Chapter 4

Theoretical comparison to known matching circuits

The SRMT presented in Chapter 3 is relatively simple to implement. In order to be able to evaluate the ease and effectiveness of this proposed technique, it must be directly compared to other standard and wideband matching techniques. In this chapter a direct comparison is made between standard matching techniques often used in the industry and the SRMT. The examples presented include the single and double stub matching techniques, called the parallel-element matching technique in this chapter. Furthermore, a comparison is made with the quarterwave matching section and a triangular matching line. They are referred to as series matching since the matching element is in serie with the patch antenna. Lastly the SRFT example presented in [2, 4] is taken as reference, and the LC-matching circuit is applied on a similar microstrip patch antenna.

4.1 Parallel-element matching circuits

These standard matching techniques are aimed at matching an arbitrary impedance to a specified impedance. In order to be able to compare different techniques a patch antenna with a minimum return loss at 1.8 GHz was used with an optimum return loss of only -11 dB. The response of this test case is shown in Figure 4.1.

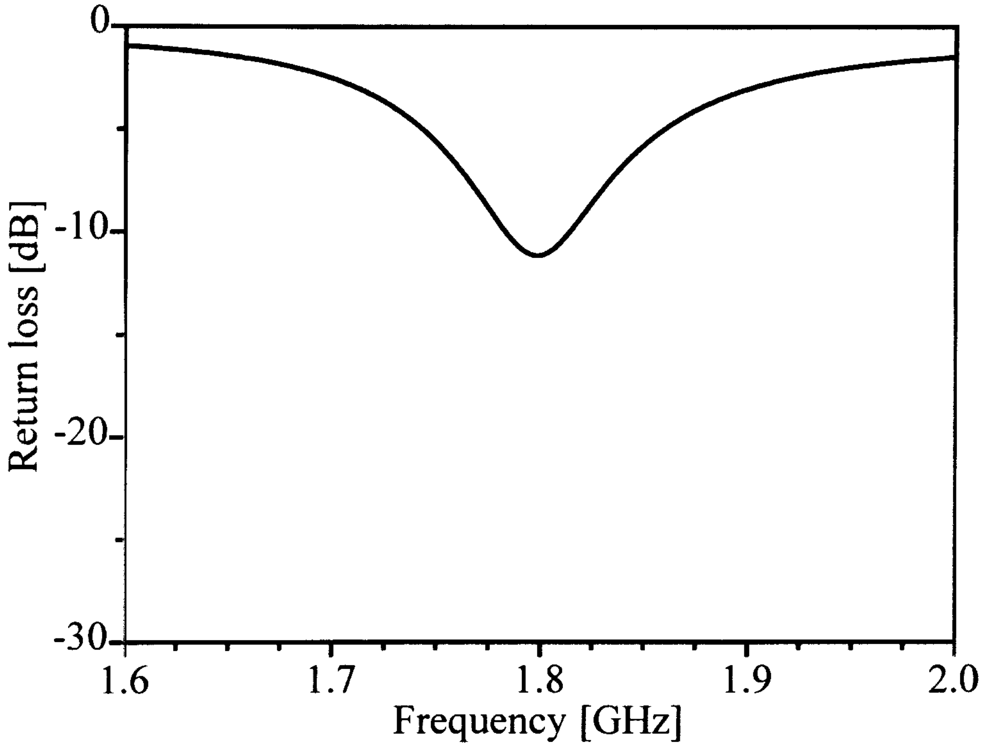


Figure 4.1 Example patch impedance for implementation of standard matching circuits

The input impedance at 1.8 GHz for the patch antenna is 47.3-*j*27.9 Ω. The first matching circuit implemented on this test case is a single stub matching circuit. In order to be able to match this impedance to 50 Ω, a circuit consisting of a series transmission line of length 166° (at centre frequency) with characteristic impedance 50 Ω is needed. A parallel open circuit transmission line of length 30° will transform the impedance to 50 Ω at the centre frequency. Please note that there are a number of alternative ways of implementing this technique. The aim is not to evaluate the single stub matching technique, but instead simply to obtain a proper result with the technique so that it can be compared to the SRMT. The result obtained with the single stub circuit is presented in Figure 4.2.

Also shown in Figure 4.2 is the result obtained when a double-stub matching circuit is implemented. The double-stub circuit used to obtain this result consisted of an open stub of length 14° followed by a 50 Ω-transmission line of length 135° and another parallel open stub of length 23°.

