Consiglio Nazionale delle Ricerche
Istituto di Elettronica e di Ingegneria dell'Informazione e delle Telecomunicazioni

Development of high-performance Q-band waveguide assemblies for polarization measurements

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UNIVERSITÀ DEGLI STUDI DI MILANO

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ASI and INFN funded experiment aimed at the detection of the Cosmic Microwave Background B-modes at large angular scales

25% fraction of the sky in the northen hemisphere

CMB features

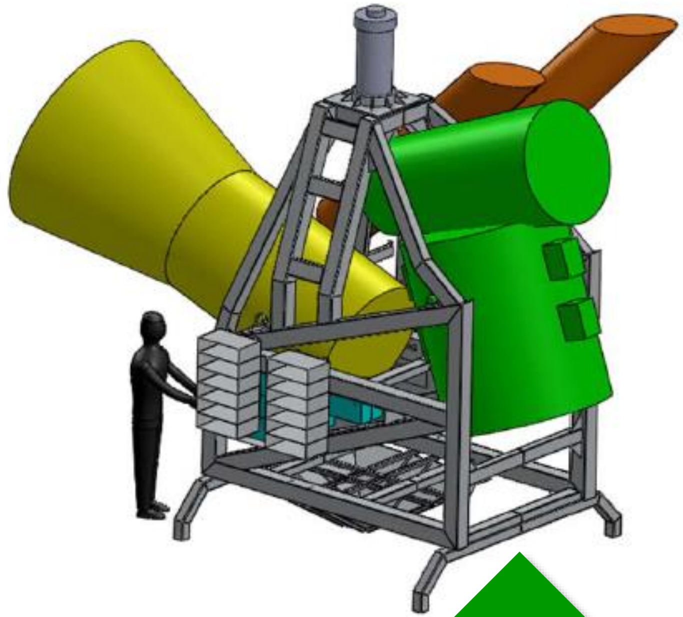
- Monopole term: 2.725 K blackbody
- Anisotropy: ~ 100 μK rms
- E-mode polarization: ~ 3 μK rms
- B-mode polarization: < 1 μK rms

Instrumentation requirements

- High sensitivity to polarization state
- High system stability
- Very low instrumental systematics: cross-polarization, noise, channel equalization, ….
- Precise foreground measurements
- Independent and multi-band measurements

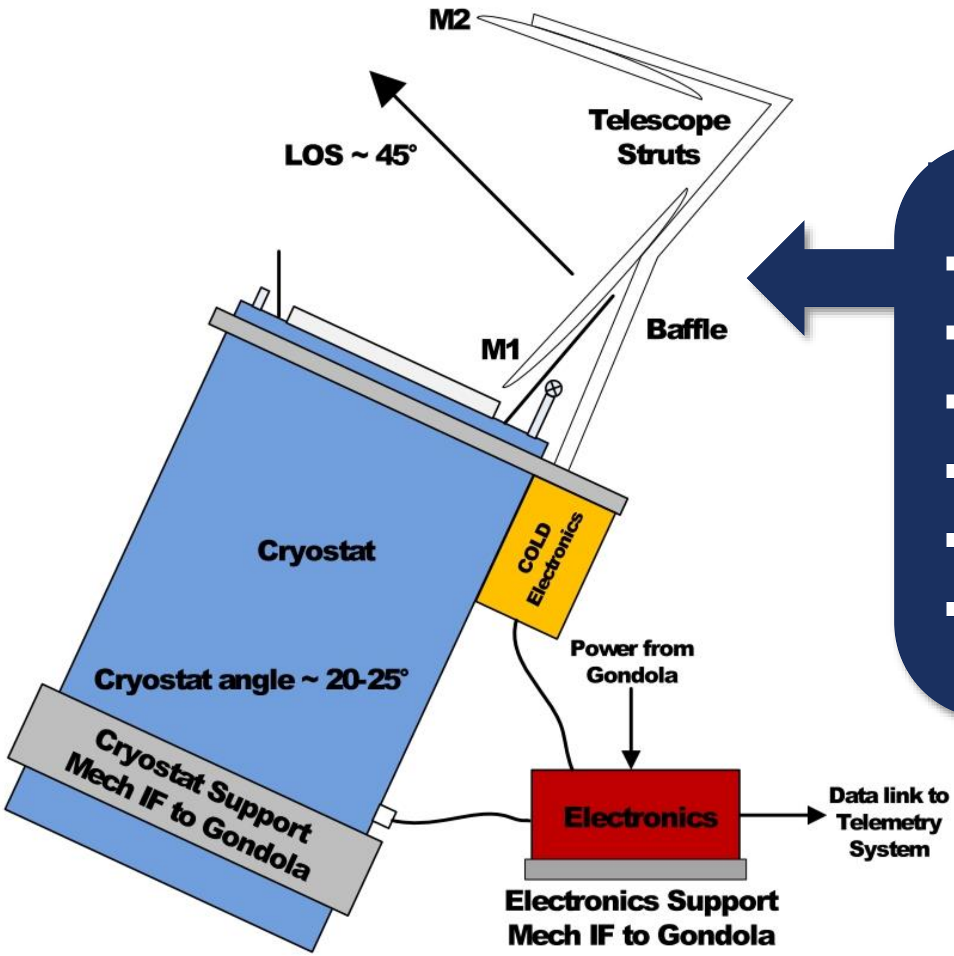
Short Wavelength Instrument for the Polarization Explorer (SWIPE):

- Bolometric detectors
- 140 - 240 GHz



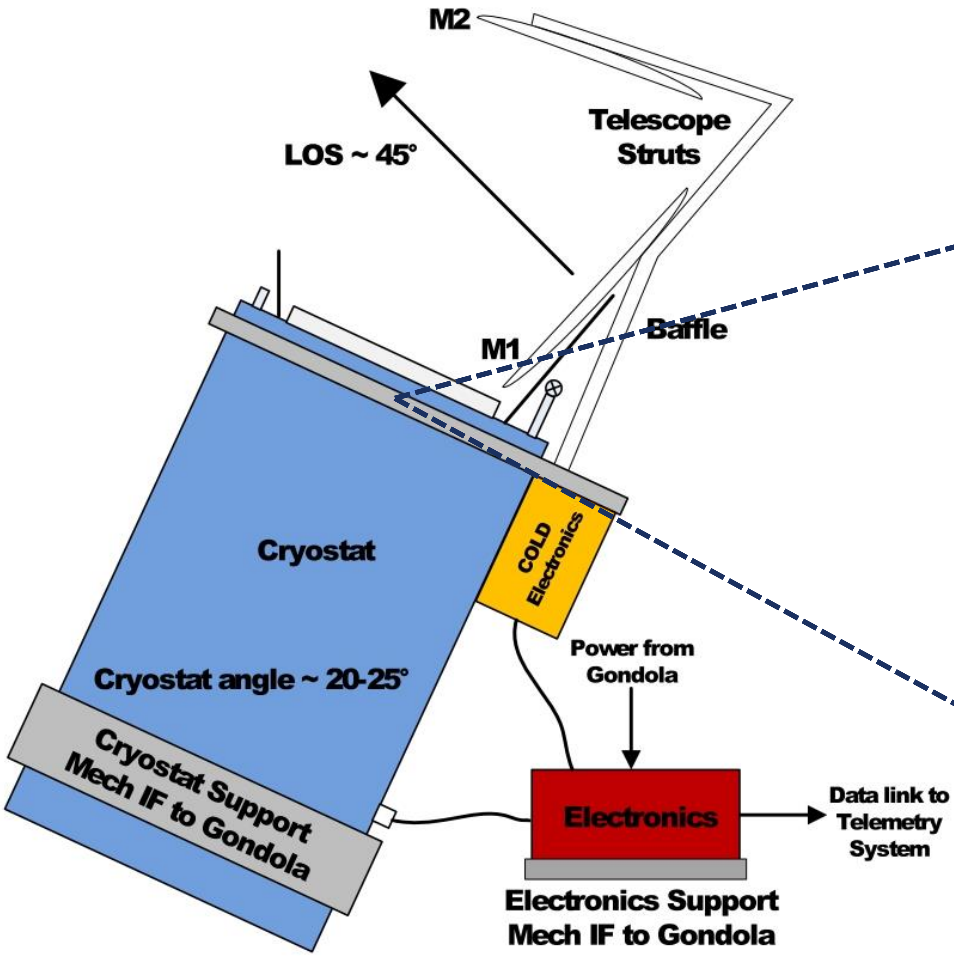
STRatospheric Italian Polarimeter (STRIP)

- Coherent detectors
- Circular-polarizations correlation polarimeters
- Q-band cluster @ 39 - 48 GHz
- W-band cluster @ 85 - 104 GHz

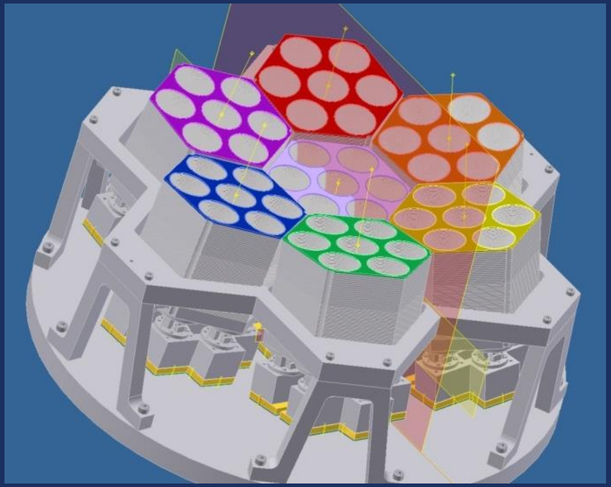


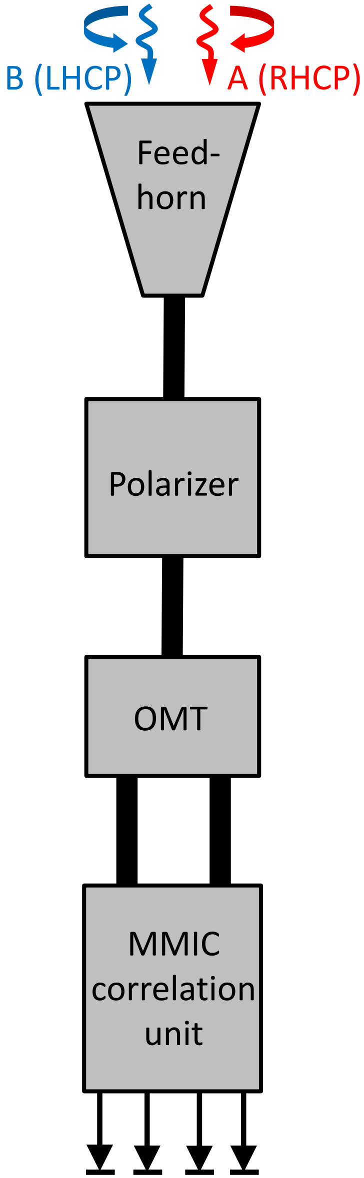
Telescope

- Angular resolution ~ 1.5 deg (FWHM)
- Cross-polarization < -30 dB
- Side-lobe levels < -55 dB
- Dragonian side-fed optics
- M1: 600 mm diameter parabolic reflector
- M2: hyperbolic reflector



