

Mass-Producible E-Plane Millimeter Wave Filters

Stephanie Smith

CSIRO Telecommunications and Industrial Physics

PO Box 76, Epping NSW 1710, Australia

Email : Stephanie.Smith@csiro.au

ABSTRACT

An E-plane filter has been designed for manufacture using low cost mass-producible manufacturing methods. This paper discusses the issues related to diecasting the waveguide filter halves. A filter suitable for LMDS applications was designed and optimised using a mode matching technique. Modelled results from HFSS are presented along with measurements.

INTRODUCTION

With the radio spectrum in the sub-millimeter bands almost fully congested, and the increased need for higher bandwidth services, millimeter wave communications is becoming the way of the future. Local multipoint distribution services (LMDS) are being introduced to allow delivery of voice, data, internet and video services to both commercial and residential customers. One hurdle with moving to higher frequencies for these systems is the cost of the customer premise equipment (CPE). An LMDS CPE is still $> \$2000$ US, and this cost is quite prohibitive for a residential customer. By reducing the cost of some key components in the system, with minimal or no loss in performance, it may be possible to reduce the cost of the CPE to enable residential customers into the market. An off-the-shelf waveguide filter for the LMDS bands currently sells for $> \$200$ US. In this paper, a filter with similar characteristics is described in which cost reductions of an order of magnitude might be possible.

E-plane filters (Fig. 1) have been used since the 1970's due to their low cost, low loss and suitability for mass manufacturing techniques [1]. Standard manufacturing techniques for these filters involve machining the waveguide halves and photoetching the septum. It currently costs $\sim \$30$ US per filter to machine the waveguide halves. This paper presents an E-Plane filter suitable for LMDS applications, covering the frequency range 27.5 – 28.35GHz. The filter was designed for manufacture using diecasting for the waveguide halves and fine blanking for the all-metal septum. Diecasting requires a die to be made using high precision machining, hardening and grinding techniques, and the die is then used to cast up to orders of a million parts depending on the metal used for the mould. Fine blanking is a precision stamping process in which the part is located and firmly held in place prior to stamping. The potential exists for filters suitable for this application to be manufactured for $\sim \$5$ US in runs of $> 100,000$. Reduced manufacturing tolerances are the price paid for the low cost manufacturing techniques. This paper discusses the manufacturing issues; tolerance requirements and measured and modelled results are presented.

