# Design and Demonstration of Integrated Passive Components Test Vehicle for 5G and mm-Wave Applications

**Students:**
Muhammad Ali
Atom Watanabe
Tong-Hong Lin

**Faculty:**
Prof. Raj Pulugurtha
Prof. Manos Tentzeris
Prof. Rao. R. Tummala
Prof. M. Swaminathan

**Industry:**
Dan Oh (Samsung)
Christian Hoffman (Qualcomm)
Yoichiro Sato (AGC)
Masahiro Karakawa (Ajinomoto)
Dan Okamoto (Taiyo Inc.)
Rajiv Parmar (Corning)

# Outline

- ❑ Goals & Objectives
- ❑ Prior Work
- ❑ Technical Approach
- ❑ Results & Key Accomplishments
- ❑ Comparison with Prior Art
- ❑ Schedule
- ❑ Summary

# Goals and Objectives

Model, design, fabricate and characterize high-performance, miniaturized and integrated passive components for 5G and mm-wave applications (28 and 39 GHz bands) with next generation of package substrates such as laminated glass

- Filters and Power Dividers
- **Diplexers and Couplers**

The research objectives for diplexers are given below:

| | Objectives | Prior Art | Challenges | Tasks to Address Challenges |
|---|---|---|---|---|
| **Task-1: Design** | • Filter Design: Doubly-Terminated<br>• Passband: <3 dB<br>• Return Loss: <15 dB | • Filter Design: Singly-Terminated | • Design doubly-terminated filters and configure them as diplexers | • Design filters to achieve lower in-band insertion loss and higher out-of-band rejection using advanced structures and high-Q resonators<br>• Achieve optimum trade-off between filter performance and footprint in simulation. Optimize for diplexer design |
| **Task-2 Miniaturization** | • Overall Size: $<0.5\lambda_0^2$ | • Overall Size: $>2\lambda_0^2$ | • Precise linespace features required for excellent model-to-hardware correlation | • Achieve optimum tradeoff between process capability, footprint and performance |

# Prior Work

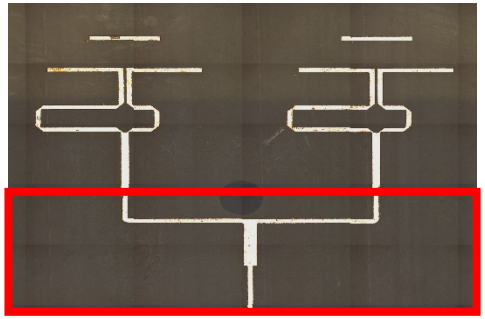
## Power Dividers for 28 GHz 5G band

**Objectives:** Model, design, fabricate and characterize power dividers with small footprint for 5G and mm-wave applications on advanced materials such as glass.

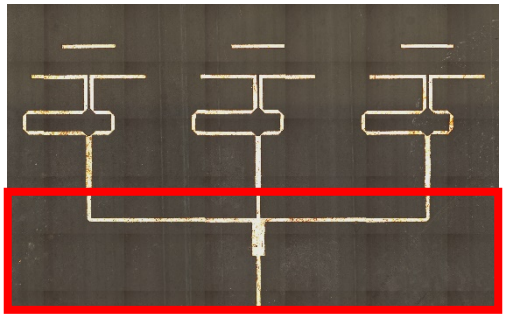
**Results:** Power Dividers configured as Yagi-Uda antenna arrays are demonstrated in two equal-split ratios: two- and three-way with corresponding antenna arrays

- Added insertion loss of 0.45-dB for two-way and 0.65-dB for three-way T-Junction based power dividers with return loss <15-dB in the passband
- Two-way power divider has a footprint smaller than $<\lambda_0 \times \lambda_0$ with just 147-µm z-height.

