IET Microwaves, Antennas & Propagation

Research Article

ISSN 1751-8725
Received on 13th August 2014
Accepted on 17th November 2014
doi: 10.1049/iet-map.2014.0552
www.ietdl.org

Design of millimetre wave diplexers with relaxed fabrication tolerances

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Abstract: A novel millimetre wave waveguide diplexer topology that can be fabricated using relaxed fabrication tolerances is presented. This is achieved by using a highpass filter/hybrid coupler topology in addition to a low order capacitive iris bandpass filter. By targeting the most sensitive centre resonators in the bandpass filter and increasing their length to full wavelength, the sensitivity to fabrication errors associated with changes to the resonator length can be reduced without the introduction of spurious responses close to the passband. The main benefit of this topology is that only one bandpass filter is required to realise the final diplexing response. This is advantageous when tolerance is considered as it is found that resonating structures associated with bandpass filters contribute to tolerance effects. In addition to this, the authors find that the choice of iris discontinuity used to realise the impedance inverters in the bandpass filter can help to relax fabrication tolerances. By subjecting the proposed circuit to a tolerance analysis, simulated results suggest that the circuit can be fabricated with relaxed fabrication tolerances. These discussions are verified with the fabrication of a Ka-band waveguide diplexer, where the measured and simulated *S* parameters are in very good agreement.

1 Introduction

The use of the millimetre wave part of the spectrum is now becoming main stream: not only are millimetre waves used in satellite communication systems, they are a solution for mobile backhaul communications where bandwidth congestion is a major problem. Considering that the guide wavelength is proportional to the size of a device, fabricating devices that operate in the 30–300 GHz part of the spectrum can be challenging because of their small size. For example, some of the key dimensions of rectangular waveguide components such as filters and diplexers are on the same order as current fabrication tolerances using conventional CNC milling processes [1]. This presents a problem as even small manufacturing errors can significantly alter the frequency response of a device, resulting in poor production yield. At lower frequencies such as X-band, this does not present too much of a problem as the devices contain tuning screws which can be used to correct shifts in frequency [2]. However, at millimetre wave frequencies this option is not always viable as the tuning screws required are extremely small and therefore are challenging to implement. In this case, devices are fabricated with tight tolerances to ensure that they meet the required specifications without tuning. This is uneconomical as the production time of components is related to the fabrication tolerance. In addition, there is also a financial implication as the extra time required to fabricate the device results in the technicians and machines working for longer periods. A better approach would be to redesign the circuit so that the fabrication tolerance of the millimetre wave components can be relaxed. The purpose of this paper is to present a novel diplexer circuit that can be fabricated using relaxed fabrication tolerances and will be of interest to anyone fabricating millimetre wave components: in particular, rectangular waveguide diplexers, filters and couplers. This paper is a follow up to [1], where we proposed a novel Ka-band diplexer that can be fabricated using relaxed tolerances. However, it should be stressed that the novelty is associated with the diplexer circuit topology and not the frequency range: the design methodology will be particularly useful for the E-band diplexer design as in [3, 4], or the new Q/V-band alphasat project [5]. The main benefit of our diplexer circuit is that it contains halve the number of resonating structures when compared with other diplexer circuits operating with a similar fractional bandwidth as a result of using only one bandpass filter [3, 4]. As a result of this, the sensitivity of the diplexer to fabrication errors is reduced, improving the tolerance of the circuit. We also investigated the tolerance implications of different iris coupling discontinuities for bandpass filters and found that capacitive iris coupling has improved tolerance handling ability over inductive iris coupling because of the positive length of the impedance inverter making the resonator length larger.

An outline of the paper is as follows. In Section 2, tolerance issues associated with resonator structures are discussed, where it is suggested that resonator structures within bandpass filters contribute to tolerance effects. A discussion of how to improve the tolerance for waveguide bandpass filter circuits is also given. In Section 3 it is suggested that capacitive iris discontinuities have benefits over inductive iris discontinuities when tolerance is concerned because of the positive length of the impedance inverter making the resonator length larger. Based on the discussions given in Sections 2 and 3, a novel diplexer topology is proposed in Section 4 that can be fabricated using relaxed fabrication tolerances. The topology consists of a range of components such as band pass filters, high pass filters and hybrid couplers. The design of these components along with simulated results ispresented in Sections 5, 6 and 7, respectively. Some promising results are presented in Section 8, which give further evidence to the discussions in Sections 2 and 3.

