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Four-Leaf Clover Antenna

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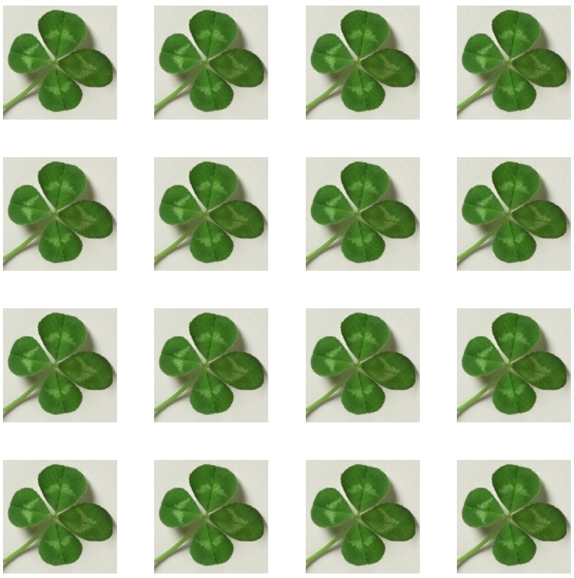

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1 Introduction

This note describes some simulations and measurements on a K-band planar array antenna. The purpose is to make a starting point for an antenna design, to highlight some critical points and to pass on the experience gained. It does not present a full design, nor are all design choices optimum. The parameters are not unified: Two different SIW widths and two different element spacings are used. Further information on similar antenna designs can be found in (1).

The key parameters of this design are:

- Frequency range: 22.55 – 23.15 GHz
- Linear polarization
- Fixed beam direction
- Must fit within a 10 cm x 10 cm square with some margin
- Gain "as high as possible", e.g. 23 – 25 dBi
- Easy to manufacture with standard PCB techniques

The design is based on the paper by Wu et. al. (2) describing a large array for the 59 - 64 GHz band.

The set-up is illustrated in Figure 1.1. On the top is a "four-leaf-clover" antenna consisting of 4 microstrip patches and feeding lines. The bottom substrate contains an SIW, Substrate Integrated Waveguide, feed line and the line is coupled to the antenna through a slot in the top of the SIW. The two substrates are bonded together by use of a bonding film. The substrate used has a relative permittivity, ϵ_r = 2.2, and the thickness of each sheet is 0.508 mm.

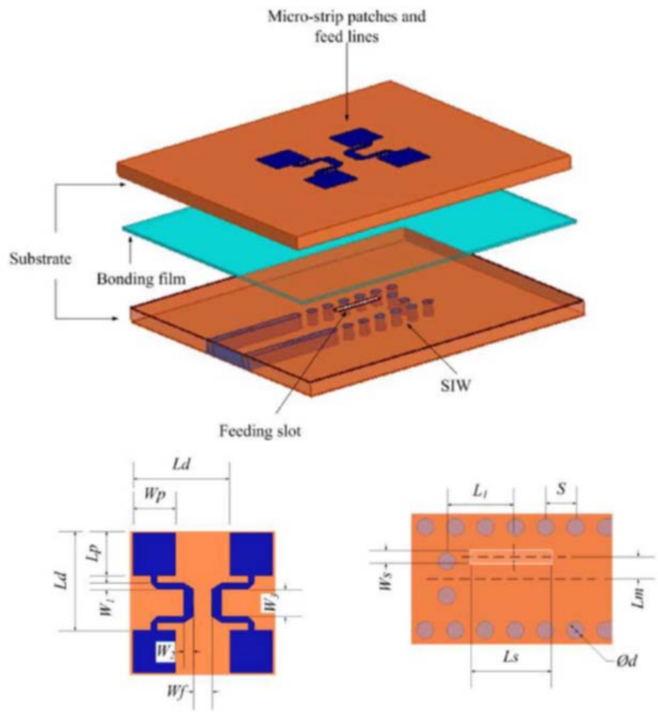

Fig. 2. Configuration of the proposed 2 × 2 sub-array.

Figure 1.1 Configuration of the antenna element and SIW feeding. From Wu et. al. (2)

As discussed in the paper, two radiation modes are significant: the radiation from the four patches and the radiation from a pair of dipoles. When the thickness of the substrate approaches 0.25 λ, the dipole effect is dominant. The thickness of the substrate affects the gain and bandwidth of the antenna, as illustrated in Figure 1.2 (2).

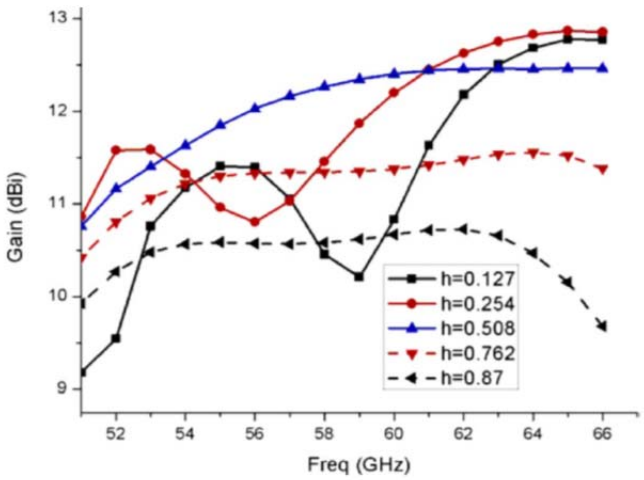

Fig. 7. Gains of the antennas with different working modes (reflection excluded).

Figure 1.2 Gain and bandwidth dependence on substrate thickness. From Wu et. al. (2)

The present design of the K-band antenna uses a glass reinforced Teflon substrate (3M CuClad LX233) with:

- relative permittivity, ϵ_r = 2.33
- dielectric loss factor, *tan(δ)* ~ 0.0009 at 10 GHz – not specified at 23 GHz. A value of 0.002 is used in some simula-

tions.
- The thickness of each dielectric sheet, *t* is 0.031″ ~ 0.787 mm.

Taking the frequency scaling into account, this corresponds approximately to the "h = 0.254″ curve in Figure 1.2., so high gain and moderate bandwidth should be achievable.

The four-leaf element is used in a 4 x 4 array with an SIW distribution network.

The design seems promising:
- A wide bandwidth indicates a low Q and may imply a low loss in the antenna element.
- A high gain of the antenna element may make the mutual coupling low.
- The SIW feeding structure may have somewhat lower loss than a microstrip or stripline.

2 Simulations on a SIW-fed 4-leaf antenna element

The dimensions of the 4 clover leafs, the coupling slot and the SIW feeding has been optimized in a lot of simulations. The definitions of dimensions are shown in Figure 2.1 and the final dimensions are shown in the table below. In order to enhance the current flow in the SIW where the slot is placed, an additional via is used (seen to the right of the slot in Figure 2.1). Its size and position is optimized to find a good match. It is probably also possible to obtain a good match without this via.

As shown in Figure 2.2, the simulated return loss is greater than 17 dB across the required band. Further improvement might be possible by continued optimization.

The 3D directivity pattern is shown in Figure 2.3. It shows a 13.36 dBi on-axis directivity and quite low radiation at θ = 90°, which may indicate low mutual coupling between the elements of the array.

The final simulations are run with a quite fine mesh, as shown in Figure 2.4.

The current flow in the area around the slot is illustrated in Figure 2.5.

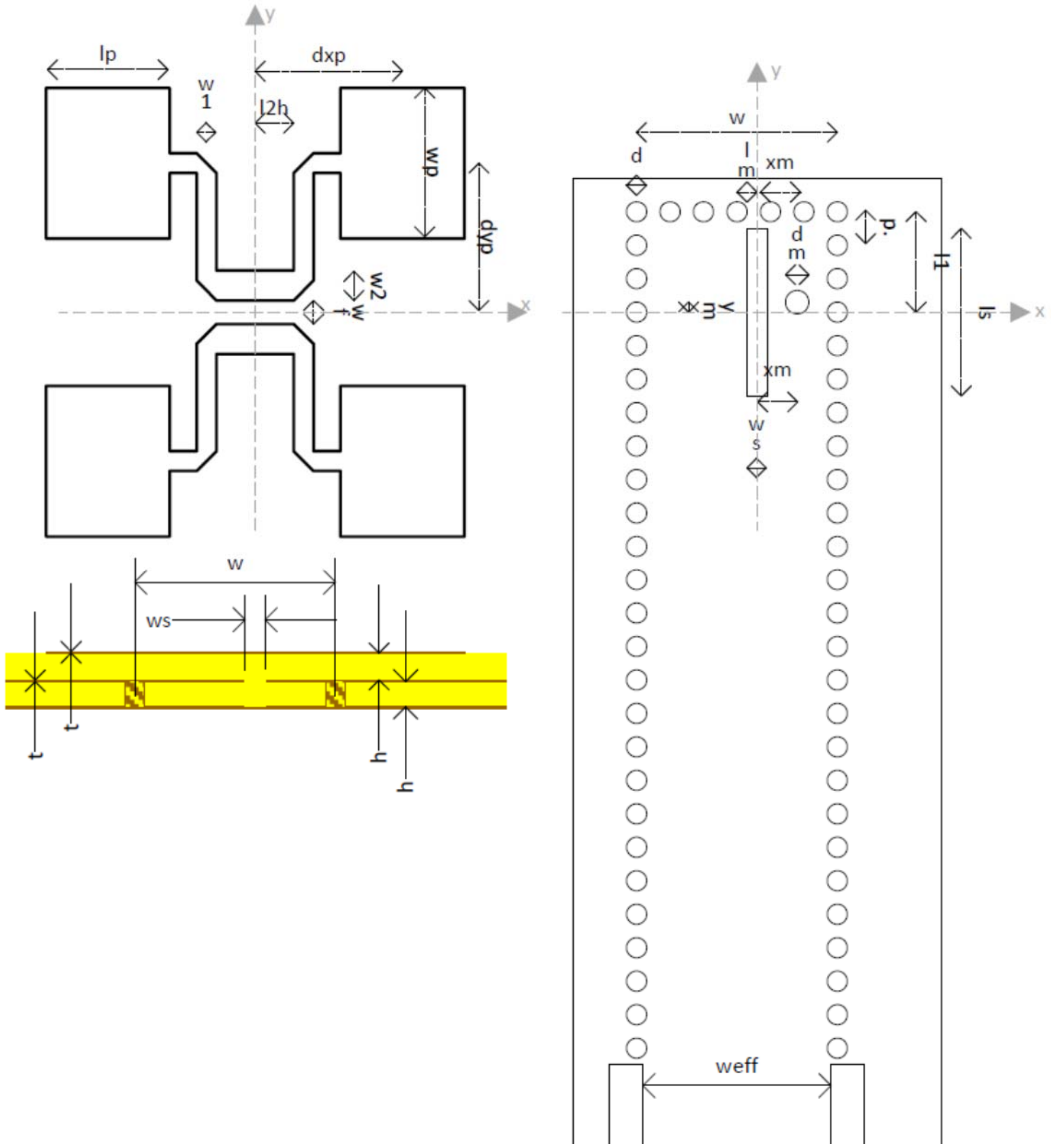

Figure 2.1 Definition of dimensions for the four-leaf element and SIW feed.