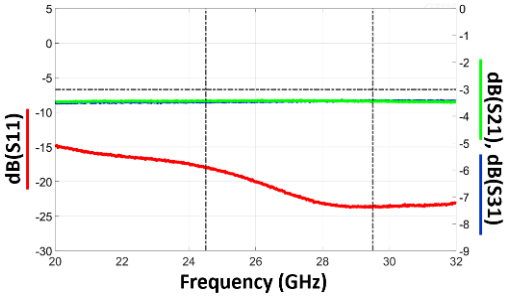
**Two-way Power Divider**



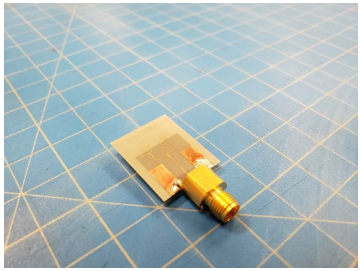
**Three-way Power Divider**



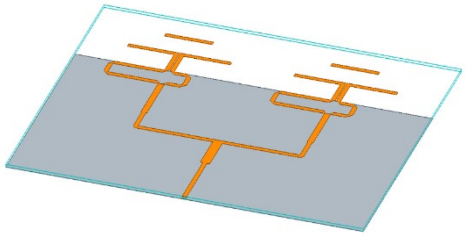
**S-Parameters – Two-Way Power Divider**