2 Issues with resonator structures

A conventional diplexer circuit consists of two bandpass filters matched to a three port power divider. This topology usually offers the best trade-off between size and performance when compared with other diplexer configurations. However, when tolerance is of a concern, this topology is not ideal. This is because of the direct coupled nature of the bandpass filters in the diplexer circuit: as each resonator within the bandpass filter is subjected to tolerance effects, slight fabrication errors can alter their frequency response and ultimately change the frequency response of the diplexer circuit. Based on this we can say that changes to the frequency repose of the diplexer circuit are related to changes to the width Δ*a*, height Δ*b* and length Δ*l* of the resonators in the bandpass filters, and can be represented with the statement Tolerance (Δ*a*, Δ*b*, Δ*l*). That is, given a set of specifications, the filter will meet these specifications so long as it is manufactured within its fabrication tolerance: out with this and the frequency shift because of Δ*a*, Δ*b* and Δ*l* as a result of fabrication errors is too significant, resulting with the filter failing to meet its requirements. Of these parameters, changes to the resonator length dominate the tolerance issues of the structure, with changes to the width and height of the filter only marginally affecting the inter-resonator coupling. This is a consequence of the bandpass filter circuit and is applicable to bandpass filters realised in any transmission line: microstrip or substrate integrated waveguide for example. It is interesting to note that the sensitivity of each parameter increases towards the centre of the filter where the coupling is at its weakest.

One way of reducing the sensitivity of a waveguide filter to fabrication errors would be to increase the volume of the resonators. This could be achieved in three ways: increasing the resonator length; increasing the waveguide height; or increasing the waveguide width. As the width and the height of the waveguide are controlled by the standard waveguide dimensions at a particular frequency, there is not much flexibility to alter these without introducing an impedance transformer into the circuit which can add additional loss and increase the filters footprint. In this case, increasing the resonator length would provide the best solution. Waveguide bandpass filters are generally designed using half wavelength resonators as they provide the best trade of between size and performance: usually full wavelength resonators have a spurious response that can be close to the passband which is undesirable. However, by targeting the most sensitive centre resonators and increasing their length so they operate as full wavelength resonators we can significantly reduce the filters sensitivity to tolerance effects without introducing spurious responses close to the passband. This has several benefits. Initially, as the resonator has doubled in length the sensitivity because of fabrication errors associated with the centre resonator is reduced. In addition, the aperture size of the input/output coupling iris of the centre resonator is increased which reduces fabrication sensitivity for that critical iris. This increase in aperture size can be explained by considering that there is more energy stored within a full wavelength resonator than a half wavelength resonator because of the larger volume. This reduces the coupling coefficient for that iris, and hence to realise the desired bandpass response of the filter the aperture size of the iris needs to be increased to accommodate the new full wavelength structure. We have found that adding adjacent full wavelength resonators to the centre resonator does not further improve the tolerance sensitivity when compared with a single full wavelength resonator at the centre of the filter, as you might expect. In fact, it adds spurious resonances into the response and degrades the stopband (SB) edge which is undesirable. By considering the design in [3] which uses full wavelength resonators entirely for the upper diplexing channel, the method presented here provides a better trade-off between tolerance and size.

3 Choice of coupling discontinuity

Another important aspect of tolerance is the choice of iris discontinuity used to realise the impedance inverters of the bandpassfilter circuit. Although there are many variations, commonly used iris discontinuities can be summarised generally as having either a shunt capacitive or shunt inductive equivalent circuit. These can be seen below in Fig. 1 along with their equivalent circuit model. In addition to the physical differences between the two irises, there are some distinct electrical differences as well. For example, by considering the electrical length of both the capacitive and inductive case, it is well known that the capacitive iris has an associated positive length whereas the inductive iris has an associated negative length [6]. The negative length of the inductive iris is unrealisable and is therefore absorbed into the resonator. This means that inductive iris filters have smaller resonator lengths when compared with capacitive iris filters which subsequently make them more sensitive to fabrication errors associated with changes to the resonator length.

