

# Measurements of microwave electrical characteristics of folded waveguide circuits

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We report experimental measurements of dispersion and wave transmission in folded waveguide (FWG) circuits for TWTs. Two complementary circuits are under investigation. One circuit, made by wire-EDM, has a relatively conventional design, with dimensions suitable for W-band operation. The other circuit is an X-band model, intended to evaluate the implications of substituting a planar gap for the conventional beam tunnel.

As illustrated in Fig. 1, the X-band circuit has been conventionally machined as two half-depth serpentine trenches. Half of a “beam tunnel” has been machined into each half of the circuit. When mated, a full FWG results with a seam in the middle of the broadwall. There are several reasons for interest in this structure: (1) the 2-piece circuit is similar to what one obtains with LIGA, micromolding, or etched-silicon fabrication of FWG circuits, (2) for standard TE<sub>10</sub> operation, this mid-broadwall seam should introduce negligible losses, even if left un-brazed, (3) this 2-piece configuration offers a natural option to introduce a gap between the



Fig. 1. 2-piece X-band FWG test circuit

two waveguide halves for beam access, vacuum pumping, thereby eliminating the need to fabricate the beam tunnel.

Figure 2 shows comparative measurements of the transmission ( $|S_{21}|$ ) between the 2-piece FWG of Fig. 1 and an otherwise identical 3-piece circuit. As shown in the inset, the 3-piece circuit has seams at the broadwall ends, rather than the midplane. This is the type of structure one would normally obtain from wire-EDM fabrication of a FWG. The 2-piece circuit exhibits negligible loss, while the 3-piece (un-brazed) circuit exhibits 3-5 dB of loss, especially below 10 GHz. A very conservative upper bound estimate of total attenuation due to wall losses for this 10-period, aluminum circuit is less than 0.5 dB. These measurements verify the expectation that a mid-broadwall seam is virtually lossless for the TE<sub>10</sub> mode, while (unbrazed) seams at the ends of the broadwall introduce significant losses by interrupting the dominant wall current pathways.

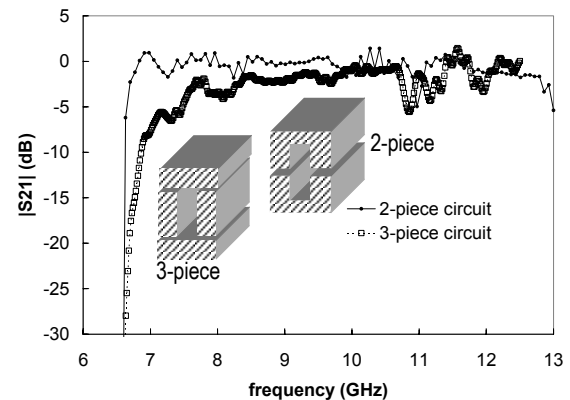


Fig. 2. Transmission data for 2-piece vs. 3-piece X-band FWG circuits

Three methods have been investigated for measuring the dispersion characteristics of the X-band FWG circuit. In one method, a synthesizer excites a signal at one end of the waveguide and the axial electric field component of the wave is detected by a small coaxial sensor. The signal phase  $\phi(z)$  is measured and Fourier decomposed to identify wavenumbers of the space harmonics [1]. A second measurement method places a scattering object (bead or wire) into the waveguide and uses a network analyzer (VNA) to measure the difference,  $\Delta\psi$ , in a reflected wave’s phase for two different positions of the scattering object, spaced a distance “ $p$ ” apart. If the wave is dominated by a single space harmonic, then the axial wavenumber,  $\beta$ , may be estimated as  $\beta \approx \Delta\psi/p$ . In a third method, a modest mismatch is introduced at the input port and a rod (wire) is drawn along the tunnel. The standing wave produced is recorded by measuring the magnitude of the reflection coefficient  $|S_{11}|$  as a function of the wire tip’s position. This

