MICROMACHINED W-BAND RECTANGULAR WAVEGUIDE UTILISING SU-8

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ABSTRACT

As the operation frequency of microwave devices for example rectangular waveguide is increased, their physical size is reduced. This is due to the dependency of the size of some microwave devices to certain operating frequencies. Hence devices that operate in the millimeter-wave region are difficult to produce by conventional means. Micromachining therefore offers an alternative technology. This paper is a study on the design of microwave waveguides suitable for micromachining process. Novel structure and processes are introduced which allow accurate fabrication of low loss transmission lines. This new technique applies micro-fabrication processes to improve fabrication accuracy. The micromachined waveguide designed in this paper use a substrate called SU-8. SU-8 is a negative, epoxy-type photoresist based on EPON SU-8 epoxy resin. The paper also focuses on an improved design for the rectangular waveguide with coplanar waveguide (CPW) transition. In this paper, a W-band micromachined rectangular waveguide utilising SU-8 micromachining with CPW input and output ports has been designed. Simulated frequency responses exhibit insertion loss of 1.38 dB across 31% bandwidth for W-band frequency range and return loss better than –20 dB. The waveguide is estimated to have an insertion loss of 0.01 dB/mm at 90 GHz.

Keywords: *rectangular waveguide, micromachining, coplanar waveguide, SU-8, low loss transmission lines*

INTRODUCTION

There is an increasing demand and interest in a variety of applications for microwave filters. In the millimeter-wave region, distributed element microwave circuits always demand low loss transmission lines. As the design frequency gets higher, the circuit dimensions become smaller and shrinks inversely proportional to frequency. Due to their small size at microwave frequencies, it is difficult to machine the components precisely using conventional techniques. Micromachining therefore offers an alternative technology. Micromachining is a process of machining components using chemicals to achieve fine structures with great accuracy and is suitable for making devices at millimetre-wave frequencies.

Planar form of waveguides such as coplanar lines (CPW) have become one of the most widely used transmission lines in monolithic microwave integrated circuits (MMICs) due to the simplicity of fabrication and its ability to easily integrate series and shunt elements [1]-[3]. However, rectangular waveguides still play an important role, especially in very high frequency systems, where the loss of such waveguide is significantly less than that of popular planar transmission lines. A technique for the fabrication of micromachined rectangular waveguides using SU-8 photoresist has been reported in [4], [5]. These techniques however did not integrate any planar elements into the design.

Since CPW and rectangular waveguide together play an important role as microwave devices, effective transitions between the two are required in many applications. Finite ground coplanar line (FGC) or conductor-backed coplanar waveguide (CBCPW) is another form of CPW, where a ground plane is added below the substrate. FGC-to-waveguide transition has been reported in [6] but using silicon micromachining where the transition utilises a printed E-plane probe, inserted into the broad sidewall of a micromachined waveguide. The micromachined waveguide is fabricated in two halves, and the two halves are put together to form a complete waveguide block. This “snap-together” technique overcomes the problem of reduced-height waveguide where the height of a waveguide was determined by a limited thickness of the photoresist; reduced-height waveguide suffers from higher attenuation and mismatch loss. However, the transition structure presented in [6] required manual assembly of the probe and waveguide combination, which becomes more difficult as the size of the components shrink. Non-micromachined integrated transition for rectangular waveguide and CPW is reported in [7], where a substrate-integrated waveguide is introduced. The waveguide utilized arrays of vias to create sidewalls in a piece of substrate, thus exhibit radiation loss between the vias. However, effective rectangular waveguide to CPW transition has bee shown.

This paper will introduce a new configuration of low loss transmission line (rectangular waveguide) that is compatible for integration with planar waveguide structure, in this case CPW. The CPW to rectangular waveguide transition is built on the same substrate, giving both advantages of having planar and non-planar form. The transition design is simple enough and requires only minimum mechanical assembly during the micromachining process. SU-8 will be utilized in the design because it allows structures with high aspect ratios to be fabricated with near-vertical sidewalls and cheaper compared to LIGA. LIGA is a German acronym consisting of the letters LI (RoentgenLItographie, meaning X-ray lithography), G (Galvanik, meaning electrodeposition) and A (Abformung, meaning molding process) [8]. The utilization of LIGA allows high aspect ratio structures to be made with submicron resolution, however it is expensive and limited by the need for access to an X-ray synchrotron facility.

