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# Submillimetre Rectangular Waveguides based on SU-8 photoresist micromachining technology

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## Abstract

Rectangular waveguides are fundamental structures for the transmission of signals at millimetre and submillimetre wavelengths. This paper describes the design and measured results for two rectangular waveguides based on layered SU-8 photoresist micromachining technology, with double-layer fabrication techniques to minimise the air gaps between layers. A brief description of the SU-8 photoresist micromachining procedure is given in the paper. One waveguide is demonstrated for the WR3 band from 220 GHz to 325 GHz the other is for the WR6 band 120 GHz to 170 GHz both are made of layered SU-8 with a 3 piece construction. Both waveguides have novel bends in order to connect to the measurement apparatus. The measured performance is presented and compared to conventional machined metal waveguide structures. The measured insertion loss for the SU8 waveguides in both bands is better than 0.03 dB/mm.

## Introduction

The desire for ever higher frequency communication systems has made implementing even the simplest of components difficult as terahertz frequencies are approached. However, due to micromachining technologies, rectangular waveguide transmission lines and passive circuits are now accessible for submillimetre frequency designs. Such micromachined circuits are also ideal conduits for active components, and with novel methods of matching, efficient high frequency systems can be constructed. One such circuit considered when initiating this research is the frequency multiplier. Multipliers are used as it is difficult to generate a local oscillator frequency high enough to mix with a high frequency target signal. Frequency multipliers typically utilise a nonlinear harmonic response to distort a lower frequency into a required harmonic multiple. The frequency spans of the two waveguides in this paper were chosen to coincide with an input and doubled output frequency range for such a multiplying circuit. Care was taken to design the waveguides using just five layers of SU-8 photo resist, so that the waveguides orientations would allow an input circuit of 150 GHz to connect to a future frequency doubler design, and the resultant 300 GHz frequency would utilise the second waveguide. Ninety degree E- plane or and H- plane bends were constructed to connect to test equipment, or potentially to other stages in a communication system.

## WR-3 Waveguide Design

The rectangular waveguide designed here is a standard WR-3 band waveguide with a cross-section size of  $a = 864 \mu\text{m}$  by  $b = 432 \mu\text{m}$ . The length of the waveguide is 15.95 mm to match previous waveguide circuits [1] and a novel bend is used to attach the waveguide to the measurement network analyser.

A device based on SU-8 pieces is easy to fabricate and is mechanically robust. It has a low insertion loss and good transmission coefficient for the specified operating frequency band. In this rectangular waveguide design, specifications for the transmission coefficient  $S_{21}$  are better than -20 dB for the whole WR-3 band. The WR-3 waveguide is built with 5 layers of SU-8 photoresist with each layer having a

thickness of 288  $\mu\text{m}$ . Three layers form the total thickness of 864  $\mu\text{m}$  for the WR-3 waveguide internal dimensions with additional two layers to design waveguide bends connecting the waveguide to the measurement apparatus as illustrated in Figure 1. The design of the waveguide bend is based on similar previous structure in [1] and it is modified and configured to meet the dimension requirements of WR-3 waveguide. The waveguide bend is specified to be an H-plane.

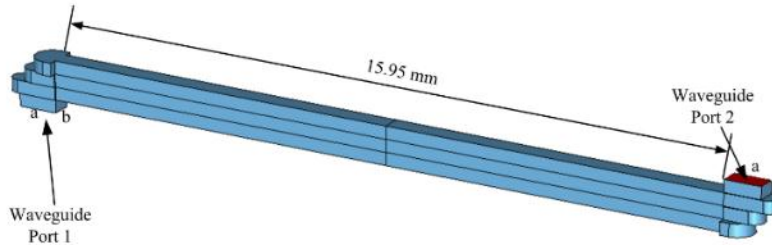


Figure 1: 3D EM model for the WR-3 waveguide with bends. Here the inside of the metal waveguide is shown in blue and the layers are clearly seen.

### WR-6 Waveguide Design

The 150 GHz waveguide dimensions are derived from the WR6 waveguide specification ( $a=1650 \mu\text{m}$ ,  $b=830 \mu\text{m}$ ), which covers the frequency range 110 GHz to 170 GHz. WR6 was chosen for its centre frequency of 150GHz, which would be useful in a 300 GHz communication system as part of the local oscillator multiplying circuit. However, because we are to construct the waveguide from layers of SU-8 photoresist which has a thickness of 288  $\mu\text{m}$  per layer, we are restricted to using a multiple of 288  $\mu\text{m}$  for one of its dimensions. The chosen implementation of the SU-8 photoresist layers is shown in figure 2, and we can see with just 5 layers that a close approximation to WR6 can be made, where only the  $b$  dimension differs in our solution, with an increase of 34  $\mu\text{m}$  (4%). A length of 15.95 mm was used.