Dimensions used in the simulation.					
Param	Value [mm]	Description	Param	Value [mm]	Description
h	0.787	Dielectric thickness	d	0.6	SIW via diameter
t	0.017	Copper thickness	p	1	SIW via pitch
dxp	4.4	Patch centre x-offset	w	6	SIW width
dyp	4.4	Patch centre y-offset	weff	5.62	Effective WG width
lp	3.7	Patch length	ls	5	Slot length
wp	4.5	Patch width	ws	0.6	Slot width
w1	0.6	Line 1 width	lm	0.6	Slot-SIW c-c offset
w2	0.9	Line 2 width	l1	3	Slot-centre to SIW end c-c
l2h	1.15	Half line 2 length	dm	0.7	Matching via diameter
wf	0.6	Line 2 spacing	xm	1.2	Matching via x-offset
wg	50	Ground brick width = length	ym	0.3	Matching via y-offset

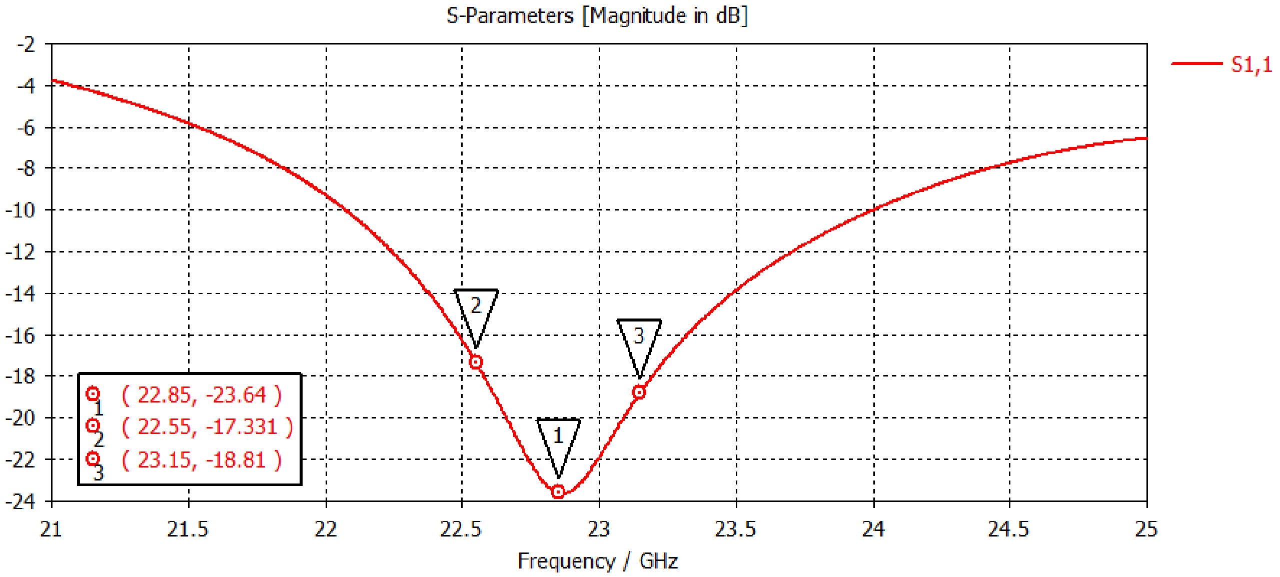

Figure 2.2 Simulated return loss for the four-leaf element.

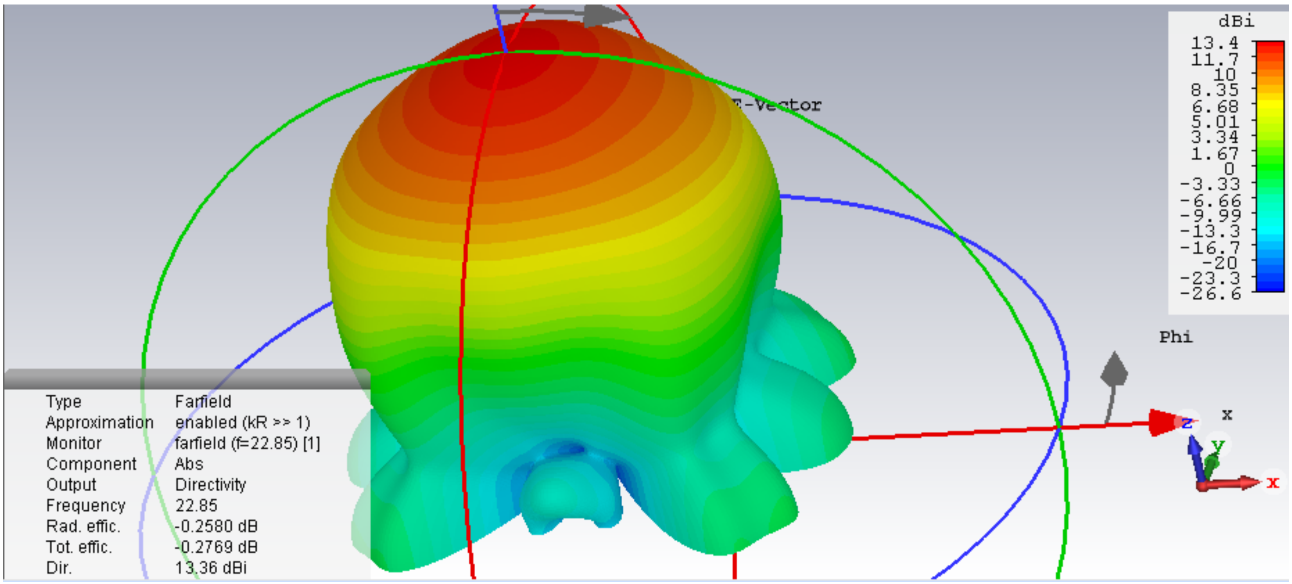

Figure 2.3 Simulated 3D directivity pattern for the four-leaf element

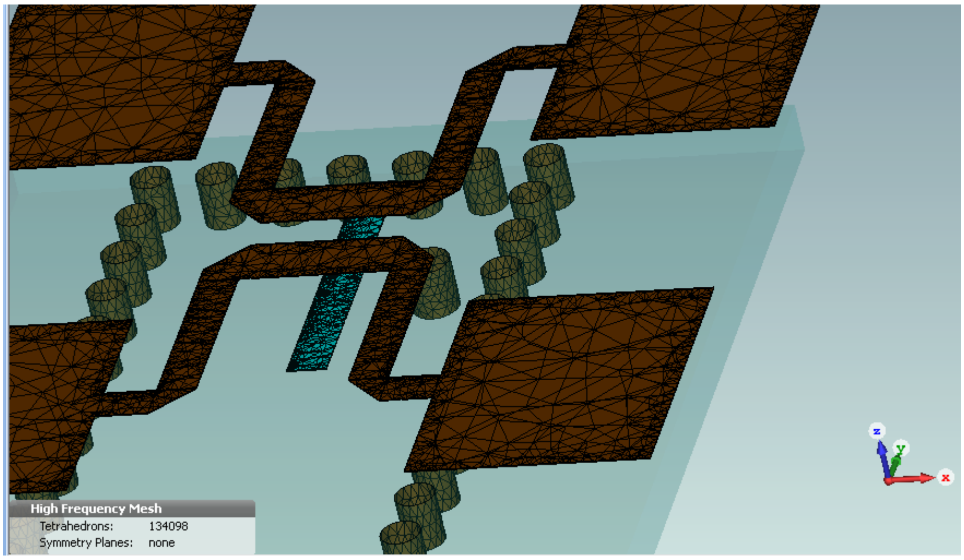

Figure 2.4 Illustration of the simulation mesh for a part of the four-leaf antenna.

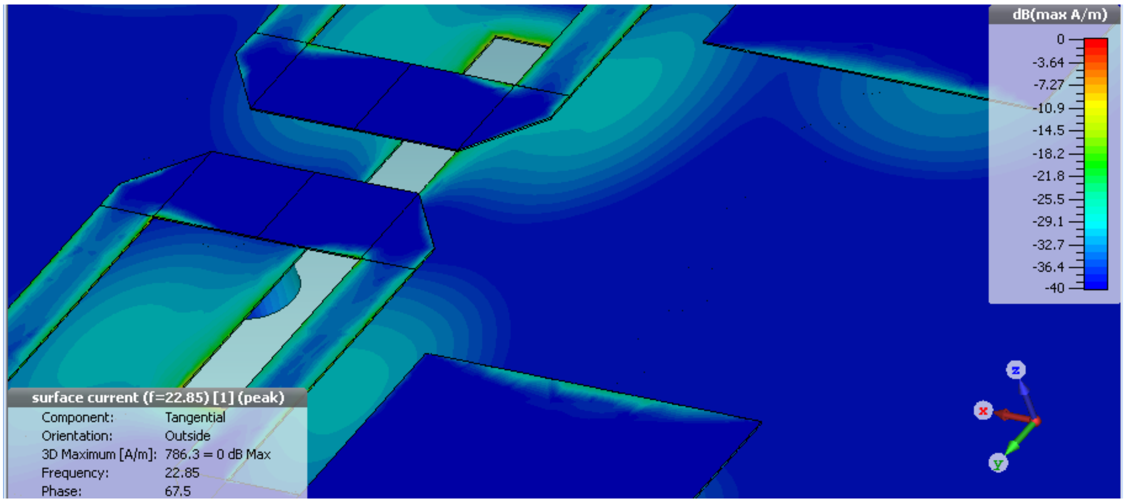

Figure 2.5 Simulated current flow around the coupling slot.

