Chapter 5

Impedance of Slot Antennas

5.1 Introduction

The characterization an antenna requires knowledge of the input impedance looking into the antenna from the detector. This includes the associated feed network used to connect the detector or receiver circuit to the antenna. In this chapter we present calculations for a slot fed by a microstrip line with a bolometer detector centered between the two slots. The feed line is electromagnetically coupled to the slot antennas so no direct connections to the ground plane are necessary which simplifies the fabrication of the feed network and antennas. We present calculations as well as some impedance measurements to check the validity of the calculations.

In the first section we present the series impedance calculations of a slot in a ground plane on a layered substrate. The ground plane is covered with a thin layer of dielectric on the top of the ground plane as shown in Figure 5.1. A microstrip line, which has a bolometer detector integrated into it, is metallized and patterned on top of the thin layer . The stacks of dielectrics supporting the antenna and ground plane are chosen as discussed in Chapter 4 to maximize the radiation through the substrates. In addition to the calculations, we present measurements made on a Hewlett- Packard 8510B network analyzer at X-band frequencies which show reasonably good agreement between calculations and measurements. In the second section we show impedance calculations for the twin slot antennas with the detector centered between them.

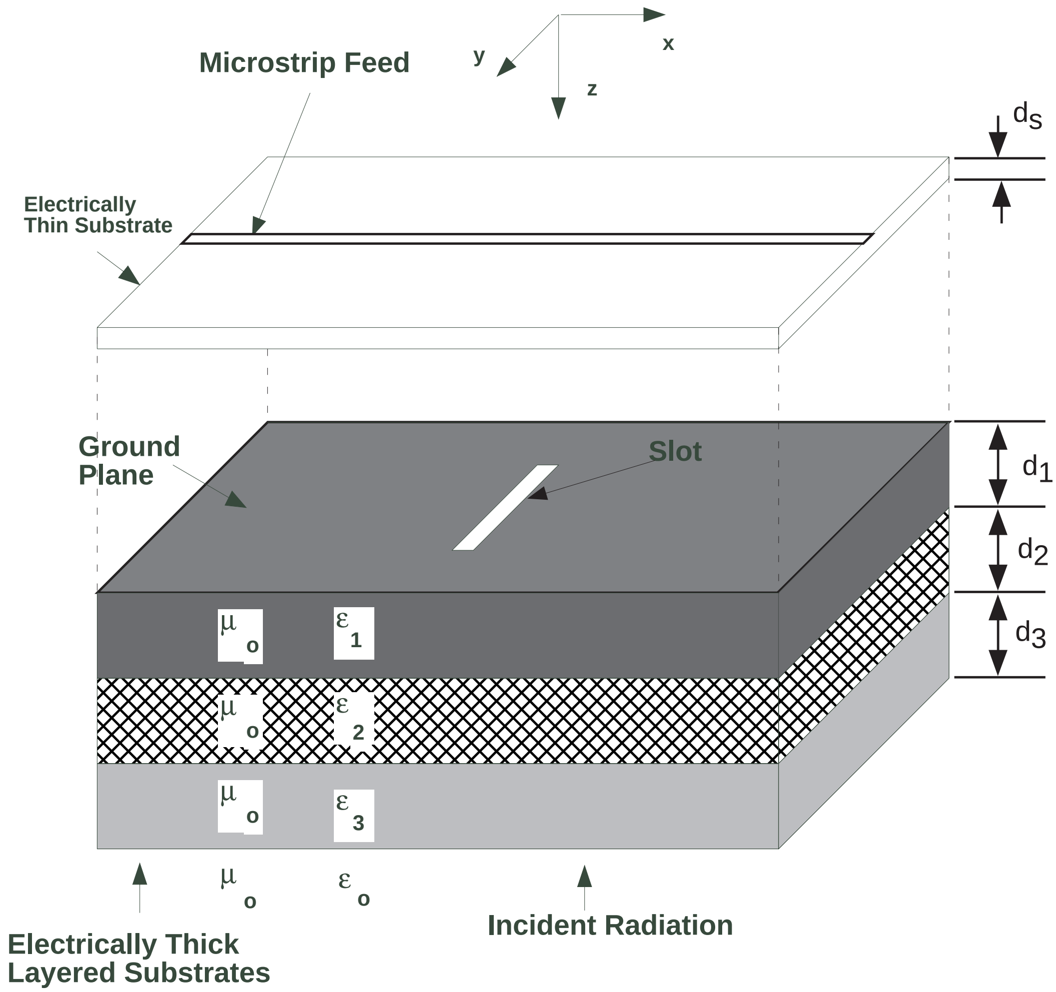


Figure 5.1) Micostrip-fed slot antenna radiating on a layered substrate. The layers are chosen to enhance the radiation through the dielectric stack. The electrically thin substrate supporting the microstrip line can be easily made by a liquid polymer that can be applied over the ground plane. The slot length is .82cm, width is .1cm, the microstrip line width is .162cm, d_s = .079cm, , ε_s = 3.15, d_1 = .376 cm, and ε_1 = 4.

