MMA 2018

‘Microwave and Millimetric Frequency Co-fired Dielectric and Ferrite Assemblies for 4G and 5G Circulator Devices’

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- Co-firing Process
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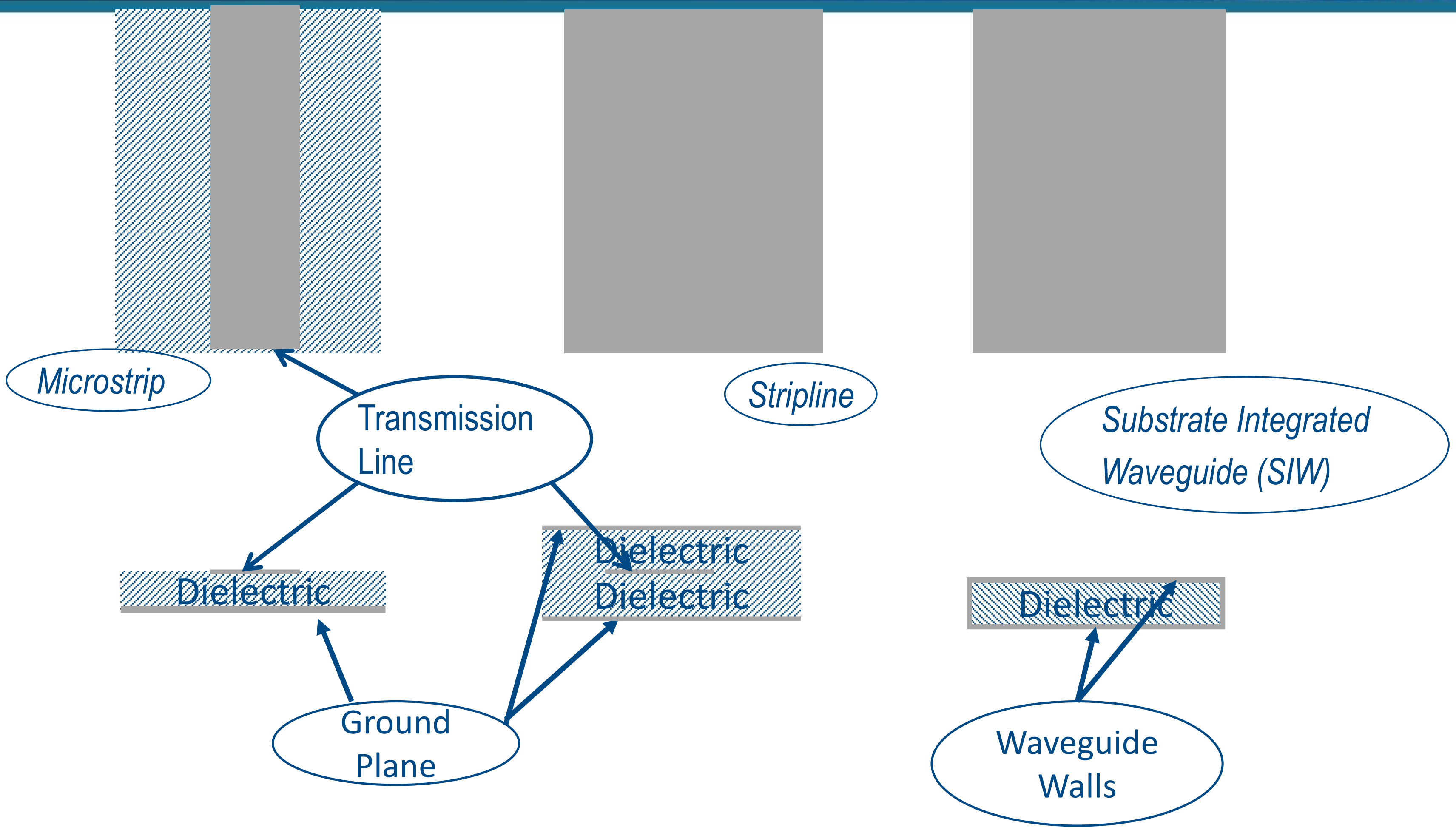
- SIW Circulators at 24 GHz
- Microstrip Circulators at 24 GHz
- Acknowledgements

Background to Microwave and Millimetric Circulators

Background :Top & Cross-section of Dielectric –based Transmission Lines used in Cellular Communications



Microstrip

Transmission Line

Stripline

Substrate Integrated Waveguide (SIW)

Dielectric

Dielectric

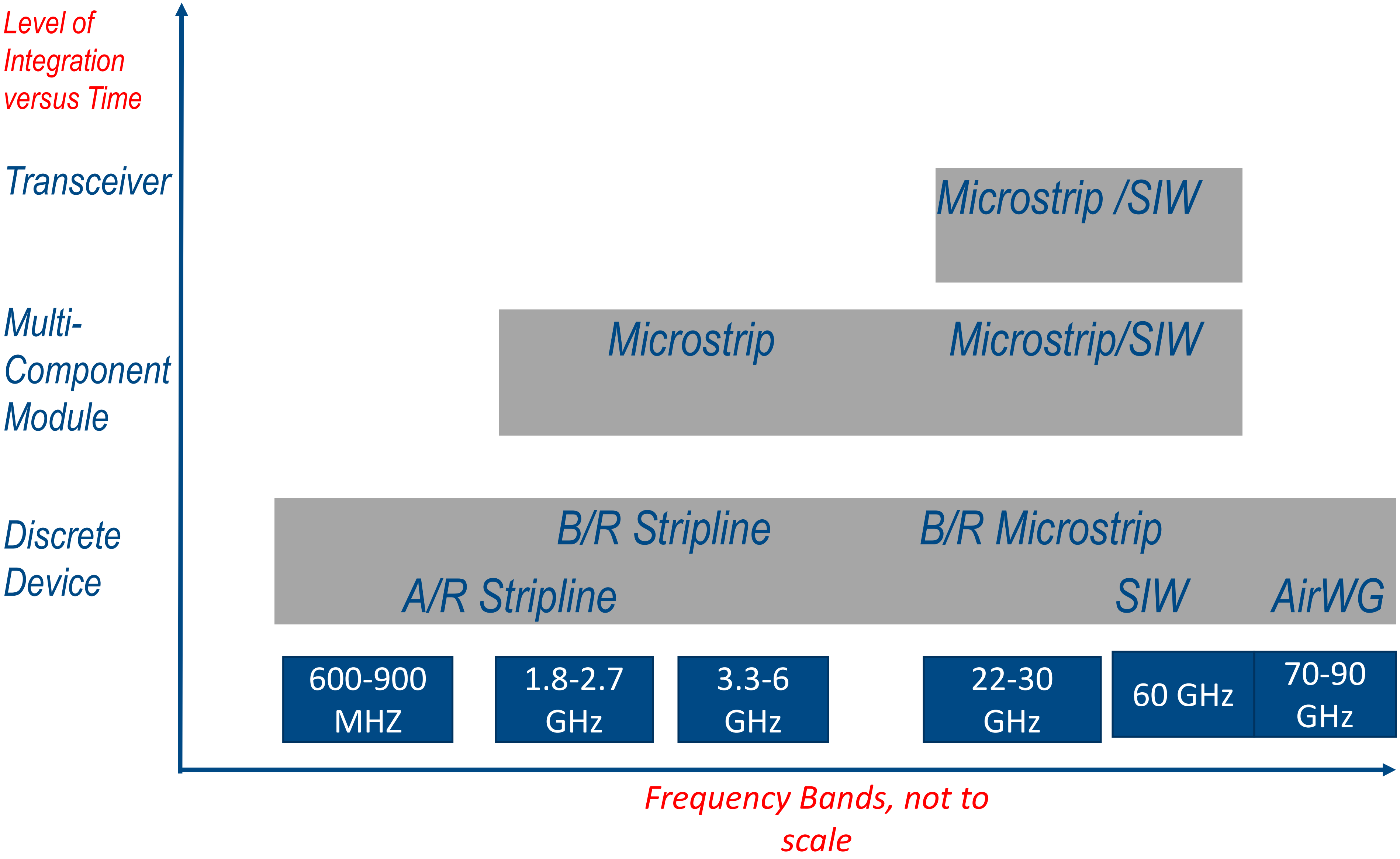
Dielectric

Dielectric

Ground Plane

Waveguide Walls

Base Station Transmission Line Usage/Integration versus Frequency



Level of Integration versus Time

Transceiver

Microstrip /SIW

Multi-Component Module

Microstrip

Microstrip/SIW

Discrete Device

B/R Stripline

B/R Microstrip

A/R Stripline

SIW

AirWG

600-900 MHZ

1.8-2.7 GHz

3.3-6 GHz

22-30 GHz

60 GHz

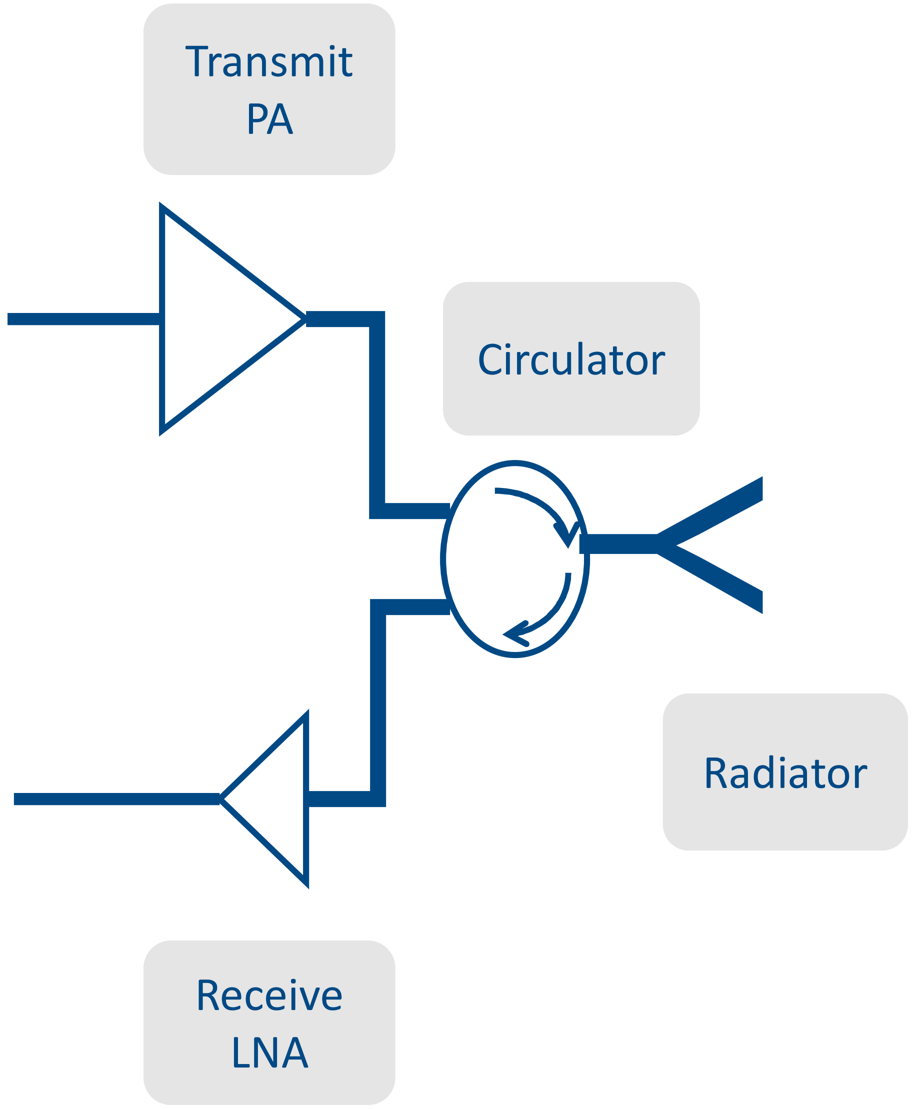
70-90 GHz

Frequency Bands, not to scale

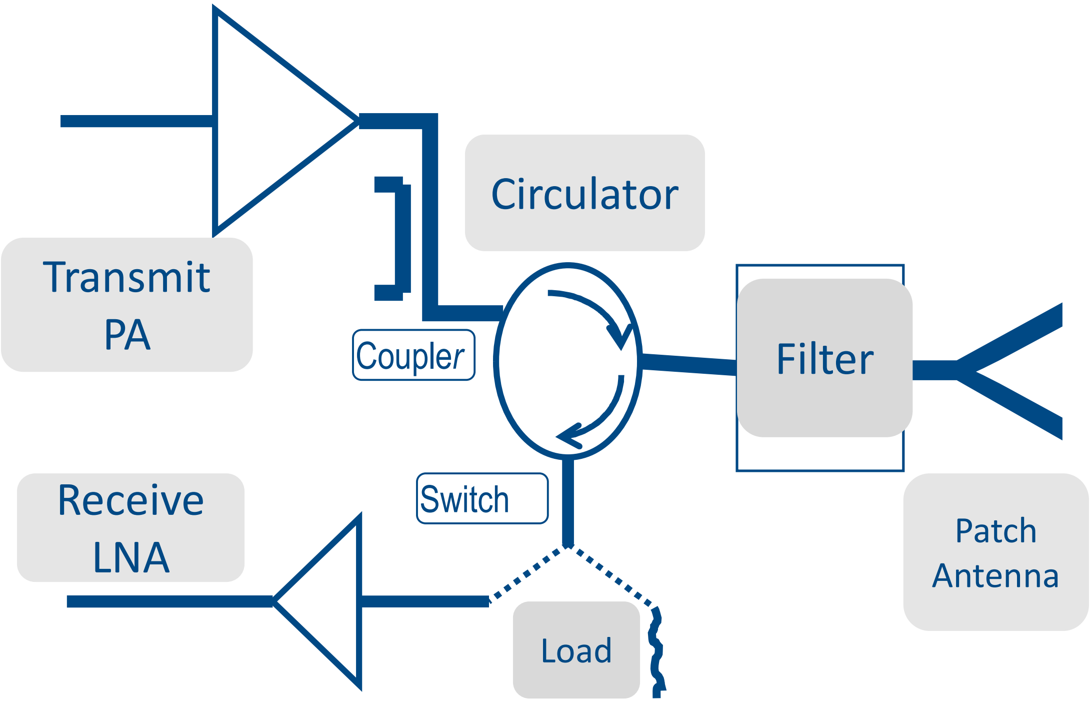
Role of Circulator in 5G Transceivers

- For 5G, one form of base station will be “Massive MIMO” based, with an array of perhaps 64-128 antennas capable of multi-beam forming to interact with handheld terminals, at very high data rates.
- One form of signal separation will be time division (TD) based, requiring a means of duplexing/switching to separate Tx and Rx signals
- Massive MIMO has been demonstrated with arrays of antennas, and is being deployed on 4G LTE
- This approach is similar to radar phased array T/R modules, with individual transceivers for each antenna element, although massive MIMO is not a phased array in the radar sense. The objective is optimum coherent signal strength at the terminals (handsets) rather than direction finding
- For discussion, it is assumed that there is one Tx, one Rx module, one duplexing circulator and one antenna filter per antenna.
- Simplified RF versions are shown, omitting drivers, switching logic, etc.