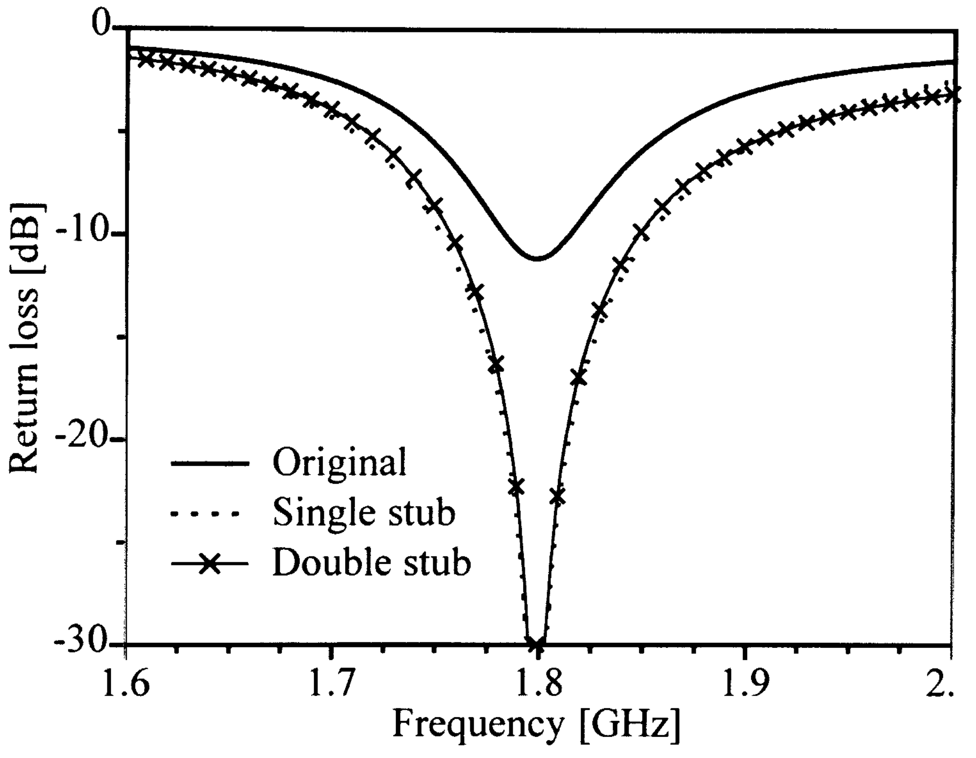


Figure 4.2 Single and double stub match implemented on an arbitrary impedance to match to 50 Ω

From Figure 4.2 it is evident that the results for the two techniques correspond very closely. The unmatched return loss was below –10 dB between 1.783 GHz and 1.815 GHz. This represents a bandwidth of 32 MHz. The single stub matched circuit has a bandwidth of 100 MHz and the double stub matched circuit an 89 MHz bandwidth. For a –14 dB matched criterium the original load has no bandwidth, but the single stub and double stub matching techniques resulted in a 59 MHz and 54 MHz bandwidth respectively. The difference between the results of the two techniques is minimal.

4.2 Series-element matching circuits

A very popular matching structure is the quarterwave matching transmission line. It is very easy to design and takes up no space in a feed network when a transmission line length of more than 90° is used. The unmatched patch (centre frequency) input impedance used in the previous section for illustration, 47.3-*j*27.9 Ω, is again used for the next example. The quarterwave matching line only works for resistive loads. To ensure that the quarterwave matching line transforms a resistive load, the original load impedance is first phase-transformed to a real value. A 50 Ω transmission line of electrical length 40° is inserted between the load and the quarterwave matching transmission line. The phase-transformed impedance is now 88.4 + *j*0 Ω. With a newly obtained load impedance of 88.4 Ω a quarterwave matching section of 66.5 Ω will result in a 50 Ω matched circuit. The return loss as function of frequency for the quarterwave section is shown in Figure 4.3.

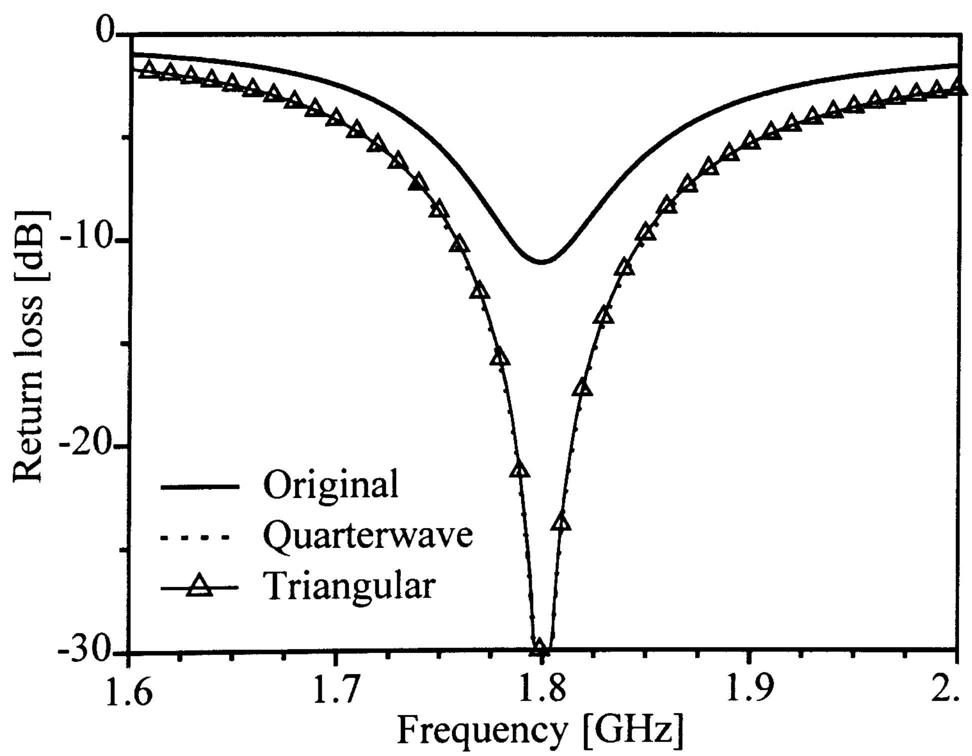


Figure 4.3 Results for the series type of matching circuits

The continuously tapered types of matching circuits are discussed in Chapter 5.8 of [21]. The types of structures discussed in [21] include the exponential taper, the triangular taper and the Klopfenstein taper. They all have similar-looking circuit layouts and particular responses. The triangular taper circuit is taken as an example. The impedance Z of the transmission line as a function of position x down the matching is described by the following relation [21]:

$$Z(x) = \begin{cases} Z_0 e^{2\left(\frac{x}{L}\right)^2 \ln\frac{Z_L}{Z_0}} & \text{for} \quad 0 \le x \le \frac{L}{2} \\ Z_0 e^{\left(\frac{4x}{L} - \frac{2x^2}{L^2} - 1\right)\ln\frac{Z_L}{Z_0}} & \text{for} \quad \frac{L}{2} \le x \le L \end{cases} \qquad (15)$$

A phase-transforming section of line is required for the triangular taper since it also works with real load impedances only. The 40° line used for the quarterwave transmission line is again implemented in this circuit. A line with a total length of 360° is chosen, consisting of 10° subsections. The final results for both the quarterwave and triangular taper, shown in Figure 4.3, are very close to each other in terms of frequency bandwidth. The quarterwave section has a –14 dB bandwidth of 56 MHz and the triangular taper 54 MHz.

A very important fact to keep in mind specifically when considering the taper match circuits is that they are known to be very frequency insensitive and can achieve large bandwidths. However, this is only valid for a frequency insensitive load impedance. Yet, as is shown in the two graphs, all the matching techniques have a relatively similar response for a load impedance that varies over frequency.

4.3 SRMT applied to load

Finally, the mismatched patch example is matched with the SRMT. In order to be able to compare the new matching technique to the standard matching techniques (as described in the previous paragraphs) the LC-resonant match is done with two different approaches.

4.3.1 Single LC-resonant match without optimum bandwidth

The resonant technique considered in this dissertation requires a matched load to function. The SRMT would not operate if the original load impedance of 47.3-*j*27.9 Ω is considered alone. Therefore, the quarterwave matched load designed in the previous paragraph is considered the load impedance. This implies that the quarterwave matching transmission line is again part of the matching circuit. The single LC-resonant circuit that results in the required match consists of a capacitor of 8.4 pF and inductor of 0.93 nH. The return loss result for this circuit is presented in Figure 4.4. The –14 dB return loss bandwidth is 83 MHz, in comparison to the original quarterwave matching circuit that resulted in 56 MHz.

4.3.2 Optimum Bandwidth Single LC-Resonant Matching Technique

The second test case application for the LC-resonant circuit is done with the real impedance transformation as described in Chapter 3.5. The circuit will also consist of a 50 Ω phase-transformer of 40°, followed by the LC-circuit and a quarterwave matching transmission line. A capacitor of 4.98 pF, inductor of 1.56 nH and quarterwave matching line of impedance 81 Ω resulted in the return loss response presented in Figure 4.4. The bandwidth for –14 dB return loss is 134 MHz.

