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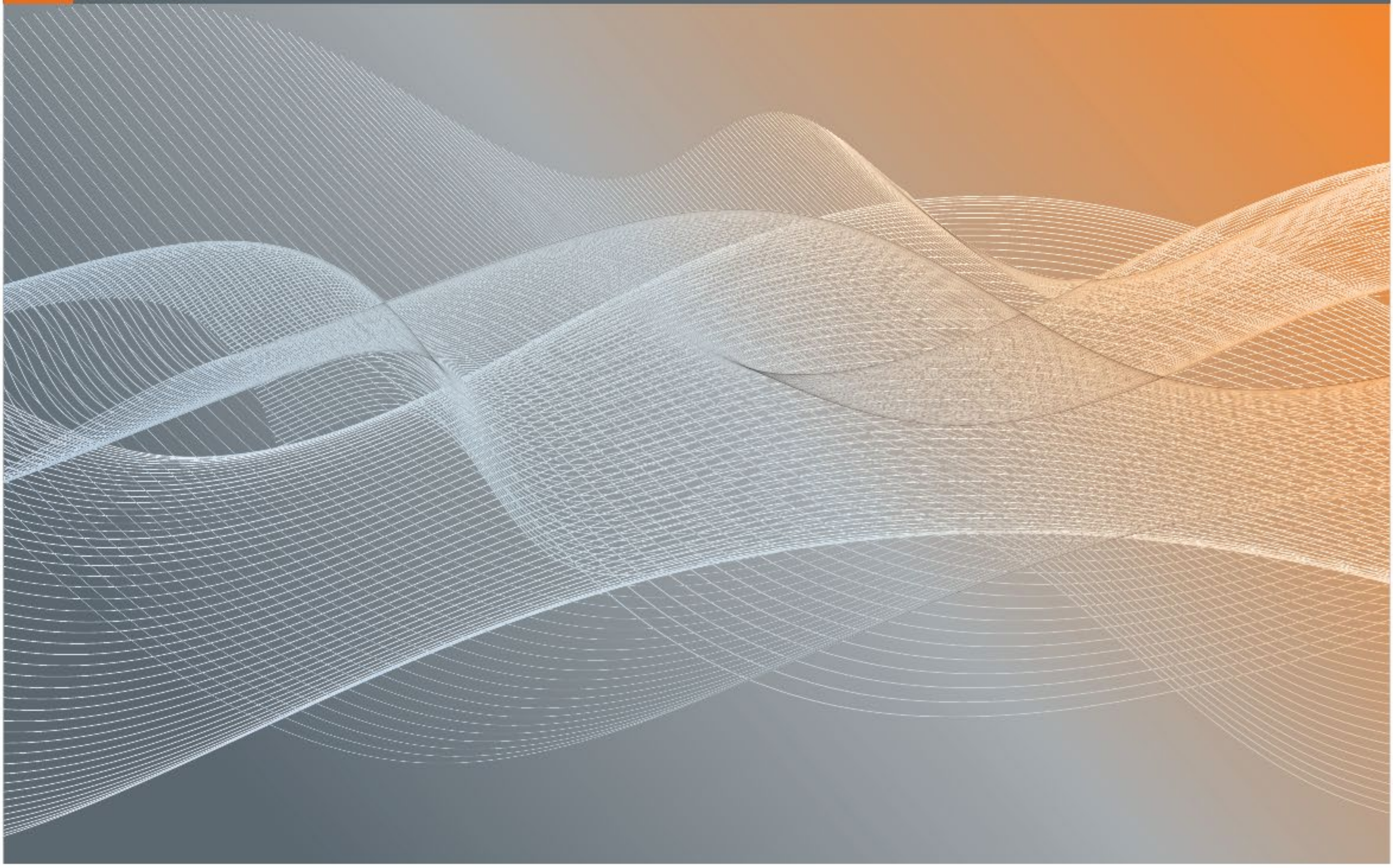
# Ultra-wideband 6 to 12 GHz Band-pass Filter using Lintek Additive Metal Processing



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# EXECUTIVE SUMMARY

The Radio Frequency Sensing and Shaping (RFSS) Science Technology Capability (STC) aims to identify and conduct research in future electronic warfare (EW) systems that can process and exploit the electromagnetic spectrum to allow the user to gain an advantage over adversaries. To extend the frequency coverage of these systems, high performance analogue band-pass filters are often employed that can separate multiple bands of signals, prior to digitisation at very high sampling rates.

This Technical Report summarises the design and testing of an ultra-wideband 6 to 12 GHz band-pass filter that has been manufactured by a precision additive metal process at Lintek in Queanbeyan, Australia. The superior agreement between filter measurements and simulation showcases an effective capability in the Defence Science and Technology Group for developing custom high precision filters on printed circuit board (PCB) technology.

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# CONTENTS

# GLOSSARY

| | |
|---|---|
| COTS | Commercial off-the-shelf |
| Cu | Copper |
| EM | Electromagnetic |
| EW | Electronic warfare |
| MSTC | Major Science Technology Capability |
| RF | Radio frequency |
| RFSS | Radio Frequency Sensing and Shaping |
| STC | Science Technology Capability |
| UV | Ultraviolet |

# 1. INTRODUCTION

The 6 to 12 GHz band-pass filter presented in this Technical Report was developed for the Wideband Spectrum Shaping Discipline, which conducts research to counter next generation threats through novel radio frequency (RF) and digital spectrum shaping techniques. To enable multiple-bands of signals to be processed simultaneously, an anti-aliasing analogue band-pass filter is needed to remove adjacent bands before digitisation.