5.2 Single Slot

Calculations

The spectral domain method described in Chapter 2 is used to calculate the impedance of the slot. The structure is shown in Figure 5.1 and is an open structure, so our analysis must include both the surface waves and the space waves. A narrow slot approximation is used. This means that the E-fields in the slot are assumed to all be pointing in the x-direction and that the x-dependence of the electric fields in the slot is assumed to be uniform. The currents on the microstrip line were also assumed to be laterally uniform. Piecewise sinusoidal basis functions were used to calculate the fields in the slot. The coupling between the microstrip line and the slot antenna is calculated using the reciprocity method proposed by Pozar [39]. The fields on the microstrip line are assumed to be quasi-TEM, and dispersion along the microstrip line is taken into account using the empirical formulas given in Appendix C. The calculated impedance, Z, that is compared against the measurement impedance uses the series impedance of the slot calculated in the circuit shown in Figure 5.2. The harmonic time dependence is now taken to be $e^{i\omega t}$ so positive reactances are inductive and negative reactances are capacitive.

Measurements

The measurements of the impedance were extracted from the S_{11} parameter measured by an HP 8510B network analyzer. The supporting substrate ($\varepsilon_r = 4$) on which the ground plane rests (layer 1 in Figure 5.1) is nominally one quarter of a dielectric wavelength thick. The substrate that supports the microstrip line is a copper-clad fiberglass-epoxy board which has a dielectric constant (estimated from

