Fermilab

RF Note #053

# The Design of a Physically Symmetric 2-Port RF Junction Applied to the CKM Input Coupler RF Feedthrough

T.Berenc
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**Abstract:** *A procedure for designing a physically symmetric 2-port RF junction is outlined and applied to a vacuum feedthrough connector design for the Fermilab Charged Kaons at the Main Injector (CKM) superconducting radio frequency (SCRF) cavity system.*

## Introduction

A 2-port RF junction can arise from the need to transition from an air region into a vacuum region through the use of a window. A symmetric geometrical design for such a junction containing a discontinuity at the window interface and uniform cross sections in the mediums can simplify the electromagnetic (EM) analysis by requiring only a field solution of the discontinuity followed by simple algebraic calculations that determine an optimum window length.

## The Design Procedure

Consider the symmetric RF junction shown in Fig. 1. It is assumed that all regions have a uniform cross-section and that there is only one mode of propagation in each medium. It is also assumed that the materials are passive such that the system can be considered to be reciprocal.

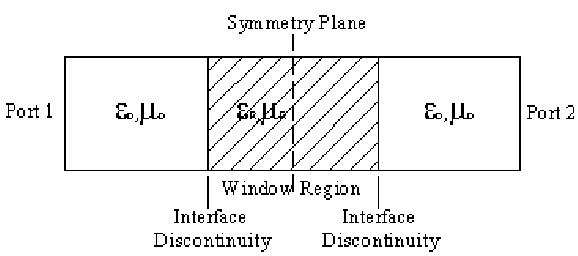


**Figure 1: A symmetric RF junction typical of a vacuum window**

If the window dielectric material is lossless then minimum reflection at the drive port corresponds simultaneously to maximum transmission from the drive port to the load port. It will be assumed that the window material has small losses and that the design goal is to minimize the reflection seen by the drive port, taken here to be Port 1, with a matched termination on the load port, taken here to be Port 2.

The geometry of Fig. 1 can be thought of as the interconnection of two mirrored identical 2-Port networks as shown in Fig. 2.

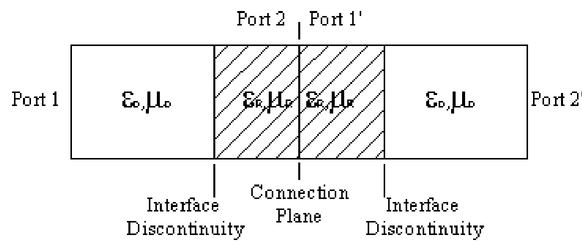


**Figure 2: Symmetric RF junction redrawn as the interconnection of identical 2-Port networks**

In a transmission line, far from a discontinuity, the evanescent modes that satisfy the discontinuity boundary conditions have decayed and only a propagating mode exists. As long as the window length is sufficient such that the two discontinuities can be separated from each other, the analysis is reduced to an electromagnetic field solution of the single 2-Port network shown in Fig. 3 containing the interface discontinuity.

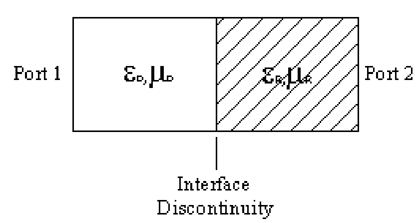


**Figure 3: Single 2-Port Network used for Analysis**

The electromagnetic response of the single 2-Port network of Fig. 3 can be represented in scattering parameter (s-parameter) notation as shown in Fig. 4,

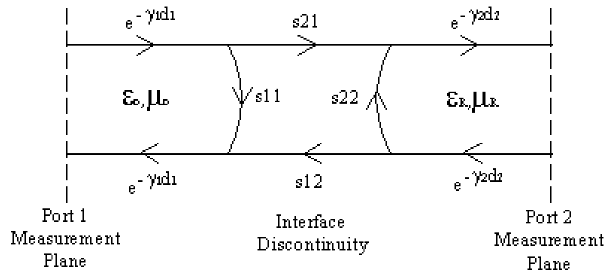


**Figure 4: s-parameter representation of Fig. 3**

where $\gamma_1$ and $\gamma_2$ are the propagation constants in the air/vacuum and window regions respectively, $d_1$ is the length between the measurement/simulation plane at Port 1 (air/vacuum side) and the discontinuity plane, and $d_2$ is the length between the measurement/simulation plane at Port 2 (window region side) and the discontinuity plane. Thus, the reflection and transmission from Port 1 to Port 2 is described by a 2-Port network which is considered to be localized at the discontinuity interface and is connected to two uniform transmission lines on each side.