Commercial-off-the-shelf (COTS) microwave band-pass filters can be used when their performance, delivery time(s) and costs are acceptable to the project. However, when COTS solutions do not meet the project requirements, the microwave band-pass filter may need to be developed ‘in-house’. This is a viable option when: 1) microwave designers are available that have the required simulation tools, and 2), a suitable high-performance manufacturing process is available.

A significant challenge presented to designers is predicting and achieving very close simulated-versus-measured results. If specifications are not achieved, a design re-spin may be needed which increases costs and can delay the project. A mitigation approach often applied in COTS waveguide filters is to provide some tuneability post-manufacturing with mechanical screws on each resonator. This increases the probability of success but introduces additional manufacturing costs, physical constraints, and required time to ‘tune’ the filter, which is often a laborious manual process. What is desired is a high-precision design and manufacturing technique for ‘tuneless’ microwave filters on planar circuit boards that can potentially achieve first-pass design success.

This Technical Report describes the design process, circuit board technology, and measured results for an ultra-wideband band-pass filter using an Australian-based precision manufacturing capability.

# 2. TECHNOLOGY AND MANUFACTURING

Lintek based in Queanbeyan Australia specialise in producing microwave and high frequency printed circuit boards using innovative technology to deliver unrivalled accuracy [1]. The patented high vacuum deposition process has been developed and refined since 1986, and can produce boards with highly accurate features and predictable impedance characteristics. Figure 1 highlights the cross-section (i.e. profile) of a *typical* metal trace and *Lintek* metal trace on a printed circuit board.

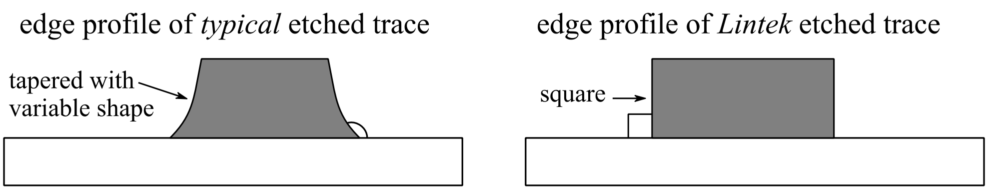


Figure 1 Profile of traces that can be produced when manufacturing printed circuit boards.

Typical etched traces (shown on the left) can have significant shape variability due to chemical etching of thick copper. On the contrary, by eliminating the need to etch thick copper, Lintek's manufacturing process produces square side walls (shown on the right). Square side-walls are very desirable in RF and microwave circuit manufacturing because they more closely represent what has been designed and simulated in typical design flows. In particular, the performance of band-pass filters is reliant on highly predictable edge profiles for closely-spaced lines.

## 2.1. Additive metal process

Lintek have developed a unique additive metal process to manufacture their circuit boards. They remove all of the existing metal to expose the 'core' circuit board material and then re-start the metallisation process again from the beginning. A patented sputtering technique is used to create a very thin (2 μm) 'seed' layer of copper over the whole board surface. Figure 2 illustrates steps 1 to 4 to create the seed layer. Via holes are mechanically (or laser) drilled through the board before the seed layer is applied. This ensures that the inside surface of the via holes are also coated in the deposition process.

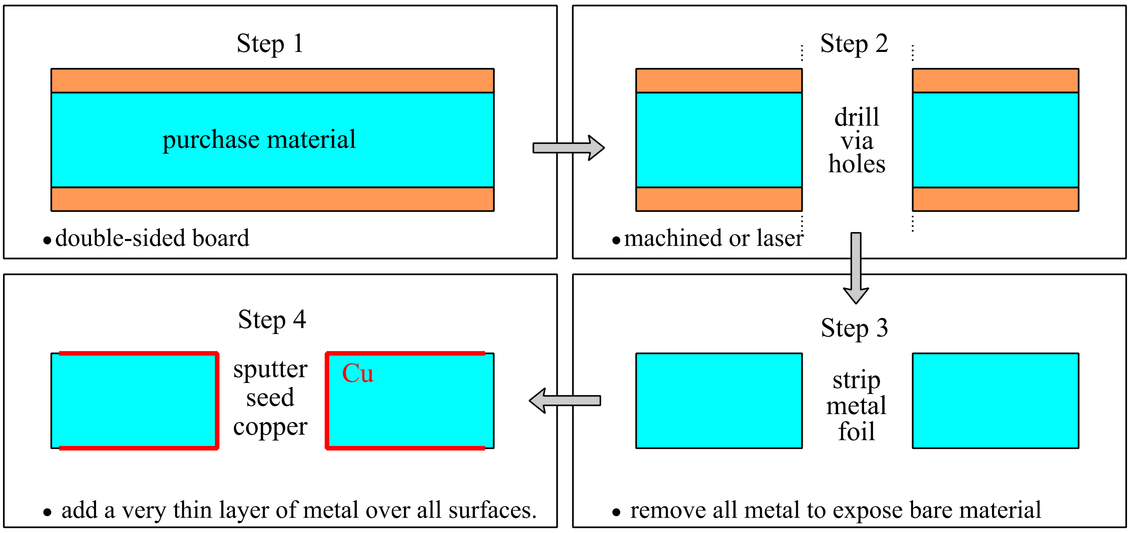


Figure 2 Steps 1 to 4 for the Lintek PCB manufacturing sequence for additive metal processing.

The next series of processing steps is to create a mask pattern on the surface of the board. After copper (Cu) metallisation the panel is laminated with an ultraviolet (UV) curable polymer film known as plate resist. A precision photo tool film is plotted and scaled to align with the panel. The aligned image is transferred onto the laminated panel using a collimated UV light source. The panel is then developed through an inline spray system to create a negative image on the panel surface. Figure 3 summarises the processing sequence steps 5 to 8, to create the mask pattern for the board.