Q-band receiver cluster





Polarimeter receiver based on the correlation of the input circular polarizations for the simultaneous detection of the Stokes parameters *Q* and *U*

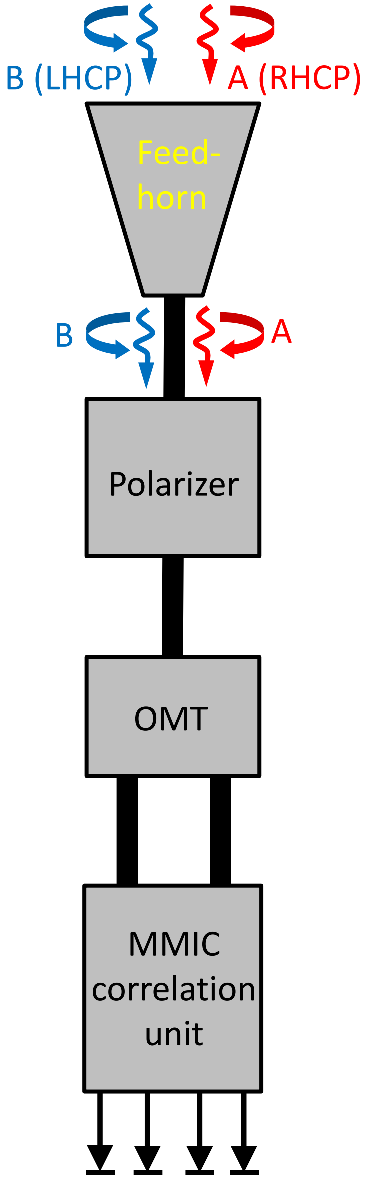
Stokes parameters

$$Q = < |E_x|^2 - |E_y|^2 > = < 2\mathrm{Re}\{AB^*\} >$$

$$U = < 2\mathrm{Re}\{E_x E_y^*\} > = < 2\mathrm{Im}\{AB^*\} >$$

$$V = < -2\mathrm{Im}\{E_x E_y^*\} > = < |B|^2 - |A|^2 >$$

$$I = < |E_x|^2 + |E_y|^2 > = < |A|^2 + |B|^2 >$$



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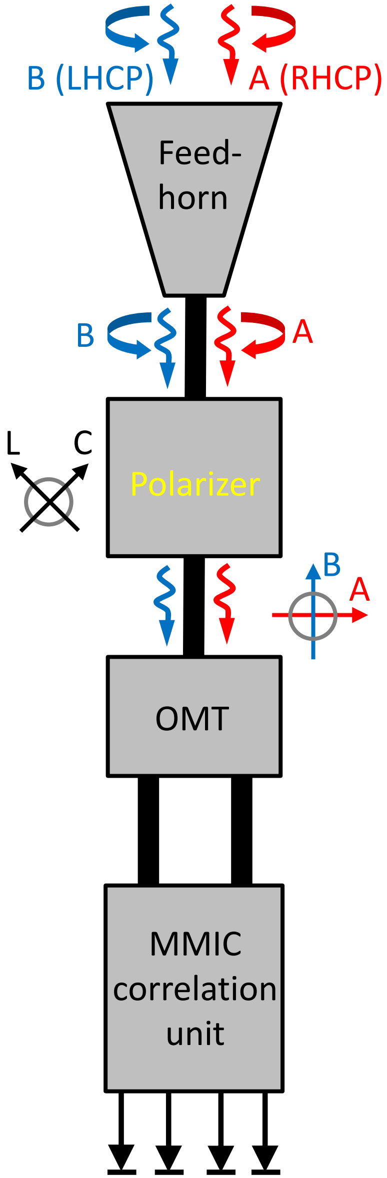

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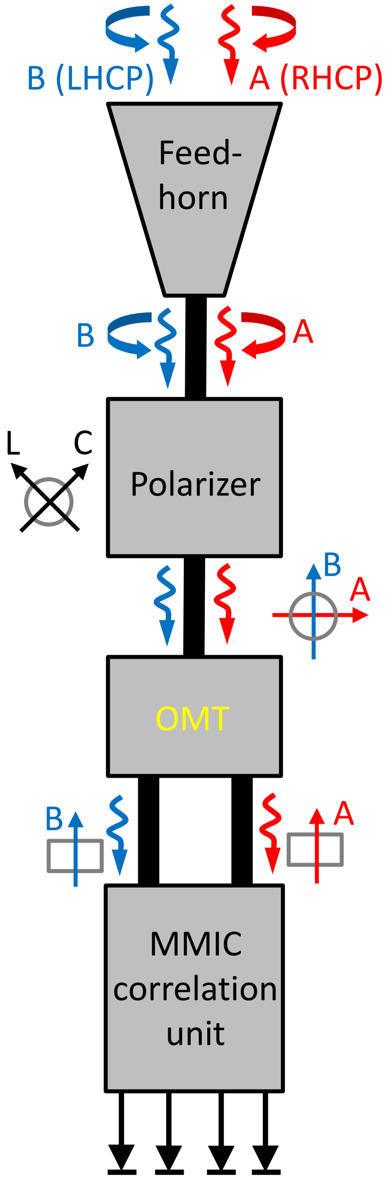

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Stokes parameters

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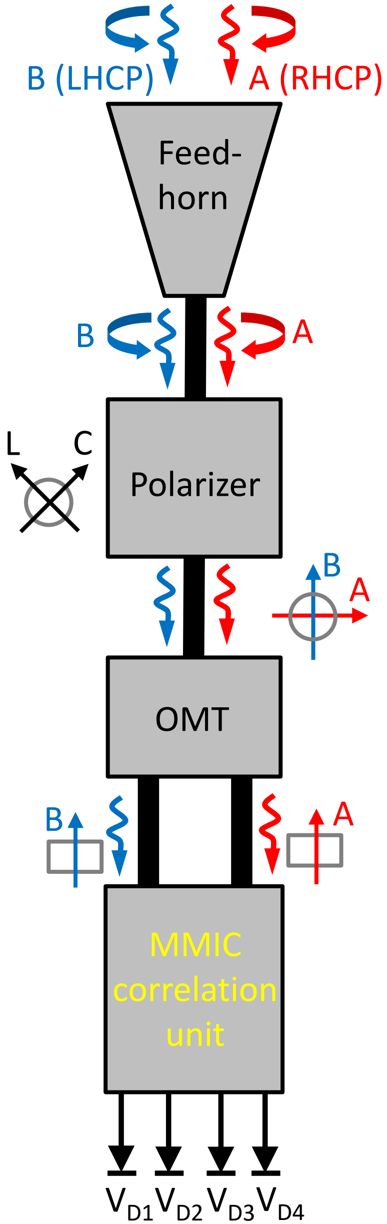
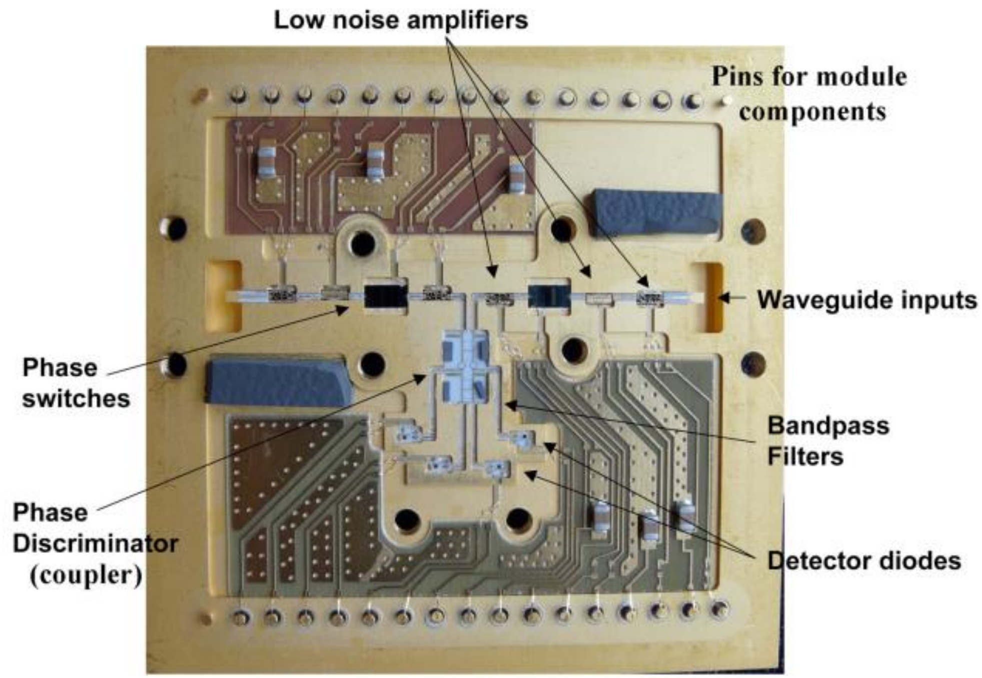
Q-band STRIP Receivers



