Printed Dipole Antenna

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Abstract

In this project a printed dipole antenna is being designed. Printed dipole antennas are of interest, when an electronic product, which is implemented on a printed circuit board (PCB) is in need of a cheap, compact antenna. This antenna has a fairly isotropic pattern, which makes it a good transmitter / receiver for portable devices. This design is based on the US patent held by Motorola [1]. It was originally designed for portable pager device for operation in the 900 MHz band.

For this design the dipole as suggested by the patent was slightly remodeled and adopted to the 400 MHz band.

The antenna was built and measured.

Index Terms

Printed dipole, resonant antenna, compact antenna

I. INTRODUCTION

Printed antennas are very popular because of their ease of fabrication. If the antenna is to be implemented on the same PCB as the circuitry, practically no additional costs arise. For a system where an isotropic pattern is required, as for example in a portable device, a dipole is a good and easy approach. To get a good performance out of a dipole, one likes to design it as resonant dipole. This requires the dipole to be slightly less then half a wavelength long. A good guess is 0.47 times the wavelength [3]. We can calculate the length of the resonant dipole with the equation (I-1).

$$_{rd} = 0.47 \cdot \lambda = 0.47 \cdot \frac{v}{f} \qquad \textbf{(I-1)}$$

Where v is the actual propagation speed on the dipole radials. This speed depends on the effective dielectric constant of the environment surrounding the radials. We can calculate the speed with the equation (I-2).

$$v = \frac{c}{\sqrt{\varepsilon_{eff}}} \qquad \textbf{(I-2)}$$

Where c is the speed of light in vacuum and ε_{eff} is the effective dielectric constant of the surrounding media.

The effective dielectric constant for a printed radial on a substrate depends on the geometry and the dielectric constant of the substrate. We can calculate the effective

dielectric constant for a narrow trace using equation (I-3) [4]

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \cdot \left[\left(1 + \frac{12 \cdot h}{w} \right)^{-\frac{1}{2}} + 0.04 \cdot \left(1 - \frac{w}{h} \right)^2 \right] \qquad \textbf{(I-3)}$$

Where h is the thickness of the substrate, w the width of the trace and ε_r the relative dielectric constant of the substrate used.

II. DESIGN

Using the equations introduced in section I we design a resonant printed dipole for 433 MHz. We use a standard FR-4 PCB with an estimated ε_r of two at 433MHz and a thickness of 1.25mm. The trace width for the radials we set to 0.625mm.

First we calculate the effective dielectric constant using equation (I-3):

$$\varepsilon_{eff} = \frac{3}{2} + \frac{1}{2} \cdot \left[25^{-\frac{1}{2}} + 0.04 \cdot (0.5)^2 \right] = 1.6 \frac{F}{m} \qquad \textbf{(II-1)}$$

With the effective dielectric constant we can calculate the speed on the radials with equation (I-2):

$$v = \frac{3 \cdot 10^8}{\sqrt{1.6}} = 2.37 \cdot 10^8 \frac{m}{s} \qquad \textbf{(II-2)}$$

With this speed we can go now into equation (I-1) to get the length of the resonant printed dipole on our PCB:

$$_{rd} = 0.47 \cdot \frac{2.37 \cdot 10^8}{433 \cdot 10^6} = 25.7 cm \qquad \textbf{(II-3)}$$

So, if we want a device to operate at 433 MHz and want to have a resonant dipole, our device shouldn't be smaller then 26cm. That's not very practical.

The idea is now to shorten the physical extent further by "folding" the dipole antenna. With this approach, we can reduce the length of the dipole again by a factor of two (ideally). Then we are at the length of

$$fd = \frac{rd}{2} = \frac{25.7}{2} = 12.9cm \qquad \textbf{(II-4)}$$

This is more of what we are looking for. If we would use a frequency of 900 MHz this even reduces to 6.2cm (assumed ε_r of the dielectric is constant over the frequency range).

III. RESULTS / EXAMPLES

A. Simulations

As the length calculated in (II-4) is based on the assumption that the physical extent is halved if we bend the radials, we now simulate a model of the antenna and find the resonant length for 433MHz.