Simplified Duplexing Transmit Receive Module



Schematic of a ~4 GHz single band TDD



Objectives of Millimetric and Microwave Materials Program

1) Development of a range of low dielectric constant (e' ~8 to 30 plus) co-firable materials for microstrip and Substrate Integrated Waveguide (SIW) applications compatible with Yttrium and Bismuth garnets used at microwave frequencies, and Nickel Zinc spinel ferrites used at millimetric frequencies
2) Development of a series of circulator microstrip designs aimed initially at 3-6 GHz microstrip, then microstrip and SIW for 20-30 GHz frequency bands, capable of integration
3) Comparison of device results from the program with competing all-ferrite, hexagonal ferrite and non-magnetic circulator solutions, and solutions using soft substrate based dielectrics
4) Consider the merits of extending these device designs to even higher frequencies

All-Ferrite Microstrip Tile Issues and Solutions

SKYWORKS

Until now, microstrip all-ferrite devices have been used for point to point radios, and some military and satellite applications

- These suffer from performance issues because it is not possible to magnetically saturate the (usually square) all-ferrite tile uniformly, resulting in higher magnetic losses and variable permeability across the tile, and the use of larger magnets to achieve stronger and more uniform applied fields
- In device terms, this manifests itself as higher insertion loss, poorer power handling and increased intermodulation products
- By substituting dielectric for ferrite away from the active junction, we can use a disk of ferrite in a dielectric tile to improve performance.
- The presence of low loss dielectric in the circulator circuit allows us to consider integration of other passive devices such as couplers, switches and loads.
- Using organic glues to join the ferrite to dielectric however, introduces more losses and makes thick film metallization difficult; co-firing or inorganic glues are possible solutions

Co-firing Process

Co-firing Requirements for Microstrip Dielectric/Ferrite Tiles

SKYWORKS

Co-firing requirements

- A series of dielectric materials giving a range of dielectric constants of 8 to 30, with low dielectric loss and reasonable dielectric constant stability over a temperature range of -40 to 125C , and with compatible mechanical expansions and firing temperatures with the existing ferrite co-firing process.
- The existing co-firing process we use is not literally co-firing dielectrics and ferrite simultaneously, as this leads to significant inter-diffusion of Fe+3 and Ti+4 particularly, causing high dielectric loss at the interface.
- This unique Skyworks approach involves firing and machining rods of ferrite to their final diameter, then "heat shrinking" green pressed, green machined or green extruded dielectric tubes of shaped cross-section around the ferrite during co-firing, such that a strong mechanical joint is obtained, without residual stress and without air gaps occurring during subsequent thermal cycling, machining or metallization processes.

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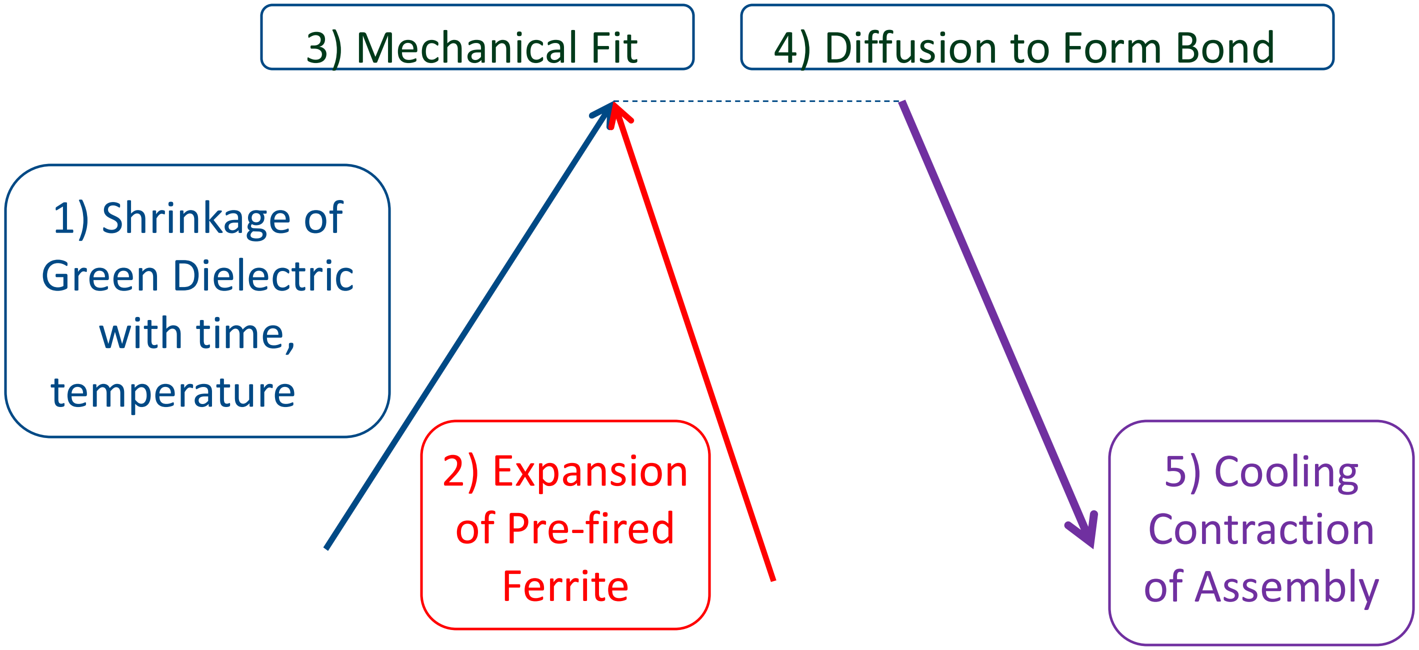
Co-fire Ideal Cycle : Ferrite and Dielectric Factors

- The ideal is that the OD of the pre-fired ferrite rod is exactly the same as the ID of the pressed dielectric tube at the end of the co-firing phase, but before cooling.
- Since the ferrite has a fixed expansion, this is done by adjusting the shrinkage and initial size of the dielectric, thru control of green density
- Diffusion occurs at the co-fire temperature after the ferrite and dielectric are in contact, forming a bond; too much diffusion may cause dielectric loss
- The ferrite and dielectric remain in contact thru cooling, because their expansion (contraction) coefficients are the same, retaining the bond

Co-Fire Process Steps



3) Mechanical Fit

4) Diffusion to Form Bond

1) Shrinkage of Green Dielectric with time, temperature

2) Expansion of Pre-fired Ferrite

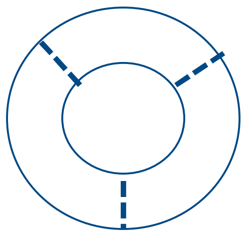
5) Cooling Contraction of Assembly

Step 1) and 2) are performed over temperature with the dielectric enclosing the ferrite, until the dielectric is fully shrunk and the parts are just in contact (step 3)
The process continues at that temperature until a bond is formed by diffusion (4)
The parts cool to room temperature, remaining in contact with a robust bond (5)

Co-fire, Non- Ideal conditions, for a rod tube assembly

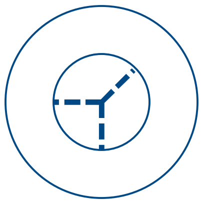
Expansion Dielectric>Expansion of Ferrite

- In this case, the ferrite is under compression, and is less likely to crack. If the surrounding dielectric is weak or thin, it will crack radially.



Expansion of Ferrite>Expansion of Dielectric

- In this case, the ferrite is under tension, and may be pulled apart, if bond is strong and dielectric is strong; A ferrite/ alumina failure indicates what can happen, because alumina has a lower expansion co-efficient. If the bond is weak, the ferrite will crack and gaps will open, however Garnet/MgTiO3+CaTiO3 success indicates some tolerance



Co-Firing for 3-6 GHz Circulators

Co-firing at lower frequencies

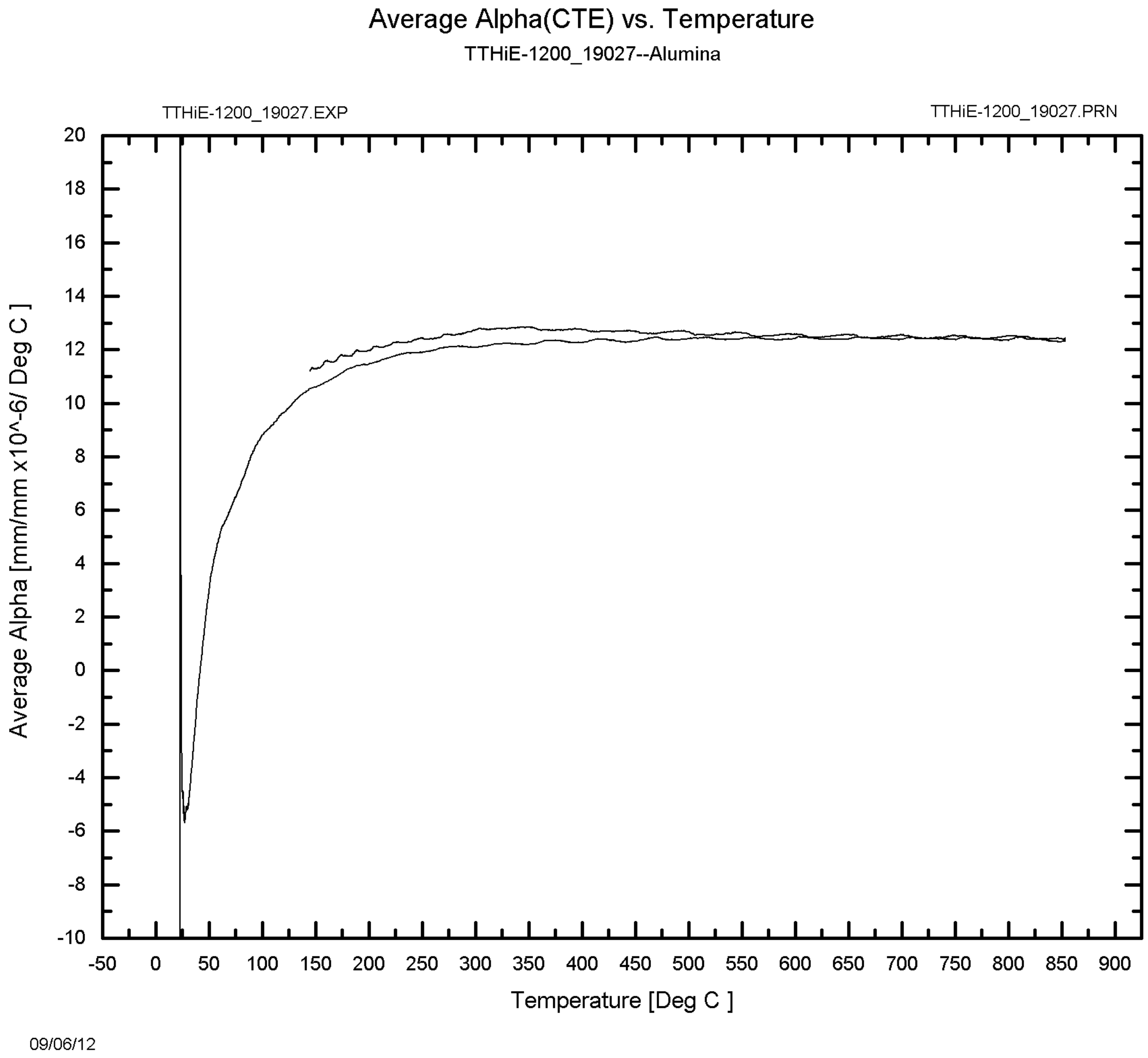
- We previously developed microstrip circulators for the 3-6 GHz band using co-fired $MgTiO_3$ Illmenite/$CaTiO_3$ Perovskite dielectrics with a dielectric constant of 20-30, and existing conventional YCaZrVFe garnets with dielectric constants from 14-16.
- We have also recently developed Bi substituted garnets ($Y_{3-x-2y}Bi_xCa_{2y}Zr_zV_yFe_{5-y-z}O_{12}$) with dielectric constants from 25-31. This is essential to take advantage of the high dielectric constant garnet’s ability to shrink the size of the microstrip tile.
- These have much lower firing temperatures and therefore are more difficult to match with corresponding co-fired dielectrics, so initial results were taken using circulators using inorganic glues to allow joining and metallization of $MgTiO_3$/$CaTiO_3$ dielectrics, but the same requirement for matching expansion co-efficients of dielectric and ferrite applies
- We continue to look for lower temperature firing, low loss, temperature stable dielectrics with such matching properties, with dielectric constants in the range 20-100.