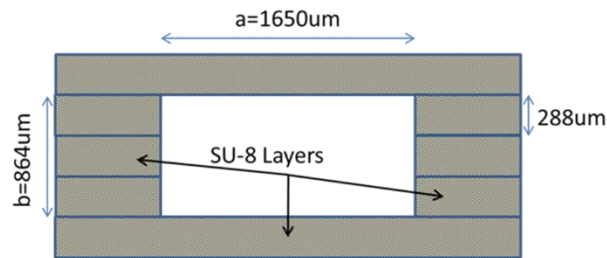


Figure 2: Structure and Dimensions of 150 GHz waveguide

The 150 GHz waveguide is to be constructed with 5 layers of SU-8 photoresist. Therefore the overall thickness of the device is  $5 \times 288 \mu\text{m} = 1440 \mu\text{m}$ . Two ninety degree E-plane bends are needed to allow the connection of test equipment. Figure 3 shows the configuration of the bends and the waveguide test ports perpendicular to the waveguide. There was also an additional complication in that only WR5 ( $a=1295.4 \mu\text{m}$ ,  $b=677.7 \mu\text{m}$ ) test heads were available for the Vector Network Analyser, so a conversion was required for this within the bend structure.

The bend was designed by constructing a simple parameterised staircase structure which widens slightly from the WR5 test head orifice to that shown in figure 2. A simple optimisation software routine was used to adjust each step to find the best solution.

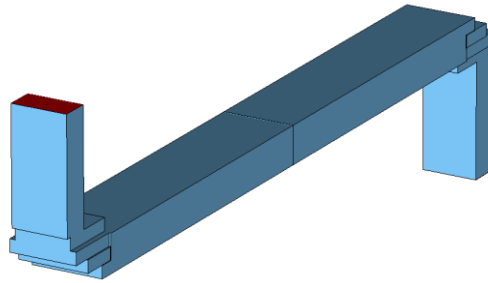


Figure 3: 3D Model of 150 GHz Waveguide and bends

**Fabrication**

Based on the CST waveguide bend model as shown in Figure 1, the layouts of the 5 SU-8 layers and their corresponding masks for micromachining photolithography are generated. There are five layers for the SU-8 waveguide and they are displayed in Figure 4. As the whole structure is symmetrical to the centre point, the Layer 1 and Layer 5 are identical to the Layer 2 and Layer 4.

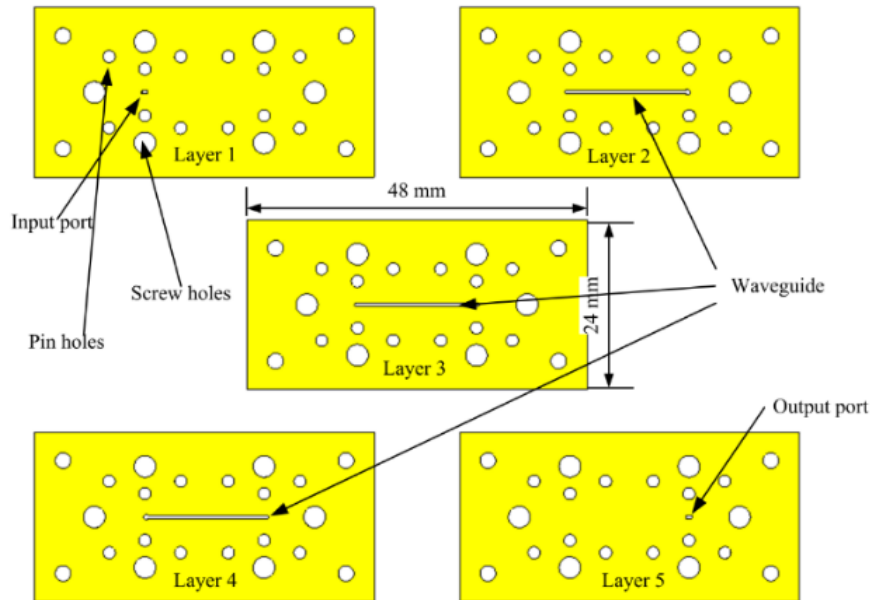


Figure 4: The SU-8 layers for the WR-3 waveguide.