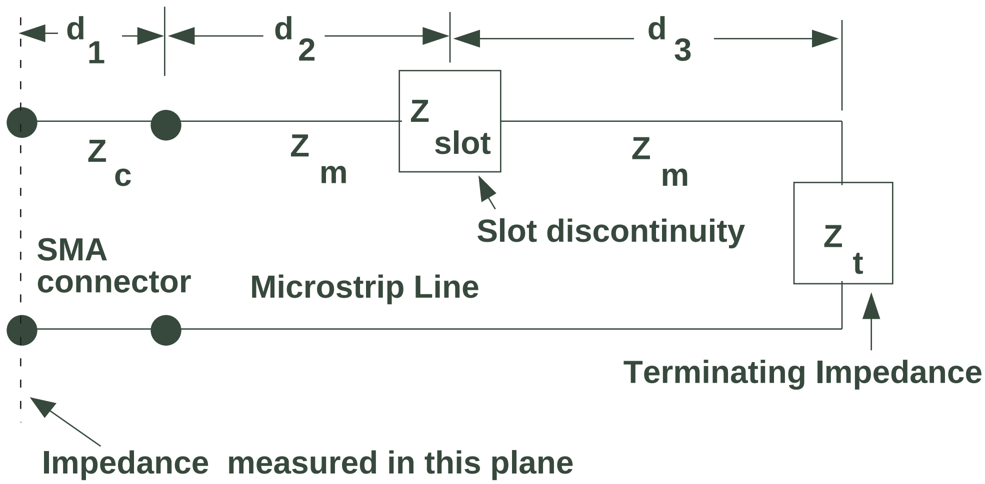
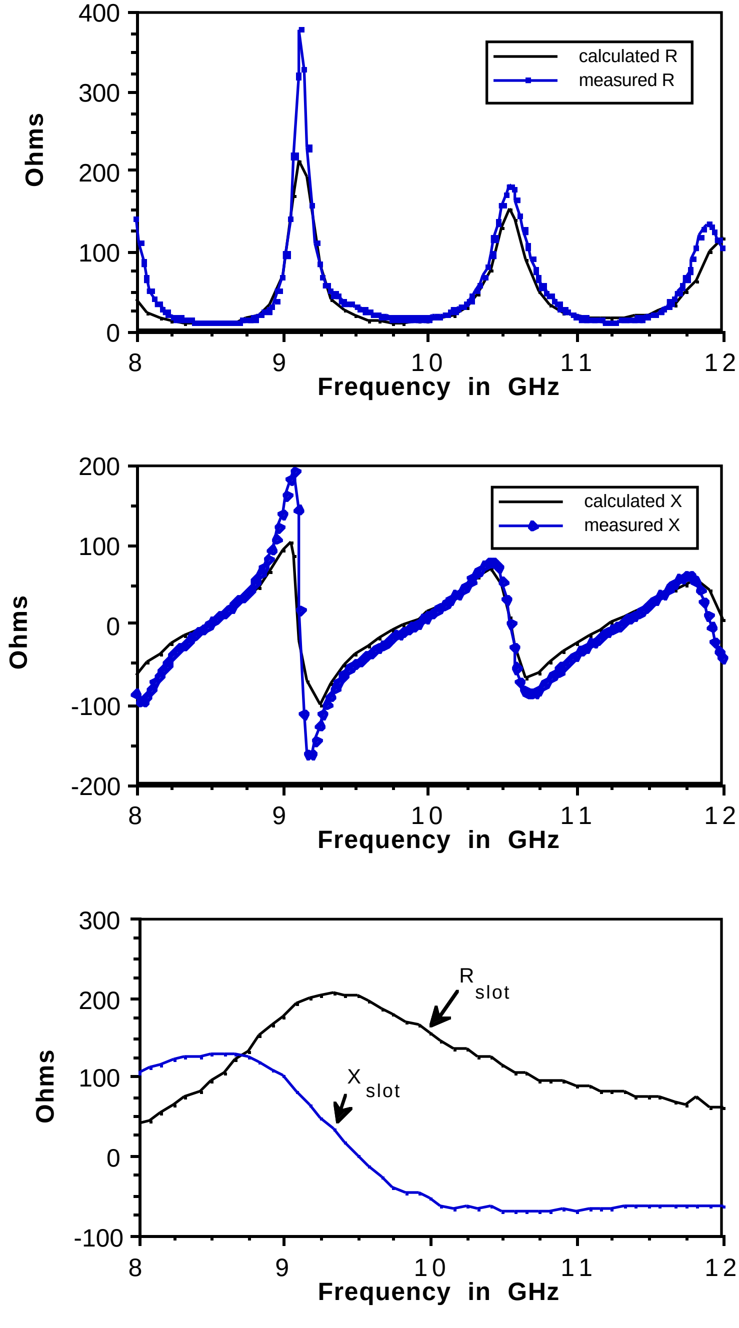


Figure 5.2) Circuit model for the measurements made on the HP 8510B network analyzer. The plane of the measured impedance, $Z = R + jX$, is shown at the dotted line. The slot is treated as a lumped series impedance, Z_{slot}, in the microstrip line. The SMA connector is also included in the calculations. Z_c is 50 ohms, Z_m is nominally 56 ohms (quasi-static calculation without correction for dispersion), d_1 = 0.75cm, d_2 = 5.66cm, d_3 = 5.72cm, and Z_t is 50 ohms.

time-domain reflectometry measurements) of about 3.15. The slot has a length-to-width ratio of about 8 to 1. The circuit that was used to measure the impedance of the slot is shown in Figure 5.2. The supporting ceramic substrates which correspond to layers 1, 2, and 3 in Fiugre 5.1 were Emerson and Cumming Stycast Hi-K dielectric slabs. These ceramic slabs were about 10.8cm on each side and the thicknesses were chosen to be nominally one quarter of a dielectric wavelength thick at 10GHz. The substrates were stacked on 15cm of foam absorber and small amount of pressure was applied to assure that all of the substrates remained flat and that there were no air gaps between the layers.