Notating the s-parameters at the measurement/simulation plane with an 'm' superscript, the s-parameters of the discontinuity can be expressed as,

$$\begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix} = \begin{bmatrix} s_{11}^{m}\, e^{2\gamma_1 d_1} & s_{12}^{m}\, e^{(\gamma_1 d_1 + \gamma_2 d_2)} \\ s_{21}^{m}\, e^{(\gamma_1 d_1 + \gamma_2 d_2)} & s_{22}^{m}\, e^{2\gamma_2 d_2} \end{bmatrix}$$

Once the s-parameters of the discontinuity are determined through measurements or simulations, the network for the complete RF junction, consisting of a mirrored connection of two discontinuities separated by a length of transmission line, can be constructed to determine an optimum window length as shown in Fig. 5. The input reflection coefficient for this network when terminated in a matched load

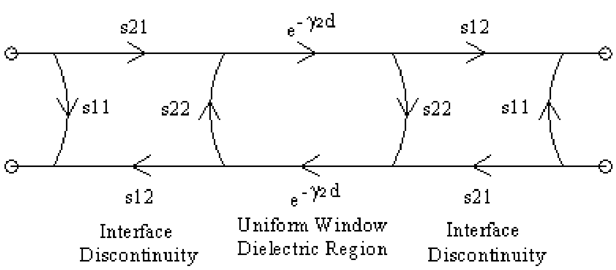


**Figure 5: 2-Port network for the complete junction whose construction is shown in Fig. 2**

can be expressed as,

$$\Gamma_{IN} = s_{11} + \frac{s_{22} s_{12} s_{21} e^{-2\gamma_2 d}}{1 - s_{22}^2 e^{-2\gamma_2 d}} \quad . (1)$$

This expression can be minimized over a specified frequency range using the window length, d, as the variable parameter. The complex propagation constant for the window dielectric medium, $\gamma_2$ , can be determined from the window's material properties and the cross sectional geometry usually within the same simulation which solves the discontinuity boundary value problem.

## Special Case (Lossless and Reciprocal)

A lossless, reciprocal 2-port network that is physically nonsymmetrical has the following properties[1]

$$\theta_1 + \theta_2 \pm \pi = 2\varphi \ , \ (2)$$

$$|s_{21}|^2 = 1 - |s_{11}|^2 \ , \ (3)$$

$$s_{12} = s_{21} \ , (4)$$

and

$$|s_{11}| = |s_{22}| \ , (5)$$

where $\theta_1$ , $\theta_2$ , and $\varphi$ are the phase angles of $s_{11}$, $s_{22}$, and $s_{12}$ respectively.

If the discontinuity and the window dielectric can be considered lossless and reciprocal, then the above properties can be exploited for a single frequency design. Using the above properties and assuming a purely imaginary propagation constant within the window dielectric, Eq. 1 can be rewritten as

$$\Gamma_{IN} = |s_{11}| e^{i(2\varphi - \theta_2 \pm \pi)} + \frac{|s_{11}| \cdot \left(1 - |s_{11}|^2\right) e^{i(2\varphi + \theta_2 - 2\gamma_2 d)}}{1 - |s_{11}|^2 e^{i(2\theta_2 - 2\gamma_2 d)}} \ . (6)$$

The root of the above equation is

$$2\gamma_2 d = 2\theta_2 + n \cdot 2\pi \ , \quad (7)$$

or

$$d = \frac{\lambda}{2} \cdot \left( \frac{\theta_2}{\pi} + n \right) . \quad (8)$$

where $\lambda$ is the wavelength in the window dielectric and is related to the assumed imaginary propagation constant by $\lambda = 2\pi\gamma_2$ , and n is an integer.