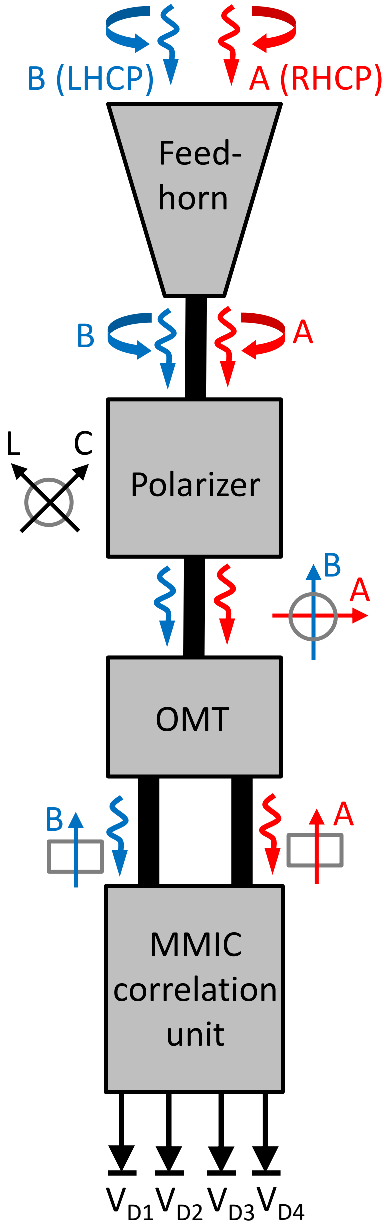


Detected signals

$$V_{D1} \propto < |A+B|^2 >$$
$$V_{D2} \propto < |A-B|^2 >$$
$$V_{D3} \propto < |A+jB|^2 >$$
$$V_{D4} \propto < |A-jB|^2 >$$

$$Q_m \propto V_{D1} - V_{D2}$$
$$U_m \propto V_{D3} - V_{D4}.$$

Q-band STRIP Receivers



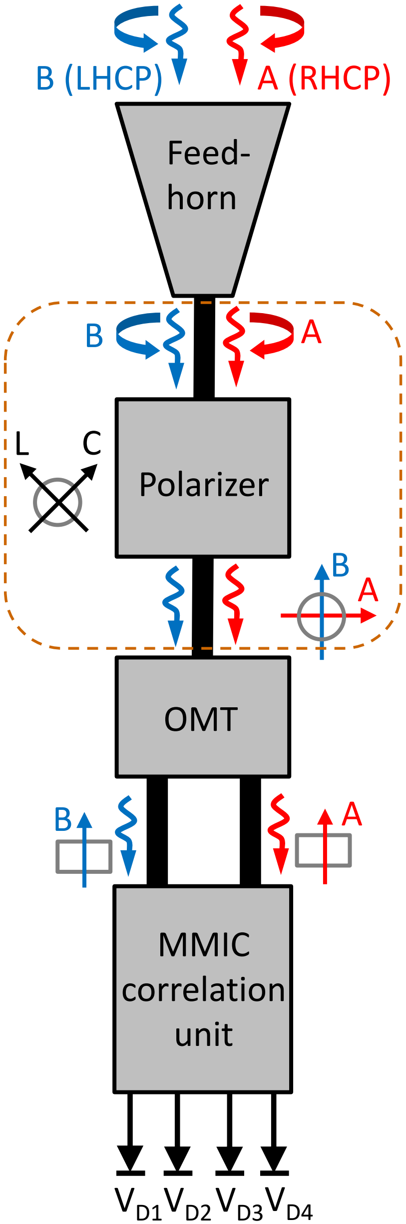
Muller matrix representation

$$\begin{bmatrix}Q\\U\\V\\I\end{bmatrix}_{\text{out}} = \boldsymbol{M}\cdot\begin{bmatrix}Q\\U\\V\\I\end{bmatrix}_{\text{in}} = \begin{bmatrix}\boldsymbol{H} & \boldsymbol{K}\\ \boldsymbol{P} & \boldsymbol{N}\end{bmatrix}\cdot\begin{bmatrix}Q\\U\\V\\I\end{bmatrix}_{\text{in}}.$$

$$\begin{bmatrix}Q\\U\end{bmatrix}_{\text{out}} = \begin{bmatrix}H_{QQ} & H_{QU}\\ H_{UQ} & H_{UU}\end{bmatrix}\cdot\begin{bmatrix}Q\\U\end{bmatrix}_{\text{in}} + \begin{bmatrix}K_{QV} & K_{QI}\\ K_{UV} & K_{UI}\end{bmatrix}\cdot\begin{bmatrix}V\\I\end{bmatrix}_{\text{in}}$$

To be minimized

Q-band Polarizers



$$S^{(2,1)} = \begin{bmatrix} T_{\mathrm{LL}} & T_{\mathrm{LC}} \\ T_{\mathrm{CL}} & T_{\mathrm{CC}} \end{bmatrix}$$

$$\begin{bmatrix} Q \\ U \end{bmatrix}_{\mathrm{out}} = \begin{bmatrix} H_{QQ} & H_{QU} \\ H_{UQ} & H_{UU} \end{bmatrix} \cdot \begin{bmatrix} Q \\ U \end{bmatrix}_{\mathrm{in}} + \begin{bmatrix} K_{QV} & K_{QI} \\ K_{UV} & K_{UI} \end{bmatrix} \cdot \begin{bmatrix} V \\ I \end{bmatrix}_{\mathrm{in}}$$

$$H_{QQ} = \frac{1}{2}\{|T_{\mathrm{LL}}|^2 + |T_{\mathrm{CC}}|^2 - |T_{\mathrm{LC}}|^2 - |T_{\mathrm{CL}}|^2\}$$

$$H_{QU} = \mathrm{Re}\{T_{\mathrm{LL}}T_{\mathrm{LC}}^* - T_{\mathrm{CL}}T_{\mathrm{CC}}^*\}$$

$$H_{UQ} = \mathrm{Im}\{T_{\mathrm{LL}}T_{\mathrm{CL}}^* - T_{\mathrm{LC}}T_{\mathrm{CC}}^*\}$$

$$H_{UU} = \mathrm{Im}\{T_{\mathrm{LC}}T_{\mathrm{CL}}^* + T_{\mathrm{LL}}T_{\mathrm{CC}}^*\}$$

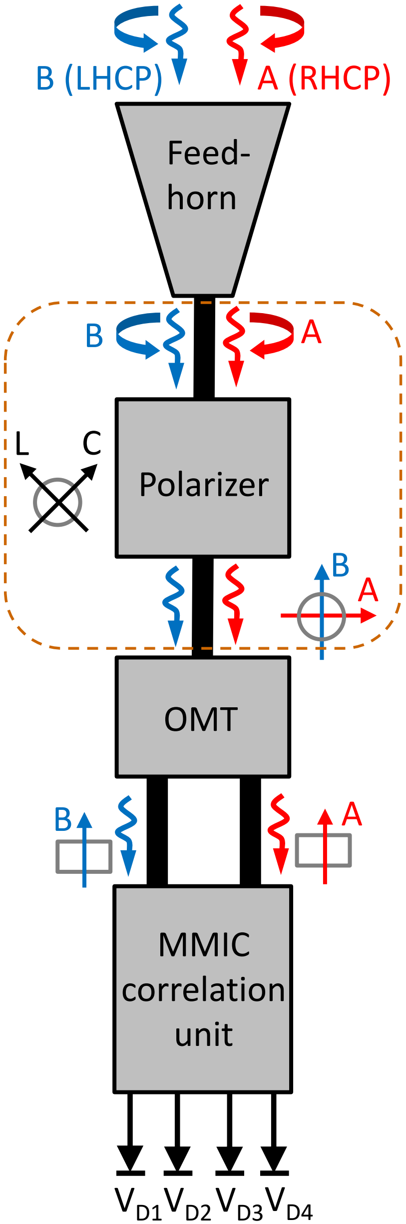
$$K_{QI} = \frac{1}{2}\{|T_{\mathrm{LL}}|^2 - |T_{\mathrm{CL}}|^2 + |T_{\mathrm{LC}}|^2 - |T_{\mathrm{CC}}|^2\}$$

$$K_{QV} = \mathrm{Im}\{T_{\mathrm{LL}}T_{\mathrm{LC}}^* - T_{\mathrm{CL}}T_{\mathrm{CC}}^*\}$$

$$K_{UI} = \mathrm{Im}\{T_{\mathrm{LL}}T_{\mathrm{CL}}^* + T_{\mathrm{LC}}T_{\mathrm{CC}}^*\}$$

$$K_{UV} = \mathrm{Re}\{T_{\mathrm{LC}}T_{\mathrm{CL}}^* - T_{\mathrm{LL}}T_{\mathrm{CC}}^*\}$$

Q-band Polarizers



$$S^{(2,1)} = \begin{bmatrix} T_{\mathrm{LL}} & 0 \\ 0 & T_{\mathrm{CC}} \end{bmatrix}$$

$$\begin{bmatrix} Q \\ U \end{bmatrix}_{\mathrm{out}} = \begin{bmatrix} H_{QQ} & H_{QU} \\ H_{UQ} & H_{UU} \end{bmatrix} \cdot \begin{bmatrix} Q \\ U \end{bmatrix}_{\mathrm{in}} + \begin{bmatrix} K_{QV} & K_{QI} \\ K_{UV} & K_{UI} \end{bmatrix} \cdot \begin{bmatrix} V \\ I \end{bmatrix}_{\mathrm{in}}$$

$$H_{QQ} = \frac{1}{2}\{|T_{\mathrm{LL}}|^2 + |T_{\mathrm{CC}}|^2\}$$

$$H_{QU} = 0$$

$$H_{UQ} = 0$$

$$H_{UU} = \mathrm{Im}\{T_{\mathrm{LL}} T_{\mathrm{CC}}^*\}$$

$$K_{QI} = \frac{1}{2}\{|T_{\mathrm{LL}}|^2 - |T_{\mathrm{CC}}|^2\}$$

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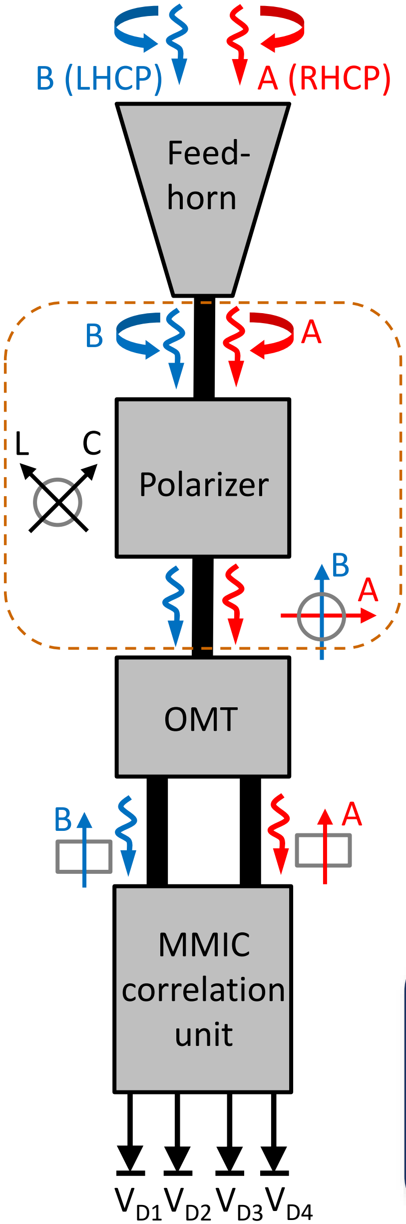
Q-band Polarizers