The 4 x 4 antenna array is illustrated in Figure 2.6. The element-element spacing is chosen to 18 mm (~1.37 λ) in each direction. A lower spacing, e.g. 16 mm, might be considered.

A simulation of the combined radiation pattern is shown in Figure 2.7. This simulation assumes uniform feeding and neglects mutual coupling. The combined directivity is simulated to 25.2 dBi, and the peak sidelobe level is approximately 13 dB below the main beam level.

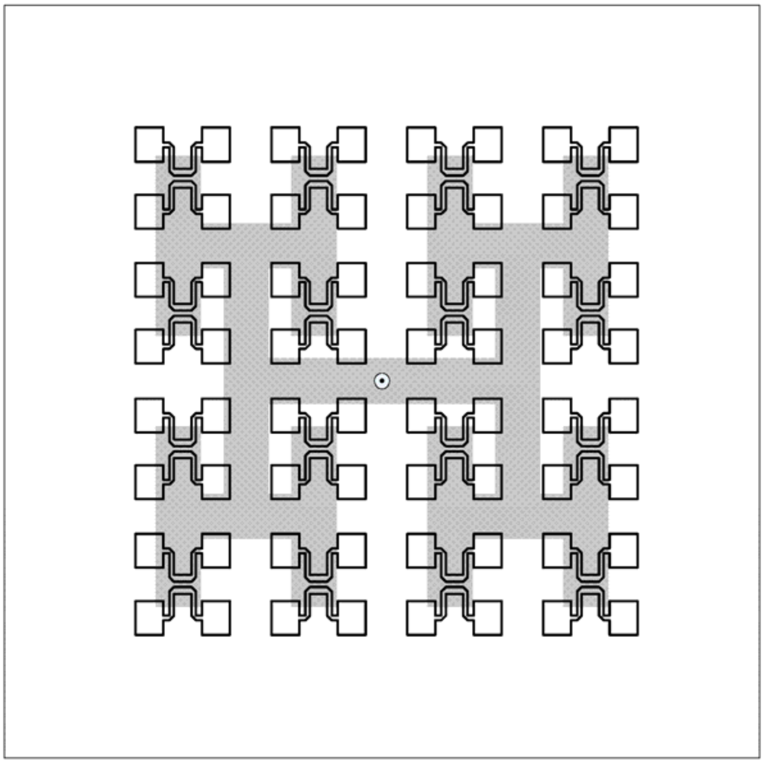

Figure 2.6 Sketch of the 4 x 4 array antenna. The grey lines indicate the SIW feeding structure with a feeding point in the centre. The frame around the antenna is 10 cm x 10 cm.

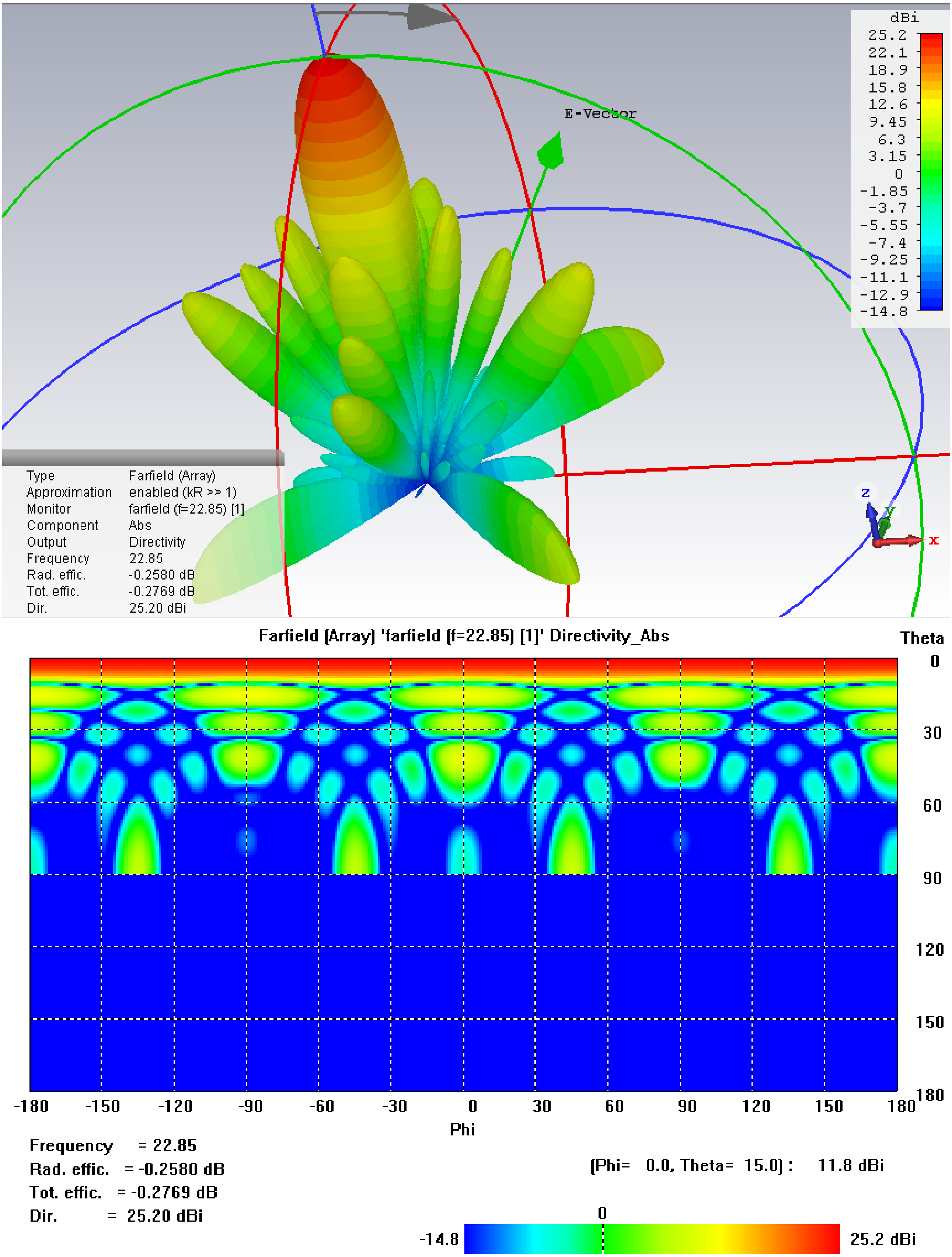

Figure 2.7 Simulated directivity of a 4 x 4 array. Mutual coupling is not included.

3 Simulations and measurements on a back-fed antenna element

All the results in chapter 2 and 4 are based on simulations. In order to have some link between simulations and the real world, a test antenna element is fabricated and tested. Since an SIW fabrication cannot be done in-house, an alternative feeding is used.

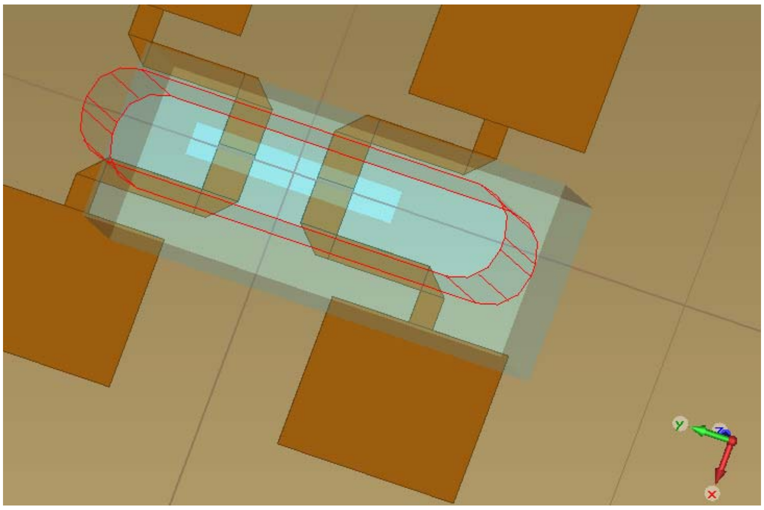

Figure 3.1 Illustration of the feed structure for the test element.

The feed structure is illustrated in Figure 3.1 and 3.2:

- The four-leaf element and the coupling slot are as previously described.
- Below the slot is a baseplate with a milled hole. This hole is a reduced height waveguide, which provides a match to a standard WR-42 waveguide. The reduced height waveguide has rounded corners, which are required for the milling.

The dimensions are defined in Figure 3.3 and the values are given in the table below.

Figure 3.2 Picture of the back-plate with reduced height waveguide and coupling slot.

3.1 Simulations on a single 4-leaf element

The simulated 3D radiation pattern of the back-fed element is shown in Figure 3.4. It is – as expected – almost identical to the one shown in Figure 2.3.

The simulated return loss is shown in Figure 3.5.

