DESIGN OF MIXER ELEMENTS FOR THE HHT 345 GHZ HETERODYNE ARRAY RECEIVER

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ABSTRACT

We present the design of mixer elements for a 7-element SIS heterodyne array receiver for operation in the 870 μm atmospheric window. The focal plane array receiver will be a facility instrument on the 10-meter University of Arizona/Max Planck Institute for Radioastronomy (MPIfR) Heinrich Hertz Telescope (HHT). The array will have a tuning range from 315 to 380 GHz. Due to prevailing physical conditions in the interstellar medium, this wavelength range is one of the richest in the submillimeter portion of the spectrum. We use results of scaled model measurements and detailed electromagnetic modeling of the mixer block to arrive at an optimum design for the individual mixers. We describe an iterative technique of optimizing mixer design in linear microwave circuit simulators, using results of finite element analysis of the waveguide embedding impedance.

1 Introduction

The 870 μm atmospheric window (see Figure 1) has the highest transmission of any submillimeter band, and due to prevailing physical conditions in the interstellar medium is also one of the richest spectroscopically. Figure 1 shows some of the important molecular transitions in this atmospheric window. The noise performance of submillimeter receivers is improving dramatically every year and is approaching limits set by quantum mechanics and/or the sky background, especially in the lower end of the submillimeter frequency band. A large increase in the speed of spectroscopic astronomical observations can be obtained by using a heterodyne array receiver. There are two approaches to obtaining a real improvement in the speed of imaging using arrays. It is possible to develop an array with a large number of elements each of which has less than optimum performance in terms of noise temperature and optical coupling. A better approach in terms of cost and speed is to build a moderate sized array without compromising mixer performance.

The seven element 345 GHz focal plane array receiver we are building for the Heinrich Hertz Telescope (HHT) will have a tuning range between 315 and 380 GHz and will make excellent use of the telescope and available atmospheric transmission. The HHT is a joint development between Steward Observatory, University of Arizona, and the Max-Planck-Institut of Radioastronomie. The overall design of the optics and cryogenic systems of the array will be outlined in a future paper [1]. In this paper we describe the design of individual mixer elements that will make up the final array.

Technical, scientific and budgetary issues dictate the following objectives for the mixer design:

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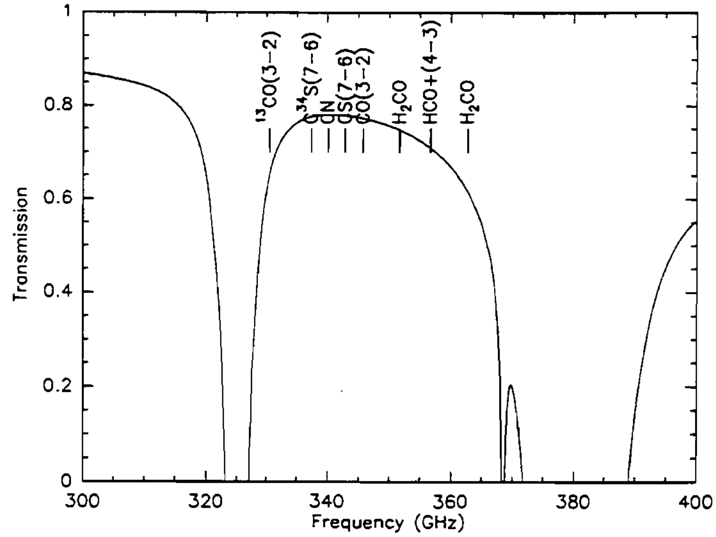

Figure 1: Model Atmospheric transmission in the 870 μm window (Mount Graham 1mm water). The frequencies of important molecular transitions are marked.

- State-of-the-art performance of the individual elements. In particular we require receiver temperatures $T_R \leq 100$ K over the band, a tuning range of 315 to 380 GHz to make full use of the atmospheric band, an IF bandwidth of 4 – 6 GHz, and good antenna efficiencies and clean beams.

