Chapter 2

Background

The use of matching networks to enhance the properties of microstrip patch antennas has not received much attention in open literature. The aim with this dissertation is to shed some light on the possibilities that exist when one includes a matching feed network as part of the antenna design. Chapter 2 presents a brief overview of current antenna impedance matching techniques. Specific attention is paid to the circuit layout, the origin of the technique and the level of impedance bandwidth improvement obtained with each of the techniques.

2.1 Concepts of impedance matching

The most basic impedance matching network consists mainly of circuits with an open or shorted stub transmission line section [21], a quarterwave transformer or in amplifier design a T- or Π-section impedance matching circuit [22]. In active circuit design where transistors and other circuit components are used, impedance matching is very important, the reason being that transistors are not necessarily, if ever, matched to the required system impedance. To accomplish a basic match a T- or Π-section is implemented, resulting in a match at the required frequency, but not necessarily at other frequencies. Figure 2.1 shows an example of a Π-section impedance matching circuit. The fact that the circuit is only matched at a single frequency can be a problem. Normally a system is not meant to work at a single frequency, but over a designated frequency range. Having a 50 Ω match at a single frequency does imply that there will be a frequency range around the matched point where the VSWR will fall below a certain value, thus resulting in a matched frequency range. The problem is that there will be no control over the frequency range impedance behaviour other than the centre frequency. Numerous techniques have been developed to address this problem.

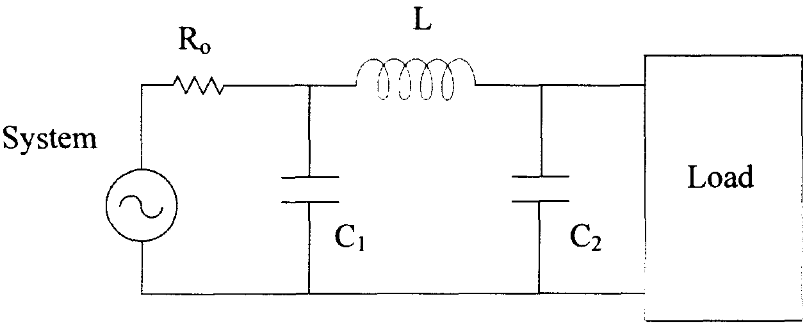


Figure 2.1 Implementation of a Π-section to match a load with arbitrary impedance to a specific system

2.2 The Real Frequency Technique

The Real Frequency Technique, known in short as the RFT, has been developed by H.J. Carlin in 1977 [23]. The method uses real frequency impedance data (for example experimental results), so that no model or prior knowledge of the load is required. This implies that the technique's aim is to find a matching solution for any arbitrary load. The load might either be a specific model, or it could be a set of tabulated load impedance values with no clearly visibly relation between them. The transducer gain $T(\omega^2)$ is taken as the starting point for the design of the matching circuit, and the gain through the matching circuit is optimised for maximum power transfer over a designated frequency range (Equation (1), taken from [23]).

$$T(\omega^2) = \frac{\text{Power to load}}{\text{Power available from generator}} = 1 - |\rho|^2 \qquad (1)$$

Transducer gain is a term often used in amplifier circuit design and is not a commonly used definition for antennas. The gain is simply a reference to the power transferred through the matching network considered, and is also known as G_T [22].

$$G_T = T(\omega^2) = |S_{21}|^2 \tag{2}$$

The whole procedure is described in [23], and examples are presented. The circuits considered consist of an LC-ladder network, as shown in Figure 2.2.