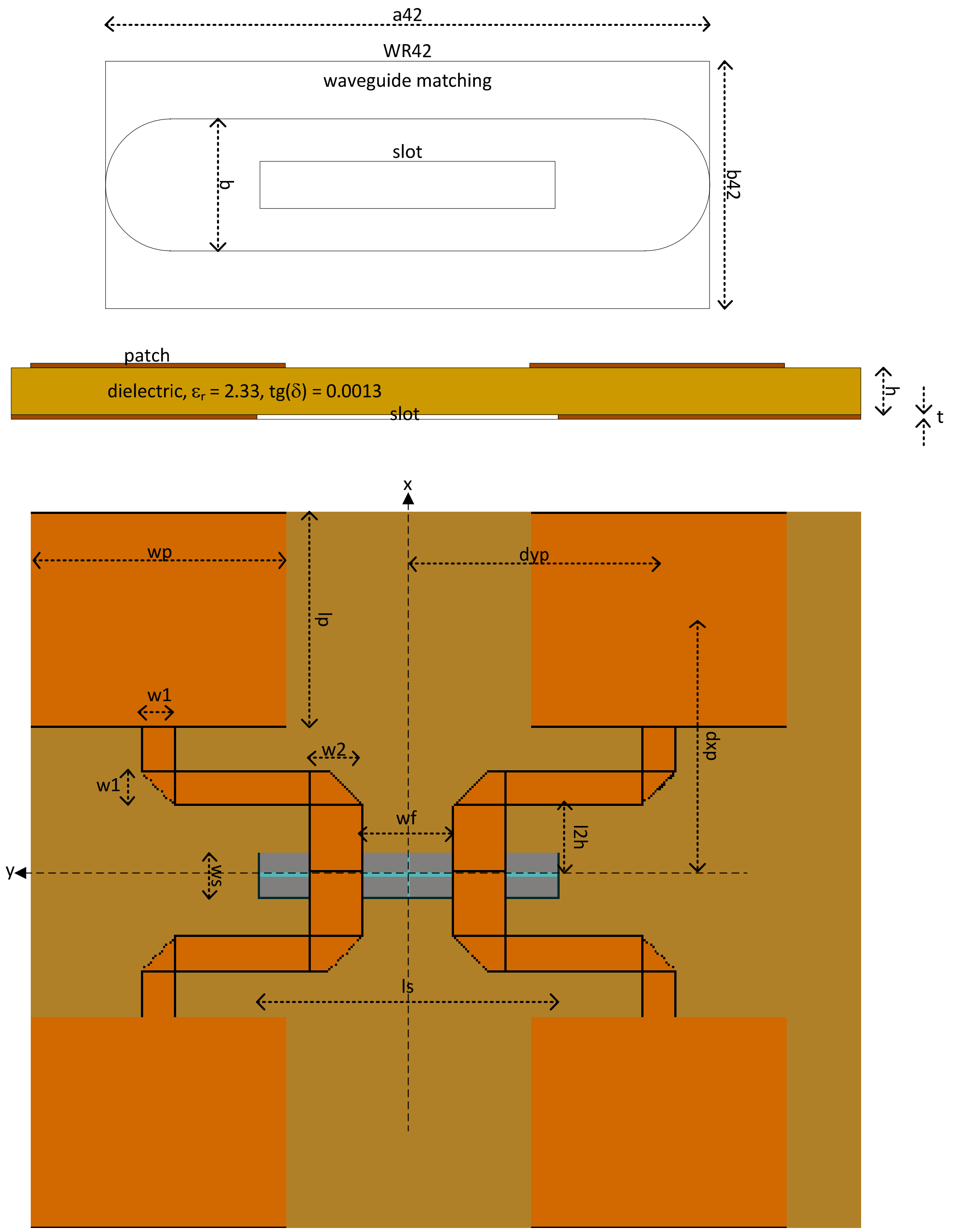

Figure 3.3 Definition of dimensions for the back-fed four-leaf element.

Dimensions for the back-fed element					
Param	Value [mm]	Description	Param	Value [mm]	Description
h	0.787	Dielectric thickness	wf	1.6	Line 2 spacing
t	0.017	Copper thickness	ls	5.24	Slot length
dxp	4.4	Patch centre x-offset	ws	0.8	Slot width
dyp	4.4	Patch centre y-offset	wg	50	Backplate width = length
lp	3.7	Patch length	tspacer	3.3	Backplate thickness
wp	4.5	Patch width	a42	10.67	Waveguide width
w1	0.6	Line 1 width	b42	4.32	WR-42 height
w2	0.92	Line 2 width	b	2.3	Reduced waveguide height
l2h	1.15	Half line 2 length	rMill	1	Milling tool radius

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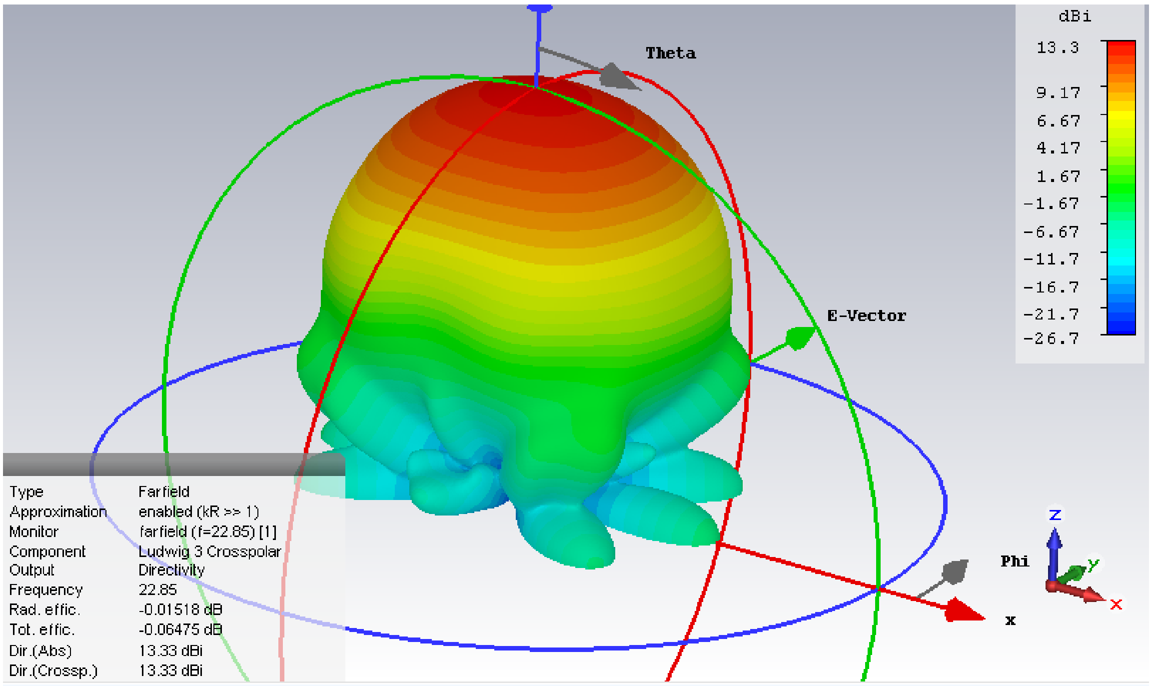

Figure 3.4 3D radiation pattern of the back-fed element.

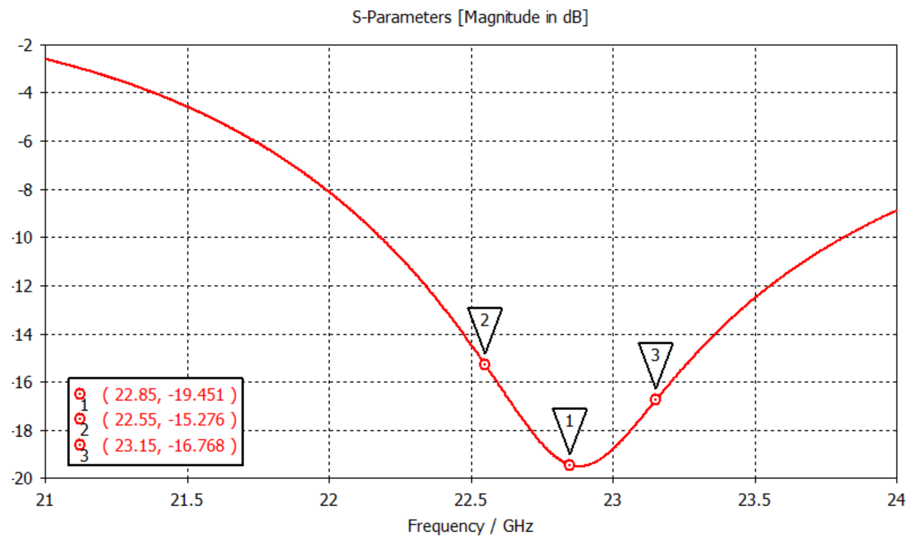

Figure 3.5 Simulated return loss of the back-fed element.

3.2 Measurements on a single 4-leaf element

The fabricated back-fed element is mounted on a Styrofoam block and tested – a picture is seen in Figure 3.6.

The measured and simulated H-plane and E-plane patterns are shown in Figure 3.7 and 3.8. The H-plane patterns have a very close match, whereas there is some discrepancy between the E-plane patterns. A possible reason may be a non-perfect electric contact between the PCB ground plane and the back-plate.

The gain was measured using a Flann 20240-20 standard gain horn as reference, but the accuracy of the measurement set-up was not good. The results are:

Frequency [GHz]	Measured gain [dBi]			Simul. direct. [dBi]
	Vert.	Hor.	Avg.	
22.55	13,07	12,53	12,80	
22.85	13,55	13,94	13,75	13,33
23.15	13,60	12,20	12,90	

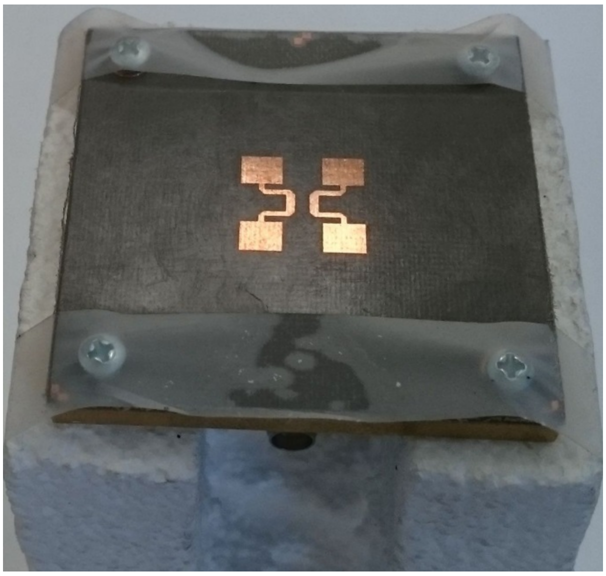

Figure 3.6 Back-fed antenna element mounted with a waveguide transition on a styrofoam block.

