Studienarbeit: Planar Multi-Beam Antenna for W-LAN

Presented by
Wu,Liangjun

Supervisor
Prof. -Dr. - Ing. K. Solbach

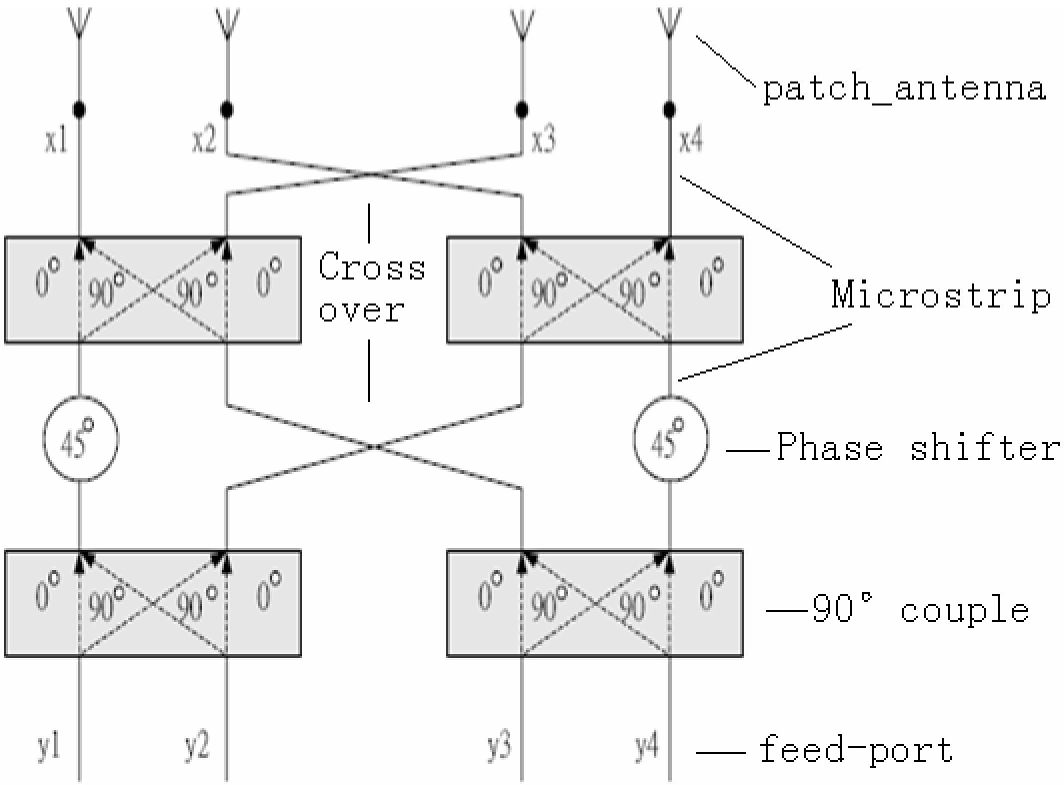
Duisburg
19. 11. 2007

1. Introduction

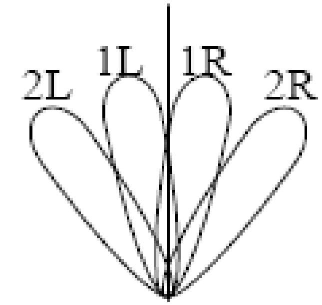
The switched-Beam antenna is one type of the small antennas, which consists of the antenna array and the beam forming network. The four-beam smart antenna generates four beams to cover 120°area.

In this thesis, we design the four-beam forming network called **Butler Matrix** (at frequency 2.4 GHz), which made of four directional coupler-power dividers (90°phase shifter) and two cross coupler (0dB).
And we use microstrip antennas as array elements.

For a special requirement, we can reduce the element spacing and bend the planar substrate carrying the radiator elements, to get coverage of a full 180°angular in azimuth (hemisphere).



4×4 Butler Matrix

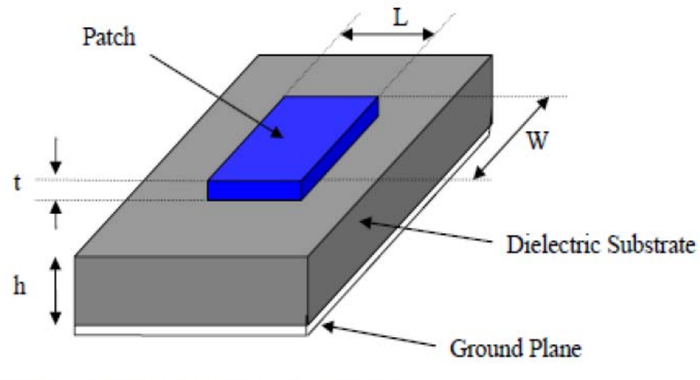


	x1	x2	x3	x4	Main beam
y1	-45	-90	-135	-180	1R
y2	-135	0	-225	-90	2L
y3	-90	-225	0	-135	2R
y4	-180	-135	-90	-45	1L

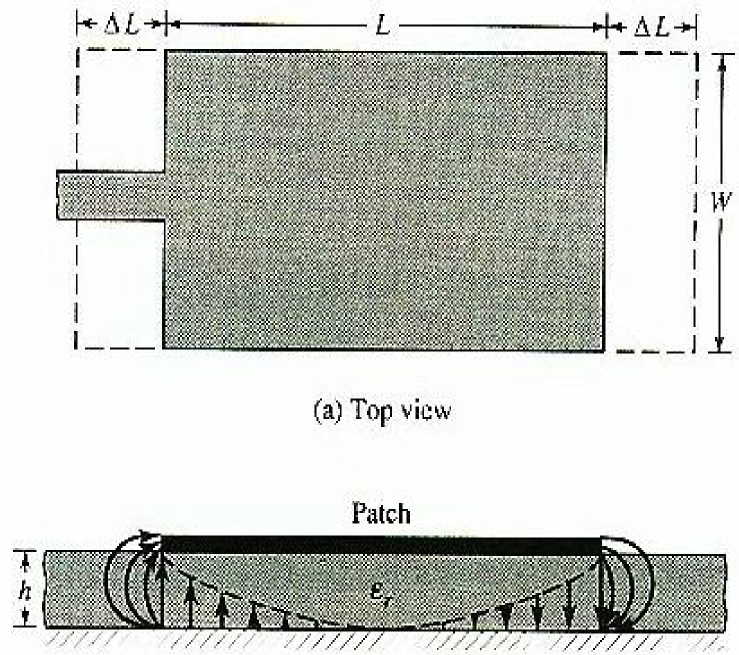
(degree)

2.Patch Antenna

- **2.1 Transmission-Line Model**



Basic structure of a microstrip antenna



(a) Top view

(b) Side view

Fringing Effekt

Leff=L+2 L

L: physical Length

Leff:effektive Length

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

$$\frac{\Delta L}{h} = 0.412\,\frac{(\varepsilon_{reff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{reff} - 0.258)\left(\frac{W}{h} + 0.8\right)}$$

$$L = L_{eff} - 2\Delta L$$

$$L_{eff} = \frac{\lambda_{eff}}{2} = \frac{1}{2}\frac{C_0}{fr\sqrt{\varepsilon_{reff}}}$$

h: Thickness of Substrate W: Width of Patch fr:Resonant Frequency

2.2 Antenna Design procedure

a) The substrate we have is ROGER4003,with

ε_r=3.38, h=0.51mm(35um Cooper), tanδ= 0.0027

b) For an efficient radiator, we let

$$W = \frac{v_0}{2fr}\sqrt{\frac{2}{\varepsilon_r+1}} = \frac{3\times10^8}{2(2.4\times10^9)}\sqrt{\frac{2}{3.38+1}} = 42.23mm$$

c) Using Transmission-Line Model, we have

$$\varepsilon_{reff} = \frac{3.38+1}{2}+\frac{3.38-1}{2}\left[1+12\frac{0.51}{42.23}\right]^{-1/2} = 3.30$$

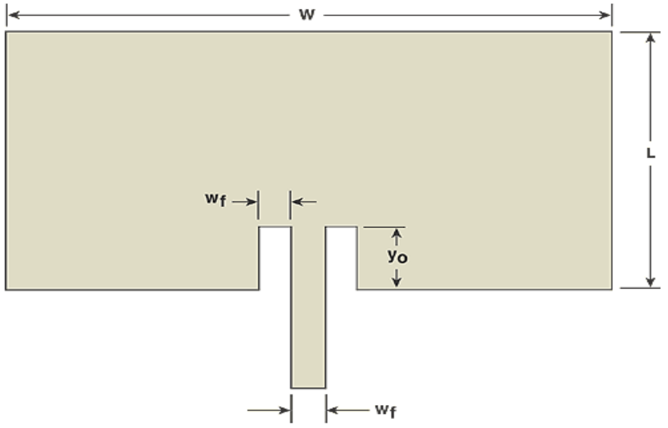
$$\Delta L = 0.51(0.412)\frac{(3.30+0.3)\left(\frac{42.23}{0.51}+0.264\right)}{(3.30-0.258)\left(\frac{42.23}{0.51}+0.8\right)} = 0.243mm$$

$$Leff = \frac{\lambda}{2} = \frac{1}{2}\frac{1}{2.4\times10^9\sqrt{3.30}} = 34.41mm$$

$$L = 34.41-2\times0.243 = 33.92mm$$

d) Microstrip-Line inset-length

From literature, we can approximately have y_0 for characteristic impedance 50 ohm



$$y_0 = \frac{L}{2\sqrt{\varepsilon_{reff}}} = \frac{33.92}{2\sqrt{3.30}} = 9.34mm$$

Let Wf =b=1.141mm

(b:microstrip line width for 50 Ohm)

Also from (http://mwrf.com/Articles/Index.cfm?ArticleID=6993) we can get the exact inset length for 50Ohm input impedance through the mathematical model

$$y_0 = 10^{-4}\{0.001699\varepsilon_r^{7} + 0.1376\varepsilon_r^{6} - 6.1783\varepsilon_r^{5} + 93.187\varepsilon_r^{4} - 682.69\varepsilon_r^{3} + 2561.9\varepsilon_r^{2} - 4043\varepsilon_r + 6697\}\frac{L}{2}$$

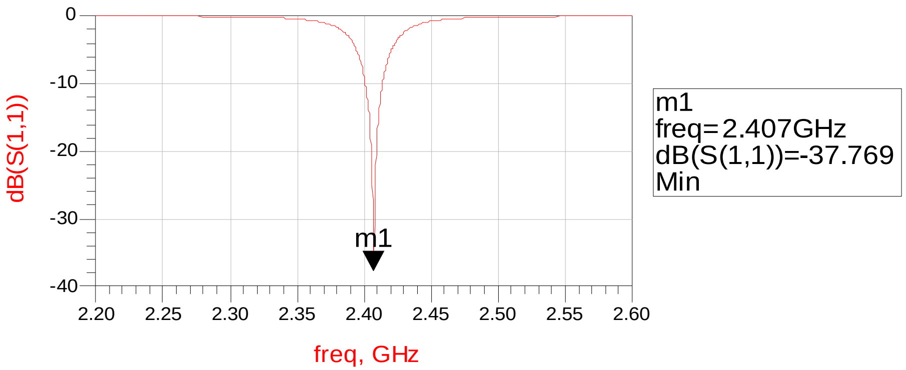
$$2 \le \varepsilon_r \le 10$$

We have y_0=9.48mm

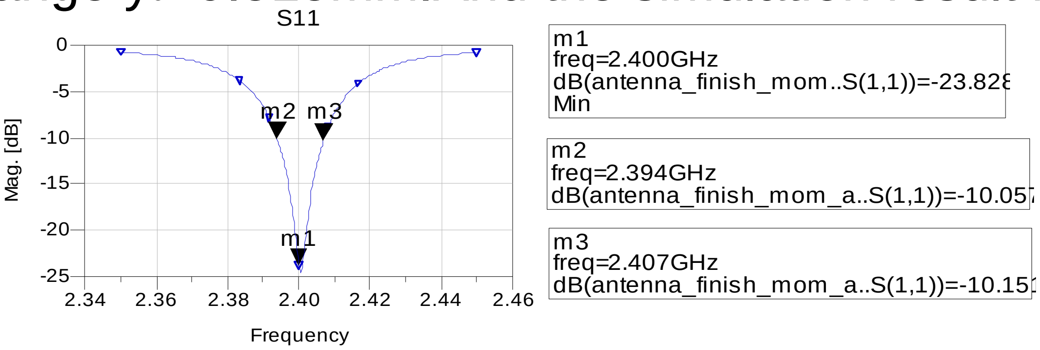
2.3 Simulation of the patch antenna

From 2.2 we have W=42.23mm, L=33.92mm, wf=1.141mm, y_0=9.48mm for the antenna.