SU-8 MICROMACHINING

The micromachined waveguide designed in this paper use a substrate called SU-8. SU-8 is a negative, epoxy-type photoresist based on EPON SU-8 epoxy resin.Originally, SU-8 was developed for the microelectronics industry. The purpose is to provide a high-resolution negative imaging resist for use in the fabrication of advanced semiconductor devices. However, the resist exhibits several attributes, which make it suitable for micromachining applications.

SU-8 is transparent and has a low UV absorption property, enabling a uniform exposure of the photoresist to a large depth, compared with other thick photoresists. Ideally, vertical sidewall profile could be obtained if the UV light went through the entire layer without losses. This makes it suitable for the fabrication of rectangular waveguide. In MEMS applications, polysilicon thin films have been widely employed as structure materials. However, polysilicon thin films cannot be used for high aspect ratio structures because they are vapour deposited, so by nature they are only a few microns thick. High aspect ratio structures are often required in many applications including MEMS.

LIGA is an ideal technique to manufacture structures with high aspect ratio. In LIGA process, a special type of photolithography using X-rays (X-ray lithography) is used to produce patterns in very thick layers of photoresist. LIGA has many advantages, one of them being achievable submicron level resolution. However, the need for X-ray source (synchrotron radiation) and special mask technology make LIGA expensive. The negative photoresist EPON SU-8 with UV illumination process offers an alternative to LIGA, due to its low-cost processing since it is compatible with conventional photolithography. The photosensitivity of SU-8 is 300-400 nm [9], which is in a region where conventional photolithography equipment is accessible. High transparency of SU-8 in the near UV allows structures with high aspect ratios to be fabricated with near-vertical sidewalls.

SU-8 micromachining on the other hand has achieved a height of up to 1 mm in a single spin [9] and aspect ratio of near 20 has been reported [10]. This process, however has lower resolution (microns to tens of microns) compared with LIGA, but still has great potential for low-cost applications that does not require submicron resolution. Due to its relatively high thermal stability, SU-8 is well suited for acting as a mould for electroplating [11]. SU-8 microstructures have the advantage of high precision, good mechanical property when compared with other resists, and much lower fabrication costs than LIGA and dry reactive ion etching (DRIE) technology.

Therefore, there is the need to design micromachined waveguide using low-cost fabrication techniques but with great accuracy. Thus, micromachining using SU-8 is an interest in this paper due to its cheaper process compared to LIGA, and its adequate precision for many microwave devices applications.

WAVEGUIDE STRUCTURE

Although rectangular waveguides are characterised by excellent insertion loss, they cannot be easily integrated with microwave or millimetre-wave planar circuits. Therefore, a practical transition between rectangular waveguide and planar components such as coplanar waveguide (CPW) is required. A transition from the waveguide to CPW has input and output ports made on the same substrate, thus this technique provides a useful technology for low cost microwave applications particularly to design MMICs components. The rectangular waveguide with back-to-back transition to CPW line is designed to operate within W-band (75 – 110 GHz) frequency range. The transition is similar to the reported CPW-to-rectangular waveguide transition in [7].

A hollow rectangular waveguide is formed by using three pieces of SU-8 bonded together, creating a multilayer structure as shown in Figure 1. The middle layer consists of the hollow rectangular waveguide with coplanar waveguide input and ouput ports. The top and bottom layers serve as lids to create an enclosure to the rectangular waveguide. Figure 1 illustrates the assembly of each of the layers to create the hollow rectangular waveguide. In Figure 1, SU-8 is made transparent. The upper SU-8 layer (Piece 1) is metallized on the lower side to serve as the top lid of the waveguide and contains part of the CPW to rectangular waveguide transition. The middle SU-8 layer (Piece 2) consists of the rectangular waveguide itself with CPWs patterned directly on top surface.