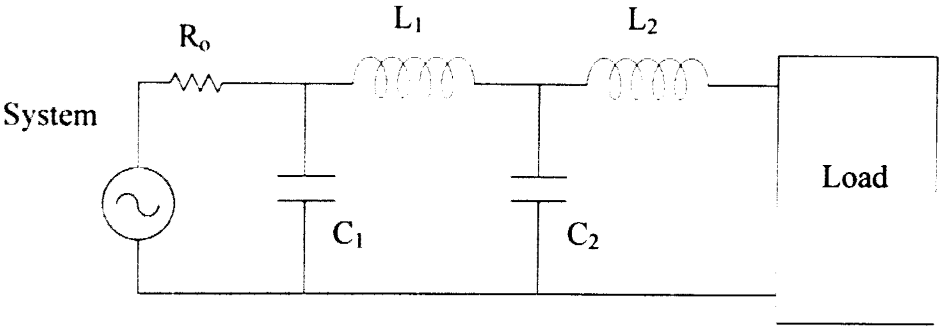


Figure 2.2 Circuit topology used for the examples given in [23]

In amplifier circuits the active circuit normally acts as an intermediate stage between two parts of the system. Figure 2.3 illustrates how a Field Effect Transistor (FET) is placed in a circuit, and how two matching circuits are required to create an overall matched system. This topology is discussed in [24]. The RFT is once again considered in this paper, but generalised for implementation in circuits such as the one shown in Figure 2.3 instead of circuits terminated in a load (Figure 2.2).

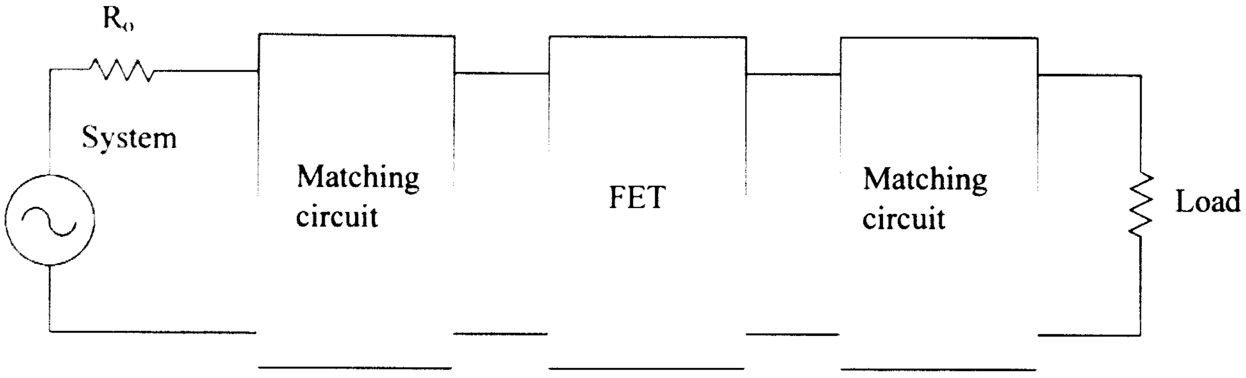


Figure 2.3 Matching of an active amplifier circuit, with a real impedance load on the right-hand side

For amplifier circuits a maximally flat transducer gain (i.e. close to constant gain over the required frequency band) is normally required [25]. Prior to the publication of [25], Chebychev gain functions were commonly used to match complex loads to resistive generators. According to [25] this method does result in an optimum response (transducer gain with the inclusion of the whole circuit) provided the load is terminated in a resistive load. Examples are presented in [25], proving the fact that the current knowledge at that stage was insufficient to provide optimum solutions for complex loads. A discussion on matching in the case where the load impedance is not resistive is found in [26]. The circuits discussed in [26] consisted of a number of microwave amplifiers and the authors provided answers to the questions they presented in [25]. The main issue addressed was multistage amplifiers, where intermediate matching was required but the transistors never reflect resistive impedances only over a wide frequency range. This presented another situation where the matching required not only matches a resistive generator to a complex load, but also a complex generator (the previous amplifier step) to a complex load (the next amplifier step). This specific scenario was addressed in [27].

The implementation of the RFT with an alternative set of circuit components is presented in [28]. In this article transmission lines are implemented as part of the design and the circuit is applied to an amplifier circuit with a frequency range of 0.1 – 5 GHz.

