W-BAND MEASUREMENTS OF 100µm HEIGHT MICRO-MACHINED AIR-FILLED RECTANGULAR WAVEGUIDES

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ABSTRACT

The first S-parameter measurements of micro-machined 100µm high air-filled rectangular waveguides are reported, which have been performed at W-band using a specially designed test fixture connected to a standard vector network analyser. The results obtained show low loss and demonstrate propagation in TE_{10} mode.

INTRODUCTION

In the millimetre wave and terahertz frequency range, fundamental mode rectangular waveguide becomes increasingly difficult to machine due to its small size. A micro-machining technique has been reported for fabricating air-filled rectangular waveguides directly onto a semiconductor substrate containing active device layers which can then be incorporated into the on-chip guide [1], [2]. These components could eventually lead to the fabrication of integrated circuits at terahertz frequencies. Applications already exist at millimetre wave frequencies which would benefit from the introduction of such an integrated circuit technology, and interest is increasing in exploiting the large bandwidths available in the submillimetre wave region [3], [4], [5] once a suitable cost-effective technology becomes available.

S-parameter measurements of these micro-machined waveguides have not previously been reported owing to the difficulty of repeatably coupling power into and out of the guide. Measurements on a different type of on-chip waveguide using wafer probing techniques have been reported [6], however the mismatch caused by the coplanar to rectangular waveguide transitions make it difficult to obtain meaningful results. A test fixture is reported here which can be connected directly to the test ports of a standard W-band vector network analyser. This test fixture minimises the mismatch at the ports of the micro-machined waveguide enabling more accurate characterisation of its S-parameters. It also affords a comparison between measurements achieved using familiar microwave test equipment and measurements which could be performed on these waveguides, at these and higher frequencies, using quasi-optical techniques.

WAVEGUIDE FABRICATION

The on-chip micro-machined waveguide fabrication process is summarised in Figure 1. The waveguide is made by first evaporating a titanium adhesion layer followed by a layer of gold with a thickness greater than one skin depth (approximately 0.25µm at W-band) onto the surface of a semiconductor wafer to form the bottom wall of the waveguide (i). A photoresist former defining the internal dimensions of the waveguide is then produced on top of this layer using photolithographic techniques (ii). The former is coated with gold by evaporation and electroplated for extra strength to a total thickness of approximately 50µm (iii). Subsequent removal of the photoresist with solvent leaves an air-filled rectangular waveguide (iv). Any semiconductor wafer protruding in front of the waveguides needs to be removed and this is achieved by filing away the wafer parallel to the open ends of the waveguides. The maximum height of the guide is governed by the thickness of the photoresist former which can be

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produced, and to date is 100μm. This corresponds to approximately 1/13th height at W-band, but approaches closer to full height at increased frequencies. This reduced height increases the loss slightly but has no bearing on the cut-off frequencies of TE_{M0} modes.

Two different lengths of waveguide were fabricated as shown in Figure 2. Both samples have a 4mm length of 2.54mm wide waveguide at the ports and then taper down to a width of 1.84mm. Sample 2 has an additional 9.23mm ($1.5\lambda_g$ at 95 GHz) length of 1.84mm wide waveguide between the two tapers. This waveguide width was chosen as it has a cut-off frequency of 81.5 GHz enabling a TE_{10} attenuation characteristic to be demonstrated in the W-band frequency range (75 GHz - 110 GHz). Both lengths of waveguide had a height of approximately 100μm.

W-BAND TEST FIXTURE

A major consideration in the design of the test fixture was the alignment of the micro-machined waveguides with those in the test fixture itself. A test fixture was desired into which the micro-machined waveguides could be inserted repeatably so that the openings coincide exactly each time a sample is inserted. This was achieved by machining two sections of W-band waveguide tapering from full height (to be connected to the VNA ports) to reduced height (to connect to the ports of the on-chip waveguide) with shoulders protruding from the reduced height sides of the waveguide to hold the sample. A diagram of the aluminium test fixture is shown in Figure 3.

The only position reference available on a sample of micro-machined waveguide is given by the plane of the substrate. This substrate rests upside-down on the test fixture shoulders so that the waveguide lies in the gap in-between, therefore the vertical position of the waveguide is known exactly. This gap is machined to allow a comfortable fit for the 50μm thickness of gold on each side of the guide, hence the waveguides will also always be aligned horizontally. Once the sample is inserted, the two tapered waveguides in the test fixture are moved together by means of a micrometer screw until they are touching the sample, resulting in a repeatable connection.