The measured return loss is shown in Figure 3.9 and shows moderate deviations from the simulated (Figure 3.5). The coax-WG adapter was not included in the calibration.

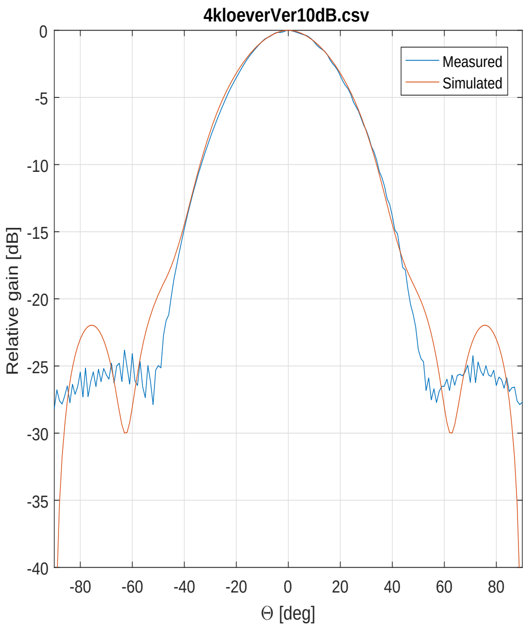

Figure 3.7 Measured and simulated relative H-plane patterns.

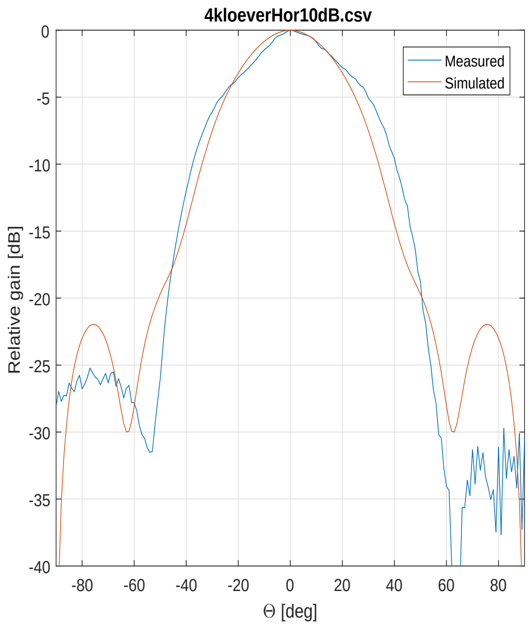

Figure 3.8 Measured and simulated relative E-plane patterns.

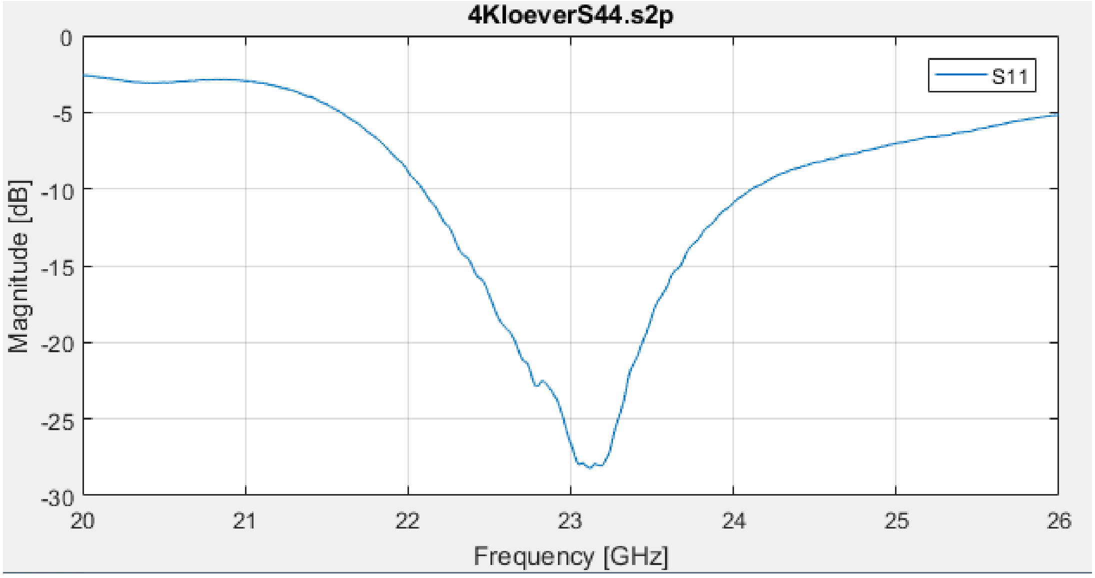

Figure 3.9 Measured return loss of the back-fed antenna.

3.3 Simulations on a 2 x 2 array

In order to get a first impression on the influence of the mutual coupling, a 2 x 2 array of back-fed four-leaf elements was simulated. The element spacing was 18 mm in both directions.

The set-up is illustrated in Figure 3.10, and the simulated directivity is shown in Figure 3.12.

The port to port isolation is shown in Figure 3.12. It is seen, that the isolations are better than 38 dB at the centre frequency.

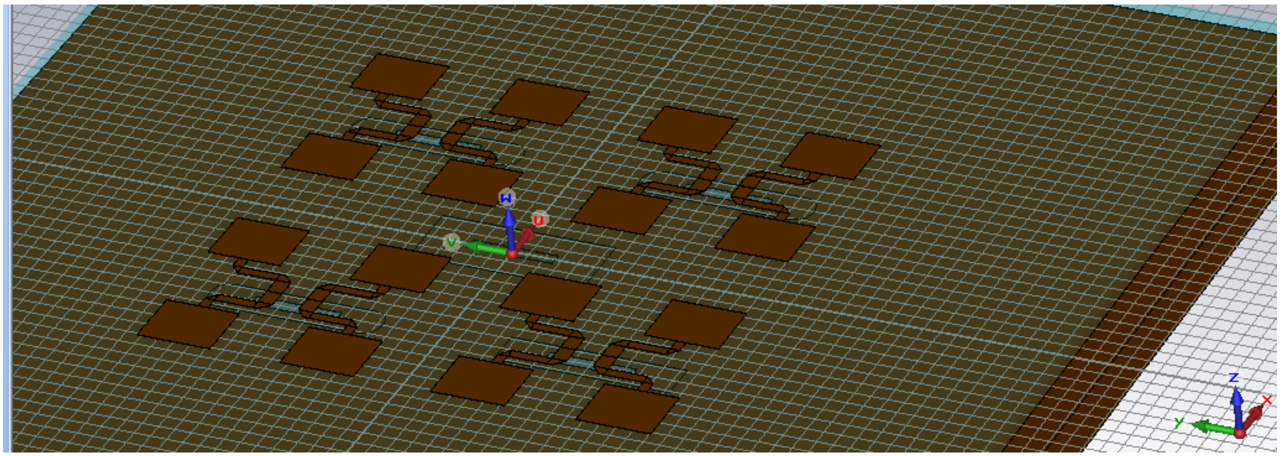

Figure 3.10 Simulation set-up for the 2 x 2 array.

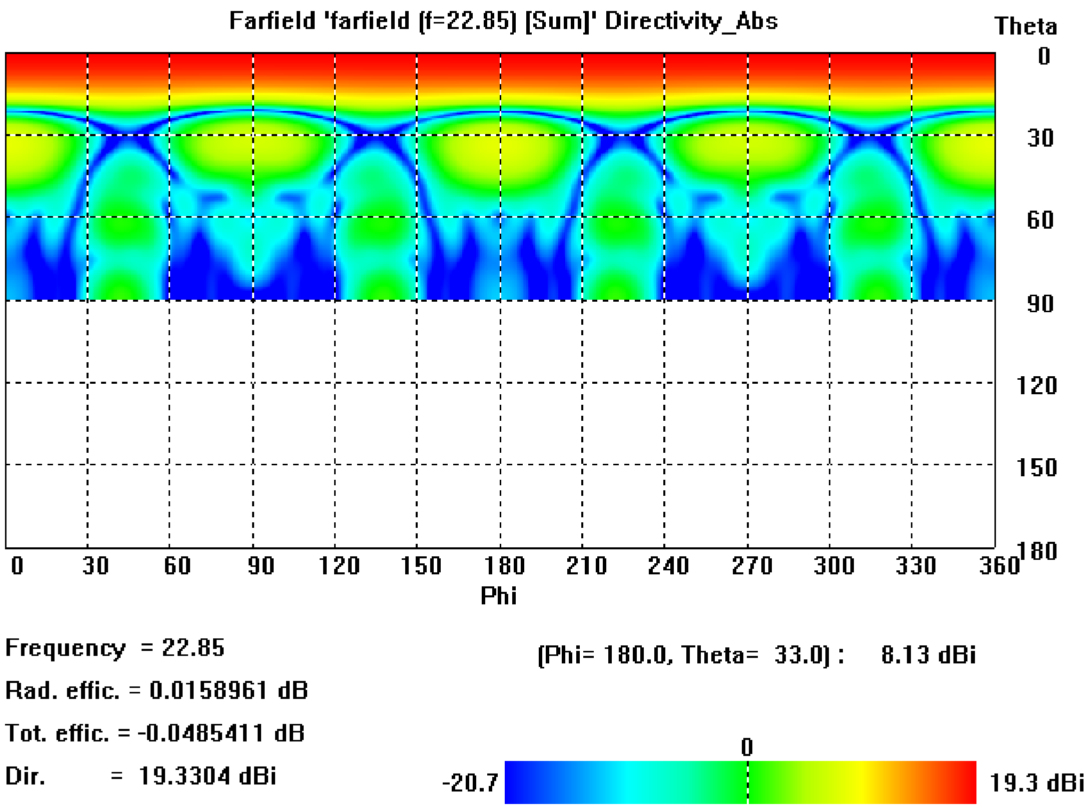

Figure 3.11 Simulated directivity of the 2 x 2 back-fed array with uniform exitation.