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$$H_{QQ} = \frac{1}{2}\{|T_{LL}|^2 + |T_{CC}|^2\}$$

$$H_{QU} = 0$$

$$H_{UQ} = 0$$

$$H_{UU} = \mathrm{Im}\{T_{LL}T_{CC}^*\}$$

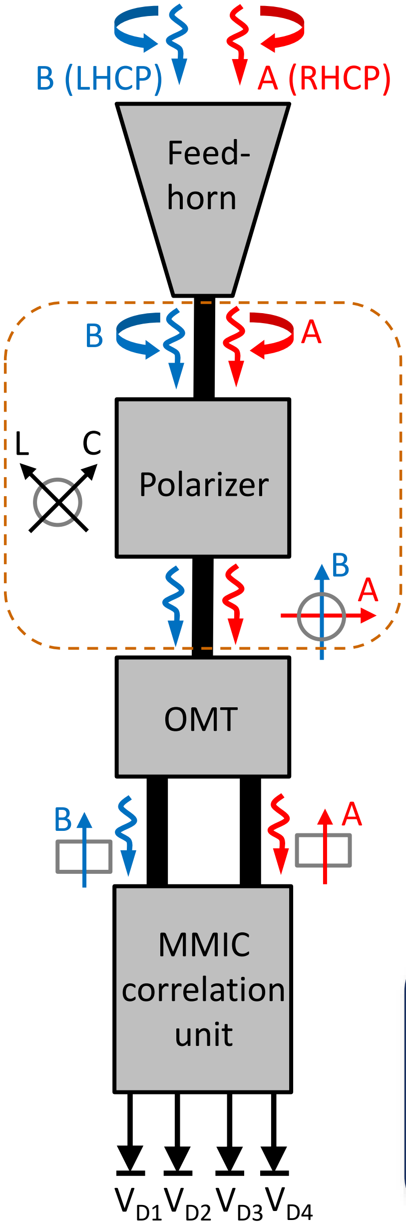
Differential phase-shift around 90 deg with minimization of phase error

$$K_{QI} = \frac{1}{2}\{|T_{LL}|^2 - |T_{CC}|^2\}$$

$$K_{QV} = 0$$

$$K_{UI} = 0$$

$$K_{UV} = -\mathrm{Re}\{T_{LL}T_{CC}^*\}$$



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$$H_{QU} = 0$$

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$$H_{UU} = \mathrm{Im}\{T_{\mathrm{LL}} T_{\mathrm{CC}}^*\}$$

Insertion-loss equalization

$$K_{QI} = \frac{1}{2}\{|T_{\mathrm{LL}}|^2 - |T_{\mathrm{CC}}|^2\}$$

$$K_{QV} = 0$$

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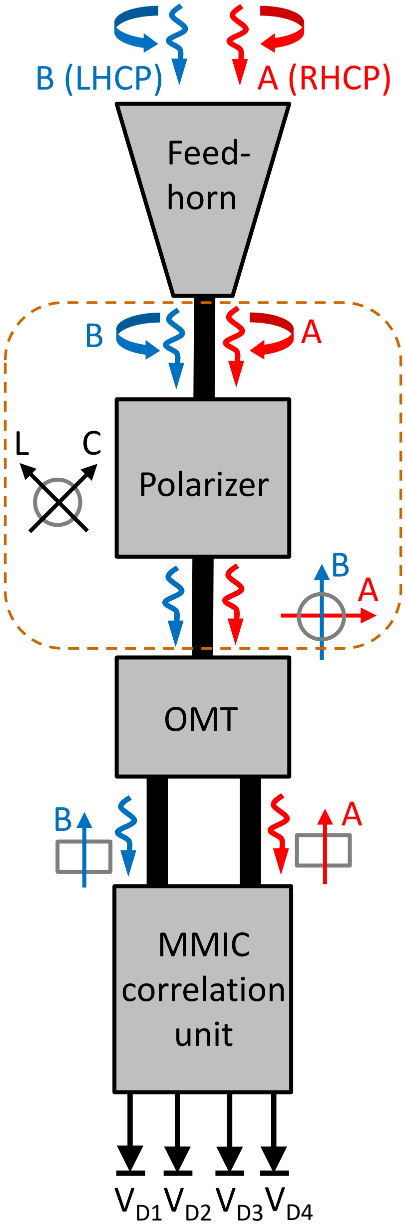
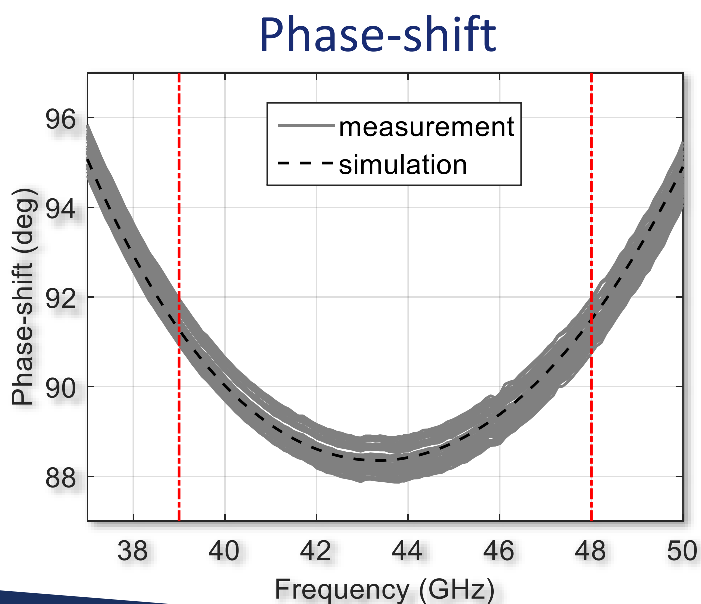
$$K_{UV} = -\mathrm{Re}\{T_{\mathrm{LL}} T_{\mathrm{CC}}^*\}$$

Q-band Polarizers



Measured performances	
Band (GHz)	39 – 48 (nominal) (21%) 29 – 50 (enlarged) (53%)
Return loss (dB)	> 36 (>20)
Insertion loss (dB)	< 0.07 (0.03 silver plated)
Insertion loss unbalancing (dB)	< 0.01
Phase-shift deviation from 90 deg (deg)	< 2.0
Cross-coupling (dB)	< -35



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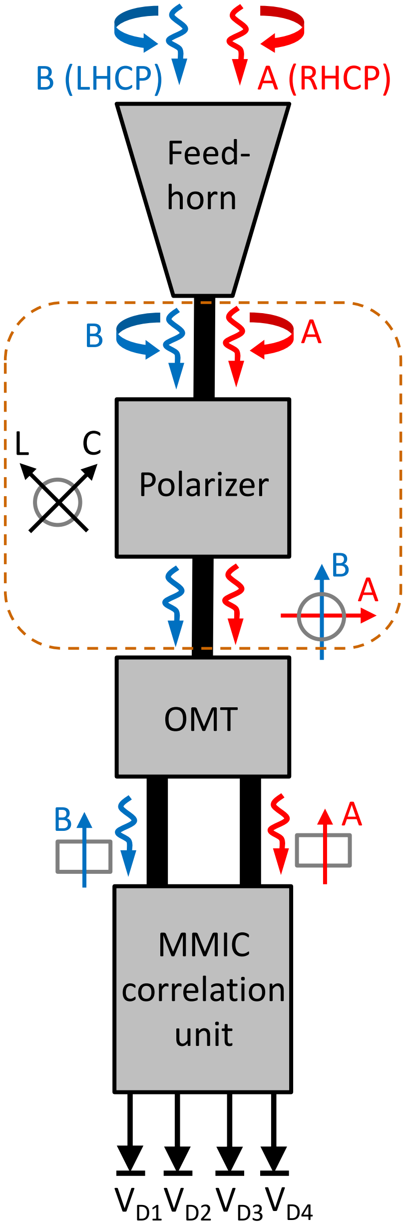

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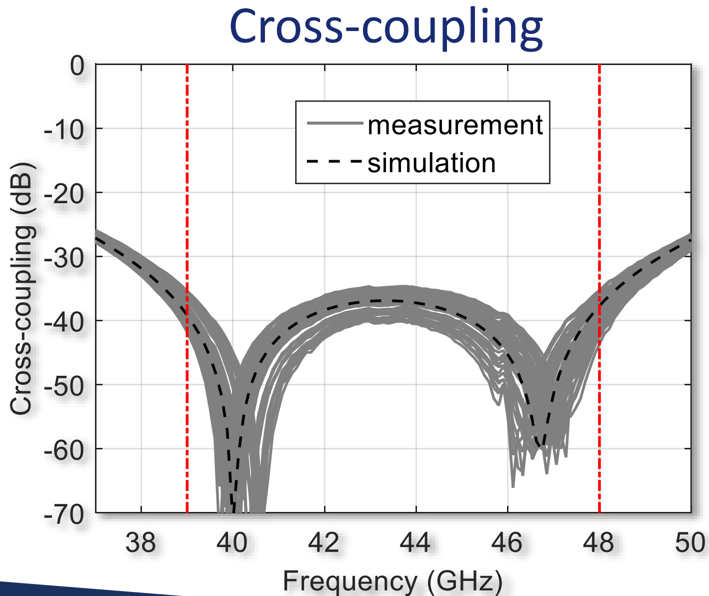

