Serpentine Waveguide 220 GHz Millimeter Wave Amplifier Cold Test

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Abstract: *We present results of an electromagnetic cold-test of an all-copper, microfabricated 220 GHz serpentine waveguide amplifier circuit. Transmission/reflection measurements are used to determine the ohmic loss, pass band, and cutoff frequency. We observe the effects of fabrication accuracy, including circuit depth and beam tunnel alignment, on the measured electromagnetic properties.*

Keywords: millimeter wave amplifier; serpentine folded waveguide; slow wave structure; microfabrication.

Introduction

Millimeter wave amplifiers capable of producing high average power over a wide instantaneous bandwidth are needed for high-data-rate communications. These amplifiers require robust all-copper structures for thermal handling capability, which limits the use of conventional wide-band traveling-wave circuits such as the helix. [1] The serpentine waveguide (SWG) circuit is chosen as a compromise between the wide bandwidth of a helix and the power handling of a coupled-cavity structure. [2] In the SWG, a TE_{10} rectangular waveguide mode travels through a series of smooth 180-degree bends in the plane of the E-field (Fig. 1). A round electron beam passes through a tunnel that intersects the waveguide in between the bends and parallel to the E-field, encountering a virtual TM slow-wave mode.

An ultraviolet photolithography and electroforming process (UV-LIGA) is used to fabricate the circuits in-house at NRL. In addition to producing high-quality monolithic copper structures, this technique allows the creation of a narrow beam tunnel (~0.0075" diameter) through the circuit over an arbitrary length. [3] Metallurgical tests confirm the purity of the electroformed bulk copper and the suitability of the circuits for use in vacuum electronic amplifiers. In this paper, we use microwave transmission measurements to determine the fabrication quality of circuits made for use in a wideband 220 GHz traveling-wave tube (design parameters shown in Table 1).

Table 1. 220 GHz amplifier design parameters.

Beam voltage, current	11.7 kV, 120 mA
Small signal gain	18 dB
Bandwidth	15.5 GHz
Output power	60 W
Beam tunnel diameter	190 um
SWG period	205 um

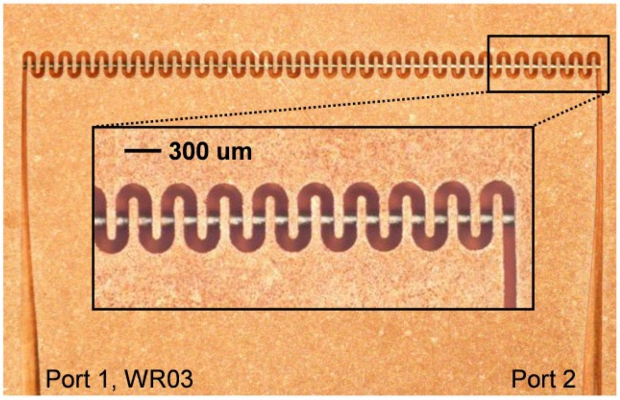

Figure 1. Photograph of an all-copper 220 GHz SWG circuit, without brazed cover. Inset: circuit detail, with steel gage pin inserted through beam tunnel.

Cold Test Measurements

Two-port S-parameter measurements were performed using an Agilent vector network analyzer. Millimeter wave extender modules covering the continuous band 140-325 GHz allow us to test the amplifier circuit beyond the operating frequency range. The measured S_{21} magnitude (Fig. 2) clearly shows the pass band of the n=0 space harmonic from 196 to 280 GHz, which is seen in the calculated dispersion diagram (Fig. 3). The measured cutoff frequency of the structure is slightly higher than the predicted value of 193 GHz, indicating that the fabricated circuit is shallower than the design. The upper band edge is lower than the predicted value of 298 GHz.

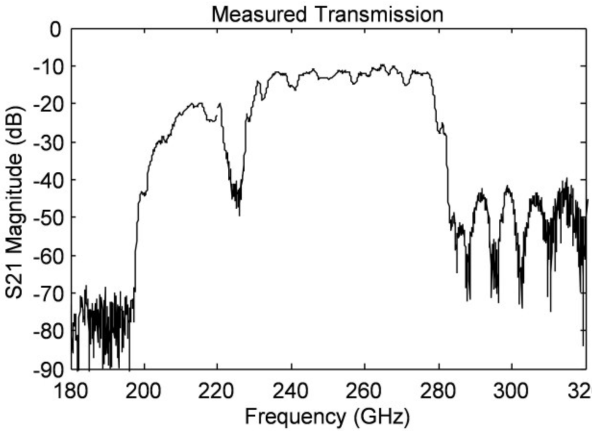

Figure 2. Measured transmission of SWG structure with beam tunnel.