- Since the array will be a facility instrument, the mixers should be robust and easy to use. Therefore, no mechanical tuners will be used.

- To keep the costs down, the mixer blocks should be designed for easy fabrication.

2 Mixer Block Design

Figure 2 shows a schematic side view of the designed mixer block. The first section is the horn block and consists of a diagonal feedhorn [2] that transitions from a full-height rectangular waveguide. The full-height rectangular waveguide is then transformed to a half-height waveguide through a three-section transformer. Diagonal feedhorns have been chosen over corrugated feeds, because of their relative ease of construction using split-block techniques. Although their Gaussian coupling efficiency is $\sim$ 13% smaller than corrugated horns, diagonal horns have been shown to be a good candidate for use in submillimeter focal-plane arrays [3]. We follow the design outlined in [3] by making a direct transition from rectangular to diagonal feed. The half-opening angle of the feedhorn is 10.2°, with a slant length of 8.26 mm. The analytical designs of the full-height to half-height transformer and the rectangular to diagonal horn transition were verified using Ansoft's High Frequency Structure Simulator (HFSS) [4]. The half-height waveguide dimensions are 0.7 by 0.175 mm.

The second section is the junction block, which also houses the IF matching network. The fused quartz substrate carrying the SIS junction sits in a suspended microstrip line configuration, which

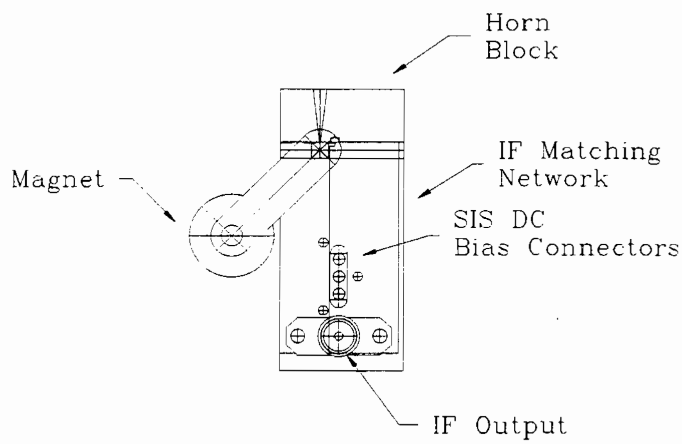

Figure 2: Schematic side-view of the mixer block.

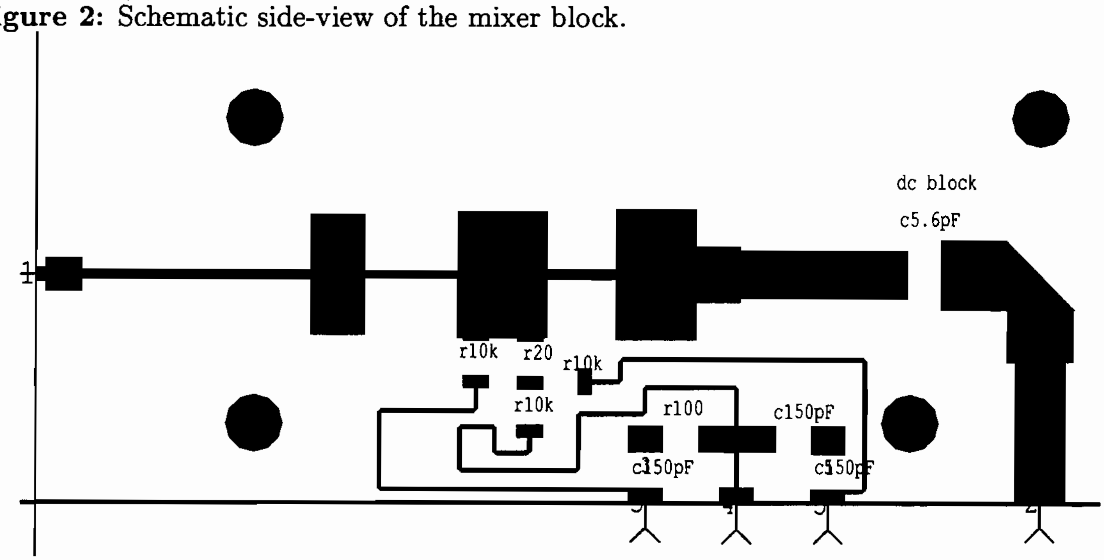

Figure 3: Layout of the 4 to 6 GHz IF matching network.

