Gunthard Kraus, DG8GB

An Interesting Program: Development of a Circularly Polarised Patch Antenna for 2.45GHz with Sonnet Lite

This article is the revised and extended version of a lecture to the 2011 VHF conference in Bensheim. The article is an "Interesting Program" dealing with the basics of Patch antennas and then the production of an antenna for circularly polarised waves.

The free software "Sonnet Lite" was used to develop the antenna. To verify the characteristics of the antenna a prototype was produced to compare it with the simulation.

1.
The project

The 2.45GHz band is familiar not only for the WLAN allocation but also for other uses for approved low power transmission. A friend who is an enthusiastic model flier complained about the uncertain and varying 2.45GHz connection to his aeroplane. An examination of the expensive remote control transmitter showed that it is fitted with an SMA connector but only a simple small tilting blade antenna. The blade antenna could be tilted and pointed at the aeroplane. Those of us who know about antennas realise that unfortunately the minimum radiation occurs exactly where the antenna is pointed, which is absurd for this application. Thus the idea was born to develop a circularly polarised patch antenna with an SMA connection for the frequency range from 2420 to 2480MHz. It can be connected to the remote control transmitter using a short piece of semi rigid cable so that the main radiation direction can be pointed exactly toward the aeroplane. Thus a stable radio link should be possible.

2.
The Basics

A patch antenna consists of a piece printed circuit board material (PCB) covered on both sides with copper. The lower surface forms a continuous ground surface and on the top side there is a simple square or rectangle made from copper making the "patch". Obviously the PCB must be larger than the patch for correct operation (approximately 3 to 5 times - and more is better).

The patch is designed in such a way to exhibit an electrical length of $\lambda/2$. A better choice:

Antenna length = 0.49 x (λ)

It can be regarded as an open circuit microstrip line. Feeding this line at the input with a signal at a frequency corre-

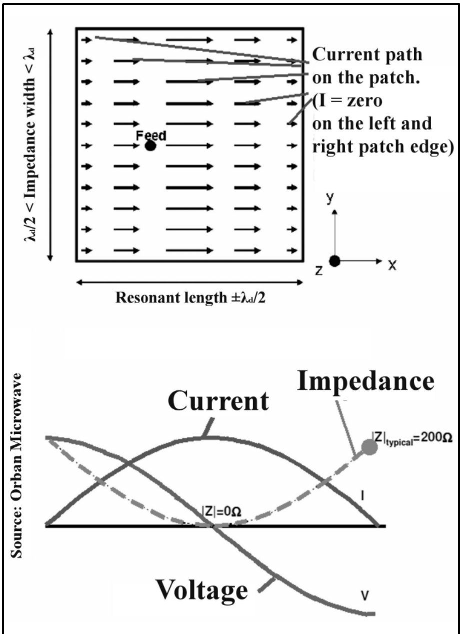

Fig 1: A patch antenna showing the current and voltage distribution along a λ/2 open circuit microstrip line.

sponding to the resonant frequency produces the current and voltage distribution shown in Fig 1 (the feed point is on the symmetry axis of the patch).

The voltage at the ends of the line is equal and in anti phase (λ/2 means 180 degrees of phase shift) but at the centre of the patch the voltage is zero. For a lossless line the current is zero at the ends and a maximum in the centre. This is shown in Fig 1.

There is a high radiation resistance at the beginning and end of the line representing the radiation. In the diagram a typical total resistance of 200Ω is shown; thus there is 400Ω at the patch edge because the two load resistances can be thought of as being in parallel.

The voltage goes through zero at the centre of the patch and thus the input impedance equals zero. Thus there is a point somewhere between the centre and the edge of the patch where the input impedance will be 50Ω - that is marked as the feed point.

The patch width (line width) only affects the self-resonant frequency slightly with this construction method. In practice the square patch is always used. If the width is increased (the patch made wider than it is long), the bandwidth increases and the radiation resistance becomes smaller.

Software is always used to design such antennas nowadays. For a long time the DOS program "patch16.zip" was used that was developed in form of a recipe for rectangular and square patch antennas (it can be found on the Internet). Modern designs use one of the "EM simulators for surface structures" and the most popular is Sonnet. For the private user there is an extremely efficient and free LITE version of this program enjoying worldwide popularity on the Internet. A Sonnet Tutorial in English or German can be downloaded from [1]. This has a complete practical design of a patch antenna for 5.8GHz described in detail.

A question remains to be answered:

Why and how does such piece of copper radiate at all?

For this, take a look at Fig 2. Taking a careful look there is an electrical scattering field at the outer edges of the patch (fringe fields) and this gives the solution! At the left and right edge the voltage is in anti phase (see Fig 1), interestingly the lines of flux at the edges both point in the same direction and are in phase! Thus these two patch edges with their scattering fields work as two parallel connected "slot antennas" (a slot antenna is similar to a dipole antenna supported on a mast. That consists of a wire and has air as an environment. The slot antenna has that, but exchanged: the mast antenna is replaced by air and in place of surrounding air, now there is a copper surface. Thus the directions of the electrical and magnetic fields exchange themselves).

Thus the question of the polarisation of

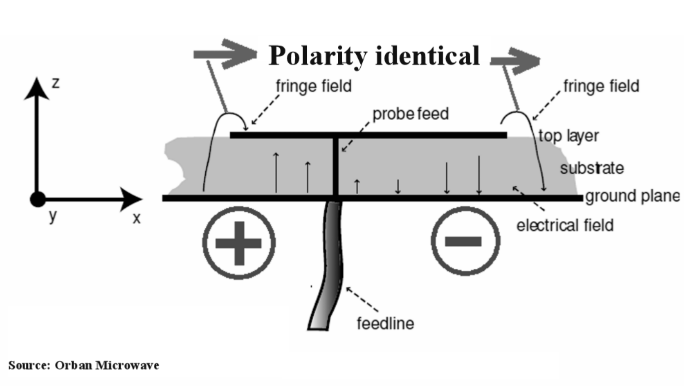

Fig 2: Despite the anti phase polarity of the voltage at the two line ends, the lines of flux are in the same direction as shown. See text.

the radiated electrical field is answered because this corresponds to the two arrows at the top of Fig 2. If the metallisation of the PCB lower surface projects sufficient far past the patch, it works as a screen and prevents the backward radiation (in Fig 2 the antenna will only radiate upwards). The radiation pattern of a simple dipole antenna is the familiar figure eight. The ideal patch antenna is missing one half of this eight, giving a simple circle without backward radiation.