Results

The agreement between measurements and calculations indicate that the narrow slot approximation is reasonably good as shown in Figure 5.3. Note that the series impedance of the slot varies slowly with respect to frequency and that the reactive part is fairly flat and is capacitive above resonance. When additional layers are added, (layer 2 is $\varepsilon_r = 2.4$ and layer 3 is $\varepsilon_r = 13$) where each layer is nominally one quarter of a dielectric wavelength thick, the impedance of the slot changes as is shown in Figure 5.4. Agreement between measurements and calculations is still good. The calculated series impedance of the slot is more peaked and narrow band than for the single layer structure. To make sure that the features seen in the impedance measurements were due to the slot discontinuity, a piece of copper foil was used to cover the slot, and hence, remove the discontinuity. This completely changed the measured impedance looking into the connector. The real part of the impedance varied from about 30 to about 70 ohms. The reactive part varied between

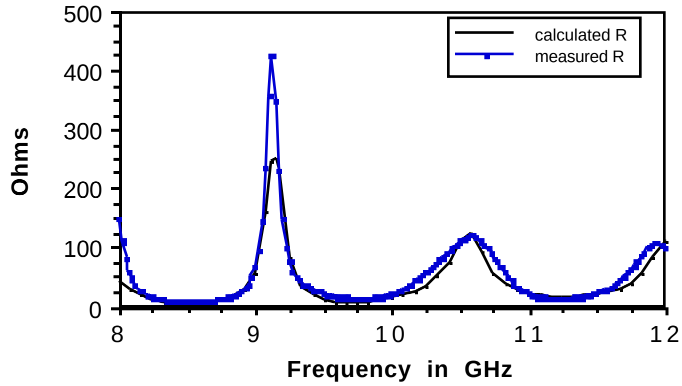


(a)

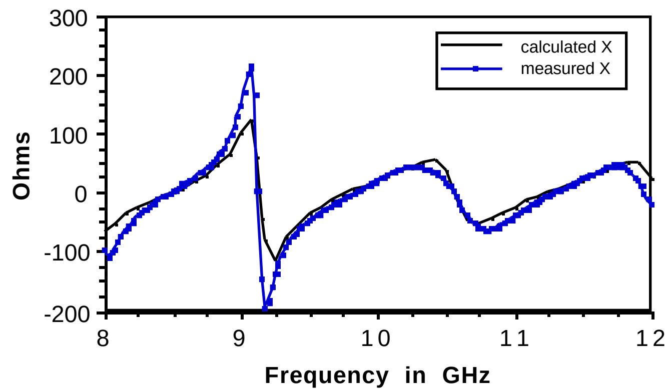
(b)

(c)

Figure 5.3) Impedance calculations and measurements for a single supporting substrate: a) the real component, R, of measured and calculated impedance, b) the reactive component, X, of the measured and calculated impedance, c) the calculated series impedance Z_{slot} presented to the microstrip line.



(a)



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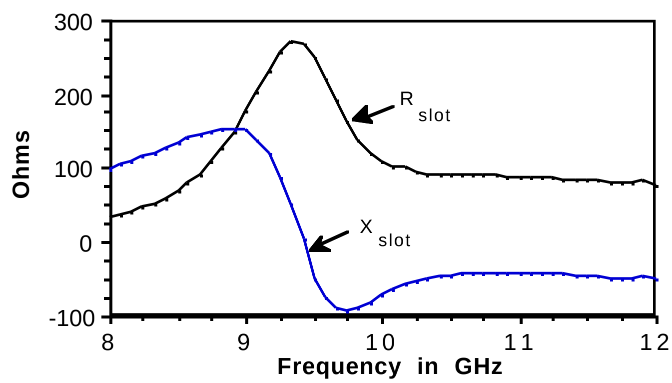

(c)

Figure 5.4.) Impedance calculations and measurements for a three layer with ε_1 the same as in Figure 5.3, and ε_2 = 2.4, d_2 = .487cm, ε_3 = 13, and d_3 = .206cm (see Figure 5.1) additional supporting layers: a) the real component, R, of measured and calculated impedance, b) the reactive component, X, of the measured and calculated impedance, c) the calculated series impedance Z_{slot} presented to the microstrip line.

about 20ohms and -20ohms. The presence of the discontinuity was also a marked feature of the TDR measurements.

