic and most of its energy is concentrated in a few narrow frequency bands which consist of the fundamental plus the lower order odd harmonics. Hence, the amplitude at each of these frequencies will be large. /13, 472/
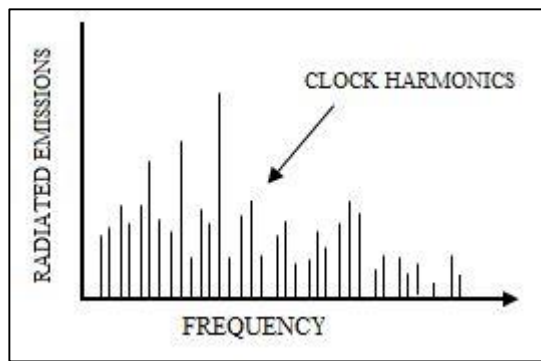
Figure 6. A digital circuit radiation emission spectrum with all circuits operational. /13, 472/
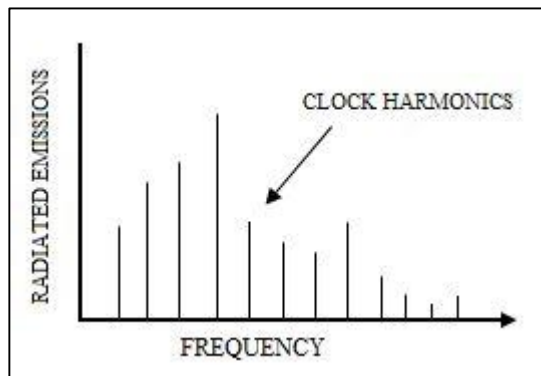
Figure 7. A digital circuit radiation emission spectrum with only clock circuit operational. /13, 472/

In both figure 6 and 7, the emission from the clock harmonics go above than emissions from other circuits and the maximum radiation is about the same.

To produce the complete smallest loop area on a PCB, clock signals should be routed and also the length of the clock trace and number of vias should be minimized. Likewise for multilayer PCB, clocks should be routed on a layer adjacent to a solid ground plane as well as space between the clock trace layer and the return plane should be very small. For double-sided boards, clock traces should have adjacent ground return traces. /13, 472/

Canceling Loops
Another way to reduce the differential mode radiation is to design two loops which cancel each other.
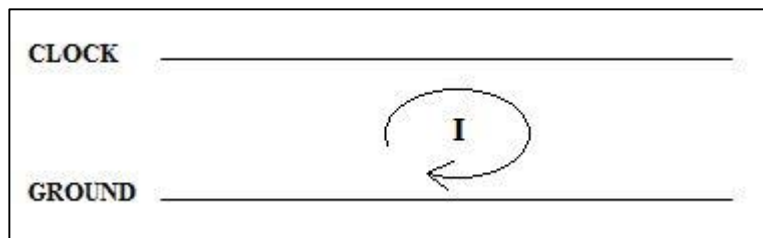
Figure 8. Clock trace with a single ground return trace. /13, 474/

In the above figure 8, above the radiation from the loop will be a function of the area and the current of the loop. If this is only the way to print the traces closest to each other, then it is difficult to reduce the emission outside that point from PCB. /13, 474/
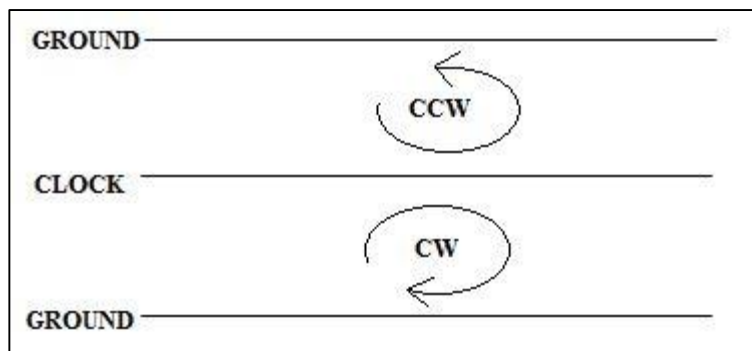
Figure 9. Clock trace with a two ground return trace. /13, 474/

In figure 9, there are two ground return traces in each sides of a clock trace and two similar loops with same area are also located in both sides. If the two ground traces are placed with respect to the clock trace, at that point the return current will be divided among the two paths. As a result, the lower loop shown in figure 9 will have half as much current as the loop in figure 8 and it will radiate 6 dB less. On the other hand, the upper loop will also radiate slightly much than lower loop but the current in the upper loop is anticlockwise, whereas the current in the lower loop is clockwise. So rather adding the radiation from the upper loop and lower loop, it cancels. Therefore, figure 9 layout will radiate 20 dB less than that of figure 8. /13, 474/

Dithered Clocks

The other process to reduce the radiation from the PCB is to spread the emission which can be done by means of dithered or spread-spectrum clock. In this process, the amplitude of the radiation at any one frequency will be reduced and frequency will control the clock. At a low frequency rate, clock dithering purposely differs the clock frequency by a small amount and as a result of that, the clock energy spreads out in the frequency domain and lowers the peak amplitude of the emission at any single frequency. The emission can be reduced about 10 to 14 dB range if optimum design is used and if the fundamental frequency is shifted by 100 KHz, then the frequency of the second harmonics shifts by 200 KHz and it will shift in ascending order. The degree of reduction is a function of the dithering wave shape along with the frequency deviation. As shown in figure 10, the optimum modulating waveform is a special waveform which is referred as "Hershey Kiss" which is patented by Lexmark (Hardin, 1997).

The "Hershey Kiss" is similar as triangular wave except the triangular modulating waveform produces few dB less than the "Hershey Kiss".
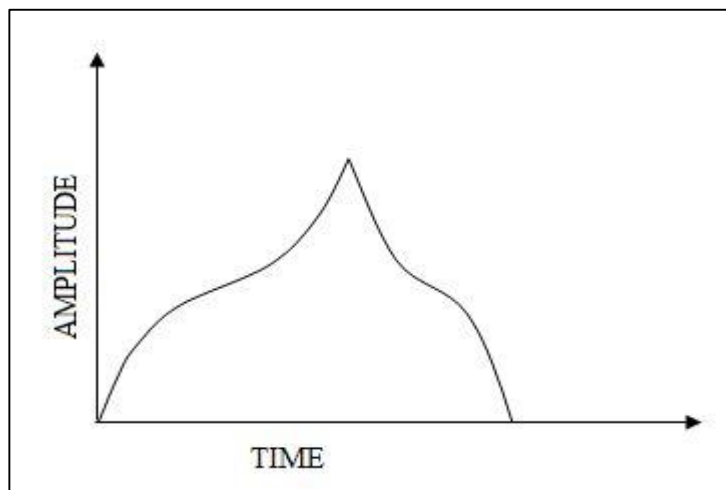

Figure 10. The optimum modulating waveform for a spread-spectrum clock /13, 475/

The terms of a typical spread-spectrum clock might read as:

- Modulation waveform: Triangular
- Modulation frequency: 35 kHz
- Frequency deviation: 0.6%

- Modulation direction: Downward

- Emission reduction: 12 dB

Most of the systems like personal computers and printers can accept a spread-spectrum clock and most phase locked loops also works fine with it but few systems cannot and also if absolute real time accuracy is needed then, there may be a problem. /13, 475-476/

Center spread and downward spread are two methods which used dithered clock technique. In center spread method, the clock is spread both above and below its uncontrolled frequency and in downward spread method, the clock is spread only below from its normal frequency. In both approaches, the reduction in radiation is the same but the benefit of downward spread is that since the clock frequency is not increased, it is less likely to cause timing margin problems. /13, 476/

Reducing loop area and canceling loops techniques only reduced the differential mode emission but it has no effect on common mode radiation which may be caused by the same clock. However, dithering clock frequency technique changes the characteristics of the clock of the radiation and it reduces emission in both differential and common modes. Therefore, a dithered clock provides significant control by decreasing all the radiation modes related with dithered clock signal. /13, 476/

3.2.2   Common mode radiation

Common mode radiation is difficult to control and controls the overall emission performance of a system regularly. Radiation from system cables or I/O cables is the most common form of common mode radiation as shown in figure 11. The emitted frequencies are determined usually by the ground voltage. The cable should be connected to the system and situated to the system ground. /13, 477/
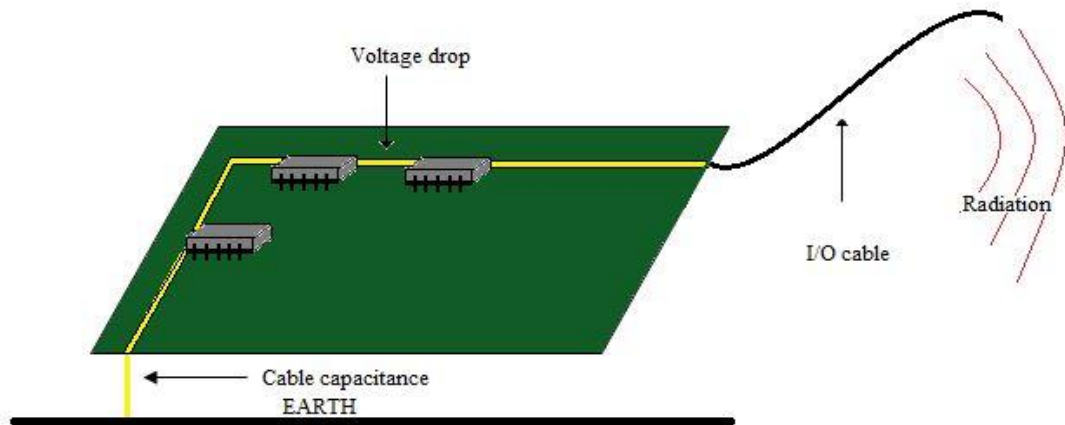
Figure 11. PCB with Common mode radiation /19, 238/

In common mode radiation, the current I_{CM} flows along all cable conductor in the same direction equally and together with the shield. /19, 238/

Common mode radiation can be showed as a dipole or monopole antennas which is driven by the ground voltage. In the far field, magnitude of the electric field strength is measured for a short dipole antenna of length l, at a distance r from the source as

$$E = \frac{4\pi \times 10^{-7}(flI_{CM})\sin\theta}{r} \qquad \text{Equation 4}$$

Where E is in V/m, f is in Hz, I_{CM} is the common mode current on the antenna in amperes, I and r are in meters, and θ is the observation (angle) made from the axis of the antenna and the maximum electrical field strength will be perpendicular to the axis of the antenna where $\theta = 90°$. /13, 477/

For a real dipole antenna, the current drives to zero at the open ends of the wire and for a small antenna, the distribution of current is right through the length of the wire therefore, the average current on the antenna is only one half the maximum current. But, in the case of an ideal dipole antenna the above equation 4 is only valid because the distribution current is uniform.

In case, the observation is made at a distance r perpendicular to the axis of the antenna where $\theta = 90°$ then, using $\sin 90°$ and pi value, equation 4 can be rewritten as

$$E = \frac{12.6 \times 10^{-7}(fl I_{CM})}{r}$$
<div align="right">Equation 5</div>

Here, the common mode radiated emission is proportional to the frequency, the length of the cable and the common mode current of the cable. Therefore, the primary method to control radiation is to limit the common mode current which does not take part for the normal process of the circuit.

