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# Advances in Technology and Design of Ultra Wideband millimeter wave planar and non-planar diplexers for applications up to 100GHz

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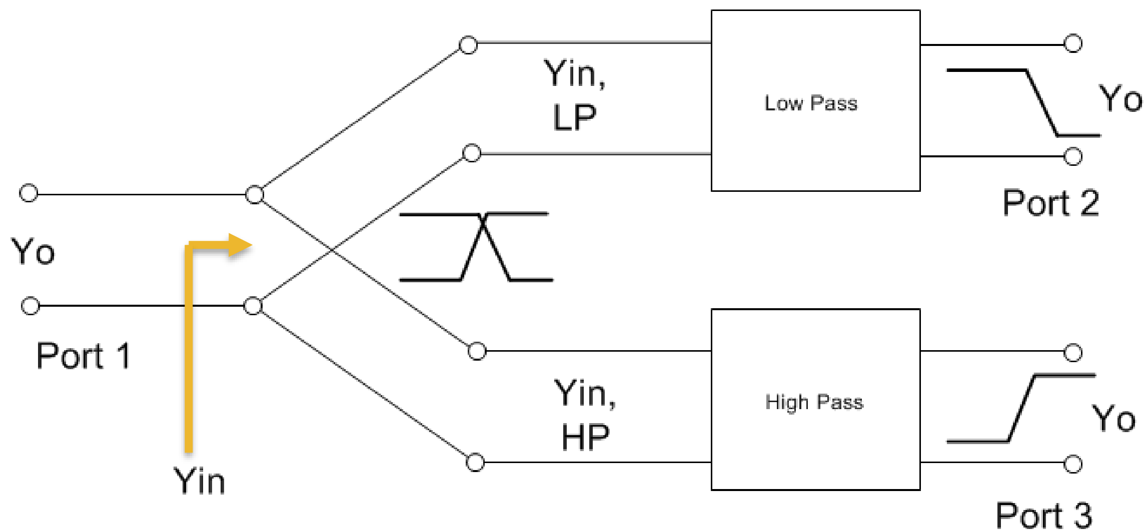
# AGENDA

- Introduction
- Theory on contiguous diplexers
- Design and comparison of planar and non-planar diplexers up to 100GHz
- Application of contiguous diplexer
- Challenges in implementing diplexer with stringent specification
- Conclusion

# Introduction

- Diplexers/Multiplexers are key components in RF application for splitting/combining frequency bands;
  - Instantaneous Frequency Measurements (IFM)
  - Millimeter Wave Transceivers for automotive, 5G wireless applications etc.
  - Broadband instruments
  - Imaging sensors

# Theory on contiguous diplexers




- For contiguous diplexer design all frequency points must meet the following conditions and both filters should be complementary to each other:

$$Y_{in} = Y_{in,LP} + Y_{in,HP} = Y_o$$

$$Re(Y_{in,LP}) + \mathrm{Re}(Y_{in,HP}) = Y_o$$

$$Im(Y_{in,LP}) + Im(Y_{in,HP}) = 0$$

(NOTE: Yo is the pure real reference admittance)

# Design of Planar DC-66-100GHz diplexer

# Material Characteristics for a Contiguous Planar DC-66-100GHz diplexer

- **Key Characteristics of Roger's Liquid Crystal Polymer (LCP) Ultralam 3850**
  - Excellent mm-wave properties ($\varepsilon_r$=2.9, tan $\delta$=0.002)
  - Does not have woven glass
  - Min dispersion (LCP thickness of 0.002")
  - Flatter group delay across the passband
  - Very low radiation

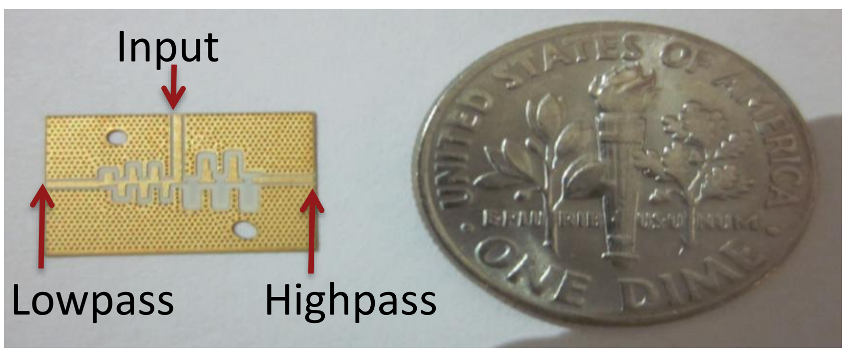
# Design Details

- **Lowpass singly terminated filter:**
  - Tchebychev 13 section filter with fc at 66 GHz
  - LC lowpass is synthesized with $\lambda/8$ series short-circuited and shunt open-circuited stubs
- **Highpass singly terminated filter:**
  - Tchebychev 11 section complementary filter, fc at 66 GHz
  - LC highpass is synthesized to series capacitive broadside coupled sections and high impedance $\lambda/2$ inductive resonators