To further investigate the effect of the dielectric layers on the impedance of the slot, calculations were performed on a five layer structure. Figure 5.5 shows the series impedance calculated for a 5 layer 4-2.4-13-4-13 dielectric stack which was also discussed in the Chapter 4. In this case, the presence of the additional layers of dielectric has only a small effect on the impedance of the slot making it slightly higher at resonance. The resonance length is determined mainly by the dielectrics on either side of the ground plane. Only a thin layer (i.e. $.05\lambda_d$) of dielectric on either side of the slot is required to cause the resonance length to be very close (within ten percent) to the length that would be obtained by using $(\varepsilon_1+\varepsilon_b)/2$ for the effective dielectric constant, where ε_1 is the dielectric constant of the supporting layer, and ε_b is the dielectric constant of the layer on top of the ground plane that supports the microstrip line. We also found that assuming uniform lateral dependence of the currents (i.e. the x-dependence of y-directed currents in the slots, and y-dependence of the x-directed currents in the microstrip line) gave calculated impedances that agreed with the measured data very well, and when the results were compared with basis functions obeying the "singularity" conditions, virtually no difference was found between the two sets of calculations [39]. The number of basis functions used was also varied from one to seven, and convergence within a percent over the range of interest was achieved with three basis functions.

Calculations were performed for the same slot and feed line structure (i.e. the same length and width) on an $\varepsilon_r = 13$ supporting substrate, which is again nominally one quarter of a dielectric wavelength thick (at resonance). In Figure 5.6 we see

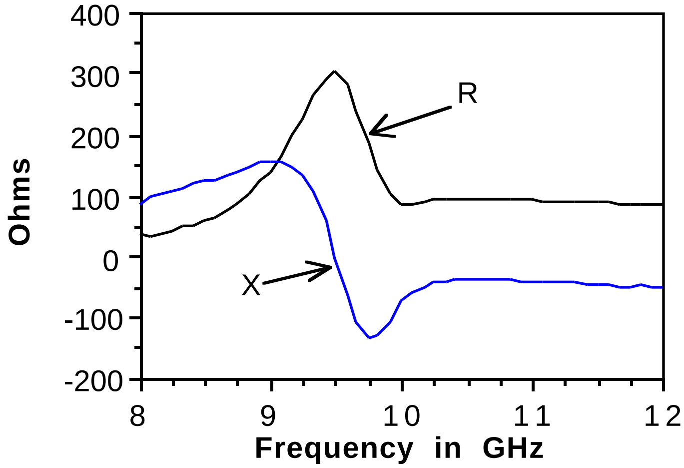

Figure 5.5) Series impedance of the same slot configuration shown in Figures 5.3 and 5.4, with 5 supporting layers of dielectrics, ε_1 = 4, and d_1 = .376 cm, ε_2 = 2.4, d_2 = .487cm, ε_3 = 13, and d_3 = .206cm, ε_4 = 4, and d_4 = .376 cm, and ε_5 = 13, and d_5 = .206cm. Note that there is very little difference between the impedance of the slot on the three layer stack and the impedance on the five layer stack.

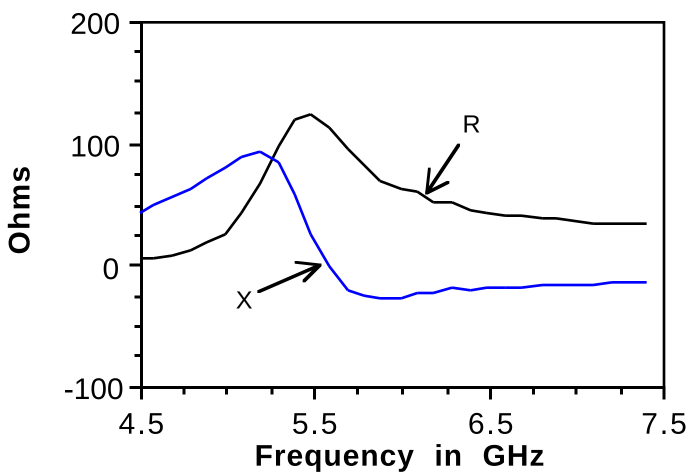

Figure 5.6) Series impedance of the same slot configuration used in Figures 5.3 and 5.4, with a supporting layer of ε_1 = 13 and d_1 = .206cm.