The model that will be used for these simulations is shown in Figure III-1. Figure III-2 and Figure III-3 show the top and bottom layer of the PCB separately. The radials on opposite sides of the PCB are connected at the outer ends with vias. The ground plane is introduced to reproduce the effect of electric circuitry on the PCB.
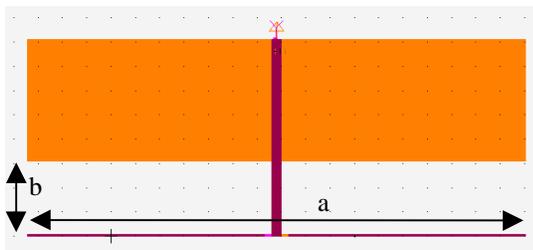
Figure III-1 Top view dipole, all layers
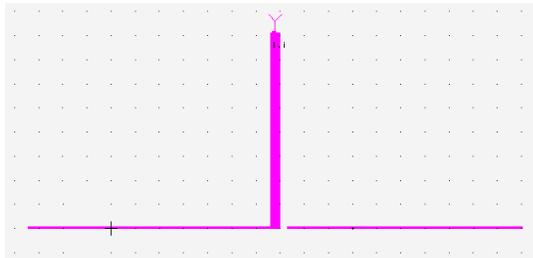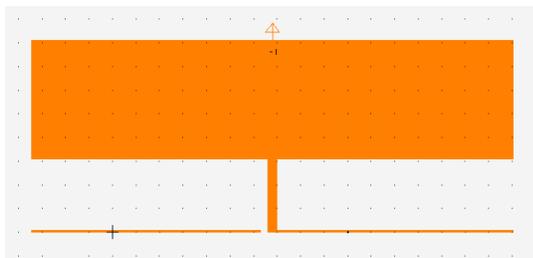

Figure III-2 Top view dipole, top layer

Figure III-3 Top view dipole, bottom layer

After several simulations the resonant length (a) for 433MHz was found. It is at 205mm for an estimated ε_r of 2. A separation of 3cm was used between the ground plane

and the antenna radials (b). Figure III-4 shows the S11 parameter of this configuration. It clearly shows the resonance with –17dB at 433MHz (marker M1).
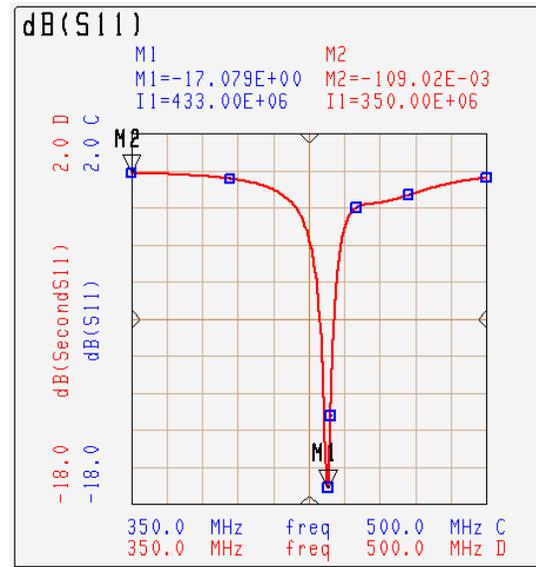

Figure III-4 S11, b=30mm

Figure III-5 shows the Smithchart of the same configuration. The upper of the two squares in the loop is at 433 MHz. The loop shows that the antenna is resonant at this frequency. It also shows that the design with the folded radials seems to be stable (i.e. no additional resonance).
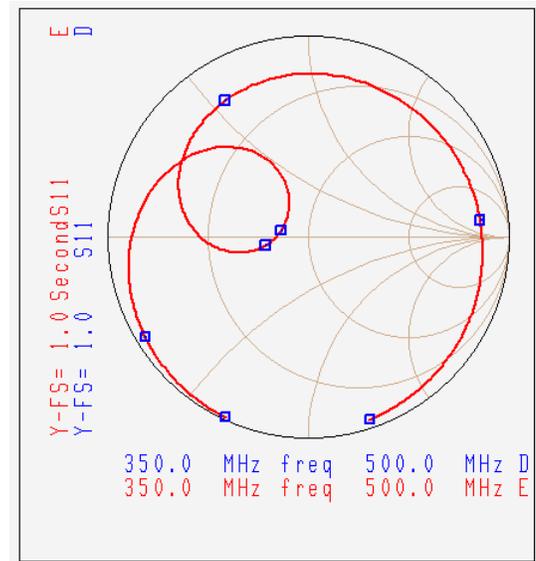

Figure III-5 Smithchart, b=30mm

Figure III-6 shows the input impedance (Z11) of the antenna. Once again the resonance is clearly visible. We can read out an input-impedance of 40Ω. This is already quiet close to 50Ω, which would be very convenient.
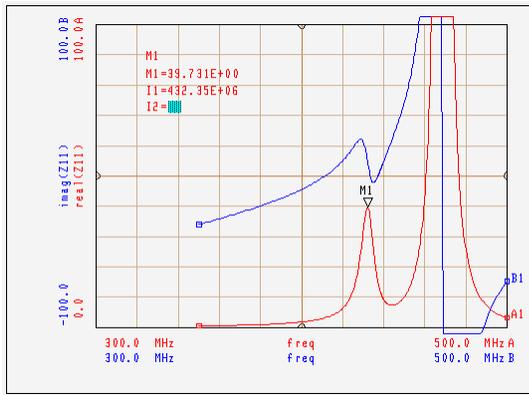
Figure III-6 Z11, b=30mm