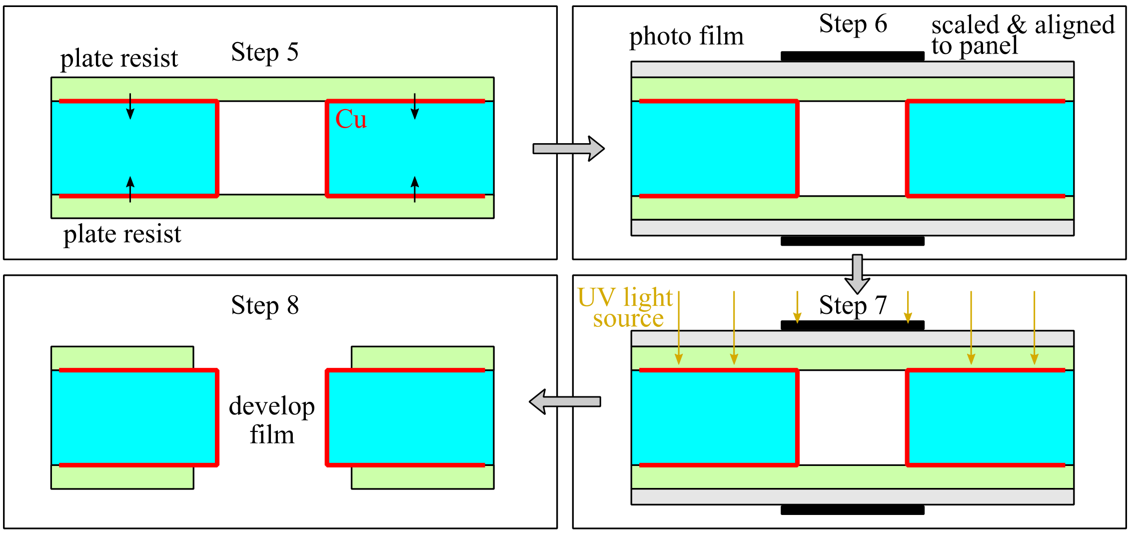


Figure 3 Steps 5 to 8 for the Lintek PCB manufacturing sequence for additive metal processing.

The final sequence of steps is to electroplate thick metal (typically 35 µm) into the regions without the negative film. The seed layer produced earlier at step 4 provides an important role in allowing current to route through all of the metal surfaces for the electroplating process. After thick Cu metal has been electroplated, other thin metal finishes (e.g. nickel) can be applied if required. The negative film is then removed from the board. The final step is a 'micro-etch' to remove the initial seed metal. This does not significantly impact the additive metal features, which maintains the desired near perfect square edge metal profiles. Figure 4 shows the manufacturing steps 9 to 12 to create the electroplated thick metal and Table 1 summarises some of the key processing dimensions and tolerances.

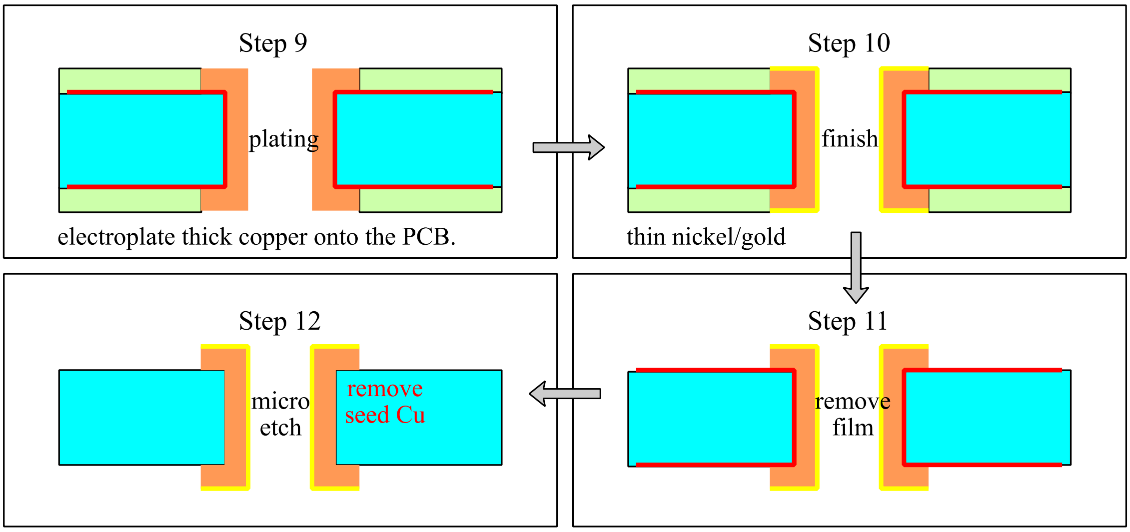


Figure 4 Steps 9 to 12 for the Lintek PCB manufacturing sequence for additive metal processing.

Table 1 Key processing specifications of Lintek additive metal processing.

| Specification | Value |
|---:|---:|
| etch factor | 0 µm (square profiles) |
| minimum trace width | 50 µm |
| minimum trace spacing | 50 µm |
| standard tolerance on edges | ± 6 µm |
| special tolerance on edges | ± 4 µm |

# 3. DESIGN AND ASSEMBLY

## 3.1. Filter design

The material selected to manufacture the filter was RT Duriod 5880 [2] from Rogers corporation. Critical RF parameters that influence the design are shown in Table 2.

Table 2 RT Duriod 5880 RF design parameters.

| Specification | Value |
|---:|---:|
| $\varepsilon_r$ (dielectric constant) | 2.2 |
| tan δ (loss tangent) | 0.0009 |
| h (board thickness) | 20 thou (508 μm) |

### 3.1.1. Structure and key parameters

The parallel coupled topology proposed by Cohn [3] is one of the most commonly used microwave filters. To achieve a high channel selectivity, a 13-section filter with symmetrically arranged parameters was chosen which is shown in Figure 5. The key parameters of the design are width, length and spacing of each coupled-line section.