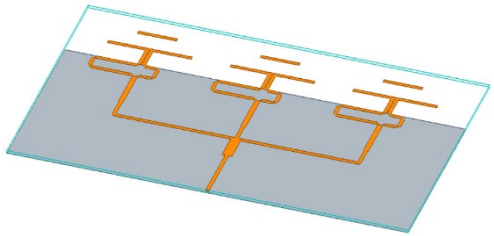

**Fabricated Coupon with SMA Connector**



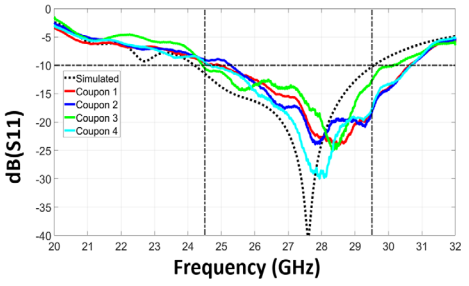
**2 × 1 Antenna Array**



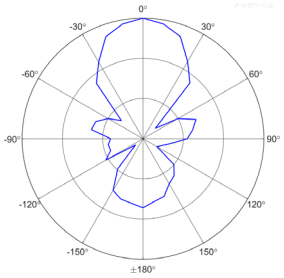
**3 × 1 Antenna Array**



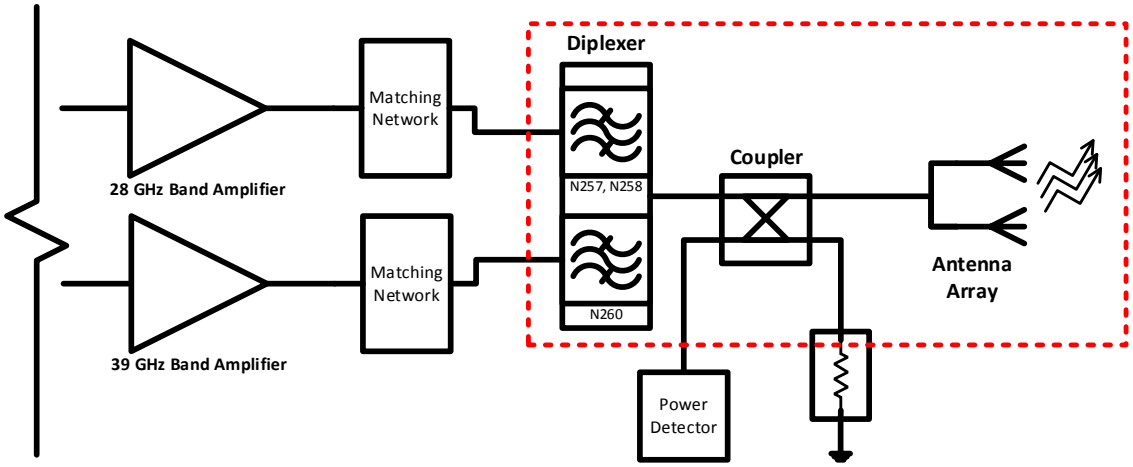
**S-Parameters – 2×1 Antenna Array**

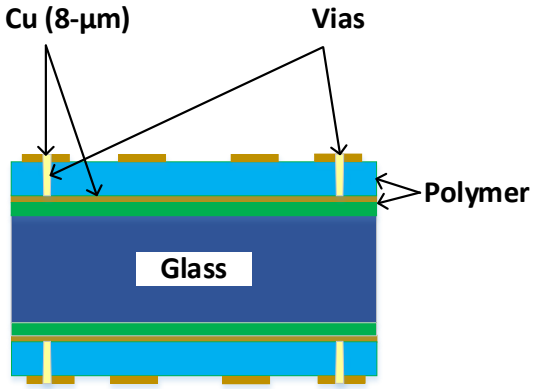


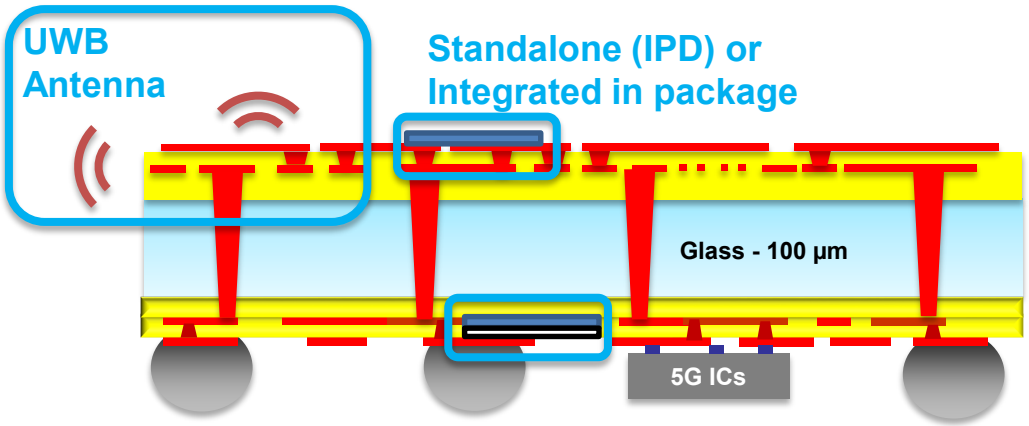

**Measured Radiation Pattern - 2×1 Antenna Array**



# Technical Approach




| Layer | Details |
|---|---|
| M4 (Top) | Microstrip Passive Components |
| Dielectric-4 | Taiyo Zaristo (71-µm) |
| M3 | GND, Via Antipads, Dicing Clearance |
| Dielectric-3 | Taiyo Zaristo (15-µm) |
| Core-Glass | AGC EN-A1 (100-µm) |
| Dielectric-2 | Taiyo Zaristo (15-µm) |
| M2 | GND, Via Antipads, Dicing Clearance |
| Dielectric-1 | Taiyo Zaristo (71-µm) |
| M1 (Bottom) | Microstrip Passive Components |