How are these characteristics influenced by the design parameters? To find that out some variations of the design have been simulated. First the distance between the ground plane and the antenna radials (b) has been reduced to 2cm. As the nearby ground plane loads down the antenna we expect a less strong resonance. In Figure III-7 we see that the resonance was shifted towards higher frequencies and that S11 at resonance increased from –17dB (with 3cm distance between ground and the radials) to –8.3dB.
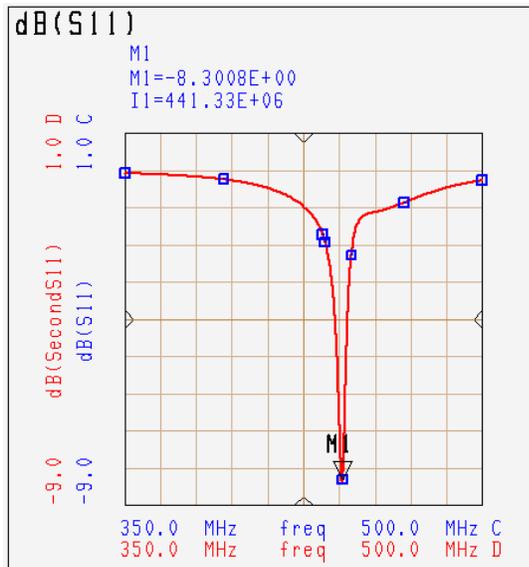
Figure III-7 S11, b=20mm

In Figure III-8 can also be seen that the loop got smaller, which indicates a weaker resonance. Finally Figure III-9 shows that we have an input-impedance of 27.5Ω at resonance.
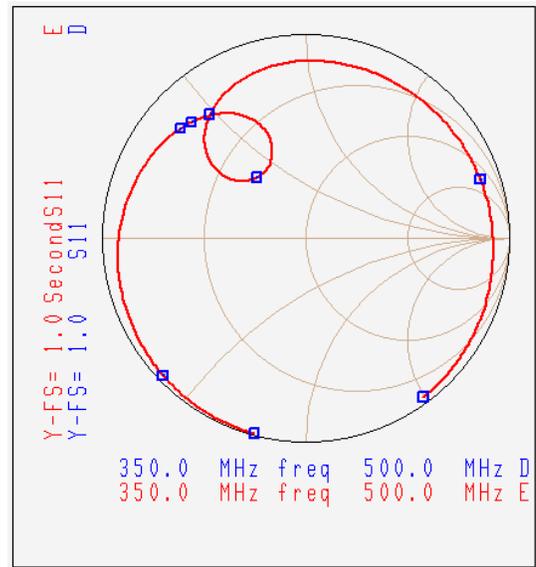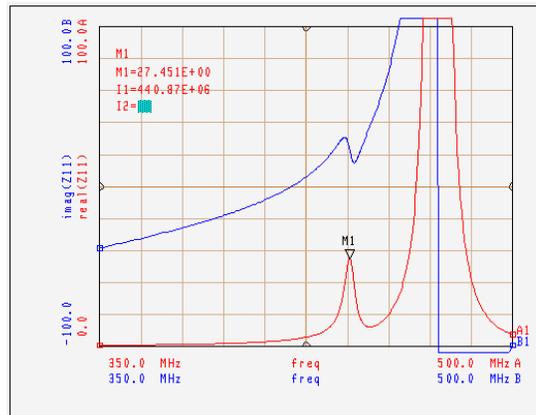

Figure III-8 Smithchart, b=20mm

Figure III-9 Z11, b=20mm

Now what happens if the radials are moved away from the ground plane? In Figure III-10, Figure III-11 and Figure III-12 the results of a simulation is presented, where the distance between the ground plane and the radials (b) is 40mm. In Figure III-10 we see that the resonant frequency has been moved to a lower frequency and that S11 at resonance decreased from -17dB to -17.7 dB. This is no big change for an increase in used space for the antenna of 33%. Also the Smithchart (compare Figure III-5 and Figure III-11) has no large change. The input impedance at resonance even decreased slightly. From this results we can say, that a distance of the radials from the ground plane (b) of 30mm is enough and a further increase doesn't bring any advantage but uses valuable PCB space.
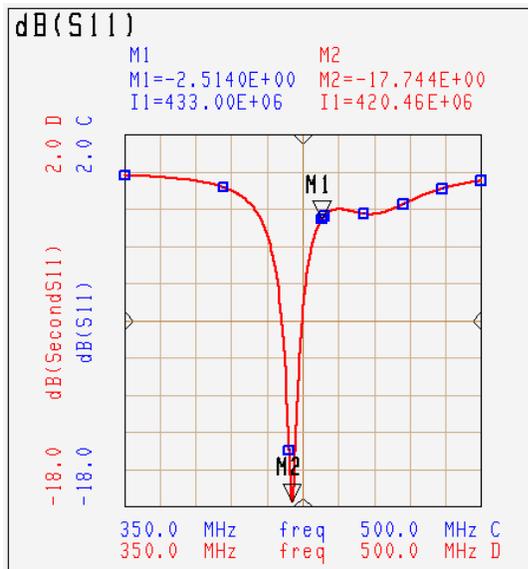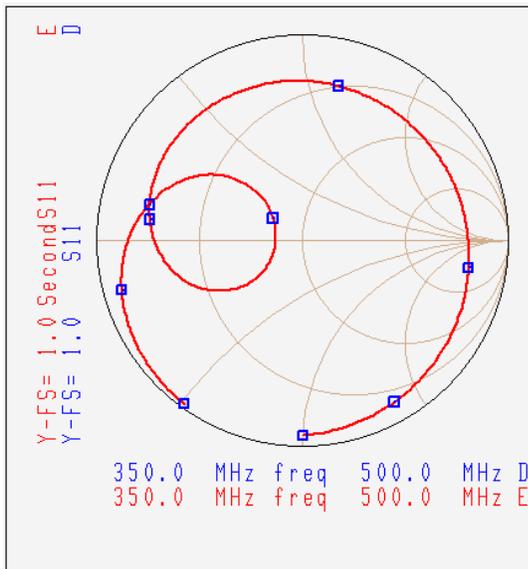
Figure III-10 S11, b=40mm