Alternative matching techniques have also been developed in the field of microwave circuits. Some of these techniques are described in [29 - 33]. They focus mainly on numerical techniques to optimise and design LC-ladder configurations similar to the circuit shown in Figure 2.2, although some different configurations are shown in [30]. The background given in this section is applicable to microwave circuits, with all the examples presented in the papers being active amplifier circuits of some kind. The difference between having an amplifier that is not properly matched and an antenna that is not near its fundamental resonant frequency is that antennas exhibit almost perfect mismatches (VSWR > 10:1 is not uncommon) when they are non-resonant. It is very difficult, if not impossible, to match an antenna if the element in itself is not reasonably close to its resonant frequency. Transistors, as part of amplifier circuits, on the other hand, are not that extreme. They are in a workable region over a much greater frequency range than antennas and general approaches to match a configuration are viable options.

2.3 The Simplified Real Frequency Technique

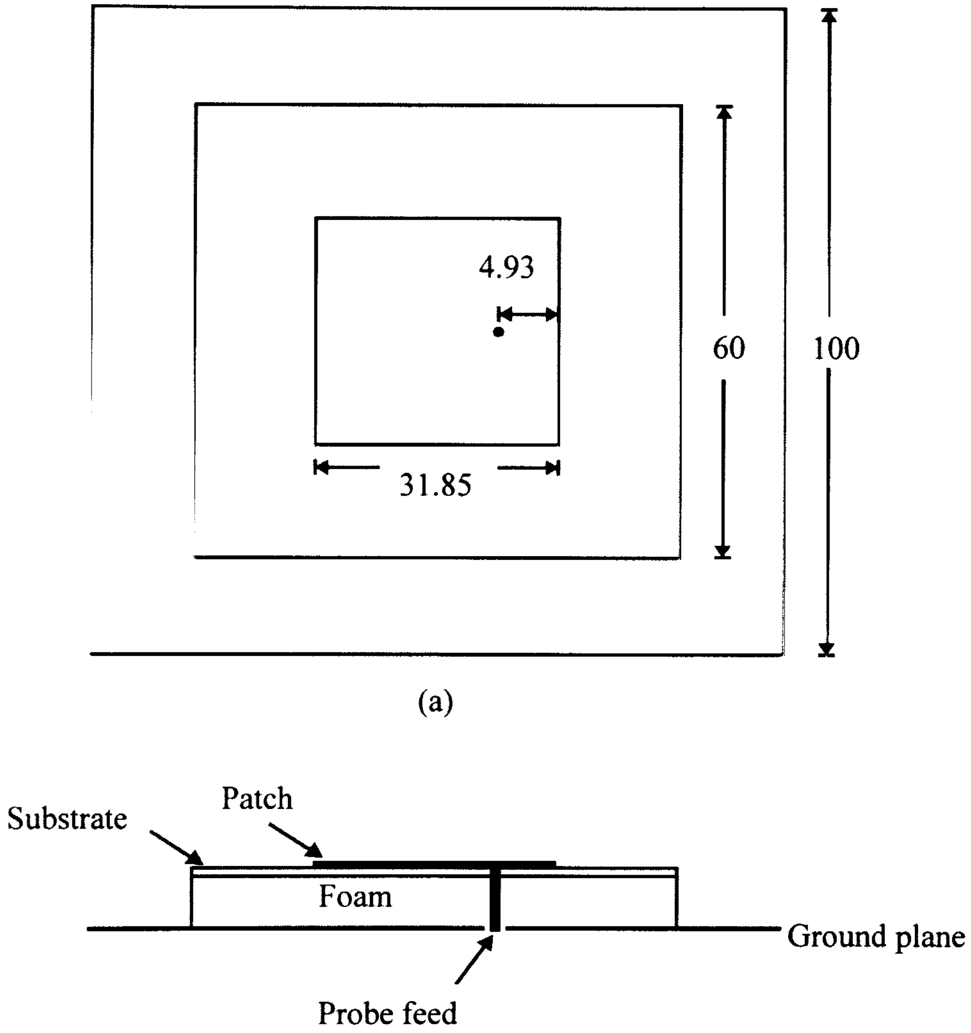
The concept of using a matching feed circuit to enhance the bandwidth of microstrip patch antennas for the first time actively received attention in 1989 from Pues et al. [1]. A study was undertaken on the possibility of designing a matching circuit for a patch antenna that would enhance the antenna's impedance bandwidth. With the technique described, an improvement factor of 3.2 compared to the original bandwidth was obtained.