Summary of Process for Co-fired Tiles at 3-6 GHz

Process requirements are obviously that the co-firing temperature must be less than the firing temperature of the ferrite, but allow full sintering of the dielectric. However other constraints apply. As mentioned previously, the mechanical dimensions of the fired ferrite rod and the green tube or machined block must be set such that at the end of the co-firing process, but before cooling, the parts are in contact with each other but not under stress. Also, as mentioned, the cooling stage of the co-fire operation require that the expansion co-efficients of the ferrite and dielectric are close enough to allow them to stay in contact without inducing stress in either part

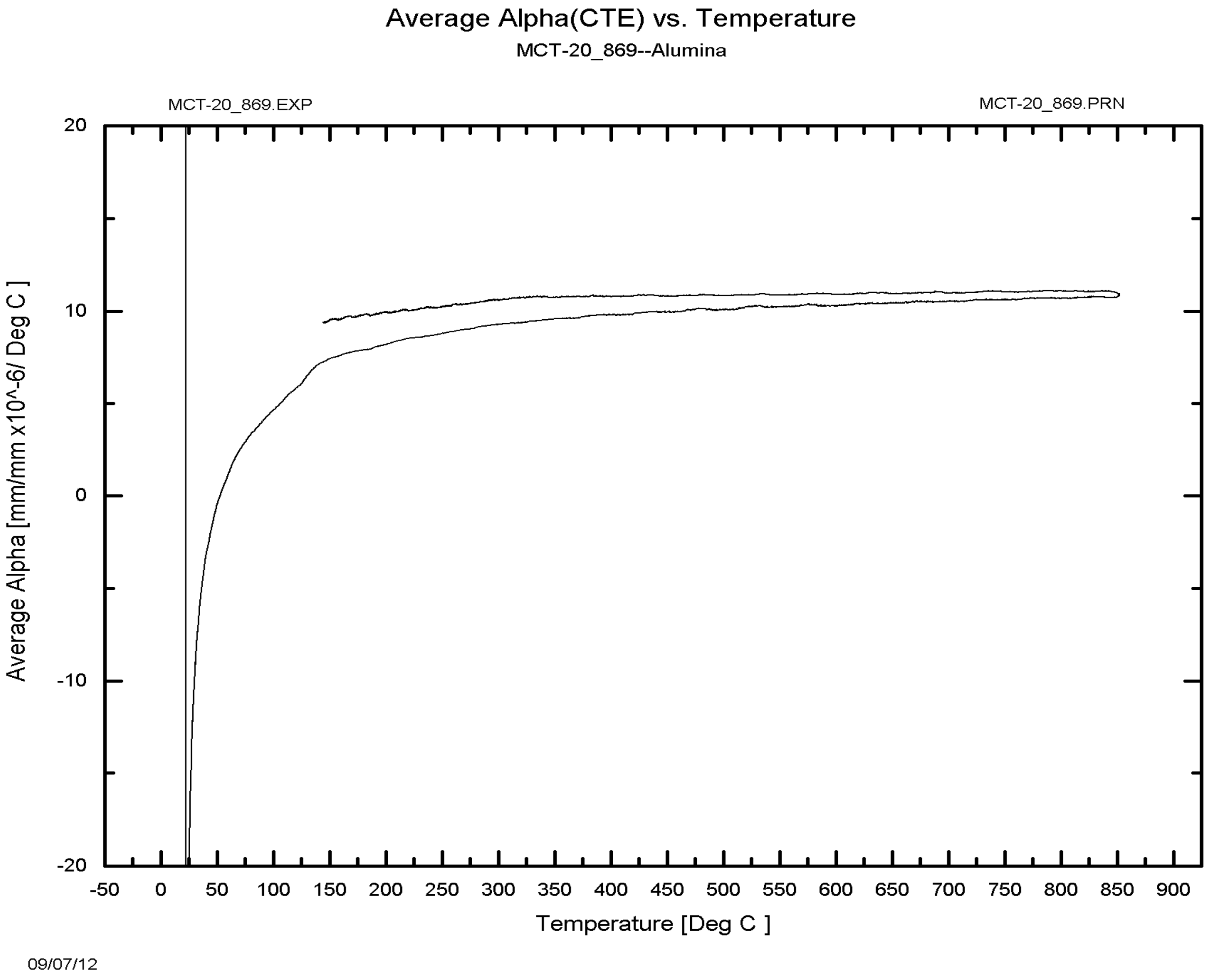
- For 3-6 GHz, it was possible to co-fire garnets from the $Y_{3-2x}Ca_{2x}Zr_yV_xFe_{5-x-y}O_{12}$ system with $MgTiO_3$/$CaTiO_3$ based dielectrics because these have compatible thermal expansion and co-firing temperatures
- Green machined blocks of dielectric were “heat-shrunk” around rods of conventional garnet to form an assembly, then sliced to form 25x 25 mm tiles.
- Thick film silver was then applied to create the microstrip circulator

Expansion of 3-6 GHz conventional YZrVFe Garnet

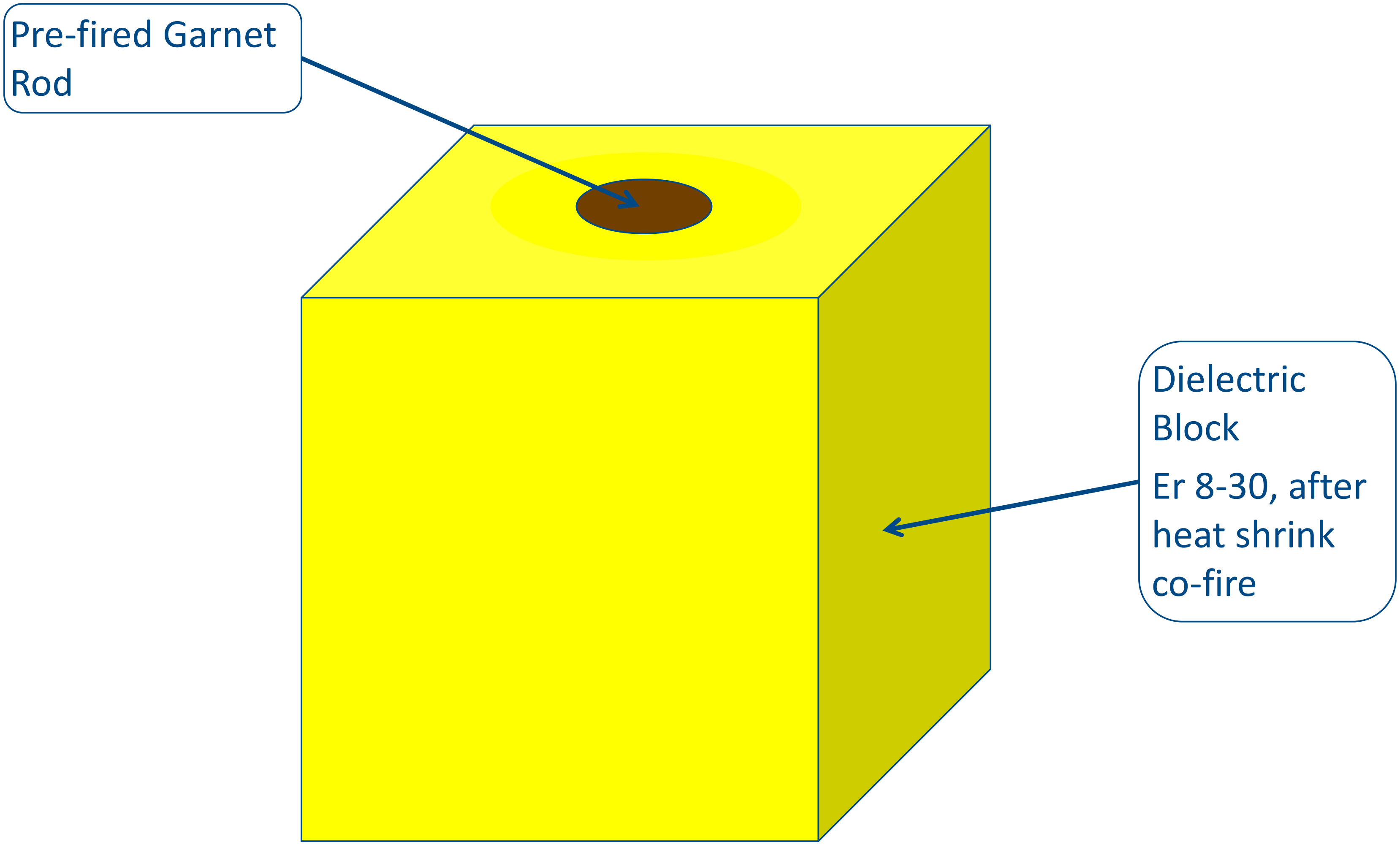


Expansion of MgTiO3/CaTiO3 Dielectric

SKYWORKS



Co-Firing Scheme for 2 part Microstrip Assembly prior to Slicing



Pre-fired Garnet Rod

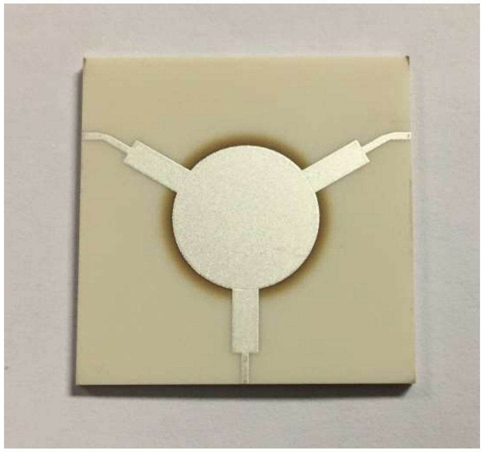
Dielectric Block

Er 8-30, after heat shrink co-fire

25x25mmMgTiO3-CaTiO3/Conventional YCaZrVFe garnet Co-fired Assembly as a Microstrip tile at 3.7 GHz

- Port Positions for Testing

Port 1

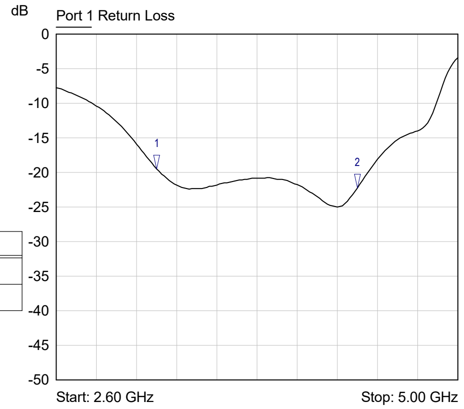


Port 2

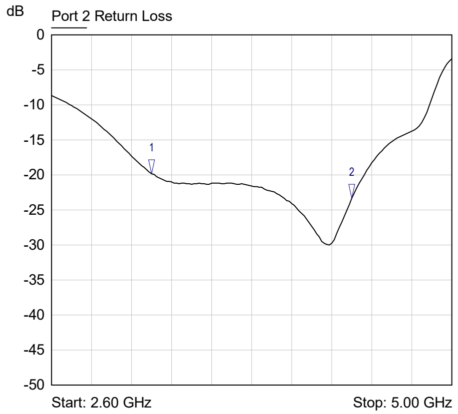
Port 3

D2000/TTVG1200 25 x 25 mm Co-fired Assembly Tested as a Microstrip 3.7 GHz Circulator

Mkr	Trace	X-Axis	Value
1 ▽	Port 1 - 2 Insertion Loss	3.20 GHz	-0.47 dB
2 ▽	Port 1 - 2 Insertion Loss	4.40 GHz	-0.40 dB