Both the WR-3 and the WR-6 waveguides consists of 5 SU-8 layers, with each layer having a thickness of 288  $\mu\text{m}$ . The fabrication integrates the top and bottom two layers with a joined double layer fabrication technique, thus making three standalone SU-8 pieces instead of 5 individual pieces. The top and bottom joined pieces are of same 576  $\mu\text{m}$  thickness and the middle piece is 288  $\mu\text{m}$ . Thick SU-8 photoresist can be used as the structural material for constructing waveguides and is very cost effective, having a good fabrication repeatability and requires low facility investment in comparison with the precision CNC milling. All the procedures are performed in the in-house clean room facilities and the metallisation stage is completed in-house also. The fabrication process for the SU-8 pieces is detailed in [2].

Two waveguide circuits for WR-3 band and one for WR-6 band are fabricated respectively, and a photo of the WR-3 waveguide circuit is shown in Figure 5. The SU-8 waveguide device is fully metallised with silver for the surface of the SU-8 pieces. Each fabricated SU-8 pieces are assembled together with clamping brass plates reducing possible losses due to the air gaps. The main part of the device in Figure 5 is the device clamped by brass plates occupies a volume of 48 mm × 24 mm × 8 mm.

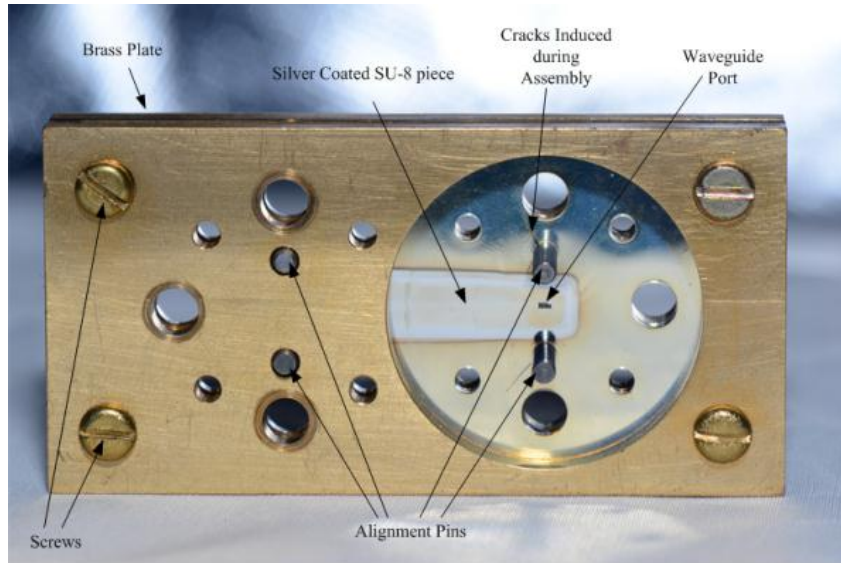


Figure 5: The photograph shows a fabricated and assembled device WR-3 waveguide.

### Measurements

Figure 6 shows the measurement configuration of the fabricated and assembled WR-3 band waveguide circuit carried out on the Agilent E8361A Vector Network Analyser with a WR-3 OML band extender T/R module at test port 1 and a receiving only T-module at port 2. Enhanced response calibrations are done before the measurements. Standard UG-387 waveguide flanges are used as the interfaces for the connection from WR-3 waveguide to the measurement ports. Screws and alignment pins are fastened to minimise the reflection, leakage and loss from the flanges.



Figure 6: A photograph shows the device WR-3 waveguide under test with the Network Analyser.

### WR3 Results

Two WR-3 band waveguide circuits are made in the in-house clean room, and both have been tested and are illustrated in Figure 7 for the insertion loss  $S_{21}$  and in Figure 8 for input return loss  $S_{11}$ . One waveguide has the measured insertion loss of 2 dB to 1 dB over the tested frequency bandwidth from 220 GHz to 325 GHz and the other waveguide has the insertion loss of 0.5 dB over the main frequencies. Both measurements include the effect of the bends. In terms of the return loss, one waveguide is tested to have at least 15 dB over the frequency band from 220 GHz to 310 GHz and best of 20 dB at 300 GHz while the other waveguide is tested to have average 10 dB over the whole bandwidth and has the best response of 20 dB at 230 GHz.