is parallel to the E-field of the waveguide. Using the suspended strip configuration considerably eases tolerances in mounting the junction on the mixer block. The junction substrate is designed to be 0.309 $\times$ 0.078 $\times$ 3.48 mm. The dimensions of the suspended microstrip line channel are derived from the successful CfA designs [5, 6]. The channel has a 0.222 $\times$ 0.038 mm airgap behind the junction substrate and a similar airgap above the substrate in the horn block (also see Figure 7). When the junction is placed in the channel, it is oriented such that the junction lies within the waveguide. The IF output and DC bias inputs are made through the matching network circuit. The matching network is orthogonal to the junction substrate. The magnetic field for suppressing Cooper pair tunneling is brought into the mixer via magnetic field concentrators embedded in the junction block [7]. The ground side of the junction will be held in place with silver paint, and the "hot" side of the junction will be connected to the IF matching network by wire-bonding.

The designed normal state resistance of the junction is expected to produce an IF output impedance of $> 100\ \Omega$. The IF output impedance of the mixer is transformed to 50 Ω through a 4-6 GHz IF matching network. A prototype IF matching network has been designed, built and tested. Figure 3 shows the layout of the matching network that was designed using HP's Microwave Design System circuit simulator program [8]. The value of the DC bias resistors and chip capacitors used for RF chokes are shown in the layout. A 5.6 pF capacitor is used as DC block. The substrate used in the microstrip design is Rogers Duroid 6002 with a thickness of 30 mils and $\epsilon_R = 2.94$ [9]. The overall dimensions of the matching network is 1.25×0.5 inches. The IF output of the SIS junction is wire-bonded to the $\sim 160\ \Omega$ line to the left of the layout. The DC bias traces shown in the bottom portion of the layout are part of a a 4-wire SIS bias circuit. IF output at 50 Ω is brought out in the lower right of the layout in Figure 3 through an SMA connector (see Figure 2). The fabricated matching networks were tested against predictions using a special purpose fixture constructed for this purpose. For an input impedance range of 100 to 180 Ω, the match to a 50 Ω output is found to be better than -10 dB throughout the 4-6 GHz band. The IF output of each mixer then passes through an isolator before entering the first amplifier. Low-noise 4-6 GHz amplifiers have been ordered from Miteq [10]. The amplifier specifications are a noise temperature requirement of ~ 5 K, a gain of $\sim$30 dB, and a power dissipation of ~ 50 mW.

The fabrication of waveguide structures at submillimeter wavelengths tends to be difficult and expensive. For higher frequencies, wet etching or laser micro-machining [11] methods may be required. At lower frequencies, conventional machining has been successful. The so-called "split-block" technique has often been used [12]. In an effort to keep the cost of machining down, the array mixer blocks will be fabricated using this approach. The mixer blocks will be machined at the University of Massachusetts (UMass), in return for which UMass astronomers will receive a proportional amount of observing time on the HHT. A new numerically-controlled precision milling machine has been constructed at UMass using Aerotech positioners [13] that will allow the fabrication of waveguide components to a few microns of accuracy at low cost.

