

Electrical Performance Enhancements of Fixed Waveguide Attenuators

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[Summary]

Attenuators have many uses in RF, Microwave, Millimeter-wave circuits and instrumentation. The quality of an attenuator is typically described by its impedance match, attenuation flatness and attenuation accuracy over the frequency band the transmission line medium supports. This paper describes impedance match improvements and examines attenuation flatness of full-band, fixed waveguide attenuators. These improvements can be scaled and applied to any waveguide size.

1 Introduction

Attenuators are critical components at RF, Microwave and Millimeter-wave frequencies to adjust the signal path loss and gain settings of electronic systems. Adjustable waveguide attenuators at receiver front ends can increase system dynamic range¹⁾ but are often bulky and expensive, increasing the overall system costs. Attenuators at the front of sensitive receiving front ends can allow for a greater input signal levels without driving the receiver into compression at the expense of increased receiver noise floor. A mechanically adjustable attenuator could prevent the receiver from compressing and maintain a low noise floor level. However, repeatability of mechanical attenuators would increase the receiver calibration uncertainty²⁾.

A recent paper³⁾ describes a 15-dB fixed waveguide attenuator in WR6. Simulation and measurement results indicate a worst-case VSWR of 1.25 (19-dB Return Loss). In this paper, a similar waveguide attenuator with fixed attenuation levels of 5-dB and 25-dB is studied with a goal of improving VSWR and examining the impact on attenuation flatness.

2 Mechanical Considerations

2.1 Waveguide Housing Split Plane

Consideration of how the waveguide housing would be machined is critical to avoid potential electrical performance issues. Typically, waveguide housings are machined as two symmetrical pieces along the E-plane or broad-wall (see Figure 1). The E-plane is the preferred split plane because it is less sensitive to seam imperfections to that of a split along the H-plane or narrow wall. Waveguide housings split along the H-plane with seam imperfections may not present sufficient conduction along the narrow wall and can introduce in-

band resonances⁴⁾. If the H-plane is located at the top-most portion of the inside cavity, the sensitivity to seam imperfections remains. Investigating and comparing the impacts to housing seam imperfections along the E-plane and H-plane can be examined using a 3D EM simulator⁵⁾.

Many waveguide housing designs incorporate an H-plane split for convenience. Reasons for choosing an E or H split plane are varied: ease of machining interior details, placement of interior substrates and components, etc. Described in this paper, the enhanced D-Band (WR-6) attenuator design utilizes an E-plane housing split which benefits not only from a low-sensitive seam placement, but also the mechanical ease in which the attenuator performance is enhanced.

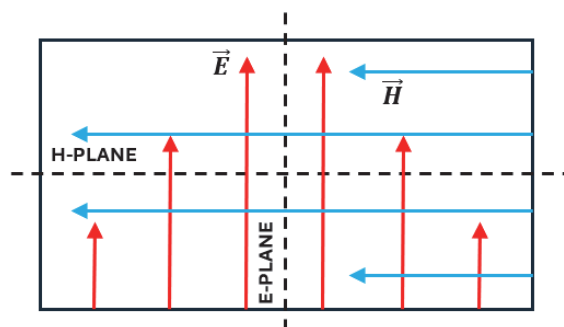


Figure 1 Waveguide housing E and H split planes

3 Measurements and Measurement Limitations

3.1 Attenuator Characteristics

An ideal attenuator has characteristics of perfect match and flat attenuation over its operating frequency band. In practice, measurement of an attenuator using a VNA will have imperfect match and attenuation flatness. The reflection characteristics of the attenuator should approach the VNA's corrected directivity value within 10 to 15-dB for a worst-case corrected directivity value of 45-dB as a practical

minimum design goal. The measurement instruments corrected directivity can be viewed as the value where the DUT return loss measurement uncertainty is large and would be in the range of -6 dB to $+\infty$ dB.

Many fixed waveguide attenuators commercially available and described in a recent paper³⁾, have a worst-case match of about 20-dB and their structures are likely similar. Relative to our stated goal, it seems this worst-case match of 20-dB could be improved by identifying and correcting the cause of discontinuity mismatches caused by the inclusion of the attenuator elements which is the focus of this paper.

4 Treating the attenuation element as a transition

4.1 Influence of substrate without resist

Assuming the waveguide housing incorporates an E-Plane housing split, and the substrate lies flat against either one or both broad-walls, the substrate must be divided into two pieces to not obstruct the housing split location as shown in Figure 2. First, the substrates without Tantalum Nitride (TaN) resist material are examined in an EM simulator for their impact on the waveguide's reflection properties. Including the substrate within the waveguide forms two transitions within the waveguide structure. Minimizing the reflections caused by the inclusion of the substrate is the goal.

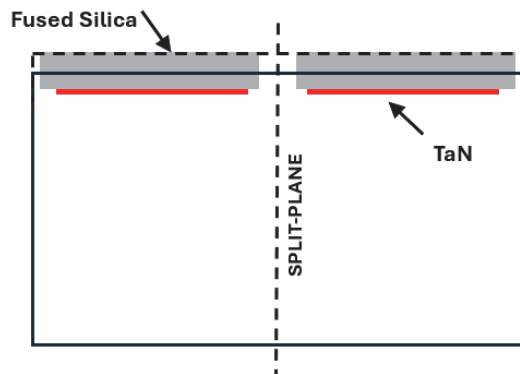


Figure 2 Broadwall placement of embedded substrates (end-view).