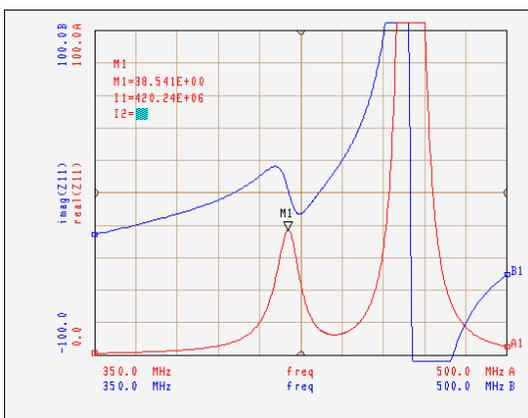**Figure III-11 Smithchart, b=40mm**

Figure III-12 Z11, b=40mm

How about other parameters like the ground plane width relative to the radial length? Let's extend the ground plane as shown in Figure III-13 and have a look at the simulation results. The antenna length (a) was kept at the resonant length of 205mm, the distance between ground plane and the radials (b) was set to 30mm and the ground plane was extended on both sides by 30mm, resulting in a total width of 265mm (c).
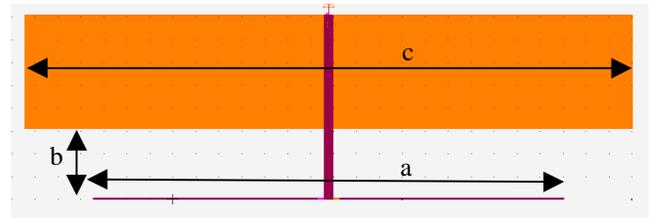

Figure III-13 All layers, extended ground plane

In Figure III-14, Figure III-15 and Figure III-16 the results of the simulation of the antenna with extended ground plane is shown. The resonant frequency was lowered from 433Mhz to 424Mhz. This might indicate that the edge of the ground plane is also working as a part of the antenna. Most interesting is the decrease of the S11 parameter from -17dB to -23dB at resonance.
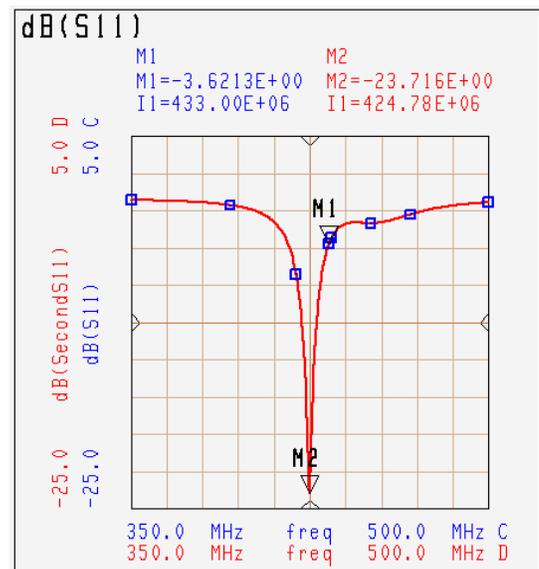