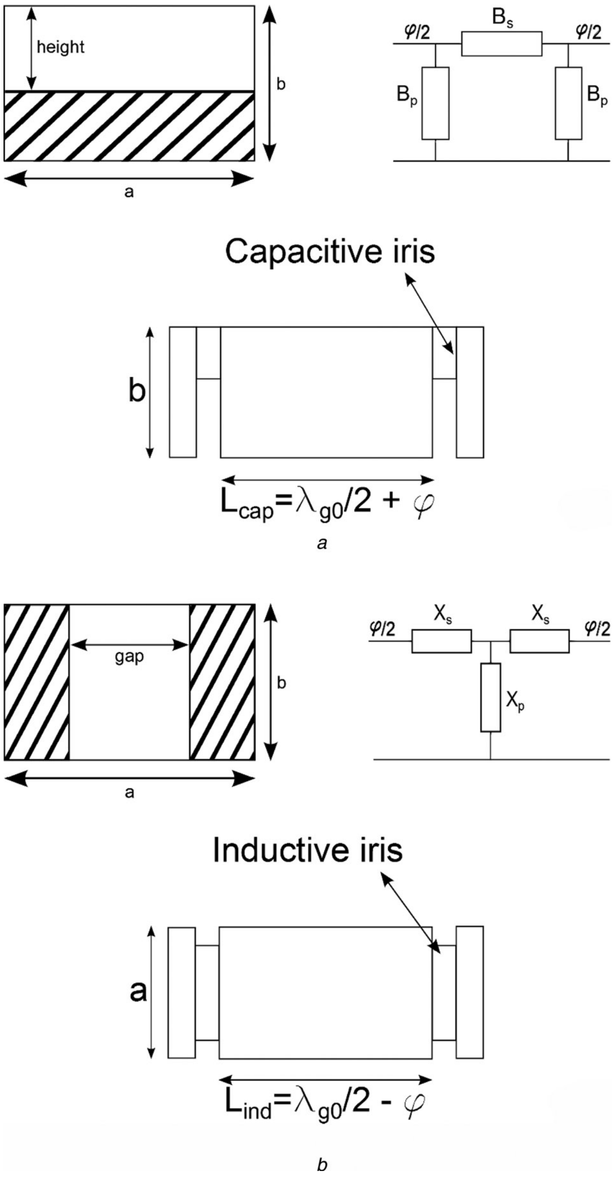

Fig. 1 *Commonly used iris discontinuities can be summarised generally as having either a shunt capacitive or shunt inductive equivalent circuit* Q1

a Capacitive iris viewed from the front and the side, along with the equivalent circuit diagram
b An inductive iris viewed from the front and the top, along with the equivalent circuit diagram. It can be seen from (*a*) and (*b*) that the capacitive iris has a longer resonator length because of the positive inverter length φ. In addition, λ_{g0} represents the guide wavelength at the centre frequency of the resonator

4 Proposed diplexer circuit

As resonant structures are sensitive to fabrication errors, it is in our interest to eliminate as much resonating structures as possible from the circuit to relax the fabrication tolerance of the diplexer. One method of achieving this is to use the topology given in Fig. 2 below. This novel topology is based on that given in [7], where highpass filters are used in place of bandpass filters in this case. A detailed discussion of the scattering matrix theory for a similar structure using bandstop filters is provided in [8] and is applicable to this design. If a narrow wall short slot coupler is used for each hybrid, and highpass filters are designed using the cut off