The common mode radiation or dipole antenna radiation can be control by the following methods:

- If the magnitude of the common mode current is reduced.
- If the frequency or harmonic content of the current is reduced.
- If the antenna length is reduced.

/13, 477-478/

3.3 PCB

PCB supports and connects electronic devices using a type of material that allows electrical current to flow. It consists of two basic parts: the board and copper traces. It is laminated with copper sheets and can be single sided, double sided or multilayer. In PCB design, conductors on different layers are connected with vias (plated-through holes). /9, 2/

For the measurement, five PCB boards are implemented and would be used in final project.

4 NEAR FIELD MEASUREMENTS BY USING EMC SCANNER

4.1 EMC Scanner Introduction

In today's world, most of the electronic components have high frequency electromagnetic fields, and there is high demand for electromagnetic compatibility of electronic products, but it is a problem to find the exact location of a radiating source for the designers.

Detectus AB, a Swedish company which was founded in 1994 has developed several measuring systems with which the designer can measure the intensity and the location of a radiation source at a component level and one of them is EMC scanner in which the measurement can be shown as two or three dimensional colored maps.

Figure 12. EMC SCANNER RSE321

EMC scanner measures the emission from electronic components, PCB's, cables, and products. It is the machine which is designed to take RF image of the electronic components which are pattern in a circuit board (PCB) and able to characterize the emission at various height over the PCB in electronic industry. It is a unique device which consists of an X-Y-Z plane, it is connected to the spectrum analyzer with near field probe and a standard PC with custom software. Spectrum analyzer measures the magnitude of an input signal as a function of frequency. This software runs in Windows operating system and is intuitive and user-friendly. This machine investigates the electromagnetic emission coming from the PCB or electronic product and addresses them so that it could be reduced easily. EMR can be inspected by the colors and dB scale. During the measurement the near field probe is moved to a grid of measuring points above the test object.

The advantage of EMC scanner is that it combines RF image over the object and the user can control the step size that are going to be taken as well as the near field probe is fixed to the EMC scanner. At each measuring point, the location of the probe (step size) and the value of the emission intensity is stored in the computer which is connected to the EMC scanner. And the step size is going to the spectrum analyzer which helps to find out noisy side of IC and also characterize traces that have lots of RF energy so that it is easier to select the correct IC. It can identify the potential emission problems in the early design phase. With the help of EMC scanner, anyone can make a measurement and draw conclusions from the informative and easily interpreted reports. It saves time and money by reducing the need for expensive and time consuming full scale measurement. /5/

In order to find the EMI emission source it is necessary to make a measurement closer to the circuit if it is failing to investigate and fixed to lower the device emission. For this, near field probes are used around the PCB board or electronics devices. Near field probes use a conductive loop to identify the magnetic fields produced by the devices. For the measurement, RF-B 0, 3-3 near field probe is used. It has a limited frequency between 30 MHz to 3 GHz. The magnetic field enters the probe point perpendicularly so it is easily detected. It is appropriate for pin-point detection of RF magnetic fields radiated by surfaces. /4, 5/

4.2   Practical measurements in full anechoic chamber

Figure 13 shows the radio frequency anechoic chamber. It is a shielded room which provides a simulated free-field environments for the testing of electronic devices. The walls, ceiling and floor of the room are lined with absorber which absorbs or distribute incident energy that can simulate free space. /1, 18/

Figure 13. RF Anechoic chamber

In far field measurements, dipole antennas (Bilog) which have a limited frequency range between 30 MHz to 1 GHz are recommended. /9, 150-151/

For the testing of PCB, it is good to have EMI source. Figure 14 shows a circuit diagram of an EMI source. The system uses +9 V DC batteries and U1 is voltage regulator which provides 5 V input voltage to the oscillator. The transistor-transistor logic (TTL) oscillator has 10 MHz square wave output and the type used was XO91 Series oscillator.
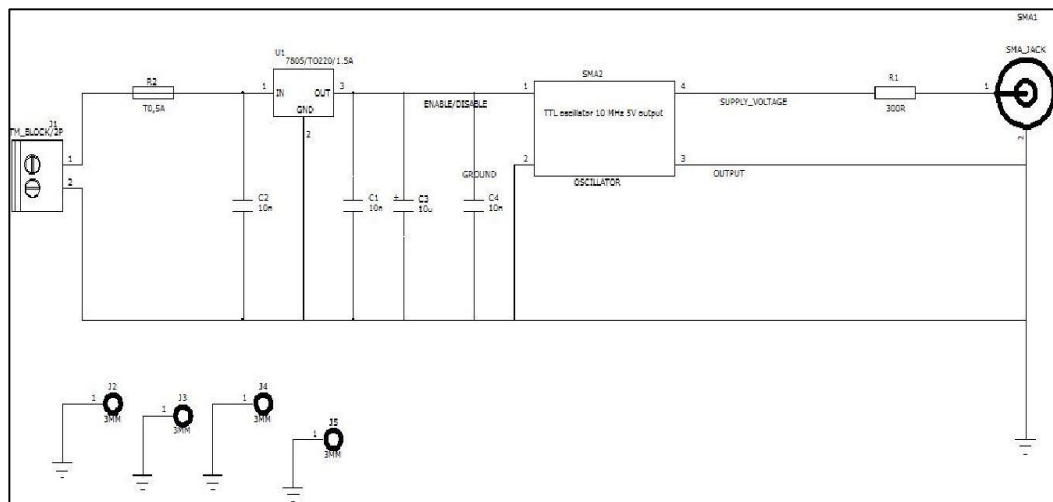
Figure 14. Circuit diagram of an EMI source

This EMI source was assembled to the aluminum box as shown in Figure 15. For the measurement self-made PCB board were placed in the anechoic chamber connected with the EMI source.

Figure 15. Assembled EMI source

4.2.1 Printed circuit board with ground plane

According to Faraday's law, a loop is simply a coil of wire which produces voltage at its terminals proportional to frequency. It is closed circuit antenna where the antenna is made right on the PCB board. A closed loop antenna can be rectangular or round and it is a simplest type of antenna where the copper is connected to the transmitter's or receiver's antenna terminals. Overall, it works more effectively, if

the circumference is great (the larger the loop = more efficient). If the loop terminal is opened, then it is no longer a loop (open loop antenna). There is no change in the direction of current flow but the maximum current flows in the end. /7/

Loops with ground plane reduces electrical disturbance and interference. It decreases crosstalk between adjacent traces. Crosstalk is an undesired capacitive or inductive coupling from one circuit to another.

Adding a ground plane is an effective change for improving EMC since a ground plane provides a low inductance ground path if only it is positioned over the tracks which need low inductance return. At the high frequencies, return current especially flow in the region of its signal trace instead of taking the geometrically shortest return path. It happens if such a route encloses the minimum area and therefore has the lowest overall inductance. In summary, ground plane allows the circuit to achieve minimum inductive loop area by its own devices ensuring the optimum return path to be always available. /19, 203-204/

Figure 16. Self-made PCB (closed loop antenna with ground plane)

Figure 16 shows self-made closed loop antenna with ground plane. The loop diameter is 114 mm.

Figure 17 contains the real measurement arrangement in far-field. The PCB board was connected to the EMI source where EMI source was set "ON" and placed in the table straight to the Bilog antenna for the measurement.

Figure 17. PCB connected to EMI source inside anechoic chamber

Figure 18 shows the measurement of closed loop antenna with ground plane (PCB) inside the anechoic chamber. At frequency range 30 MHz to 230 MHz the limit line equals 35 dBµV/m (because measurement in full anechoic chamber is three meters distance) and frequency range 230 MHz to 1 GHz, the limit line equals 42 dBµV/m and it can be seen that radiation is high at 330 MHz frequency. The electric field magnitude at that frequency is 65 dBµV/m. The numeric results are shown in Table 1.
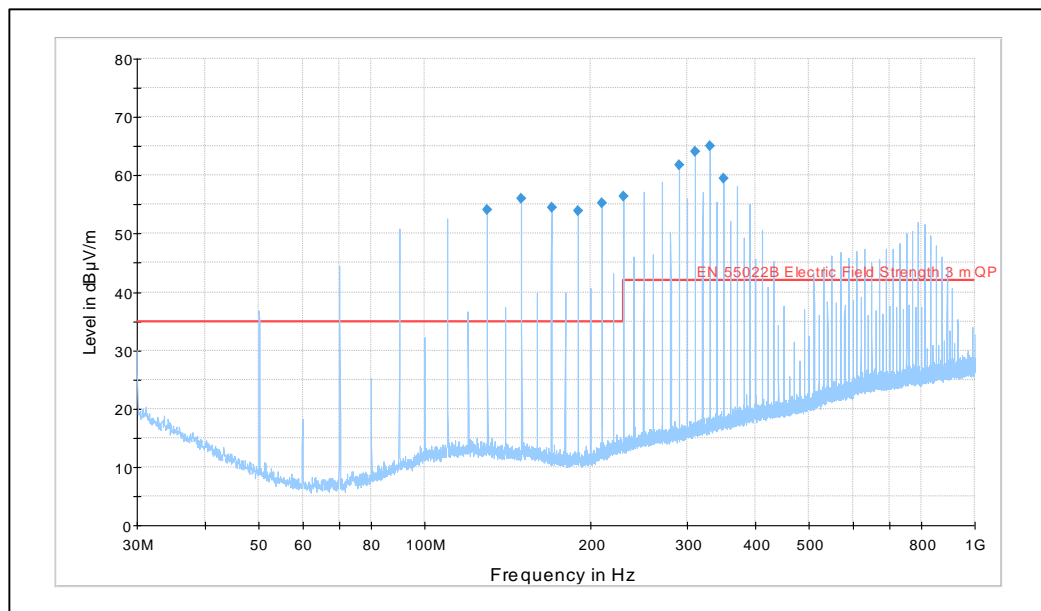
Figure 18. Results for closed loop antenna with ground plane

Table 1 contains the result of measured frequency [MHz], Quasipeak values [dBµV/m], measurement time [ms], bandwidth [KHz], antenna height [cm], antenna polarization, turnble position [degree], antenna correction factor [dB], margin [dB] which is calculated as Limit − Quasipeak = Margin.

The highest electric field magnitude is 65 dBµV/m at frequency level 330 MHz.

Frequency (MHz)	QuasiPeak (dBμV/m)	Meas. Time (ms)	Bandwidth (kHz)	Antenna height (cm)	Polarity	Turntable position (deg)	Corr. (dB)	Margin (dB)	Limit (dBμV/m)
130.020000	54.2	1000.000	120.000	155.0	V	0.0	11.6	-19.2	35.0
150.000000	56.0	1000.000	120.000	155.0	V	0.0	10.8	-21.0	35.0
169.980000	54.5	1000.000	120.000	155.0	V	0.0	9.7	-19.5	35.0
190.020000	54.0	1000.000	120.000	155.0	V	0.0	9.4	-19.0	35.0
210.000000	55.3	1000.000	120.000	155.0	V	0.0	10.3	-20.3	35.0
229.980000	56.4	1000.000	120.000	155.0	V	0.0	11.6	-21.4	35.0
289.980000	61.7	1000.000	120.000	155.0	V	0.0	13.9	-19.7	42.0
310.020000	64.2	1000.000	120.000	155.0	V	0.0	14.3	-22.2	42.0
330.000000	65.0	1000.000	120.000	155.0	V	0.0	14.9	-23.0	42.0
349.980000	59.5	1000.000	120.000	155.0	V	0.0	15.5	-17.5	42.0

Table 1. Numerical results for closed loop antenna with ground plane

Figure 19. Self-made PCB (open loop antenna with ground plane)

Figure 19 is an open loop antenna with ground plane. The loop diameter is 110 mm.