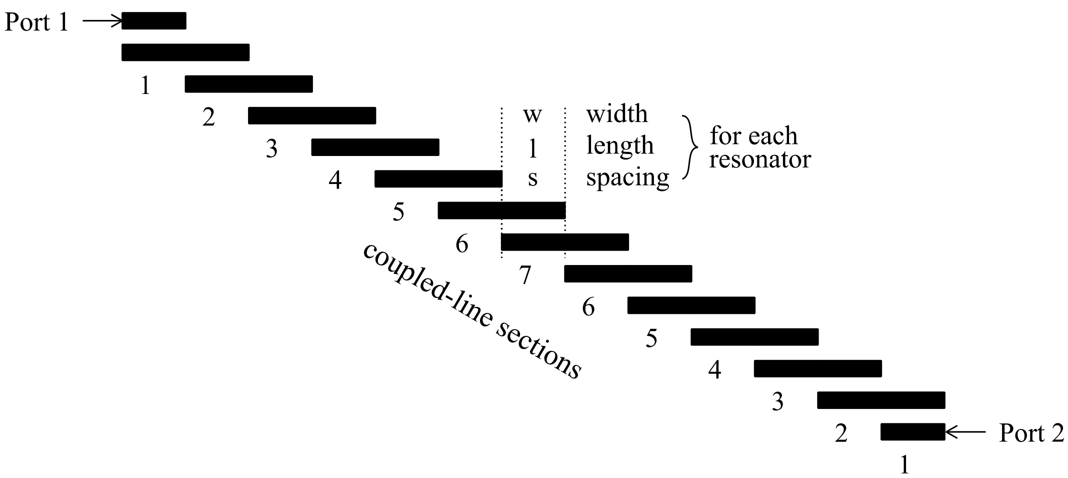


Figure 5 Structure and parameters for the 13th order coupled-line band-pass filter

### 3.1.2. Design method

Several methods are available to design microwave filters. They can be established by synthesis using normalisation prototype tables [4] or automated wizards such as iFilter [5]. In this work, the filter was designed by using direct numerical optimisation in the software AWR Microwave Office [6].

### 3.1.2.1. Closed form models

The first design iteration of the filter was performed using closed-form models. Figure 6 shows the built-in microstrip coupled line model (MCLIN) [7] that was used to construct the complete 13-section filter.

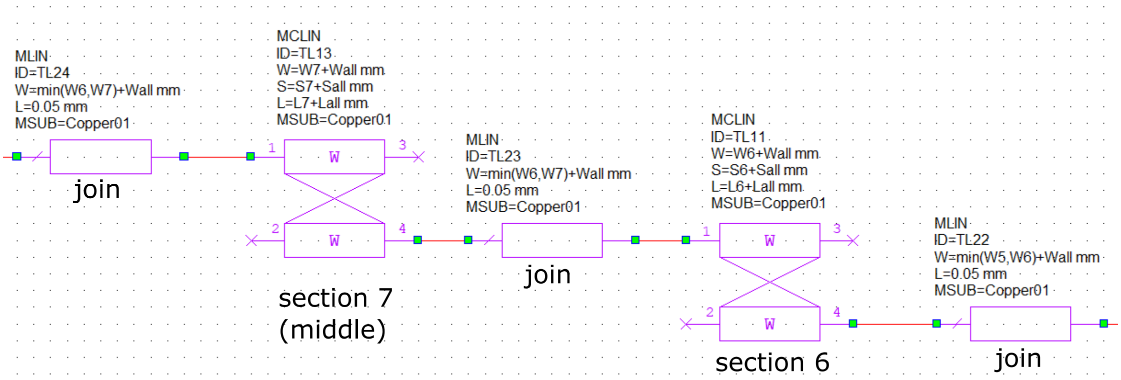


Figure 6 Zoomed view of the 6th and 7th coupled-line section. The MCLIN component shown here was stagger-cascaded 13 times to form the complete filter.

Common parameters (Wall, Sall, Lall) were defined for all lines and fine-tuning parameters (W, S, L) were defined for individual lines. There were 42 parameters that need to be chosen. To reduce the design burden, the spacing between all the lines was fixed to 75 µm. Only the width and length of the coupled lines was varied in optimisation to complete the design. A significant benefit using closed-form models in the initial design is very fast simulation time (< 0.1 sec), which benefits the quasi-random optimisation approach. Several thousands of iterations (n = 1000+) were run to find an initial set of best design parameters. The optimisation metric chosen was S11 < -20 dB across the band 6 to 12 GHz.

### 3.1.2.2. Electromagnetic simulation

The 3D-planar electromagnetic (EM) simulation tool Axiem was used to conduct the second iteration of the design as shown in Figure 7. All EM simulations conducted in this report apply manufacturer supplied EM data ($\varepsilon_r$, $\tan\delta$). No attempt was made to tune these EM parameters to artificially improve the report outcome. A benefit of EM simulation over closed-form modelling is the ability to predict inter-section coupling across the entire filter structure. A disadvantage is longer simulation time (~4 minutes for each simulation of the proposed filter).

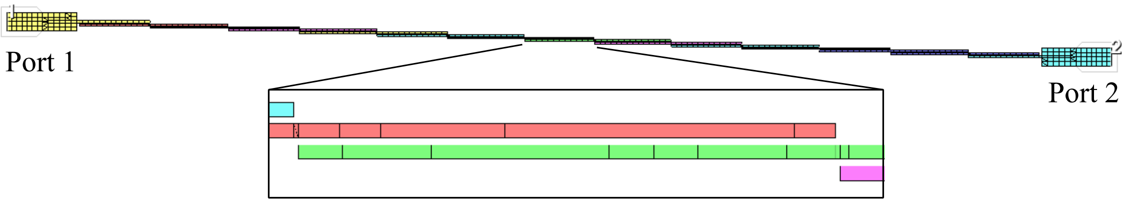


Figure 7 EM simulation of the complete filter showing an expanded view of one of the coupled line sections

Final design parameters for the filter are shown in Table 3.