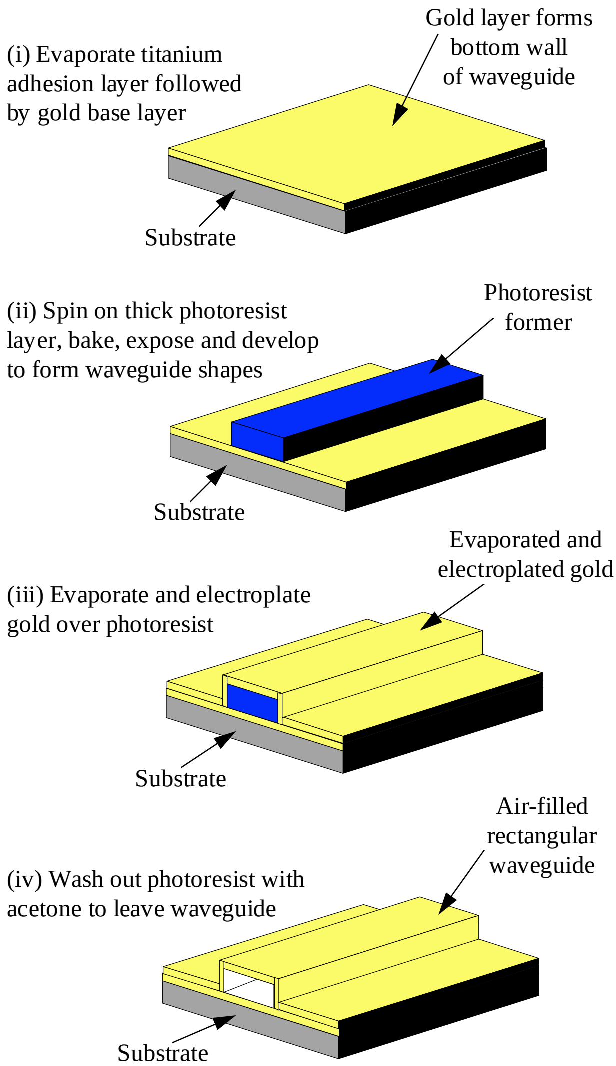

Figure 1. Fabrication of Micro-machined Air-Filled Rectangular Waveguides.

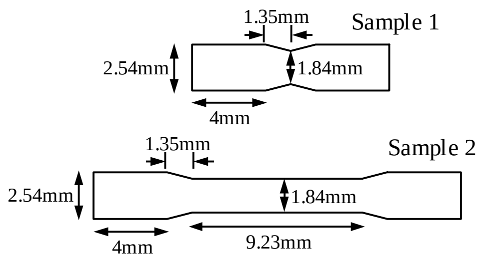

Figure 2. Diagram of Waveguide Samples.

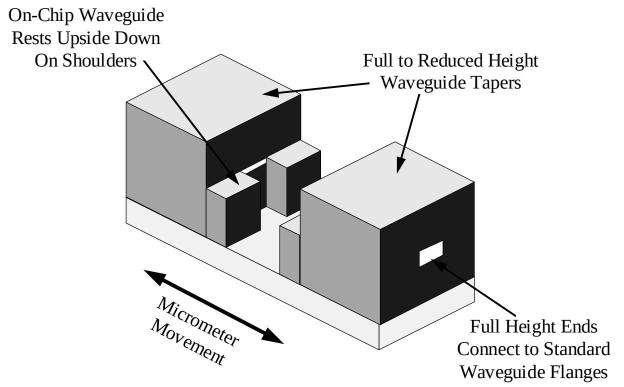

Figure 3. Diagram of W-band Test Fixture

MEASUREMENT RESULTS

A TRL calibration was performed at the waveguide test ports of a vector network analyser. The test fixture was then connected between the test ports and the samples inserted one at a time. The insertion loss of the two samples (plus the aluminium waveguide tapers in the test fixture) is shown in Figure 4 and Figure 5, and the residual leakage between the ports is much less than -40 dB. The results show the characteristic shape expected from a length of waveguide close to its cut-off frequency (81.5 GHz) showing that the TE_{10} mode is propagating successfully down the waveguide. The attenuation of air-filled gold-walled rectangular waveguide for TE_{10} mode can be calculated from standard formulae [7] and is found to vary between 0.5dB and 0.34 dB over the 90 GHz to 110 GHz frequency range for the additional 9.23mm length of waveguide contained in Sample 2. The attenuation of this additional length can also be deduced from the measured results by subtracting the attenuation of the shorter sample from that of the longer as shown in Figure 6. The measured attenuation varies between 0.2 dB and 5 dB and the average attenuation value is higher than calculated due to mismatches caused by the difficulty in accurately filing away the wafer to the edge of the waveguide i.e. if the edges of the wafer are not exactly perpendicular to the side walls of the waveguide, there will be a difference in the mismatch occurring for each sample. Some additional loss is thought to occur because the bottom wall of the waveguide has a thickness of only one skin depth. This could be solved by evaporating a thicker layer of gold onto the substrate before spinning on the photoresist, and will not be a problem at higher frequencies where the skin depth is