3. Circularly polarised patch antenna

3.1. Circular polarisation

The principle of circular polarisation is to work with two antennas:

- Radiating individual fields at 90 degrees to each other.
- Additionally the two antennas are fed with signals that have a 90 degrees phase difference.

That has astonishing consequences, viewed from in front of the antenna; the polarisation of the radiated field rotates nonstop in the circle like a propeller. Since the fields move away with the speed of light the radiation vector describes a spiral (more descriptively; a corkscrew).

A linear polarised antenna can be used for reception because no matter how it is aligned it always receives this propeller movement of the radiation vector giving the same antenna voltage. Twice per revolution this vector is aligned with the linear polarised receiving antenna and results in maximum antenna voltage (with opposite sign). Likewise the vector is perpendicular to the antenna twice per revolution and produces no antenna signal. The drawback is that only one of the two radiated EM field components is received and therefore 3dB less signal than a circularly polarised antenna (with the correct direction of rotation).

3.2. Production of the circularly polarised patch antenna

This is not difficult at all because both antennas at 90 degrees to each other are already available by the length and width of the patches. As soon as they are fed with two signals at 90 degrees to each other (a 90 degree shift is produced using a power splitter with an additional quarter wave line), the problem is solved, see Fig 3.

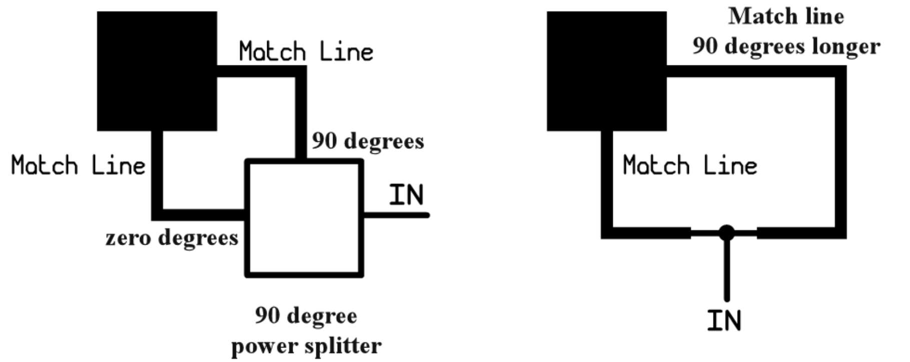

Fig 3: The two possibilities to produce circular polarisation with a square patch antenna.

There is another much simpler, but highly interesting way:

By using different dimensions for the patch length and patch width the resonant frequencies for the two antennas are easily shifted. In an equivalent circuit each antenna can be represented by a tank circuit producing an interesting effect when fed at the centre frequency.

The shorter antenna (e.g. formed by the patch length) is operated below its resonant frequency and behaves like an inductance. The current lags the voltage. The other longer antenna (in this case the patch width) is operated above its resonant frequency and behaves like a capacitor with leading current.

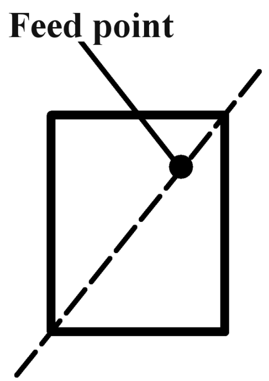

Fig 4: First possibility: Length and width of the patch are different, the feed point lies on the diagonal. See text

When the same voltage feeds both antennas within, for instance, 1 to 3% of the resonant frequency it gives the desired 90-degree phase difference between the two antennas (responsible for the radiation).

Naturally the feed point must be selected correctly so that both radiation directions become excited. Usually moving diagonally across the patch face finds the feed point.

The voltage is always zero at the patch centre (with maximum current) giving an impedance of zero. At the patch edges the radiation resistance measures more than 100Ω. Therefore between them a feed point of 50Ω input impedance can be found. In practice there are one of these three possibilities:

- In Fig 4 length and width have different dimensions, the feed point lies on the diagonal. This version is unfortunately very sensitive to tolerances. Differences of a hundredth

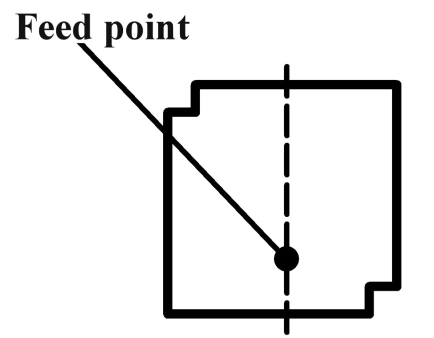

Fig 5: Second possibility: the patch is square with the corners punched out, the feed point is on the centre line.

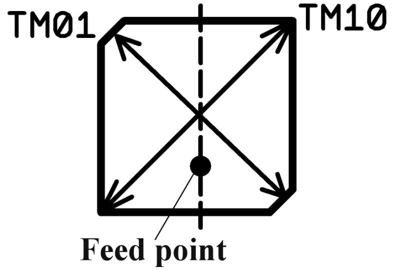

Fig 6: Third and most popular possibility: the corners are cut at 45 degrees, otherwise the same as Fig 5.

of a millimetre in the length or width greatly affect the feed point.

- Fig 5 shows a square patch with punched out corners. The feed point is on the centre line. The size of the punched out corners determines the difference of the two resonant frequencies (and works like different coupling with a double-tuned bandpass filter). Now the patch diagonals are different lengths and form the two antennas. This version is easy to design.
- The most frequently used variant is shown in Fig 6. It is a square patch with corners tapered at 45 degrees. This gives diagonals of different lengths (as with B) to ensure circular polarisation. It develops a TM01 and a TM10 mode with the individual waves. It gives the same behaviour as B), it is more good-natured and error tolerant. Such an antenna is to be described now.

4.

Antenna design with Sonnet Lite

(Preface: The design process to produce the final version that can be converted into a PCB antenna naturally takes innumerable simulations to arrive at the optimum. These will be skipped over here but are assumed to have taken place.)