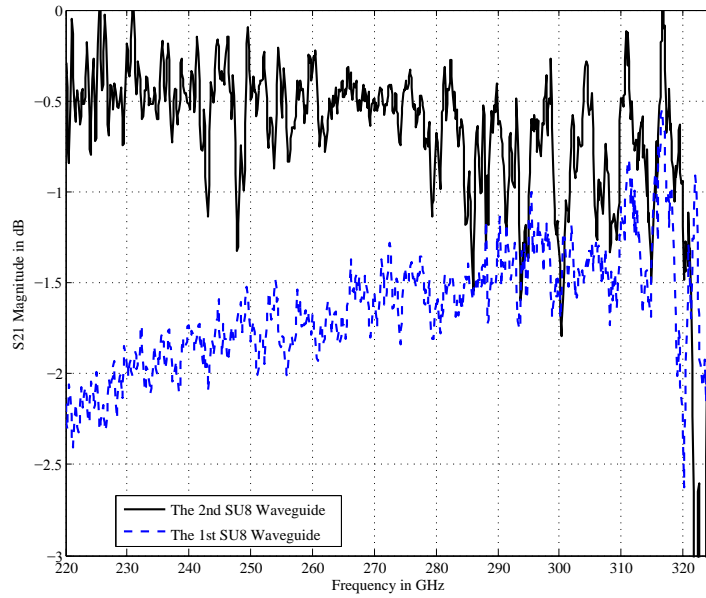


Figure 7: The measurement results for the two fabricated results in  $S_{21}$

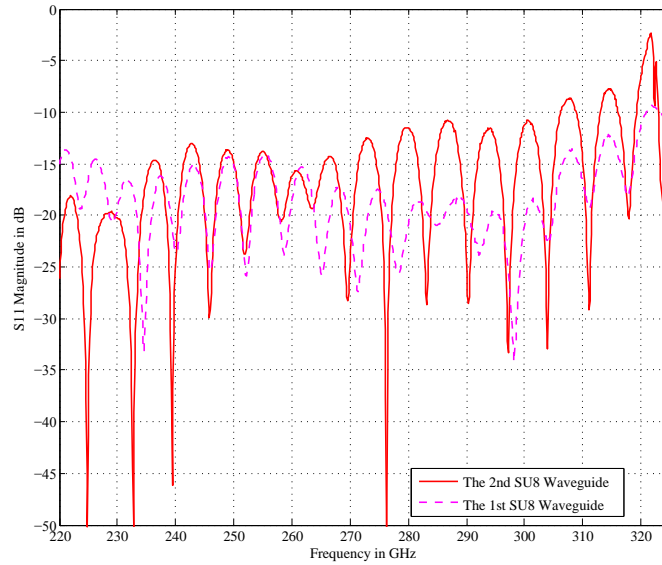


Figure 8: The measurement results for the two fabricated results in  $S_{11}$

### WR6 Results

The 150 GHz waveguide was tested using the Agilent E8361A Vector Network Analyser with a pair of OML WR-5 heads (T/R module at test port 1 and a receiving only T-module at port 2), covering the range from 140 GHz to 220 GHz. The designed range is from 120 GHz to 170 GHz, so we can only show measured results from 140 GHz upwards, as shown in figures 9 and 10. The loss per mm in shown in

figure 11.  $S_{11}$  follows the simulated results well with a return loss better than 12 dB across the measured band, and an average return loss of 24 dB. The  $S_{21}$  result shows that the losses are better than 0.034 dB/mm across the band, with an average loss of 0.011 dB/mm.