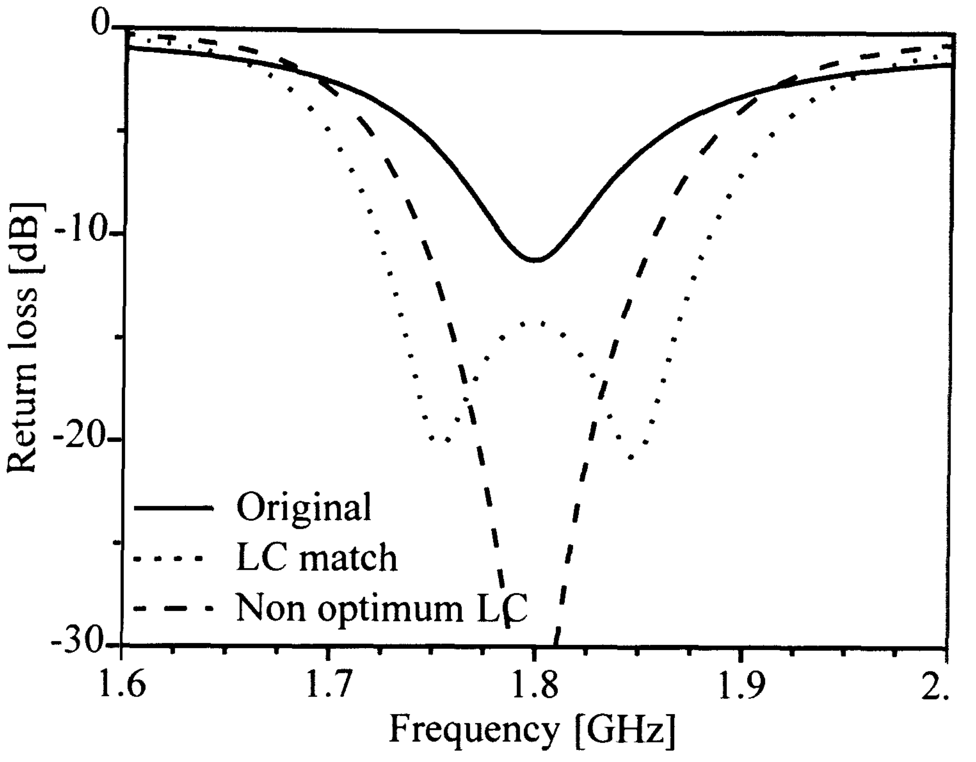


Figure 4.4 Matching results with the implementation of the proposed LC-circuit

It is evident from Figure 4.4 and the previous two sections that the LC-matching circuit can result in a vast improvement in bandwidth results. One must keep in mind that the standard techniques are mostly aimed at either a single frequency match (the quarterwave matching circuit when considered alone as well as the single and double stub matching circuits) or matching of a constant load impedance over a relatively wide frequency range (the tapered transmission line structures, as well as the quarterwave matching circuit to some extent). It would therefore be incorrect to state that the SRMT is an improvement for matching circuits in general, but any circuit or load with a similar frequency response to the examples illustrated so far can be significantly improved with the SRMT.

4.4 Patch example from the SRFT

The SRFT is mentioned in Chapter 3 as one of the commonly discussed microstrip patch antenna wideband impedance matching techniques found in open literature. The publications that presented this technique [2, 4] were also included in a very popular compendium of papers concerning microstrip patch antennas [37]. For this reason it is very important to measure the presented LC-matching technique to the SRFT, so that one can be able to make a proper judgement on the working of the LC-technique and whether it would work as effectively as the well-known SRFT. The authors of the SRFT publications implemented the technique on a single patch antenna for all their publications on the SRFT [2, 4 and 16]. The graphical representation of the patch antenna presented in all the above-mentioned papers is shown in Figure 2.4 and for ease of reference repeated in Figure 4.5. The microstrip antenna is a square patch. On the ground plate a foam sheet of thickness 5 mm and ε_r = 1.03 is placed. On the foam sheet a substrate with thickness 0.5 mm, ε_r = 2.17 and $tan\delta$ = 0.0009 is placed. A similar type of dielectric substrate is used for the feed network on the back plane of the ground plate, but with thickness t = 1.575 mm instead of 0.5 mm. Since the antenna is described in detail in all three the papers regarding the SRFT, it was decided to take this same antenna and simulate it in IE3D. The resulting return loss obtained from the simulation and the published results from [2, 4 and 16] is shown in Figure 4.6.