In Figure 20, most of the electric field strength magnitude is higher than compared to Figure 18. This means that the reduction of interference is remarkable at every frequency. The highest electric field magnitude of open loop antenna with ground plane is 64.8 dBµV/m at frequency 210 MHz.
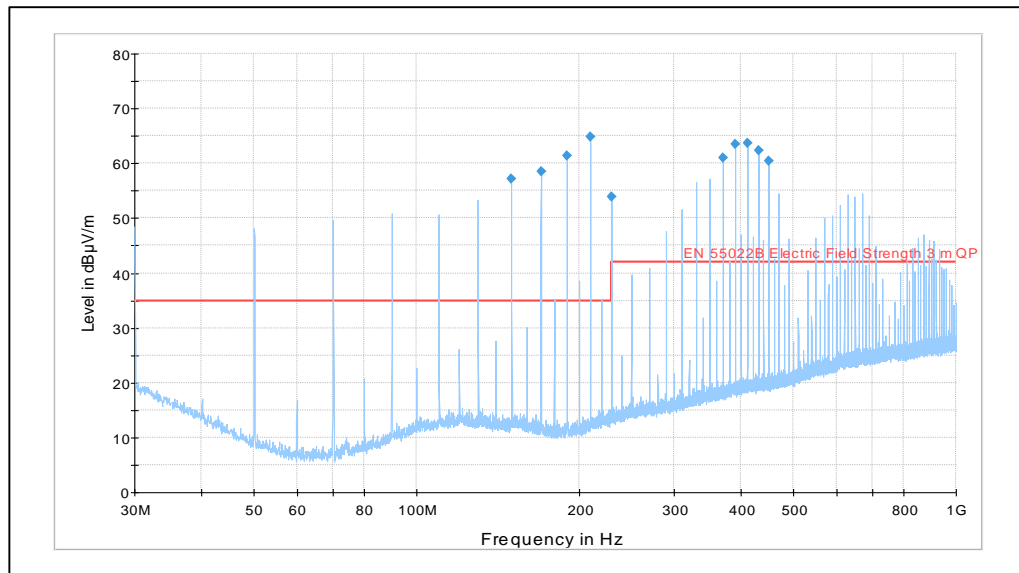

Figure 20. Results for open loop antenna with ground plane

Table 2 shows that radiations between frequencies 150 MHz to 450 MHz.

Frequency (MHz)	Qua-siPeak (dBµV/ m)	Meas. Time (ms)	Bandw idth (kHz)	Antenn a height (cm)	Polari ty	Turntabl e position (deg)	Corr. (dB)	Margin (dB)	Limit (dBµV/ m)
150.000000	57.2	1000.000	120.00 0	155.0	V	0.0	10.8	-22.2	35.0
169.980000	58.5	1000.000	120.00 0	155.0	V	0.0	9.7	-23.5	35.0
190.020000	61.5	1000.000	120.00 0	155.0	V	0.0	9.4	-26.5	35.0
210.000000	64.8	1000.000	120.00 0	155.0	V	0.0	10.3	-29.8	35.0
229.980000	53.9	1000.000	120.00 0	155.0	V	0.0	11.6	-18.9	35.0
370.020000	61.0	1000.000	120.00 0	155.0	V	0.0	16.1	-19.0	42.0
390.000000	63.4	1000.000	120.00 0	155.0	V	0.0	16.7	-21.4	42.0
409.980000	63.7	1000.000	120.00 0	155.0	V	0.0	17.2	-21.7	42.0
430.020000	62.4	1000.000	120.00 0	155.0	V	0.0	17.3	-20.4	42.0
450.000000	60.5	1000.000	120.00 0	155.0	V	0.0	17.5	-18.5	42.0

Table 2. Numerical results for open loop antenna with ground plane

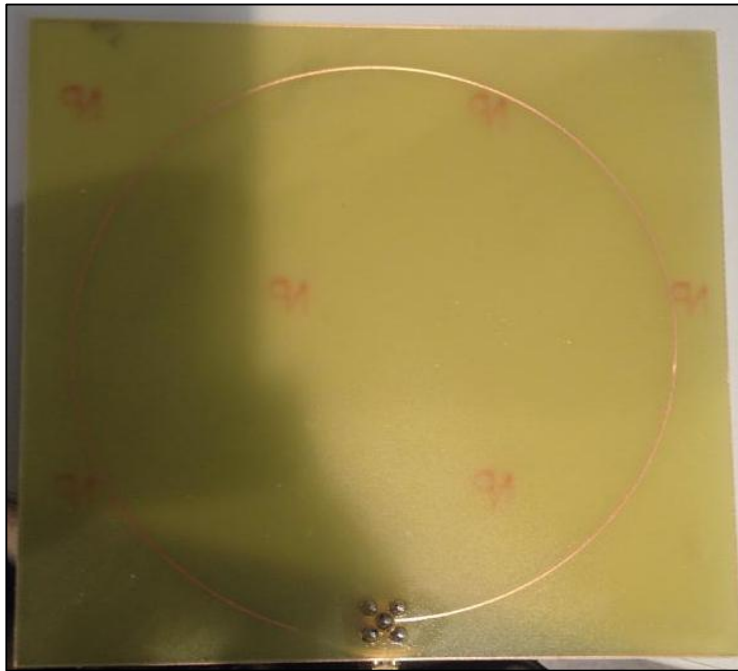## 4.2.2 Printed circuit board without ground plane

Figure 21. Self-made PCB (open loop antenna without ground plane)

Figure 21 shows an open loop antenna without ground plane. The loop diameter is 110.2 mm.

Comparing Figure 20 and Figure 21 it seems that the electric field strength varies within the same frequency.
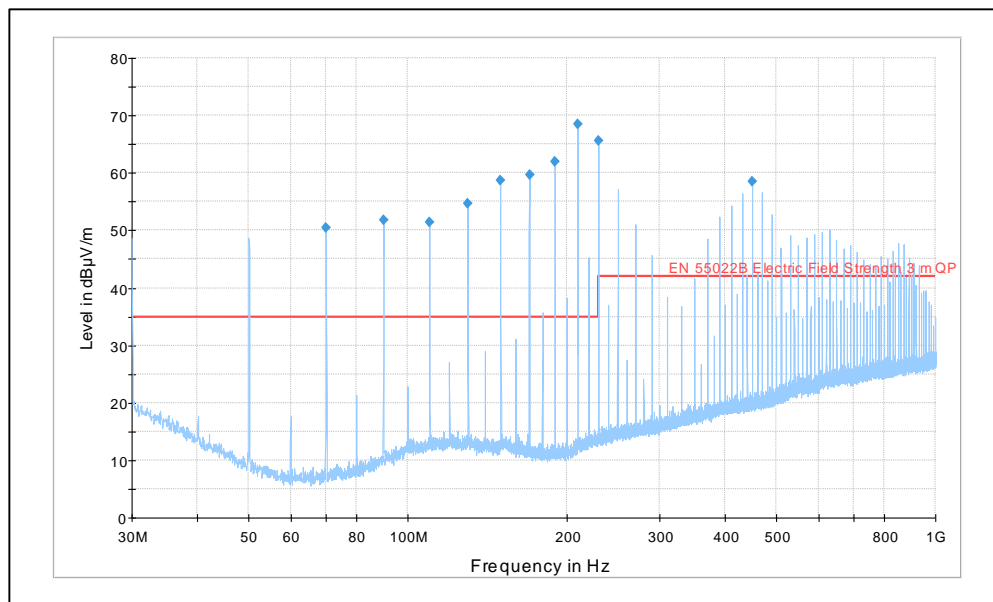
Figure 22. Results for open loop antenna without ground plane

Table 3 shows that at frequency 210 MHz the electric field magnitude is maximum.

Frequency (MHz)	Quasi Peak (dBµV/ m)	Meas. Time (ms)	Bandw idth (kHz)	Antenna height (cm)	Polar ity	Turntabl e position (deg)	Corr. (dB)	Margin (dB)	Limit (dBµV/m)
70.020000	50.4	1000.000	120.000	155.0	V	0.0	5.7	-15.4	35.0
90.000000	51.7	1000.000	120.000	155.0	V	0.0	9.1	-16.7	35.0
109.980000	51.4	1000.000	120.000	155.0	V	0.0	11.5	-16.4	35.0
130.020000	54.8	1000.000	120.000	155.0	V	0.0	11.6	-19.8	35.0
150.000000	58.7	1000.000	120.000	155.0	V	0.0	10.8	-23.7	35.0
169.980000	59.7	1000.000	120.000	155.0	V	0.0	9.7	-24.7	35.0
190.020000	62.1	1000.000	120.000	155.0	V	0.0	9.4	-27.1	35.0
210.000000	68.6	1000.000	120.000	155.0	V	0.0	10.3	-33.6	35.0
229.980000	65.7	1000.000	120.000	155.0	V	0.0	11.6	-30.7	35.0
450.000000	58.5	1000.000	120.000	155.0	V	0.0	17.5	-16.5	42.0

Table 3. Numerical results for open loop antenna without ground plane
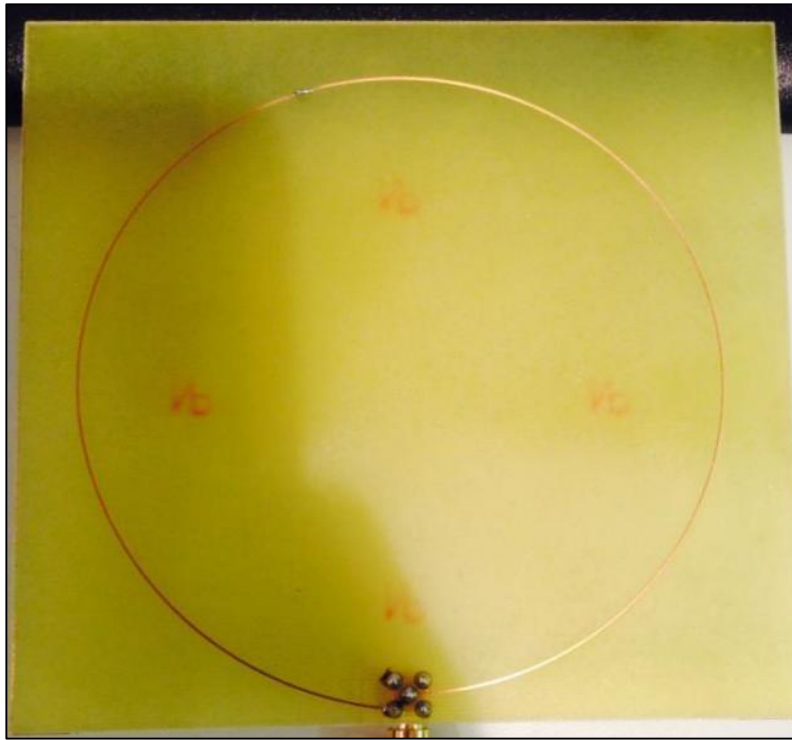
Figure 23. Self-made PCB (closed loop antenna without ground plane)

Figure 23 shows a closed loop antenna without ground plane. The loop diameter is 114 mm.