First a few words about Sonnet (for those who have no experience):

Sonnet is a marvellous thing, an EM simulator (using the moment method) for all conceivable planar structures. These are mainly Microstrip, Stripline or Coplanar circuits including; couplers over transformation lines, filters, Gaps and Stubs can be examined and patch antennas etc. For those coming from SPICE simulation or S parameter simulation there are some introductory problems because an EM simulator contains every-

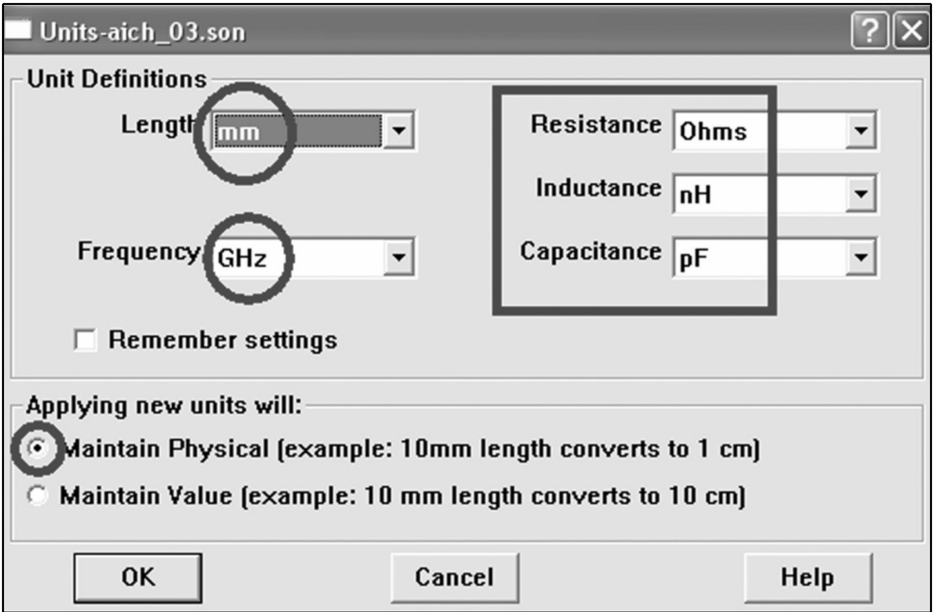

Fig 7: The basic parameters to be set when starting Sonnet.

thing but everything is different. First the structure to be examined must be divided into small cells that are valid for consideration. The characteristic of each individual cell is examined, computed, stored and then the program combines them by integration into the total effect. Each item under test by Sonnet must be placed in a cubical metal box where several basic adjustments to are made.

The walls of the box are always made of loss-free metal therefore they work as mirrors. The cover or the ground looks different; if e.g. an antenna is simulated the energy must escape from the box somewhere (in this case via the cover).

Therefore there are different options, i.e. loss-free, WG load, free space and naturally a metal that can be selected, e.g. copper.

The field behaviour in such a box is well-known and calculably, producing simulations with quite high accuracy. It depends on, the cell size selected normally somewhere between 1% and 4% (the smaller, the more exact, however more computing time is required) and attention to the rules, particularly with the restrictions of the Lite version. Sometimes the resonant frequency is simulated a little too high particularly with resonant objects (e.g. patch antennas) - that must be known and manually adjusted.

4.1. Setting attributes

When the program is started the Sonnet task bar appears. Start your own project from “Project/new Geometry”.

Open the “units” window from the “Circuit” menu and set the values: mm, GHz, ohms, nH, and pF as shown in Fig 7.

Open the “Metal Types” window from the “Circuits” menu and set the values as shown in Fig 8. If only “Lossless” is in the list, click on “ADD” and then on “Select metal from Library” and choose copper. Click OK to open the Property menu of the copper layer; this should then look like Fig 8. The thickness of the

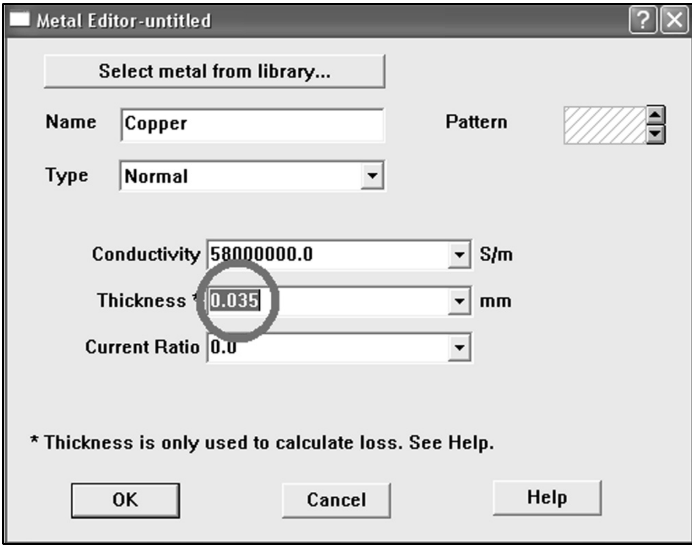

Fig 8: This is important: The PCB is 0.035mm thick and coated with copper.

copper layer is set to 35µm = 0.035mm and confirmed by pressing OK. The overview menu ensures that everything drawn later is realised in copper (Fig 9).

Fig 9: Do not forget this: All objects in the structure will be made from copper.

This can be identified easily in the drawn structures because copper surfaces appear in green and lossless surfaces in red.

Now select the "Dielectric Layers" option from the "Circuits" menu and select the "Edit" option on the upper level for the air cushion in the box to be simulated by Sonnet (Fig 10). This air cushion (according to Sonnet manual) should be about half a wavelength thick for a patch antenna - that would be about 60mm. To improve the overview add "Air" to the names.

This is confirmed with OK then final select the "Edit" option for the lower level. The PCB will be made from Rogers RO4003 material with a thickness of 32MIL (0.813mm) with a dielectric constant of ε_r = 3.38 and a dissipation

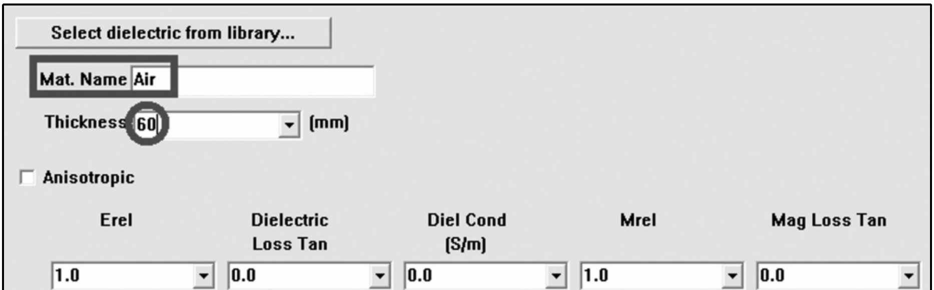

Fig 10: The area above the PCB in the box is filled with a thick air layer. See text