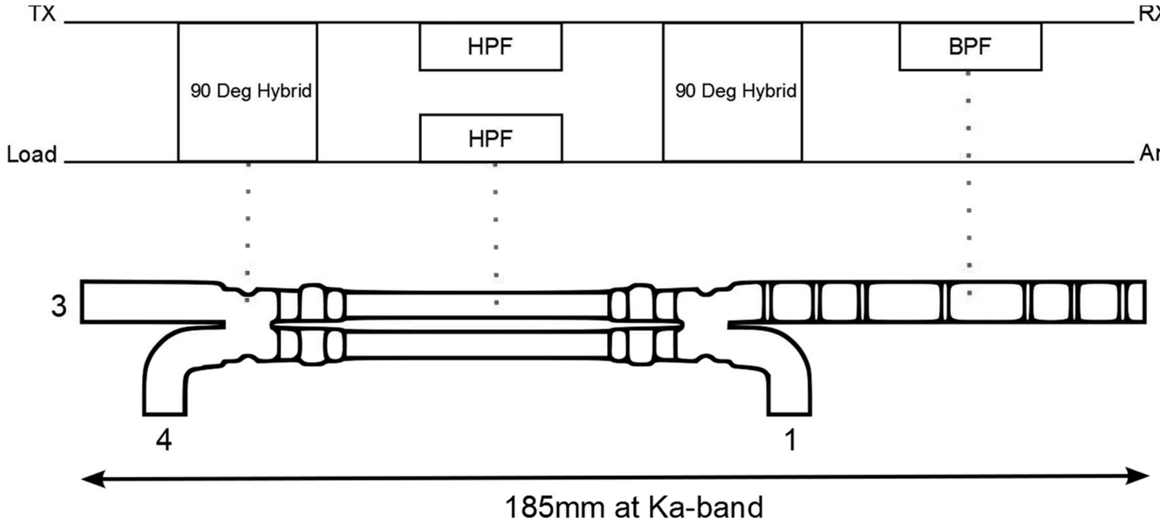

Fig. 2 *Schematic diagram of the proposed diplexer topology*

frequency of rectangular waveguide, the bulk of the circuit consists of nothing more than impedance steps and waveguide transmission lines, with the addition of an *RX* bandpass filter. This simplifies the circuit topology which in turn makes the milling process easier. In terms of tolerance, the *RX* bandpass filter order is crucial. It is therefore essential to keep the filter order as low as possible to limit the number of resonators the circuit uses. The design of each component will now be briefly discussed for a Ka-band diplexer designed to operate with the requirements in Table 1 below.

5 Design of capacitive iris bandpass filters

The theory of direct coupled bandpass filters is well known and therefore will not be discussed here in detail. A capacitive iris approximates an impedance inverter over a narrow bandwidth close to the centre frequency of the filter. In terms of the physical discontinuity used to realise the iris, a single stub as was shown in Fig. 1*a* is the preferred choice. This allows the structure to be fabricated into the body of the filter where a lid is used to complete the circuit, simplifying the fabrication process. Based on the required specifications in Table 1, a six pole bandpass filter was designed to operate in the frequency range of channel 1. This means that the proposed diplexer circuit uses halve the number of resonating structures when compared with other diplexer circuits that have a similar fractional bandwidth [3, 4]. The filter was designed using the impedance inverter method as discussed in [6, 9] using a commercial mode matching based software. This method is quite versatile in that the physical dimensions of the filter can be obtained by simulating the scattering parameters of the iris geometry over a particular range: in the case of the capacitive iris, the scattering parameters were obtained for different stub heights. By using (1) and (2), the series and shunt normalised susceptance of the iris is determined and a plot of the normalised inverter impedance for various stub height scan be made. By calculating the normalised inverter impedance K/Z_0 required to realise the ideal bandpass response from (3)–(5), the physical iris dimensions can be determined from Fig. 3

Table 1 Required specifications for the proposed diplexer circuit

Channel 1		Channel 2	
passband	30.96–33.14 GHz	passband	35.32–37.50 GHz
stopband rejection	–60 dB between 35.32–37.5 GHz	stopband rejection	–60 dB between 30.96–33.14 GHz
return loss	–14 dB	return loss	–14 dB
insertion loss	–0.7 dB	insertion loss	–0.7 dB

These specifications have a similar fractional bandwidth to the designs presented in [3, 4]

$$\frac{B_p}{Y_0} = \frac{1 - S_{12} - S_{11}}{1 + S_{11} + S_{12}} \tag{1}$$

$$\frac{B_s}{Y_0} = \frac{2S_{12}}{(1 + S_{11})^2 - S_{12}^2} \tag{2}$$

$$\frac{K_{01}}{Z_0} = \sqrt{\frac{\pi\omega_\lambda}{2g_0g_1}} \tag{3}$$

$$\left.\frac{K_{j,j+1}}{Z_0}\right|_{j=1 \text{ to } n-1} = \frac{\pi\omega_\lambda}{2\sqrt{g_jg_{j+1}}} \tag{4}$$

$$\frac{K_{n,n+1}}{Z_0} = \sqrt{\frac{\pi\omega_\lambda}{2g_ng_{n+1}}} \tag{5}$$

Here, ω_λ represents the guide wavelength fractional bandwidth and g_n represents the element values for a chebychev lowpass

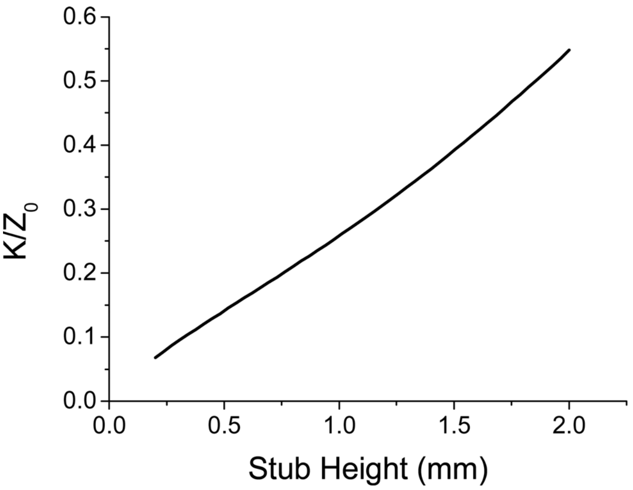

Fig. 3 *Plot of the normalised inverter impedance against the stub height of the capacitive iris*