[1] See [1] pp.190-191, 370-372 and [2] pp.199-201

There are a few special cases to which Eq. 8 can be applied. One particular familiar case is the case when the window region has the same cross section as the air/vacuum region but contains a different dielectric material. Neglecting any energy storage at the dielectric interface, this is the special case of a half-wavelength window. In this case the reflection coefficient has either a phase angle of 0 or $\pi$, depending upon whether the characteristic impedance in the window region is higher or lower than that of the air/vacuum region. Eq. 8 properly dictates that d should be a multiple of a half-wavelength. For another case, that of a discontinuity with a very small shunt capacitive reactance, Eq. 8 predicts that the two identical discontinuities should be separated by roughly a multiple of a quarter wavelength since such a discontinuity has a reflection coefficient angle close to $-\pi/2$.

## Application to a Vacuum Feedthrough for the CKM Kaon Separator Cavity Input Coupler

The above design procedure was applied to the design of a RF vacuum feedthrough for the CKM Kaon Separator Cavity RF input coupler transmission line system. The design was a modification to an existing connector available from Ceramaseal[2] with part number 18066-01-W. The software used to perform a frequency domain electromagnetic field analysis on the connector was HFSS[3]. The s-parameter results from HFSS were exported to Mathcad[4] for algebraic manipulations to determine the design window length.

First, to validate the HFSS model and the reduced model, the original connector was analyzed and compared to measurements. The measurement apparatus used is shown in Fig. 6. It consists of the original connector attached to a uniform air-filled transmission line with an open termination. The length of the line is approximately one foot, which is long enough to separate the reflection of the connector from the reflection due to the open at the end of the transmission line during a time-domain reflection measurement. The time-domain measurement was performed using the time-domain option on an Agilent 8753E vector network analyzer (VNWA). Time-domain gating is used to look only at the reflections caused by the connector thereby gating out the reflection from the open at the end of the transmission line.

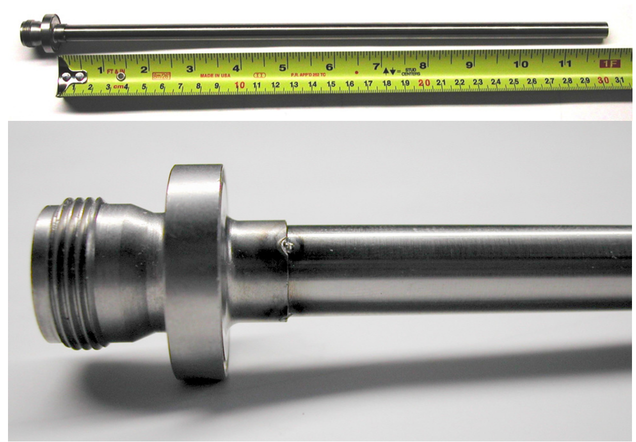

**Figure 6: Connector Measurement Apparatus, full view (top) zoomed view (bottom).**

Simulation results are compared to experimental measurements in Fig. 7. The simulation results shown include both the results from a complete connector model and the results from algebraic calculations performed on the reduced model. The reduced model was setup as described in the text to include only the interface entering into the connector. Equation (1) was then solved with the appropriate original connector window length.

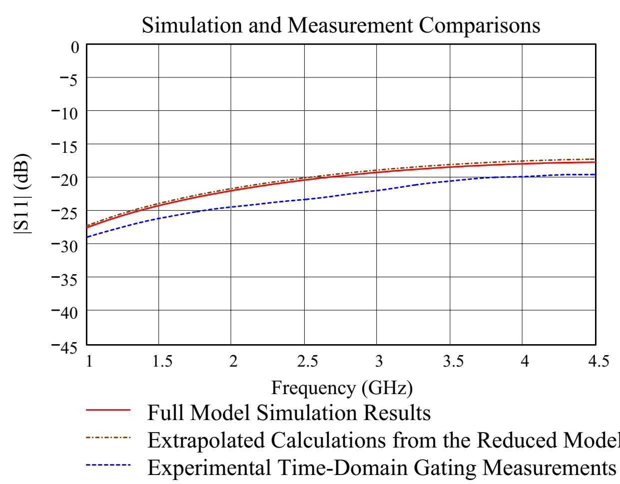


**Figure 7: Comparison between Simulations and Experimental Measurements**

[2] Ceramaseal, a Division of CeramTec, 1033 State Route 20, NewLebanon, NY 12125, http://www.ceramaseal.com