Important to note at this stage is how the improvement factor is specified. For this dissertation, a specification is set, for example a VSWR of 2:1. When comparison is made between the bandwidth before and after a matching circuit is included, the results for the specified VSWR (2:1) are presented. This would probably not result (percentage-wise) in the optimum answer, but it does provide a constant repeatable result. The result presented in [1] is compared between the matched and unmatched patch antenna for the optimum improvement point. Data analysis provided in [1] showed that the best improvement was obtained at a VSWR of 2.14:1. Therefore the published result for this VSWR is stated as the improvement factor, although this is only valid for the single VSWR value.

Although the improvement factor of 3.2 might seem very little when compared to the results of the previous section where amplifier matching was discussed, it is in fact a substantial improvement for single element microstrip patch antennas.

The above-mentioned technique [1] is an analytical procedure, and the same group furthered their research and came up with the Simplified Real Frequency Technique (SRFT). The procedure for the SRFT is described with examples in [2, 4]. The SRFT is derived from the Real Frequency Technique (RFT) [23]. It is a simplification, requiring less computation than the original RFT, but keeping all the advantages normally associated with the original technique [4]. An example is presented in the paper that uses an LC-ladder similar to the circuit shown in Figure 2.2. The antenna in this example is designed for operation around 3.5 GHz. The antenna is a square probe-fed antenna, with a foam substrate of thickness 6.35 mm and ε_r = 1.03 beneath the supporting substrate with thickness t = 0.5 mm and ε_r = 2.17. The example patch antenna is shown in Figure 2.4, with the matching network and its equivalent etched version as described in [2, 4] shown in Figure 2.5.

The circuit consists of three inductors and one capacitor, as shown in Figure 2.5. The values obtained with the SRFT are L_1 = 6.46 nH, L_2 = 8.381 nH, L_p = 2.606 nH and C_1 = 0.531 pF.



(a)

(b)

Figure 2.4 Antenna example for the SRFT [2, 4]. In (a) the top view of the patch is shown, with the side view given in (b) . All dimensions are presented in millimeters