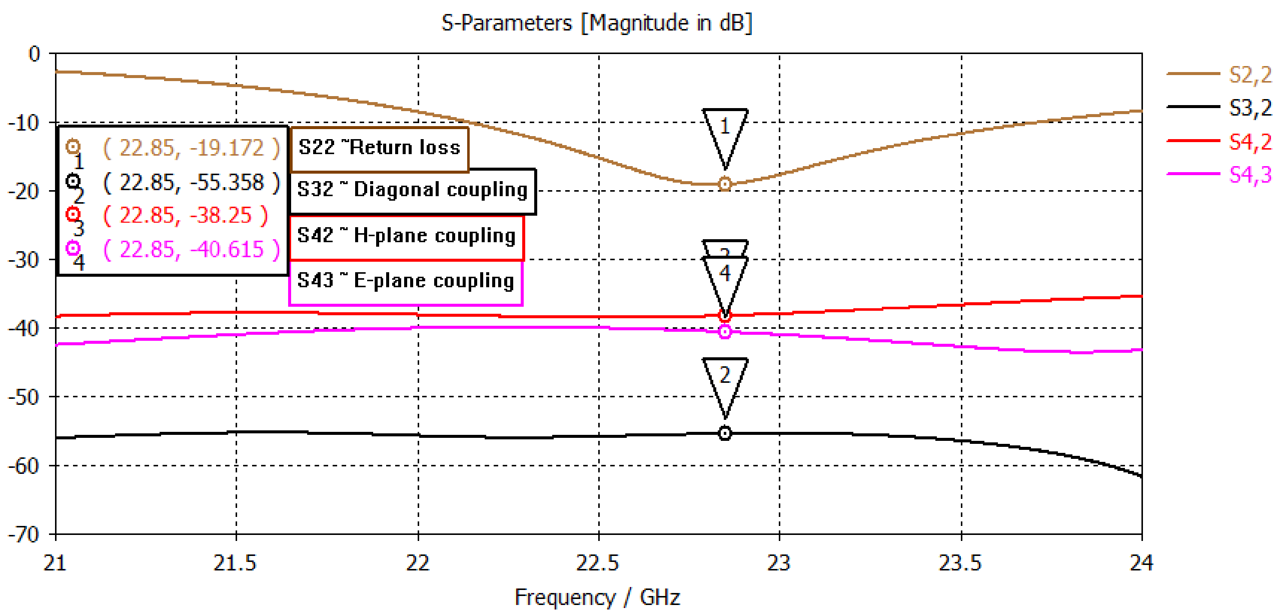

Figure 3.12 Simulated isolation of the 2 x 2 array.

4 Simulations on the SIW-feeding network

4.1 SIW properties and design considerations

An SIW is basically a dielectric filled waveguide, where the side walls are replaced by rows of vias. An SIW with a width, w, (centre to centre of vias) has the same cut-off frequency as a dielectric filled waveguide with width, w_{eff}, where the relation is (3):

$$w_{eff} = w - 1.08\frac{d^2}{p} + 0.1\frac{d^2}{w} \qquad (4.1)$$

where d is the diameter of the via and p is the via pitch along the row.

The via diameter and pitch must be chosen so that the radiation, and the consequent unwanted coupling, is low. In all simulations in this note, $d = 0.6\ mm$ and $p = 1.0\ mm$.

Two different widths and corresponding cut-off frequencies, f_{Cut}, are investigated:

$$w = 6\ mm \sim w_{eff} = 5.62\ mm \sim f_{Cut} = 17.47\ GHz$$

$$w = 7\ mm \sim w_{eff} = 6.62\ mm \sim f_{Cut} = 14.83\ GHz$$

The current flow in a 7 mm SIW is illustrated in Figure 4.1.

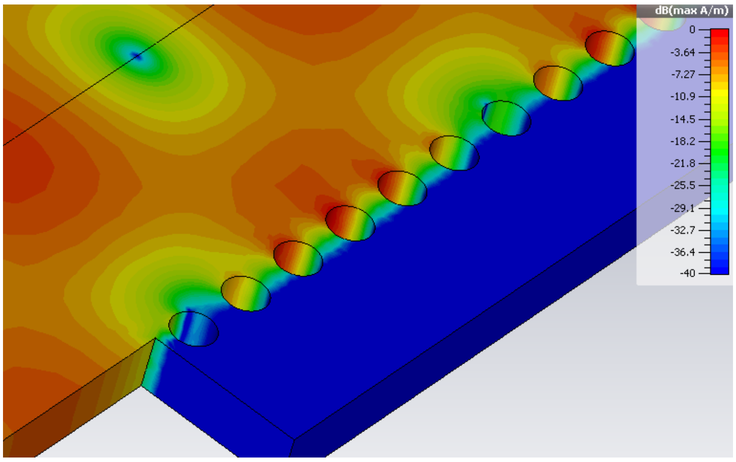

Figure 4.1 Simulated current flow in a 7 mm SIW. The color bar range is 40 dB.

The losses of an SIW are high compared to an air-filled waveguide because:

- Dielectric losses are introduced
- The dielectric reduces the size for a given cut-off frequency and this causes increased conductor loss.
- The very low height causes excess conductor loss.
- The via walls are more lossy than a flat wall
- Surface roughness of the vias and copper foils will increase the conductor loss.

The conductor loss for a TE_{10} wave in a dielectric filled waveguide can be found in textbooks and expressed as:

$$\alpha_c = \frac{R_s}{\eta_0\sqrt{1-\left(\frac{f_c}{f}\right)^2}}\left[\frac{\varepsilon_r}{b_1} + \frac{2\varepsilon_r}{a_1}\left(\frac{f_c}{f}\right)^2\right] \quad [Np/m] \qquad (4.2)$$

$$a_1 = a\sqrt{\varepsilon_r} \qquad b_1 = b\sqrt{\varepsilon_r}$$

where ε_r is the relative permittivity, R_s is the conductor surface resistance, a_1 and b_1 are the width and height of the equivalent air-filled waveguide [m], σ is the conductors conductivity [S/m] and η_0 is the TEM wave impedance in vacuum. It is seen, that the conductor loss is proportional to the relative permittivity if the cut-off frequency is kept constant. It is also seen, that a low waveguide height increases losses.

Prediction of SIW losses is difficult because of problems with modeling of the effect of conductor surface roughness and lack of knowledge of via surface roughness. A 6 mm SIW with a length of 51 mm was simulated with smooth copper foils and vias and a dielectric loss factor, $\tan(\delta)$, of 0.002. The result is shown in Figure 4.2. The loss is 0.93 dB corresponding to 18 dB/m and for a 7 mm SIW it is 0.69 dB corresponding to 13.5 dB/m. These numbers are expected to increase because of conductor roughness. More simulations on SIW losses can be found in (1).

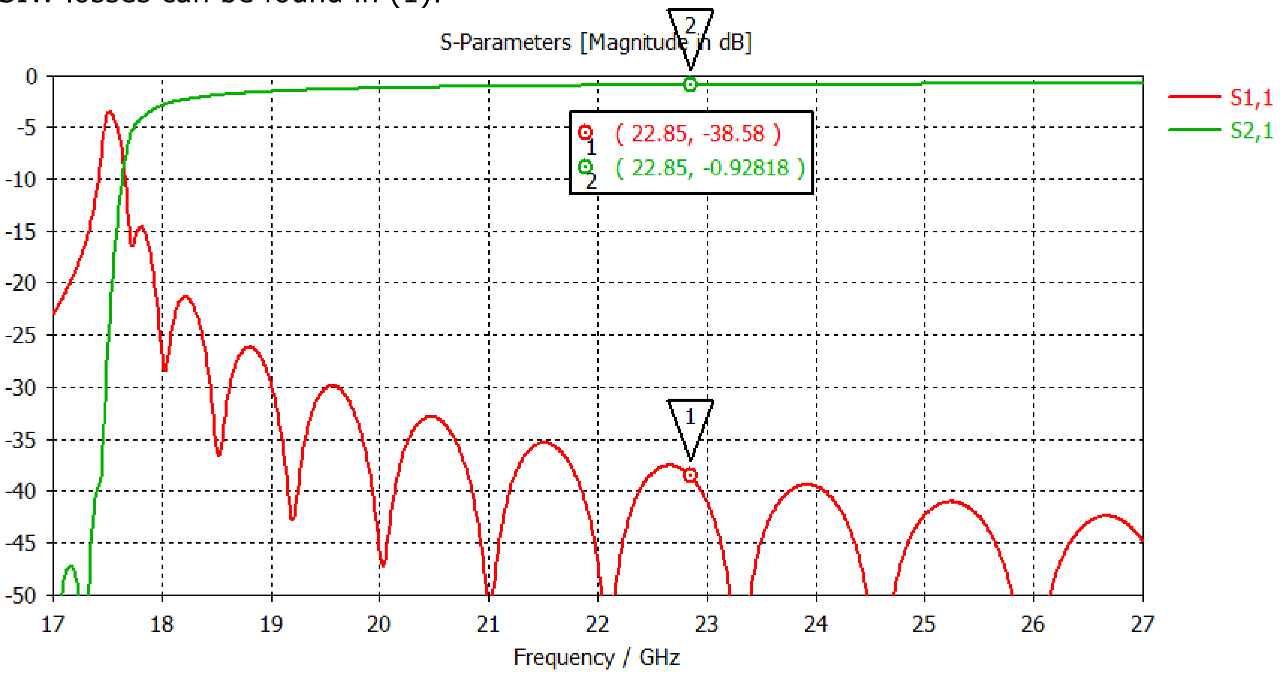

Figure 4.2 Simulated transmission and reflection of a 6 mm SIW with length 51mm, dielectric loss factor = 0.002 and smooth copper vias and foils.

4.2 Antenna array feeding structure for a 4 x 4 array

A diagram of the feed structure is shown in Figure 4.3. The feed structure consists of a series of H-plane T-junctions used as power dividers. From the feed point, half of the power is sent to the right and to the left, then divided in T1, then divided in T2 and finally divided in T3 or T4. When each of the T's are matched, it is a non-resonant structure, so line lengths are not critical and a wide bandwidth is expected.