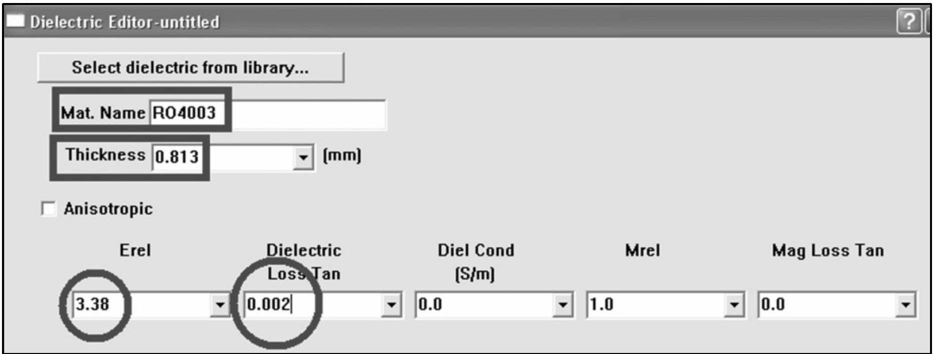

Fig 11: The characteristics of the PCB material (Rogers RO4003) must be registered accurately. See text.

factor - "loss tangent" = 0.002 at 2.5GHz. This data is entered in sequence in accordance with Fig 11.

Now the most important thing, i.e. the "Box" that Sonnet will use for the simulation is shown in Fig 12. The dimensions of the "cells" that Sonnet will use to divide the structure must be specified. A good approximation is 1% of the wavelength, this would a bit more than 1mm x 1mm in this case. But: smaller cells give higher simulation accuracy, however in the Sonnet Lite version 12.53 the memory is limited to 16Mb. Therefore 0.5mm x 0.5mm was selected.

Sonnet recommends that the structure to be simulated should be kept away from the box wall by between one and three wavelengths. For the patch antenna the maximum should be used if possible if the Lite version does not terminate with an error message. The cover of the box

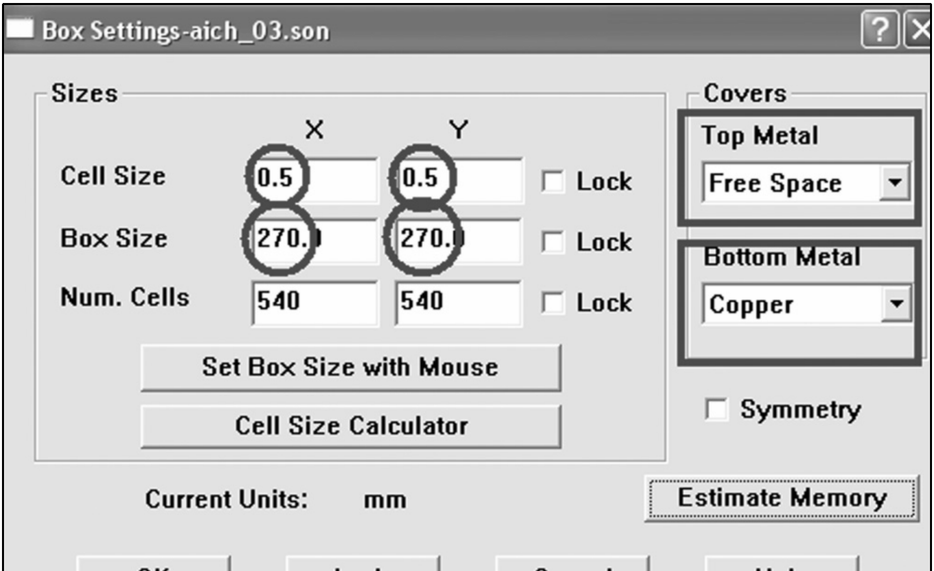

Fig 12: Very important: the entries for the cell size and the box dimensions as well as "free space" for the cover. See text.

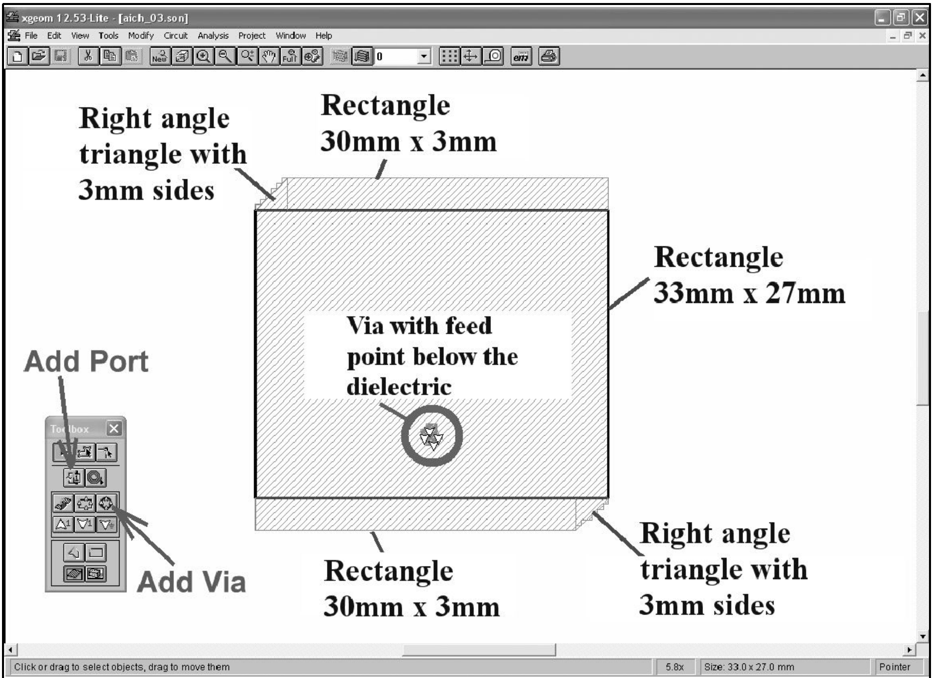

Fig 13: After some work: The complete antenna structure is centred provided in the box.

may not consist of metal. That must be replaced with "Free space" because we want it to radiate. Copper is used for the ground of the box.

The box size should be:

2 x wavelength + 1 x Patch edge length,

therefore approximately:

2 x 12cm + 3cm = 27cm.

That fits into the approved 16Mb of main memory for the Sonnet Lite version.