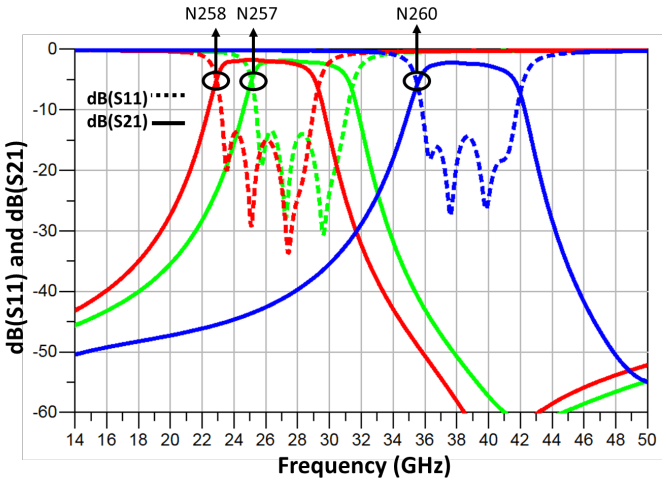
# Results & Key Accomplishments

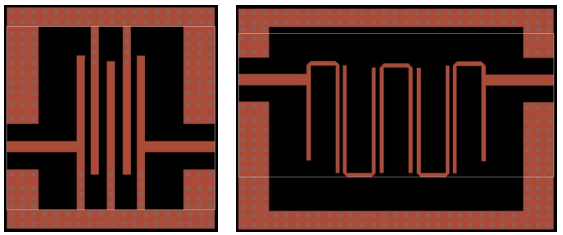
List of Structures

- Band Filters (5th Order)
  - Hairpin and Interdigital for band N257 (26.50-29.50 GHz, 10.71%), N258 (24.25-27.50 GHz, 12.6%) and N260 (37.00-40.00 GHz, 7.8%)
- Diplexer
  - Hairpin and Interdigital N257 & N260
  - Hairpin and Interdigital N258 & N260
- Couplers covering 24.25-40.00 GHz
  - Branch-Line
  - Coupled-Line

# Results

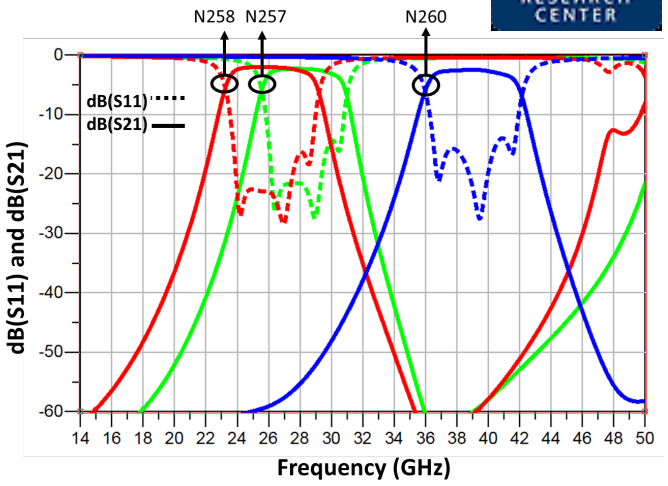
## Bandpass Filters – Interdigital and Hairpin



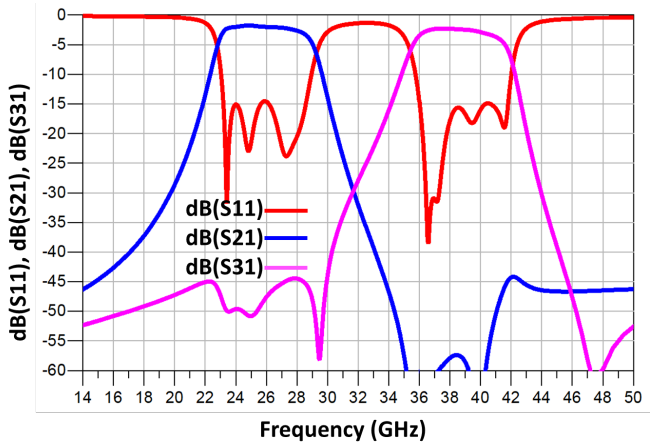
Interdigital Hairpin

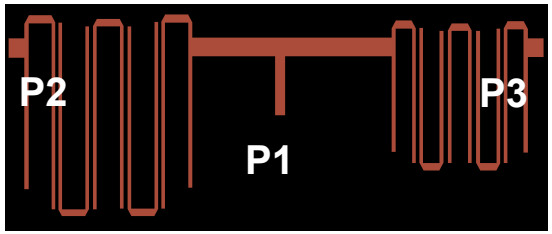
Maximum in-band Insertion Loss
Interdigital and Hairpin: 2.7 dB