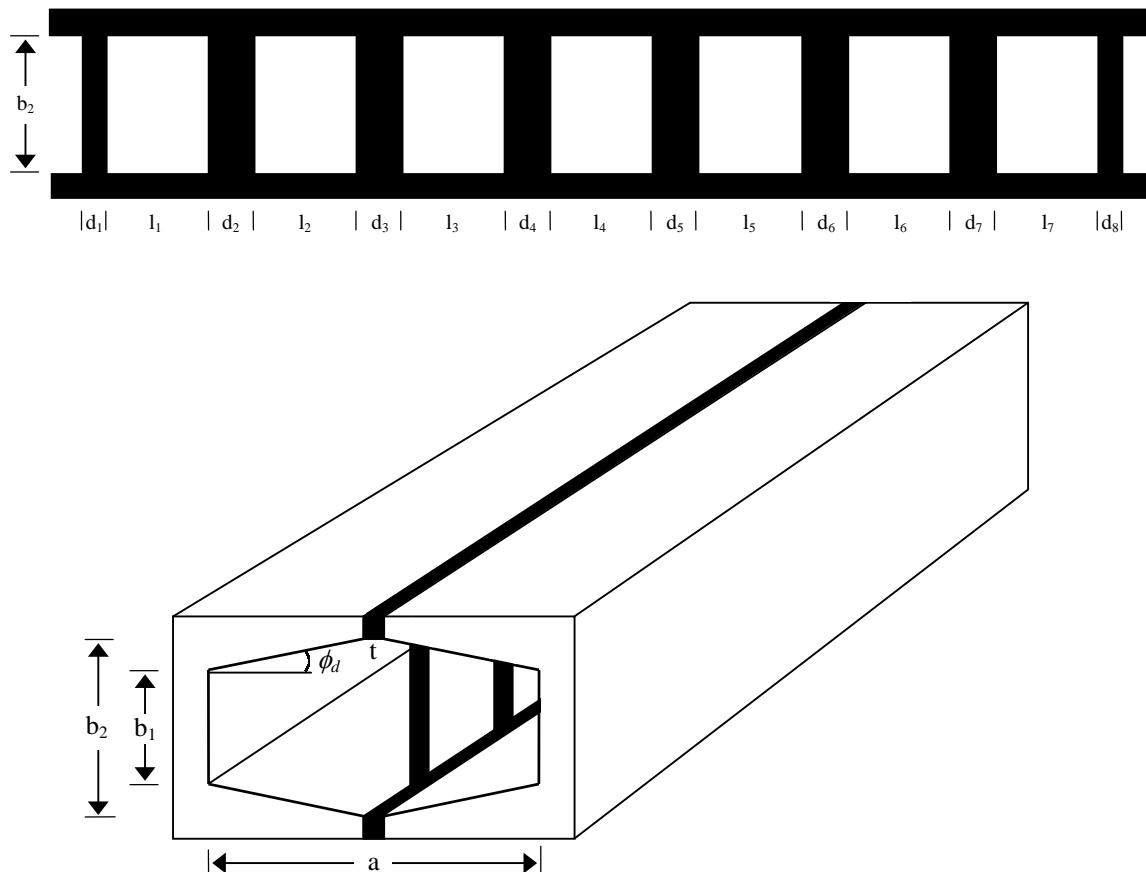


Fig. 1. 7 section E-plane filter.

DIECASTING ISSUES

Diecasting is an extremely cost effective method of manufacturing metal objects in large volume. This technique is generally neglected for the manufacture of high performance microwave or millimetre wave components due to the tight tolerances required, however, it is believed that there is a place in the market for low cost mass-producible filters with a slightly relaxed tolerance. The standard tolerance on a machined waveguide half for an E-Plane filter is $\pm 10\mu\text{m}$. It would be quite difficult to reduce this tolerance below $\pm 10\mu\text{m}$ using any mass manufacturing techniques, without increasing the cost considerably. The waveguide halves can be diecast with a tolerance of $\pm 15\mu\text{m}$ [2].

The main manufacturing issue with diecasting is the necessity to have a draft angle (ϕ_d) on the waveguide halves to enable them to be easily removed from the mould after the process (as shown in Fig. 1). A draft angle of at least 2° is generally required for ease of manufacture, and the draft angle must be accounted for in the electrical design of the waveguide. When applying the draft angle to the waveguide, the new waveguide cross section dimensions were calculated so that the cross sectional area of the waveguide with draft angles was equal to the cross sectional area of the standard waveguide. This gave the smallest mismatch when connecting standard rectangular waveguide to waveguide with draft angle. However, the addition of a draft angle to the waveguide also results in an increase in

its wavelength and a decrease in its cut-off wavelength; the amount of each depends on the draft angle. For example, in WR34 waveguide ($a = 8.636\text{mm}$, $b = 4.318\text{mm}$), the cut-off wavelength of the guide is 17.289mm and the waveguide wavelength at 28GHz is 13.6382mm . The introduction of a 3° draft angle ($b_1 = 4.0969\text{mm}$, $b_2 = 4.5391\text{mm}$) results in a waveguide wavelength of 13.8218mm at 28GHz and a cut-off wavelength of 16.934mm . This corresponds to a 1.35% increase in the waveguide wavelength and a 2.05% decrease in the cut-off wavelength.

The waveguide wavelength in a standard guide does not vary linearly with frequency. As illustrated in Fig. 2, the addition of a draft angle results in a change in the slope of the wavelength versus frequency plot, where there is a larger change in the wavelength at lower frequencies than there is at higher frequencies. This effect of the draft angles on the waveguide wavelength is not a linear function versus angle, and is due to the change in the cut-off wavelength. It has been found that the non-linearity does not adversely affect the filter response for moderate bandwidths. The data in Fig. 2 covers the entire WR34 waveguide band and was obtained from HFSS [3].