Table 3 6 to 12 GHz band-pass filter design parameters. Dimensions are in mm.

| Coupled line | Width (W) | Length (L) | Spacing (S) |
|---|---|---|---|
| 1 | 0.194 | 6.09 | 0.075 |
| 2 | 0.15 | 6.685 | 0.075 |
| 3 | 0.15 | 6.12 | 0.075 |
| 4 | 0.156 | 6.65 | 0.075 |
| 5 | 0.154 | 6.06 | 0.075 |
| 6 | 0.154 | 6.58 | 0.075 |
| 7 | 0.15 | 6.01 | 0.075 |

## 3.2. Connector transition design

Although a microwave probe-station would provide unrivalled accuracy in measurement of filters [8], RF connectors were required for the filter to interface with existing customer experimental hardware using RF cables. To simplify assembly procedures, a solderless press mount connector from SV Microwave SF1521-60107 [9] was chosen that has rated performance to 40 GHz; the maximum operating frequency of the filter is nominally 20 GHz, so this connector was deemed sufficient to characterise the filter accurately assuming a suitable de-embedding calibration procedure was applied.

### 3.2.1. Structure

Figure 8 illustrates a 3D model of the connector which forms a coaxial to micro-strip transition. The centre-pin of the connector (shown in red) presses down onto a coplanar waveguide line. There is a critical ground return-path that is formed by the body of the connector (shown in blue) pressing down onto an array of vias. Progressive tapering of the ground plane away from the micro-strip line completes the transition.

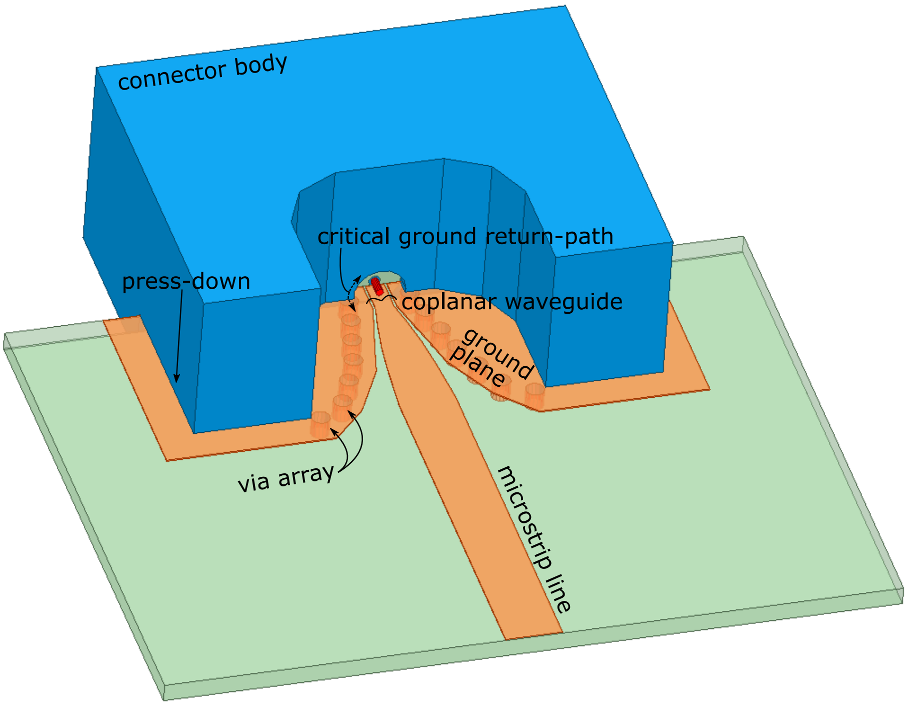


Figure 8 Connector to circuit board structure image from 3D Electromagnetic simulation

### 3.2.2. Design method

A fully-parameterised 3D model was constructed in Ansys' High Frequency Structure Simulator (HFSS) [10]. In addition, smaller portions (e.g. micro-strip line, coplanar waveguide line, and coaxial feed) were modelled separately to allow tuning of critical circuit parameters before the whole structure was simulated together.

### 3.2.3. Simulation results

Figure 9 shows the simulated performance of the connector transition. The impedance match ($S_{11}$ and $S_{22}$) is lower than -17 dB and the insertion loss ($|S_{21}|$) is less than 1.0 dB from DC to 40 GHz. In the critical frequency band of 6 to 12 GHz, the impedance match is lower than -27 dB, which is good enough to ensure that the filter can be characterised sufficiently-well if the customer does not apply the recommended custom calibration procedure.