# Physical Implementation

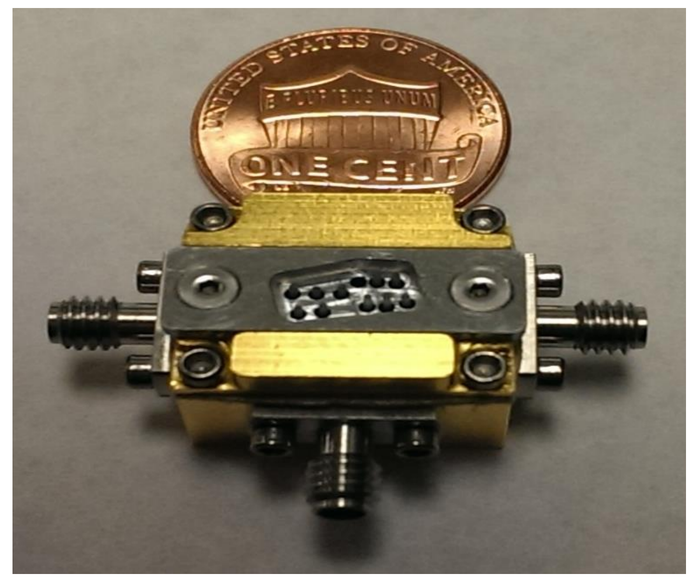
## SOFT BOARD

- RO 3850 softboard with dielectric constant of 2.9
- Etch tolerance of better that 0.0127 mm
- Vias spaced $\frac{\lambda}{20}$ at highest frequency

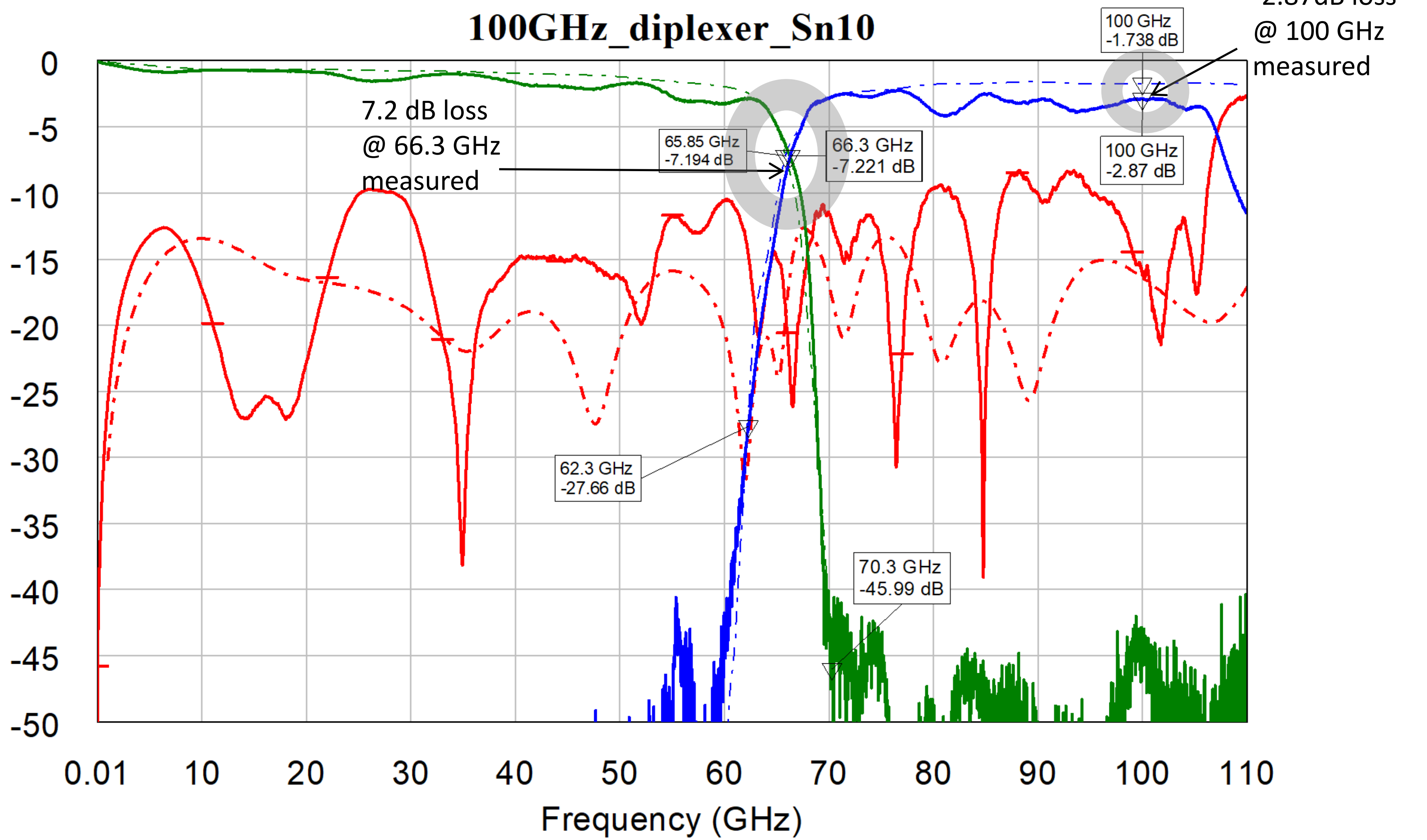



## HOUSING

- Brass top and bottom housing with Ni/Au plating
- 0.25 mm diameter sapphire rod used as tuning element