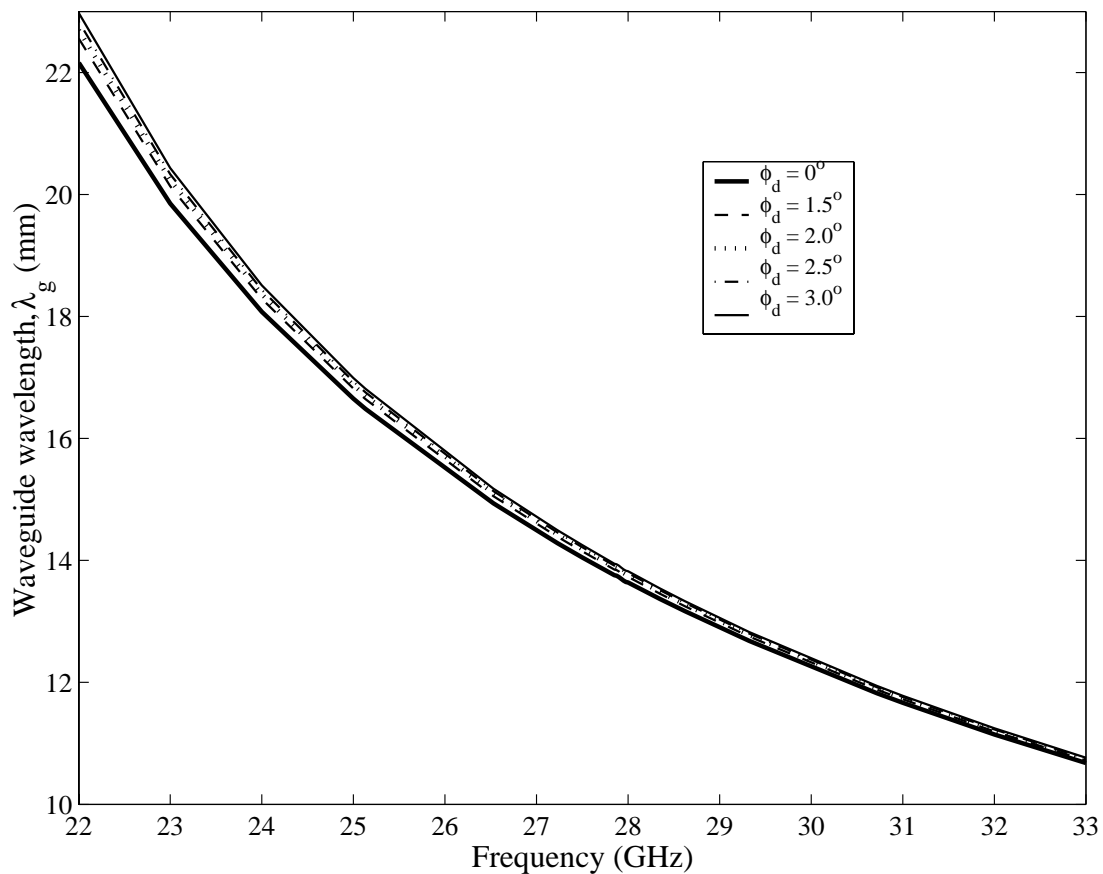


Fig. 2. Waveguide wavelength versus frequency for various draft angles.

The overall effect is the same for each draft angle, and that is to increase the centre frequency of the filter over that in a standard waveguide, while scaling the % bandwidth accordingly and with very little change in the shape of the filter. The simplest method to account for the introduction of the draft angle is to design the filter at a correspondingly lower frequency such that with the addition of the draft angles, the centre frequency is correct.

For example, if a filter is required with a centre frequency of 27.925GHz, a 3% bandwidth and a draft angle of 3°, equation 1 can be used to calculate the scaled centre frequency that should be used for the filter design:

$$\lambda_0 = \frac{\lambda_g}{\sqrt{1 + \frac{\lambda_g^2}{\lambda_c^2}}} \quad (1)$$

where λ_0 is the free space wavelength, λ_g is the waveguide wavelength and λ_c is the cut-off wavelength of the guide.

With no draft angle, if $\lambda_g = 13.6978\text{mm}$ and $\lambda_c = 17.289\text{mm}$, equation 1 gives; $\lambda_0 = 10.737\text{mm}$, and so $f_0 = 27.942\text{GHz}$.

To find the frequency in the waveguide with 3° draft angle at which the waveguide wavelength is the same as in rectangular waveguide, the same $\lambda_g = 13.6978\text{mm}$ is used, but with the cut-off wavelength of 3° draft angle waveguide, $\lambda_c = 16.934\text{mm}$. Equation 1 gives; $\lambda_0 = 10.650\text{mm}$, and so $f_0 = 28.169\text{GHz}$.

This corresponds to an increase in the centre frequency of 0.812% in the 3° draft angle waveguide over that in standard waveguide. The filter can thus be designed and optimised using conventional software, such as mode matching [4] with a centre frequency of 27.698GHz, which will scale to 27.925GHz when the draft angles are added.