## Diplexers

### Interdigital N258 and N260

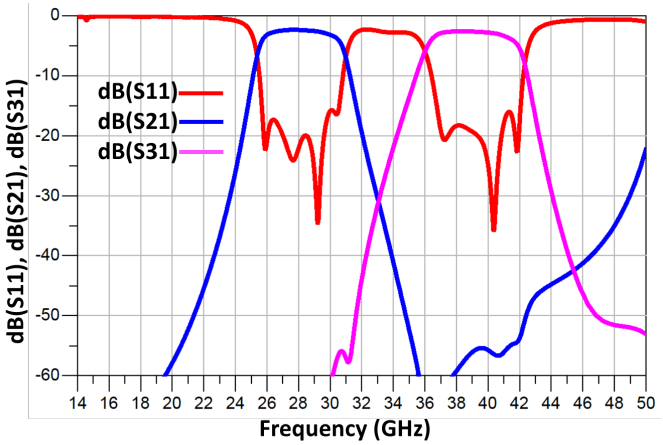



Hairpin N257 and N260 Diplexer

Maximum in-band Insertion Loss
Interdigital: 3.0 dB
Hairpin: 2.9 dB

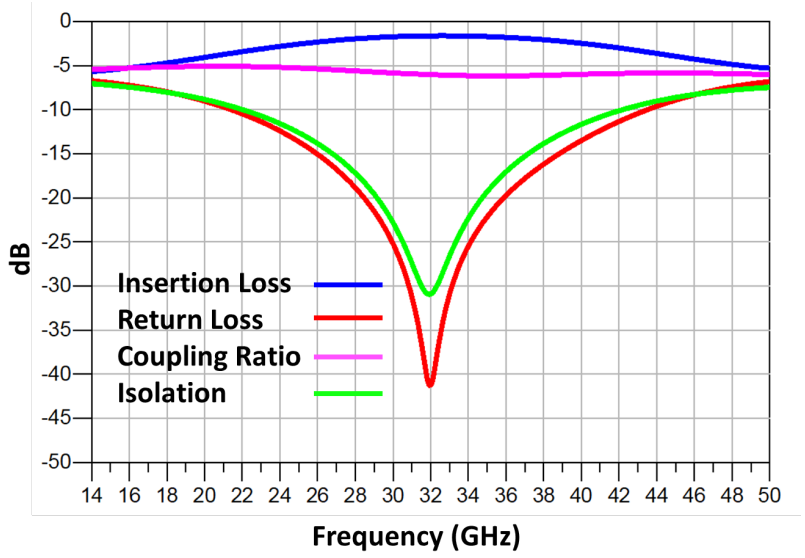
### Hairpin N257 and N260



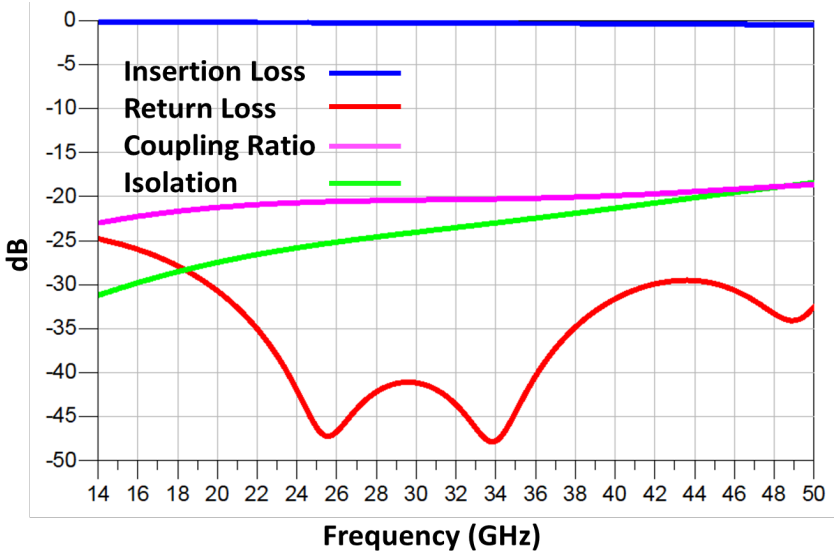
# Results (Cont'd)