This data was extracted from the scattering parameters of a capacitive iris by using various stub heights. By using (3)–(5), the required iris dimensions can be extracted from this plot

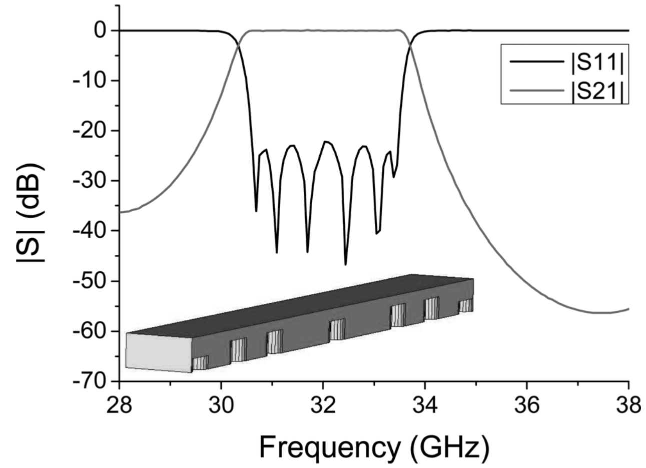

Fig. 4 *Simulated frequency response of the bandpass filter along with a 3D image*

Here, resonators three and four have been made full wavelength because of the symmetry of the six pole design. RL is better than −22 dB in the 30.96–33.14 GHz range

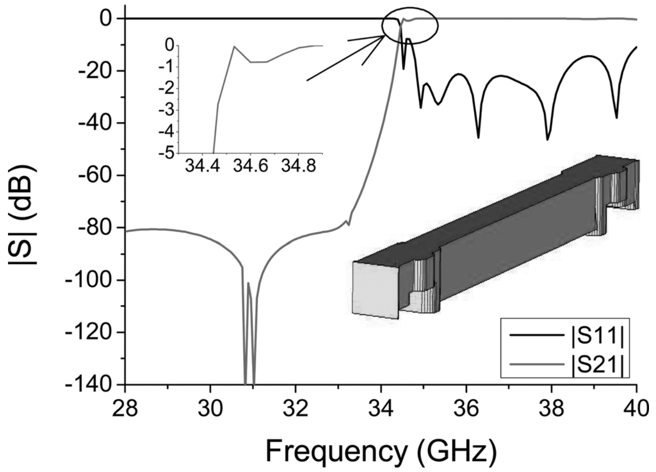

Fig. 5 *Simulated frequency response of the highpass filter with a third order matching transformer along with a 3D image*

Return loss is better than −21 dB in the 35.32–37.50 GHz range. Owing to the dispersive effects close to the cut off frequency of the waveguide, the IL is larger here. However, this is away from the desired passband

prototype filter. Initially, the filter is designed using half wavelength resonators. However, as these are only initial dimensions, an optimisation stage was included so that the filter using half wavelength resonators met the required specifications. From these optimised dimensions, the lengths of resonators three and four were then doubled and the filter circuit is fine tuned. During this tuning process, both the resonator length and the coupling strength for this resonator were increased to accommodate the new full wavelength structure. A final optimisation stage is then carried out ensuring the filter meets the required specifications. The simulated frequency response of the bandpass filter can be seen below in Fig. 4.

6 Design of highpass filters

The design of highpass filters in rectangular waveguide can be achieved by equating the cut off frequency of the waveguide to the cut off frequency of the highpass filter [10]. Thus, knowledge of the traditional prototype circuit for filter design is not required here as waveguide naturally acts as a highpass filter: only knowledge of the propagation constant for a particular mode is required. Below cut off, the wave attenuates exponentially following $e^{\alpha z}$, where α is the attenuation constant and z is the distance travelled by the wave, which represents the length of the highpass filter in this case. We can calculate z for a particular SB rejection at a particular frequency by using (6)

$$z = \frac{-\ln\left(10^{(\mathrm{SB}/20)}\right)}{\alpha} \tag{6}$$

Here, SB is the stopband attenuation in dB. As the cut off section of waveguide will have a width narrower than the standard waveguide dimensions for a particular frequency range, an impedance transformer is required to match the highpass filter to a standard waveguide flange. These are standard components and can be designed using the method presented in [11]. The simulated frequency response of a highpass filter at Ka-band frequencies can be seen in Fig. 5 below, where a third order inhomogeneous matching transformer was required.