Using ADS---Momentum, we draw the antenna and have the Simulation result :



Then we change the L=34.05mm, to get fr=2.4GHz. At the same time, we must change y_0=9.515mm.And the simulation result ist:



Finally we have W=42.23mm, L=34.05mm, y_0=9.515mm. And the bandwidth (at -10dB) of the antenna is approximately B=13MHz (0.542%).

3. Butler-Matrix

3.1 4×4 Butler-Matrix

For Butler Matrix, from literature, we have the observation angle of the Main beam

$$\theta = \sin^{-1}\left(-\frac{\beta}{kd}\right) = \sin^{-1}\left(-\frac{\lambda\beta}{2\pi d}\right)$$

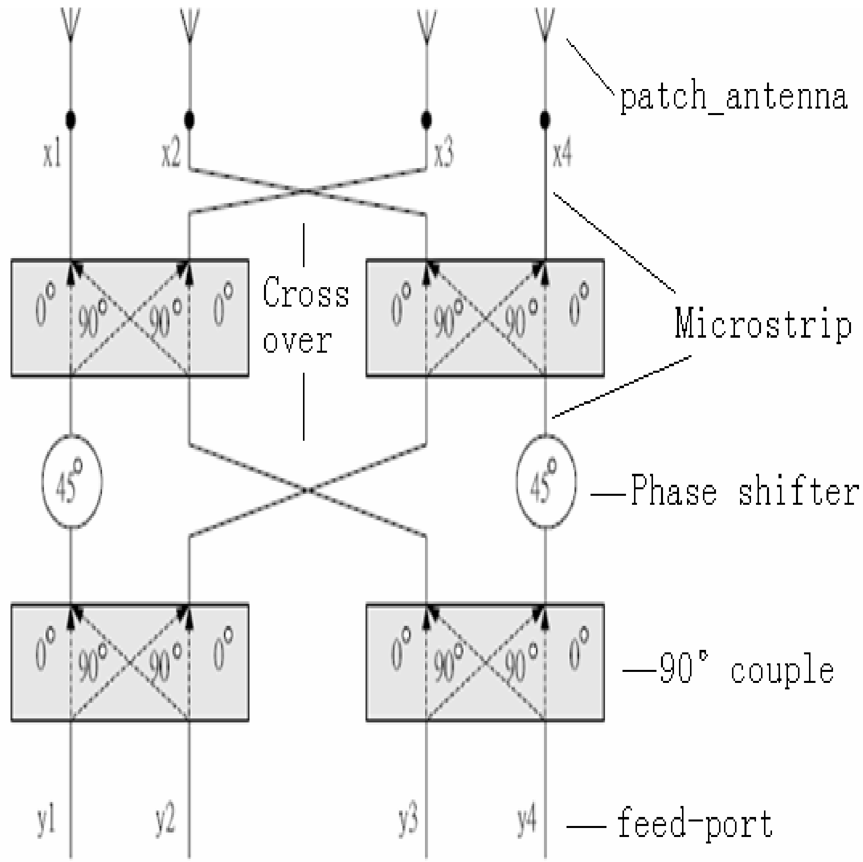
β is the difference of phase between any two successive elements, which is decided by Butler-Matrix

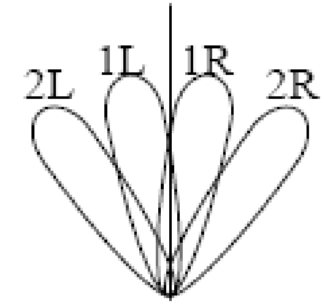
$$\beta = \pm \frac{(2i-1)\pi}{N} \qquad i = 1, 2, 3 \ldots \frac{N}{2}$$

d is the spacing between antennas, by reducing the d,we can have bigger θ

For a 4×4 Butler-Matrix, we have N=4, we let $d = \frac{\lambda}{2}$

Then we can caculate the observation angle of the Main beam (θ)





	x1	x2	x3	x4	β	θ
y1	-45°	-90°	-135°	-180°	-45°	14.5° (1R)
y2	-135°	0°	-225° (135°)	-90°	135°	-48.6° (2L)
y3	-90°	-225° (135°)	0°	-135°	-135°	48.6° (2R)
y4	-180°	-145°	-90°	-45°	45°	-14.5° (1L)

4×4 Butler-Matrix

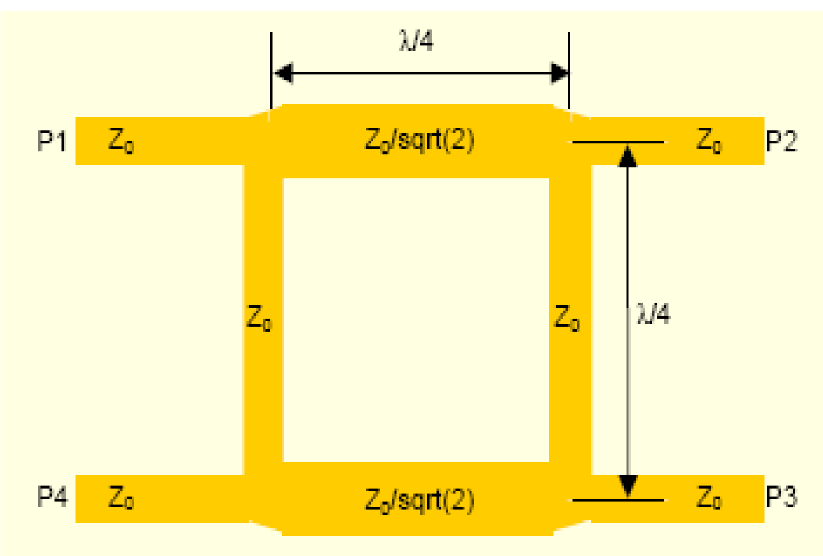
3.2 3dB 90°Hybrid Coupler and Cross Coupler

Using ADS---LineCalc

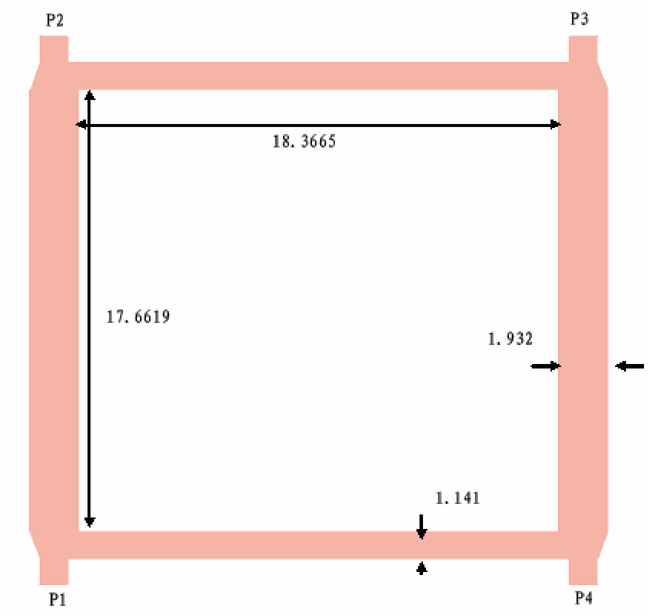
a) For Z0=50 Ohm, W=1.141mm

b) For $Z0 = \frac{50}{\sqrt{2}}$ Ohm, W=1.932mm

3.2.1 3dB 90°Hybrid Coupler

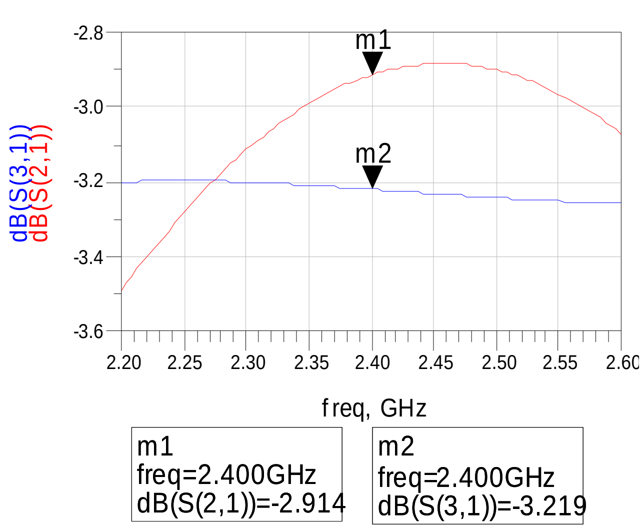


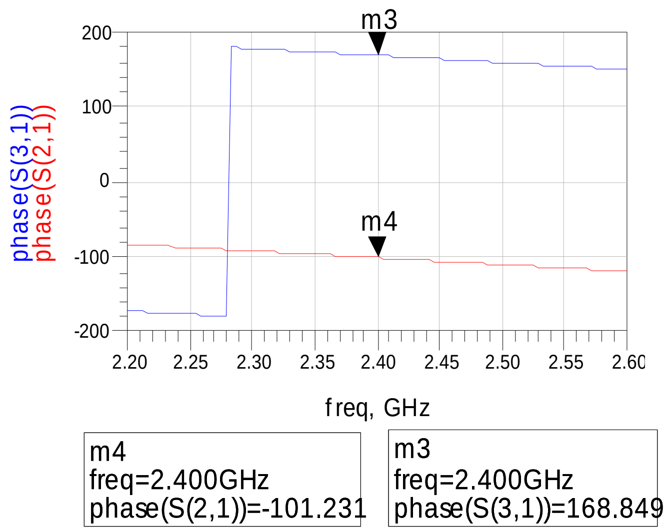
90° hybrid coupler built around transmission lines



The optimized 90°Hybrid Coupler (mm)