that, due to the change in ε_r, the resonance frequency of the slot is now lowered to a resonance of about 5.7GHz. The thicknesses of the supporting substrates (layers 1, 2, 3 in Figure 5.1) are now adjusted to be nominally one quarter of a wavelength thick at 5.7GHz. The impedance of the slot is lower because the higher dielectric constant substrate raises the radiation admittance of the slot. Figure 5.7 shows the impedance of a slot an a 13-2.4-13 stack of dielectrics. The series impedance of the slot is almost the same as in Figure 5.6. In both cases the series impedance is lower than in the cases when layer 1 has a relative dielectric constant of $\varepsilon_r = 4$. This could be qualitatively anticipated from the results given in the previous chapter where the total power radiated by an elemental slot was larger for the 13-2.4-13 dielectric stack than it was for the 4-2.4-13 stack. The most important layer in determining the resonant length of the slot is the layer adjacent to the slot. The resonant length of the slot is determined by the dielectric layers on either side of the ground plane as thin as $0.05\lambda_d$. The effect of the additional layers on resonant length of the slot is slight. However, the impedance of the slot presented to the microstrip line is affected by the total integrated power radiated by the slot either to the guided waves or to air. The real part of the series impedance due to the slot decreases as the total integrated power radiated by the slot increases although the impedance presented to the microstrip line also depends upon the dimensions of the slot as well as the dimensions of the microstrip line.

5.3 A 94GHz Twin Slot Design

As discussed in Chapter 3, twin slots operating in the even mode (in phase) and properly spaced can cancel the majority of power delivered to the TM guided

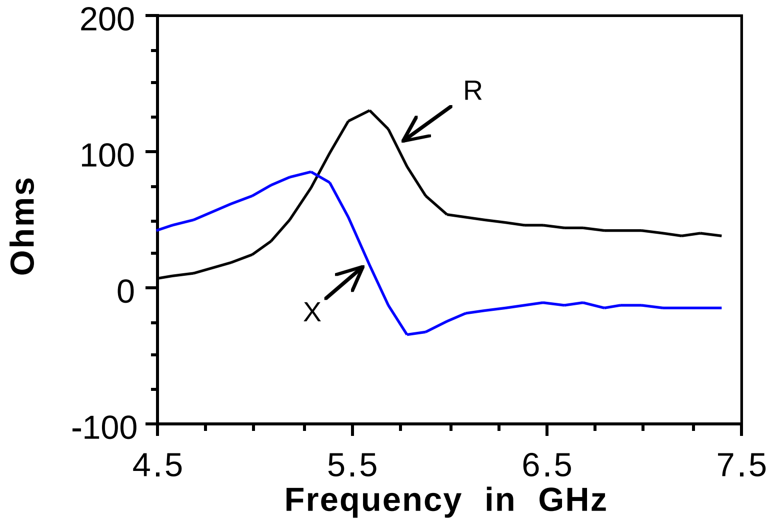

Figure 5.7) Series impedance of the same slot configuration used in Figures 5.3.and 5.4 with three supporting layers, $\varepsilon_1 = 13$ and $d_1 = .206$cm, $\varepsilon_2 = 2.4$, $d_2 = .487$cm, and $\varepsilon_3 = 13$, and $d_3 = .206$cm. (13-2.4-13 stack). Dielectric thicknesses were chosen to be nominally one quarter of a dielectric wavelength thick at 5.7GHz.