[3] HFSS (High Frequency Structure Simulator) is written by Ansoft Corporation, http://www.ansoft.com

[4] Mathcad is by Mathsoft, http://www.mathsoft.com

Using the reduced model results, an optimum window length for operation at 3.9 GHz was sought. A design constraint was that the window length had to be a multiple of the original window length. The extrapolated simulation results for the reflection coefficient are shown in Fig. 8 as a function of the original window length at 3.9 GHz and in Fig. 9 as a function of frequency for the chosen design length of twice the original window length. This modification has been incorporated into a design that is being produced by Ceramaseal.

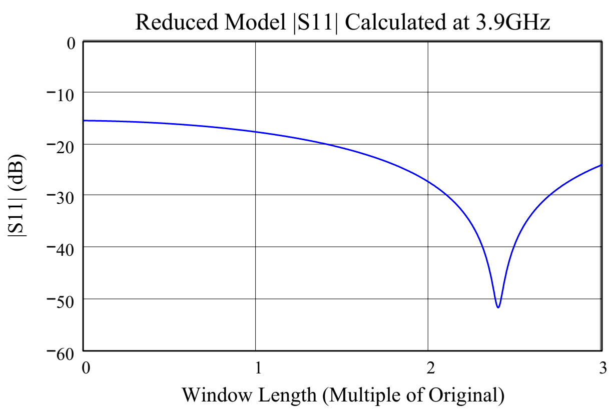


**Figure 8: Reflection coefficient magnitude as a function of window length at a fixed frequency of 3.9GHz Units are in multiples of the original connector window length.**

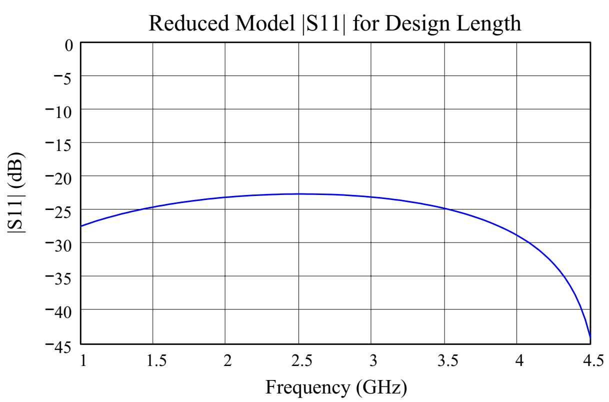


**Figure 9: Reflection coefficient magnitude as a function of frequency for the design window length of 2 times the original window length**
**These results were extrapolated in Mathcad from the swept frequency results of the reduced model.**

## Conclusion

A RF vacuum feedthrough connector design for the CKM Kaon Separator Cavity input coupler transmission line was simplified by taking advantage of physical symmetry. Iterative electromagnetic field simulations for various dimensions can be replaced by algebraic manipulations of a single simulation. Furthermore, a general formula for the optimum length of a symmetric window at a single frequency has been shown as a function of the interface reflection coefficient angle.


## Acknowledgments

I would like to thank Craig Deibele of Oak Ridge National Laboratory for his measurement suggestions and Allan Rowe for the initial mechanical design of the modified connector and the design of the measurement apparatus.


## References


[1] R.E. Collins, “Field Theory of Guided Waves”, McGraw-Hill Inc., New York, 1960.

[2] D.M. Pozar, “Microwave Engineering”, 2nd Edition, J.Wiley&Sons, Inc., New York, 1998.

[3] G. Gonzalez,“Microwave Transistor Amplifiers”, Prentice-Hall, Engelwood Cliffs, 1984, Chapter 1.