It is clearly noticed that in Figure 24 and Table 4, the radiation is between frequency 150 MHz to 390 MHz and the highest electric field strength is 64.1 dBµV/m at frequency level 330 MHz which is above the limit level 42 dBµV/m.
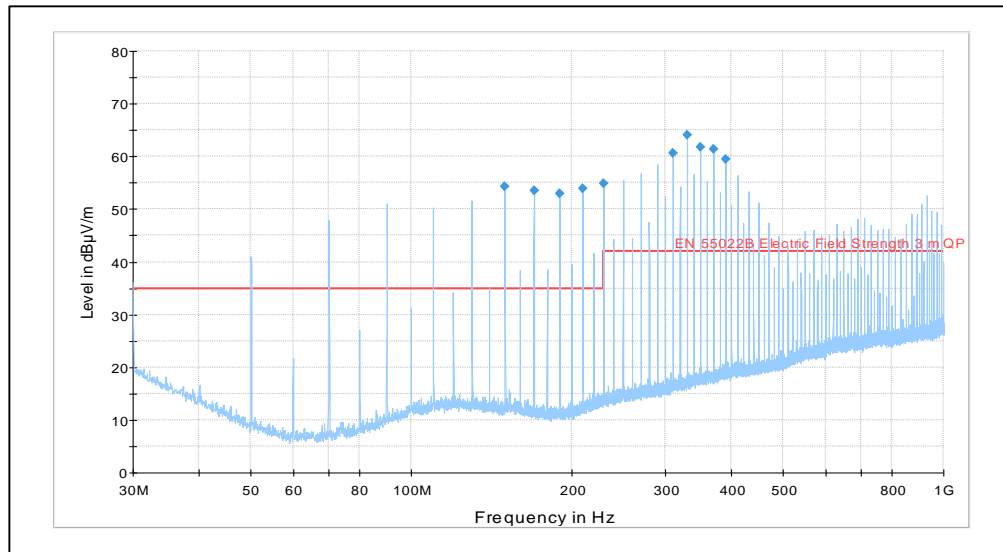
Figure 24. Results for closed loop antenna without ground plane

Frequency (MHz)	QuasiPeak (dBµV/m)	Meas. Time (ms)	Bandwidth (kHz)	Antenna height (cm)	Polarity	Turntable position (deg)	Corr. (dB)	Margin (dB)	Limit (dBµV/m)
150.000000	54.3	1000.000	120.000	155.0	V	0.0	10.8	-19.3	35.0
169.980000	53.5	1000.000	120.000	155.0	V	0.0	9.7	-18.5	35.0
190.020000	53.0	1000.000	120.000	155.0	V	0.0	9.4	-18.0	35.0
210.000000	54.0	1000.000	120.000	155.0	V	0.0	10.3	-19.0	35.0
229.980000	54.9	1000.000	120.000	155.0	V	0.0	11.6	-19.9	35.0
310.020000	60.6	1000.000	120.000	155.0	V	0.0	14.3	-18.6	42.0
330.000000	64.1	1000.000	120.000	155.0	V	0.0	14.9	-22.1	42.0
349.980000	61.8	1000.000	120.000	155.0	V	0.0	15.5	-19.8	42.0
370.020000	61.4	1000.000	120.000	155.0	V	0.0	16.1	-19.4	42.0
390.000000	59.5	1000.000	120.000	155.0	V	0.0	16.7	-17.5	42.0

Table 4. Numerical results for closed loop antenna without ground plane

Figure 25. Self-made PCB (small loop antenna without ground plane)

Figure 21 shows a small loop antenna without ground plane. The loop diameter is 32.3 mm.

By decreasing the loop area the radiation is somehow minimized. It can be observed in Figure 26 and Table 5. The highest electric field strength is 48.3 dBµV/m at frequency 790 MHz but it is still above the limit level.
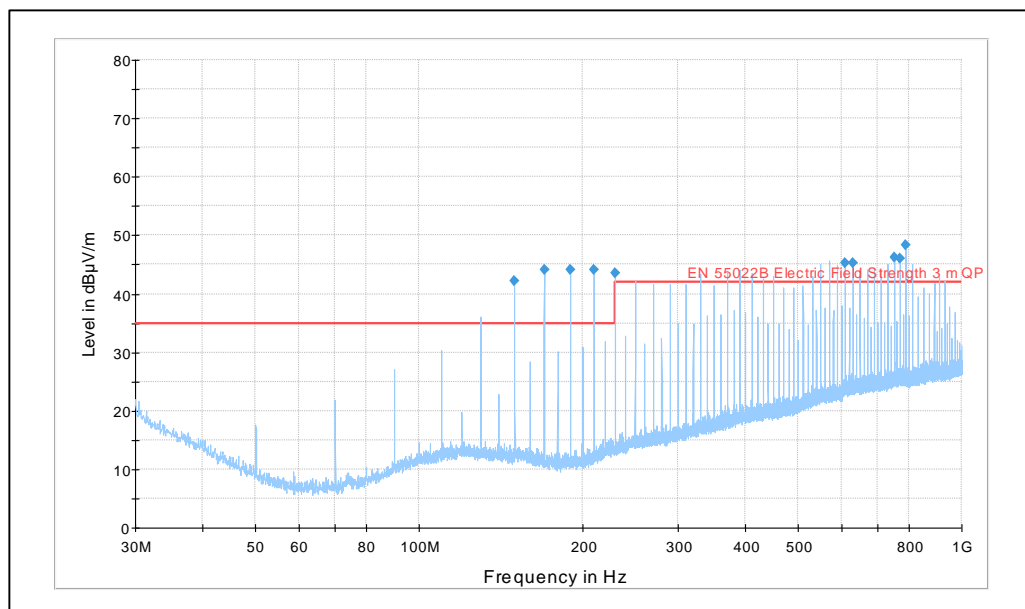

Figure 26. Results for small loop (closed) antenna without ground plane

Frequency (MHz)	QuasiPeak (dBµV/m)	Meas. Time (ms)	Bandwidth (kHz)	Antenna height (cm)	Polarity	Turntable position (deg)	Corr. (dB)	Margin (dB)	Limit (dBµV/m)
150.000000	42.3	1000.000	120.000	155.0	V	0.0	10.8	-7.3	35.0
169.980000	44.2	1000.000	120.000	155.0	V	0.0	9.7	-9.2	35.0
190.020000	44.1	1000.000	120.000	155.0	V	0.0	9.4	-9.1	35.0
210.000000	44.2	1000.000	120.000	155.0	V	0.0	10.3	-9.2	35.0
229.980000	43.6	1000.000	120.000	155.0	V	0.0	11.6	-8.6	35.0
610.020000	45.3	1000.000	120.000	155.0	V	0.0	19.8	-3.3	42.0
630.000000	45.3	1000.000	120.000	155.0	V	0.0	20.1	-3.3	42.0
750.000000	46.2	1000.000	120.000	155.0	V	0.0	21.4	-4.2	42.0
769.980000	46.0	1000.000	120.000	155.0	V	0.0	21.5	-4.0	42.0
790.020000	48.3	1000.000	120.000	155.0	V	0.0	21.6	-6.3	42.0

Table 5. Numerical results for small loop (closed) antenna without ground plane

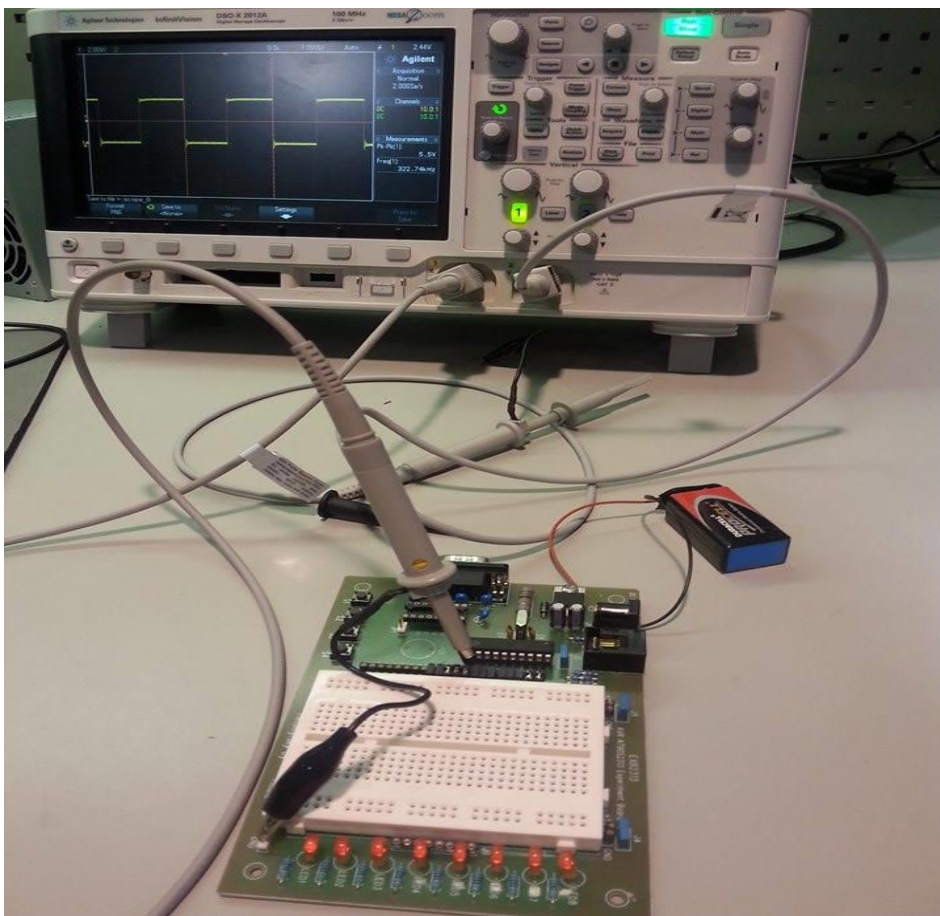### 4.2.3   Simple embedded system radiation