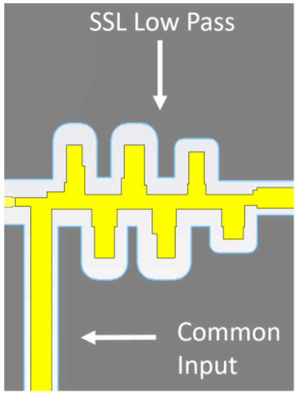
# Simulated vs Measured result



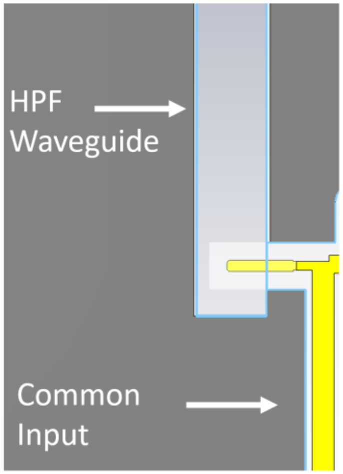
# Design of Non-Planar DC-66-100GHz diplexer

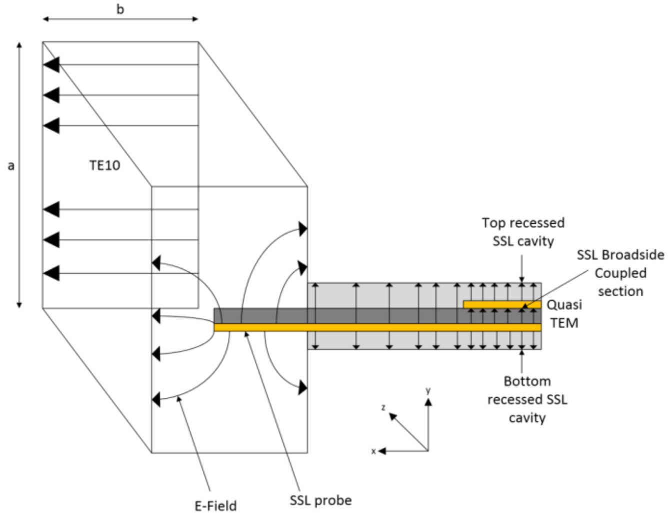
# Design of Non-Planar DC-66-100GHz diplexer

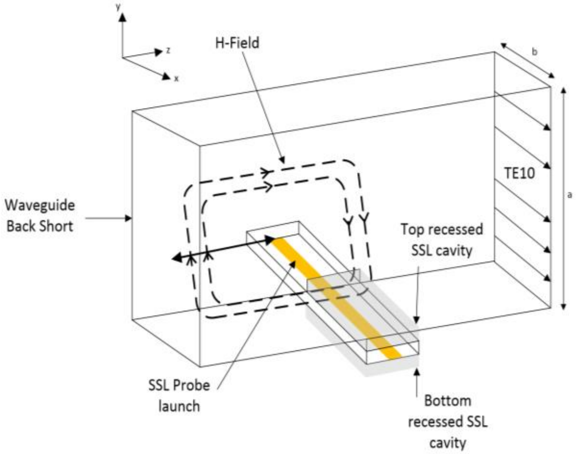
- Lowpass section is realized with 13th order stepped impedance resonators
- Implemented using series λ/8 high impedance and shunt λ/2 low impedance resonators.




- Highpass filter implemented with single capacitive broadside coupled section connected to a E-Plane stub suspended in a rectangular waveguide

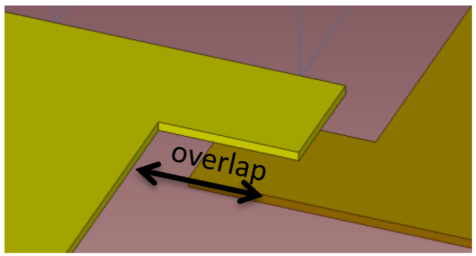


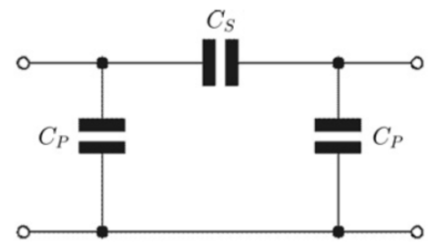



# Highpass series coupled section

- Implemented by overlapped coupled sections between resonators in Suspended Stripline (SSL)
- Capacitance value depends on overlap length




- Cs and Cp values can be determined using:

$$C_s = j\frac{y_{21}|_{f=f_o}}{2\pi f_o} \qquad C_p = j\frac{(y_{11}+y_{21})|_{f=f_o}}{j2\pi f_o}$$

- Y-matrix extracted from the EM model of the overlap coupled section:

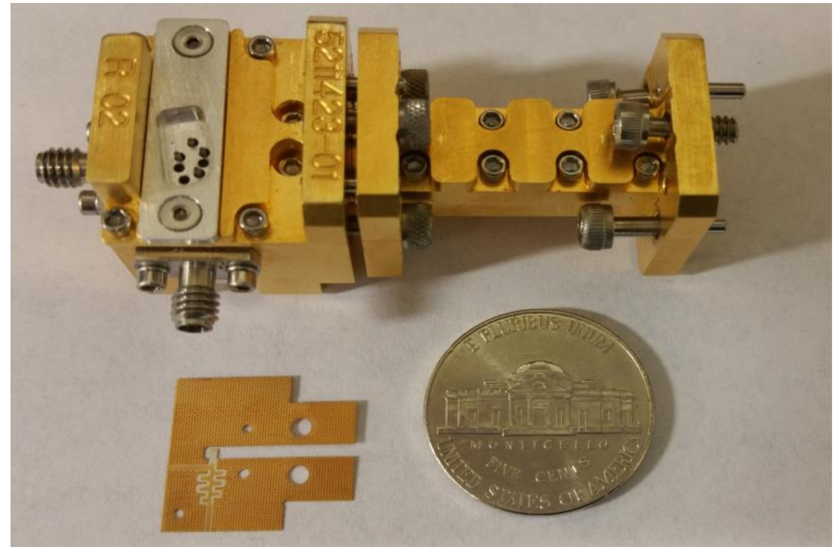
$$\mathrm{Y} = \begin{bmatrix} Y_{11} & Y_{21} \\ Y_{12} & Y_{22} \end{bmatrix} \qquad y_{21} = y_{12} \text{ and } y_{11} = y_{22}$$