The preparations are complete and it time to draw the antenna structure. It consists of a square with 33mm long edges with the corners shortened by around 3mm each. This can be constructed from three rectangles and two triangles (Polygons) see Fig 13. There are some useful tools

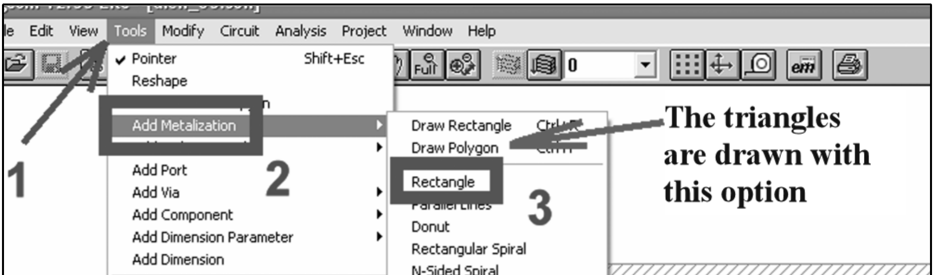

Fig 14: The tools to draw the rectangles and triangles.

Fig 15: The feed port can only be seen if you switch to "ground" on the menu.

for drawing the structure that make drawing the three rectangles as well as the two triangles child's play. Select the path:

"Tools/Metalization/Rectangle

and

"Draw Polygon" (see Fig 14).

After the puzzle has been joined together and positioned in the centre of the box a plated through hole (via) with a diameter of 1.27mm must be inserted at:

Position X = 16.5mm Y = 9mm

(relative to the lower left corner of the antenna)

Before adding the "via" set the zero point (origin) on lower left corner of the patch. This can be done easily, right click on the patch to open the menu and select "Place origin". The "via" diameter (1.27mm) corresponds to the pin of the SMA socket used, this can be adjusted in the menu. Another port is required that is attached automatically after the placement on the "via" by the program on the lower surface of the dielectric. This port can only be seen if the "Ground" level is selected (Fig 15), it presents itself as a simple rectangle with the number "1" inside. Double clicking on this number opens the Properties menu to correct the attributes (type = Standard/Resistance = 50Ω). Now the simulation can be started.

4.2. Simulation

First go to "Analysis" on the main menu and complete the Setup as shown in Fig 16. Set: Start, 2.4GHz; Stop, 2.5GHz and "Adaptive Band Sweep ABS" that results in shorter computing time, the current

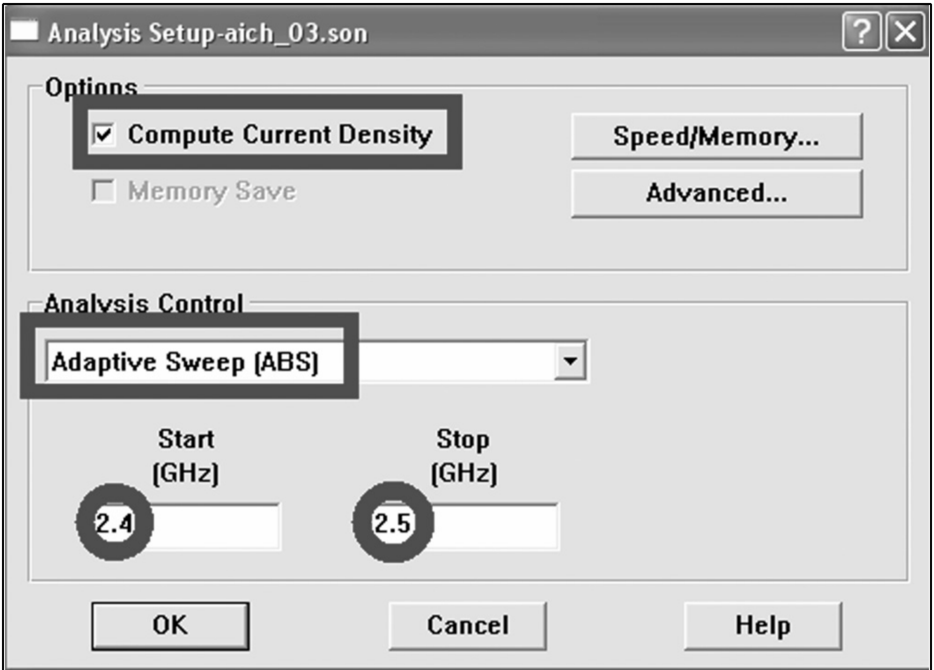

Fig 16: The last job before starting the simulation is to programme the sweeps.

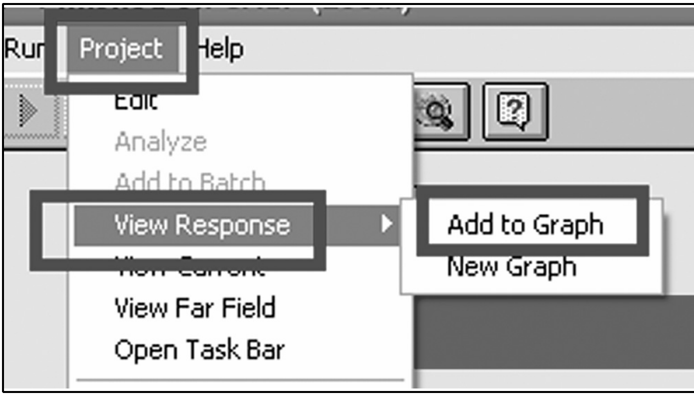

Fig 17: As is the case for most modern programs, nothing is displayed after a successful simulation. The output results must be programmed.

density on the patch can also be calculated.

Start the computation by pressing the "EM" button on the right above in the menu border. If it ends successfully the results shown in Fig 18 can be selected as shown in Fig 17. The resonant frequencies of both single antennas can be recognised and the desired operating frequency should lie in the centre. The resolution of Sonnet Lite is limited but we must be content with the result. Click the "Graph/Type/Smith" option in the menu on the border to display the Smith