7 Design of broadband short slot couplers

When tolerance is considered, the short slot coupler has benefits over other types of hybrid couplers, such as the branch line coupler. This is because of the short slot coupler possessing a large coupling region in place of tight coupling slots which at millimetre wave frequencies can be difficult to realise [12]. For this diplexer, the coupler is required to operate over both diplexing channels, resulting with a 19.2% bandwidth requirement. To achieve this broadband performance, the coupler was designed as a series of steps where the TE_{10}, TE_{20} and TE_{30} modes are excited: the TE_{30} mode is allowed to propagate in the outer sections of the coupling region, but is evanescent in the centre region, as is shown in Fig. 6. The excitation of the TE_{30} mode is essential for broadband performance [13, 14]. With the addition of more steps in the circuit, the bandwidth of the coupler can be increased [15]. However, the required bandwidth performance for this design was

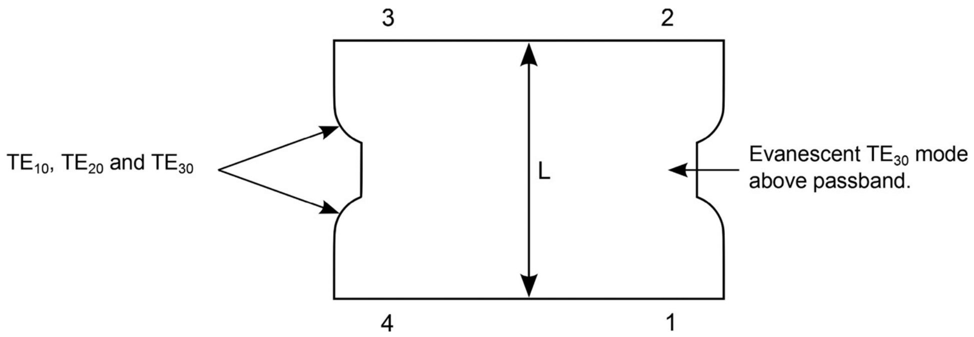

Fig. 6 *Schematic diagram showing the excited modes within the coupling region*

TE_{30} mode is evanescent in the centre of the coupling region: this is essential for broadband performance [13, 14]

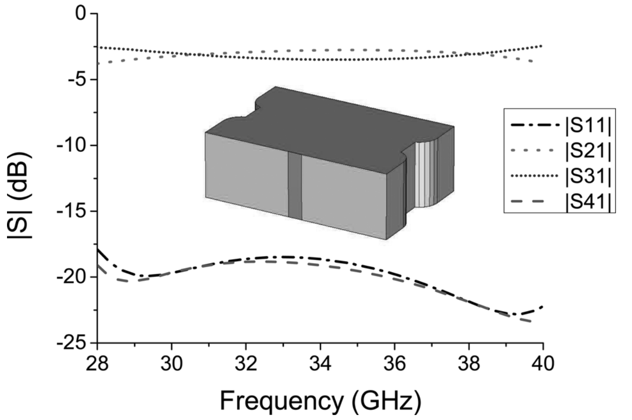

Fig. 7 *Simulated frequency response of the coupling region without matching transformers along with a 3D image*

Over the 30.96–37.5 GHz range the S21/S31 variation is ±0.37, with the isolation and RL better than −18 dB