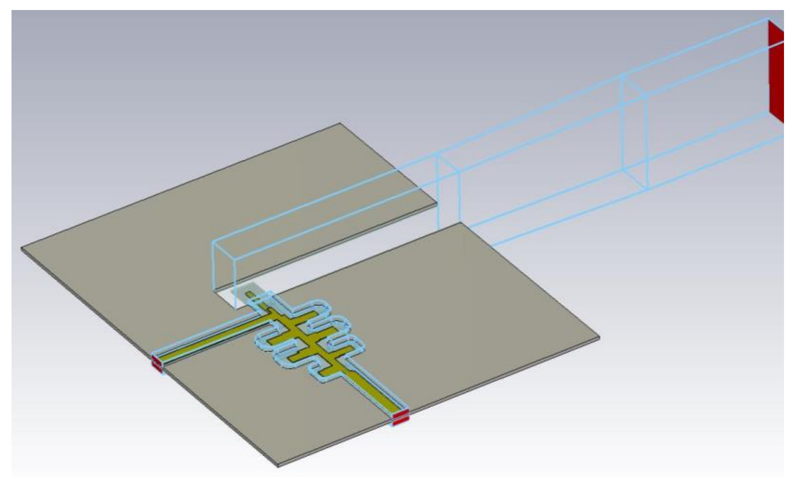
- Overlap structure follows reciprocity, hence