Figure III-14 S11, wide ground plane, c=265mm

Also in the Smithchart (Figure III-15) the stronger resonance is obvious (larger loop). The input impedance we can read out of Figure III-16 is 56Ω.
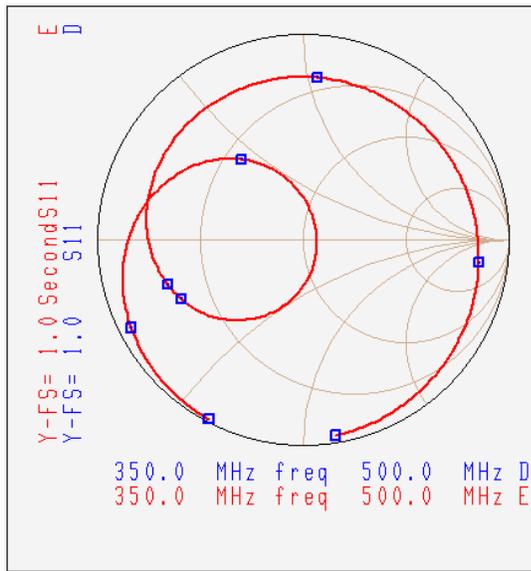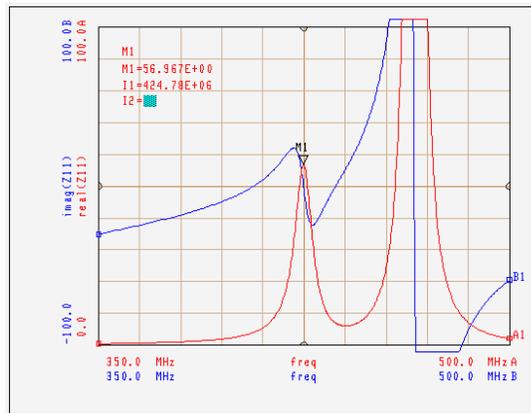
Figure III-15 Smithchart, c=265mm

Figure III-16 Z11, c=265mm

B. Discussion of Simulation Results

If we compare now the different results of the simulations we come to the conclusion, that the length of the radials (a) determines the resonant frequency (which is obvious from the theory). The ground plane near the antenna further influences the resonance frequency. Here both of the two investigated parameters, width of the ground plane and distance from the radials, influence the resonant frequency. The further away the ground plane, the lower the resonant frequency. The wider the ground plane, the lower the resonant frequency. This brings up the question if a part of the ground plane works as antenna.

Furthermore the ground plane influences the "strength" of the resonance and therefore the input impedance. The further away the ground plane, the stronger the resonance.

C. Measurements

To verify the theory and the simulation results, two printed dipole antennas have been built and measured. Figure III-17 shows the top and bottom view of antenna ①. Figure III-18

shows the top and bottom view of antenna ②. Table III-1 shows the dimensions of the antennas.
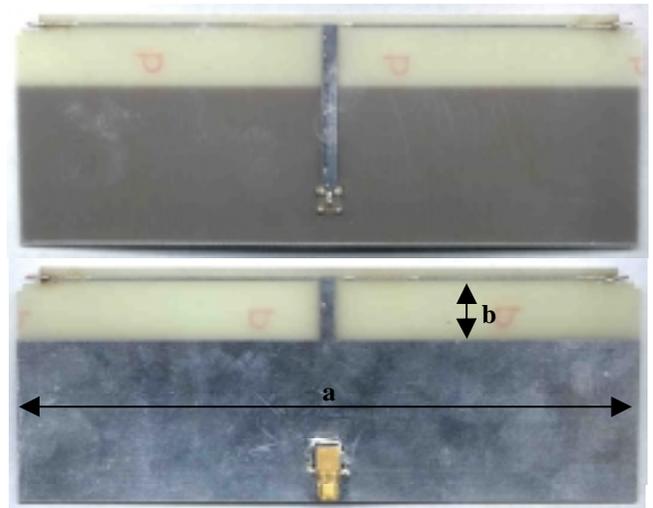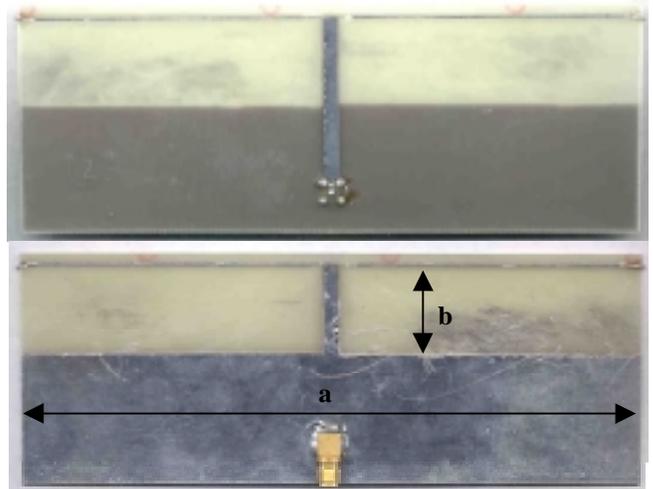

Figure III-17 Antenna ① top and bottom view

Figure III-18 Antenna ② top and bottom view

Table III-1 Dimensions of prototype antennas

	Antenna ①	Antenna ②
Substrate material	FR-4 PCB	FR-4 PCB
Substrate thickness	1.25 mm	1.25 mm
Width (a)	180 mm	180 cm
Ground distance (b)	17 mm	25 mm
Tuning style	Outer end shortening	Inner end shortening

First the input impedance of the two antennas was measured with a network analyzer. This measurement was performed inside the laboratory. The antenna was kept away from metallic objects as far as possible. Of course the ground plane on the PCB and also the connecting cable will always be close to the antenna.