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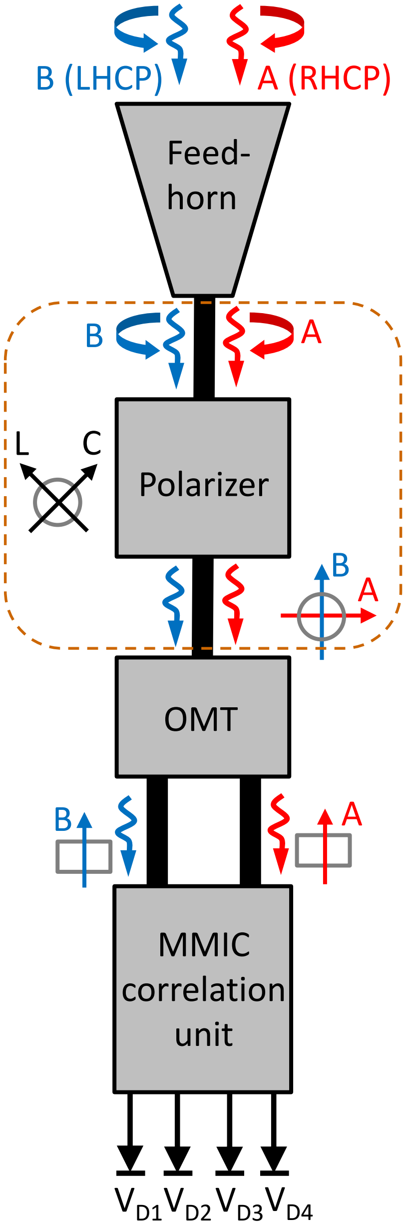

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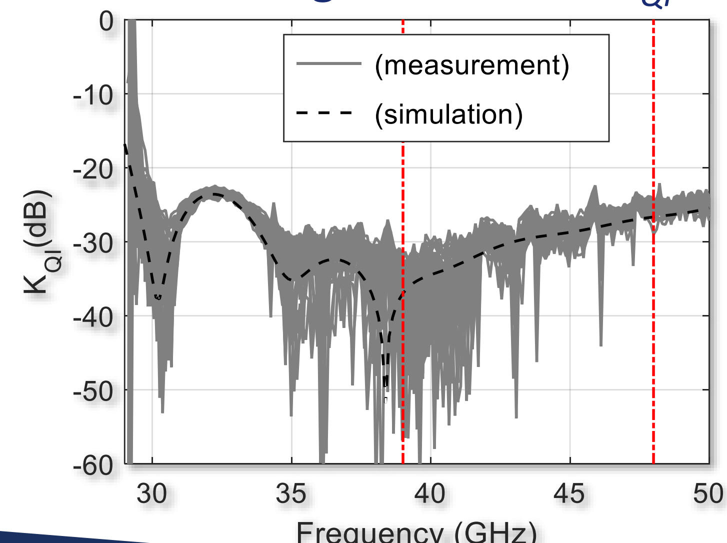
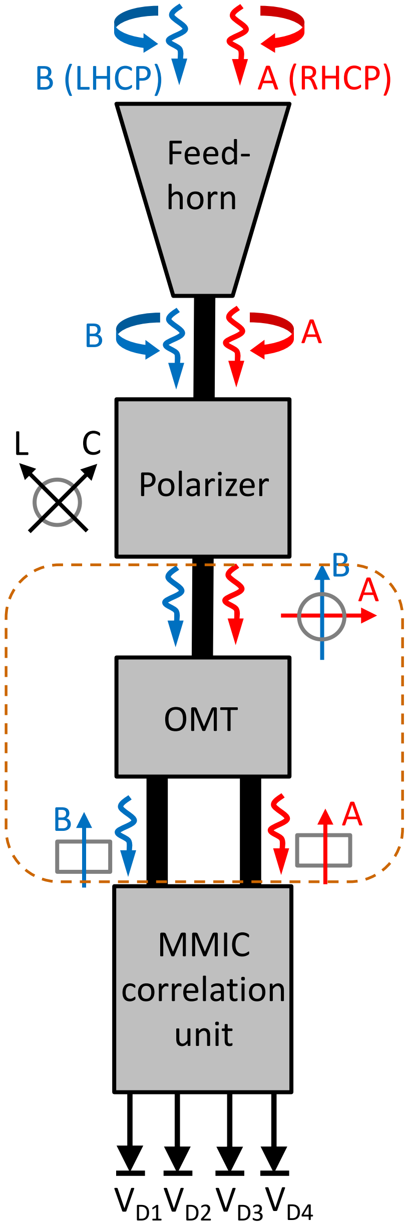
Leakage coefficient K_{QI}



Q-band OMTs



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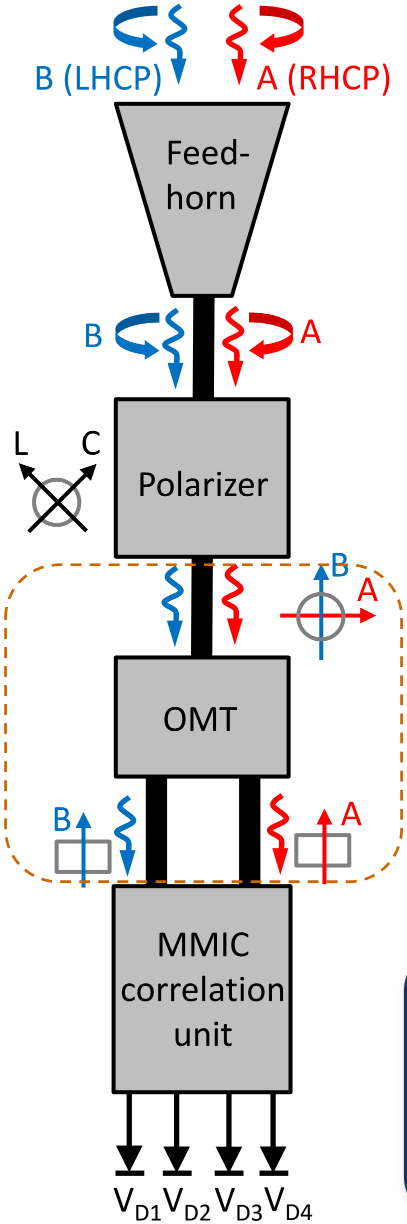

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Channel equalization

$$K_{QI} = \mathrm{Re}\{T_{AA}T_{BA}^* + T_{AB}T_{BB}^*\}$$

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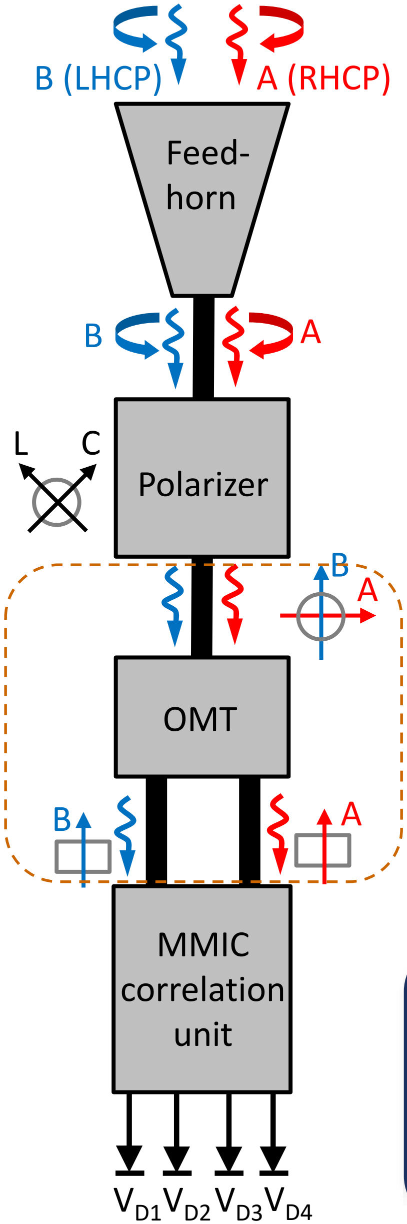

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Low cross-couplings

$$K_{QI} = \mathrm{Re}\{T_{AA}T_{BA}^* + T_{AB}T_{BB}^*\}$$

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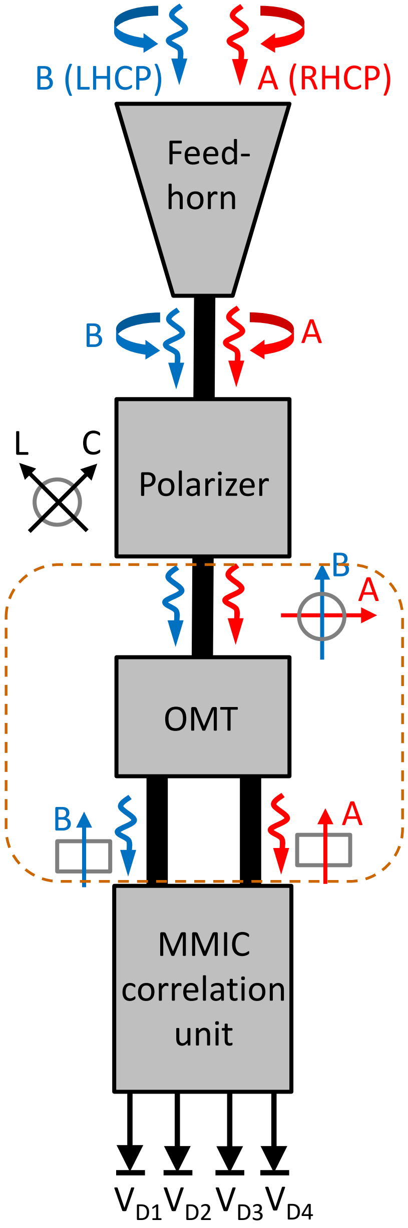
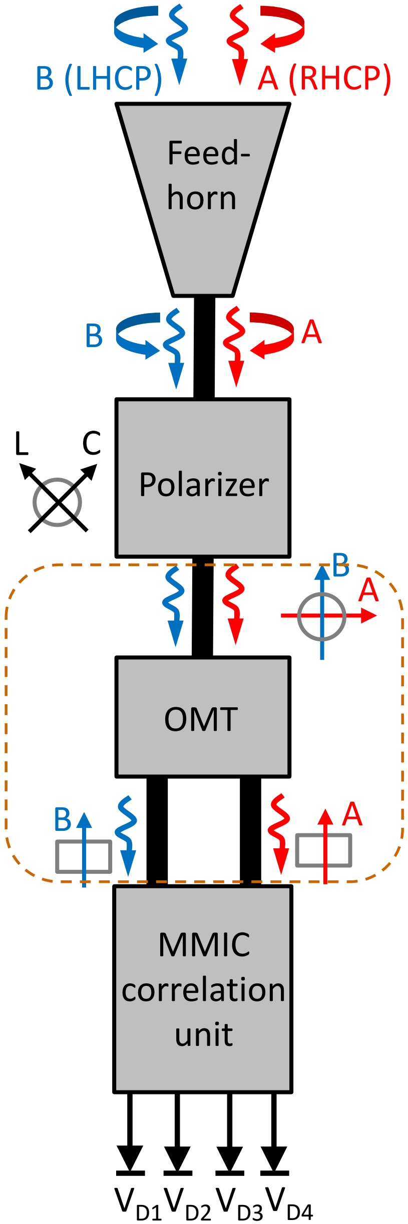