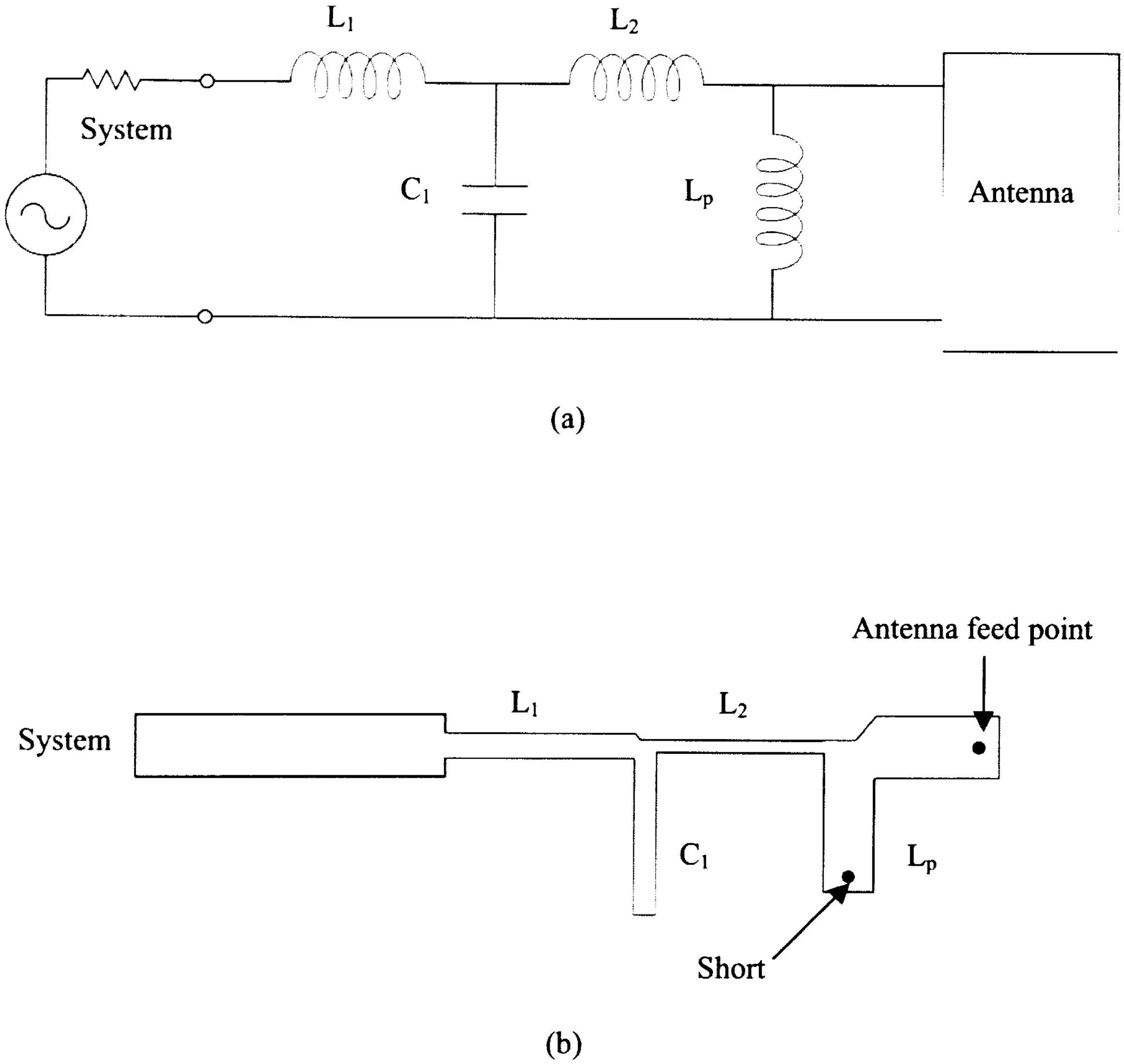


Figure 2.5 Matching network designed and presented in [2, 4] with the SRFT. Figure 5(a) presents the circuit resulting from the technique, and Figure 5(b) shows the actual circuit that was implemented on microstrip material

In Figure 2.4(a) the size of the ground plane is 100 x 100 mm and the substrate on which the patch antenna is placed is 60 x 60 mm. The etched circuit shown in Figure 2.5(b) was placed on the back of the ground plane of the antenna illustrated in Figure 2.4. The substrate used for the feed network consists of similar dielectric as the patch antenna, but the thickness is 1.575 mm instead of 0.5 mm. The $\varepsilon_r = 2.17$. No dimensions of the circuit are included in [2, 4]. The calculated results with and without the matching network are presented graphically in Figure 2.6. The aim with the matching circuit was to create a wideband matched antenna system. The antenna alone is not matched for a VSWR < 1.5:1 anywhere in the frequency range considered. The addition of the matching circuit resulted in the antenna being matched over a 12.1% bandwidth. The same antenna was also optimised for a VSWR < 2:1 and the bandwidth obtained for this example was 16.8%.