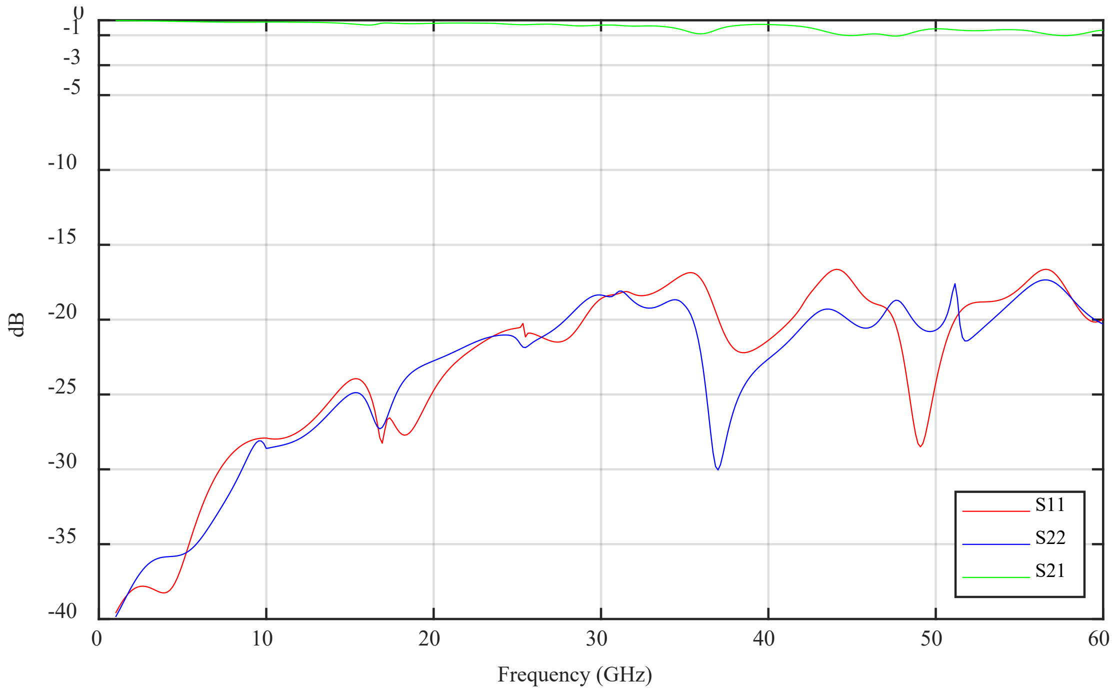


Figure 9 Simulation results for the connector to circuit board transition

## 3.3. Final assembly

Figure 10 illustrates the final assembly of the manufactured filter. The connectors were mounted onto the circuit board using the supplied screws.

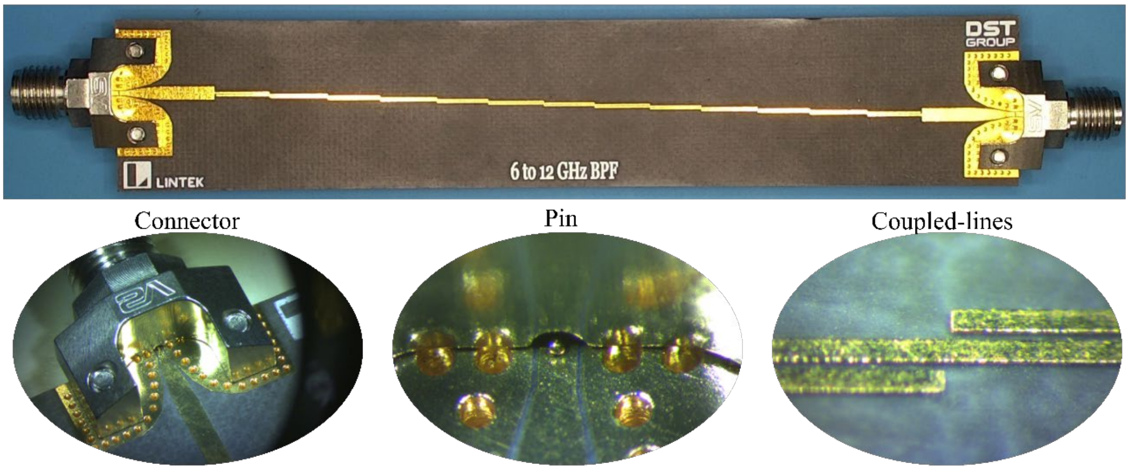


Figure 10 Final assembled 6 to 12 GHz band-pass filter including zoomed sub-images.

# 4. MEASUREMENTS

The filter was measured using a Rohde and Schwarz ZNA-43 [11] Vector Network Analyser. To achieve the highest measurement accuracy, the connector transition was de-embedded from the measurement by manufacturing a custom calibration board.

## 4.1. Custom calibration board

Figure 11 shows an image of the custom calibration board required to perform through reflect line (TRL) calibration. This includes a:

- Thru – back-to-back measurement of connectors.
- Line – 4.5 mm long (physical) 50 Ohms line between the Thru that represents a phase shift of approximately 89 degrees at 12 GHz and a time delay of 21.14 pS. The TRL calibration was applied over the band-limited frequency range 2 to 20 GHz to ensure that the electrical length of the Line did not exceed past the range 10 to 160°.
- Open – the connectors are separated to produce a reflected signal at each port.

The additional structure ‘Beatty’ [12] is a reference standard that is 3× the width of a 50 Ohm line and 1” (2.54 mm) long. This is not discussed further in this report.

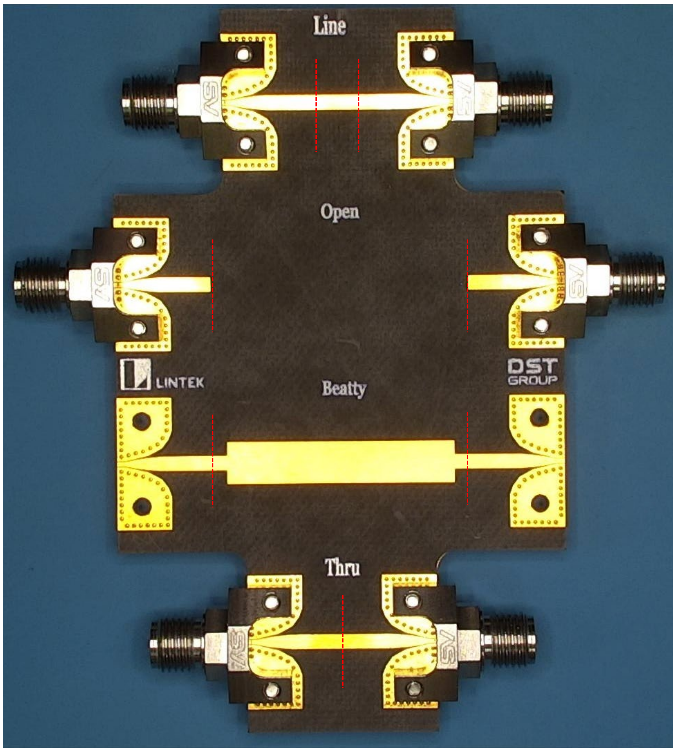


Figure 11 Image of the TRL calibration board for the connector de-embedding. The red dashed lines indicate the position of the measurement reference plane, aligning to the filter simulation.