mode in the substrate. In this section we discuss the design of a twin slot antenna on a single quarter wavelength thick quartz ($\varepsilon_r = 4$) substrate. For the calculations presented here, we use 5 piecewise sinusoidal basis functions per slot, and assume, as before, that the current is uniform in the x-direction across the slot and in the y-direction across the microstrip line. All of the electric currents on the microstrip line are assumed to flow in the x-direction (along the microstrip), and all of the magnetic currents in the slot are assumed to flow in the y-direction (lengthwise to the slot). The layer of dielectric covering the top side of the ground plane is polyimide and is assumed to be 2μm thick with $\varepsilon_r = 2.2$. The width of the center conductor is about 25μm which gives the microstrip a characteristic impedance of about 16 ohms. Figure 2.3 shows the blow-up diagram of the twin slot structure that has the detected signal (low frequency) extracted from a low-pass filter. At 94GHz, the low pass filter has a low impedance compared to the microstrip line so that, ideally, the high frequency signal is confined to the section of microstrip between the antennas which contains the detector.

The length of the slots is chosen to be slightly longer than resonance. This was done to achieve a better match in impedance between the detector and the antenna. Also, when the element is tuned off resonance, its input impedance is not as sensitive a function of frequency as it is when it is operating on resonance. Figure 5.8 shows the input impedance of the antenna looking from the detector as a function of feed line length. Note that there are two regimes where the reactance looking into the antenna is zero. One is a low impedance regime where the real part of the impedance is near zero, the other is a higher impedance where the impedance looking into the antennas is on the order of hundreds of ohms. An interesting point to note

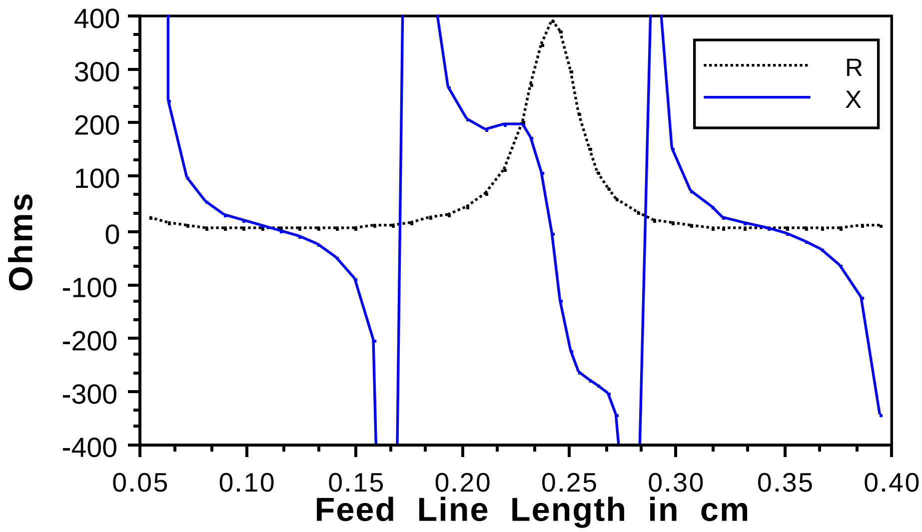

Figure 5.8) Impedance seen at the detector (see Figure 2.4 in magnetic current sheet plane). The feedline width is 25µm, the dielectric thickness between the microstrip line and the ground plane is 2µm and the dielectric constant is assumed to be about 2.2, the slots are 1.1mm long and .04mm wide. The separation is about 1mm, and the support substrate (layer 1 in Figure 5.1) is a quarter wavelength thick piece of quartz ($\varepsilon_r = 4$).

about the antennas is that as the elements are separated, their coupling through guided waves and space waves is reduced. The coupling through the feed line, however, does not diminish with increasing distance, and hence the slots communicate with each other through the feed lines more than through the guided and space waves.

5.4 Conclusion

This chapter has presented results that show that the impedances of single and twin slot antennas fed by a microstrip line can give input impedances in the range that can be coupled to detectors reasonably well. The dielectric layers adjacent to the ground plane determine the resonance frequency of the slot, and hence its dimensions. The additional dielectric layers, however, affect on the real part of the impedance of the slot primarily by changing the radiation characteristics of the slot.