Figure 27. A simple embedded system connected to the oscilloscope

Figure 27 shows the simple embedded system connected to the oscilloscope, AVR AT90S2313 Experimental Board. The frequency of the board is 322.74 KHz as shown in Figure 28.
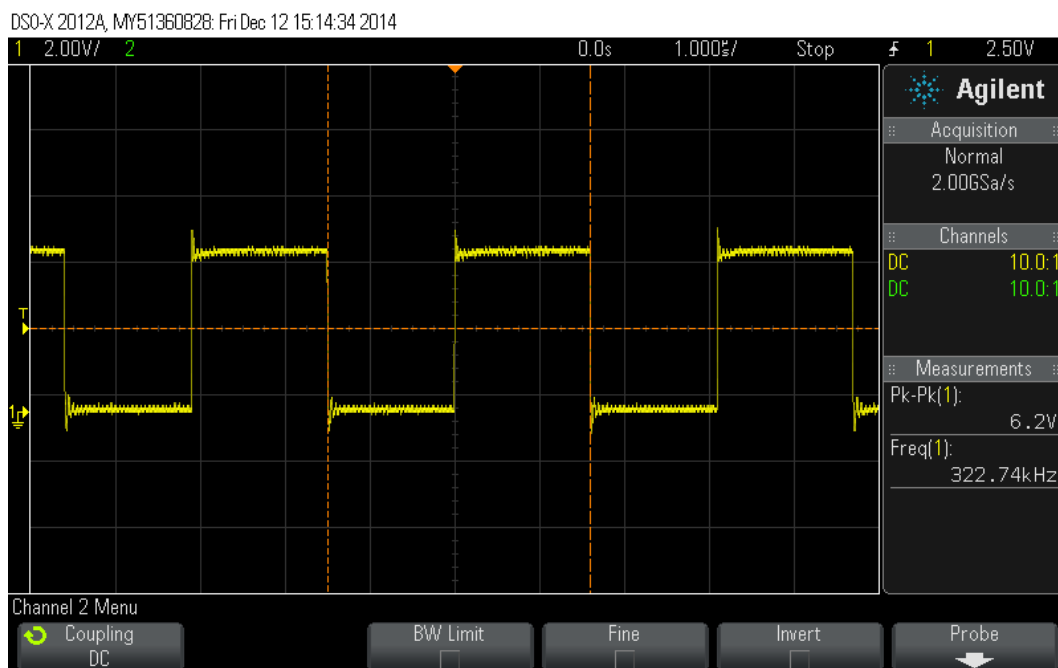

Figure 28. Oscilloscope captured from AVR experimental board

Figure 29 contains the measurement result of a simple embedded system. The result shows that the radiation reduces when compared to other self-made PCB boards. Here it can be remarked that the result is good and radiation is below the limit level.
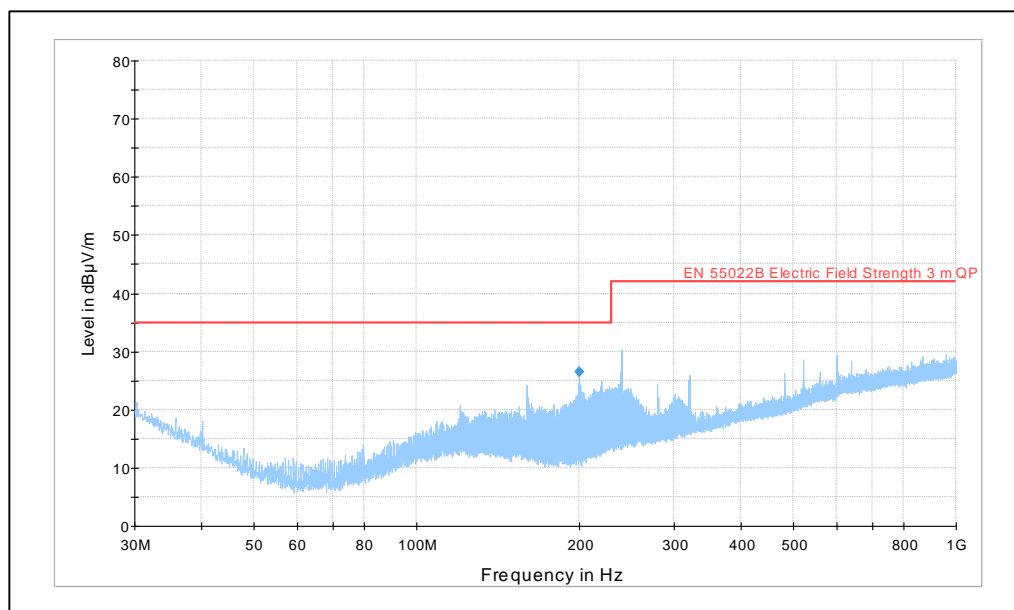
Figure 29. Results for a simple embedded system

Table 6 contains the electric magnetic strength at 200 MHz frequency.

Frequency (MHz)	QuasiPeak (dBµV/m)	Meas. Time (ms)	Bandwidth (kHz)	Antenna height (cm)	Polarity	Turntable position (deg)	Corr. (dB)	Margin (dB)	Limit (dBµV/m)
200.400000	26.6	1000.000	120.000	155.0	H	0.0	9.6	8.4	35.0

Table 6. Numerical results for a simple embedded system

4.3 Practical measurements with EMC-scanner

All five self-made PCB boards and embedded system boards were tested with EMC scanner. First, the PCB board was connected with the EMI source and the EMI source was set as "ON" as shown in Figure 30. Then, the measurement was started by using Detectus Scanner Software. The measurement points like step size, Z-level and X, Y plane were set in Detectus Scanner Software. For all the PCBs, Z-level was measured and set in the software.
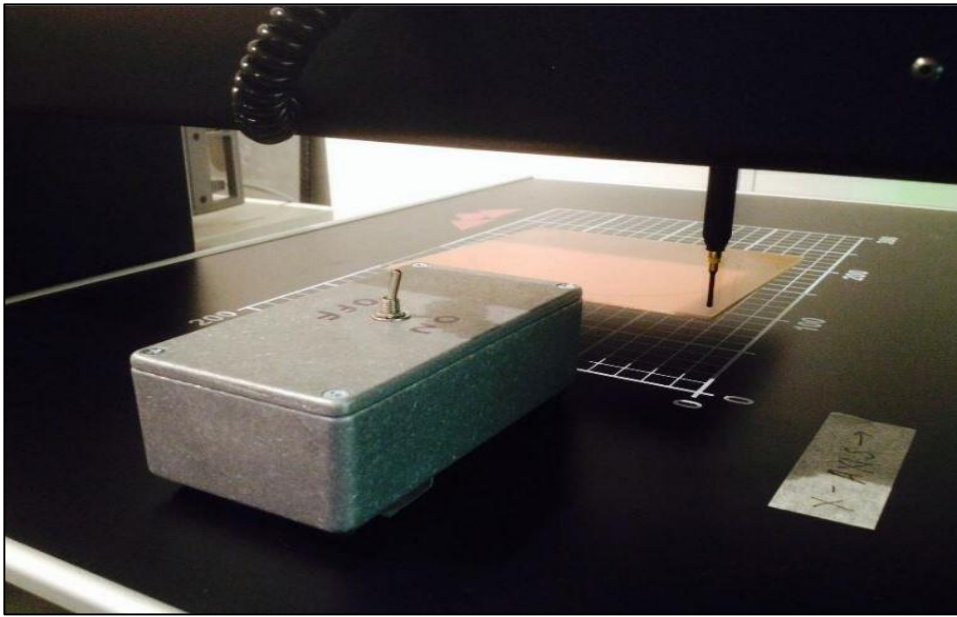
44

Figure 30. PCB board placed in EMC scanner

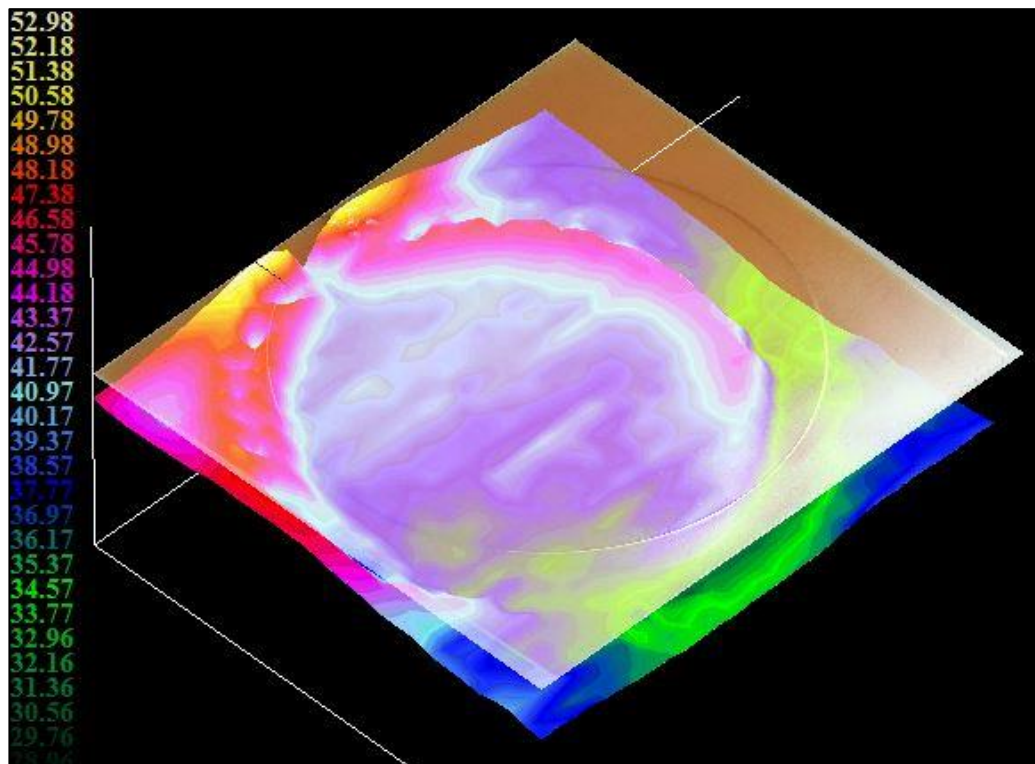### 4.3.1   Printed circuit board with ground plane

Figure 31. EMC scanner results for closed loop antenna with ground plane

Figure 31 shows the measurement done with EMC scanner. For the measurement on this PCB, the Z-level (distance between near-field probe and PCB) was set as 35 mm which is comparatively close than far-field antenna. The colorful numbers shown in the figure is electric field magnitude. The green color stands for radiation below the limit level 35 dBµV/m. Blue, pink color for radiation below limit level 45 dBµV/m and red and white color for high radiation. The near-field probes also spot at what point there is radiation.
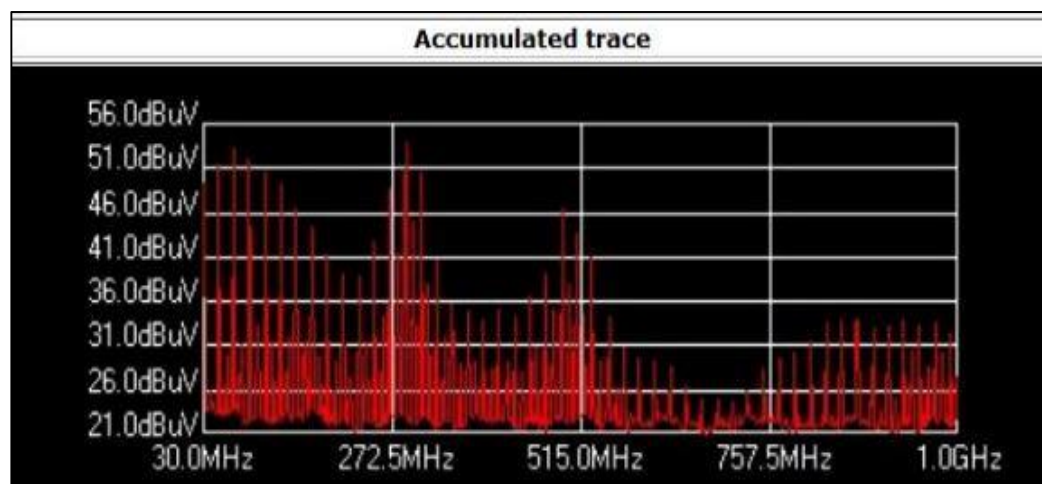
Figure 32. Trace for closed loop antenna with ground plane