The inner side of the substrate is deposited with metal to create the sidewalls for the rectangular waveguide. The top and bottom surface of the middle layer are all metallized. The lower SU-8 layer (Piece 3) is just a piece of SU-8 with metal deposited the top side. These three pieces are bonded together to create a hollow rectangular waveguide with CPWs at both ends.

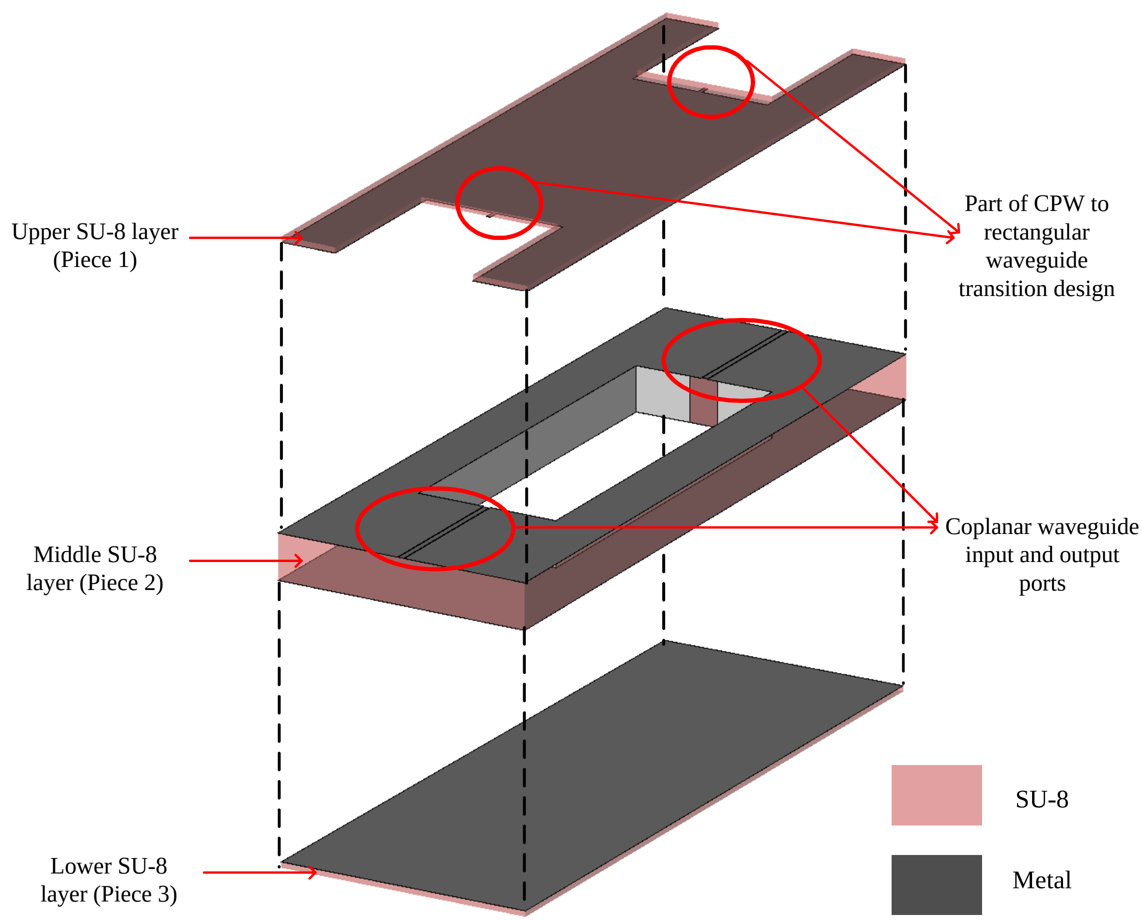

Figure 1: Assembly of the three pieces of SU-8 to create micromachined waveguide with coplanar waveguide input and output ports

Note that all the three pieces have the same length including the upper SU-8 layer (Piece 1) even though it can be made shorter just to cover the rectangular waveguide. However, it is made to have the same length as the