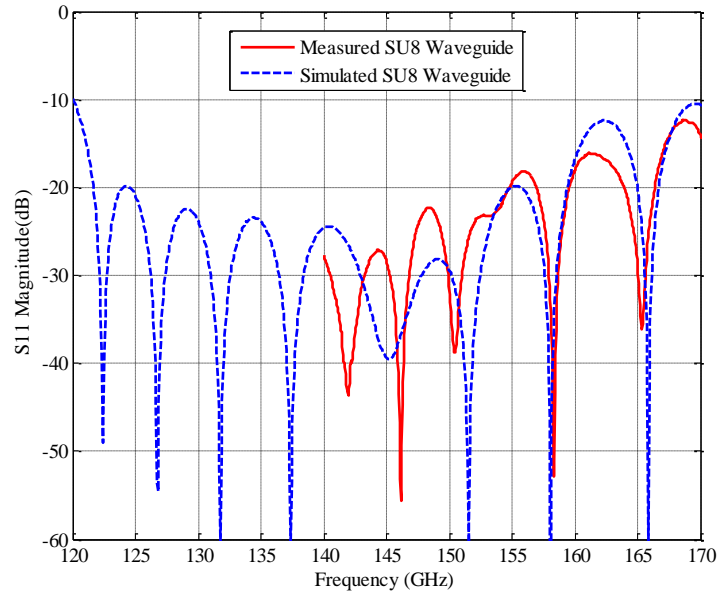


Figure 9:  $S_{11}$  Results of 150 GHz waveguide

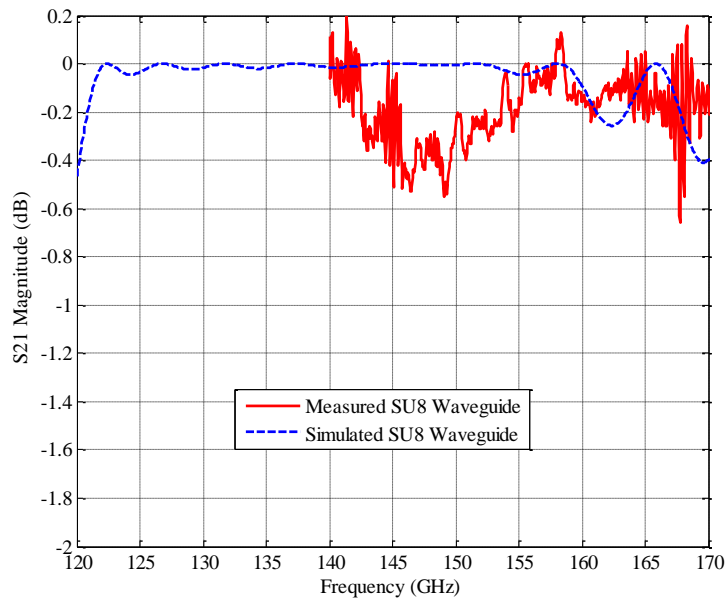


Figure 10:  $S_{21}$  Results of 150 GHz waveguide



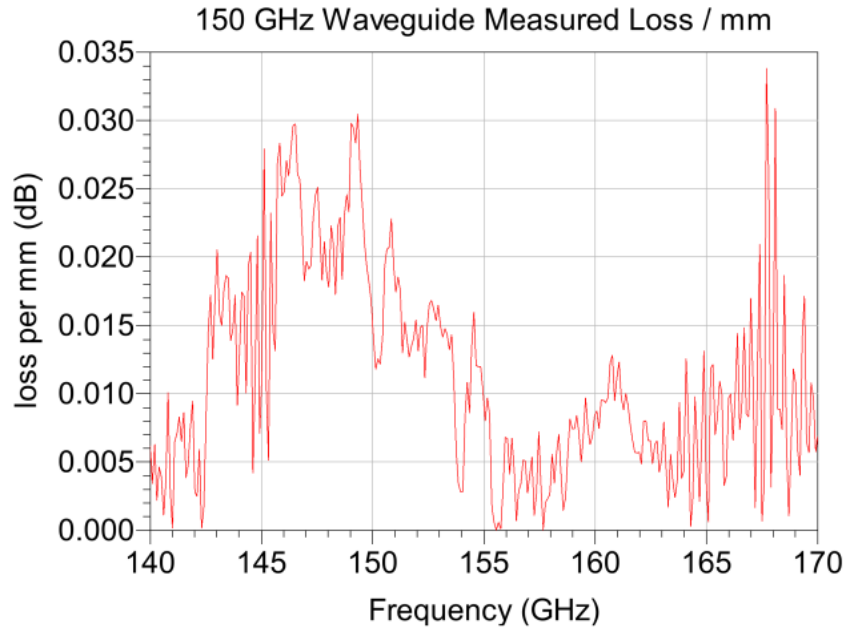


Figure 11: Insertion Loss per mm for 150 GHz waveguide

## Conclusion

We have shown it is possible to design and fabricate two fit for purpose waveguides from 5 layers of SU-8 photoresist to operate at the WR3 and WR6 frequency bands, and also have workable ninety degree bends to allow connection to test fixtures or other circuit stages. These would be ideal conduits for a future communication system or its sub circuits, such as a frequency multiplier.

## References

- [1] X. Shang, ML Ke, Y. Wang, and MJ Lancaster. Micromachined wr-3 waveguide filter with embedded bends. *Electronics Letters*, 47(9):545–547, 2011.
- [2] Yingtao Tian, Xiaobang Shang, and Michael J. Lancaster. Fabrication of multi-layered su8 structure for terahertz waveguide with ultralow transmission loss. *Journal of Micro/Nanolithography, MEMS, and MOEMS*, 13(1):013002–013002, 2014.10.1117/1.JMM.13.1.013002.