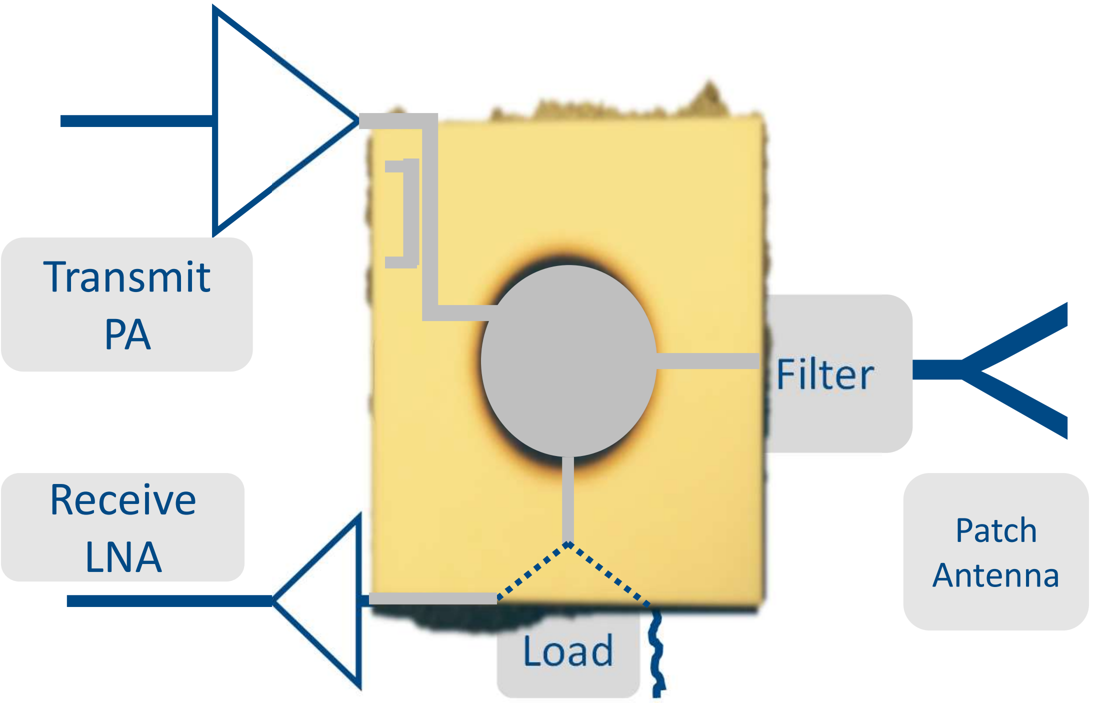


Mkr	Trace	X-Axis	Value
1 ▽	Port 1 Return Loss	3.20 GHz	-19.47 dB
2 ▽	Port 1 Return Loss	4.40 GHz	-22.27 dB



Mkr	Trace	X-Axis	Value
1 ▽	Port 2 Return Loss	3.20 GHz	-19.80 dB
2 ▽	Port 2 Return Loss	4.40 GHz	-23.37 dB

Proposed Integration of Microstrip Circulator/ Coupler/ Switch/ Load Assembly into a 3-6 GHz 5G Transceiver


Transmit PA

Receive LNA

Filter

Patch Antenna

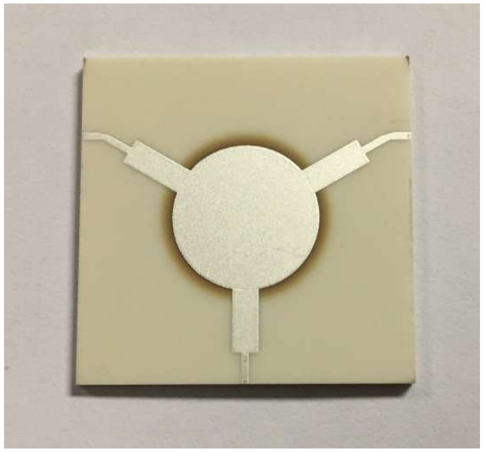
Load

Not to Scale

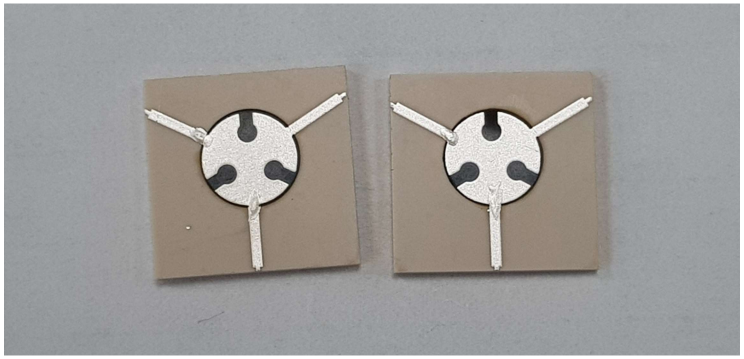
Reducing Size at 3-6 GHz

- Although the microwave performance was good, the dimensions of the tile at 3.7 GHz are too large for some MIMO applications
- The new garnet system based on BiYZrVFe, because of its high dielectric constant, and with some circuit adjustment, reduces the area of the device by a factor of 3, allowing us to reduce the overall tile dimensions from 25 x 25 mm to 15 x 15 mm.
- Because we do not yet have a compatible dielectric to co-fire with BiYZrVFe, the same $MgTiO3/CaTiO3$ dielectric system was used but was fired separately, then machined to fit the fired garnet rod. The requirement to match expansion co-efficients still applies, however, for thermal processing of gluing, metallizing and device temperature operation
- It was glued to form an assembly, sliced to the required tile size, then metallized

15x15mm 3.7 GHz TTHiE 1200/D20 Microstrip Circulator



original 25 x 25 mm co-fired device with standard garnet,, dielectric constant 14

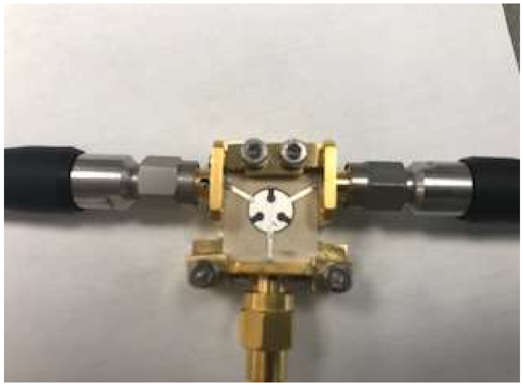


new 15 x 15mm device with Bi garnet, dielectric constant 27

15 x 15mm Microstrip Circulator

- The 15 x15mm tile is a combination of YCaZrVFe garnet and a MgTiO3/ CaTiO3 dielectric with dielectric constant of 30. The test port designations are shown below

Port 1

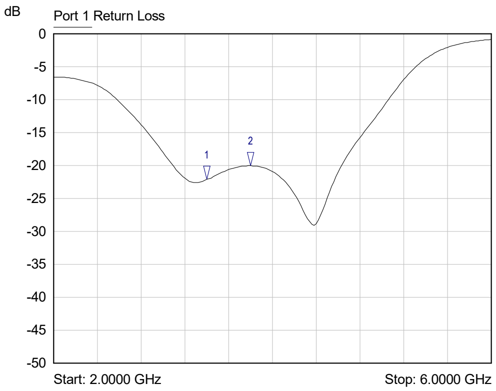


Port 2

Port 3

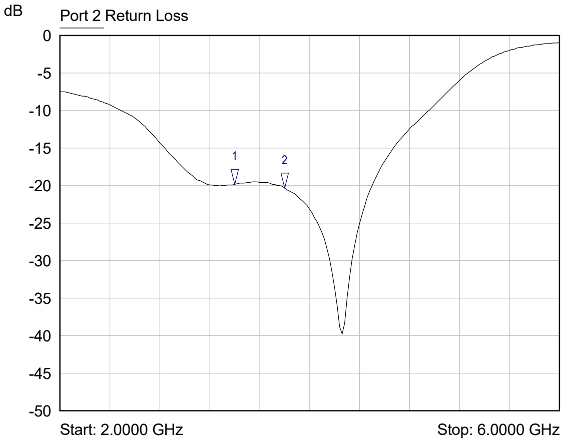
15 x 15mm S-parameter Measurements

- Port 1 Return Loss



Mkr	Trace	X-Axis	Value
1 ▽	Port 1 Return Loss	3.4000 GHz	-22.08 dB
2 ▽	Port 1 Return Loss	3.8000 GHz	-19.99 dB

- Port 2 Return Loss



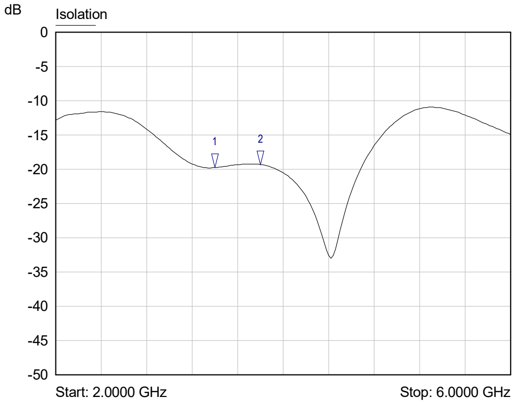
Mkr	Trace	X-Axis	Value
1 ▽	Port 2 Return Loss	3.4000 GHz	-19.80 dB
2 ▽	Port 2 Return Loss	3.8000 GHz	-20.35 dB

15 x 15mm S-parameter Measurements

- Insertion Loss (Includes the loss of the test connectors)

Mkr	Trace	X-Axis	Value
1 ▽	Insertion Loss	3.4000 GHz	-0.33 dB
2 ▽	Insertion Loss	3.8000 GHz	-0.36 dB

- Isolation



Mkr	Trace	X-Axis	Value
1 ▽	Isolation	3.4000 GHz	-19.78 dB
2 ▽	Isolation	3.8000 GHz	-19.31 dB

Co-Firing for 24 GHz Circulators

Co-firing Materials for Millimetric Frequencies

The magnetic and dielectric requirements at millimetric frequencies are quite different to 3-6 GHz. The magnetization of the ferrite needs to be around 5000 Gauss, necessitating a Nickel Zinc spinel ferrite, and the maximum dielectric constant of the dielectric has to be considered to avoid moding issues in the microstrip transmission lines.

The key to this is obviously matching the expansion co-efficients carefully. As the ferrite expansion co-efficient cannot be changed without affecting it's magnetic properties, the adjustment is made to the dielectric composition, taking into account the intended dielectric constant, as was done with 3-6 GHz garnet and dielectric

This was done by looking at the range of compositions possible with the MgO-TiO2-Al2O3-ZnO system, by using solid solutions of the spinels Mg2TiO4 and MgAl2O4, with small additions of Al2O3 and ZnTiO3 to create compatible expansion co-efficients and dielectric constants

Dielectric constants were measured using X-band cavity perturbation and TE dielectric resonator techniques, expansion by standard dilatometry

Because known compatible materials existed for dielectric constants of 16, 20 and 30, the emphasis was on the range 8 to 13.

Available SIW and Microstrip Low Dielectric Constant Dielectrics

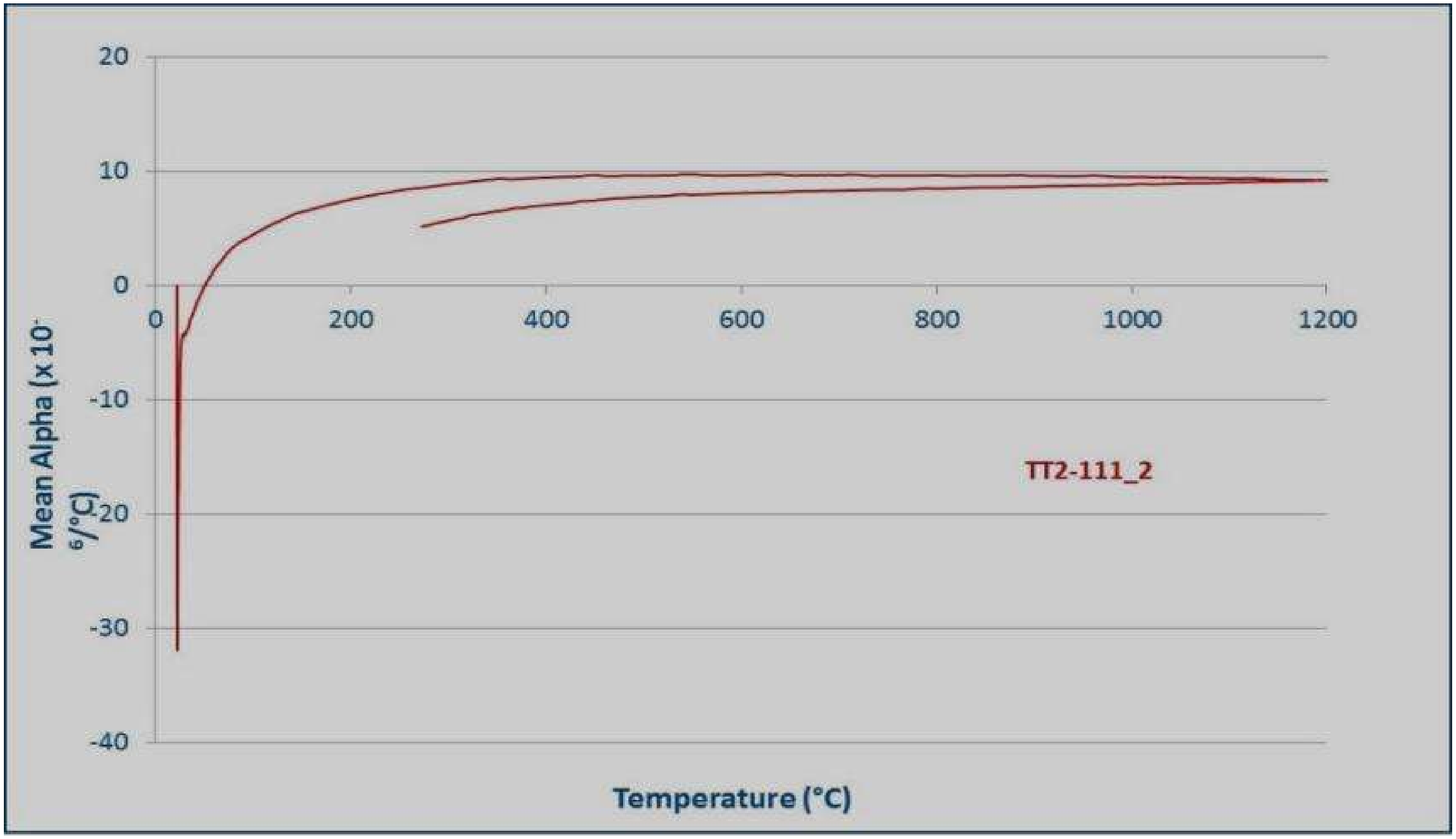
- Technical Approach: Based on the EM simulations, best approach seemed to be co-firable versions of the spinel end member materials $MgAl_2O_4$ and Mg_2TiO_4.
  - For Microstrip, $MgAl_2O_4$ based, with a target dielectric constant of 8
  - For SIW, Mg_2TiO_4 based, with a target dielectric constant of 13, as 16 and 20 materials existed in Skyworks TransTech
  - For both SIW and Microstrip, an expansion co-efficient of ~9.5 cm/cm/C at the co-fire temperature appeared to be required, based on measured NiZn ferrite data
- Firing tests at standard co-firing temperatures showed good densities, but at temperatures too close to NiZn ferrite, creating possible severe interdiffusion, so adjustments in composition were made to reduce co-firing temperatures/time, and to adjust expansion to be as close as possible to the ferrite.