# Physical Implementation 100GHz hybrid diplexer

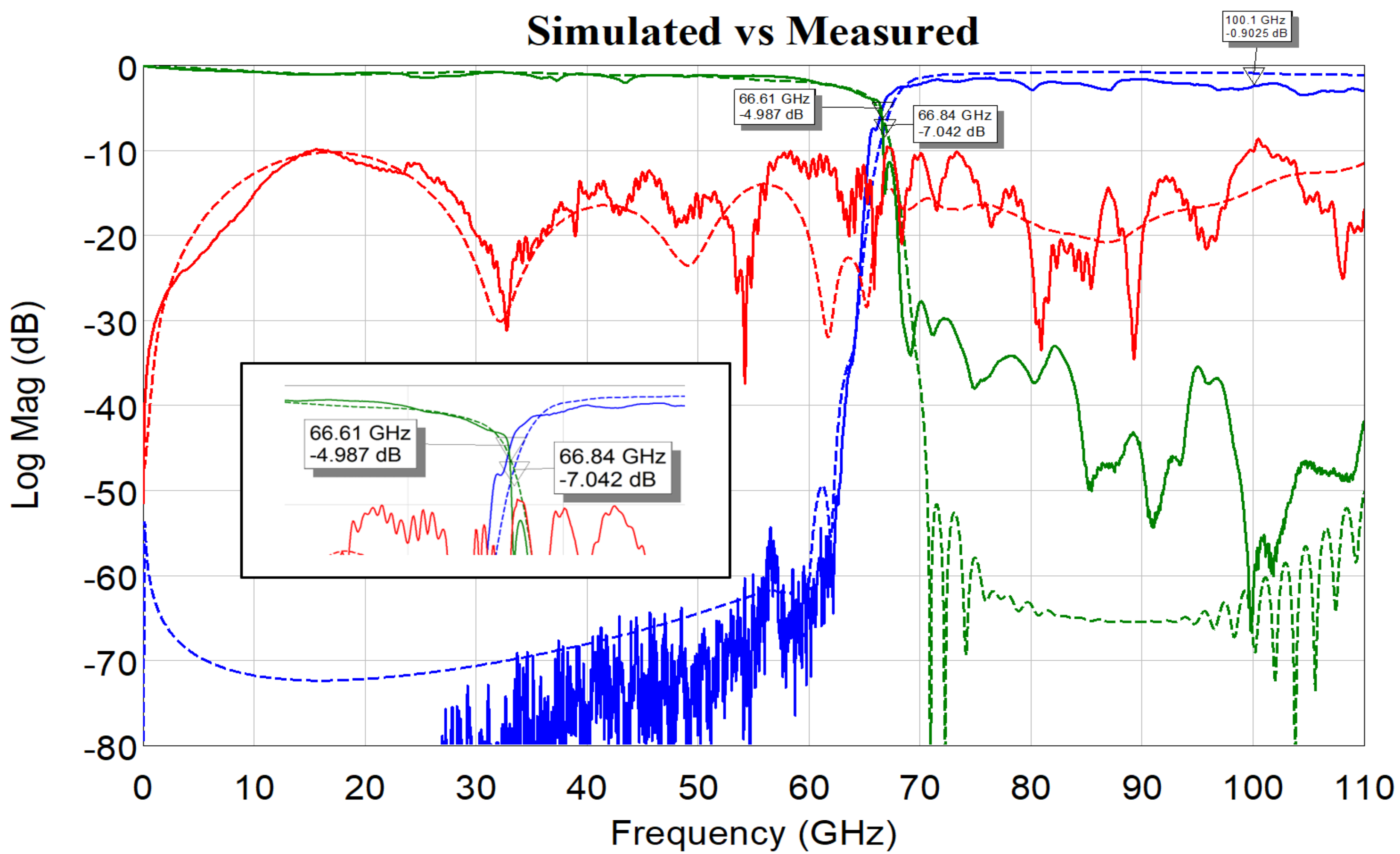
## HOUSING

- Brass top and bottom housing with Ni/Au plating
- 0.25 mm diameter sapphire rod used as tuning element
- Non-Standard to WR-10 transition at the highpass port



# Simulated versus Measured results



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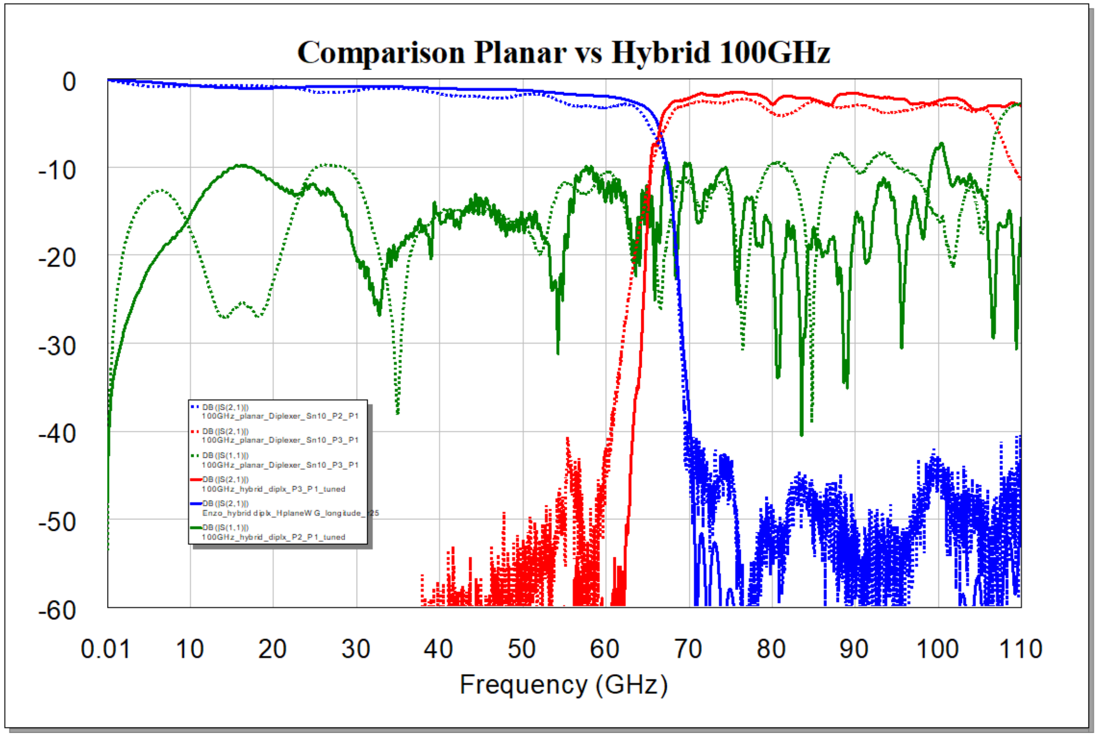
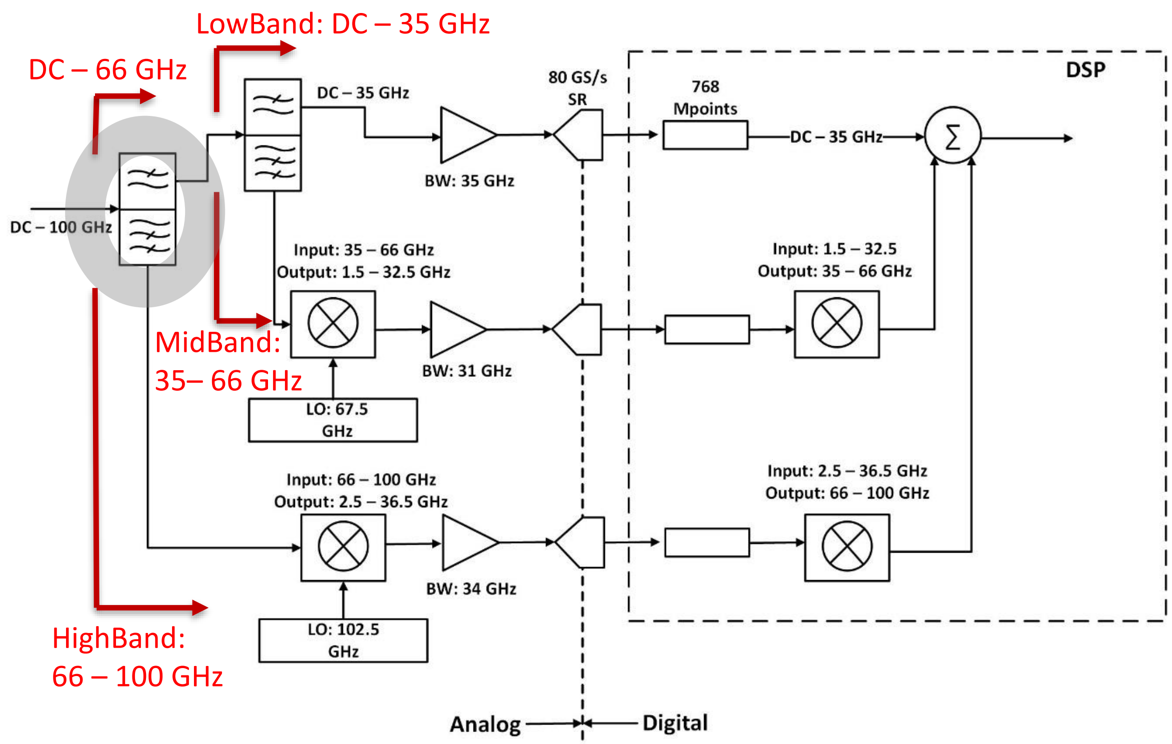
# Comparison of two design approaches