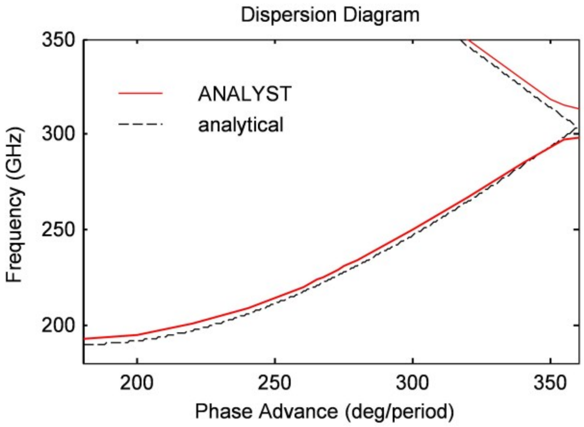

Figure 3. Dispersion diagram, *n*=0 and *n*=1 space harmonics: analytical (dashed black line) and ANALYST simulation (solid red line).

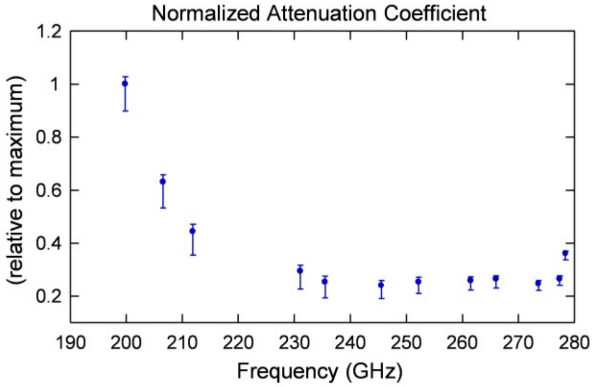

Figure 4. Measured ohmic attenuation coefficient, normalized to maximum value.

The measured insertion loss is 10-18 dB in the range 210-235 GHz. The ohmic loss in the circuit is calculated from the S_{21} and S_{11} data using the simplifying assumption that all reflection occurs at the structure input. The normalized ohmic attenuation coefficient is shown in Fig. 4, with error bars generated by varying S_{11} by ± 3 dB. The shape of the loss as a function of frequency is very similar to 3D simulation predictions. We will discuss a model that includes reflections at the transitions from straight to serpentine waveguide at the input/output, to accurately determine the absolute magnitude of the ohmic loss.

A prominent dip in the transmission is observed near the operating frequency 220 GHz. Using 3D electromagnetic simulations (HFSS) and an analytical transmission line model, we find that this is due to offset and/or tilt of the beam tunnel in the plane of the waveguide bends; this misalignment introduces additional periodicity that opens a stop band in the middle of the operating band. [4] Optical microscope measurements confirm the presence of a misalignment in the circuit that was tested. Subsequent circuits are being carefully evaluated for tunnel alignment prior to testing. After electroforming and brazing, the diameter of the beam tunnel was measured to be 0.0065" by inserting precision gage pins through the tunnel.

Half-wave resonant windows have been fabricated using BeO ceramic. The ceramic disks, 0.0115" thick and 0.047" in diameter, are brazed into a copper ring. Initial measurements of the un-tuned window and mode-converter assembly show -20 dB reflection over 15 GHz bandwidth, centered at 225 GHz (Fig. 5).

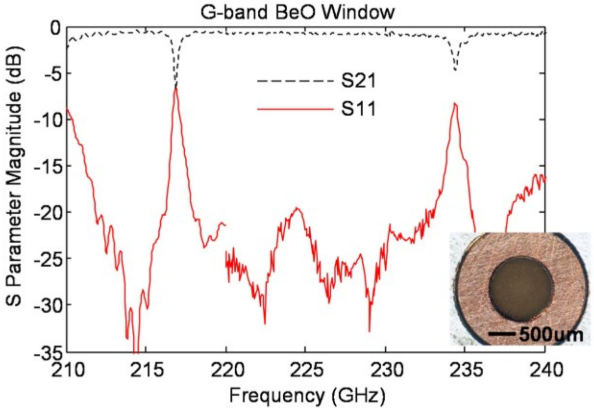

Figure 5. Measured transmission (dashed black line) and reflection (red solid line) of BeO window. Inset: window at 50x magnification.

Conclusion

The cold test measurements verify that the circuit has been successfully fabricated close to the design dimensions. Misalignment of the beam tunnel is seen to open a stop band in the middle of the main pass band, near 220 GHz.

We are working to further develop the UV-LIGA fabrication process. The technique has been demonstrated at 220 and 670 GHz at NRL, and work is underway to build a 95 GHz SWG structure.

Acknowledgements

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