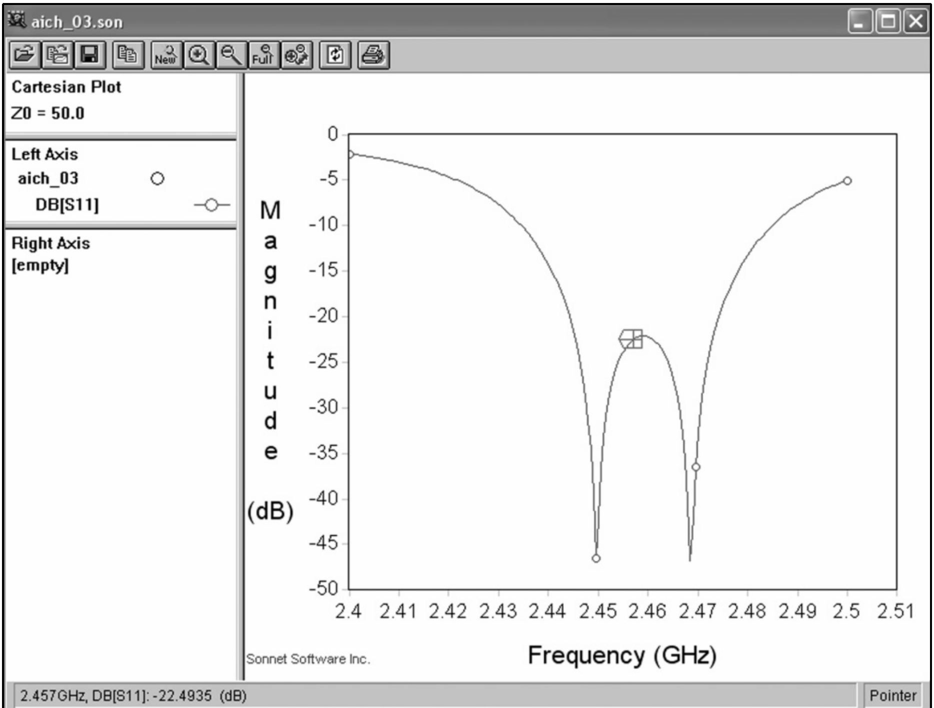

Fig 18: The results are pleasing and show that the design is correct.

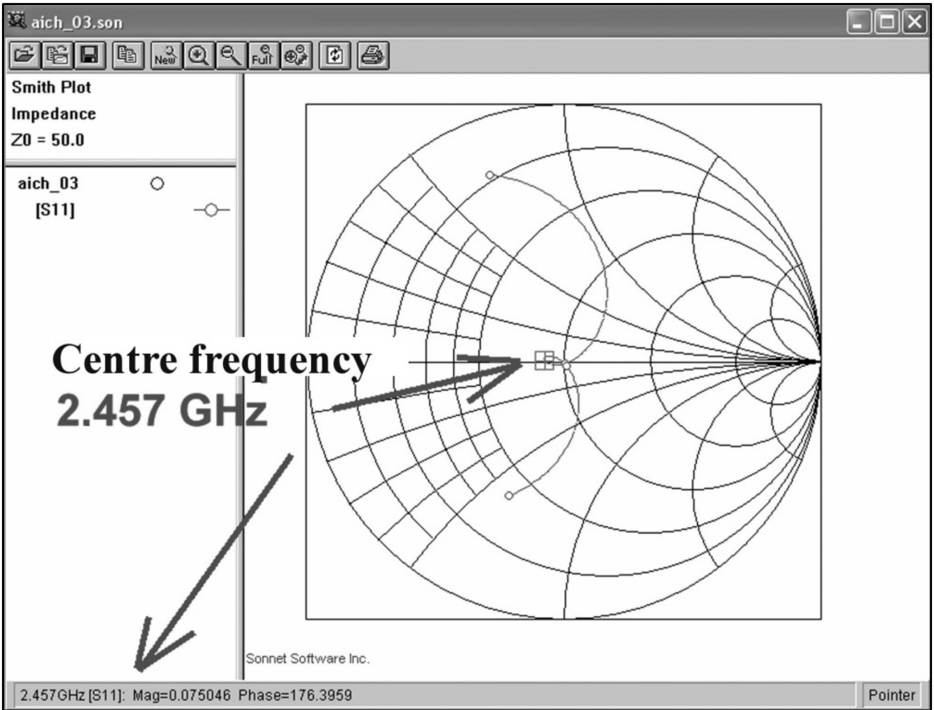

Fig 19: The Smith chart can be produced for the specialists after providing substantial additional information.

chart shown in Fig 19 after some computation.

Having reached this point simulations were stopped and a prototype PCB was made and measured. A centre frequency of 2393MHz was measured (approximately 2.5% lower than desired).

In relation to the required value of 2.45GHz it was too low by the factor (2393/2450) = 0.9767346. The patch measurements were made smaller by this amount and a new PCB made.

The external dimensions of the patch were therefore:

0.9767346 x 33mm = 32.23mm

and the corners:

0.9767346 x 3mm = 2.93mm

Now the new feed point is (measured from the left lower corner):

X = 0.97673 x 16.5mm = 16.12mm

and

Y = 0.97673 x 9mm = 8.79mm.

The results were most interesting and can be seen in Fig 20.

The centre frequency was approximately 8MHz too high in the last simulation and then it was too low when measured. When the new PCB was measured it was approximately 10MHz too low and the two resonant frequencies of the antennas were somewhat further from each other. That means that the corners would have to be filed to cut off the corners because these are responsible for the frequency difference of the antenna resonances (this is reminiscent of the coupling of a double-tuned band-pass filter). But this

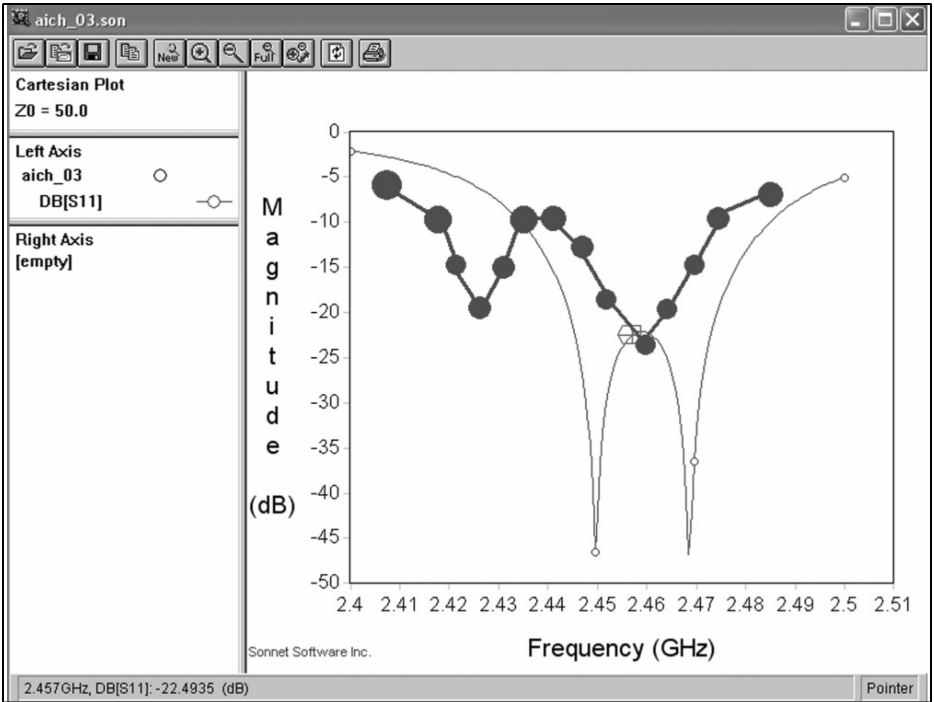

Fig 20: That is the difference between theory and practice! The result is 10MHz below the required centre frequency of 2.45GHz.