## Couplers

### 6-dB Branch-Line Coupler

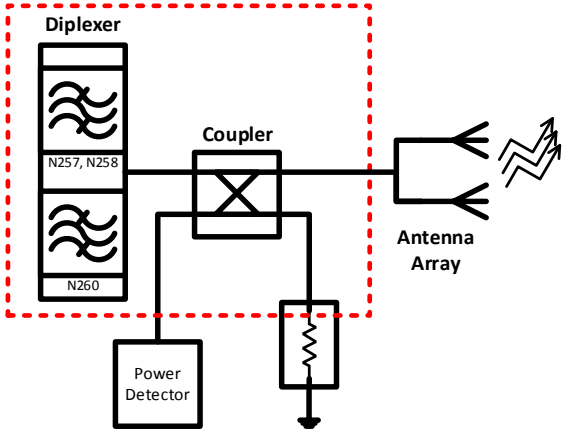



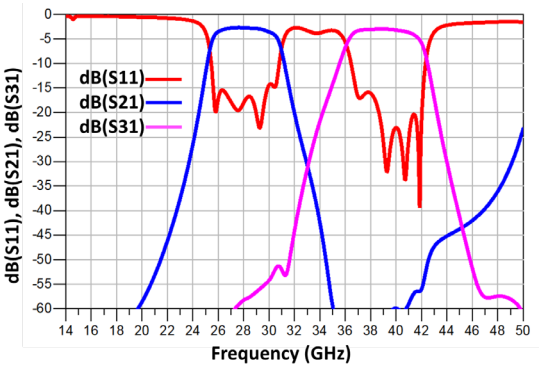

### 20-dB Coupled-Line Coupler

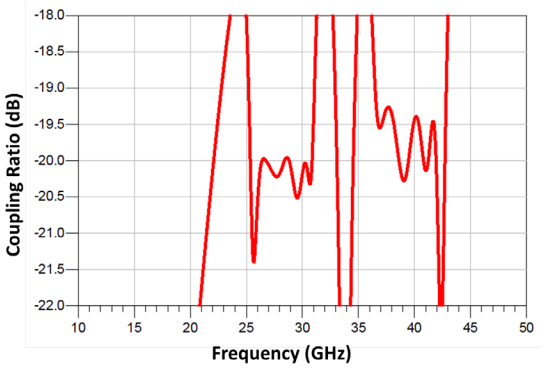



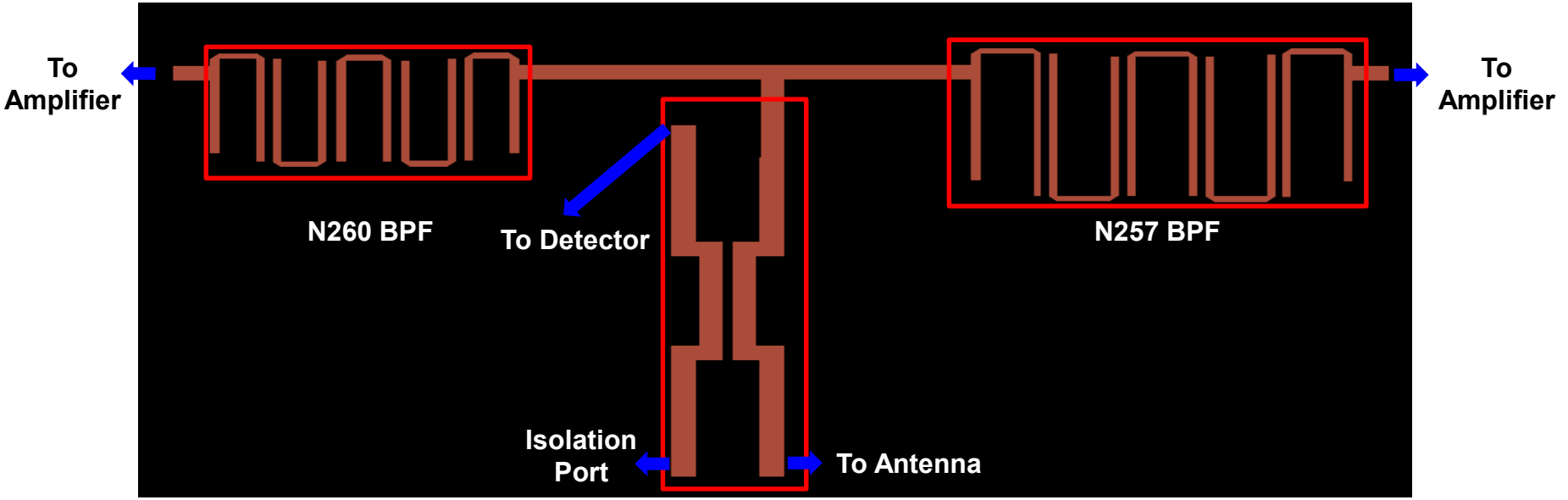
# Results (Cont'd)