It can be observed from the frequency and amplitude trace also as shown in Figure 32. From the above figure, it can be found that at what frequency level there is high radiation or low radiation. The maximum amplitude is 54 dBuV in the closed loop antenna with has a ground plane.
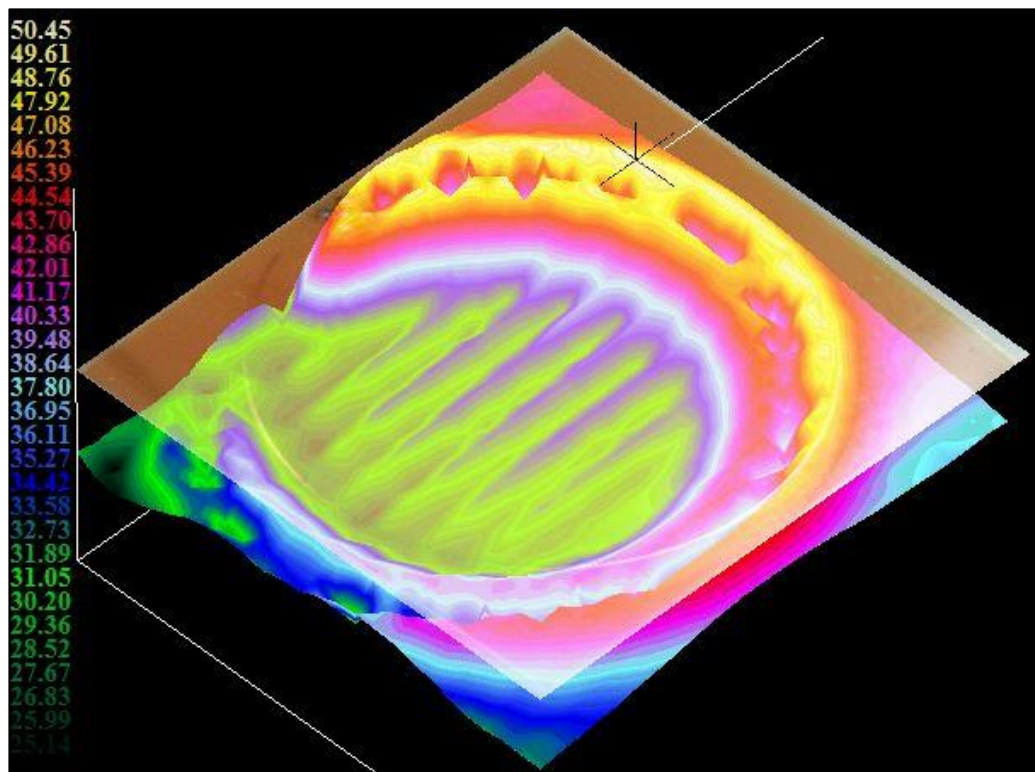
Figure 33. EMC scanner results for open loop antenna with ground plane

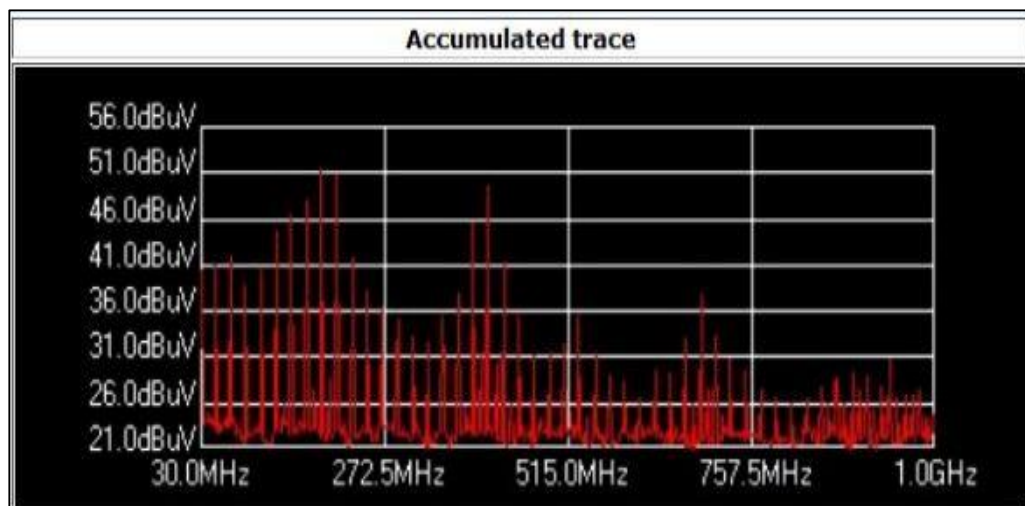In Figure 33, the black marker shows the highest radiation area.

Figure 34. Trace for open loop antenna with ground plane

From the Figure 34, the highest electric field magnitude is 51 dBuV.

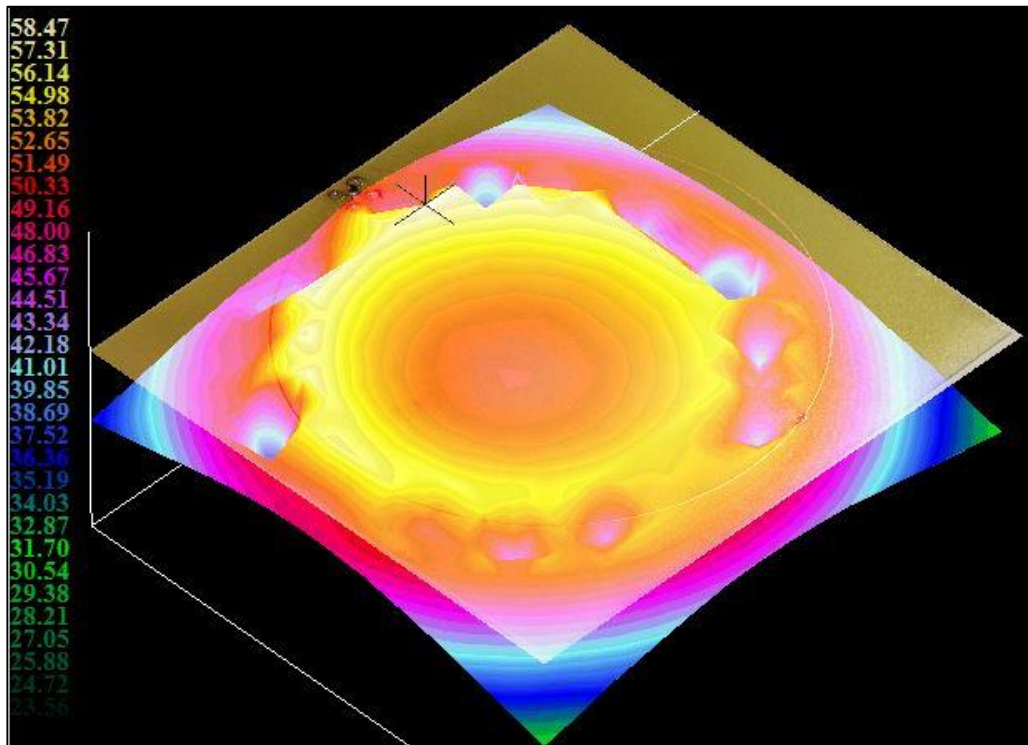### 4.3.2   Printed circuit board without ground plane

Figure 35. EMC scanner results for closed loop antenna with no ground plane

A Loop without a ground plane has a higher radiation then the loop with ground plane which can be distinguished by the Figures. The maximum electric field magnitude is 60 dBuV as shown in Figure 36.
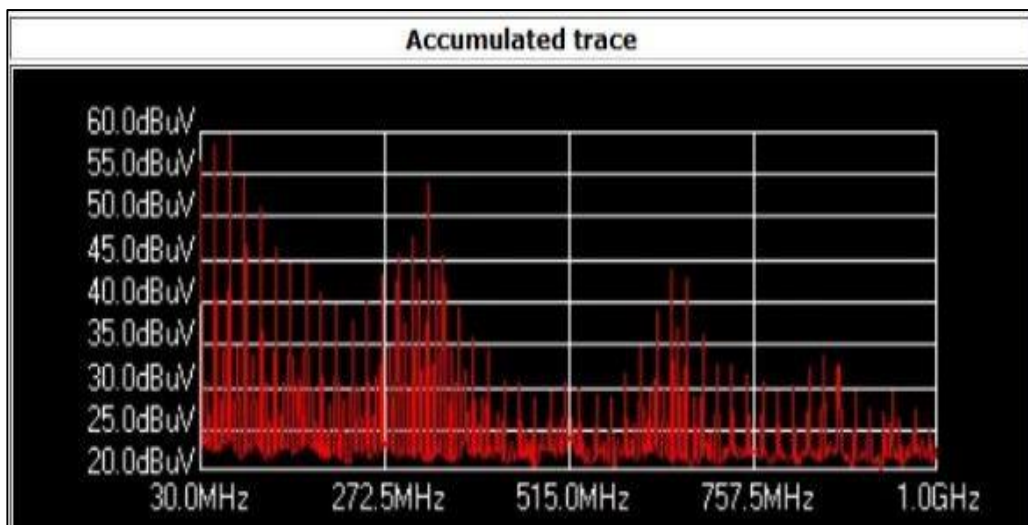

Figure 36. Trace for closed loop antenna with no ground plane
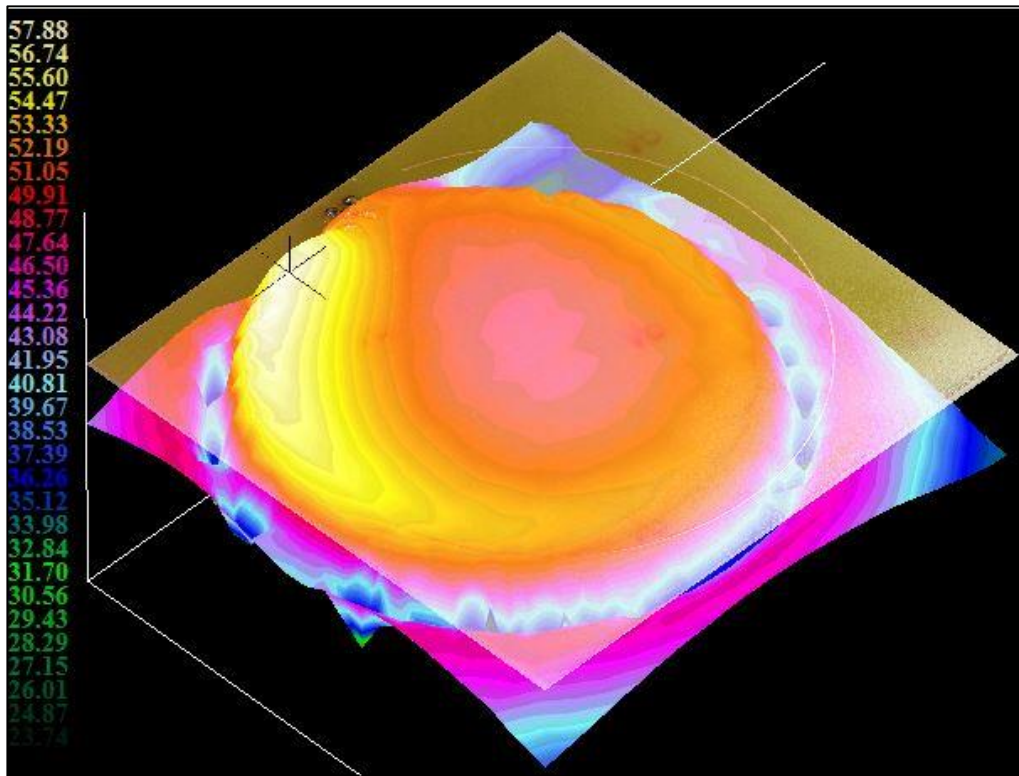
Figure 37. EMC scanner results for open loop antenna with no ground plane