Turnstile-junction design

- Multi-layer layout with standard-thickness metal layers (platelet technique)



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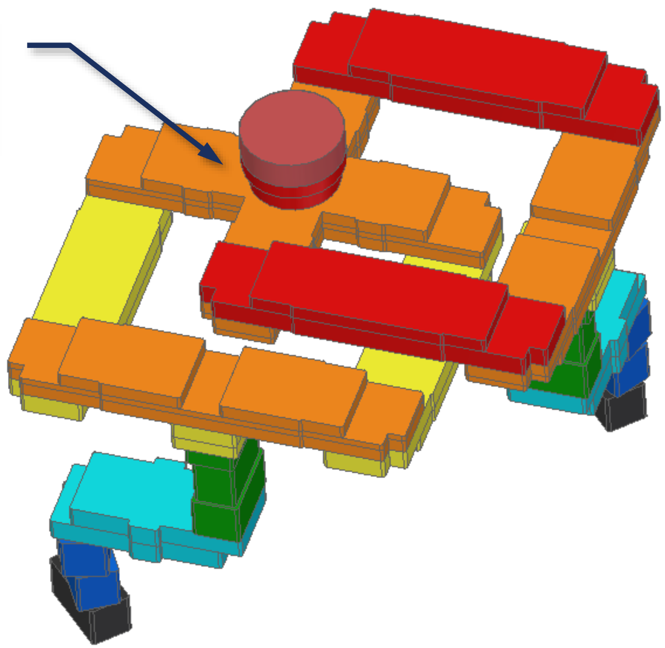

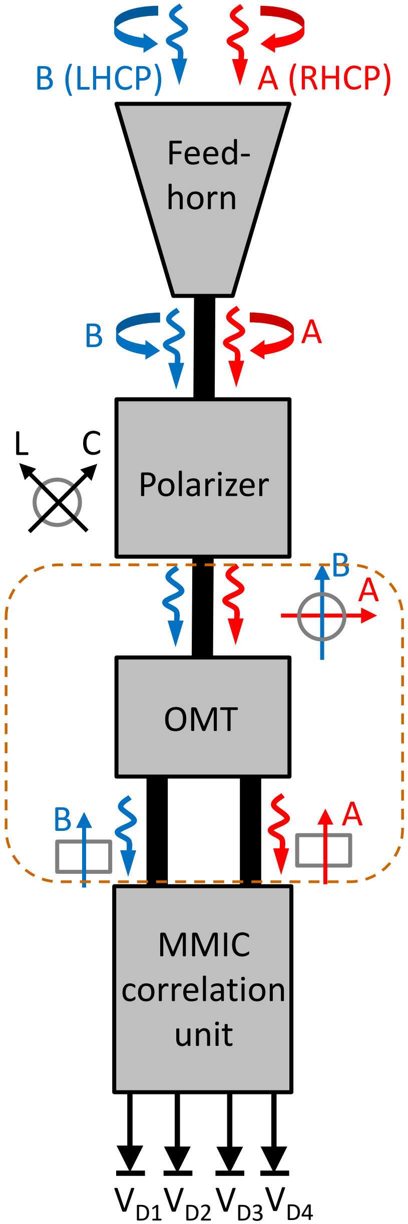

Turnstile-junction design

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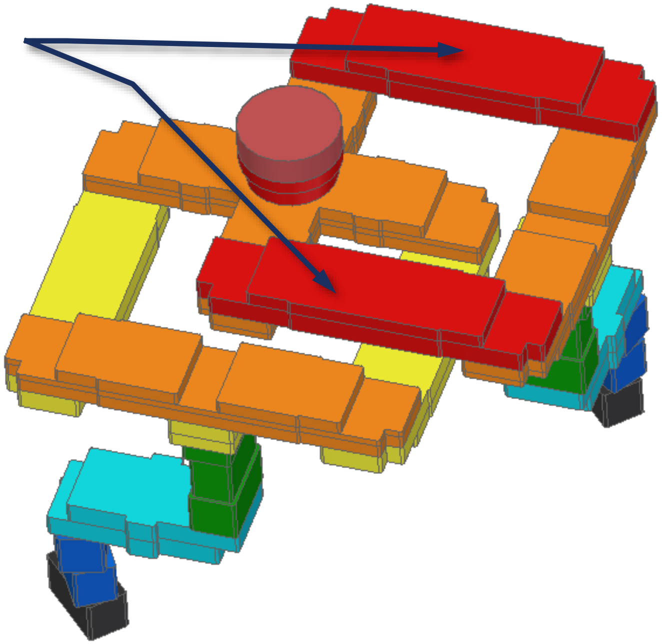
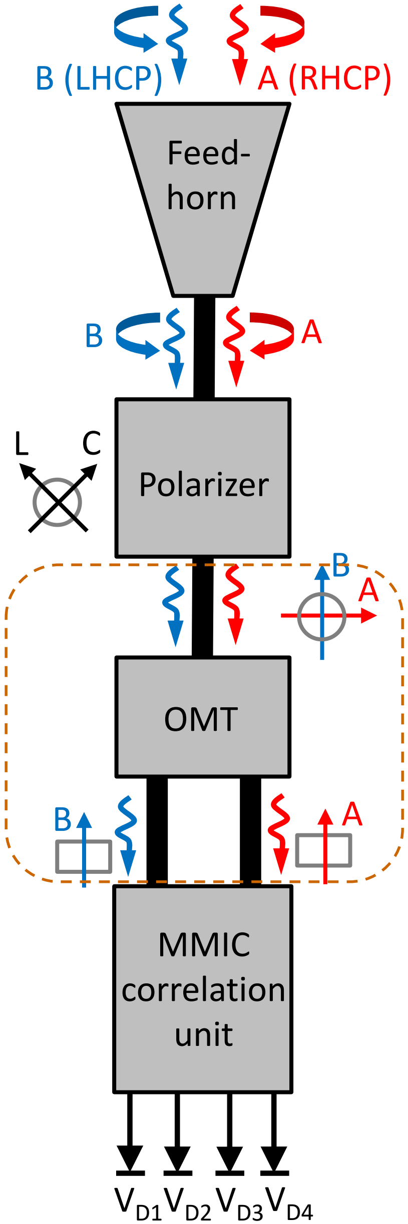
Upper stepped C-bends

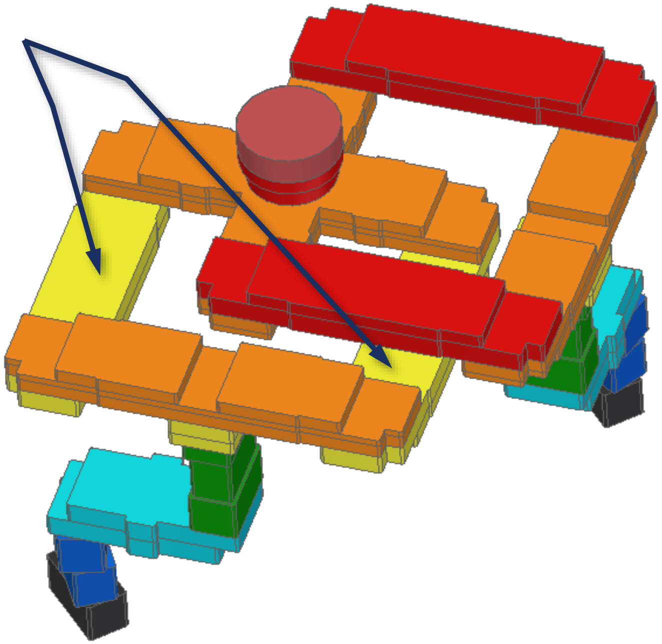


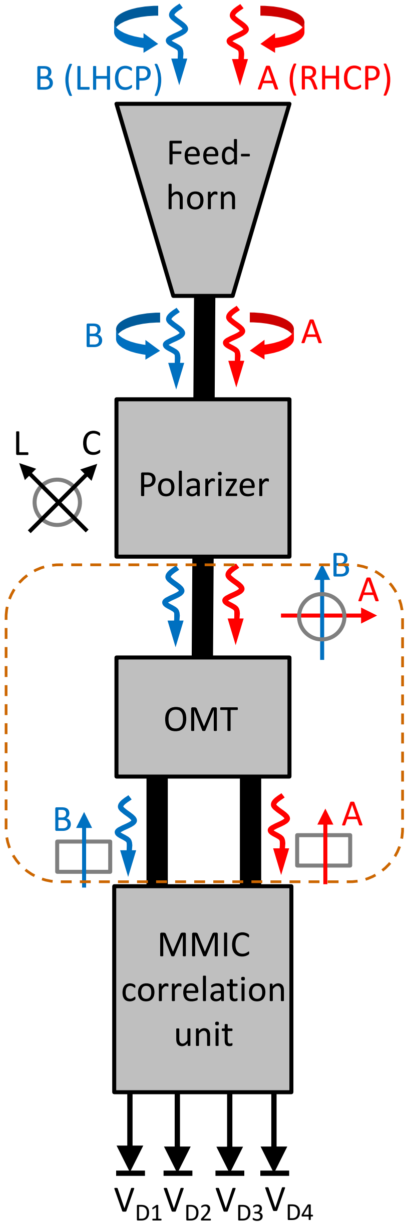


Turnstile-junction design

- Multi-layer layout with standard-thickness metal layers (platelet technique)