Microstrip and SIW Materials Dielectric Compositions

Material Examples of Target Dielectrics of 8 for microstrip and 13 for SIW	*Firing Temperature*	*Measured Dielectric Constant*	*Density (g/cc)*	*Shrinkage*	*Estimated Thermal Expansion Coefficient (ppm/˚C) at co-fire temp.*
84.9 mole % $MgAl_2O_4$ + 8.95 mole % $ZnTiO_3$+ 6.15 mole % Al_2O_3	1310 C/4h	7.27	3.332	Not fully dense	~8.5
	1360/4h	7.97	3.569	Fully Dense	~8.5
84.9 mole % Mg_2TiO_4 + 8.95 mole % $ZnTiO_3$+ 6.15 mole % Al_2O_3	1310 /9h	12.47	3.288	Not Fully Dense	~10.5
	1360/9h	13.27	3.498	Fully Dense	~10.5

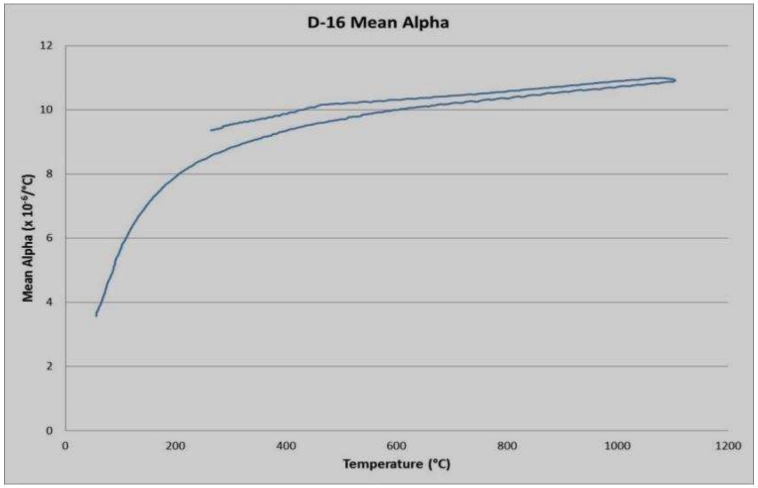
Expansion of NiZn Ferrite

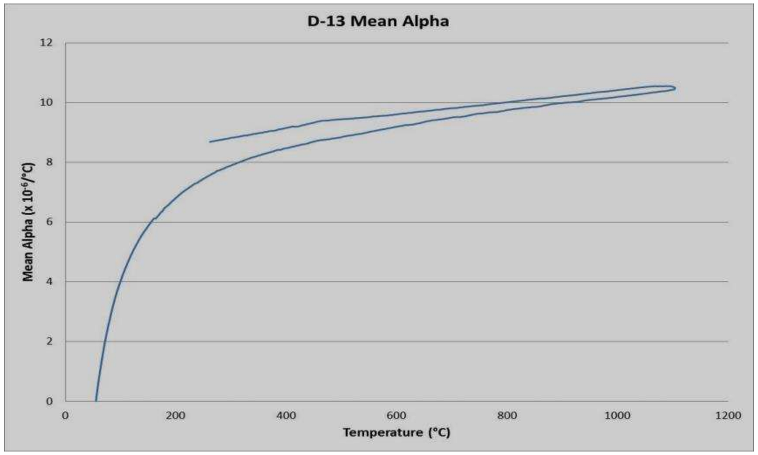
- Dilatometer expansion and contraction curve for NiZn Spinel Ferrite, ~9.5 cm/cm/C at co-fire temperature



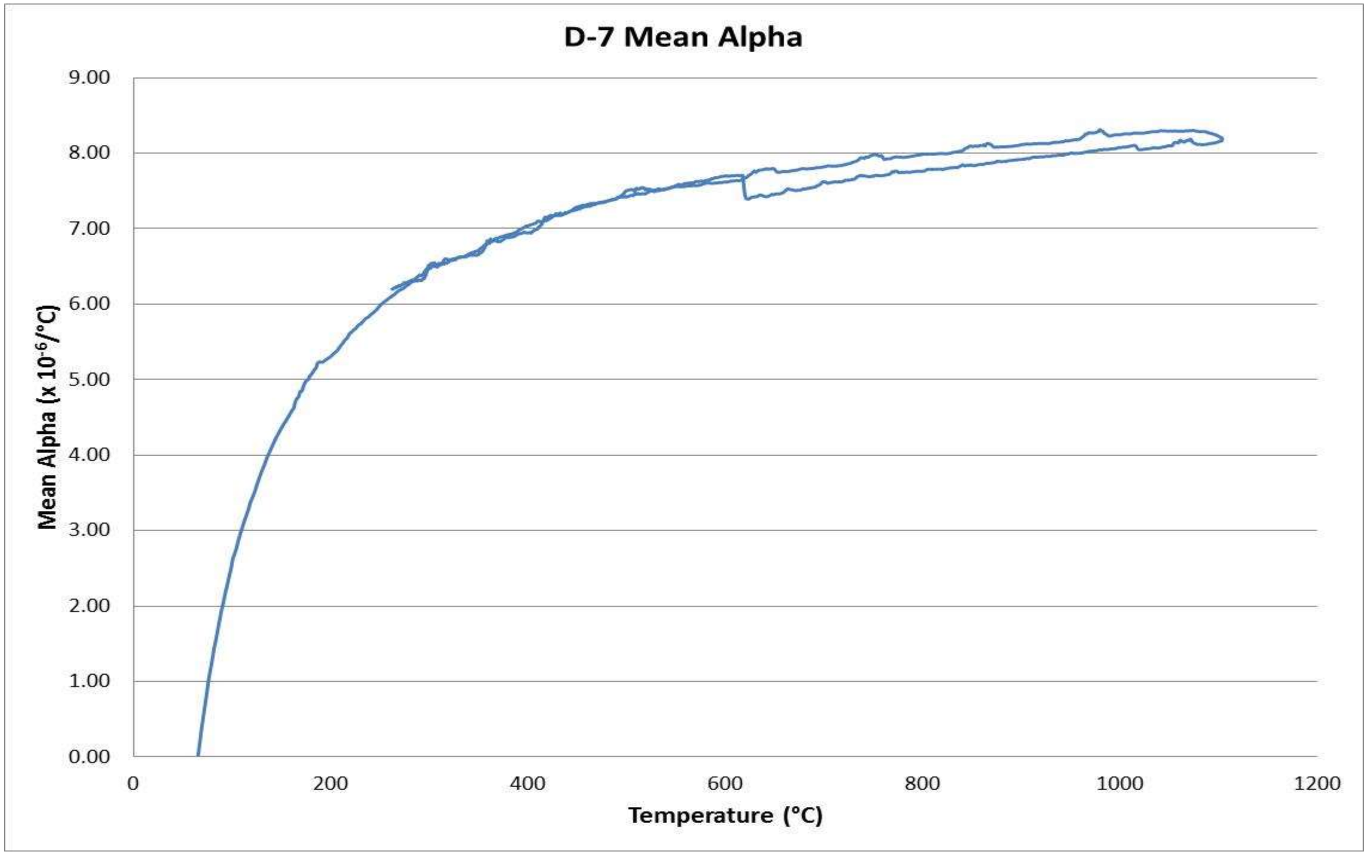
Expansion of Dielectrics for SIW

- An existing dielectric with a dielectric constant of 16 existed, and with minor modification had an acceptable expansion co-efficient, so no further work required
- The expansion of the experimental co-fire material with dielectric constant of 13 was adjusted to give acceptable results



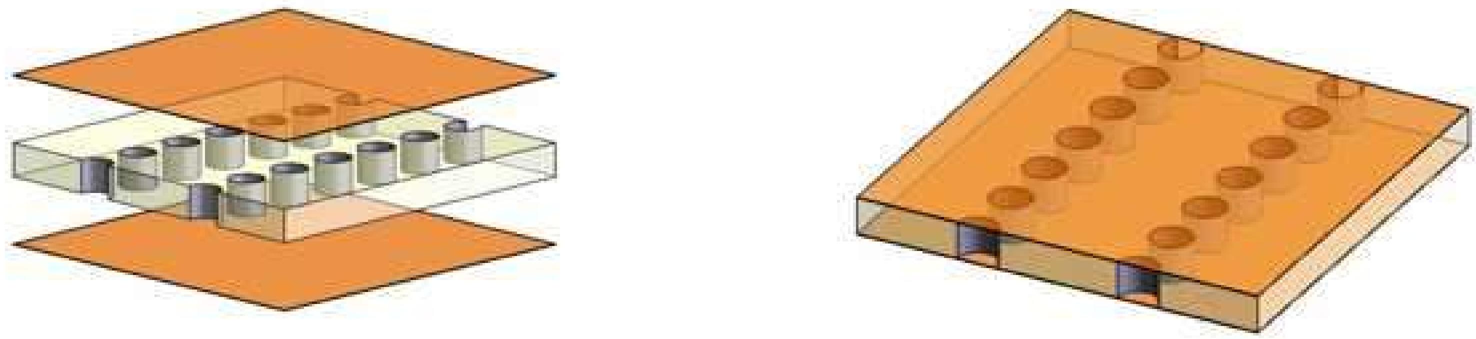


Expansion of Dielectric with Dielectric Constant of ~8 for Microstrip

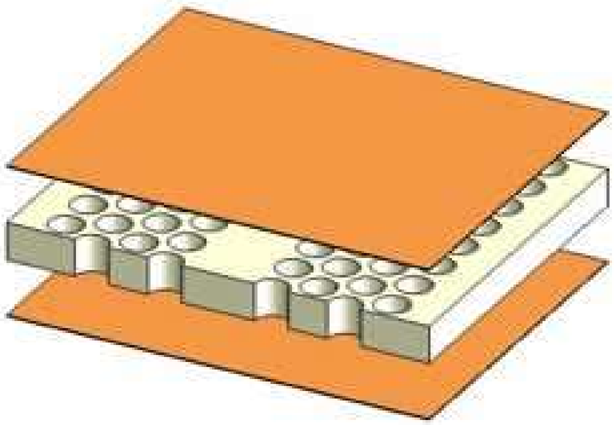


SIW Circulators at 24 GHz

Current SIW Transmission Lines using Vias at Millimetric Frequencies



(a)