The maximum amplitude is 59 dBuV, which is comparatively more than the open loop antenna without ground plane.
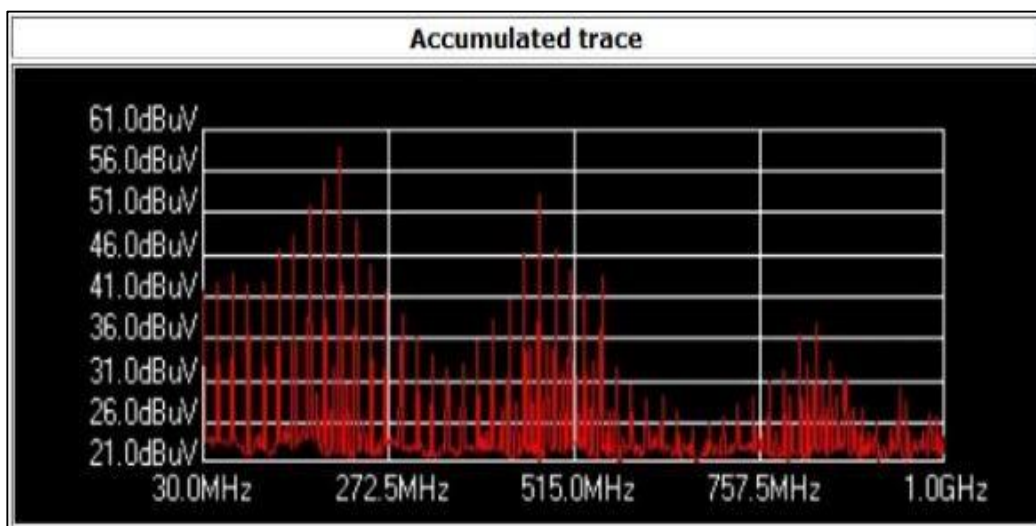

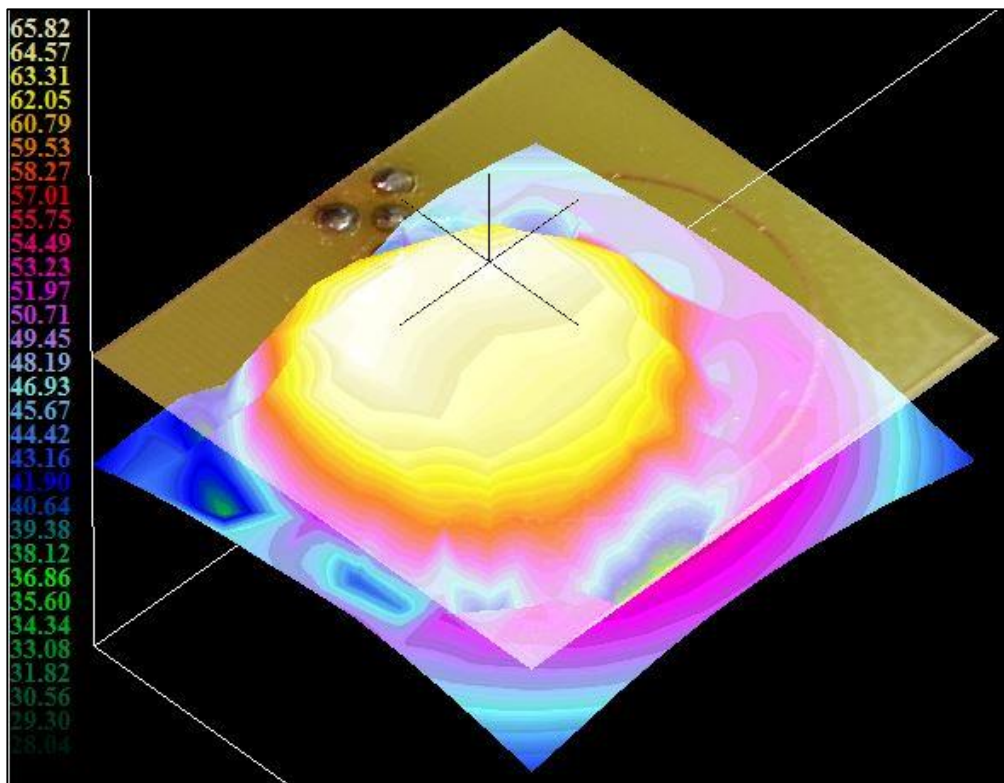**Figure 38**. Trace for open loop antenna with no ground plane

Figure 39. EMC scanner results for small loop (closed) antenna with no ground plane

Figure 39 shows that measurement of the small loop antenna with no ground plane with EMC-scanner spot more radiation than the other antenna with a big area which is an abnormal observation. The reason may be the z-level is in the same distance (35 mm) for all the antennas. Figure 40 shows the maximum radiation is 67 dBuV.
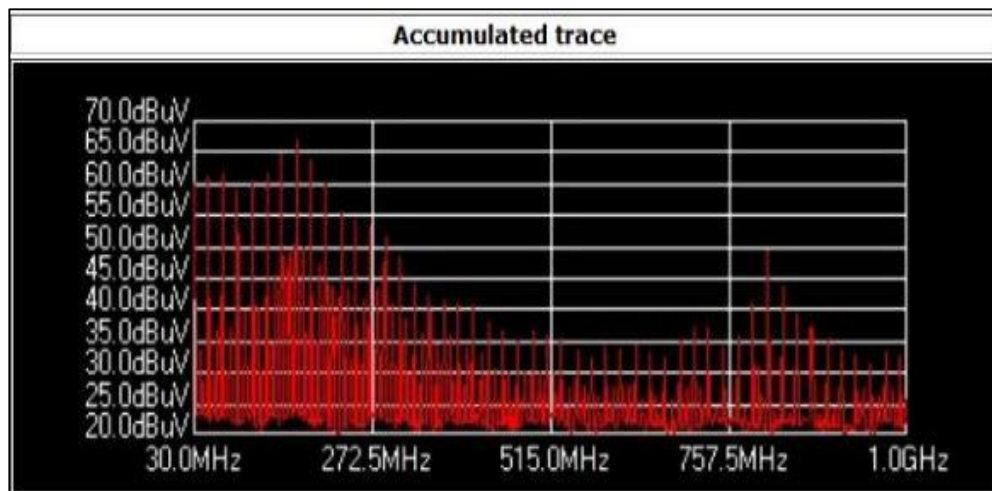
Figure 40. Trace for small loop (closed) antenna with no ground plane

On the other hand, when the measurement was done with the z-level distance 70 mm and step size 1 mm, the result was quite good as shown in Figure 41 and Figure 42.

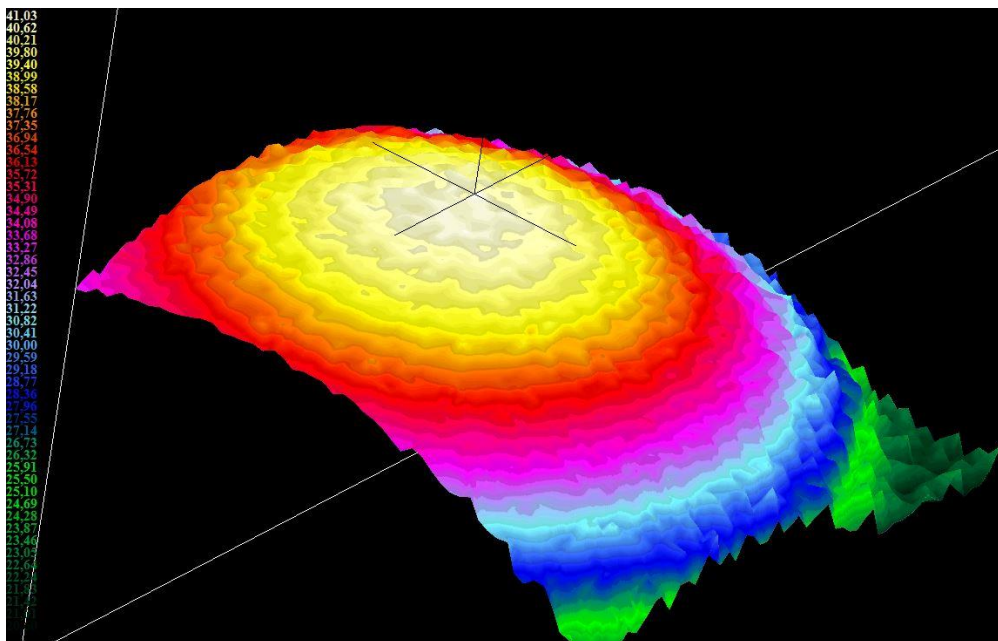

Figure 41. EMC scanner results for small loop (closed) antenna with no ground plane at 70 mm z-level

Now, the radiation is reduced to 41 dBuV when the near field probes is kept little above the PCB board as shown in Figure 41 and Figure 42.
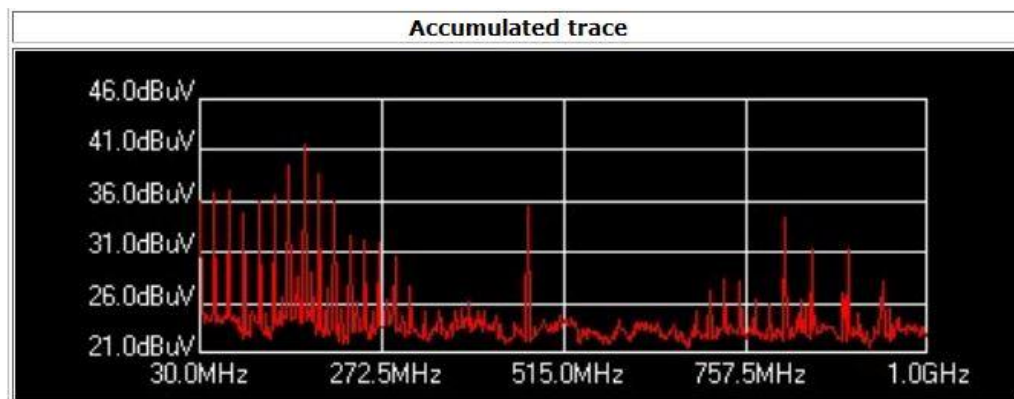
Figure 42. Trace for small loop (closed) antenna with no ground plane at 70 mm z-level