The two prototype antennas are same, except for the distance between the radials and the ground plane (b). Antenna ① has a distance of b=17mm, antenna ② a distance of b=25mm. The two antennas have been mechanically tuned to a resonance at 433MHz. This was done by simply shortening the radials until the resonance occurred at 433MHz. Antenna ① was tuned by shortening the outer end of the antenna (bends around the PCB), antenna ② was tuned by shortening the inner end of the antenna (end of radials close to feed).

The antennas have an extent of a=180mm. This is close to the simulated 205mm. The difference can be explained due to an incorrectly assumed ε_r=2.

In the following figures the S11 plots and Smithcharts of the two antennas are presented.

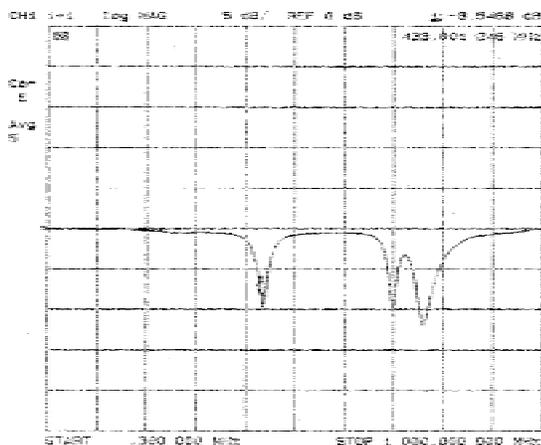Figure III-19 shows the S11 Parameter of antenna ①. At 433MHz we have –8.6dB.

Figure III-19 Measured S11, antenna ①

Figure III-20 shows the S11 Smithchart of antenna ①. Also here is the loop of resonance clearly visible. The additional two loops indicate resonance of higher order or other modes. These were not visible in the simulation results, as they occur above the simulation limit of 500MHz. The measured input impedance at 433MHz of antenna ① is 47 + j34 Ω.
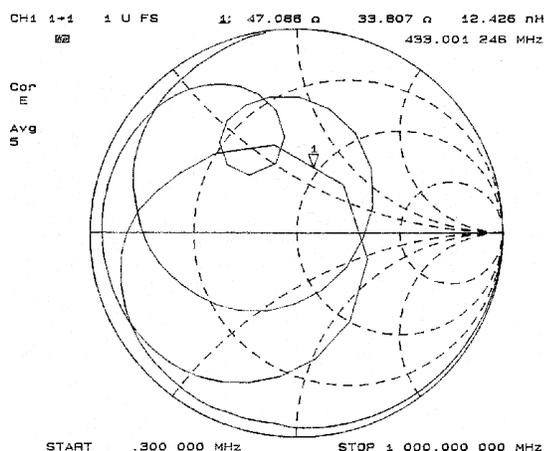

Figure III-20 Measured Smithchart, antenna ①

Figure III-21 shows S11 of antenna ②. Note the different vertical resolution compared to Figure III-19. Antenna ② has an S11 at 433MHz of –12.4dB. This is what we expected from the simulations.
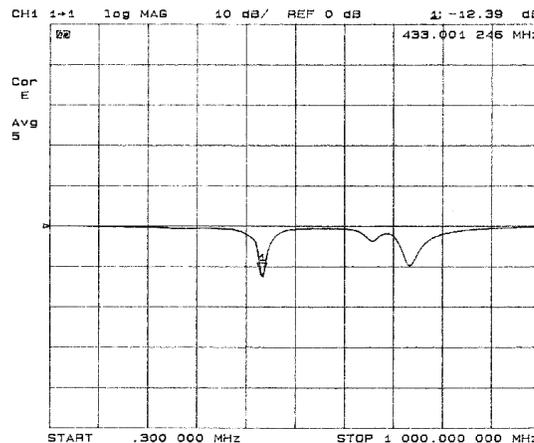

Figure III-21 Measured S11, antenna ②

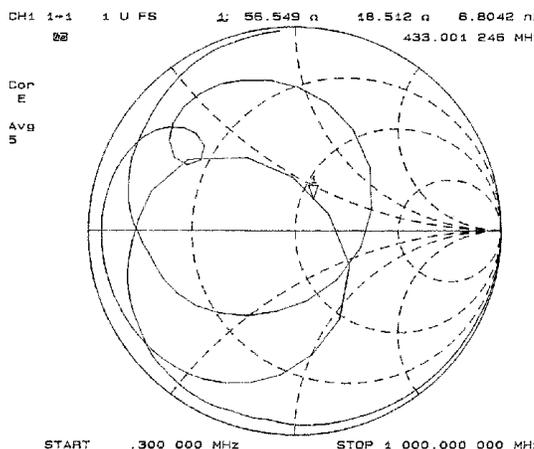The Smithchart in Figure III-22 shows again the resonance at 433MHz and an input impedance of 56 + j19 Ω

Figure III-22 Measured Smithchart, antenna ②

D. Far Field Radiation Pattern

The far field radiation pattern of the antenna with a distance between the radials and the ground plane of 30mm was simulated and is shown in Figure III-23 and Figure III-27. The coordinate system for the simulations and measurements is defined by the following: The PCB where the antenna is printed on lies in the x-y plane, where the radials are in the direction of the x-axis. The positive y direction goes from the radials to the ground plane. The positive z-axis rises perpendicular from the top plane of the antenna. The graphs have been rotated in such a manner, that the curves can be compared directly (measurement and simulation uses different angle definitions). The measurements show the E-fields in phi direction (as much as a separation is possible with the used antennas). As transmitter was antenna ① used. A constant power level of 7.5 Watts at 433 MHz was applied to the antenna. The

receiver antenna (antenna ②) was rotated in such a manner, that the desired patterns where measured.