Since the SIW width is the same in all T's, they all look equal. But since the line lengths between T2 and T3/T4 and between T3/T4 and the coupling slots are very short, higher order waveguide modes are significant at the interfaces between them. This means that a structure with T3, T2, T4 and four coupling slots must be designed and simulated in combination.

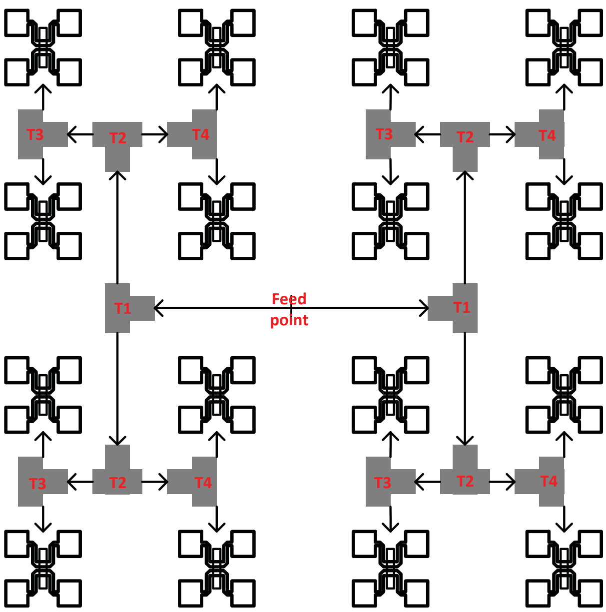

Figure 4.3 Diagram of the array feed structure.

This junction is shown in more detail in Figure 4.4. It is seen, that for the four signal paths', the wave propagations are all different. If not taken into account, it may lead to amplitude and phase variations between the antenna element exitations.

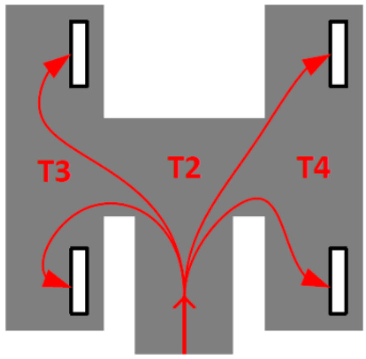

Figure 4.4 Illustration of details of the combination of T2-T3-T4 and coupling slots.

4.3 SIW H-plane T's

A commonly used method to match a H-plane T is to place a conducting post (here a via) as shown in Figure 4.5. The dimensions used here are:

Param	Value [mm]	Description
h	0.787	Dielectric thickness
w	7	SIW width
weff	6.62	WG effective width
d	0.6	Via diameter
p	1	Via pitch
dMv	0.5	Matching via diameter
yMv	3 – 3.15	Matching via distance from the T's "top" (centre-centre)

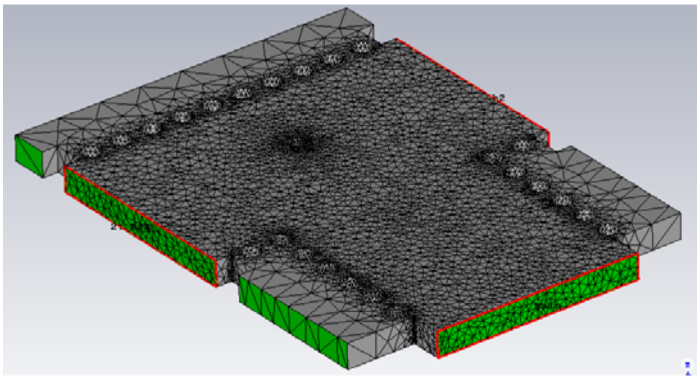

Figure 4.5 Mesh view from a simulation of a 7 mm SIW H-plane T.

The simulated results are shown in Figure 4.6. It is seen, that it is possible to obtain a good match in the required bandwidth. More details on the optimization of this junction can be found in (1). This type of junction can be used for T1 and with modifications for T2 and T3/T4.

The next step is to simulate the T3-T2-T4 junction, which is shown in Figure 4.7. The dimensions used are (coordinate system centred):

Param	Value [mm]	Description
h	0.787	Dielectric thickness
w	7	SIW width
weff	6.62	WG effective width
d	0.6	Via diameter
p	1	Via pitch

Param	Value [mm]	Description
dT2v	0.5	T2 via diameter
yT2v	0.45	T2 via y-position
dT3v	0.5	T3/T4 via diameter
xT3v	±8.45	T3/T4 via x-position
Δ x	16	Spacing between antenna elements
Δ y	16	

With this set-up, around 27 dB return loss is obtained, but the forward/backward transmissions are not balanced (@ 22.85 GHz):

- $|S_{21}|$ ~ -6.68 dB (backward)
- $|S_{31}|$ ~ -5.62 dB (forward)

It should be noted, that this result is for an SIW width of 7 mm and an x-y spacing between the antenna elements of 16 mm, which is a bad case.

One way to compensate this amplitude balance is to move the T3 and T4 vias in the y-direction. With an offset, yT3v = 0.25 mm, the results at 22.85 GHz are:

- $|S_{21}|$ ~ -6.23 dB, $\angle S_{21}$ = -68° (backward)
- $|S_{31}|$ ~ -6.01 dB, $\angle S_{31}$ = -54° (forward)

It seems to be difficult to obtain both phase and amplitude balance with this solution.

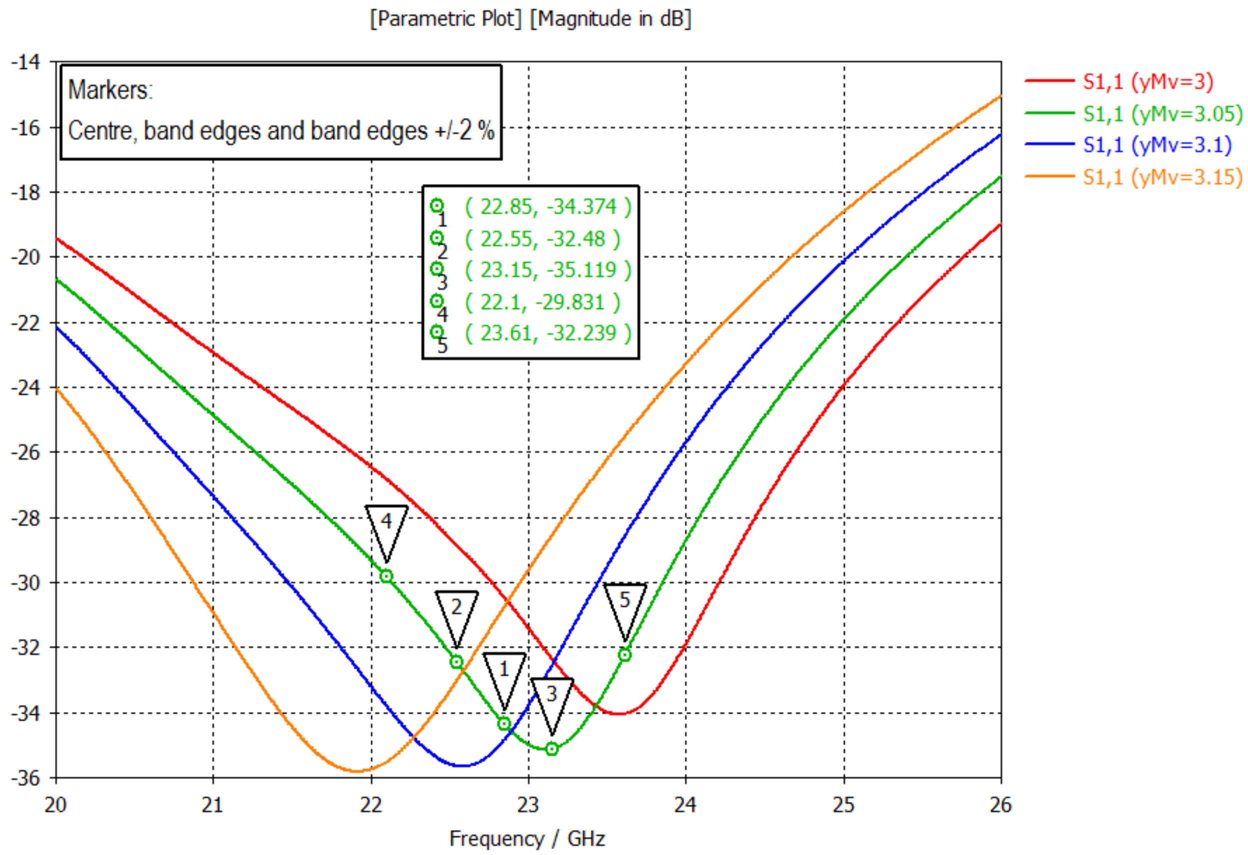

Figure 4.6 Simulated return loss of a H-plane T in 7 mm SIW.