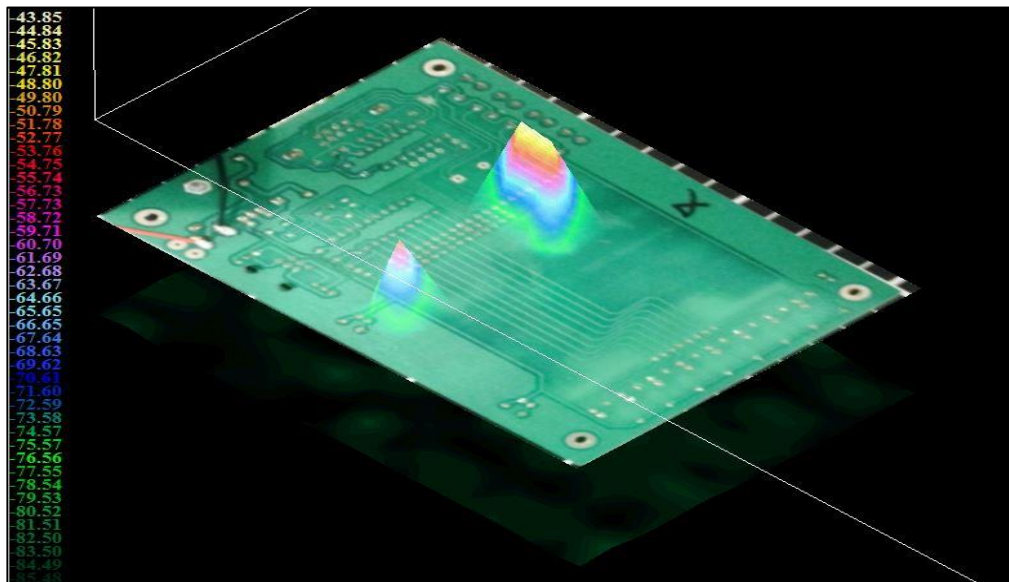### 4.3.3 Simple embedded system radiation

Figure 43. EMC scanner results for embedded system

The simple embedded system result is very good as compared with the self-made loop antenna.
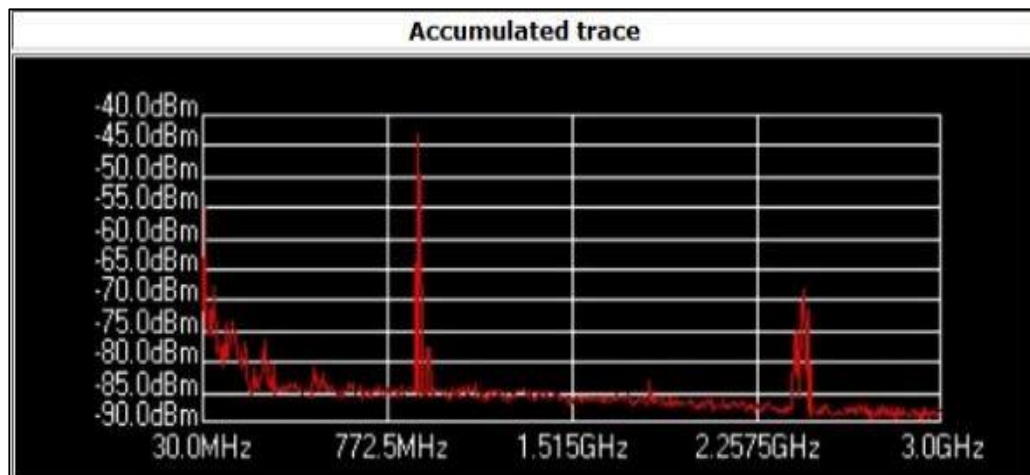
Figure 44. Trace for embedded system

From Figure 44, it seems that there is almost no radiation.

PCBs	Far-field radiation (dBuV/m)	Near-field radiation (dBuV)
Closed loop with ground plane	65	54
Open loop with ground plane	64.8	51
Closed loop with no ground plane	64.1	60
Open loop with no ground plane	68.6	59
Small loop with no ground plane	48.3	41.03
Simple embedded system	26.6	-43 dbm

Table 7. Comparable result of anechoic chamber and EMC-scanner

As explained in the theory of this report, the characteristics of a field are figured out by the antenna as a source, the media around the antenna, and the distance among the antenna and the observation point.

From the above Table 7, all PCBs have a high radiation values while the measurement is done in far-field as compared to near-field. The reason behind it is that near-field probes spot a particular source of RF fields.

Besides comparing the PCBs with ground plane and without ground plane, the above table clearly state that the PCBs with ground plane has significantly less electric field magnitude. The principle of this is that ground plane reduces the magnitude of radiation by letting the current to spread out providing many parallel paths.

PCBs	Loop antenna radiation in near-field (dBuV)	Loop antenna impedances with miniVNA (ohm Ω)
Closed loop with ground plane	54	38.1
Open loop with ground plane	51	48.4
Closed loop with no ground plane	60	55.3
Open loop with no ground plane	59	64.2
Small loop with no ground plane	41.03	52.8

Table 8. Comparison of loop antenna impedances and radiation

The loop antenna impedances was measured with the miniVNA pro which is a smaller version of Vector Network Analyzer, capable of measuring the RF of any antennas or RF circuits. The range of miniVNA pro is only up to 200 MHz but with the additional extender device the range can be increased to 1.5 GHz.

Impedance is the ratio of the electric field (E) to the magnetic field (H) of the medium. In near-field measurement, whenever the medium has a high current and low voltage then it is mostly magnetic and if it has a low current and high voltage then it is mostly electric.

5   IMPLEMENTATION OF PRINTED CIRCUIT BOARD

To implement the PCB board, PADS Logic and PADS Layout were used. Five different PCB boards were designed. PADS Logic was used to design circuit and PADS layout was for physical component pin design according to the datasheet. "2 D outline" was also added (a rectangle to distinguish a two side position). Figure 45 shows the schematic of closed loop antenna in PADS Logic and Figure 46 in PADS Layout.
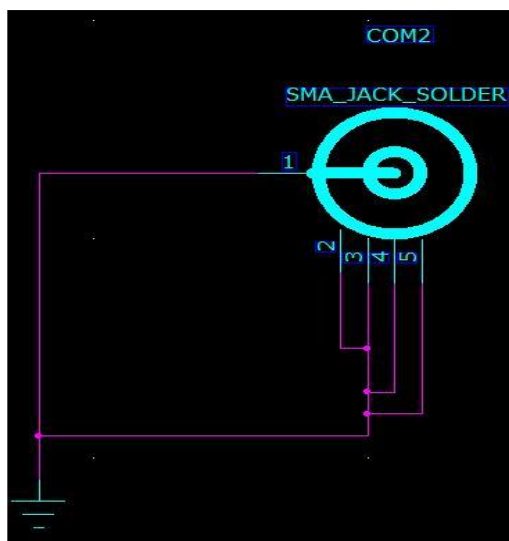

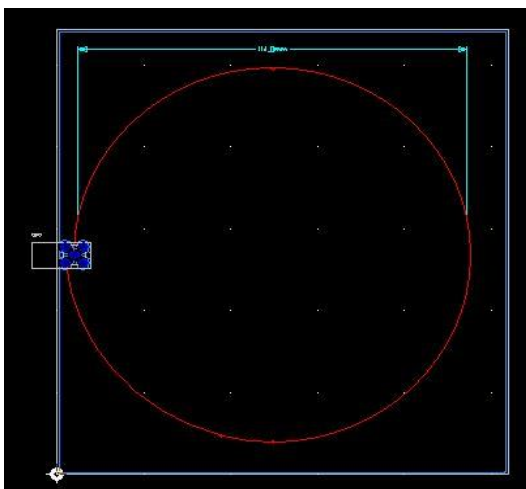**Figure 45**. Closed loop antenna schematic in PADS logic

Figure 46. Closed loop antenna schematic in PADS layout

Then PADS layout was used to post-process the design and convert it into a format which can be used by photoplotter. Photoplotter is a machine which is used to light the format on the copper board. The time was set as 5 minutes, which work very well and the circuit was clearly shown on the board. Figure 47 shows the format which is called Gerber format. /9/ (Mitzer, Kraig 2007, 12)
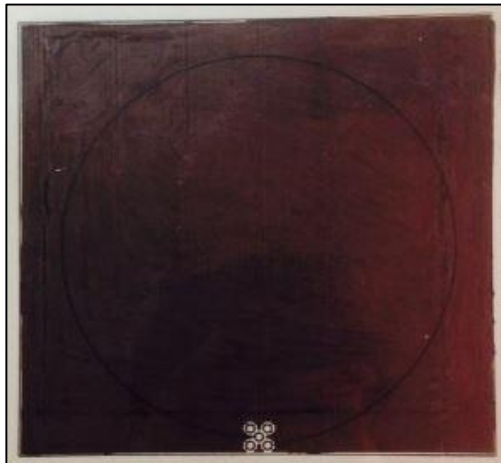

Figure 47. Gerber format used by photoplotter

In the process of assembling PCB, the board was placed in the wet acid to selectively removed the copper cladding and foil by etching. For this process, Sodium Hydroxide (NaOH) was used for the appearance of the circuit and Sodium PerSulfate ($Na_2S_2O_8$) was used to remove excessive copper from the board and the temperature was 45 Celsius. This board was well flushed and polished and the component were soldered properly. The copper (ground plane) and solder side was at bottom layer in PCB board. Hence, PCB board was built. Figure 48 shows the self-made PCB. Likewise, five different PCB boards were made for the measurement.

Figure 48. Self-made PCB board

6 TESTING AND RESULT

Testing is the most important process to confirm the correct result. All the PCB boards have been tested extensively during the measurement phases. Tests have been implemented for each PCB board in anechoic chamber as well as in EMC scanner. Anechoic chamber measures the radiation in far-field and EMC scanner in near-field.

The results after the measurement have shown that most of the PCB board without ground plane emits more radiation than a PCB board with ground plane. Also, reducing loop antenna area can control the level of radiation. When the measurements are done in far-field, it shows high electric field strength than the measurements in EMC scanner. It is because the anechoic chamber antenna is kept in limited distance (some meters far) to the PCB board whereas EMC scanner probes are very near (some millimeter) to electronic devices. After the measurement was done in near-field the radiation areas were spotted as well as the level of radiation was inspected.

7   CONCLUSION

Radiation sources in electromagnetic devices are very difficult to identify because it contains many active and passive components. Near-field antenna is very beneficial for the development of the electronic devices with electromagnetic compatibility. With all the work that has been done, it is possible to identify the electromagnetic interference of any PCB.

The measurements were done in an EMC room with both far-field and near-field probes. In far-field, it was found that the level of radiation is too high compared to near-field as the PCB board is at a certain distance far from the antenna. But with near-field probes, the results were quite low. In addition, when the loop area is reduced, then the radiation is controlled more as well as putting a ground plane in the PCB board also helped in controlling radiation. In general, the best way of decreasing interference is to reduce the loop area and the amount of current flow.

Most of the measurement results satisfied the theory of the thesis as PCB with ground plane radiated less interference and the near-field probes worked properly. Most significantly, the radiation was reduced with the explained ways of improving it.

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