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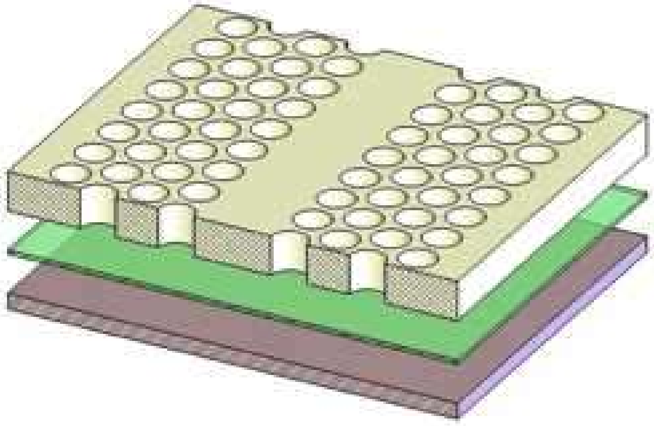
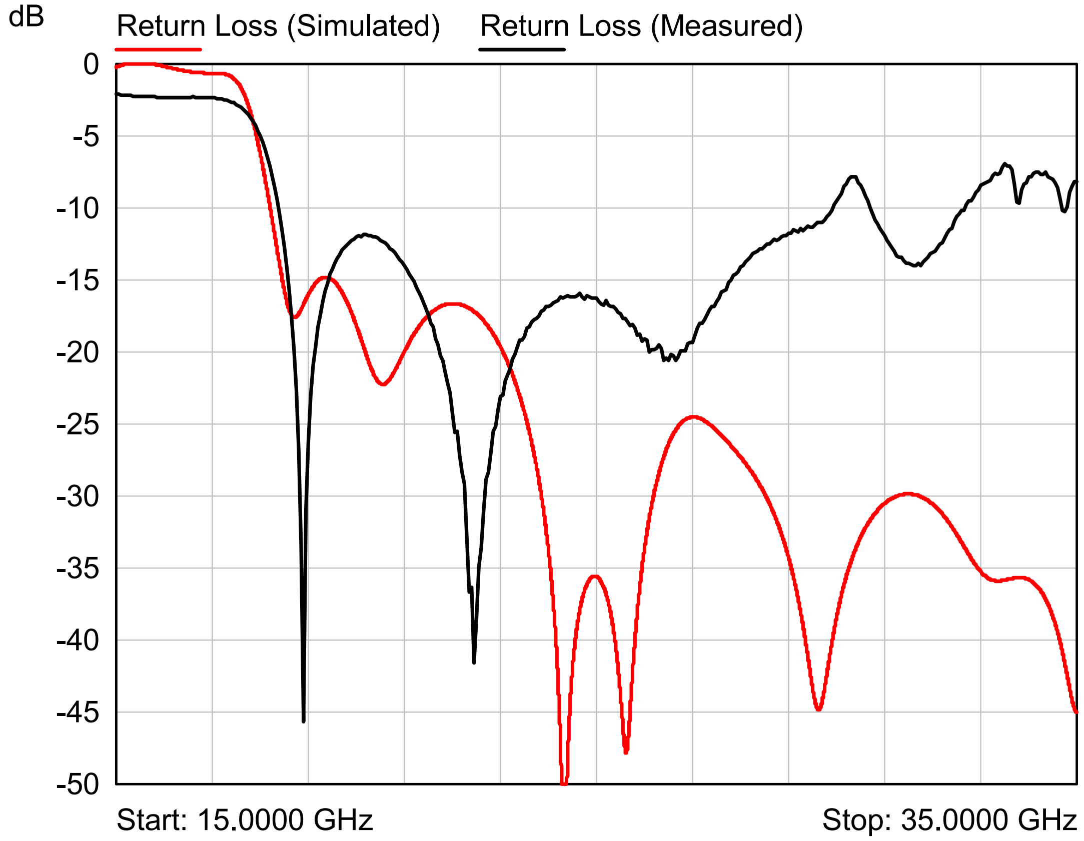


(c)

Choice of Dielectric for Ceramic/Thick Film SIW

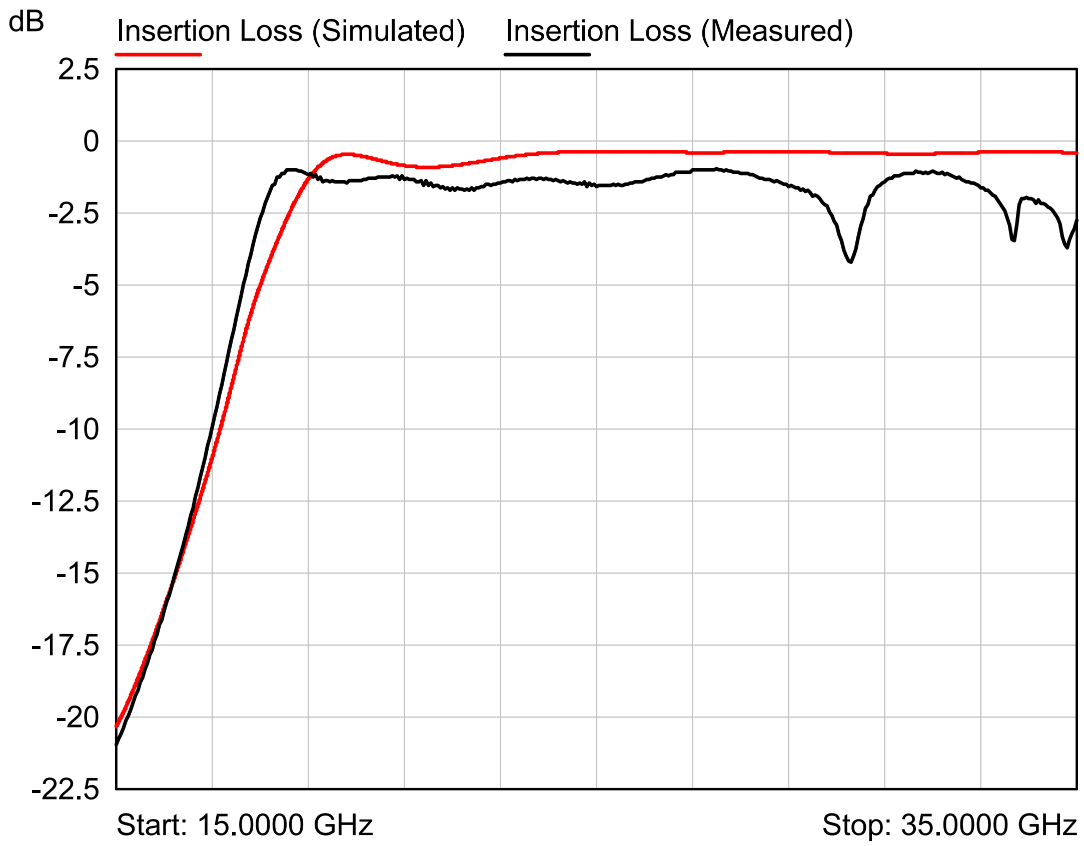
- Before attempting to make a co-fired SIW device, it was necessary to test out transitions between microstrip and SIW transmission lines in an existing dielectric constant of 20, as this is rather high for mode-free operation in microstrip at 20-30 GHz, but would give the smallest device
- The transition was made from a simple slab of dielectric suitably thick film silver printed with an SIW section at the center and in and out microstrip transitions

Return Loss of Microstrip SIW Transition



Insertion Loss of Microstrip SIW Transition

SKYWORKS

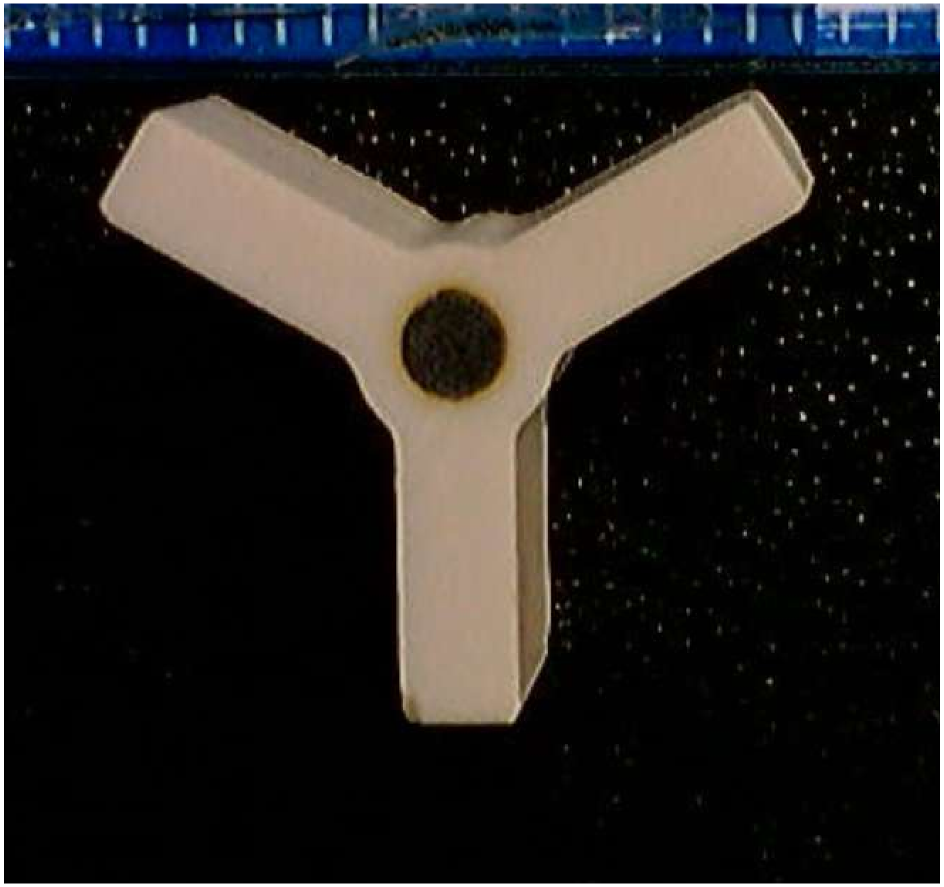


SIW Fabrication

- Initial simulation showed that it might be possible to fabricate a SIW based circulator based on a combination of NiZn spinel ferrites and an existing co-firable 20 dielectric constant dielectric, as it had a compatible firing temperature and matching expansion co-efficient
- The SIW shape was created by green machining the 20 dielectric to the required Y shape, with a hole in the y-junction to accommodate the machined ferrite rod of the approximate same length
- These were adjusted in dimensions to achieve matching sizes after co-firing to give good mechanical integrity
- The co-fired piece was then sliced to the required SIW narrow wall and microstrip transition thickness, then metallized using silver thick film ink to the desired pattern

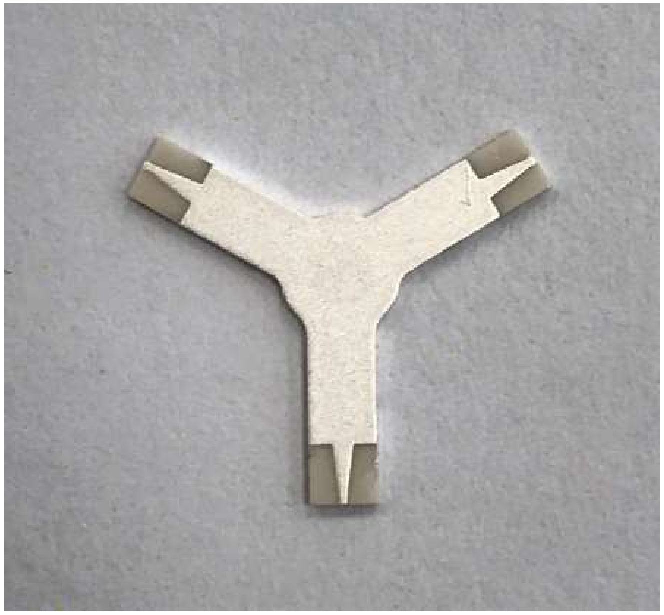
Co-Fired Fabrication; NiZn ferrite and dielectric

- Co-fired assembly before slicing and metallizing

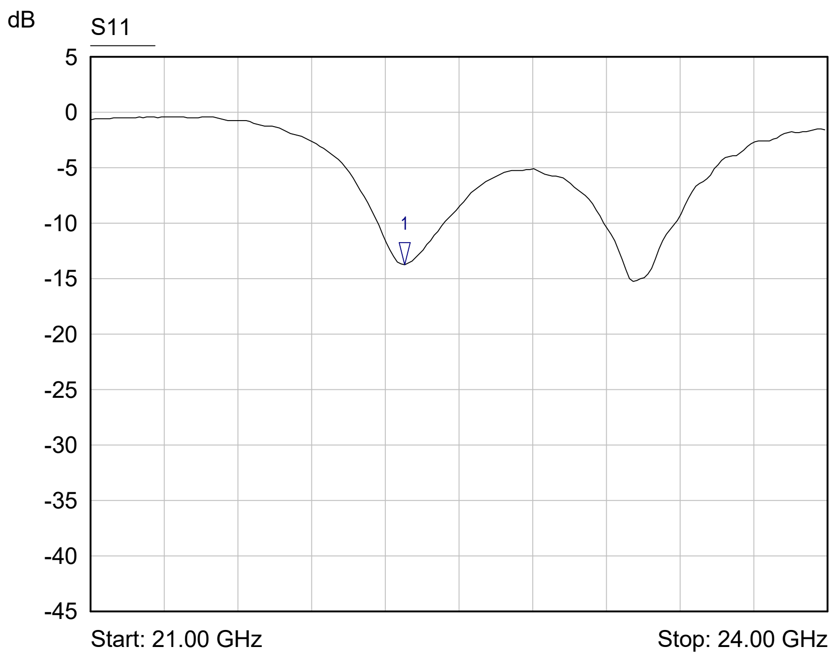


Finished SIW Circulator

- SIW Circulator using NiZn ferrite and dielectric constant of 20 (magnet omitted for clarity)