And the simulation result of the Hybrid Coupler is

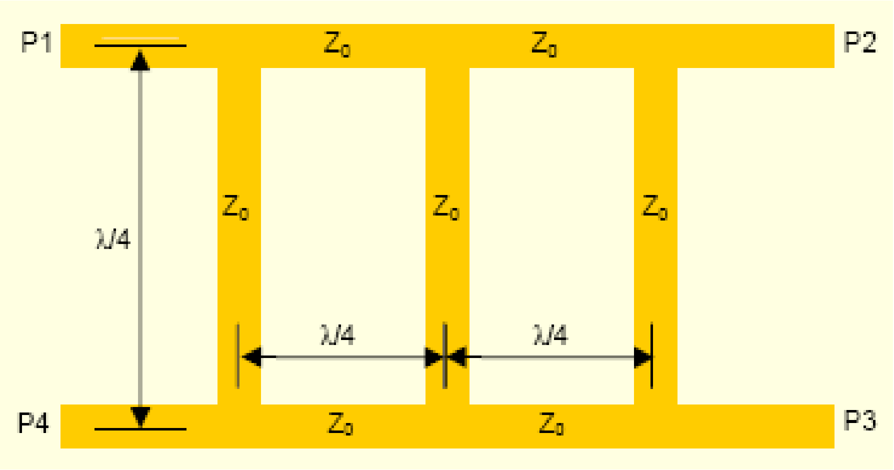




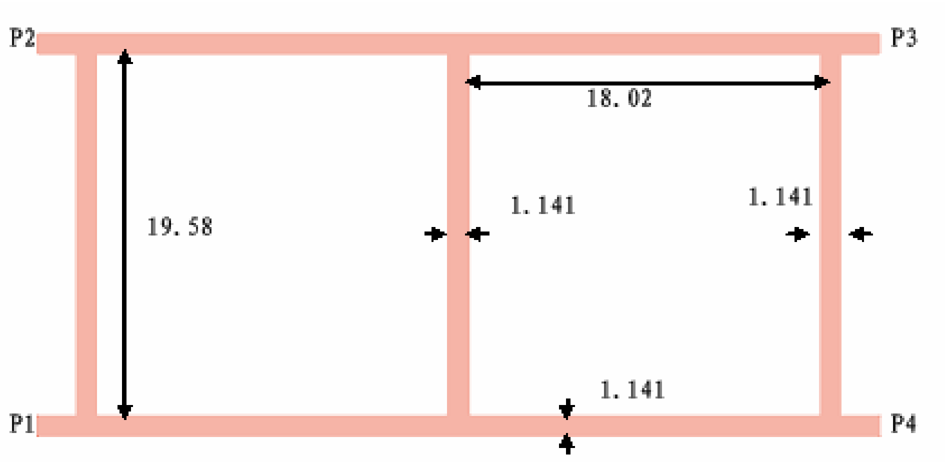
As expected, the phase difference between port 3 and port 2 is 168.849-(-101.231)=270.08 (-89.92) degrees.

And the dB(S(2,1))   dB(S(3,1)) are close to -3dB.

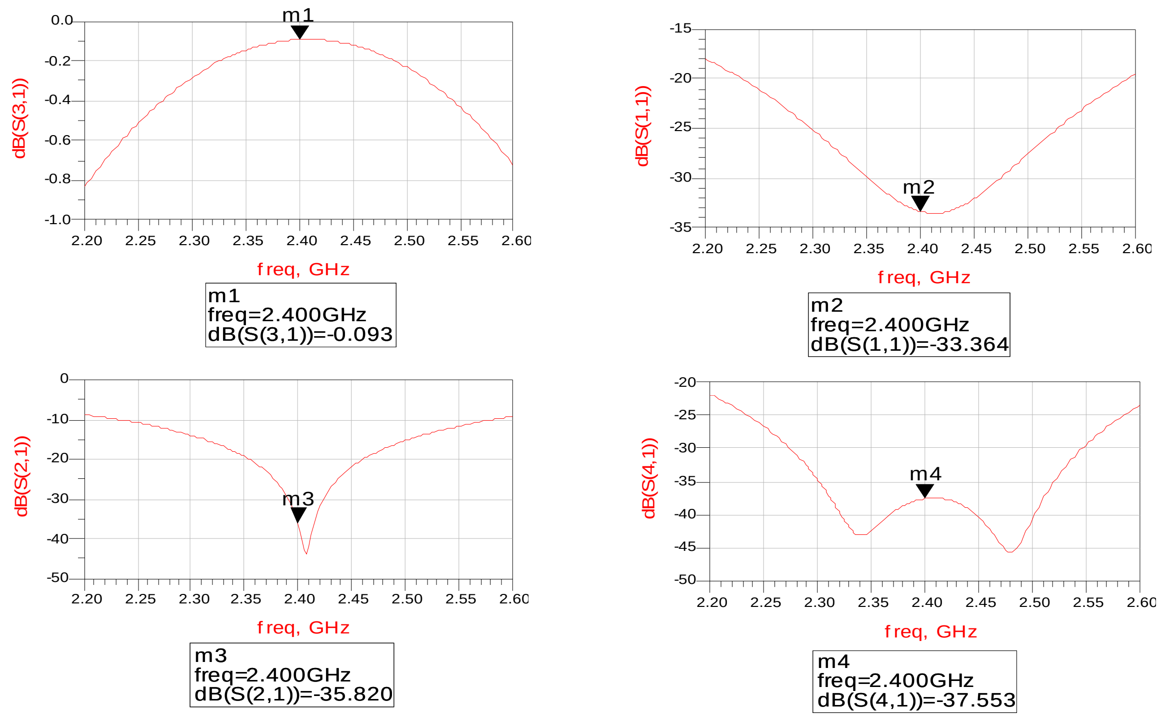
3.2.2 Cross Coupler



0dB Cross Coupler build around transmission lines



The optimized Cross Coupler (mm)

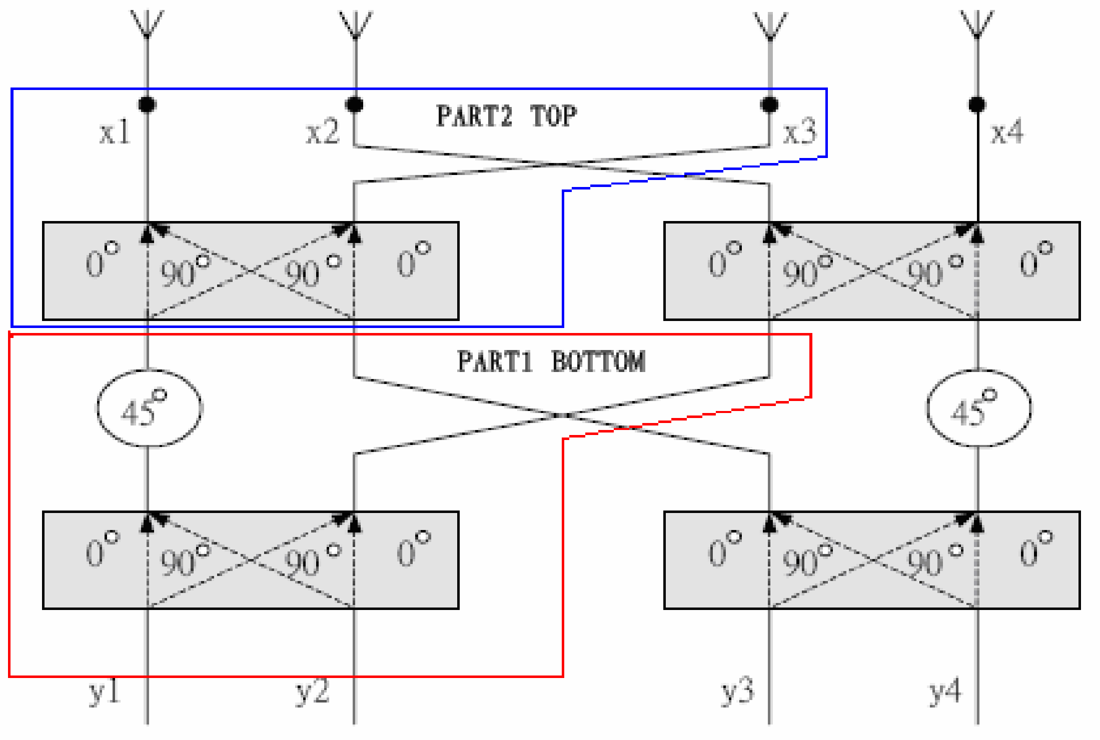


Simulation results of the Cross Coupler

The insertion loss for the coupled port is dB(S(3,1))= -0.093 dB while isolation ports are smaller than -30 dB

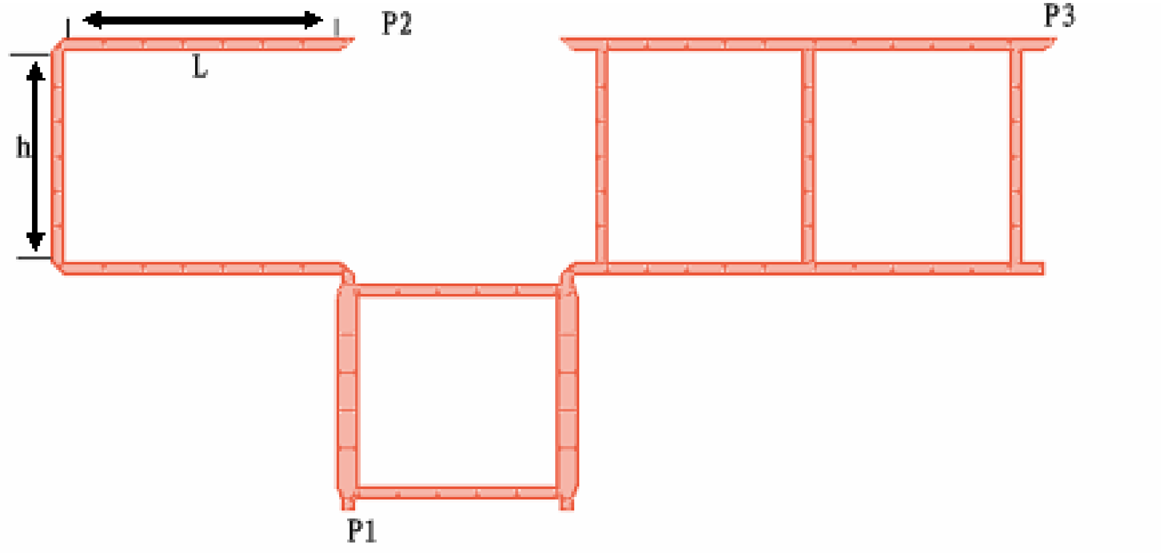
3.3 Optimization and simulation of 4×4 Butler-Matrix Network

The left and the right parts of the Butler Matrix are symmetric, so we can just consider the left side of the Butler Matrix. Now we divide the left side into 2 Parts: PART1 (BOTTOM) and PART2 (TOP).



Two Parts of the Butler Matrix (Bottom and Top)

3.3.1 Part 1 (Bottom)



a) Simulation of the right side Phase (S(3,1))=-129.140°

b) We can caulate h=19.4818mm (the same height with right)

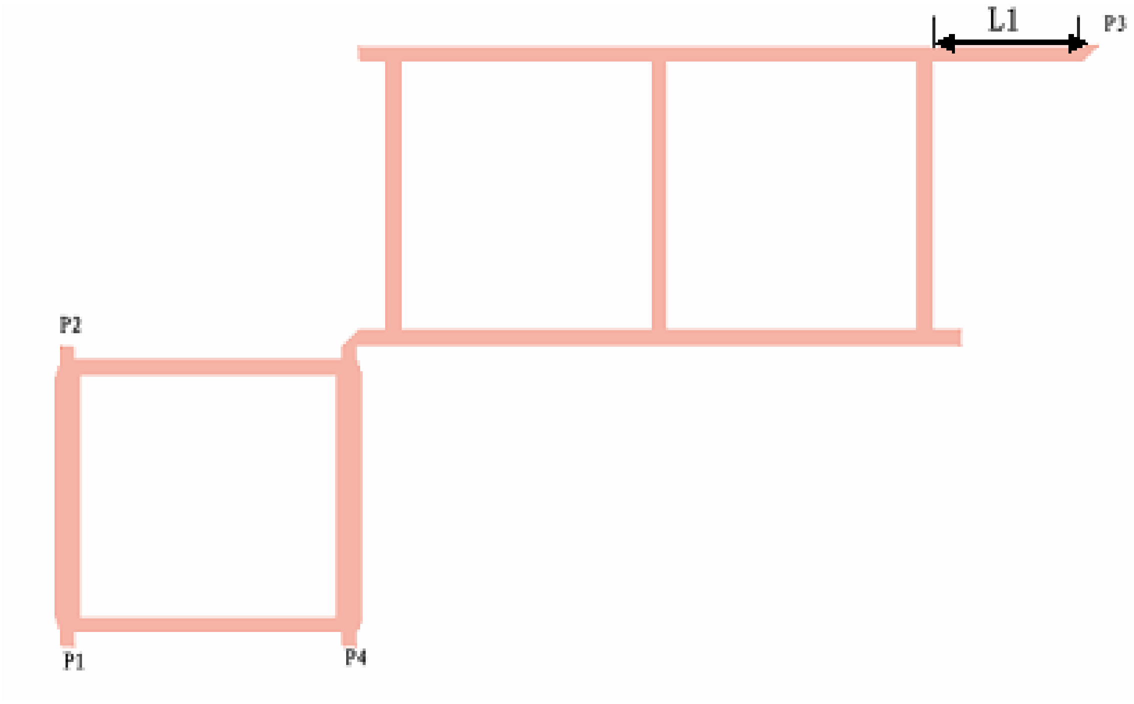
c) S=S31-S21 should be -45°, allow L to vary, set the optimization S21=-84.14°After optimization we have L=25.61mm.