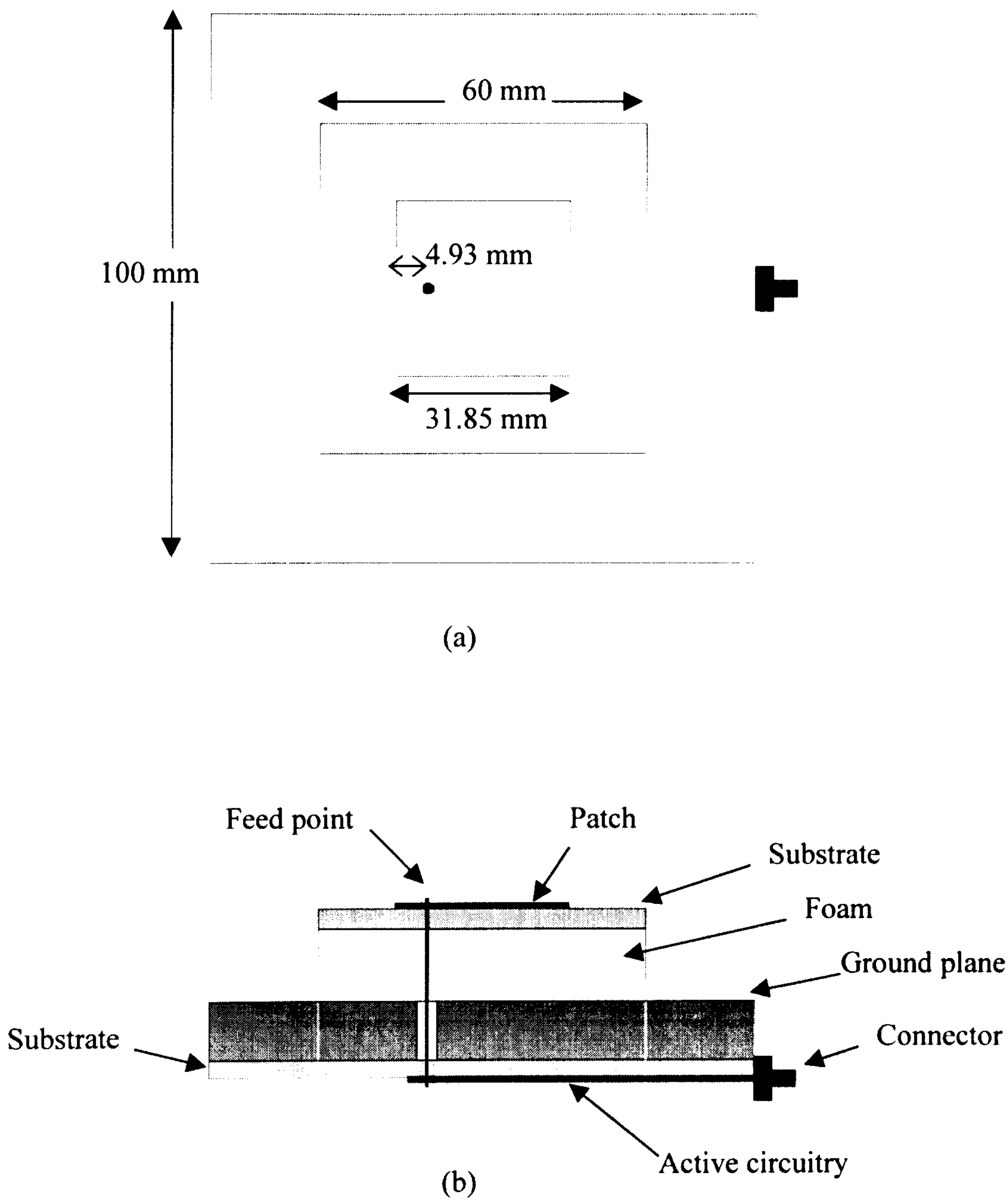


Figure 4.5 Example patch antenna described and wideband matched in [2, 4 and 16]

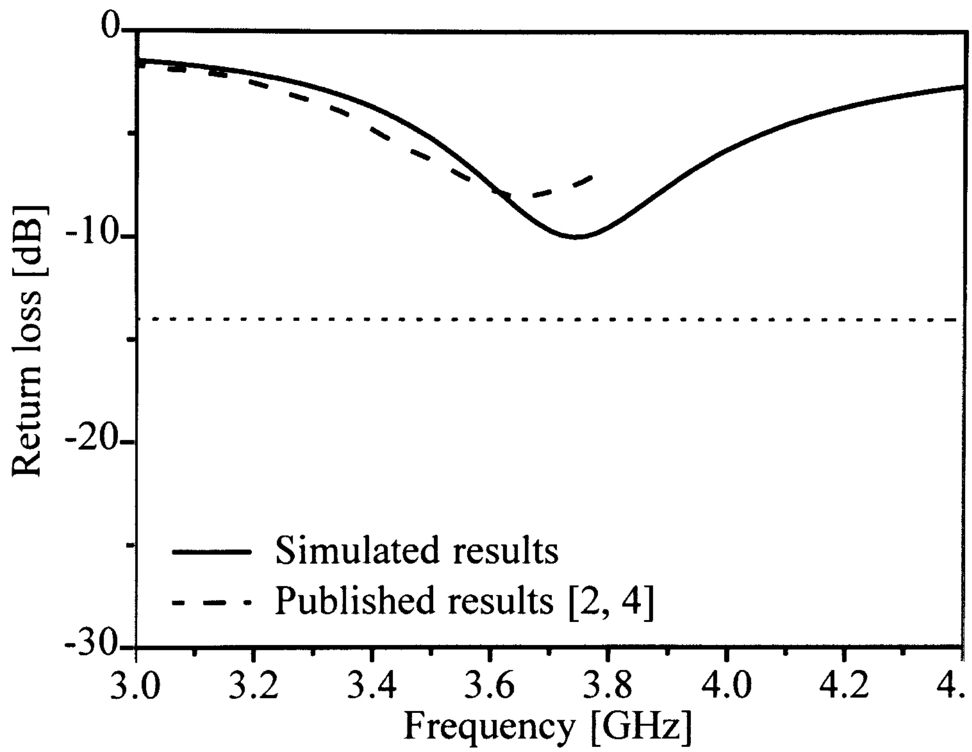


Figure 4.6 Published and simulated results for the example patch antenna implemented for the SRFT

Figure 4.6 shows reasonable correlation between the simulation and the published data for the patch antenna shown in Figure 4.5. A frequency shift in the order of 4% is encountered, and the simulation shows 2 dB better return loss when compared to the published results. The published results from [2, 4] end at 3.8 GHz. When comparing the results of the two techniques this deviation must be kept in mind before a final comment is made about the results that will be shown in this section.

The SRMT was applied to the simulated patch antenna data. The results are shown in Figure 4.7. The circuit implemented consists of a 14° phase transforming line, a capacitor of 0.637 pF, an inductor of 2.77 nH and a quarterwave transmission line of 83 Ω. The design frequency was 3.74 GHz. Also included in Figure 4.7 is the result that was obtained when the SRFT was applied [2, 4]. The SRFT circuit consists of (seen moving away from the load) a parallel inductor of 1.993 nH, a series inductor of 7.7336 nH, parallel capacitor of 0.516 pF and a series inductor of 6.9056 nH (Refer to Figure 2.5).