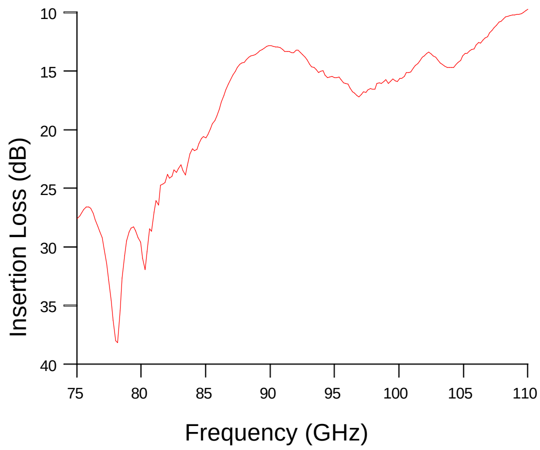

Figure 4. Insertion Loss of Sample 1 and Test Fixture.

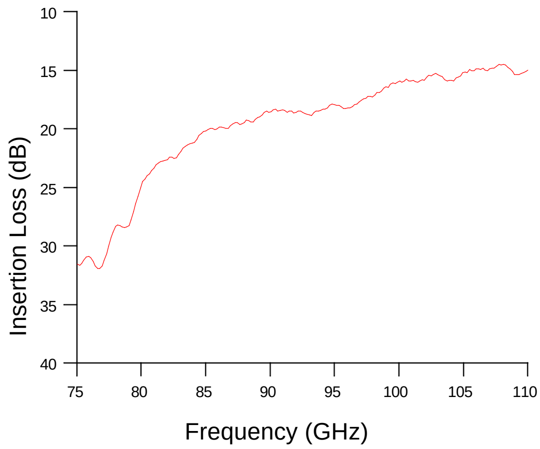

Figure 5. Insertion Loss of Sample 2 and Test Fixture.

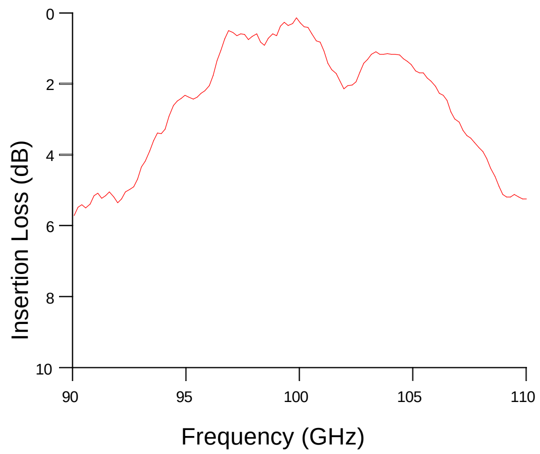

Figure 6. Attenuation of 9.23mm Length of 1.84mm Wide Waveguide.

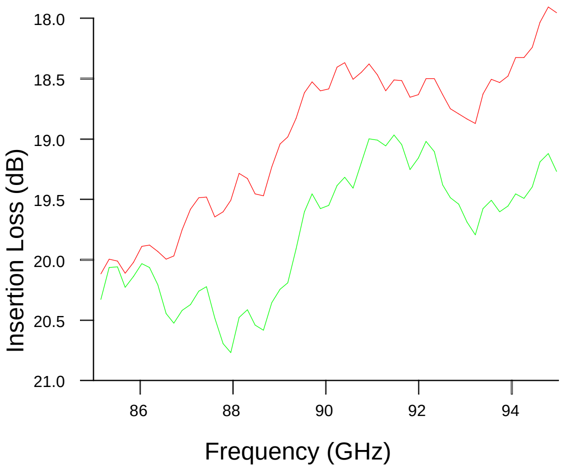

Figure 7. Difference in Insertion Loss Measurements on Sample 2.

smaller. The measured attenuation is still significantly lower than for previously reported on-chip waveguide [6] however.

Figure 7 shows two separate insertion loss measurements performed on Sample 2, removing the sample and replacing it between the measurements. The insertion loss repeatability can be seen to be approximately ± 0.5 dB and could be improved with more accurate removal of the excess wafer at the open ends of the waveguide.

CONCLUSIONS

The first measurements of air-filled micro-machined waveguides have been performed at W-band using a standard vector network analyser and a test fixture. The TE_{10} mode of propagation has been shown to be supported in the waveguides with the correct cut-off frequency. The insertion loss of a length of waveguide has been measured and found to be higher than calculated due to mismatch effects and the thinness of the bottom waveguide wall. This could be improved by putting down a thicker bottom layer of gold and will not be a problem at higher frequencies where the skin depth is smaller. The attenuation is still significantly lower than for previously reported on-chip waveguide. The measurements show good repeatability which could be further improved using more accurate techniques such as etching or laser ablation to remove the excess wafer in front of the waveguide, hence reducing mismatch. These measurements could be used as a comparison with quasi-optical measurements at these and higher frequencies.

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