If we compare the simulated and the measured results of the x-y plane pattern we see clearly, that the actual antenna behaves very much like the simulation. We also see that the main beam is not pointed perpendicular to the radials, but about 20° to the 'left'. This could be a further sign that the edge of the ground plane is acting as second dipole radial. As the ground plane is set back by 25mm from the radial that is connected to ground, this would result in a rotation of the pattern to the 'left'. The nulls, perpendicular to the main beam, typical for a dipole, are 15dB deep in the simulation and 10dB to 15dB deep in the measurement.
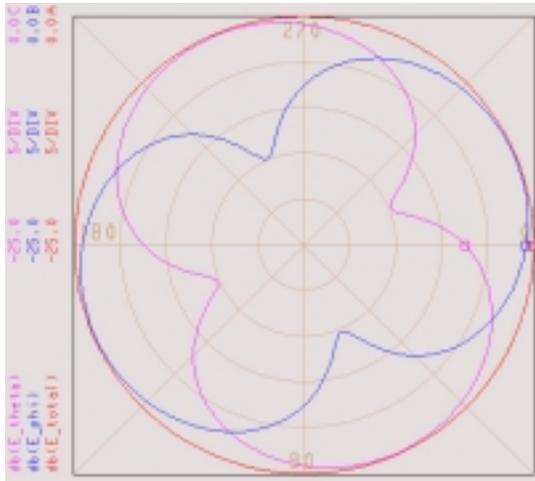

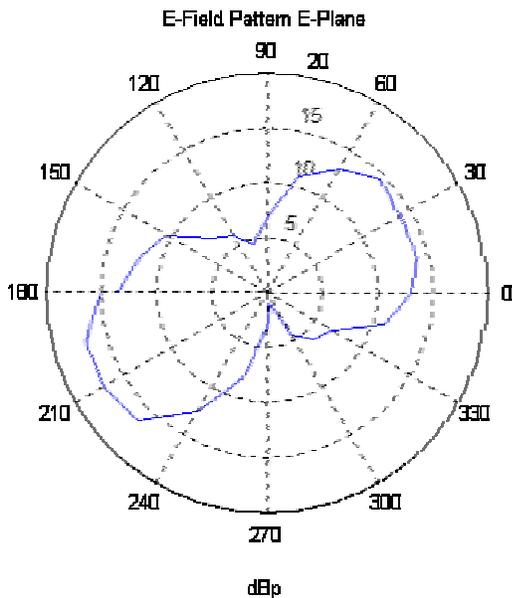**Figure III-23 Simulated E-field pattern in x-y plane**

Figure III-24 Measured phi directed power-pattern in x-y plane

To verify the assumption, that a part of the ground plane is radiating, a reason is to be found. One reason could be, that the abrupt change of the ground plane to the transmission line to feed the dipole causes reflections. To find out more about that , a modification was made to the original design. The line feeding the dipole from the ground plane was tapered, as shown in Figure III-25.
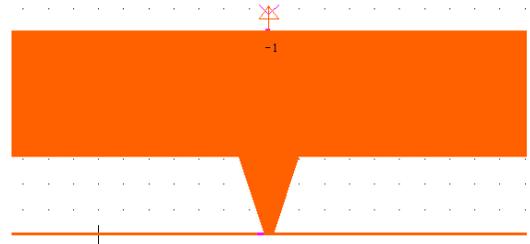

Figure III-25 Dipole with tapered ground feed line

The resulting far field in the x-y plane is shown in Figure III-26. It is clearly visible that the rotation of the pattern disappeared. It seems that really the reflection at the transition from the ground plane to the feed line caused the rotation.
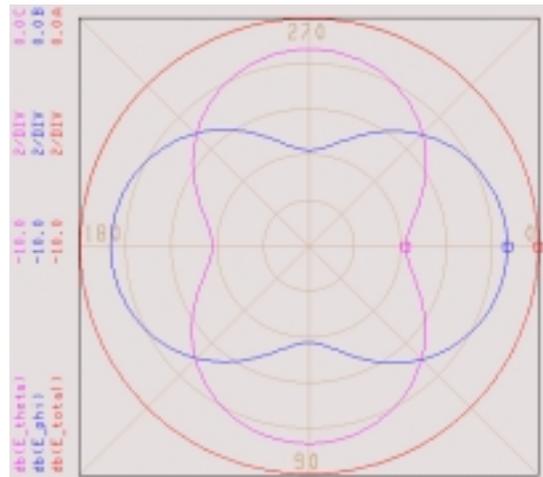