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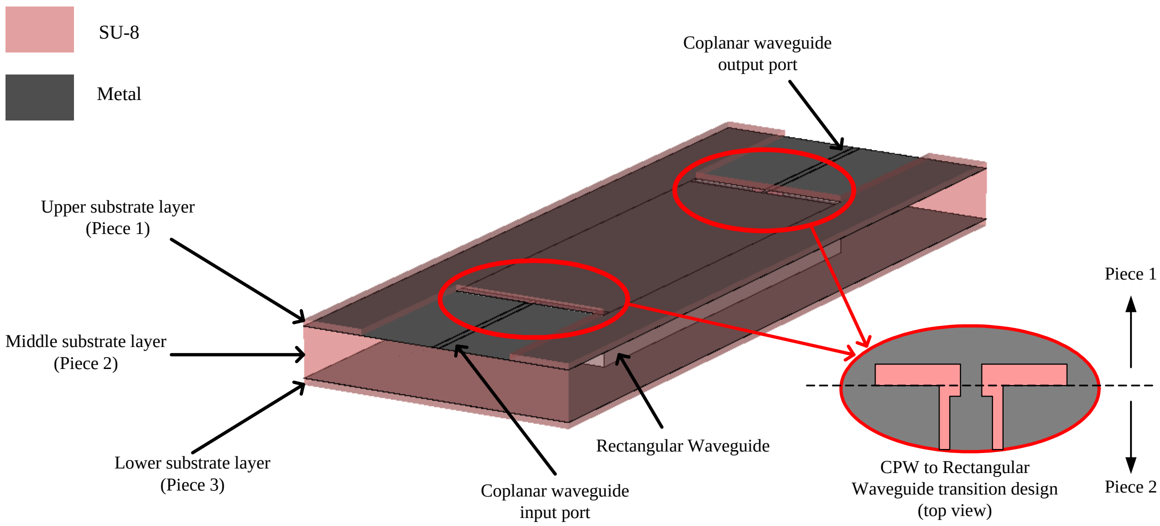
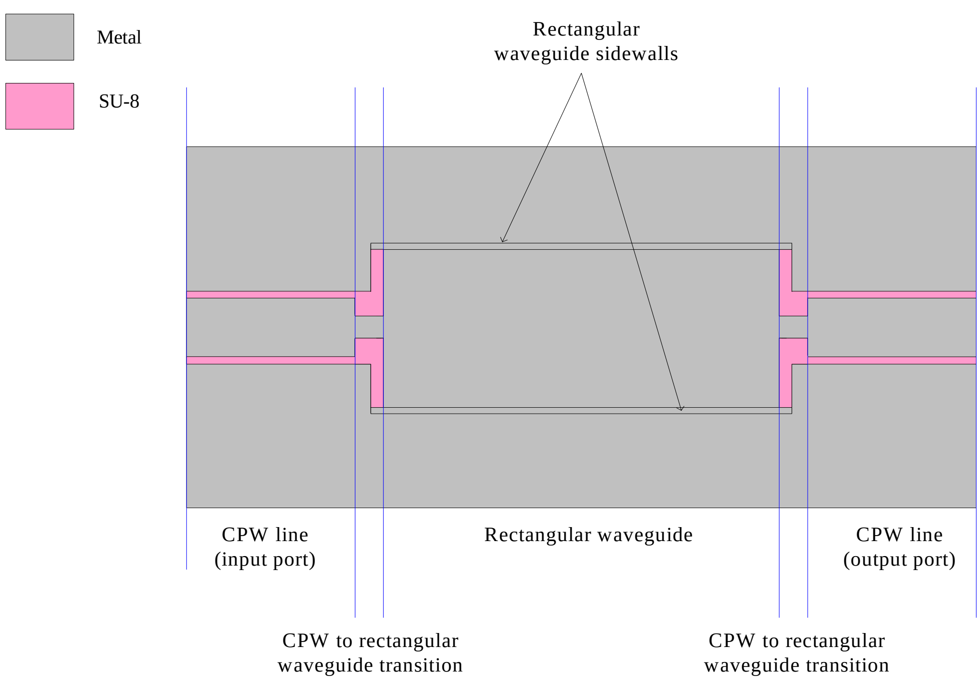
other two pieces so that the three pieces can be easily alligned for bonding. The windows at each end of Piece 1 are made to accommodate the CPW lines, allowing probes to be connected at the input and output ports for measurement. Figure 2 (a) shows the overall waveguide structure where SU-8 is also made transparent so that the metal layers on the backside of the substrate layers can be seen. Figure 2 (b) shows the top view of the structure regardless of the SU-8 layers.