# Performance Comparison between planar and non-planar diplexer




| Performance parameters | Planar | Non-Planar |
|---|---|---|
| Insertion loss at cross-over (dB) | 7 (66GHz) | 5 (66.5GHz) |
| Input port match (dB) | >8 (DC-100GHz) | >10 (DC-100GHz) |
| Band selectivity +/- 2GHz from cross-over (dB) | >20 (67GHz) | >30 (67GHz) |
| Highpass max frequency (GHz) | 100 | 110 |

# Application of contiguous diplexer




## Real-time oscilloscope front-end

P. Pupalaikis, B. Yamrone, R. Delbue, A.S. Khanna, K. Doshi, B. Bhat, and A. Sureka, "Technologies for Very High Bandwidth Real-time Oscilloscope," IEEE Bipolar/BiCMOS Circuits and Tech. Meetings (BCMT), Oct. 2014.

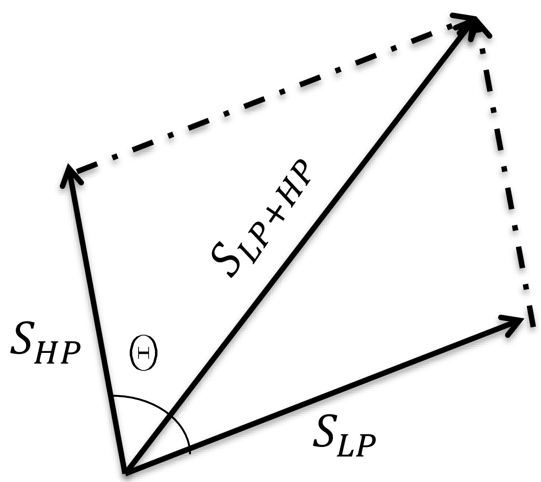
# Challenges in implementing diplexer with stringent specification

# Phase linearity

- In the digital data acquisition domain, the lowpass and highpass S-parameters in vector form are required to add up in magnitude to compensate for the loss at the crossover
- Sum of the magnitudes of vectors can add up constructively, if and only if both lowpass and highpass vectors are in phase.

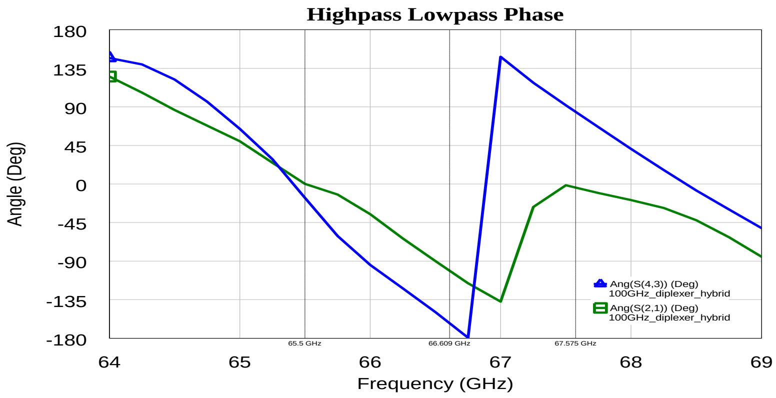
$$\left|\overrightarrow{S_{LP+HP}}\right| > \left|\overrightarrow{S_{LP}}\right| \text{ and } > \left|\overrightarrow{S_{HP}}\right|$$

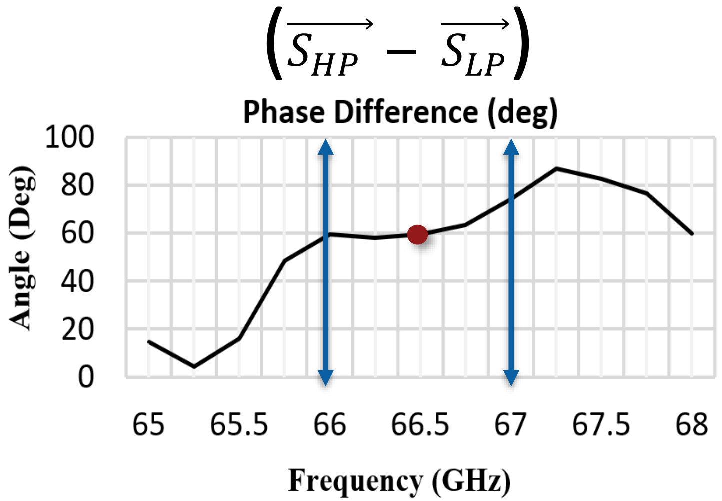
- In order to be in-phase the angle between the lowpass and highpass vectors are required to be in the range of 0-90 degrees