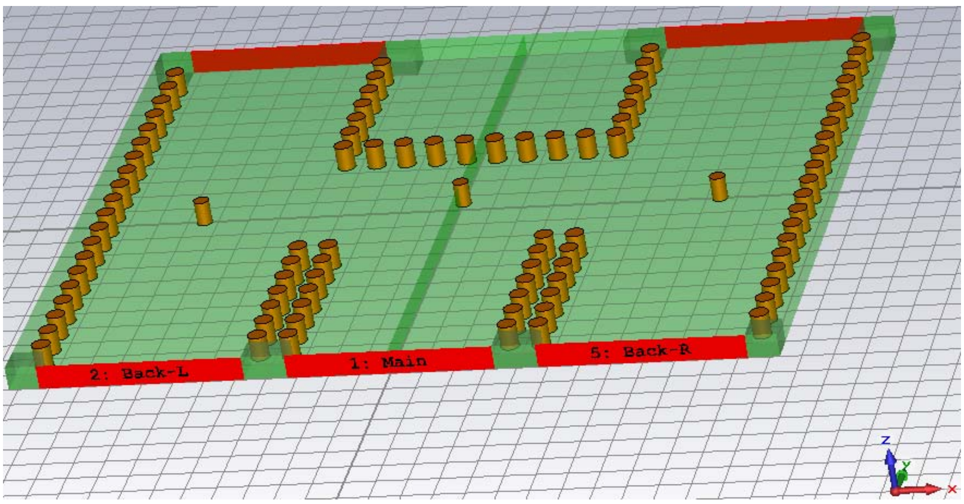

Figure 4.7 T3-T2-T4 junction in 7 mm SIW

A better solution is obtained, if you add extra vias as shown in Figure 4.8. Here the dimensions are:

Param	Value [mm]	Description
h	0.787	Dielectric thickness
w	7	SIW width
weff	6.62	WG effective width
d	0.6	Via diameter
p	1	Via pitch
Δ x	16	Spacing between anten-

Param	Value [mm]	Description
dT2v	0.5	T2 via diameter
yT2v	0.15	T2 via y-position
dT3v	0.5	T3/T4 via diameter
xT3v	±8.45	T3/T4 via x-position
yT3v	0	T3/T4 via y-position
dEv	0.4	Extra via diameter

Param	Value [mm]	Description
Δ y	16	na elements

Param	Value [mm]	Description
xEv	±4	Extra via x-position
yEv	2.6	Extra via y-position

With this solution, the results at 22.85 GHz are:

- $S_{21} = 0.498\angle 314°$ (backward)
- $S_{31} = 0.501\angle 310°$ (forward)

This corresponds to an "EVM" of:

$$"EVM" = 2\left|\frac{S_{21} - S_{31}}{S_{21} + S_{31}}\right| = 0.07$$

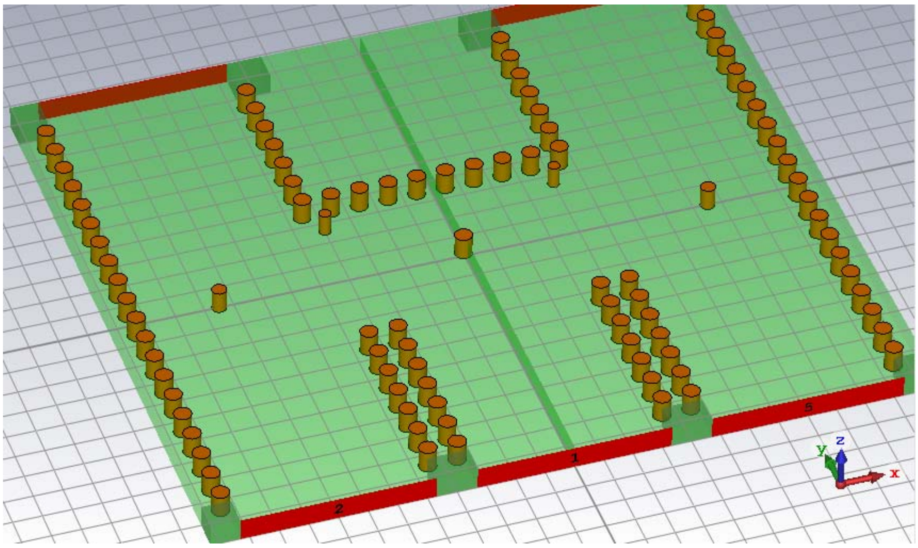

Figure 4.8 T3-T2-T4 junction in 7 mm SIW with extra vias for improved front/back-balance.

These simulations are made with waveguide ports at the SIW branch ends. Another simulation was made with the coupling slots as waveguide ports as shown in Figure 4.9. In this set-up, there is no longer symmetry around x = 0. The input port will not be matched, since the waveguide ports do not have the same impedance as the four-leaf-clover elements.

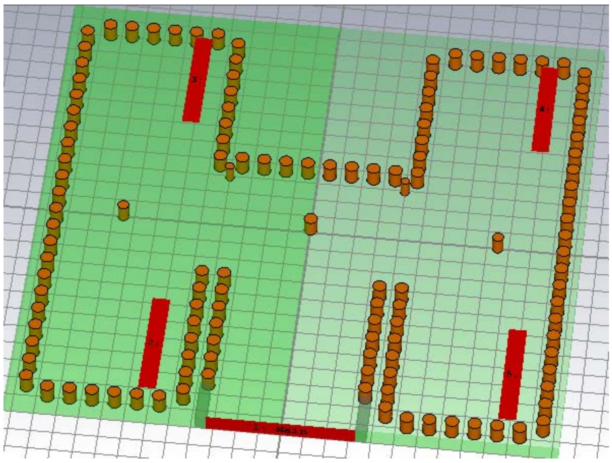

Figure 4.9 T3-T2-T4 junction with extra vias and coupling slots as waveguide ports.

The dimensions used in this simulation are:

Param	Value [mm]	Description
h	0.787	Dielectric thickness
w	7	SIW width
weff	6.62	WG effective width
d	0.6	Via diameter
p	1	Via pitch
Δ x	16	Spacing between anten-
Δ y	16	na elements
dT2v	0.5	T2 via diameter
yT2v	0.15	T2 via y-position

Param	Value [mm]	Description
dT3v	0.5	T3/T4 via diameter
xT3v	±8.5	T3/T4 via x-position
yT3v	0	T3/T4 via y-position
dEv	0.4	Extra via diameter
xEv	±4	Extra via x-position
yEv	2.9	Extra via y-position
ls	5.24	Slot length
ws	0.8	Slot width
lm	1.9	Slot-SIW c-c offset
l1	3	Slot-centre to SIW end

With this set-up, the results at 22.85 GHz are:

- S_{21} = 0.424∠134°; "EVM" = 0.040 (left-backward)
- S_{31} = 0.450∠131°; "EVM" = 0.040 (left-forward)
- S_{41} = 0.449∠131°; "EVM" = 0.038 (right-forward)
- S_{51} = 0.425∠134°; "EVM" = 0.038 (right-backward)

The "EVM" values are calculated as:

$$"EVM_k" = \left| \frac{S_{k1} - S_{Avg1}}{S_{Avg1}} \right| \qquad S_{Avg1} = \left(S_{21} + S_{31} + S_{41} + S_{51}\right)/4$$

If the SIW width is reduced to 6 mm and the element spacings are kept at 16 mm, the distances between T's are increased a bit, and this has a very significant effect. Adequate performance can be obtained without the extra vias. The layout is shown in Figure 4.10.

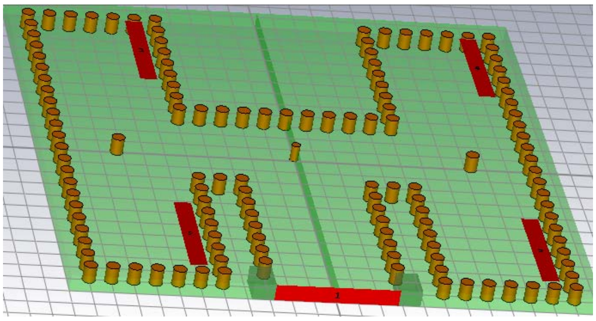

Figure 4.10 T3-T2-T4 layout with a SIW-width of 6 mm and the coupling slots as waveguide ports.

The dimensions used in this simulation are:

Param	Value [mm]	Description
h	0.787	Dielectric thickness
w	6	SIW width
weff	5.62	WG effective width
d	0.6	Via diameter
p	1	Via pitch
Δ x	16	Spacing between antenna elements
Δ y	16	
dT2v	0.4	T2 via diameter
yT2v	0.15	T2 via y-position

Param	Value [mm]	Description
dT3v	0.6	T3/T4 via diameter
xT3v	±8.25	T3/T4 via x-position
yT3v	0.05	T3/T4 via y-position
dEv	0.4	Extra via diameter
xEv	±4	Extra via x-position
yEv	2.9	Extra via y-position
ls	5.24	Slot length
ws	0.8	Slot width
lm	1.9	Slot-SIW c-c offset
l1	3	Slot-centre to SIW end

With this set-up, the results at 22.85 GHz are:

- S_{21} = 0.467∠262°; "EVM" = 0.024 (left-backward)
- S_{31} = 0.450∠264°; "EVM" = 0.027 (left-forward)
- S_{41} = 0.451∠264°; "EVM" = 0.025 (right-forward)
- S_{51} = 0.470∠262°; "EVM" = 0.029 (right-backward)

The case of 7 mm SIW in combination with 18 mm element spacing has not been simulated.

5 Conclusions and recommendations

- This type of antenna seems well suited for the purpose and the PCB structure is rather simple. A rough estimate of the performance of the 4 x 4 array would be:
  - A directivity of 25 dBi.
  - A gain of 23 dBi, but the losses in the feed network are difficult to estimate.
- A good agreement between simulation and measurement results (Chapter 3) indicates that the simulations are reliable.
- The transition between the SIW network and the (coax) feed has not been designed.
- The choice of SIW width should be carefully considered:
  - A 6 mm SIW has somewhat higher loss and dispersion than a 7 mm SIW.
  - The mutual coupling between the H-plane T's, T_2 and T_3, is much stronger for the 7 mm SIW than for the 6 mm SIW, so this must be included in the design.
- The optimum spacing between the four-leaf elements has not been determined.
- It is recommended to use rolled or "reverse treated" copper foils since electrodeposited foils have larger roughness and higher loss.
- In some simulations it is possible to use dielectric filled waveguides instead of SIW's to speed up the simulation.

6 References

1. **Squadrito, Paolo.** *K-band antenna for nano satellite.* s.l. : Aalborg University, Student report, Electronics and IT, 2016.
2. *A Wideband High-Gain High-Efficiency Hybrid Integrated Plate Array Antenna for V-Band Inter-Satellite Links.* **Jie Wu, Yu Jian Cheng, and Yong Fan.** 4, 2015, IEEE Trans on AP, Vol. 63.
3. *Guided-Wave and Leakage Characteristics of Substrate Integrated Waveguide.* **Feng Xu, Ke Wu.** s.l. : IEEE Trans. on. Microwave Theory and Techniques, Vols. 53, pp 66-73.