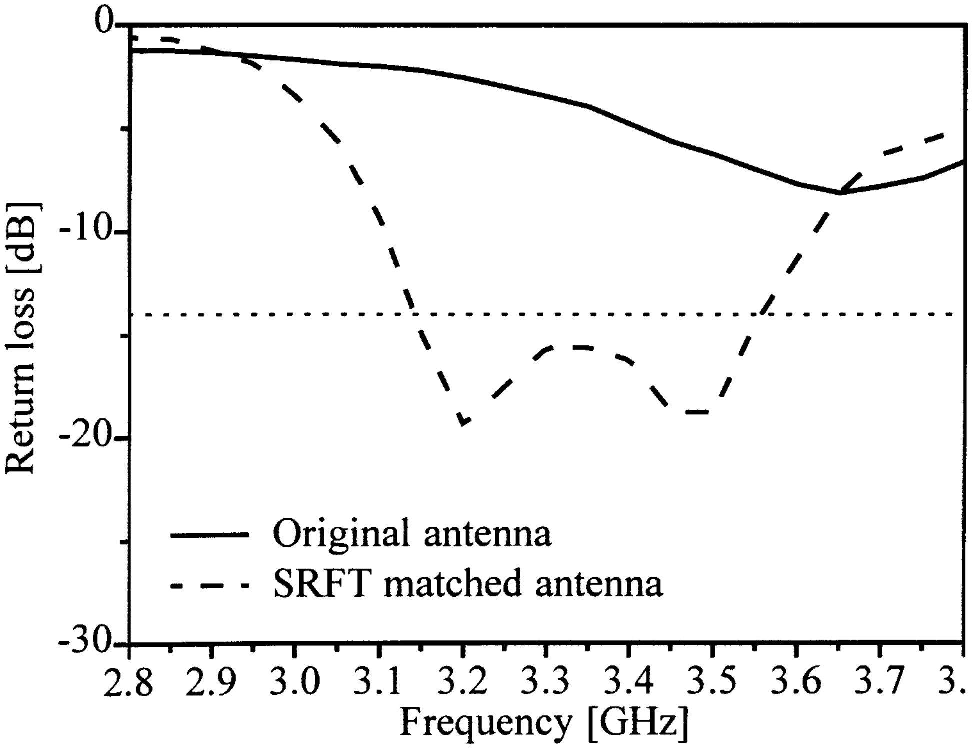


Figure 2.6 Return loss for the patch antenna discussed in [2, 4]

The RFT was first presented in [23] and has been developed with the specific aim of creating a broadband amplifier design. The implementation of the SRFT in microstrip patch antenna technology was done with good results, but the integration of the two applications (amplifiers with patch antennas) was the main aim with the development of the SRFT. This is evident from the range of publications written by the authors and inventors of the SRFT, as well as the final thesis published by An [34]. In [16] a wideband patch was designed, with the aid of the SRFT, to integrate with a wideband amplifier circuit and obtain an overall broadband active antenna. Good results were obtained, and the patch antenna used for the publication was exactly the same one described in both [2] and [4] and shown in Figure 2.4.

The RFT and the subsequent SRFT proved to work very effectively for their specific application, i.e. amplifier and microstrip patch antenna design, respectively. Many of the current matching circuits and the techniques with which they are designed aim to find an optimum solution for an LC-ladder. The LC-ladder is most often (but not always, as evident from the SRFT example) made up of series inductors and parallel capacitors. In microstrip patch antenna development several alternative ways to improve the impedance bandwidth of the antenna have been identified. Some of the techniques will be discussed in the following section. Most of the time the technique is an alteration of the radiating element to improve the impedance bandwidth, but often this is at the expense of other characteristics such as radiation properties of the antenna. Some of the current technologies will be presented in the next few sections.

2.4 Microstrip antenna array bandwidth improvement

The use of resonant circuits to enhance the bandwidth of patch array antennas significantly has recently come under investigation. One such matching technique was presented in [17]. The idea that coupled lines can be used to increase the impedance bandwidth of microstrip patch arrays was presented. Detail about the working of coupled lines can be found in [21]. The main argument presented in [17] is the ease with which one can design this matching structure when compared to techniques such as the SRFT. The circuit discussed in [17] is shown in Figure 2.7. Although no design procedures were presented, it is assumed that the resonant frequency of the coupled lines must be the same as the resonant frequency of the patch array. Later in this dissertation it will become clearer why this is probably the case.