Lower stepped C-bends

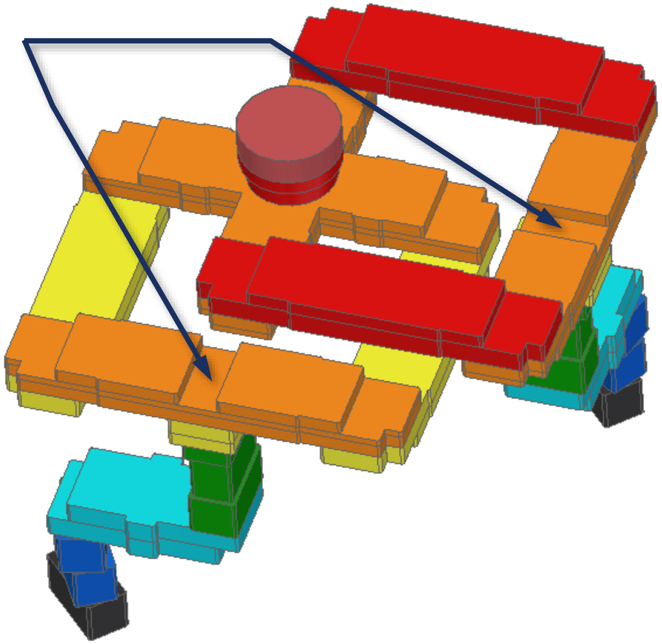


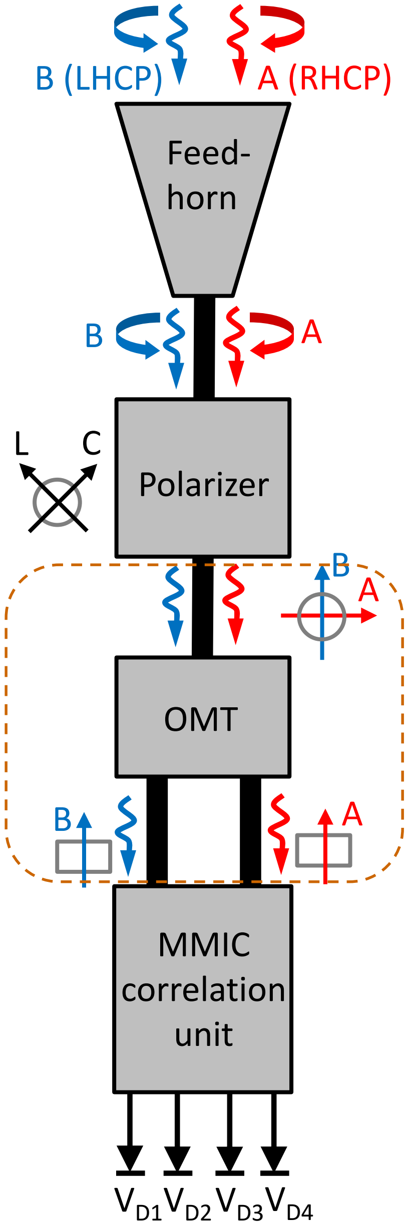


Turnstile-junction design

- Multi-layer layout with standard-thickness metal layers (platelet technique)

Stepped T-junctions

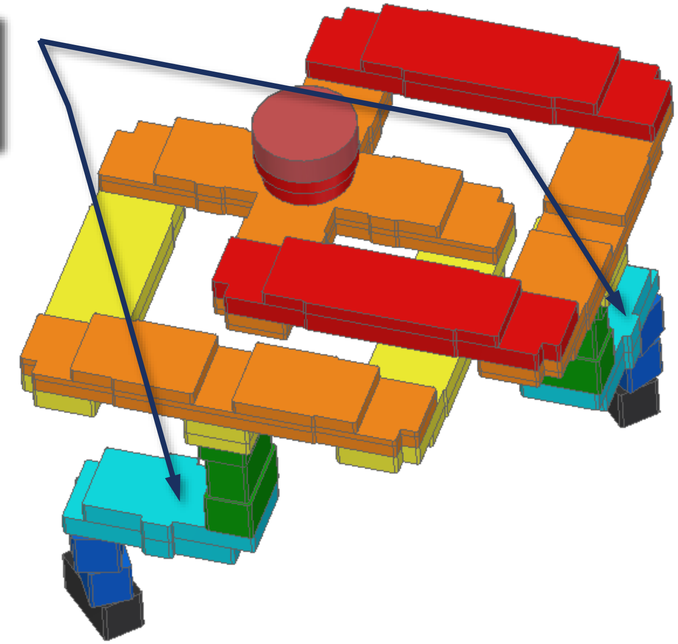


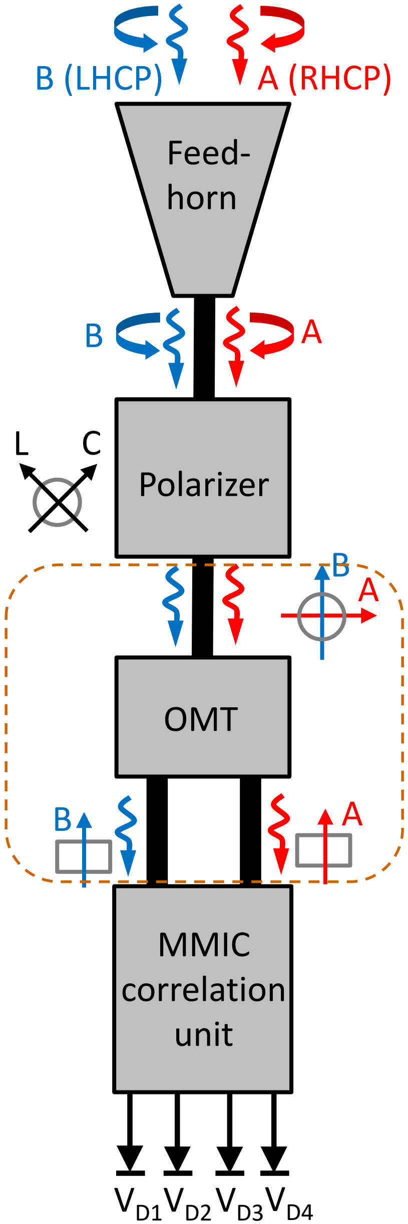


Turnstile-junction design

- Multi-layer layout with standard-thickness metal layers (platelet technique)

Stepped S-bends

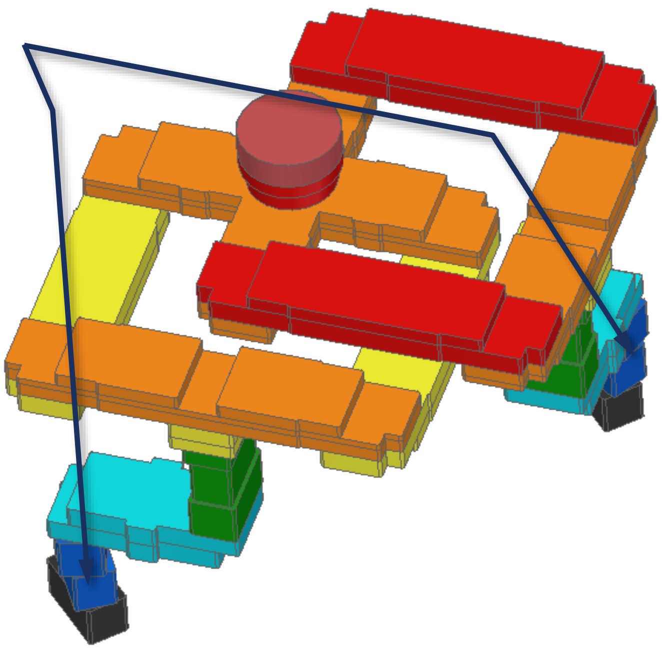


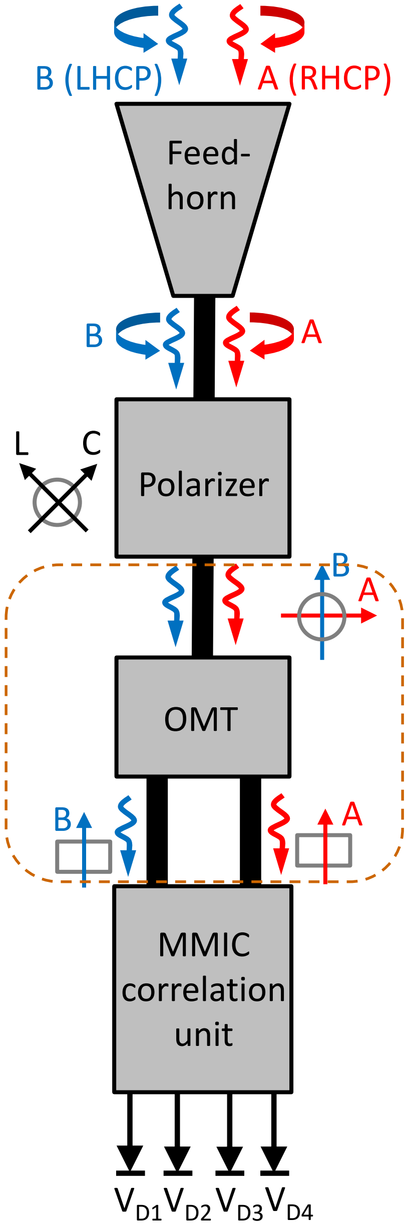


Turnstile-junction design

- Multi-layer layout with standard-thickness metal layers (platelet technique)