(a)

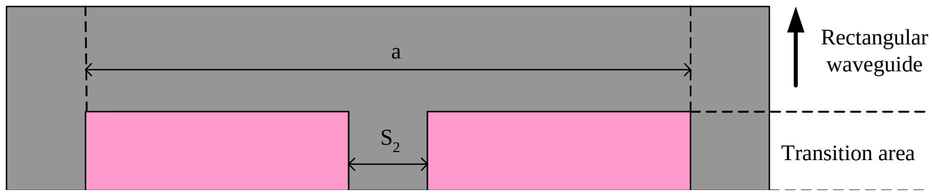


(b)

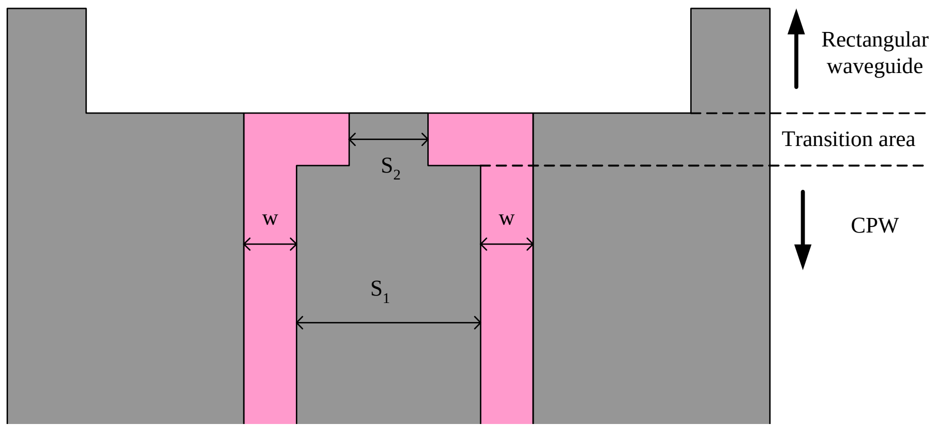
Figure 2: Micromachined rectangular waveguide with CPW input and output ports (a) Overview of the multilayer structure (inset picture: CPW to rectangular waveguide transition design) (b) Top view regardless of any SU-8 layers

CPW TO RECTANGULAR WAVEGUIDE TRANSITION DESIGN

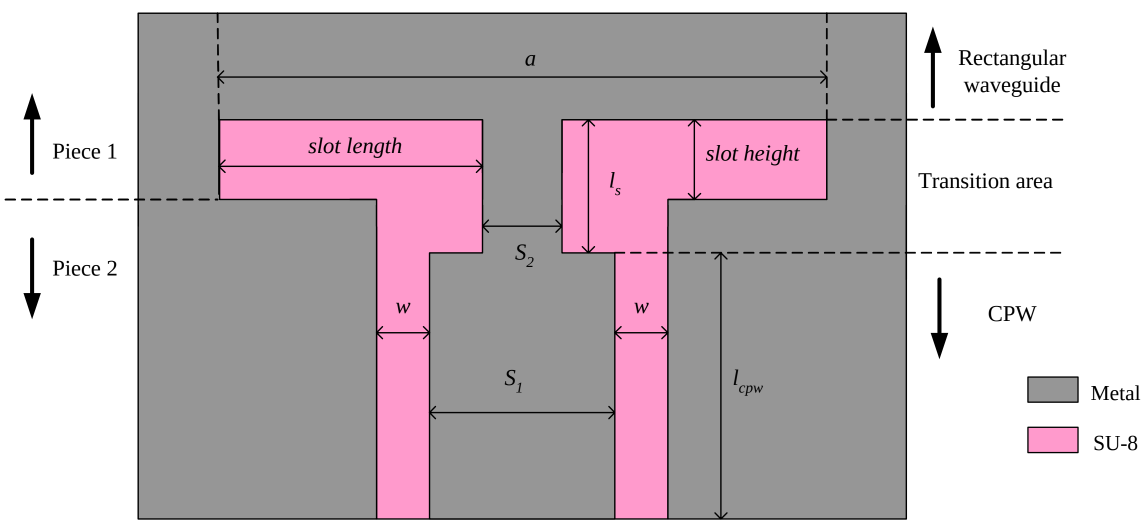
The transition structure is made out of the combination of the upper and middle layers of SU-8 (Piece 1 and Piece 2). Figure 3 shows the CPW to rectangular waveguide transition design, patterned on both pieces.