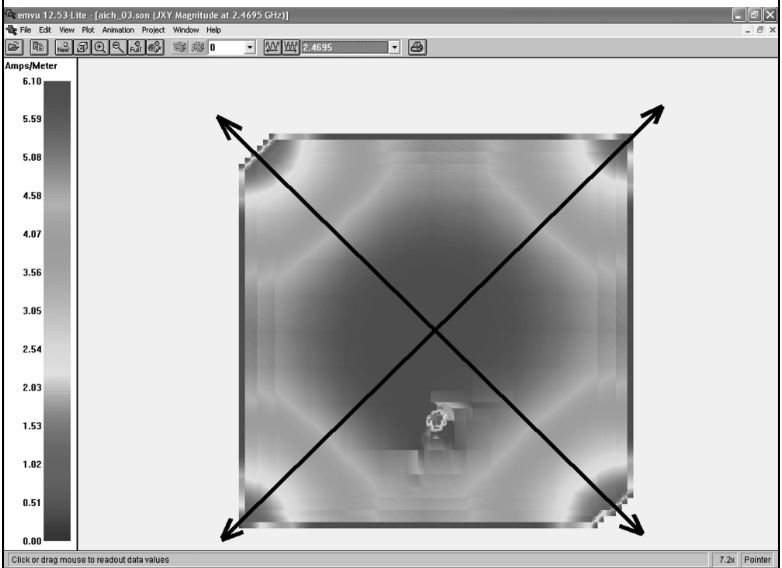

Fig 21: The current distribution at the required centre frequency is fascinating. It is easy to see the two active antennas, even in black and white. It looks much better in colour - Andy.

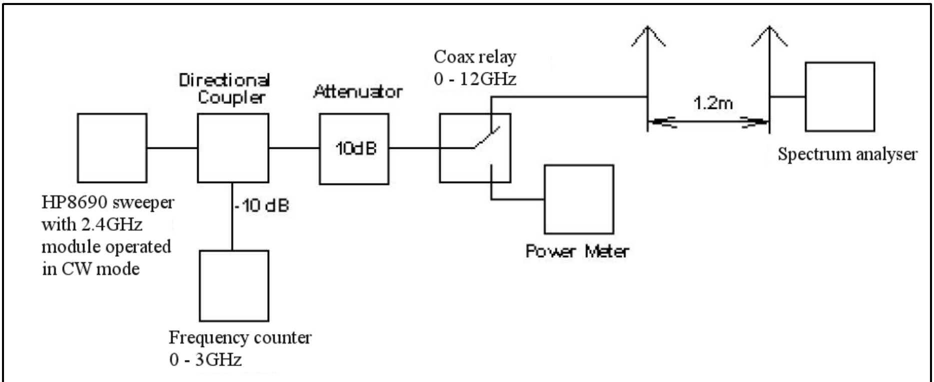

Fig 22: This is the measurement setup (here for 2.45GHz) that has been used successfully several times to perform gain measurements on antennas in the far field. See text.

could be continued eternally…

4.3. The current density

In the menu on the border when the patch is drawn there is an option "View Current" under "Project". Selecting the frequency f = 2450MHz in this option shows visual confirmation of the theory and simulation. It is very beautiful (much better in colour - Andy) showing the two radiating diagonals because the current is zero at the four corners and maximum at the patch centre (Fig 21).

5.

Radiation pattern and gain

The measurement setup shown in Fig 22 was used with the first two identical linear polarised patch antennas that were perfectly adjusted (input impedance accurately = 50Ω). The left antenna is fed with exactly 1mW (zero dBm). A frequency counter supplies information over the measuring frequency. The gain measurement takes place according to the method shown in full in [1]. Here is an edited version:

The distance between the two antennas was 120cm and this corresponds to approximately 10 wavelengths at 2.45GHz. Thus one is in the far field giving a receive level so that the famous "Friis formula" is valid:

$$P_{receiver} = P_{sender} \cdot G_{senderantenna} \cdot G_{receiverantenna} \cdot \left(\frac{\lambda}{4\pi \cdot d} \right)^2$$

If this is converted into logarithmic representation and remembering that both antennas are identical, the formula takes the following form for "dB" representation:

$$\mathrm{Re}\,ceiverlevel = Senderlevel + 2 \cdot antennagain + 20 \cdot \log\left(\frac{\lambda}{4\pi \cdot d} \right)$$

With a transmit level of 0dBm, an antenna distance of 120cm, a wavelength of 12.24cm and the two antennas with identical behaviour a receive level of –29dBm results. Changing the above formula round for the antenna gain the result is:

$$Antenngain = \frac{\mathrm{Re}\,ceiverlevel - 20 \cdot \log\left(\frac{12.24cm}{4\pi \cdot 120cm} \right)}{2} = \frac{129dBm + 41.8dB}{2} = 6.4dB$$

A condition for a correct result is that the measurement is in the genuine far field. Increasing the antenna distance the antenna gain determined according to this

Fig 23: The final result, the prototype antenna, measured and given to the model flier.

formula and method remains constant. For antennas with very high gain and too small distance to the transmitter an error can occur and the computed gain can suddenly become negative. The gain produced can be interpreted in such a way that it is produced between the transmitting and receiving antennas or that the transmitting power of the generator was raised. In each case these antennas form the near field (Fresnel zone) or the zone up to the far field, called the Fraunhofer-Region.

Therefore the default must be that the distance between the two antennas is greater rather than too small (the receive level should still be determined correctly and with changes in distance the gain determined should remain constant). This information and considerations originate from the publication [3] that can be found on the Internet.

Back to the current project. The control antenna connected to the analyser input was replaced by the new circularly polarised version. It was then turned in steps of approximately 30 degrees in a circle and at each angle the change the level from the spectrum analyser was read.

Ideally (according to the theory) a constant level decreased by 3dB would be to be expected in relation to linear polarisation with the radiation pattern that should be a circle (logically with circular polarisation the transmitting power is split in two equal components shifted by 90 degrees not only spatially but also in the phase. The linear polarised receiving antenna can only receive one component - thus one antenna receives only half the maximum power possible and that is the 3dB mentioned). The fact is that everything is not so simple as it sounds as shown in the appendix of the article written for the specialists. In the literature [2] it was suggested that the ideal case is rarely reached in practice and an ellipse instead of the circle is usually observed. But less gain in the two minima by up to 3dB can normally be tolerated. Unfortunately there was between 4 and 5dB!? Fortunately this effect was not as strong in practice as feared and the model flier was overjoyed (original quotation from his mails: "I tested the antenna in the model airfield and determined at ground level a range increase of 30 - 50%"). Fig 23 shows the prototype supplied including an SMA semi rigid cable fitted that has been given an acid test in the field.