3.3.2 Part2: (Top)

a) Consider right side of the Top, we must let L1=10.8989mm to get the spacing between antennas

$$d = \frac{\lambda_0}{2} = \frac{1}{2}\frac{C_0}{fr} = 62.5mm$$

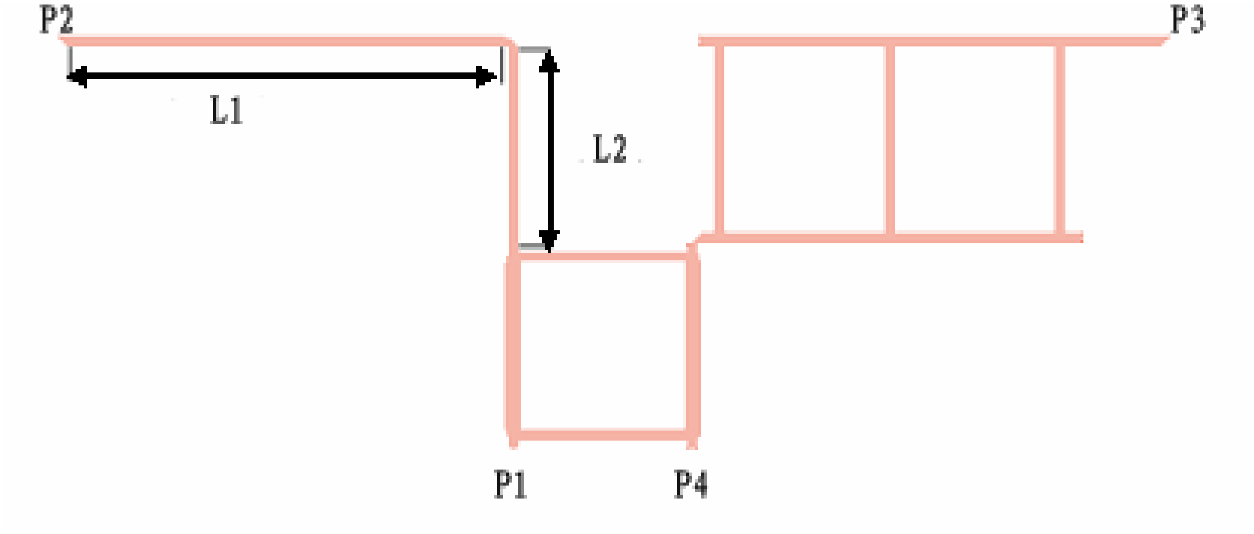
b) Then we have simulation result S31=-170.987°



The right side of the Top

c) Consider the left side, we can caculate L2=20.721mm, we must let L1=49.861mm to get the space between antennas d=62.5mm

d) We have simulation result S21=-78.783°



The left side of Top

e) We have S31= -170.987° and S21=-78.783°.

Then we have S=S31-S21= -92.2037°(Target: -90)

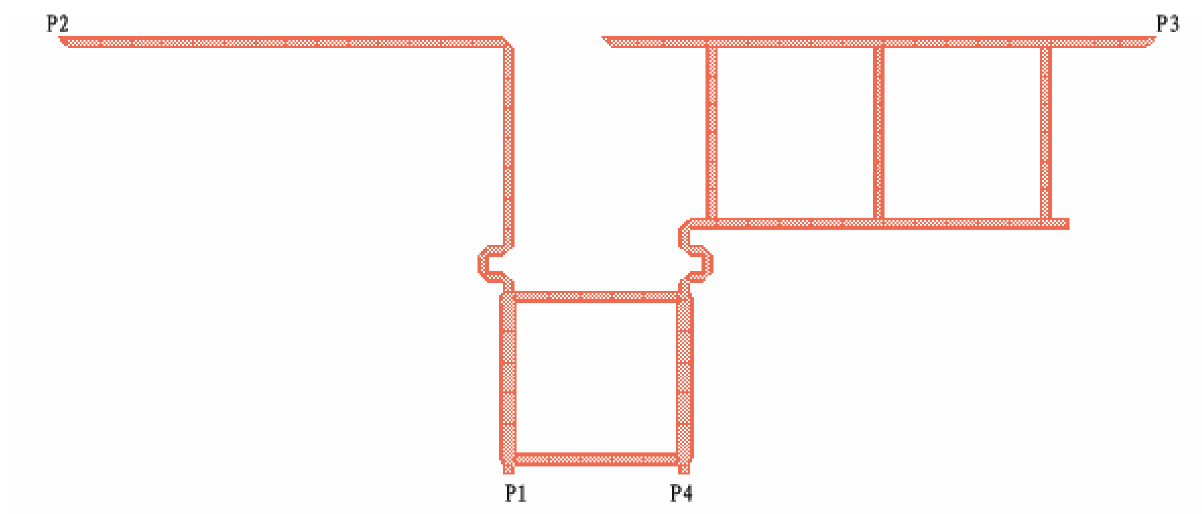
f) This means we should increase ∠S21=-2.2037°, (also L21=0.4708mm). Es is difficult such a short length to increase with bends.

g) Then we have 2 choices:

(1) Increase ∠S21=-2.2037°-360°=-362.2037° (also L21=77.3799mm)

(2) Increase ∠S31, then increase ∠S21= ∠S31+ (-2.2037°)

h) We choose (2),we first increase ∠S31 (arbitrarily), we have the simulation result S31=145.302°

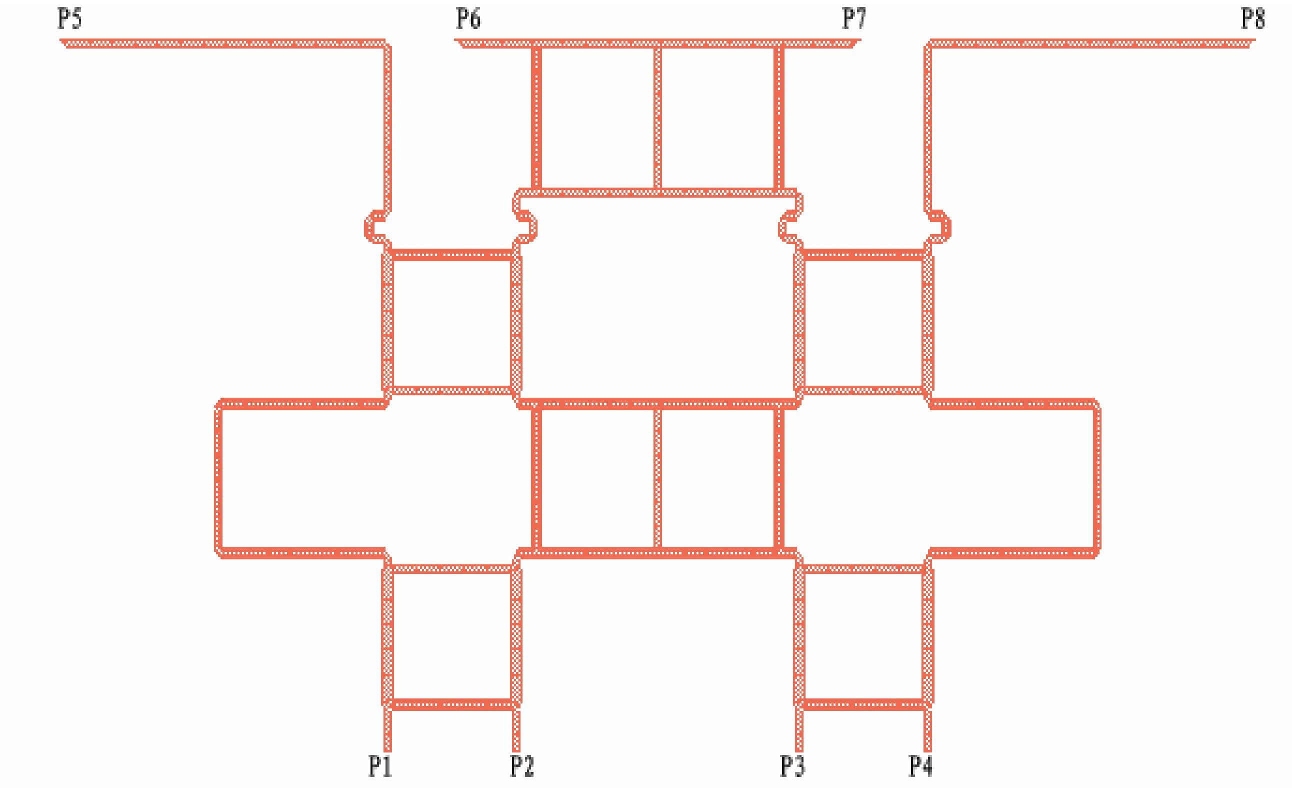


The top of the Butler-Matrix

i) Then we setup the goal of the optimization S21= -124.698° (S= -90°). After optimization we can confirm the design of the left side.