## Layout



# Results (Cont'd)

## Design-level Dimensional Analysis

| Structure | Physical Dimensions ($mm^3$) | Electrical Dimensions ($\lambda_0^3$) |
|---|---|---|
| Hairpin Filter for N257 | 4.64×2.11×0.202 | 0.43×0.20×0.019 |
| Hairpin Filter for N258 | 4.75×2.20×0.202 | 0.44×0.21×0.019 |
| Hairpin Filter for N260 | 4.14×1.72×0.202 | 0.54×0.22×0.026 |
| Interdigital Filter for N257 | 2.98×2.62×0.202 | 0.28×0.34×0.019 |
| Interdigital Filter for N258 | 2.94×2.76×0.202 | 0.27×0.26×0.019 |
| Interdigital Filter for N260 | 3.12×2.17×0.202 | 0.41×0.28×0.026 |
| Diplexer - Hairpin N257 & N260 | 8.42×1.70×0.202 | 0.90×0.18×0.022 |
| Diplexer - Hairpin N258 & N260 | 8.71×2.02×0.202 | 0.93×0.22×0.022 |
| Diplexer - Interdigital N257 & N260 | 5.09×2.62×0.202 | 0.54×0.28×0.022 |
| Diplexer - Interdigital N258 & N260 | 5.10×2.77×0.202 | 0.55×0.30×0.022 |
| Branch-Line Coupler | 4.24×1.86×0.202 | 0.45×0.20×0.022 |
| Coupled-Line Coupler | 3.91×0.78×0.202 | 0.42×0.08×0.022 |

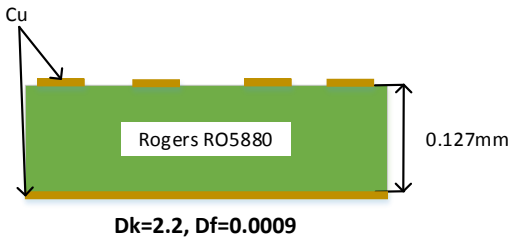
Note:

1. For the filters, physical dimensions are normalized by the wavelength corresponding to band frequency of 28 and 39 GHz 5G bands. The corresponding wavelengths are 10.71 mm and 7.7 mm, respectively.
2. For diplexers and couplers, the physical dimensions are normalized by the wavelength corresponding to 32.125 GHz (center of 24.25-40 GHz). The corresponding wavelength is 9.34 mm.

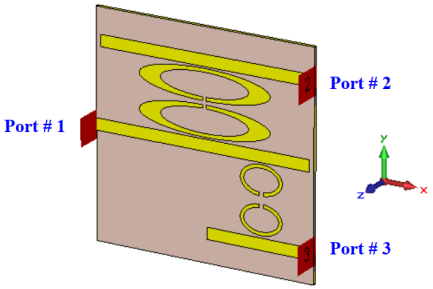
**All diplexers and couplers are smaller than $0.21\lambda_0^2$**