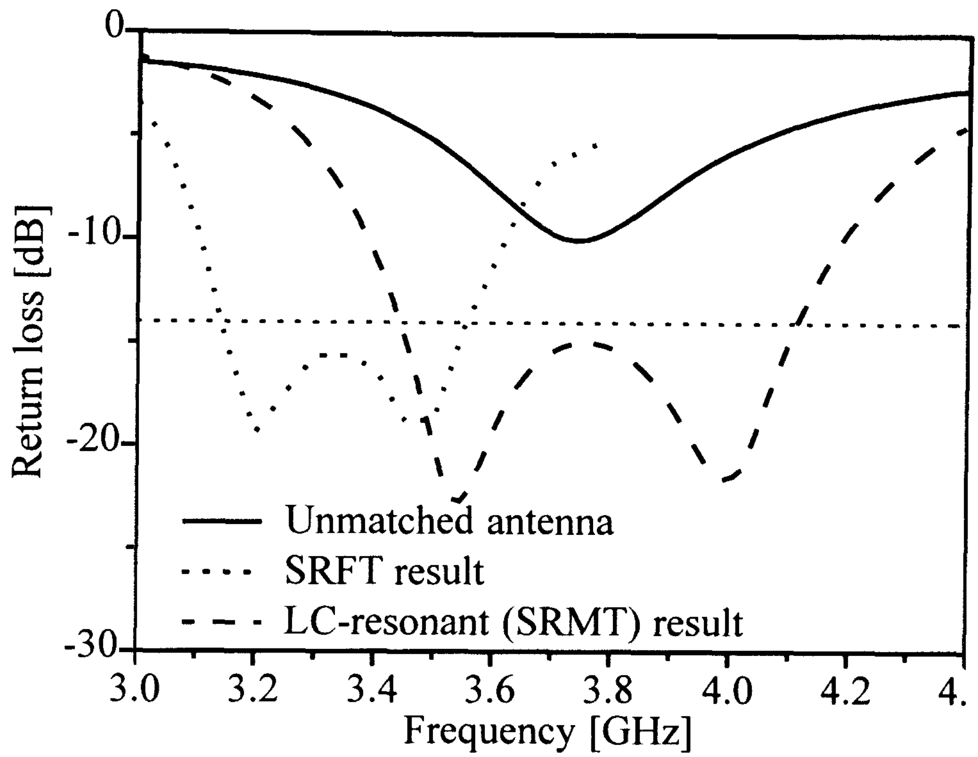


Figure 4.7 Return loss results for the published SRFT patch antenna example, matched with the mentioned technique and the LC-resonant network

Figure 4.7 presents some important results. The SRMT manages to establish a VSWR < 1.5:1 bandwidth of 680 MHz, between 3.44 GHz and 4.12 GHz. The SRFT result that was published had a bandwidth of 400 MHz, between 3.15 GHz and 3.55 GHz. The main difference is the choice of frequency range for the SRFT matching network to match the antenna. In Figure 4.7 it is evident that the centre design frequency for the SRFT case is close to 3.3 GHz. A statement made in [4], where the result from Figure 4.7 is obtained, reads as follows. "The fundamental resonant frequency of the patch is 3.3 GHz." This statement might be somewhat confusing, but it leads one to the final conclusion as to why the published result was not taken at the frequency where the return loss for the unmatched antenna was already a minimum, namely 3.74 GHz. [3] states the following:

"In fact, for the thicker antennas, the reactance curve never passes through zero at all. For this reason, the resonant frequency has been redefined as the point at which the resistance reaches a maximum, independent of the value of the reactance."

The real part of the simulated impedance of the unmatched antenna is shown in Figure 4.8 together with the SRFT-matched return loss response obtained in [4]. The article in which the statement about the resonant frequency presented in the previous paragraph is made, is also referred to in [4]. One can only assume that the choice of matching frequency for the authors of the SRFT in [4] is based on the real impedance of the patch antenna, and not so much the frequency where minimum reflections are originally obtained.