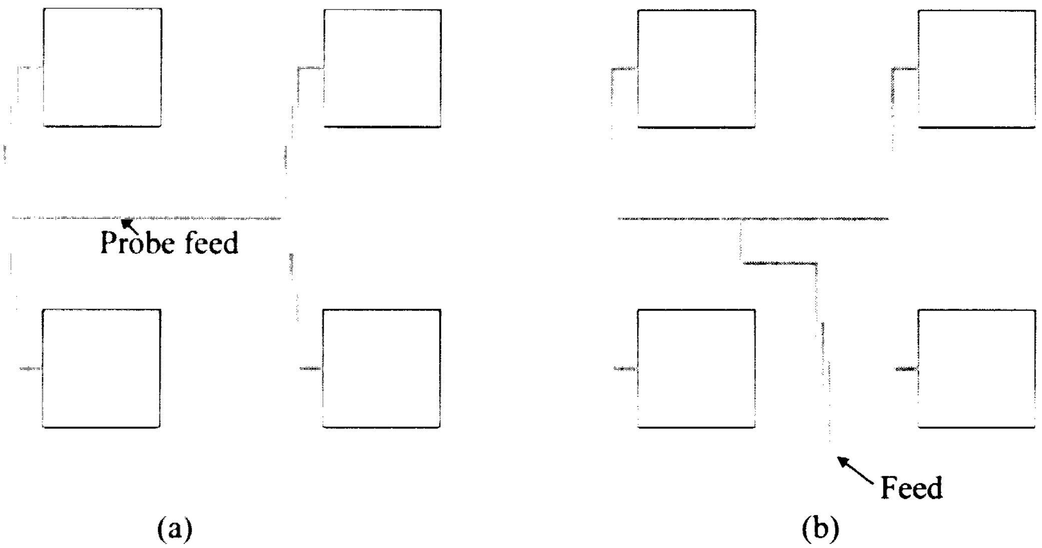


Figure 2.7 Implementation of quarter wave coupled lines for impedance bandwidth improvement. In (a) a probe excitation is used at the same position as where the transmission line connects to the horisontal line in (b)

A problem encountered with this technique is mainly the physical space occupied by the coupled structure. This is overcome in [17] by implementing the feed in an array, where there is a lot of extra space not being used between the patch elements. Two feed structures are discussed and shown in Figure 2.7(a) and Figure 2.7(b) respectively. The different quarterwave coupled arrays present similar impedance and radiation bandwidth. The gain for the array without the matching feed network, as well as with the structure shown in Figure 2.7(a) and (b), is only shown at three discrete frequency points. From the data shown in [17] it is, however, clear that the gain tends to drop rapidly once a frequency other than the resonant frequency is considered. A reason provided in [17] is possible spurious radiation obtained by the quarterwave feed lines included in the matched antenna arrays. The VSWR bandwidth increased by a factor of 2 after addition of the coupled quarterwave.

2.5 Single antenna-element bandwidth improvement

The use of coupled lines for bandwidth improvement is also presented by van Wyk et al. in [18]. The proposed technique is shown in Figure 2.8. The coupled lines are implemented in a similar manner as in [17], but the feed network is used to feed a single edge-fed patch element. There is no physical connection between the antenna and the feed line. The last coupling quarterwave section is taken between the feed line and the radiating patch. This reduces the overall space required for the feed line considerably. An edge-fed patch, similar to the patch used in [1], has been built and tested. The simulated bandwidth improvement is more than double the original impedance bandwidth (VSWR < 2:1) and the radiation pattern shows good similarity between the edge-fed and coupled patch. The main difference is the beam squint obtained. This can be attributed directly to the coupling lines that are placed on the same side as the radiating patch antenna.

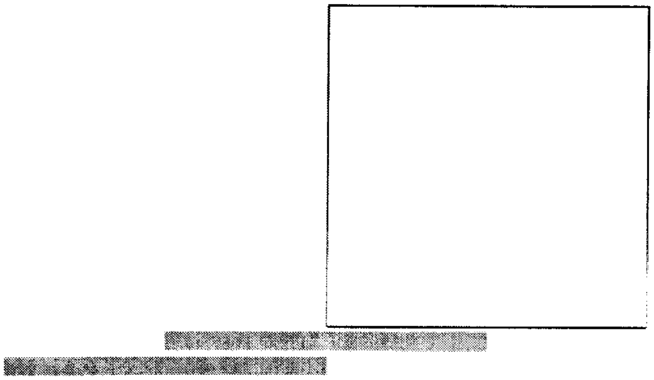


Figure 2.8 The use of a resonant coupling structure to feed a patch on the non-radiating side of the patch antenna. The coupling lines overlap by a quarter wavelength as described in [18]