3 Scale Model Tests

SIS quasiparticle tunnel junction mixers have a rather large geometric capacitance that has been traditionally tuned out using high quality non-contacting backshort and E-plane tuners [7]. The reliance on waveguide tuners alone has two major disadvantages. The large capacitance and small normal state resistance of the SIS junction typically places a severe demand on the waveguide tuners and results in a relatively small frequency band over which an adequate match can be achieved. In addition, the process of tuning with waveguide tuners becomes very complicated and time consuming from the point of view of an astronomer using the full array. To improve the junction match to the embedding impedance of the waveguide circuit and to increase the instantaneous bandwidth of the mixer, a variety of inductive tuning circuits fabricated along with the junction have been used [14]. For such designs, a knowledge of the waveguide embedding impedance is essential. Scaled model tests are a traditional technique to obtain the embedding impedance of a probe in a waveguide. In this section, we describe the results of scaled model tests of the half-height 345 GHz mixer block presented in Section 2. In the next section, we discuss finite element analysis (FEA) methods to obtain embedding impedances.

We constructed a half-height scale model (see Figure 4) with a center frequency of 5 GHz (scale factor of ~ 68) and measured three different RF choke structures to determine a favorable

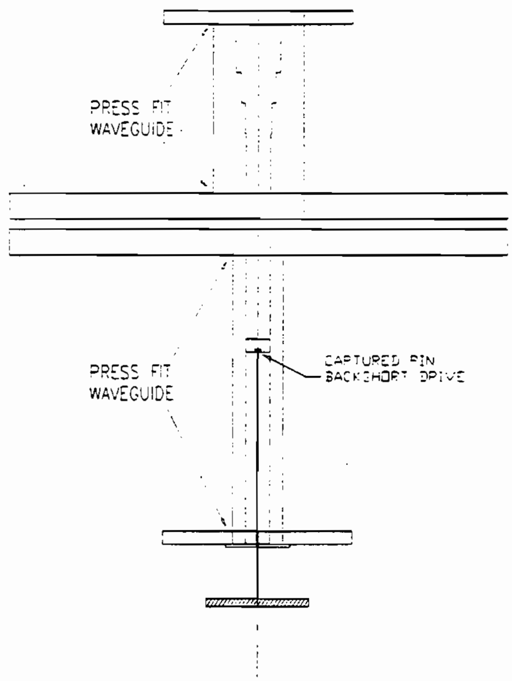

Figure 4: Schematic of the Scaled Model Test Jig. The backshort drive was constructed with a captured pin and a precision screw to ensure smooth and repeatable motion inside the waveguide.

embedding impedance. Acetyl was used as the substrate to approximate fused quartz. The real and imaginary parts of the embedding impedance for one of the choke structures is shown in Figure 5(a) for a backshort distance of 0.2 mm. Shown in Figure 5(b) is the input match of this waveguide-probe combination to a tuned junction with an effective impedance of $40 + j20\ \Omega$. This impedance value is being considered for one of the baseline designs of the 345 GHz array junction to be fabricated by JPL [15]. As can be seen from Figure 5, this combination of embedding impedance and junction design is able to provide a broadband match for the desired band of the array.

4 Finite Element Analysis

Typically, accurate scale model measurements are difficult, time-consuming and prone to uncertainties for the following reasons: (1) the wide range of sizes (> 1000:1) in an SIS mount are difficult or impossible to achieve in a model (2) The iterative process of modifying the scale model to study the effect of changes involves re-machining and/or re-layout of probe circuits and (3) the problem of providing small coaxial probes to the location of the SIS junction involves uncertainties in the scale model measurements due to calibration errors and the fact that the probe itself is disturbing the field at the measurement point.

We have performed numerical electromagnetic simulations of the waveguide mount. The advantages of numerical analysis are that one may study the effects of the dielectric, optimize the SIS