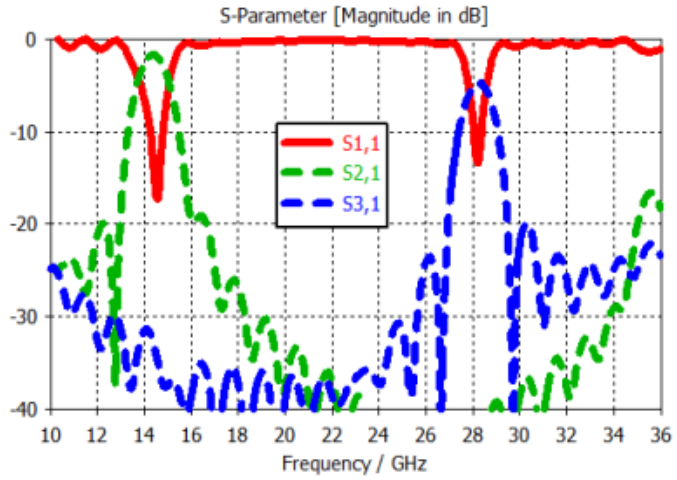
# Comparison with Prior Art

## Millimeter-Wave Microstrip Diplexer using Elliptical Open-Loop Ring Resonators




Dk=2.2, Df=0.0009

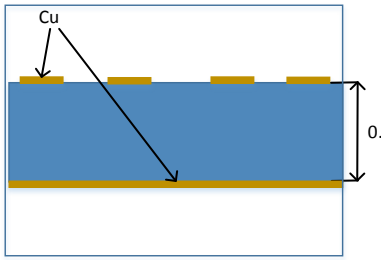


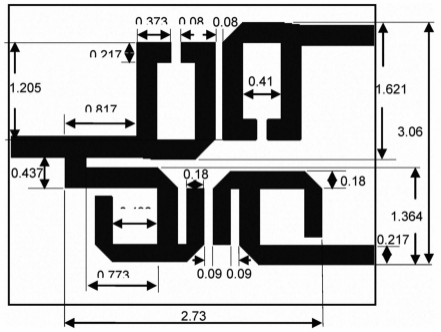



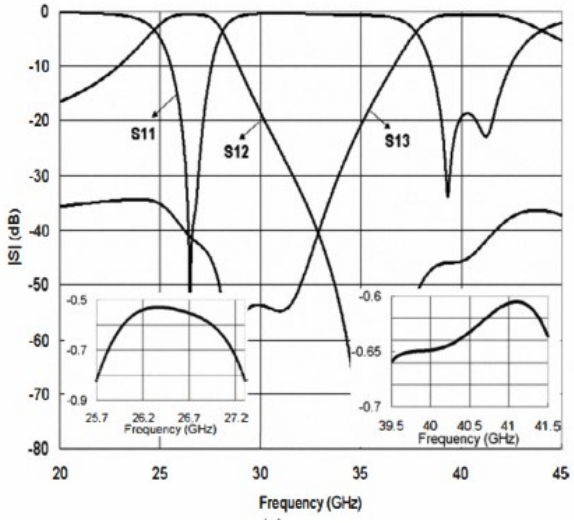

Frequency Bands: 14 and 28 GHz (<3% FBW)
Insertion Loss: 1.9 and 4.7 dB
Size: 7.82 mm × 7.82 mm

*(Source: H. Shamam et. al, IEEE MMS 2014)*

## Compact Diplexer using Modified Hairpin Filters




Frequency Bands: 26.5 and 40.5 GHz (<6.6% FBW)
Insertion Loss: <1.5 dB and <1 dB
Size: 2.73 mm × 3.06 mm

*(Source: N. He et. al, IEEE APEMC 2010)*

# Schedule

| | | 2019 | | 2020 | |
|---|---|---|---|---|---|
| | | Q3 | Q4 | Q1 | Q2 |
| Done | 1 – Filter Design | | | | |
| Done | 2 – Diplexer Design | | | | |
| Done | 3 – Coupler Design | | | | |
| In Progress | 4 – Integrated Components Optimization | | | | |
| In Progress | 4 – Fabrication of Test Vehicle (TV) without TGVs | | | | |
| | 5 – Characterization | | | | |
| | 7 – TGV Fabrication | | | | |
| | 8 – Antenna Design | | | | |
| | 9 – Fabrication of Test Vehicle (TV) with TGVs | | | | |
| | 10 – Characterization | | | | |

Light blue: TV w/o TGVs
Dark blue: TV w/ TGVs
Light Yellow: Current time window

Electrical Design and Optimization
Fabrication
Characterization and Correlation
Graduation

# Summary

- Accomplishments
  - Optimized designs for filters, diplexers and couplers for integrated passive components TV covering the following bands:
    - Filters and Diplexers: N257, N258 and N260
    - Couplers: 24.25-40.00 GHz
  - Layout optimization for different components for individual and combined characterization
- Next Set of Challenges and Risks
  - Design
    - Design of multiband antenna for 28 and 39 GHz bands
  - Process
    - Optimize process conditions for four-metal layer design with without TGVs


Thank
You