A discussion on single element electromagnetically coupled microstrip patch antennas with a tuning stub is presented in [35]. The feed is presented graphically in Figure 2.9. The advantage of this technique is that the tuning stub is placed directly underneath the radiation element. The tuning stub is designated in Figure 2.9 by the length L2. The length L2 starts at the split and is considered till the end of the line. A great degree of freedom in tuning is provided with this antenna, since a number of variables are provided. L1 is mainly used for matching and L2 for the resonance in conjunction with the patch size.

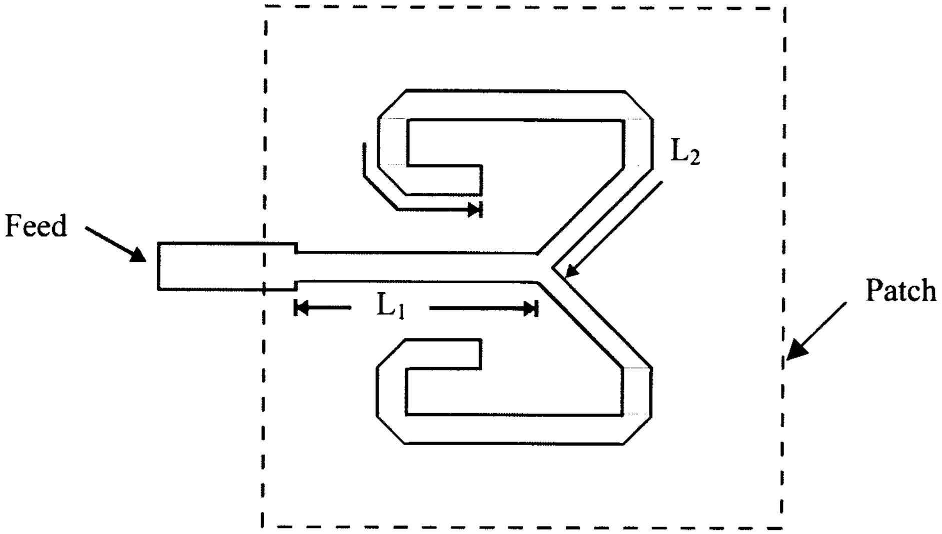


Figure 2.9 Coupled line wideband patch presented in [35]. L1 is a quarter wave transformer and L2 the coupling line having a half wave length at the desired centre frequency

Bandwidth improvement of 1.25 over the original band was obtained. No physical connection between the patch and the feed is made, reducing the margin of construction error possible when adding a probe, for instance. The technique was applied to normal coupling feed structures as well as aperture-coupled antennas. The aperture-coupled patch obtained an increase in backlobe radiation, although only 1.5 dB worse than the original.

2.6 Conclusion on impedance matching

In this section a number of impedance matching techniques are summarised. The need for bandwidth improvement becomes evident in the literature, where numerous papers that have something to do with the impedance of microstrip patch antennas highlight the narrow impedance bandwidth property of the antennas. The SRFT is a very effective technique with good results. The circuit that results from the SRFT is not predefined, and possibilities arise that the circuit might become physically large. The coupling structure presented in [35] is a solution for a number of patch configurations. The main working mechanism is coupling that might become difficult when the patches become electrically too thick.

The coupling lines presented in [17, 18] are the first actual references where a purely resonant circuit is used to implement a matching structure. The results in terms of impedance bandwidth enhancement are very good, and the only possible problems encountered with this idea might be the physical space occupied by the feed or degradation of the radiation pattern. The physical space problem is effectively dealt with in [17]. The fact that the matching feed line is etched on the same side of the dielectric substrate as the patch antenna, imposes a height restriction on the antenna [17, 18]. This limits the number of antennas possibly considered for the quarterwave coupled line matching technique as well as the maximum bandwidth obtainable with the circuit.