LMDS FILTER DESIGN

A seven section E-plane filter (Fig. 1) was designed for the LMDS band from 27.5 – 28.35GHz (3.044% bandwidth) in WR34 with; $a = 8.636\text{mm}$, $b_1 = 4.1338\text{mm}$, $b_2 = 4.5022\text{mm}$, $t = 0.200\text{mm}$, $d_1 = d_8 = 0.4869\text{mm}$, $d_2 = d_7 = 3.1981\text{mm}$, $d_3 = d_6 = 4.4065\text{mm}$, $d_4 = d_5 = 4.7714\text{mm}$, $l_1 = l_7 = 4.8871\text{mm}$, $l_2 = l_6 = 4.9257\text{mm}$, $l_3 = l_5 = 4.9240\text{mm}$, $l_4 = 4.9235\text{mm}$, and $\phi_d = 2.5^\circ$. The filter was designed and optimised with a mode matching technique using the scaled centre frequency of 27.736GHz with a bandwidth of 3.044% (27.314 – 28.158GHz).

When modelled on HFSS with these dimensions and the 2.5° draft angle, and using the conductivity of zinc for the waveguide halves and copper for the septum, the filter response is shown in Fig. 3. Conductivity of zinc ($\sigma = 1.6e7 \text{ S/m}$) was used for the waveguide, because the filter was manufactured from Zamak #3 zinc alloy, which is a suitable material for diecasting. The septum was manufactured from stainless steel but was copper plated, so the conductivity of copper ($\sigma = 5.8e7 \text{ S/m}$) was sufficient for the modelling due to the skin depth being less than the plating thickness of the copper.

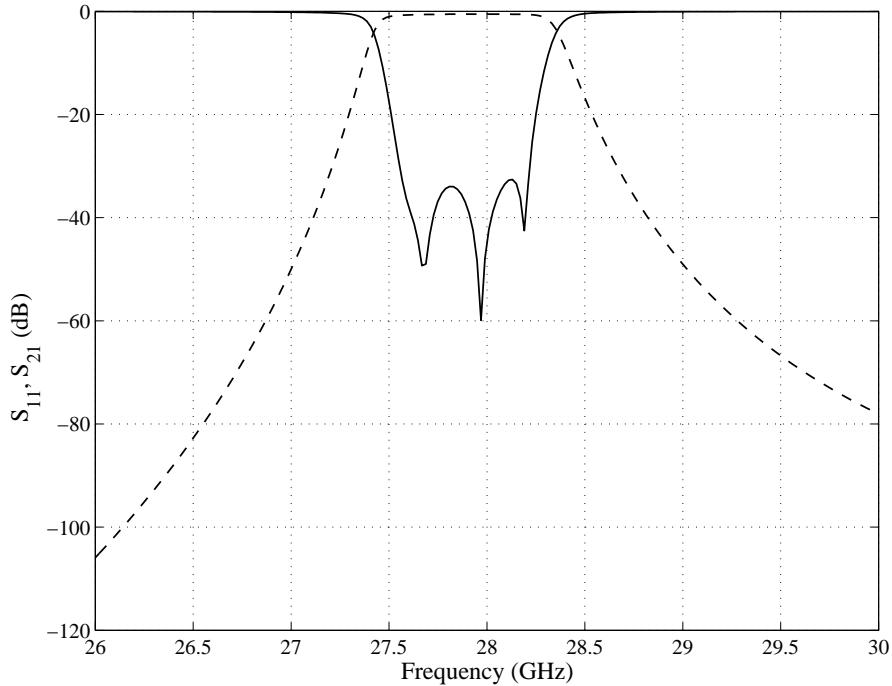


Fig. 3. HFSS response of 7 section E-plane filter from Fig. 1.

MANUFACTURING ISSUES

A tolerance study on the 7 section filter described in the previous section has revealed that the critical mechanical parameters are; width of the waveguide halves ($(a-t)/2$), septum thickness (t) and draft angle (ϕ_d).

The waveguide halves can be diecast with an accuracy of $\pm 15\mu\text{m}$ on the critical dimensions and $\pm 50\mu\text{m}$ across the length of the waveguide. The tolerance on the draft angle is $\pm 0.5^\circ$. The septum can be manufactured using fine blanking with an accuracy of $\pm 15\mu\text{m}$ on the critical dimensions and $\pm 25\mu\text{m}$ across the length. The tolerance on the thickness of the metal used for the septum depends on the type of metal, for example if the septum were manufactured from $200\mu\text{m}$ thick stainless steel, the tolerance on the thickness is $\pm 20\mu\text{m}$. Using thinner stainless steel can reduce this tolerance, for example, the tolerance for the thickness of $100\mu\text{m}$ thick stainless steel is $\pm 10\mu\text{m}$ and the tolerance for the thickness of $50\mu\text{m}$ thick stainless steel is $\pm 7.5\mu\text{m}$.