3.4 Simulation of the Butler Matrix Network

From 3.3 and and symmetry of the Butler Matrix, we have the Butler Matrix Network



Butler-Matrix Network

The simulation results are shown in the Table

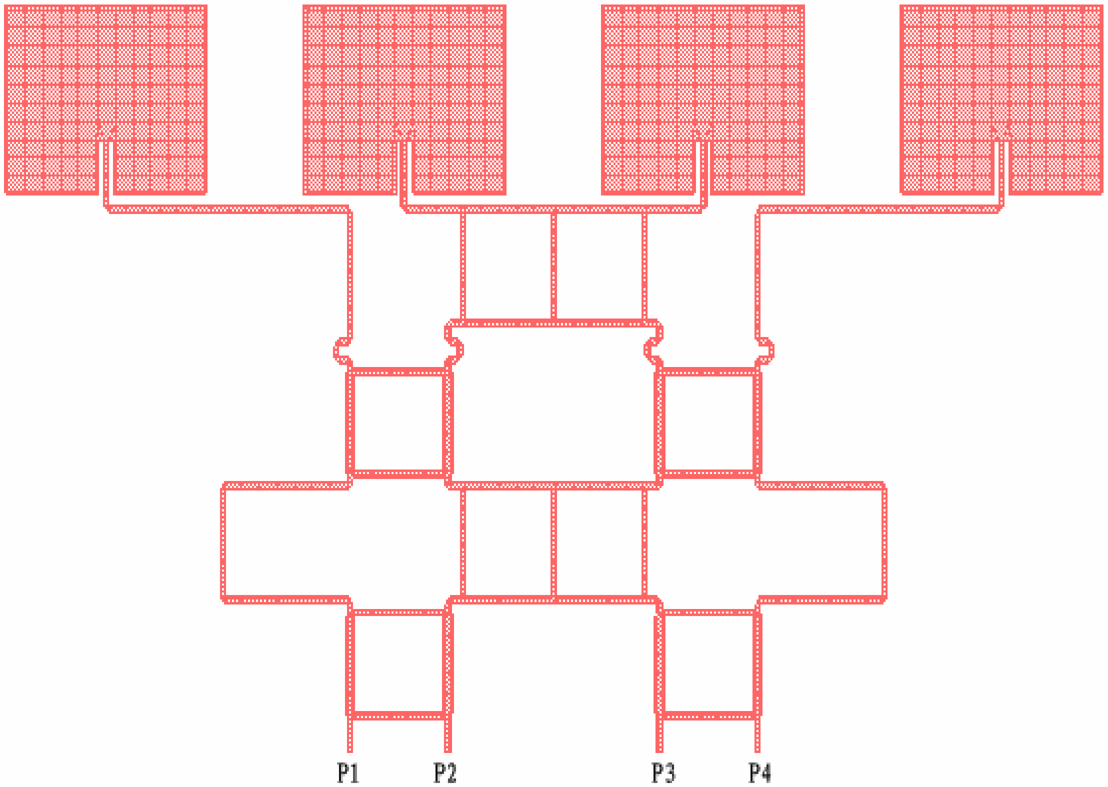
	P5	P6	P7	P8	β
P1	126.272	84.418	39.043	-6.513	-45
P2	38.422	171.941	-54.383	83.405	135
P3	83.361	-54.481	171.935	38.387	-135
P4	-6.516	38.985	84.435	126.237	45

The phase difference between input and output (°)

a) For input P1, we have Phase difference -41.854°, -45.375°, -45.556°
b) For input P2, we have Phase difference 133.519°, -226.324° (133.676°), 137.788°
c) For input P3, we have Phase difference -137.842°, 226.416° (-133.584°), -133.548°
d) For input P4, we have Phase difference 45.501°, 45.45°, 41.802°

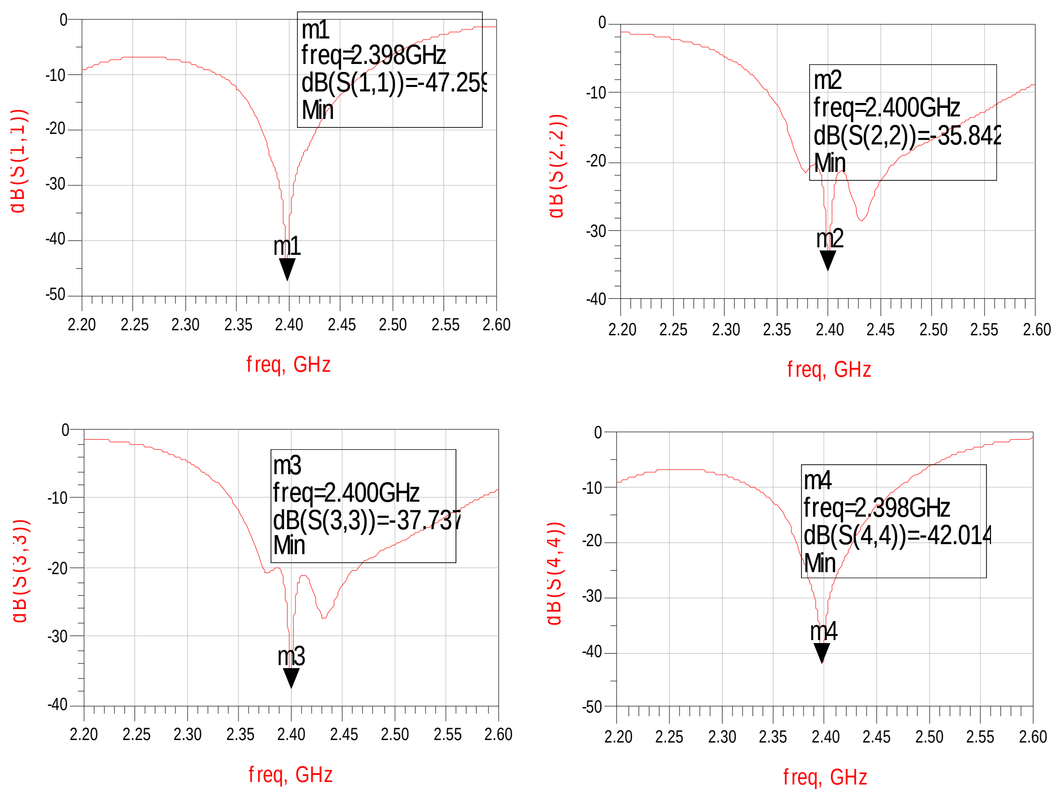
3.5 The simulation results of Butler-Matrix (with antennas)

We have already the network of the Butler Matrix Now we just add the 4 patch antennas (see 2.3)

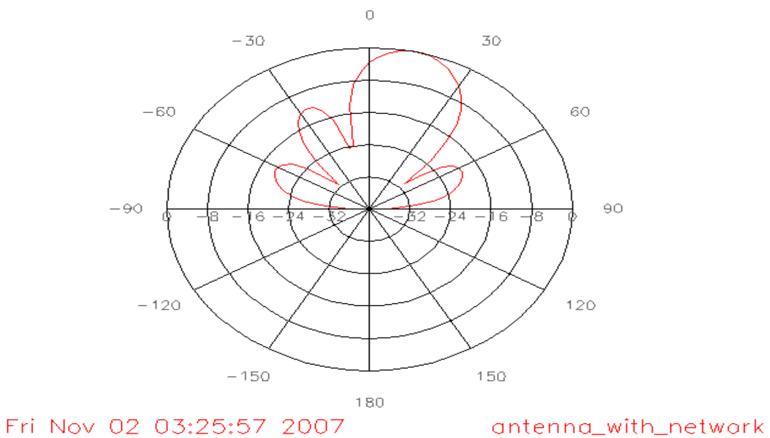


Butler Matrix with antennas

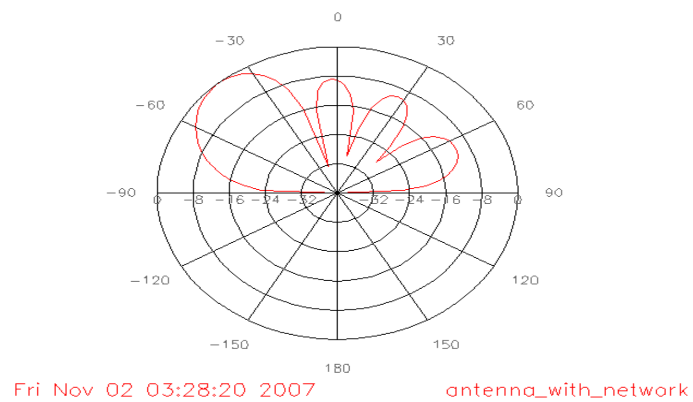
The simulation results are



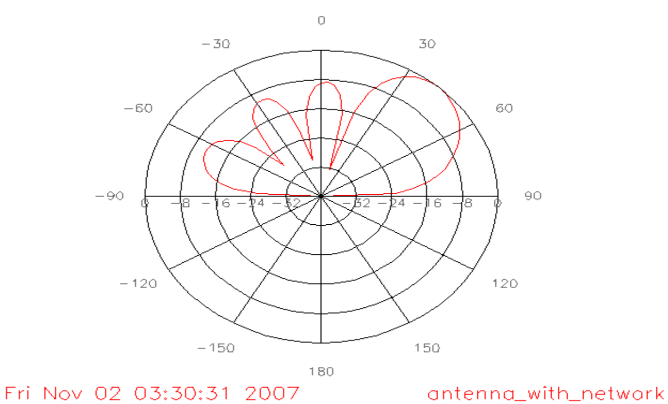
Using Momentum---Post Processing---Radiation Pattern Control, we have 2-D Polar Far Field of the Butler Matrix