4.2 Compensating the transition

It was found that embedding a 250-mil $\times$ 61-mil $\times$ 5-mil thick Fused Silica substrate within the WR6 waveguide on the broad wall by 60% (as shown in Figure 3) improves the reflection response significantly vs. not embedding the substrate at all. Figure 4 shows the S11 reflection response. Embedding the substrate shows approximately a 10 to 15-dB improvement in S11 over the full WR6 waveguide band. This

gives confidence that the attenuators match can be improved with a minor waveguide housing change. Due to structure reciprocity, S12 and S22 are not included in the results.

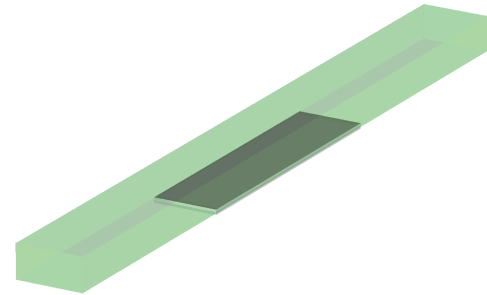


Figure 3 WR6 Embedded fused silica substrate without the TaN resist layer.

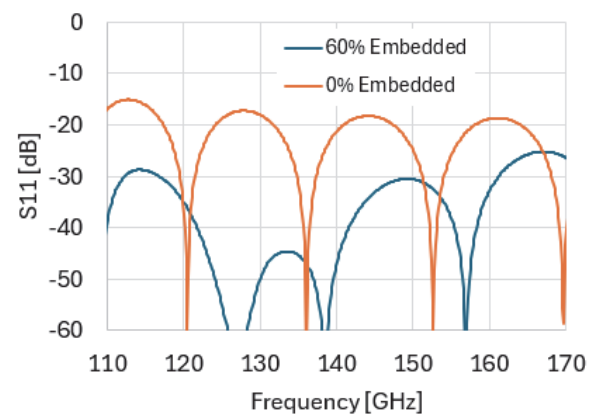


Figure 4 WR6 reflection response of embedded and non-embedded substrate without the TaN resist layer.

An end-mill machine tool is used to machine the compensation feature into the broad wall. Typical end-mill tools have a flute length-to-diameter ratio of 3:1. The required end-mill flute length is 32.5 mils so its diameter would be approximately 11-mils. Figure 5 shows the radius formed by the end-mill tool just beyond the substrate edge. This housing feature was incorporated into the simulation models and didn't show significant impact on the results.

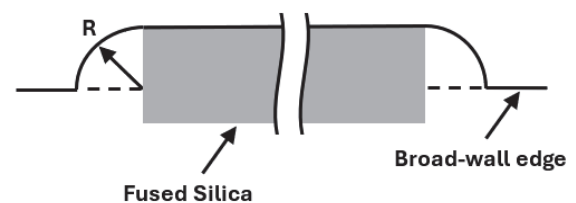


Figure 5 End-mill tool radius detail at substrate ends

5 Attenuator Designs: 5-dB and 25-dB

5.1 Thin film resist taper

A TaN sheet resistivity was chosen as 50 ohms/square pulled back from each substrate edge by 2-mils. Instead of

using an elliptical taper of the thin film resist material, a simple linear taper was examined for its impact on S11 and S21. Linear taper angles of 0°, 22.5° and 45° at both substrate ends were examined using the simulators parametric sweep option. Since the thin film resist is near the embedded substrate transition, it is expected the resist material will have some impact on match. Sections 5.1 and 5.2 below discuss the impact on match with thin film resist linear taper values.

5.2 5-dB attenuator design

A 5-dB attenuator was designed with two 5-mil thick Fused Silica substrates each having a size of 150-mil × 30.5-mil centrally positioned on the broad wall of a WR6 waveguide as shown in Figure 6. Due to structural symmetry, a magnetic plane boundary condition along the waveguides E-plane was used to simplify model computation.

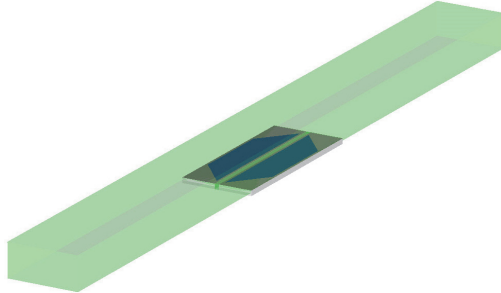


Figure 6 WR6 5-dB split-substrate attenuator w/tapered TaN resist layer.

The influence of taper angles with S11 and S21 was found to be modest for the 5-dB design. A small trade-off between taper angle, match and attenuation flatness as shown in Figure 7. A taper angle of 0° exhibits the best match but slightly worse attenuation flatness. Conversely, A taper angle of 45° exhibits the best attenuation flatness but worse match relative to smaller taper angles. A similar trade-off was found for negative taper angles.