# Phase variation $\overrightarrow{S_{HP}} - \overrightarrow{S_{LP}}$ at cross over frequency for hybrid diplexer at 66.5GHz

- Theoretical the phase difference of $\overrightarrow{S_{HP}} - \overrightarrow{S_{LP}}$ is required to be constant over the frequency band of interest.
- Blue trace represents the phase of highpass and green trace is the phase of lowpass in +/- 2GHz around the cross over region
- Phase variation from 66 to 67GHz with 66.5GHz center is only 8 degrees.



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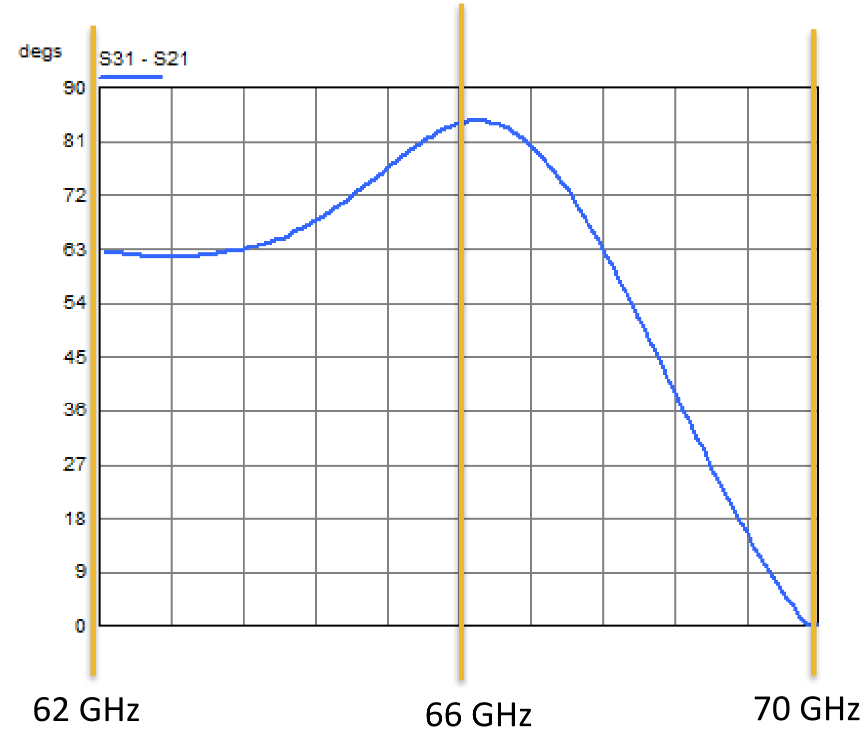
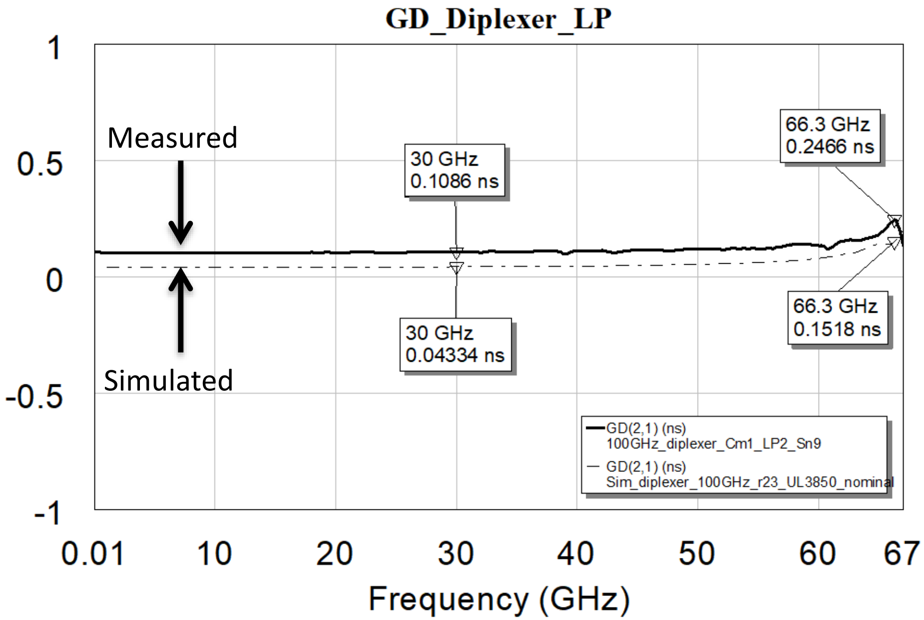
# Phase variation $\overrightarrow{S_{HP}} - \overrightarrow{S_{LP}}$ at cross over frequency for planar diplexer at 66.5GHz