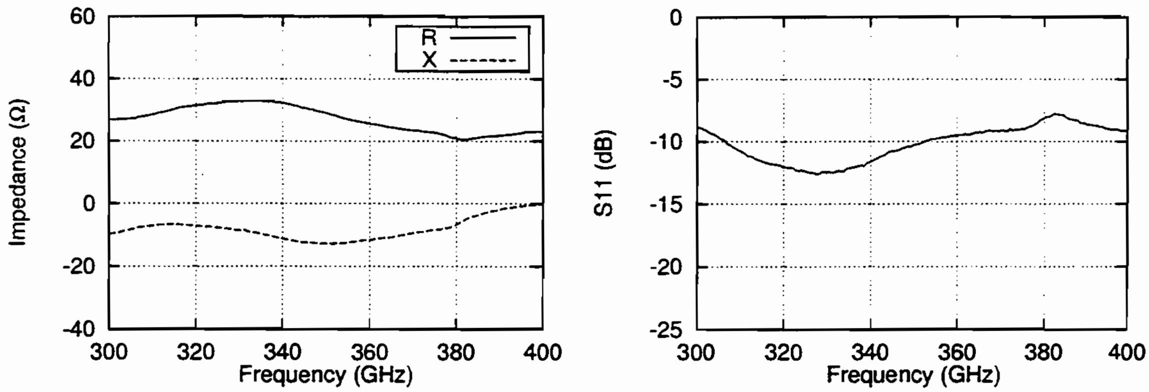

Figure 5: (a) Scale model test results. Real and imaginary parts of embedding impedance of half-height waveguide in combination with RF choke and probe in a suspended microstrip configuration for a backshort distance of 0.2 mm at 345 GHz. (b) Input match scaled back to the frequency of operation for an impedance of $40 + j20\ \Omega$ looking into the tuned junction.

tuning circuit using the embedding impedance, and modify the structure easily. Other advantages include the ability to study the small size scales of the junction mount with the antenna probe, and the ability to reduce the complexity of the problem by exploiting symmetry considerations. The finite element analysis was done using Ansoft's HFSS [4]. The accuracy of HFSS in predicting embedding impedances has already been demonstrated in the design of multipliers [16].

We tried several different approaches in the numerical analysis. Initially, voltage sources were used at the location of the gap between the two antenna probes in the center of the waveguide. The field-calculator in the post-processor of HFSS was then used to determine impedance by calculating the Poynting power flow through the gap and using the Z_{PV} definition to determine the impedance. This technique gave reasonable results in measuring the embedding impedance, but was slow and laborious. It also suffers from the fact that these impedances are time-dependent, and hence care must be taken to set the phase of the excitation right. The next method was to "subtract" the RF choke and antenna structure from the waveguide structure. Subtraction in HFSS is an "exclusive-or" operation, and results in a new structure that contains one of the two objects but not both. This has the effect of bringing the buried gap in the center of the waveguide to the outside world, thereby allowing us to define a port and excite the gap with a TEM-type transmission line. In Figure 6, we show the comparison of the scale model from the previous section to an HFSS model configured using this technique. The backshort distance in the HFSS model was set to 0.2 mm, and is the same as the scale model. It can be seen that although their location is in the same general vicinity in the Smith Chart, the agreement between the scale models and finite element analysis is not very good. We modeled the antenna structure as a perfect conductor, and this could account for some of the discrepancy. However, since the HFSS model is performed at the frequency of operation, much of the discrepancy is attributed to uncertainties in the scaling and calibration of the scaled model measurements.

A third approach to the numerical analysis is to reproduce as faithfully as possible, the actual

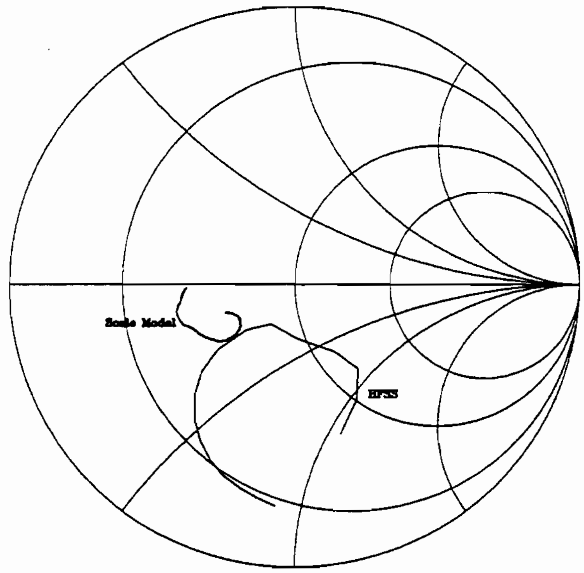

Figure 6: Comparison of the embedding impedance of the scale model with HFSS analysis. The equivalent back-short distance of the scale-model at the frequency of operation is 0.2 mm, and is the same for the HFSS model. The HFSS results are shown after renormalizing to 50 Ω. The two plots are for an equivalent frequency range of 300 to 400 GHz.