A change in the width of the waveguide of $\pm 15\mu\text{m}$ results in a frequency shift in the filter response of $\pm 60\text{MHz}$; a change in the thickness of the septum of $\pm 20\mu\text{m}$ results in a frequency shift in the filter response of $\pm 120\text{MHz}$; a change in the draft angle of the waveguide of $\pm 0.5^\circ$ results in a frequency shift in the filter response of $\pm 30\text{MHz}$. The maximum combined effect of all three parameters is; a frequency shift of $+200\text{MHz}$ when the width of the waveguide is $-15\mu\text{m}$, the thickness of the septum is $+20\mu\text{m}$ and the draft angle is $+0.5^\circ$; a frequency shift of -200MHz when the width of the waveguide is $+15\mu\text{m}$, the thickness of the septum is $-20\mu\text{m}$ and the draft angle is -0.5° . The tolerances of $\pm 15\mu\text{m}$ on the remaining critical dimensions of the filter will reduce the return loss and increase the

insertion loss of the filter, but will not shift the frequency considerably. Overall however, with all tolerances accounted for, the return loss of the filter will be greater than 15dB.

The filter was manufactured to mimic the diecasting process for the waveguide halves with the same tolerances as would be expected from the mass-producible manufacturing techniques. The measured filter response is shown in Fig. 4 for a number of different septa.

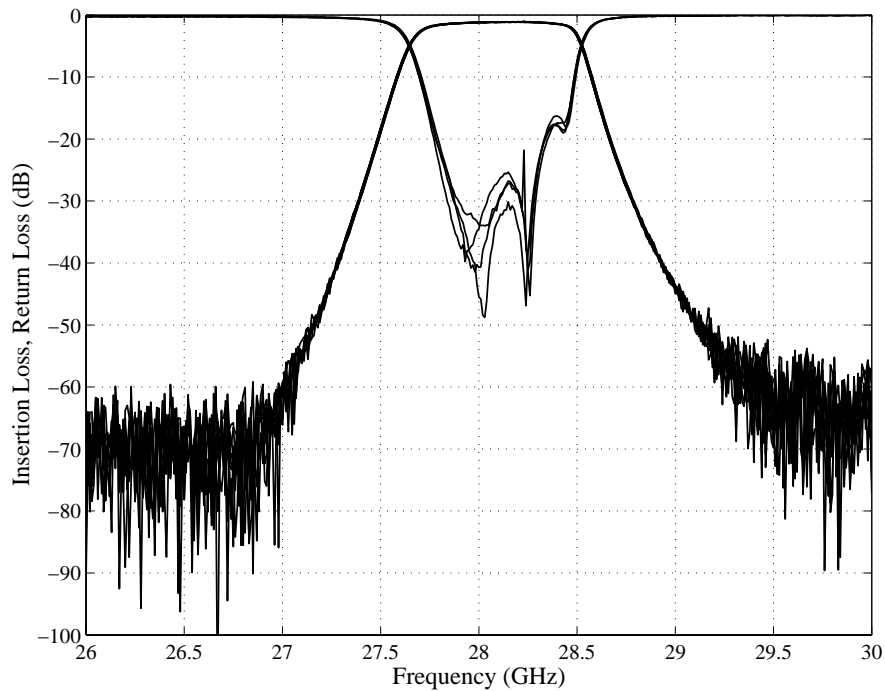


Fig. 4. Measured filter response with 4 different septa.

SUMMARY

The problem with this type of mass production is the shift in the frequency. It has been found that the response of the filter remains within the desired specifications, even though the centre frequency of the filter may be shifted by up to $\pm 25\%$ of the total bandwidth. The main contributor to this frequency shift is the tolerance on the thickness of the septum, and this can be improved by using a thinner septum. Despite this, a tuning process is being investigated that will enable the centre frequency of the filter to be corrected in a simple one step automated process. This will not add considerable cost to the production of the filter.

REFERENCES

- [1] Yi-Chi Shih, "Design of waveguide E-plane filters with all-metal inserts," *IEEE Trans. Microwave Theory Tech.*, vol. 32, no. 7, pp. 695-704, 1984.
- [2] Miniature Casting Corporation, Rhode Island, USA.
- [3] Ansoft Corporation, "HFSS Version 8.0.25," USA, 2001.
- [4] J. Uher, J. Bornemann and U. Rosenberg, *Waveguide Components for Antenna Feed Systems : Theory and CAD*, Artech House : Boston, 1993.