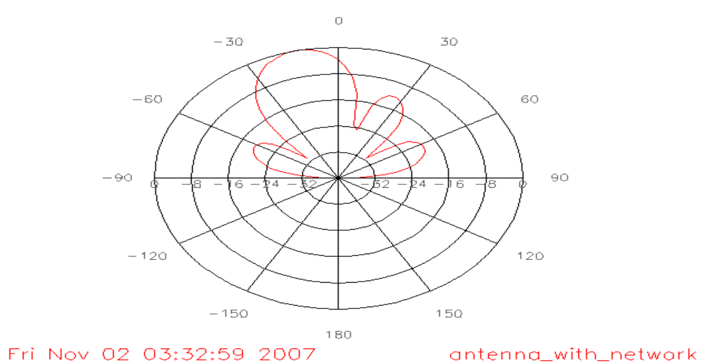
For Input P1



For Input P2



For Input P3



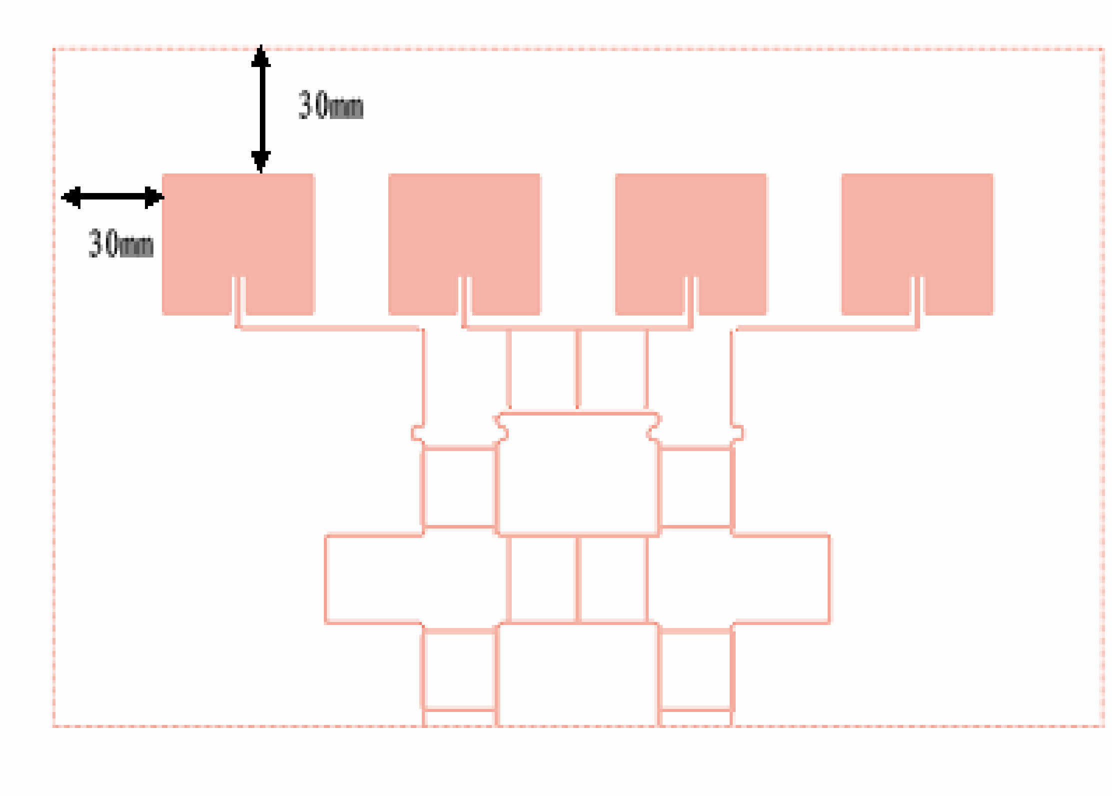
For Input P4

4. **Manufacture and test of the Butler Matrix**

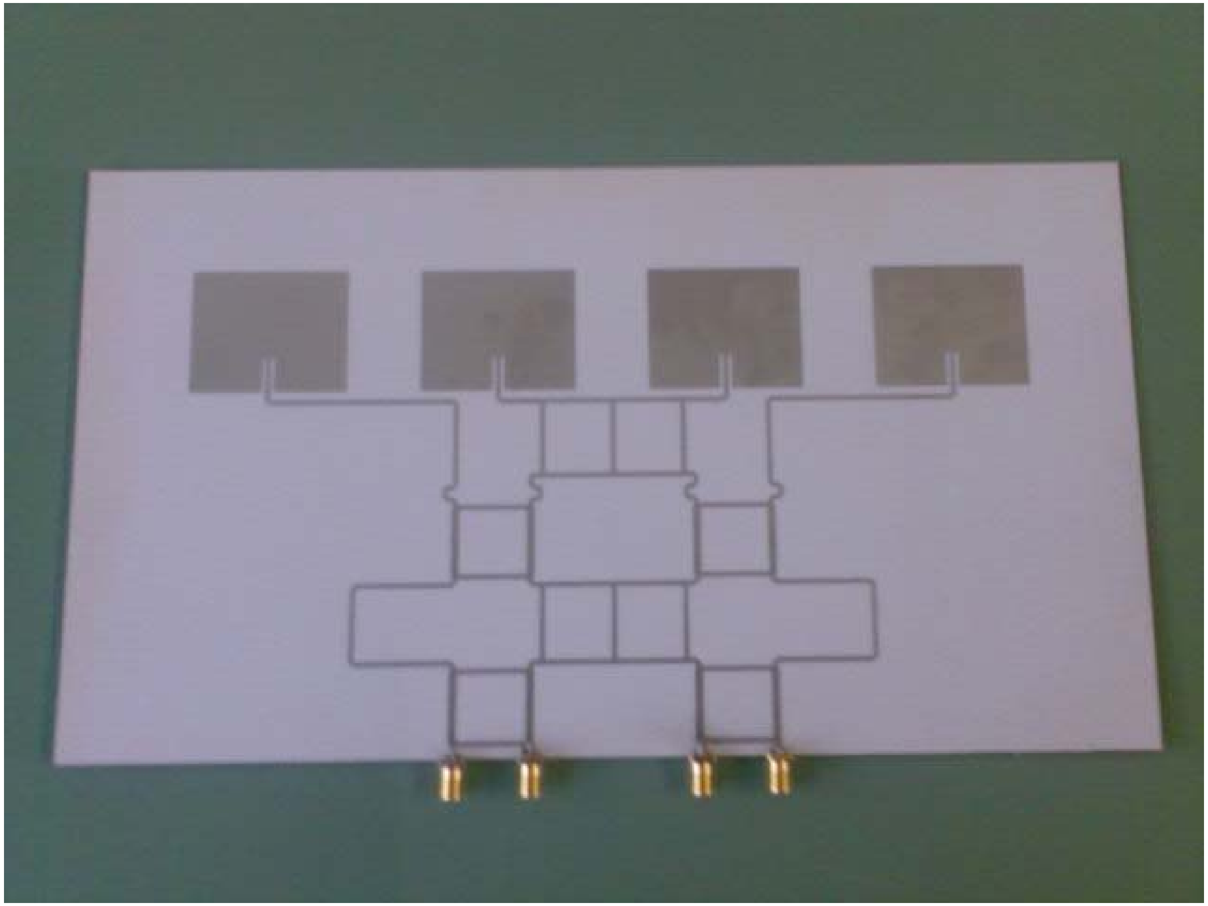
4.1 **Manufacture of the Butler Matrix**

We define the cutline of the Butler-Matrix, then expert this design as

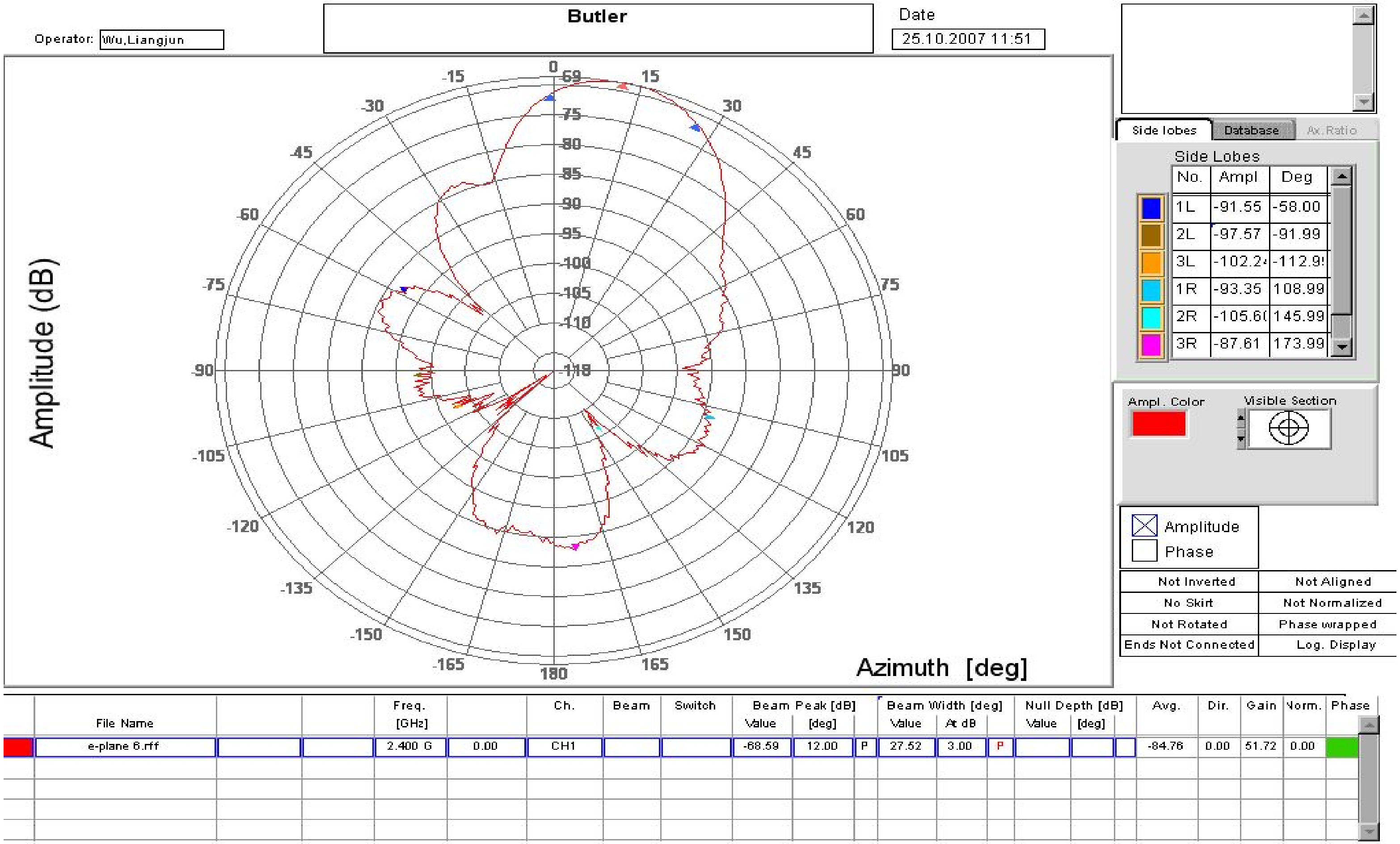
Gerber file, send the file cond.gbr to the factory to produce the Board.



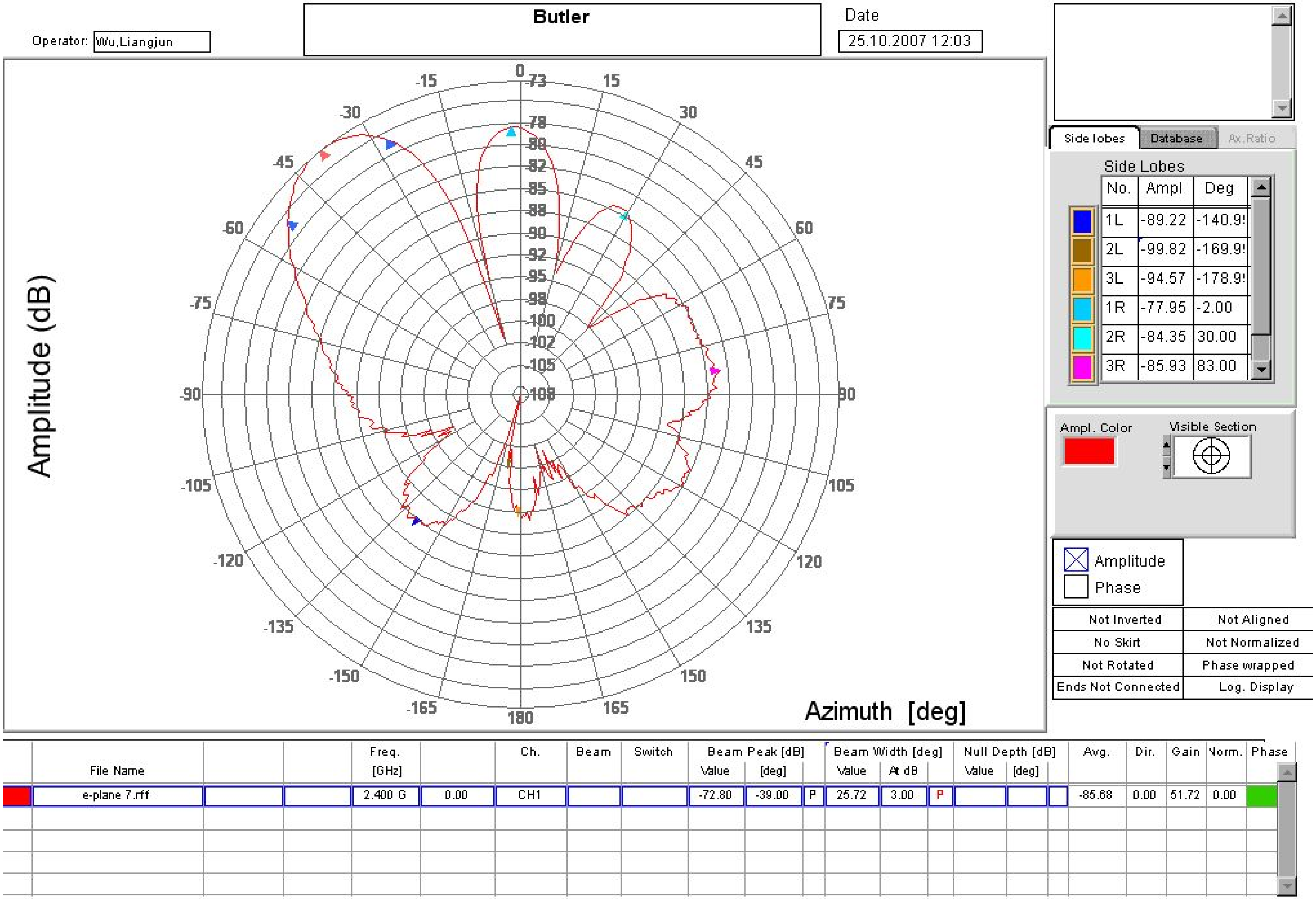
Then we have the finished Butler-Matrix with 4 coupled devices