P.S.: The best message last - in the time between giving the lecture and the publication of this article the maximum usable main memory for the newest Sonnet Lite version 13.51 has increased from 16 to 32Mb. Therefore after the update the above simulations were immediately repeated with a cell size of only 0.1mm x 0.1mm and afterwards even 0.05mm x 0.05mm (0.5mm x 0.5mm in the article). The result reads: only minimum and insignificant deviations and therefore all simulations, results, corrections, measurements and statements are valid. Thank God….

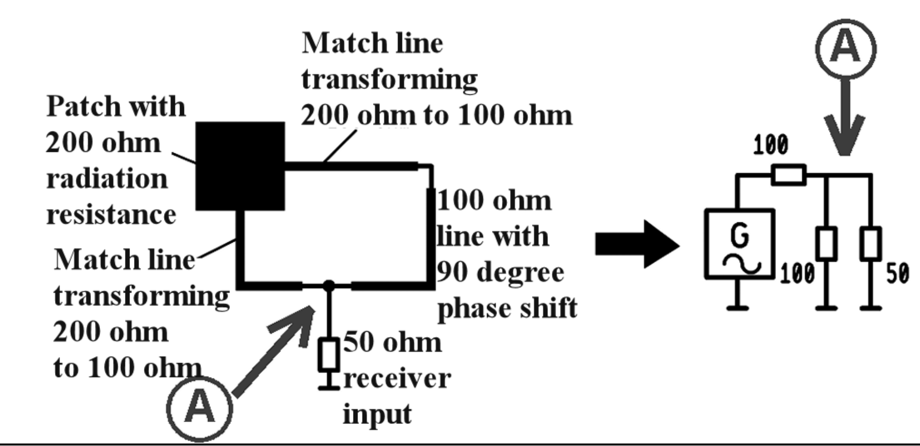

Fig 24: The equivalent circuit produced from the antenna on the left makes it possible to understand the behaviour of the antenna. See text.

6.

Literature:

[1] An interesting program: Simulation and construction of a Helix antenna for 2.45GHz using 4NEC2, Gunthard Kraus, DG8GB: VHF Communications Magazine, 2.2011 pp 89 - 101; (www.elektronikschule.de/~krausg)

[2] Orban Microwave Application note: The Basics of Patch Antennas, Updated. To found on the Internet

[3] Paul Shuch, N6TX: Far Field Fallacy. Appeared in QEX December 1987, find page 10 on the Internet.

7.

Appendix

The level decrease of approximately 3dB when receiving a circularly polarised signal with a linear polarised antenna was justified logically and the simulation confirmed the considerations. This stimulated a discussion among friends and an easy confusion about the procedures with different possible antenna combinations. A list of possibilities is shown below (those that occur in practice) with the signal conditions that can be observed.

A) We begin with the simplest case: Transmitting with a linear polarised patch antenna and using the same linear polarised model for reception. Both antennas are optimally aligned and thus accurately form the case from chapter 5 where the measuring position is calibrated with propagation in the far field. The received level of the antenna can be determined according to the Friis formula and simply named "P1".

B) Both linear polarised antennas replaced by two identical circular polarised antennas (see chapter 3.2, Fig 3). The power supplying the transmitting antenna is divided into two portions out of phase by 90 degrees and then supplied to the two individual antennas at 90 degrees to each other. The two radiated signals are then only half transmitting power. On the receive side two individual antennas at 90 degrees to each other pick up the signals, that is half the size of P1, to produce a received level. These two halves are phased together; the phase difference is correctly compensated by 90 degrees with the phase shifter in one arm of the circular polarised antenna. That results in the level P1 at the receiver input. But be careful: “phased” means that the receiving antenna must exhibit exactly the opposite circular polarisation to the transmitting antenna…

C) The transmitting antenna is circular polarised and the receiving antenna is linear polarised. Thus only one of the two radiated components is used and the linear polarised receiving antenna supplies only half of the level P1. That results in the famous 3dB less gain in relation to case A), but the advantage is that the receiving antenna can be rotated at will.

D) This is getting exciting with the possibility of a linear polarised transmitting antenna and a circular polarised receiving antenna. The linear polarised transmitting antenna radiates the full power only in one polarisation plane. If the circular polarised receiving antenna is aligned accurately to the transmitting antenna, the same receiving level P1 is developed as in case A). The path of this energy in the phasing circuit is shown in Fig 24.

The received signal (e.g. supplied from the lower right antenna) goes through only a λ/4 matching line to bring the radiation resistance of the patches from 200Ω to 100Ω. The equivalent circuit on the right can be used; this antenna is represented by 100Ω including the matching line as a supply with an internal resistance. This supply now sees a load at point “A” consisting of a parallel connection of the receiver input (50Ω) and the second antenna including its matching line and its phasing line - thus again a resistance of 100Ω. The total resistance of this parallel connection is approximately 33.33Ω. If level P1, coming from the antenna is considered as a incident wave the reflection factor that the supply terminal sees can be calculated:

$$r = \frac{33.33\Omega - 100\Omega}{33.33\Omega + 100\Omega} = \frac{-66.66\Omega}{133.33\Omega} = -0.5$$

Thus the reflected level becomes a portion of:

$$P_{reflected} = r^2 \cdot P1 = [-0.5]^2 \cdot P1 = 0.25 \cdot P1$$

This level is reflected to the feeding antenna and radiated again.

The remaining part is three quarters of P1 and it is feeding two load resistances. But the receiver input of 50Ω absorbs twice of the part which enters the 100Ω transmission line leading to the second antenna.

The result is: The receiver input “swallows” two quarters, thus half of P1 (the familiar 3dB reduction). The remaining quarter of P1 goes to the other transmission line and feeds to the other patch antenna after a 90-degree phase shift.

Summary:

Only one antenna in the circular polarised receiving antenna supplies the level P1 in this example. Half is supplied to the receiver and results in the familiar level difference of –3dB in the case of a circular polarised antenna receiving a linear polarised signal. A quarter of P1 is reflected back to the receiving antenna. The missing last quarter is radiated from the other antenna with a 90-degree phase shift giving a “circular polarised reflection radiation”.

What an effort - it cost a lot of sweat to come up with the details of the procedure. But honestly: The effort was worthwhile?!