layout of the junction with relation to the antenna probe. Figure 7 shows the view of the HFSS model used. The model is a 4-port network with port 1 being the SIS junction, port 2 the IF port and ports 3 and 4 the input and the output waveguide ports respectively. The output port is deembedded at a later stage and a backshort attached to it using analysis outside HFSS. The zoomed-in view of the antenna-probe to junction transition shows the junction defined as a square area. The insulator gap of the junction for this problem is a virtual object to help with creating an adequate mesh for the problem. The actual port for the TEM transmission line is capped off at the end with a perfect conductor. The capped feed ensures that the field propagates only into the junction area, which is the area of interest. Once the problem is analyzed in HFSS, the four-port S-parameter is exported (after renormalization to 50 Ω and deembedding) to a linear circuit simulator (MDS) and optimized there. Figure 8 shows the MDS equivalent circuit model. The backshort is modeled with a shorted half-height rectangular waveguide transmission line in the circuit simulator. For the purpose of this analysis, the tuned SIS junction was replaced with an equivalent impedance of $40 + j20\ \Omega$. The circuit was then optimized for the best backshort distance, resulting in the best case input RF match shown in Figure 9. In practice, the SIS junction and tuning circuit as well as the backshort can be optimized *together* with the embedding impedance S-parameter set derived from HFSS for the best optimization. It can be seen from Figure 9 that the input match is much better than that shown in Figure 5 using the scale-model measurements, and that one backshort setting covers the entire band of interest. Another advantage of this analysis is that the coupling of RF to the IF port and the effectiveness of the RF choke is easily calculated, and any transverse resonance modes in the substrate channel can be studied carefully.