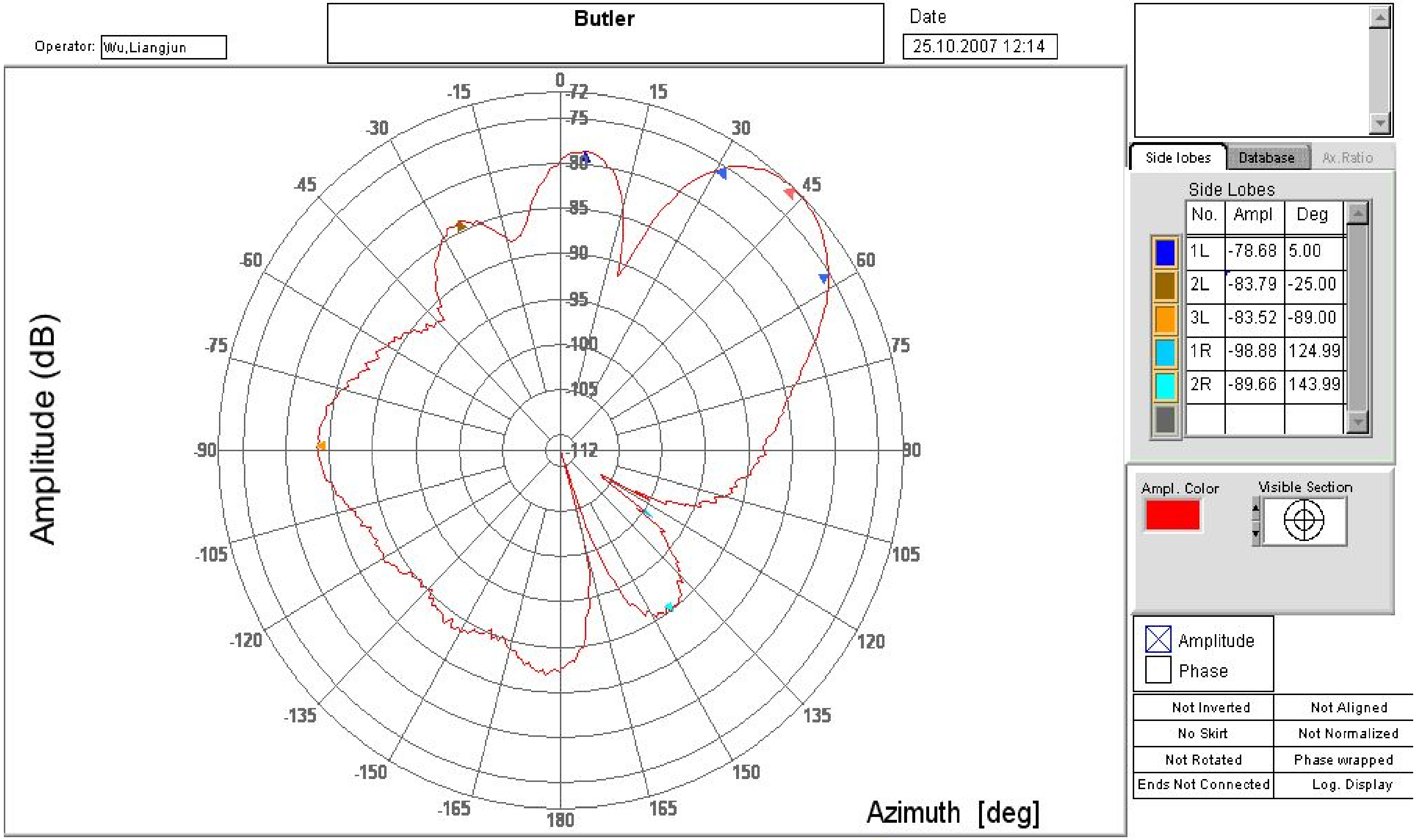
4.2 Test results of the Butler Matrix



Antenna diagram of Butler Matrix for input P1 (Polar)

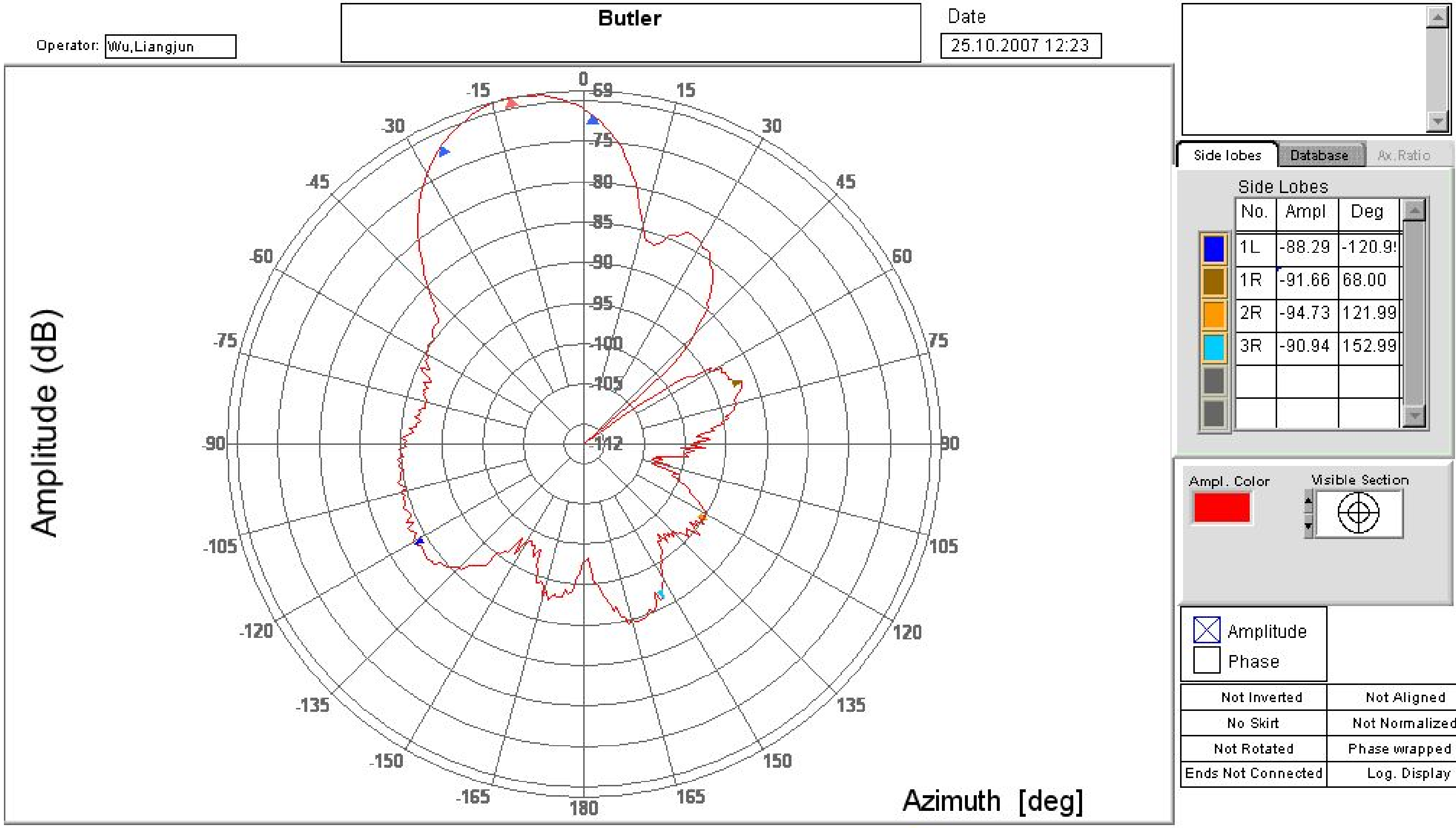


Antenna diagram of Butler Matrix for input P2 (Polar)



	File Name			Freq. [GHz]		Ch.	Beam	Switch	Beam Peak [dB] Value	Beam Peak [dB] [deg]		Beam Width [deg] Value	Beam Width [deg] At dB		Null Depth [dB] Value	Null Depth [dB] [deg]		Avg.	Dir.	Gain	Norm.	Phase
	e-plane 8.rff			2.400 G	0.00	CH1			-72.16	43.00	P	26.48	3.00	P				-84.51	0.00	51.72	0.00	

Antenna diagram of Butler Matrix for input P3 (Polar)



	File Name			Freq. [GHz]		Ch.	Beam	Switch	Beam Peak [dB] Value	[deg]		Beam Width [deg] Value	At dB		Null Depth [dB] Value	[deg]		Avg.	Dir.	Gain	Norm.	Phase
	e-plane 9.rff			2.400 G	0.00	CH1			-68.73	-12.00	P	26.98	3.00	P				-84.57	0.00	51.72	0.00	

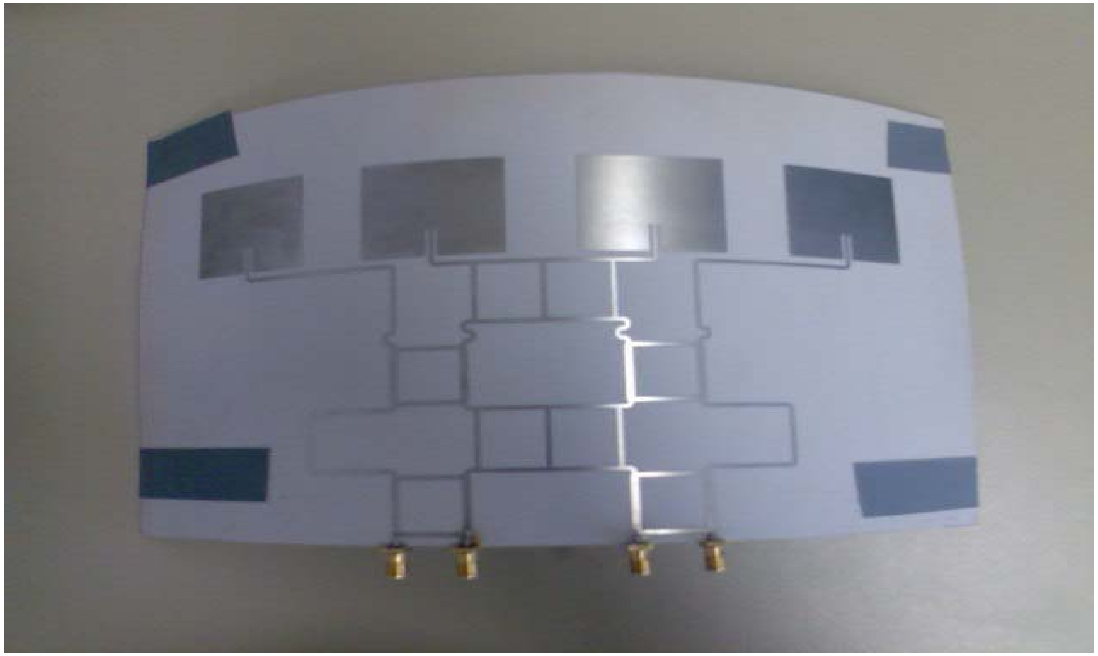
Antenna diagram of Butler Matrix for input P4 (Polar)

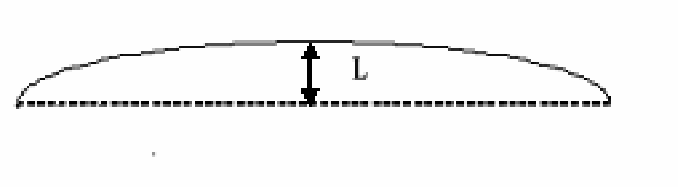
We have

	(theoretic) θ_i	(simulation) θ_i	(test) θ_i
P1	14.5°	12°	12°
P2	-48.6°	-42°	-39°
P3	48.6°	42°	43°
P4	-14.5°	-12°	-12°