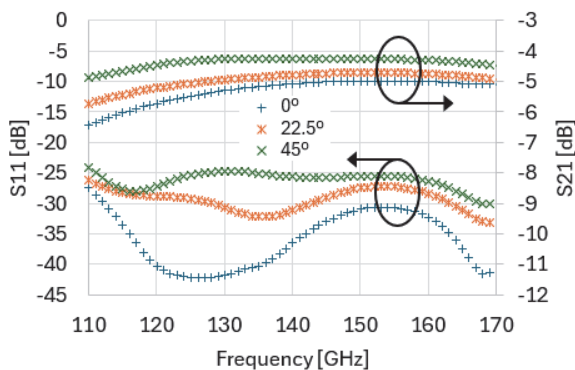


Figure 7 WR6 5-dB attenuator reflection and transmission response vs. TaN resist taper angle.

5.3 25-dB attenuator design

A 25-dB attenuator was designed with four 5-mil thick Fused Silica substrates each having a size of 375-mil × 30.5-mil centrally positioned along the length of a WR6 waveguide as shown in Figure 8. To increase attenuation, substrates were attached to both broad walls. Structural symmetry allowed use of a magnetic boundary condition along the waveguides E-plane and an electric boundary along the waveguides H-plane to simplify model computation.

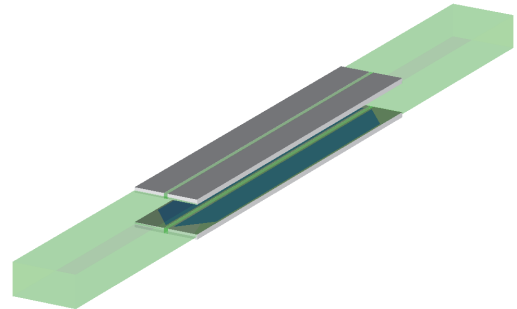


Figure 8 WR6 25-dB split-substrate attenuator w/tapered TaN resist layer.

As in the 5-dB attenuator design, the 25-dB attenuator shows only modest improvements in S11 with taper angle. However, there was no observable difference in attenuation flatness. Like the 5-dB attenuator design, attenuation value decreases with increasing taper angle since an increasing amount of TaN resist material is removed. S11 and S21 results are shown on Figure 9.

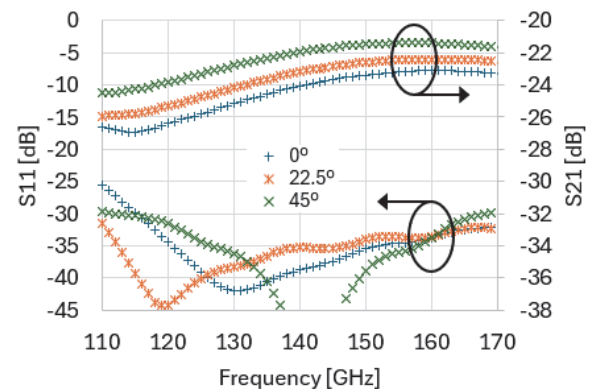


Figure 9 WR6 25-dB attenuator reflection and transmission response vs. TaN resist taper angle.

5.4 Manufacturing considerations for high attenuation value designs

The 25-dB attenuator design described in section 5.3 utilized both broad walls and an increased substrate length to increase the attenuation value. Fused Silica substrates are relatively fragile depending on their thickness and length-

to-width aspect ratio. Substrates with large length-to-width aspect ratios may exhibit smaller thin film processing yields. For the 25-dB attenuator design, the length-to-width aspect ratio is about 12.3:1 which may exceed thin film substrate manufacturing design guidelines and result in poor yields due to cracking or breakage. This problem can be addressed by sub-sectioned substrates while adhering to a maximum substrate length-to-width ratio.

The attenuator substrate design only needs to be processed with a TaN resist layer on the substrate topside. The backside of the substrate does not need a metal layer, so this reduces thin film processing costs. A low dielectric constant epoxy can be used to attach each substrate to the housing inside channels.

6 Conclusions

RF, Microwave and Millimeter wave components can often be broken down into their constituent parts to examine and improve their electrical performance parameters. In this paper, two examples of WR6 fixed attenuators were examined by treating the waveguide transmission line structure as a transition optimization problem with the TaN resist layer removed. Once the electrical parameters (i.e. S11) of this low-loss transmission line structure are optimized, the TaN resist material is introduced to gauge its impact on the attenuator's electrical parameters such as match, absolute attenuation and attenuation flatness.

Unfortunately, time constraints did not allow the completion of the built 5-dB and 25-dB attenuator assemblies and compilation of test results. Results of the built and measured WR6 attenuators will be provided in a future paper.

7 References

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- 2) Leinonen, Marko E., et al. "Repeatability of 220-330 GHz variable waveguide attenuator and frequency extenders for 6G measurements." 2022 98th ARFTG Microwave Measurement Conference (ARFTG). IEEE, 2022.
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