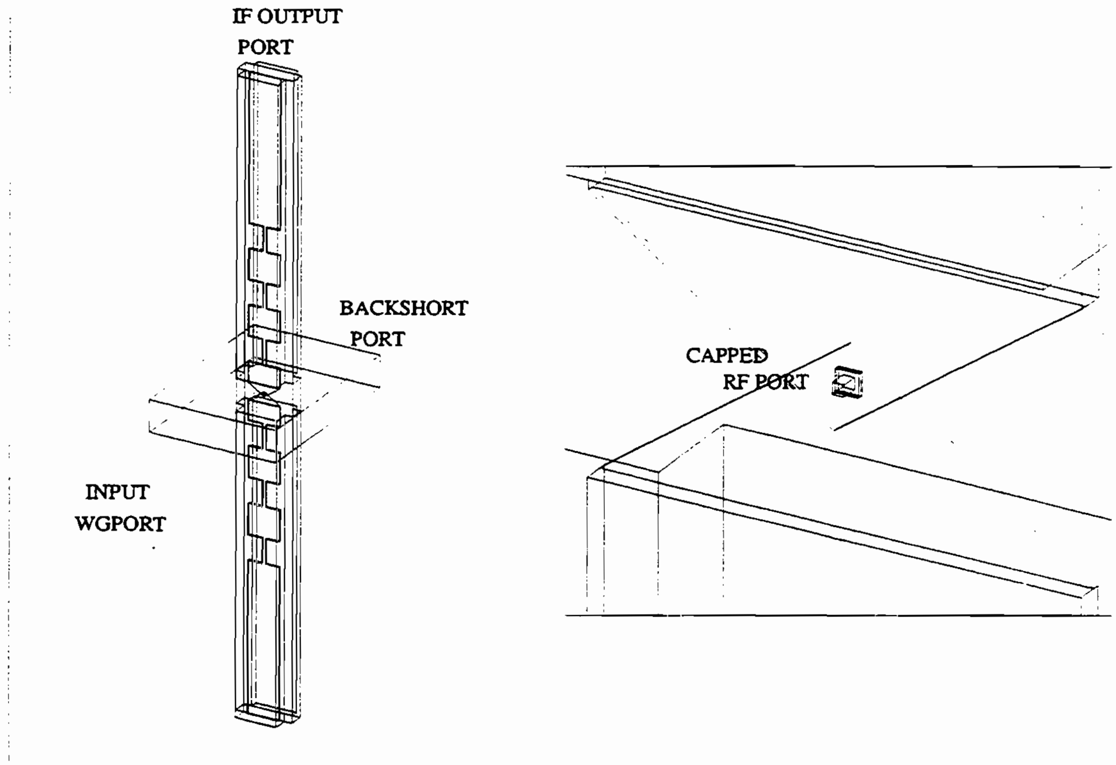

Figure 7: View of the HFSS model and the defined ports of the 4-port model. The zoomed-in view to the right shows the definition of the SIS junction as a square gap, with a TEM port and a capped feed.

5 Conclusion

We have described the mixer block design for a 7-element SIS heterodyne array being built for the HHT. The mixers employ half-height tunerless waveguide mounts with the junctions mounted in a suspended microstrip configuration. Details of the feed horn, IF matching network and fabrication issues were discussed. Scale model measurements were made of the embedding impedance offered by the waveguide mount and compared with numerical simulations using state-of-the-art electromagnetic simulators. A technique to combine FEA with optimizing circuit simulators was used to arrive at a design that provides a broad-band match for the entire frequency range of interest.

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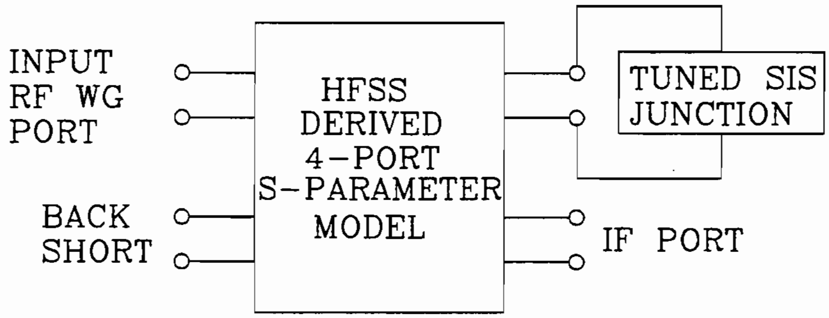

Figure 8: Equivalent MDS circuit model. The backshort is treated as a short-circuited transmission line.

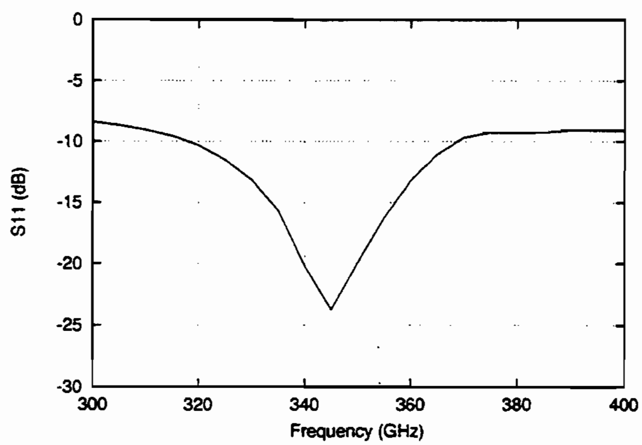

Figure 9: Optimized input RF match into a tuned SIS junction of impedance $40+j20\ \Omega$ using embedding impedance model from HFSS and optimization in MDS. The equivalent backshort distance is 0.25 mm.

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