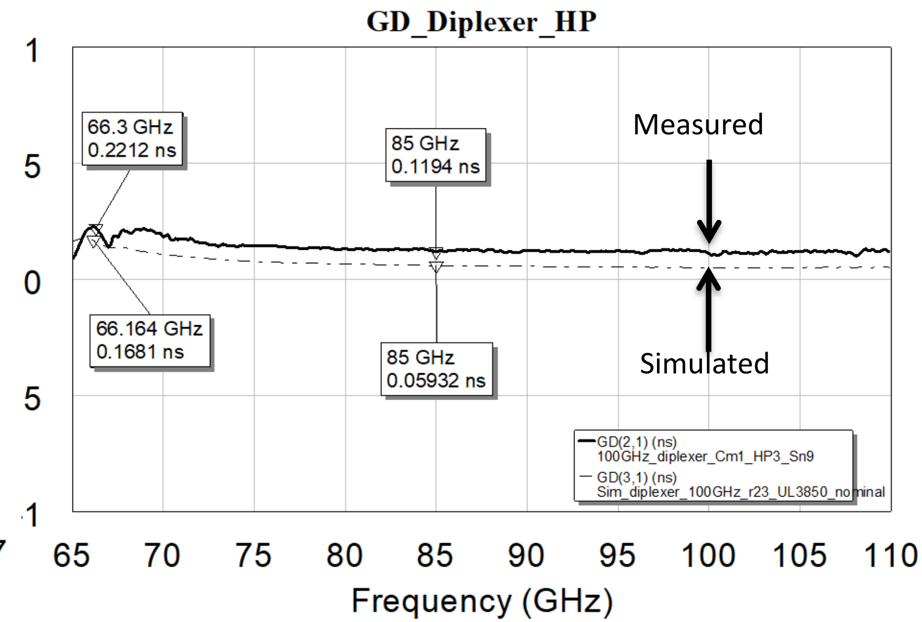
- The phase difference between lowpass (S21) and highpass (S31) is required to in the range of 0 to 90 degrees for constructive vector addition.




Phase difference
$\angle S31 - \angle S21$

# Measured Group delay comparison



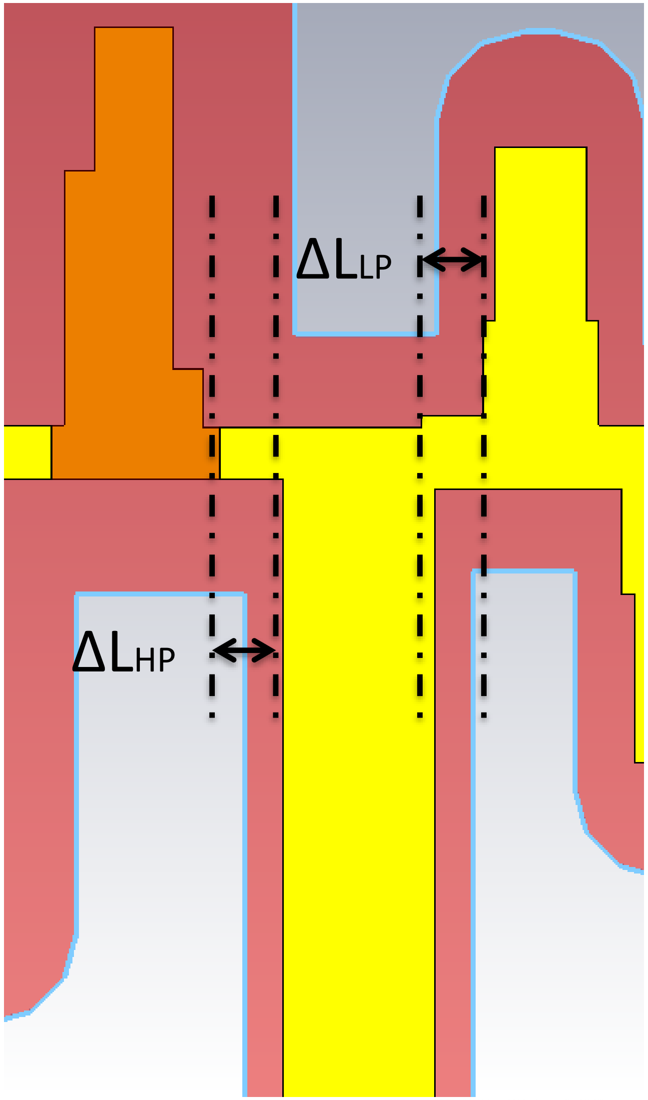




| LOWPASS | GD @ 30GHz (pS) | GD @ 66.3GHz (pS) | Variation (pS) |
|---|---|---|---|
| LP (meas) | 108.6 | 246.6 | 138 |
| LP (sim) | 43.3 | 151.8 | 108.5 |

| HIGHPASS | GD @ 85GHz (pS) | GD @ 66.3GHz (pS) | Variation (pS) |
|---|---|---|---|
| HP (meas) | 119.4 | 221.2 | 101.8 |
| HP (sim) | 59.3 | 168.1 | 108.8 |

# Optimizing the input junction for the planar diplexer

- $\Delta L_{HP}$ and $\Delta L_{LP}$:
  - Lengths are optimized to avoid undesired phase shift variation around cross over
  - These play a critical role in improving return loss at the cross over



# Conclusion

- Validation of material performance up to 110GHz
- Ability to integrate with other planar and waveguide structures
- Demonstrated improved performance of non-planar waveguide compared to planar diplexer
- Highlighted application for contiguous diplexer in cascaded fashion in Test and Measurement domain.

# Questions ?