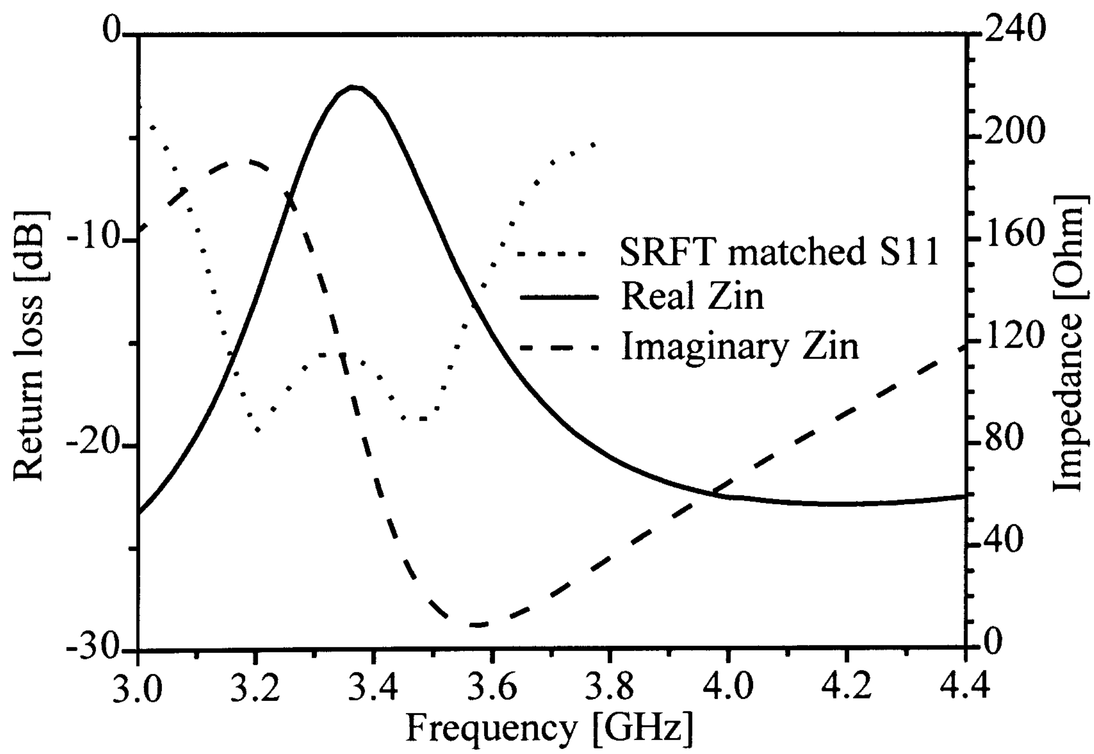
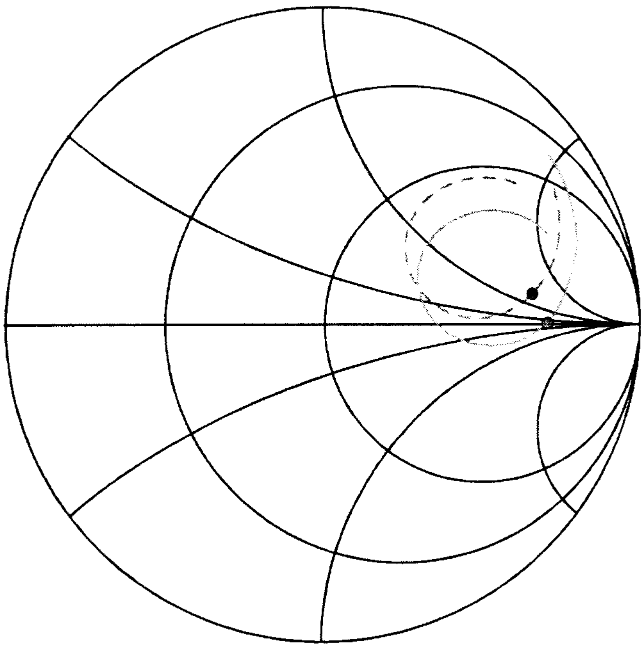


Figure 4.8 Input impedance simulated for the patch antenna presented in [2, 4]

The results obtained and presented in Figure 4.7 show that the LC-matching technique is comparable to the SRFT in terms of bandwidth enhancement results. It also shows that the deviation obtained between the simulation done and the published results is not particularly crucial since there are a number of other parameters that also play a very important role in determining the final match. The selection of frequency range where the wideband match must be done is one of these parameters. It is evident that a different approach is taken for the LC-resonant match, which aims at enhancing the minimum return loss already available. The published results for the SRFT, on the other hand, show that this is not the case for the SRFT. An in-depth study of the SRFT would probably provide more information.

An alternative design with the SRMT was done on the patch antenna example presented in this section to establish whether it would be possible to obtain a frequency shifted match as well. The result is academic in nature, since the circuit obtained is difficult to realise in practice. The steps taken to obtain the required match are shown and explained with the aid of a number of Smith charts. Figure 4.9 shows the original impedance locus of the unmatched antenna on the Smith chart.



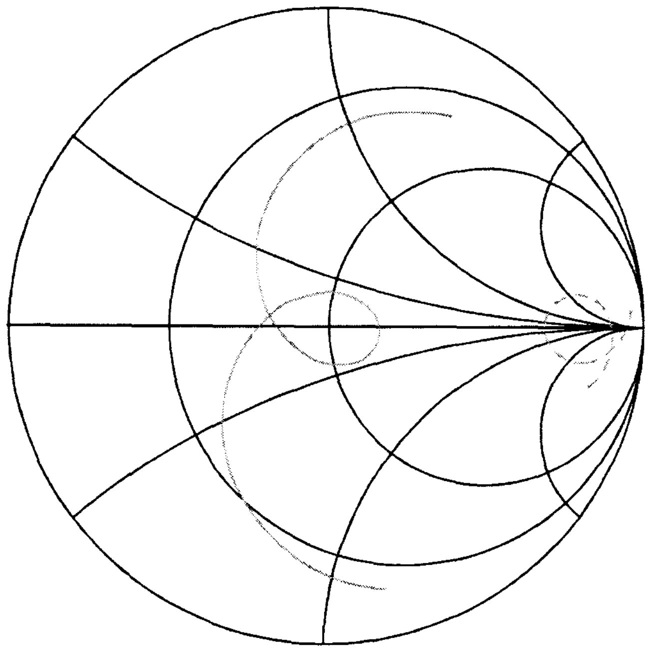
Original S11 curve

Initial phase transforming

Figure 4.9 Return loss of original patch antenna and phase transforming to obtain real impedance at new design frequency

The dots shown on the locus on the Smith chart represent the new frequency positions where the antenna will now be matched. This is the frequency where the antenna has a maximum real impedance, irrespective of the reactance value. The first aim for the new circuit was to get the newly defined center frequency on the real axis. This was done with a

50 Ω transmission line of 5° at center frequency, now considered to be 3.35 GHz. This is different from the value of 3.3 GHz stated in [2, 4] because of the slightly shifted frequency response obtained with the IE3D simulation. Figure 4.10 shows the next two steps taken to match the patch antenna to the required level.