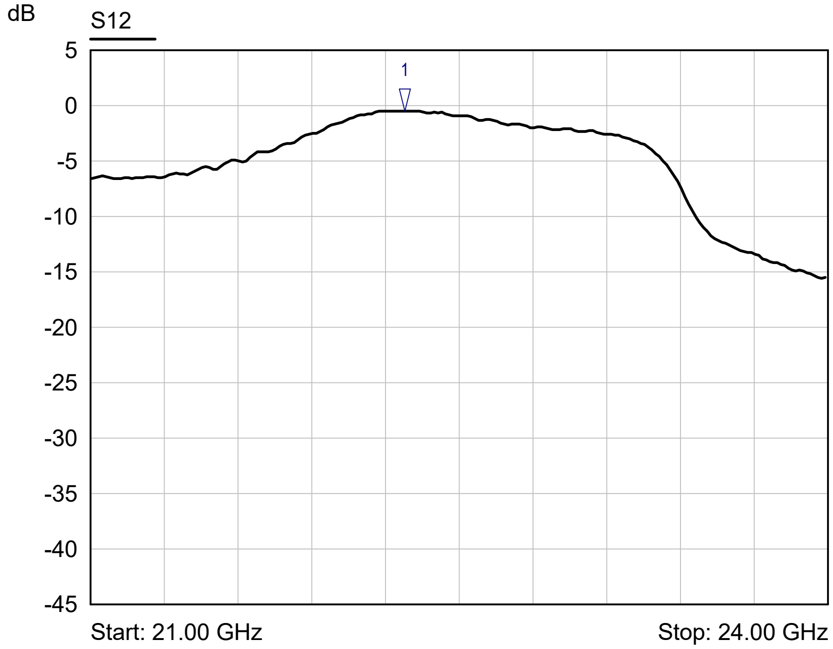
SIW Return Loss Port 1 and 2



Mkr	Trace	X-Axis	Value
1 ▽	S11	22.28 GHz	-13.73 dB

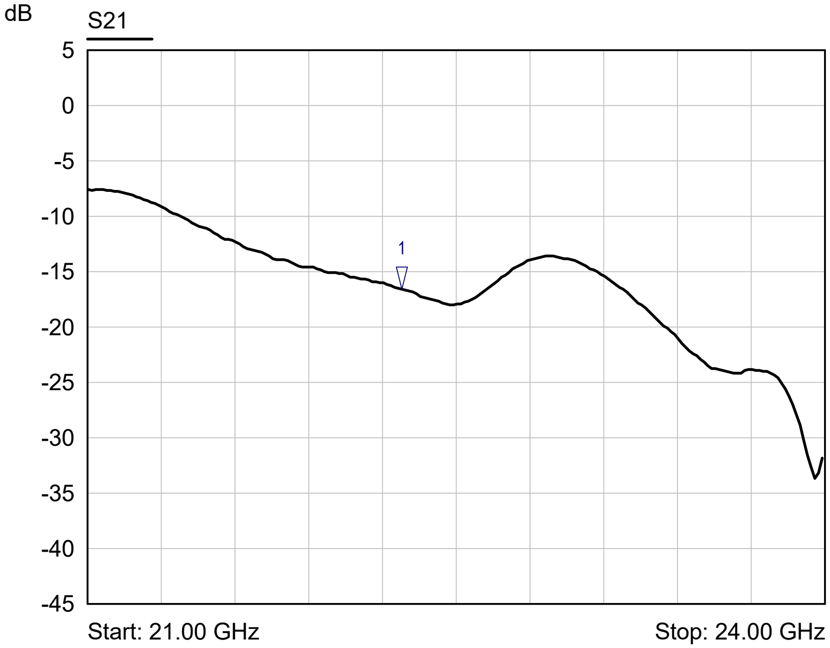
Mkr	Trace	X-Axis	Value
1 ▽	S22	22.28 GHz	-15.48 dB

SIW Insertion Loss



Mkr	Trace	X-Axis	Value
1 ▽	S12	22.28 GHz	-0.52 dB

SIW Isolation



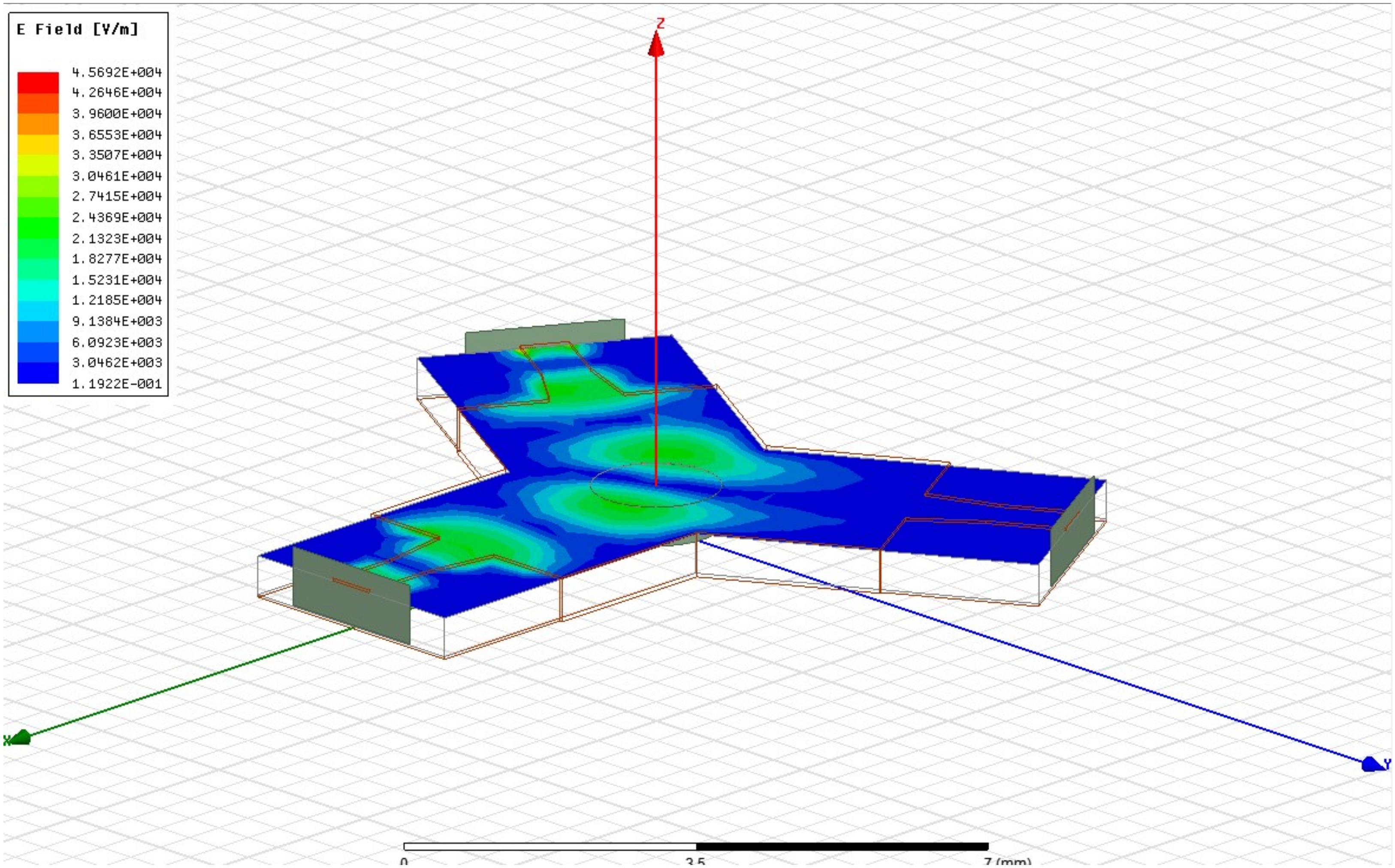
Mkr	Trace	X-Axis	Value
1 ▽	S21	22.28 GHz	-16.60 dB

SIW Circulator Dielectric Choice

- First prototype SIW circulator showed promise, with very low insertion loss (<0.5 dB) reasonable return loss (low reflections) but poor isolation
- The TT2-111/D20 combination results in an operating frequency of around 22.25GHz, too low for the application
- A lower dielectric constant dielectric material is required to shift the frequency up.
- Simulation software and data feedback from the first prototype indicated this should be in the range 13 to 16
- SIW Devices are being fabricated and tested currently using lower dielectric constant dielectrics

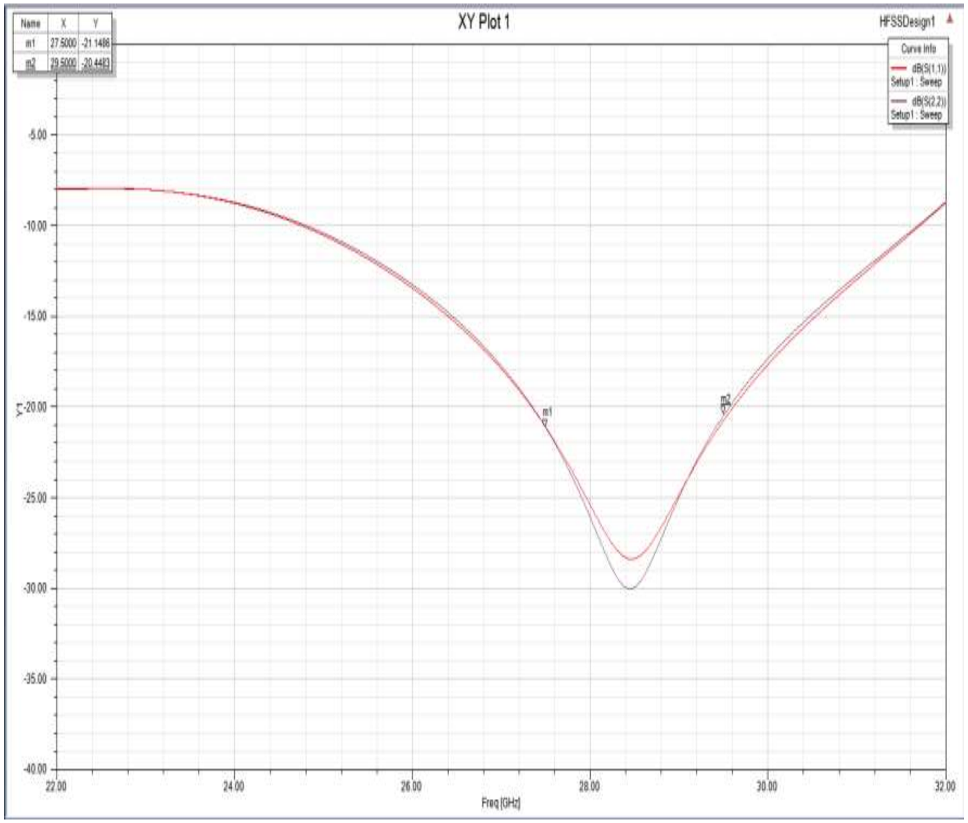
SIW Simulation

- Simulation of SIW Circulator

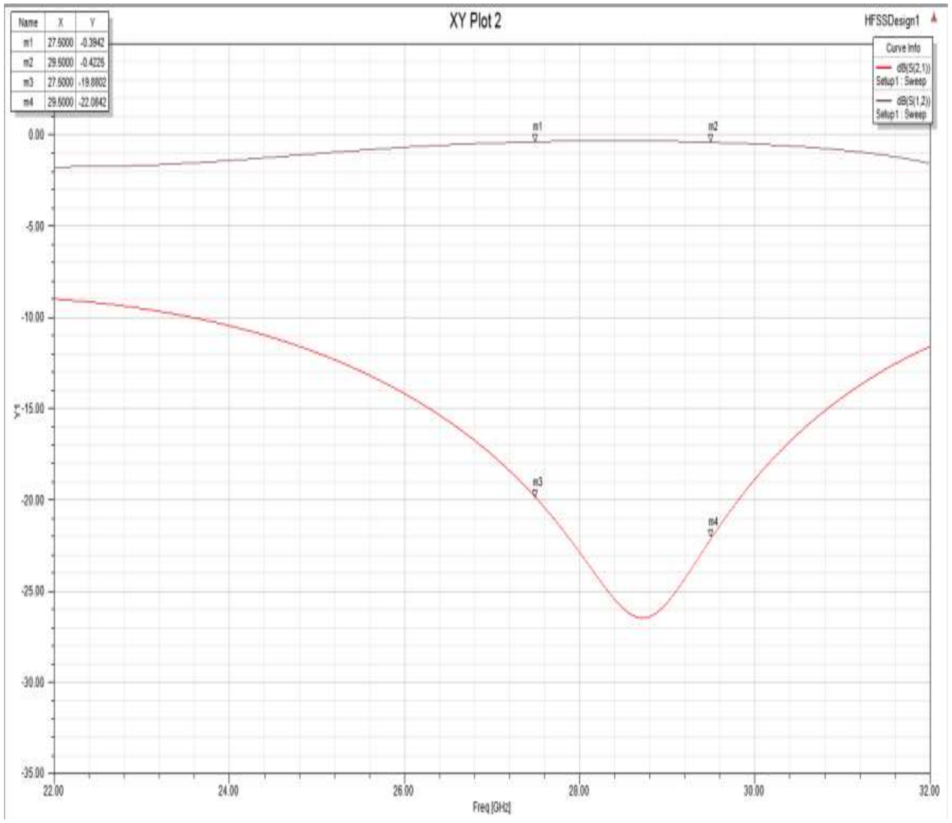


SIW Simulation

- Simulation of Return Loss, Insertion Loss and Isolation



Name	X	Y
m1	27.5000	-21.1486
m2	29.5000	-20.4483



Name	X	Y
m1	27.5000	-0.3942
m2	29.5000	-0.4226
m3	27.5000	-19.8802
m4	29.5000	-22.0842