## 4.2. Filter performance

Five samples were measured to determine the filters performance against typical process variation. Several measurement graphs are shown including:

- Full frequency, 2 to 20 GHz (S11 and S21) in Figure 12.
- Zoomed frequency, 5 to 13 GHz (S11 and S21) in Figure 13.
- Zoomed frequency and passband, 5 to 13 GHz (S21), in Figure 14.

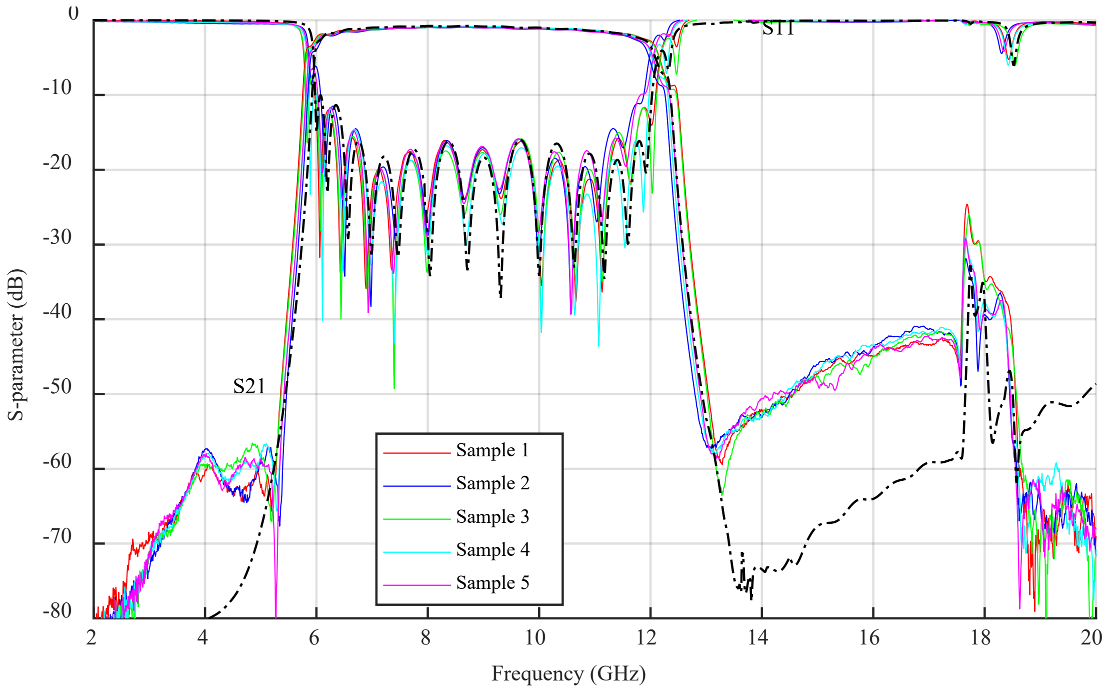


Figure 12 Measurement data TRL calibration (solid traces) vs. simulation (dashed trace). Full frequency span 2 to 20 GHz.

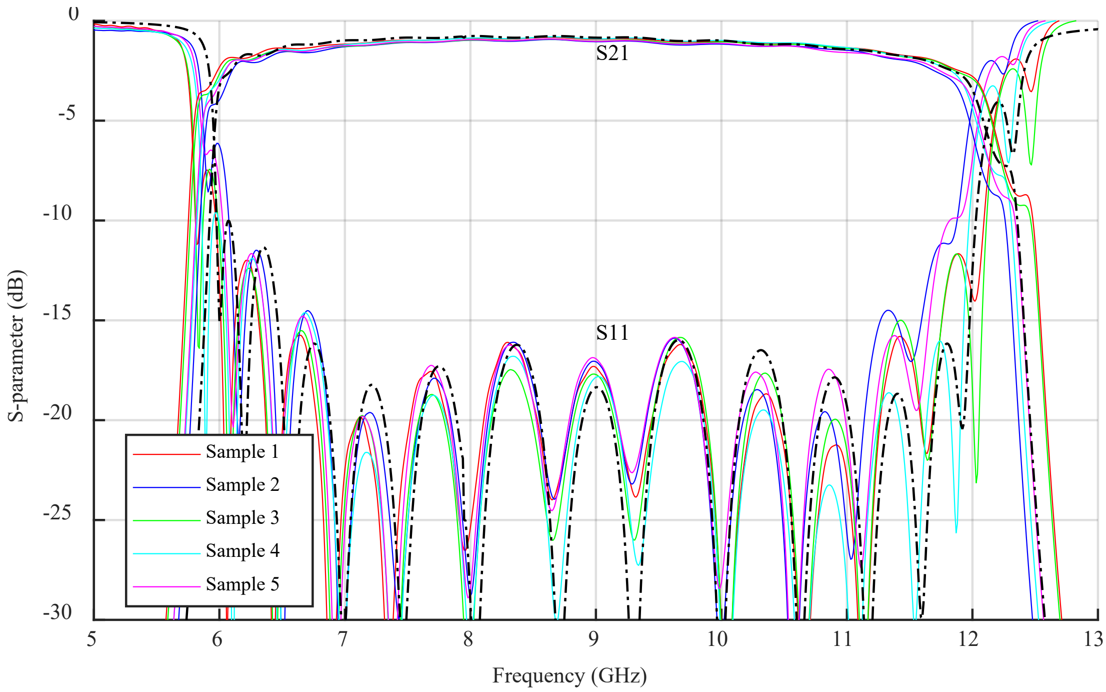


Figure 13 Measurement data TRL calibration (solid traces) vs. simulation (dashed trace). Reduced frequency span 5 to 13 GHz.