method is commonly used to measure dispersion properties of various slow wave circuits. The results of initial measurements are shown in Fig. 3, along with preliminary simulation results obtained with MWS. Frequency-domain and time-domain simulations were conducted. Also shown is the prediction of a simplified analytic model of the FWG. Several tentative conclusions are drawn. First, the standing wave method and the axial probe method of measuring dispersion are in good agreement, and these measurements agree with the predictions of the simplified analytic model (which does not account for reflection effects from the beam tunnel or waveguide bends). There is discrepancy, however, with the eigenmode simulations, which was surprising. It was also expected that the reflected phase measurement method would agree with the time-domain simulation results. While they qualitatively agree in producing a larger effective phase advance for each frequency than the more conventional methods (as expected), they do not agree on the actual values of the phase advance. Also, in Fig. 3 are three points at 7.0, 7.5, and 10 GHz produced by the standing wave method for a circuit in which the beam tunnel is replaced by a gap. Simulations predict that this gap should have an almost negligible effect on the dispersion, except for a small increase in the cutoff frequency, and this is exactly what we observe in the experiments. Other measurements not shown here establish that an additional “gap” mode predicted by simulations is not excited.

Both S21 and initial dispersion measurements have been completed on a first prototype of 3-piece wire-EDM’ed W-band circuit. The S21 results, in Fig. 4, show a broad pass-band, consistent with numerical simulations that predict that the pass band extends from 77 GHz to 123 GHz, (123 GHz is beyond the measurement range of the VNA). The attenuation for this 48-period, 3-piece, copper circuit is significant, e.g.,  $\sim 10$  dB between 90-110 GHz, consistent with the results of Fig. 2, while accounting for the additional length and higher frequency of operation. The dispersion results, using the standing wave method are shown in Fig. 5, and agree well with the eigenmode method of simulation, as expected. The experimental error bars are dominated by the precision of measuring distance between minima in the  $|S_{11}|$  standing wave pattern. This research was funded by a Phase I U.S. Army Small Business Innovation Research Grant No. DAAD19-03-C-0089, and by a U.S. Air Force Small Business Innovation Research Grant No. F29601-03-C-0049.

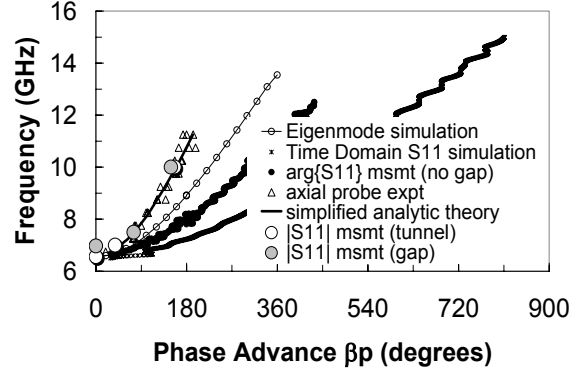


Fig. 3. Measured and simulated dispersion properties of 2-piece X-band FWG test circuit

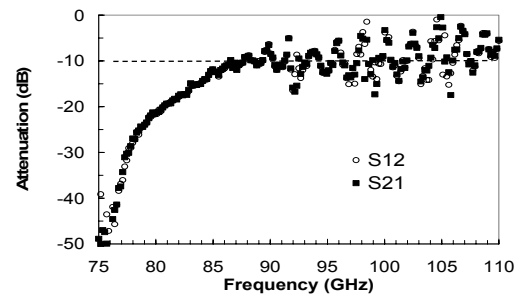


Fig. 4. Measured S21 data for 3-piece W-band FWG test circuit (unbrazed).

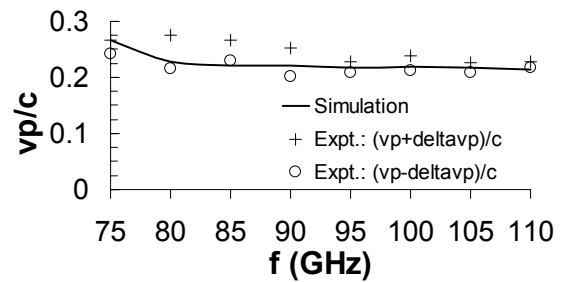


Fig. 5. Dispersion in prototype W-band FWG circuit. Standing wave measurements and eigenmode simulations

[1] J. Joe, L.J. Louis, J.E. Scharer, J.H. Booske, and M.A. Basten, *Phys. Plasmas*, Vol. 4, No. 7, 1-9 (1997).