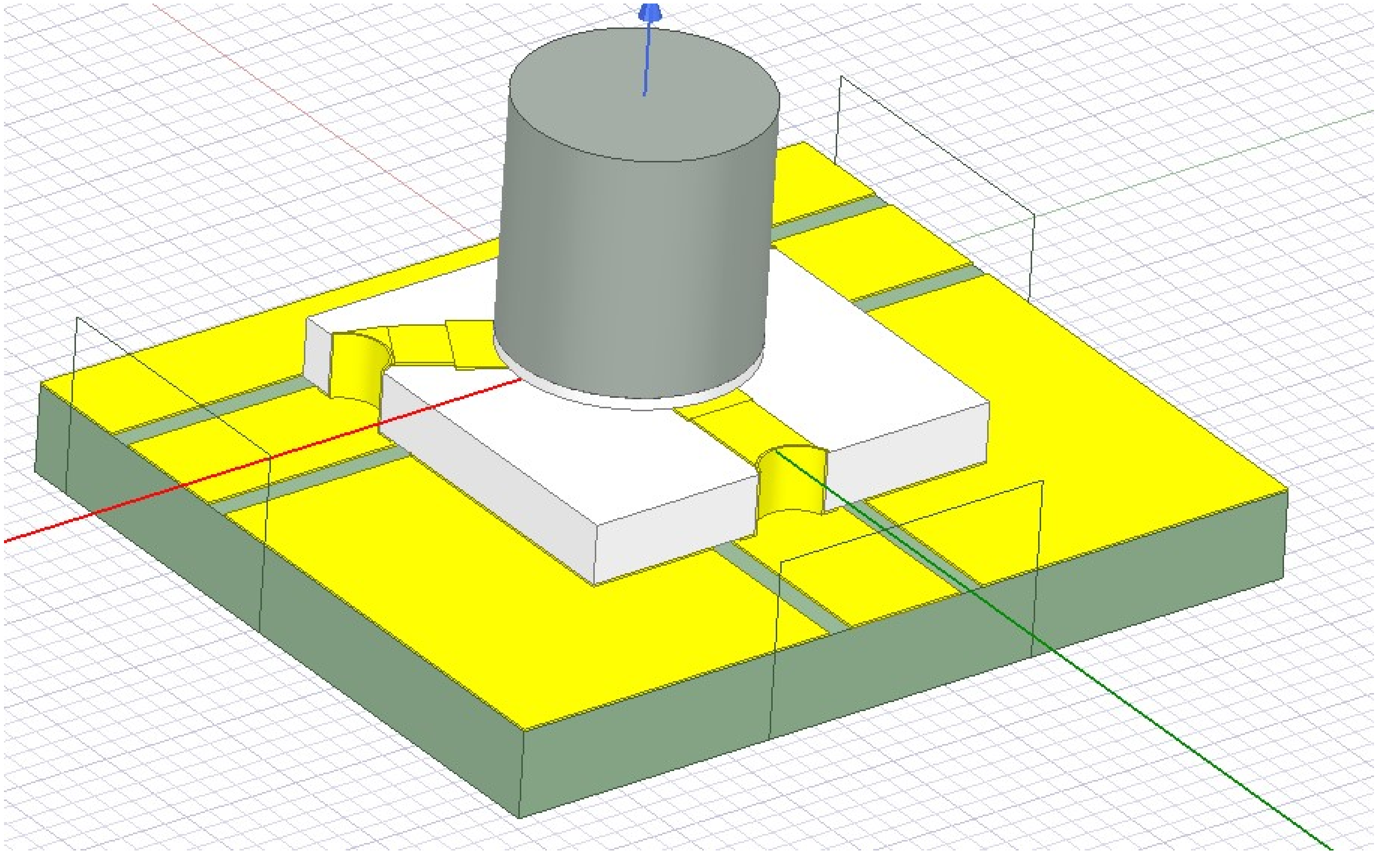
Microstrip Circulators at 24 GHz

Microstrip Simulation at Millimetric Frequency

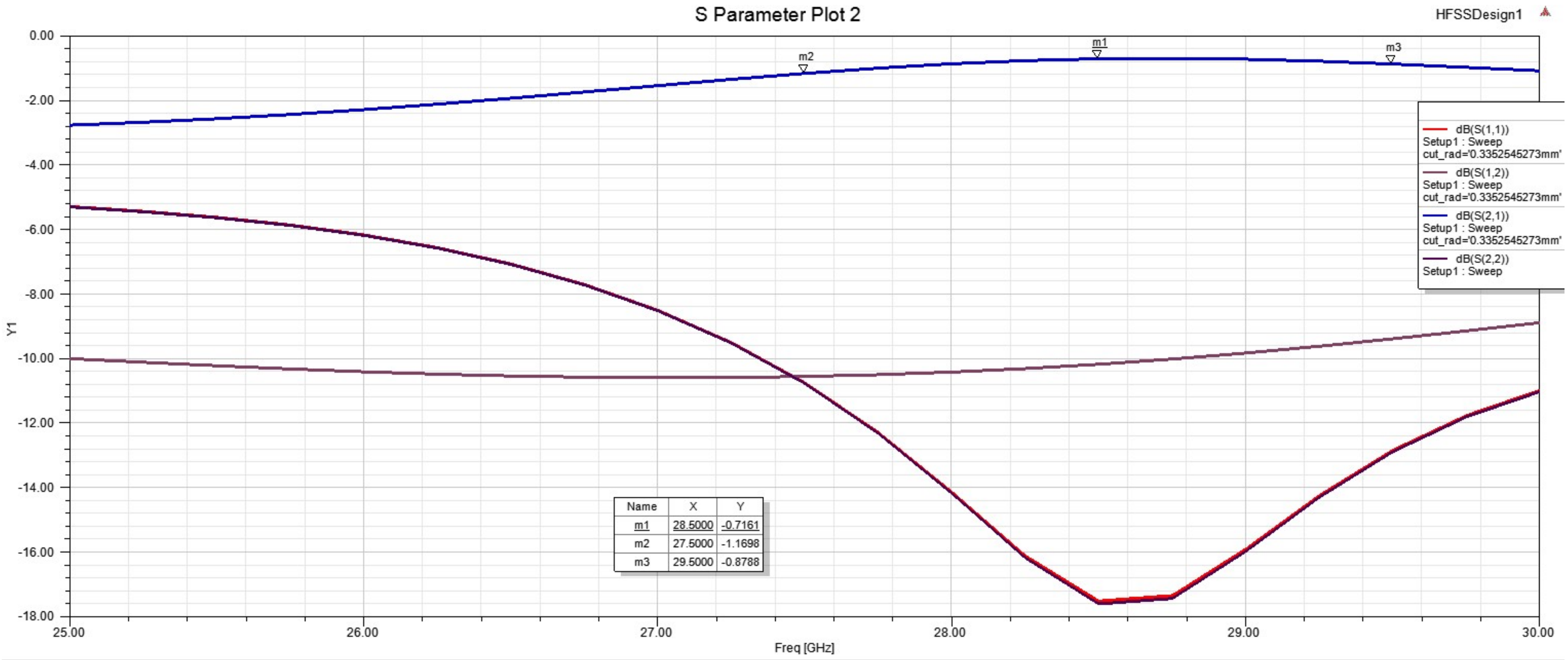
Simulation of a Microstrip Circulator at the same frequency as the SIW circulator showed that a different dielectric constant, approximately 8, would give good isolation and return loss

This was modeled both as a “drop-in” circulator as used at 3-6 GHz, and as a surface mount (SMT) circulator.

Millimetric SMT Microstrip tile with edge via transitions



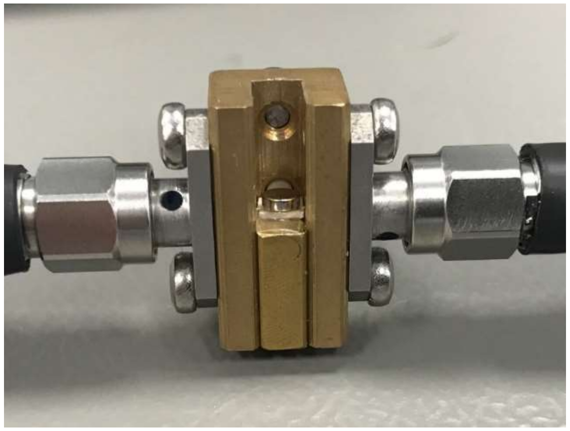
Simulated S-parameters for edge via transitions



Name	X	Y
m1	28.5000	-0.7161
m2	27.5000	-1.1698
m3	29.5000	-0.8788

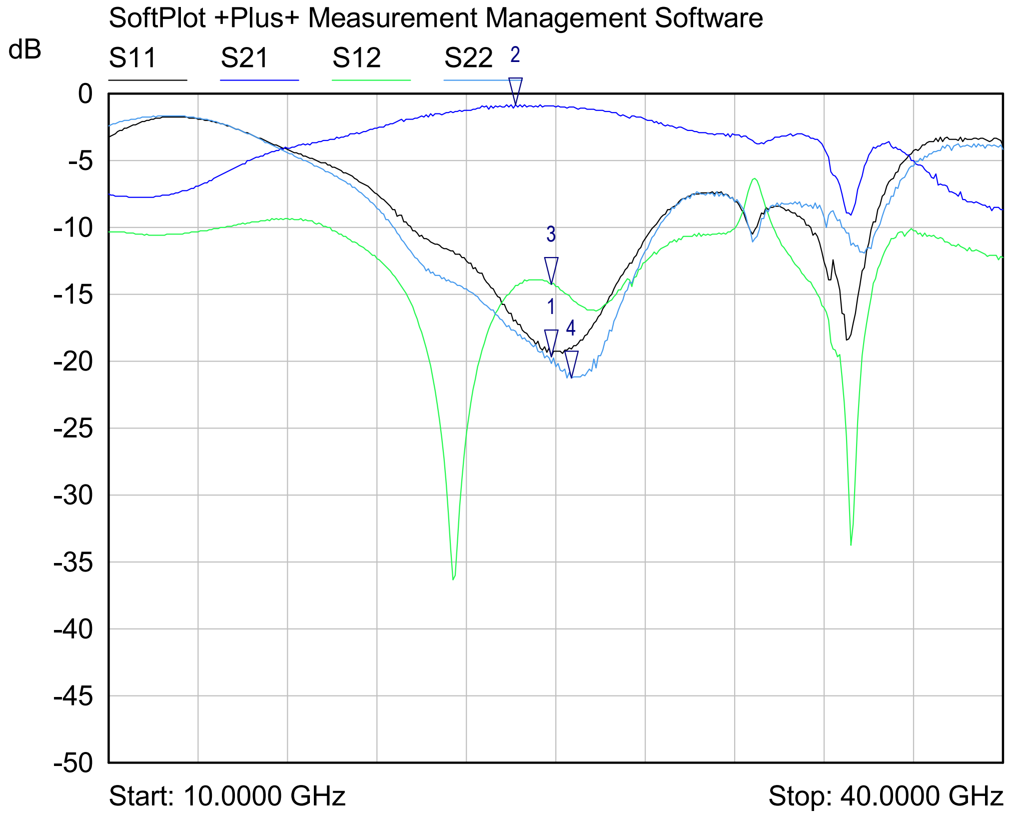
- Insertion loss is increased with addition of edge via transitions
  - Design needs to be further optimized

Ferrite and Dielectric Co-fired Tile for 28GHz Microstrip Circulator



- Co-fired tile is 3.6mm square, with the ferrite offset in position
- A dielectric constant of 8 was used for the dielectric
- Magnet is placed on top of the circulator with a thin dielectric separating it from the metallization
- Pins of connectors placed directly onto the lines of circulator

Ferrite and Dielectric Co-fired Tile for 24GHz Microstrip Circulator



Mkr	Trace	X-Axis	Value	Notes
1 ▽	S11	24.8500 GHz	-19.63 dB	
2 ▽	S21	23.6500 GHz	-0.79 dB	
3 ▽	S12	24.8500 GHz	-14.24 dB	
4 ▽	S22	25.5250 GHz	-21.29 dB	

- First prototype is working as a circulator ~23-25GHz

Microstrip versus SIW Circulator

- For 20-30 GHz, an all-microstrip square or rectangular tile circulator solution is possible using co-fired ferrite and dielectric
- The microstrip design should be smaller, because the SIW design includes transitions. Transceivers for Cellular Base Stations at 20-30 GHz will also tend to use microstrip based components and subsystems, easing integration
- Although all -ferrite microstrip solutions already exist, they tend to have high loss, limited power handling and potentially poor non-linear behavior resulting in higher harmonic and intermodulation products, because the ferrite is not magnetically saturated due to its square shape
- Replacing the unsaturated part of the ferrite with non-magnetic dielectric s improves these characteristics
- However, to avoid overmoding in microstrip transmission lines, it is desirable to use a lower dielectric constant dielectric outside of the ferrite disk. A dielectric constant of ~8 was considered as a first step.
- For higher frequencies, for example 60 GHz, SIW is likely to be the lowest loss and most easily integrated solution

Additional Slides for Reference

Advantages (Adv.) and Disadvantages (Dis.) of Alternative Types of Circulators

Circulator Type/ Frequency	*UHF Adv.*	*UHF Dis.*	*3-6 GHz Adv.*	*3-6 GHz Dis.*	*24 GHz Adv.*	*24 GHz Dis.*	*60 GHz Adv.*	*60 GHz Dis.*
Ferrite/ Dielectric microstrip	None	Cost	Loss, linearity Integration	None	Size, Integration	None	Size	Loss
Ferrite/ Dielectric SIW	None	Size	None	Size	Loss	None	Size	None
All-Ferrite Microstrip	None	Cost	Integration	linearity	Size, Integration	linearity	Size	Loss
All-Ferrite Hexagonal	None	Cost	None	Cost	height	Loss, linearity	height	loss
Ferrite Stripline	Low loss	Size?	loss, linearity	Integration	None	Cost	N/A	N/A
Ferrite Konishi	Size	Loss?	None	Loss, BW	N/A	N/A	N/A	N/A
Non-ferrite Semiconductor	Size	V. High loss	Size?	v. High loss	Size?	v. High loss	Size	v. High Loss