- - - - Phase transformed in preparation for match

——— Matched response

Figure 4.10 Phase transformed impedance and final matched result for center frequency 3.35 GHz

The actual impedance encountered after the 5° phase transformation was 270 + j0 Ω. This is a very high real impedance value and becomes difficult to work with. The next step in the matching sequence is the phase transformation so that the imaginary admittance curve will lie favourable around the design centre frequency. The easiest way to get this done while using the minimum amount of space was to turn the locus around its new impedance value, 270 Ω. The correct phase transformation, shown in Figure 4.9, was obtained with a transmission line of length 65° at 3.35 GHz and characteristic impedance 270 Ω. This part of the circuit would be extremely difficult to realise in practice. The final design of the circuit to match the antenna to 50 Ω over an optimum frequency band around 3.35 GHz was done with a capacitor of 0.187 pF and an inductor of 11.73 nH. The quarterwave matching transmission line for optimum bandwidth from 270 Ω to 50 Ω was 139 Ω. The final resulting return loss with comparison to the SRFT result is shown in Figure 4.11.

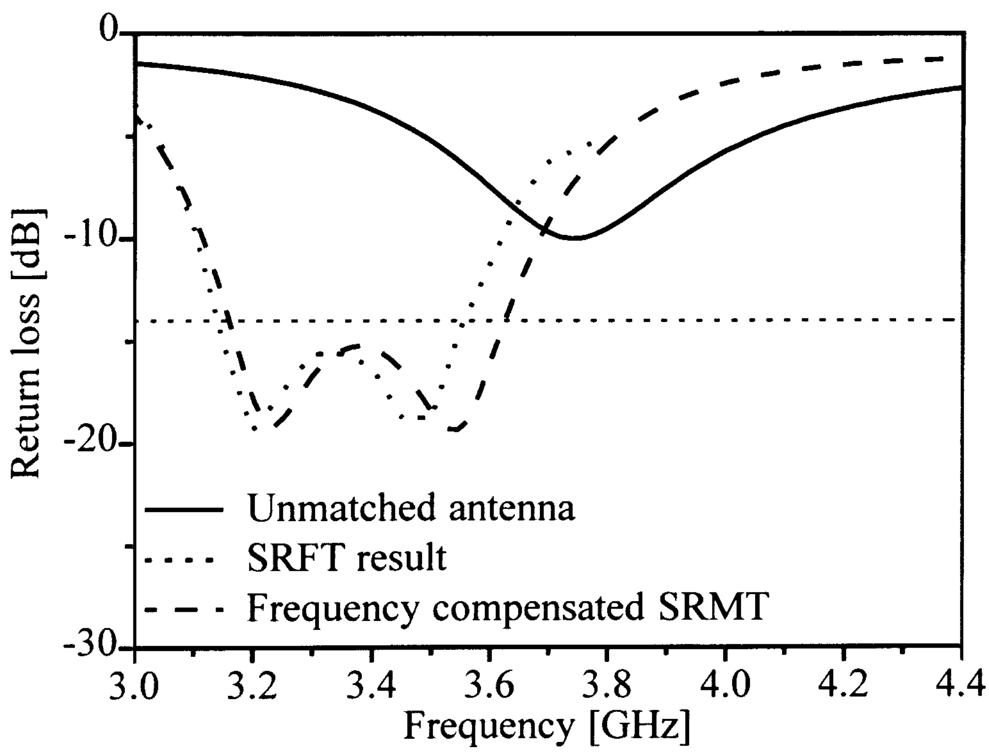


Figure 4.11 Adapted LC-match for direct comparison with the SRFT

The result obtained by implementing the frequency compensated matching circuit results in a frequency band of 470 MHz, between 3.16 GHz and 3.63 GHz. The SRFT-match presents a 400 MHz matched bandwidth. For the specific antenna the adjusted LC-resonant matching circuit resulted in a wider bandwidth than the SRFT. One must keep in mind that there was a slight difference between the simulated patch antenna and the initial antenna presented in [2, 4]. Therefore it is more fair to state that the SRMT provides comparable results with that published in [2, 4] for the SRFT, since there are number of unknown variables between the simulation and the publication. For this specific example the SRFT result is more practical to implement than the SRMT circuit, due to the frequency shifted match.

4.5 Summarising statement on comparing analysis

The SRMT is a technique aimed specifically at matching single resonance antennas. Probe-fed patch antennas have a distinctive resonant impedance behaviour, and the SRMT can improve this load impedance very effectively. Different loads do not necessarily present similar frequency behaviour and alternative matching techniques should be considered for these loads. Examples of this are the single and double stub matching structures applied to an arbitrary load impedance to match it to any required impedance at a single frequency. Quarterwave matching lines and tapered matching lines can match a constant load impedance very effectively over a much broader frequency band than the stub matching circuits. The load impedance example presented in this chapter illustrates how the SRMT is just as easy to design as the above-mentioned matching techniques, and that it is superior for the specific example used. Other scenarios, as mentioned in this paragraph and in the chapter, will obviously reign superior in their respective applications.

In the second part of the chapter the SRFT was taken and compared to the SRMT. The results proved that the improvement obtained is similar in terms of percentage improvement, but that the procedure for the design of the SRFT leads to another frequency range. A brief discussion of this phenomenon is presented in the chapter.