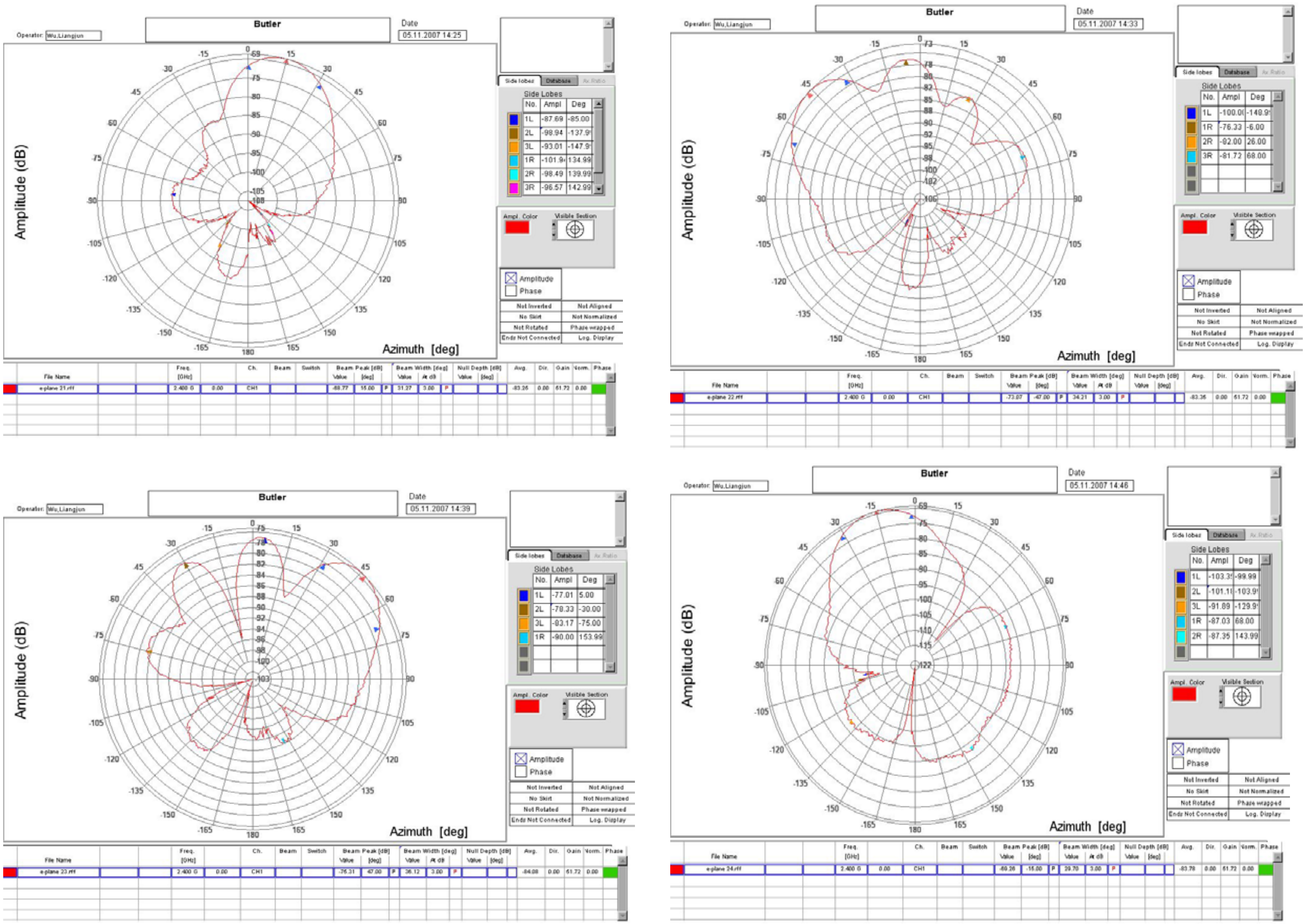
4.3 Test results of the Butler Matrix with bend

Now we can experimentally bend the board

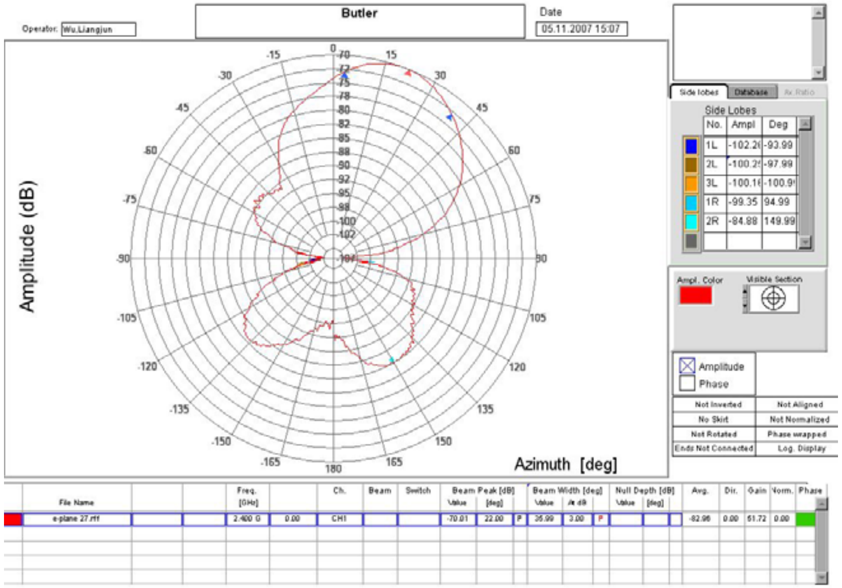


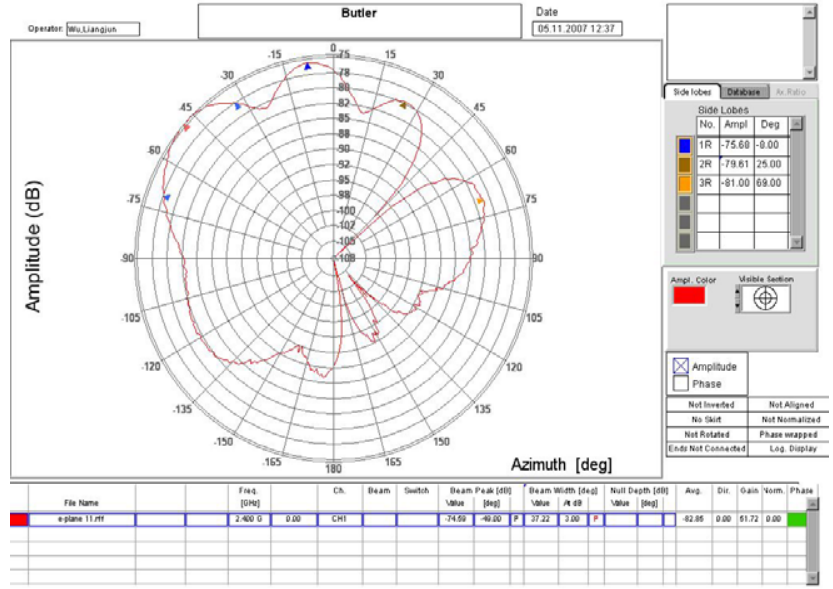


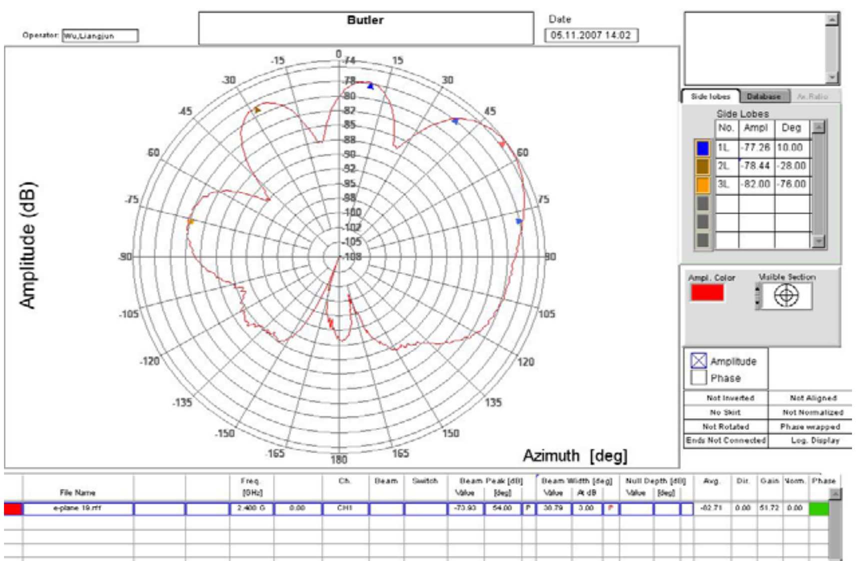
For L=30mm,the test results are shown in Figure

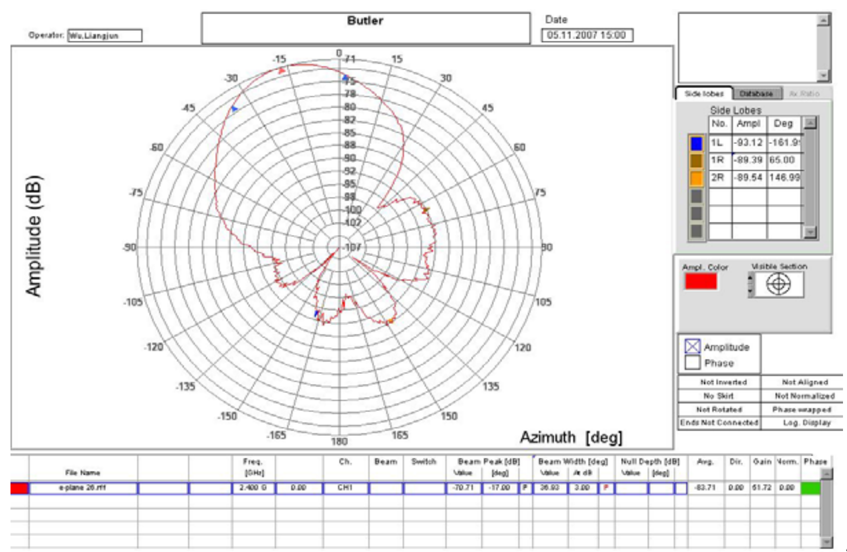


And for L=50mm,the test results are shown in Figure









We have

	Without bending		With bending (L=30 mm)		With bending (L=50 mm)	
	θ_i	Beam Width	θ_i	Beam Width	θ_i	Beam Width
P1	12	27.57	15	31.27	22	35.99
P2	-39	25.72	-47	34.21	-49	37.22
P3	43	26.48	47	36.12	54	38.79
P4	-12	26.98	-15	29.70	-17	36.93

Analysis of the test results (degree)

From the Table, we know that, when we increase the bend L, we can get bigger and bigger Beam Width. By bending of the board, we can get a bigger coverage area.

5. Conclusion

In this thesis we have designed the 4×4 Butler Matrix (at frequency 2.4 GHz), which consists of four 3dB Hybrid-Coupler, two Cross-Coupler, and four Patch-Antennas.

The test result of the Butler Matrix is just like expected. With four different inputs we can switch the direction of the main beam. (Switched-Beam antenna).

By reducing the element spacing and by suitable bending of the planar substrate carrying the radiator elements, we can get coverage of a full 180°angular in azimuth (hemisphere).

Thank you for your attention!