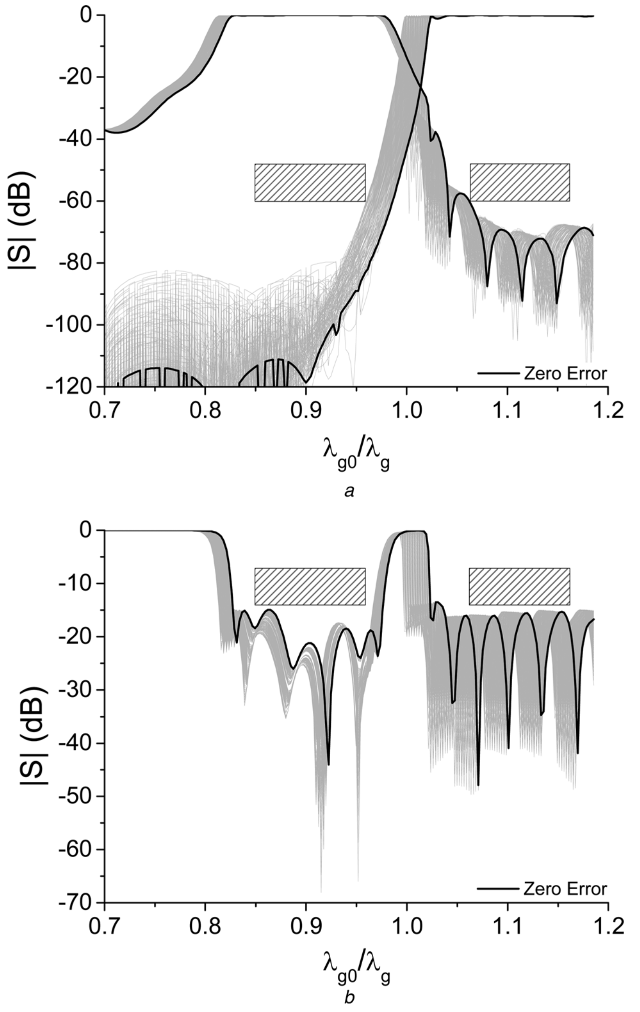

Fig. 8 *Simulated results of the diplexer being subjected to systematic fabrication errors with*

a Showing |S21| and |S31|
b Showing |S11|. A 100% pass rate of the samples can be observed, which suggests that the diplexer can be fabricated with up to +0.07 mm fabrication tolerance at Ka-band frequencies while still meeting the requirements in Table 1

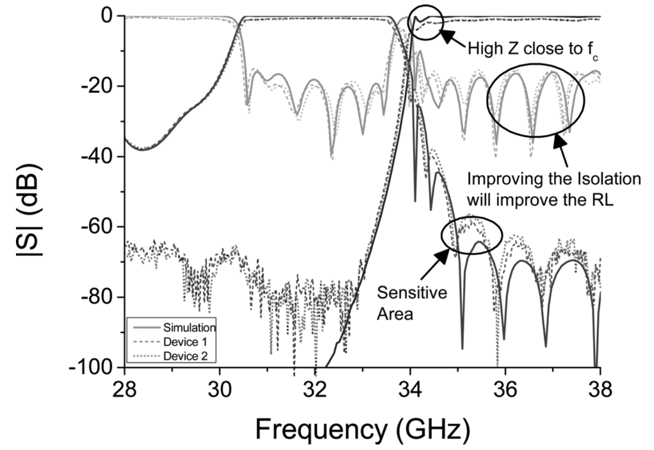

Fig. 9 *Simulated and measured results of the Ka-band diplexer*

Measured results of two diplexers are presented here and demonstrate very good agreement with the simulated *S* parameters without requiring tuning

achieved by using only three steps. A design procedure for broadband short slot couplers can be found in [13], where the initial length of the coupling region can be calculated using Riblets formula [16]

$$L = \frac{\lambda_{\text{odd}}\lambda_{\text{even}}}{4(\lambda_{\text{odd}} - \lambda_{\text{even}})} \tag{7}$$

Here, λ_{even} and λ_{odd} represent the guide wavelengths of the TE_{10} and TE_{20} modes, respectively. To match the input and isolated ports of the coupling region to a standard waveguide flange, a two section inhomogeneous transformer was designed using the methods in [11]. The simulated frequency response of the coupling region after an optimisation cycle can be seen in Fig. 7.

8 Simulated and measured results

To gain an understanding of how fabrication errors will affect the diplexers performance, a tolerance analysis was carried out where it was assumed the fabrication process would systematically overcut key circuit dimensions with up to +0.07 mm error. The analysis includes changes to all circuit variables (Δa, Δb, Δl) and iris dimensions. Simulated results from 101 samples can be seen below in Fig. 8 together with the specification marks for the return loss (RL) and out of band rejection. A 100% pass rate of the samples can be observed, which suggests that the diplexer can be fabricated with up to +0.07 mm fabrication tolerance at Ka-band frequencies while still meeting the requirements in Table 1. To emphasise that both the diplexing response and fabrication tolerance are scalable, the magnitude of the scattering parameters have been plotted against the normalised guide wavelength. For example, if f_0 is 78 GHz then the fabrication tolerance would be reduced to +0.03 mm [1].

Owing to the cut off frequency being inversely related to the width of the waveguide for the TE_{10} mode, the cut off frequency of the highpass filter appears to be sensitive to Δa. However, the stopband rejection could be increased to accommodate this by increasing the length of the highpass filter section. To validate the

Table 2 Summary of the fabricated Ka-band diplexers performance

	Channel 1			Channel 2		
	IL, dB	RL, dB	SB, dB	IL, dB	RL, dB	SB, dB
device 1	−0.71	−19.15	−58.67	−1.05	−15.68	−63.75
device 2	−0.79	−18.37	−56.45	−0.97	−14.82	−68.26

Maximum IL is given at the centre frequency of the passband; the RL and SB are given as the minimum value in the passband