(a) Piece 1: Part of transition pattern on the backside of the upper SU-8 layer



(b) Piece 2: Part of transition pattern on the topside of the middle SU-8 layer



(c) Transition structure when Piece 1 and Piece 2 are bonded together

Figure 3: Transition from CPW to rectangular waveguide for the W-band micromachined rectangular waveguide

The transition design for the micromachined W-band rectangular waveguide in Figure 3 (c) is made similar to the transition structure for the substrate-integrated waveguide in [7], which consists of the slots of coplanar waveguide being bent at an angle of 90^o. Each slot that has been bent acts as a short circuit where the electric field is minimum at the shorted end, therefore the electric field is maximised at the discontinuity of the centre strip conductor. The width of the signal line of the CPW is smaller at the transition area. Thus, a stub, l_s is created for the purpose of impedance matching and obtaining return loss better than –20 dB.

The CPW line has a characteristic impedance of 50Ω with S_1 and w, the width of the centre strip conductor and slots respectively. The length of the stub at the transition area is denoted by l_s and its width is S_2. The rectangular waveguide has a standard width *a* of a hollow rectangular waveguide for W-band (WG27), a height of 800 μm and a length of 7000 μm. The dimensions of the transition structure based on Figure 3 are shown in Table 1.

Table 1: Dimensions of transition for the W-band micromachined CPW-to-rectangular waveguide

Parameter	**Dimension (μm)**
Centre conductor of CPW, S_1	100
Slot of CPW, *w*	13
Length of CPW, l_{cpw}	2670
Stub width, S_2	80
Width of bent slot, *slot height*	150
Length of bent slot, *slot length*	1230
Length of stub, l_s	180
Width of waveguide, *a*	2540

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RESULTS AND DISCUSSION

The simulated frequency responses for the W-band micromachined rectangular waveguide are shown in Figure: 4.

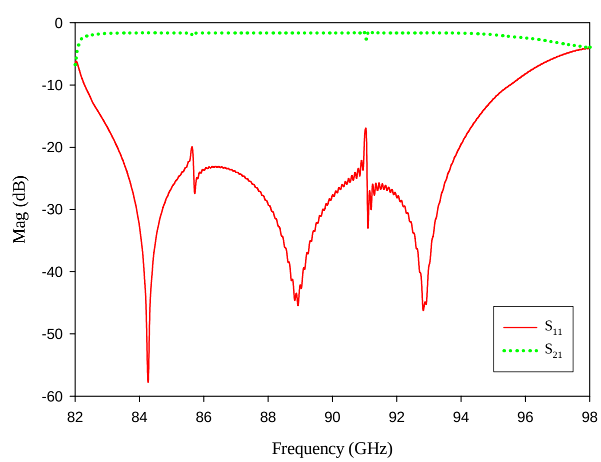

Figure 4: Simulated frequency responses for the W-band micromachined rectangular waveguide with CPW input and output ports