Figure III-26 Simulated E-field pattern in x-y plane with tapered ground feed

If we compare the simulated and the measured results of the y-z plane pattern we also see that the actual antenna behaves very much like the simulation. We also see in simulation and measurement, that the dipole radiates about 2 dB more towards the ground plane than away from the ground plane. The sharp, deep null as it appears in the simulation could not be measured.
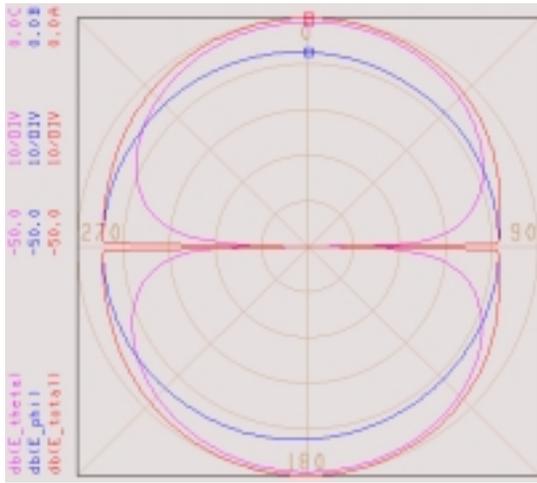
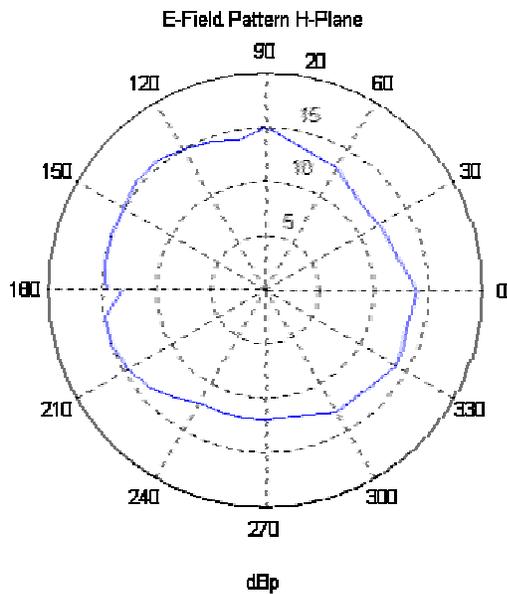**Figure III-27 Simulated E-field pattern in y-z plane**

Figure III-28 Measured phi directed power-pattern in y-z plane

E. Gain

Even though no standard gain antenna for the used frequency of 433 MHz was available, a rough measurement should show the approximate gain of the antenna. Using antenna ① as transmitter and antenna ② as receiver, we try to calculate the gain of the system. Using Friis transmission formula [3]

$$P_r = \frac{P_t \cdot G_t \cdot G_r \cdot \lambda^2}{(4 \cdot \pi \cdot R)^2}$$ **(III-1)**

the total gain of the system can be calculated

$$G^2 = \frac{P_r \cdot (4 \cdot \pi \cdot R)^2}{P_t \cdot \lambda^2}$$ **(III-2)**

As gain is not taking mismatch in account, the measured power values have to be adjusted to take the mismatch in account.

$$P_t = P_t^{measured} \cdot \left(1 - |s_{11}|^2\right) = 7.5 \cdot 0.891 = 6.68W$$

$$P_r = \frac{P_r^{measured}}{1 - |s_{11}|^2} = \frac{10^{\frac{-43}{10}}}{0.967} = 51.8pW$$ **(III-3)**

Using the parameters of the measurement and assuming the two antennas have the same gain we get

$$G = \sqrt{\frac{51.8 \cdot 10^{-9} \cdot (4 \cdot \pi \cdot 33)^2}{6.68 \cdot 0.48}} = 42.7 \cdot 10^{-3}$$ **(III-4)**

This is a rather small gain. As we use antenna ①, which has only a distance of 17 mm between the radials and the ground plane, we can assume that the gain of antenna ② with 25 mm distance between the radials and the ground plane is considerably larger. Also was the transmitter antenna not exactly oriented for maximum directivity.

IV. CONCLUSIONS

A resonant dipole antenna for the frequency of 433 MHz has been designed which uses a space of 18 cm by 2.5 cm at the edge of a PCB. Measurement and Simulation results have been presented. From these results, we can conclude that such an antenna is convenient for a design of a base station of a portable device such as a hand-held remote control. Further investigation of the effect of the ground plane size would be interesting. Design alterations to increase radiation efficiency are necessary.

V. REFERENCES

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     Warren L. Stutzmann
     Garry A. Thiele
     ISBN 0-471-02590-9

[4] High-Speed Digital Design
     Howard Johnson
     Martin Graham
     ISBN 0133967241