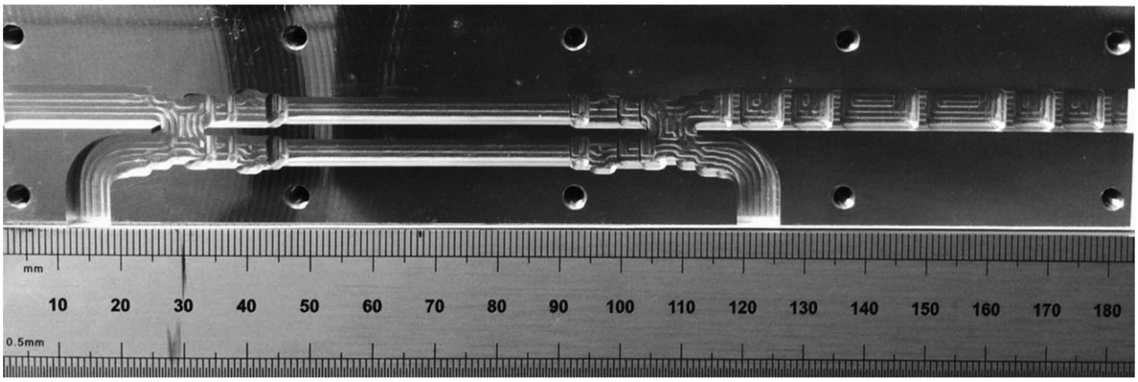

Fig. 10 *Photograph of a fabricated diplexer circuit*

simulated results in Fig. 8, two Ka-band diplexers were fabricated using an aluminium alloy. Fig. 9 shows very good agreement between the measured devices and simulated S parameters. However, when comparing Fig. 8 to Fig. 9, there is a slight shift in cut off frequency because of a 0.05 mm deviation in the dimensions of the transformers altering the cut off frequency of the highpass filters. Even when considering this, both devices are close to meeting the required specifications without requiring tuning. A summary of the measured performance of the diplexers can be found in Table 2. When comparing the insertion loss (IL) of the highpass filter to the bandpass filter, it appears as though the highpass filter has a larger IL. This could be because of the isolation of the coupler being too low, allowing reflected waves to destructively interfere with the highpass filters passband. In this case, the isolation of the coupler can be improved by adding additional steps into the coupling region [15]. In addition, as the simulated scattering parameters where created using a perfect electrical conductor, plating the aluminium in silver could further help to improve the IL. However, the larger IL close to the cut off frequency is because of the high change of impedance as a result of the dispersive nature of the waveguide and will be difficult to improve. In this case, moving the passband away from the highly dispersive region would provide the best solution as is the case in this design. The bandpass filter rejection between 35.32–37.5 GHz varies by up to 8 dB from the simulated response. This is most sensitive part of the frequency response, and suggests that further work is needed to reduce the sensitivity of the bandpass filter to fabrication errors. Reducing the number of resonators in the bandpass filter could provide a solution. A photograph of the fabricated device can be seen in Fig. 10.

9 Conclusion

This paper has concerned itself with fabrication issues associated with millimetre wave diplexer circuits and how they can be relaxed. We find that the resonating structures contained within bandpass filter circuits contribute to fabrication tolerance. More specifically, the sensitivity of these structures increases towards the centre resonator in the bandpass filter where coupling is at its weakest. By targeting the most sensitive centre resonators and increasing their length from half wavelength to full wavelength we can improve the tolerance of the circuit without introducing spurious responses close to the passband. In addition to this, we find that the choice of iris discontinuity used to realised waveguide bandpass filters can help to relax fabrication tolerances. For example, the use of capacitive iris discontinuities over inductive iris discontinuities is recommended because of the positive length of the impedance inverter making the resonator lengths larger. From these considerations, we have proposed a novel Ka-band diplexer topology that consists of halve the number of resonating structures when compared with similar diplexer circuits in the literature [3, 4]. We achieve this by using a highpass filter/hybrid coupler topology in addition to a low order capacitive iris bandpass filter with full wavelength centre resonators. By subjecting our circuit to a tolerance analysis, we find that the structure can be fabricated with up to +0.07 mm tolerance at Ka-band frequencies while still meeting our design requirements. We validated our simulated results by fabricating two diplexers using an aluminium alloy, where the measured results agree very well with the simulated results. However, the results suggest that further work needs to be done to further reduce the sensitivity of the bandpass filter to fabrication errors.

10 Acknowledgment

The authors wish to acknowledge the support of EPSRC.

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MAP20140552

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Q1 Please check and confirm insertion of main caption for Fig. 1.