The simulated frequency responses in Figure 4 denote that the micromachined rectangular waveguide in Figure 2 operates well between 83 GHz to 94 GHz that is 31% bandwidth for the W-band frequency range. S_{11} better than –20 dB is obtained for the bandwidth and an insertion loss of 1.38 dB across the band. The waveguide is estimated to have an insertion loss of 0.01 dB/mm at 90 GHz. The simulated responses include the dielectric and conductor loss, where the loss tangent for SU-8 of 0.02 is used and conductivity of gold is assumed to be 4.08 x 10^7 S/m. The permittivity of SU-8, $\varepsilon_r = 3$ is used in the simulation. The two odd peaks at 85.5 GHz and 91 GHz in the responses are due to tight coupling of the transition to the waveguide.

FABRICATION PROCESS

Figure 5 shows the summarised steps involved in the fabrication process that can be used to make the W-band rectangular waveguide. For simplicity, the process is only for the cross section of the rectangular waveguide. As shown in Figure 5, bulk micromachining can be utilised with SU-8 to fabricate the rectangular waveguide. With SU-8, tall structures such as the rectangular waveguide can be made with accuracy and precision.

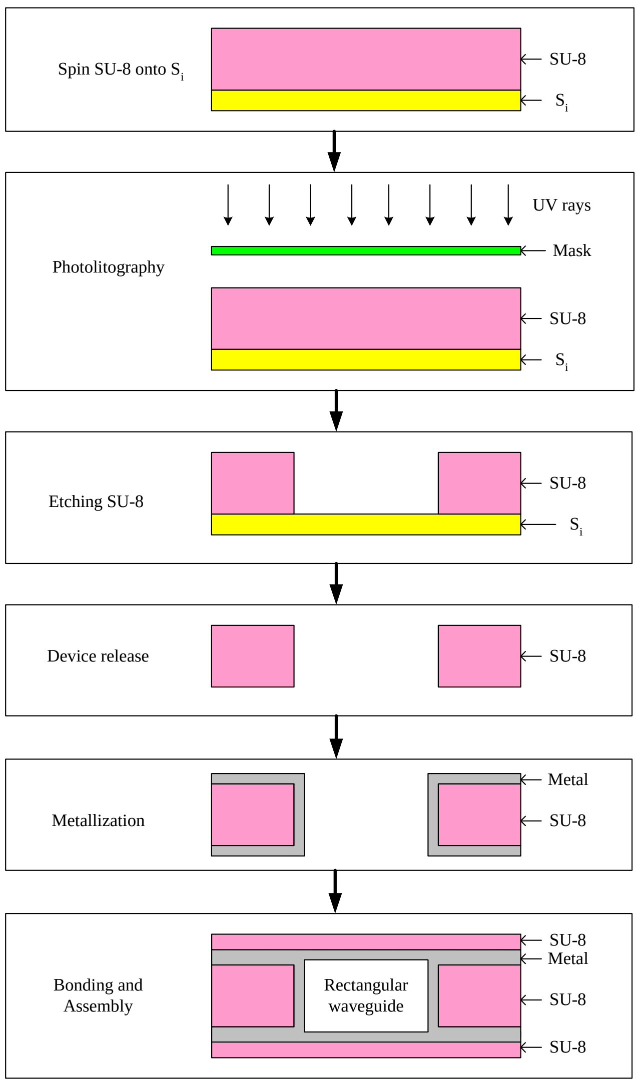

Figure 5:Summary of micromachining fabrication process for the rectangular waveguide (at the cross section)

CONCLUSION

The advantages and disadvantages of micro fabrication technologies and the aim to find a cheap and easy micromachining process have inspired the use of SU-8 in the design of W-band rectangular waveguide. The design of the micromachined rectangular waveguide using SU-8 processing techniques is succesful for a 31% bandwidth in the W-band frequency range. Further work will be carried out fabricate and measure the micromachining waveguide. The application of the waveguide structure is almost endless, one of them is microwave filter for MMIC. The structure of the waveguide, having both the advantages of planar and non-planar form has produced a low loss design with simple fabrication process, but utilising an interesting negative photoresists, SU-8.

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