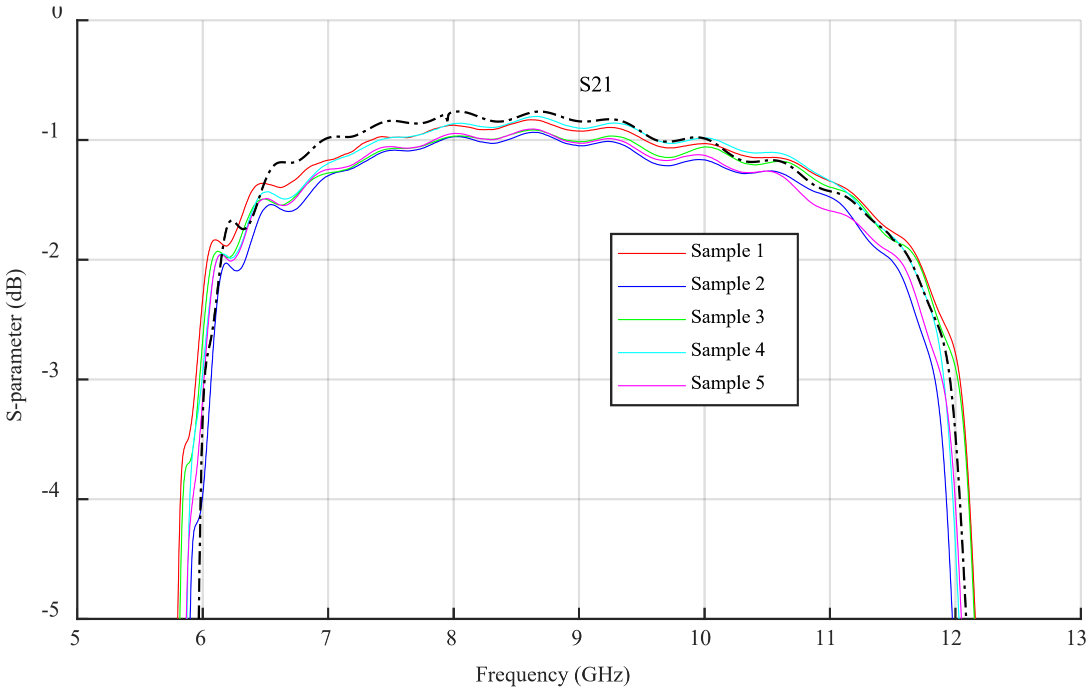


Figure 14 Measurement data TRL calibration (solid traces) vs. simulation (dashed trace). Reduced frequency span 5 to 13 GHz, zoomed y-axis.

Agreement between measured and simulated responses was excellent; in particular, the shape of the frequency response, the absolute positioning of the 3 dB points, insertion loss, and match. Table 4 highlights several key comparisons between the simulated and measured data for the five samples. In each field, the worst and best of the five samples is reported.

Table 4 Comparison of key measured versus simulated data points

| Parameter | Simulation | Worst measured | Best measured | Units |
|---:|---:|---:|---:|---:|
| Insertion Loss @ 9 GHz | 0.84 | 1.05 | 0.9 | dB |
| Left 3 dB passband frequency | 5.98 | 5.82 | 6.00 | GHz |
| Right 3 dB passband frequency | 12.04 | 11.93 | 12.00 | GHz |
| S11 from 7 to 11 GHz (dB) | < -15.9 | < -15.85 | < -16.8 | dB |
| S21 upper stop-band @ 16 GHz | -64 | -43.7 | -44.9 | dB |

# 5. CONCLUSION AND FUTURE WORK

The purpose of the study was to select a challenging RF filter design and report on the measured versus simulated accuracy, focusing on the unique additive metal processing technique that is available at Lintek, Queanbeyan, Australia. The success of the study was influenced by many factors including the:

- Chosen filter topology.
- Designer's approach.
- Measurement technique to de-embed connectors.
- Repeatability of connectors.
- Accuracy of supplied EM data.
- Preference for EM simulation tool.

Agreement to simulation was excellent for the passband characteristics for all five samples of the filter:

- Positions of S11 peaks and nulls (generally below -15 dB) showcase a 'tuneless' filter, made possible by the accurate manufacturing.
- Insertion loss was within 0.2 dB.
- Positions of 3-dB points was within 160 MHz at both ends (from 0 to 1.3 % error).

The results were based on a single-design spin using supplied EM data from the circuit board manufacturer. No post-measurement EM simulation tuning was applied to artificially improve the results.

In the filters' stop-band, ideal EM simulation predicted 64 dB isolation where measured results were approximately 44 dB. From an academic perspective this warrants further investigation (e.g. surface waves, isolation between ports, shielding) which is highly unlikely to be influenced by the metal fabrication accuracy that is the focus of this report.

Valuable future work would be a comparison of EM simulation methods (and tools) using this filter example or similar structures. Surface roughness was not modelled but could be investigated to get better results in the insertion loss. More convincing results could be achieved by using a microwave probe-station instead of using RF connectors which can vary from sample-to-sample.

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