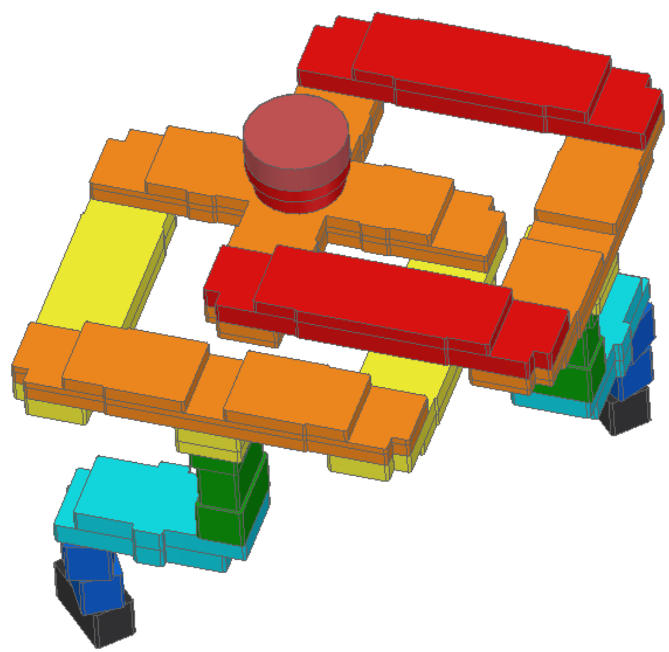
Stepped twists

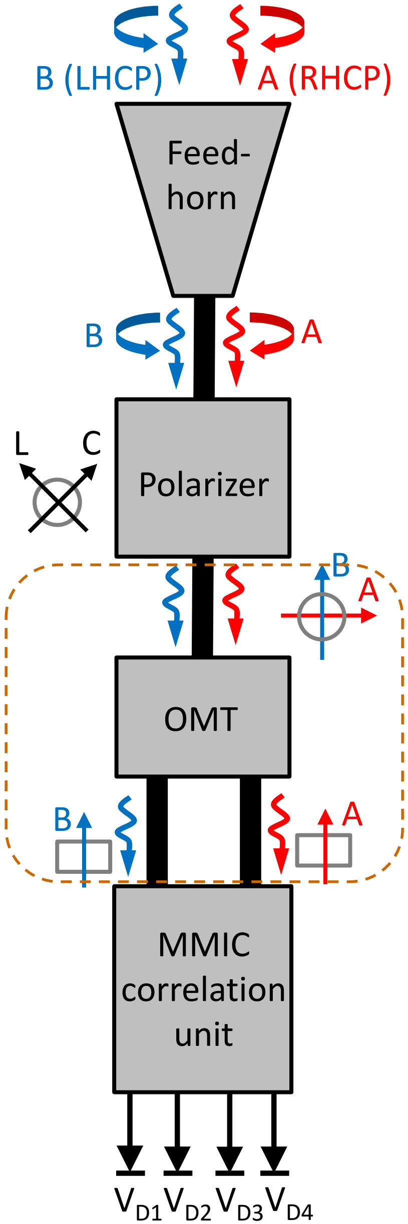




Turnstile-junction design

- Multi-layer layout with standard-thickness metal layers (platelet technique)
- Symmetric design ⇔ channel equalization
- Plumbing to match the correlation unit flange





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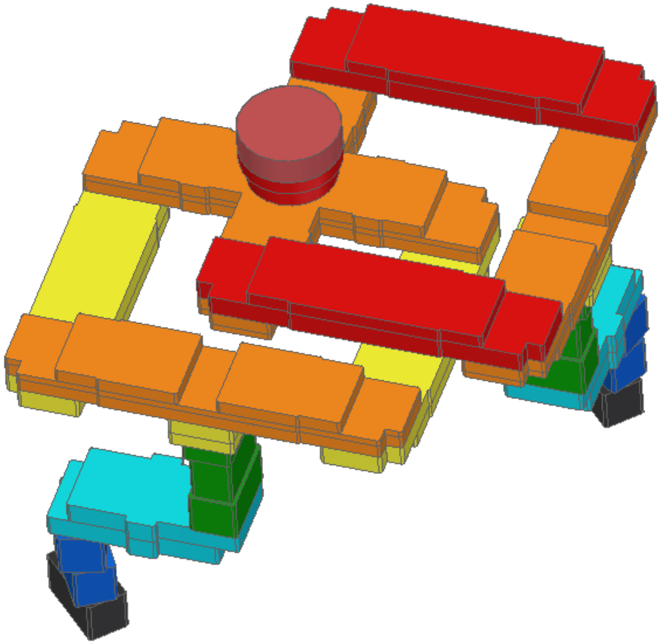
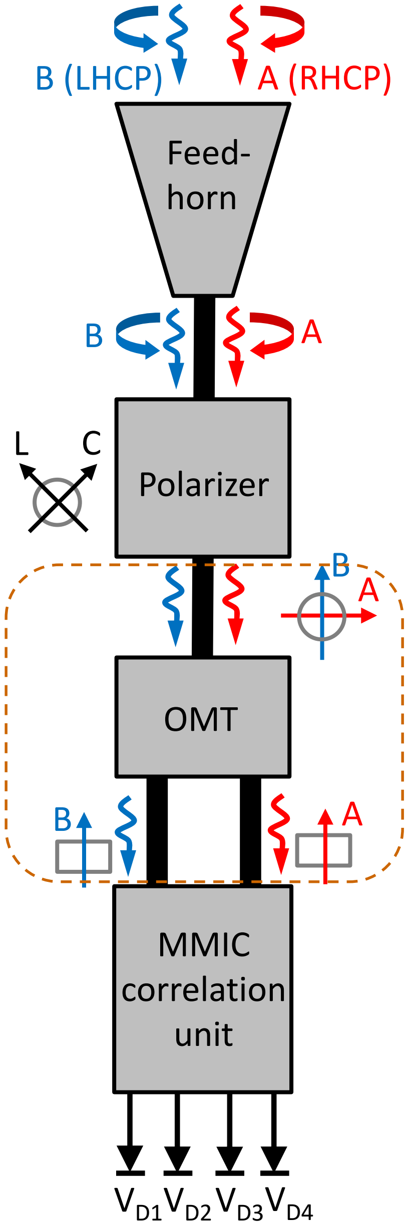
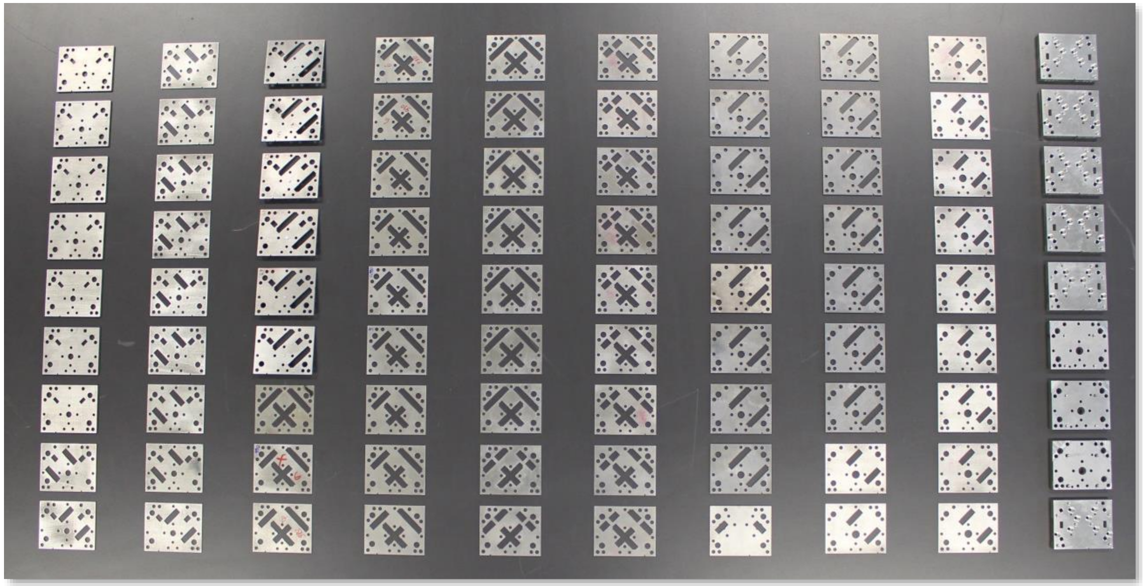


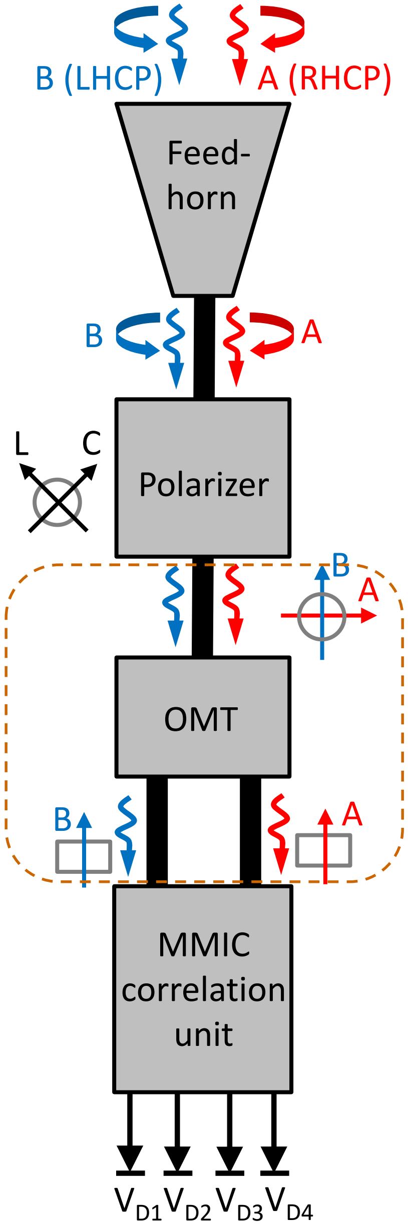


Turnstile-junction design

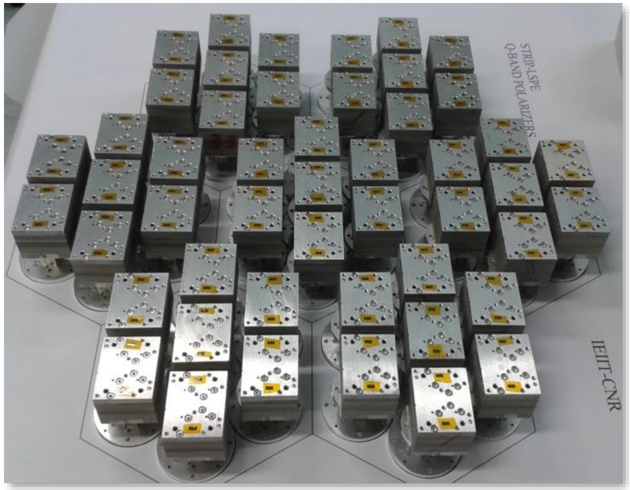
- Multi-layer layout with standard-thickness metal layers (platelet technique)
- Symmetric design ⇔ channel equalization
- Plumbing to match the correlation unit flange
- Manufacturing process parallelization (wire EDM)

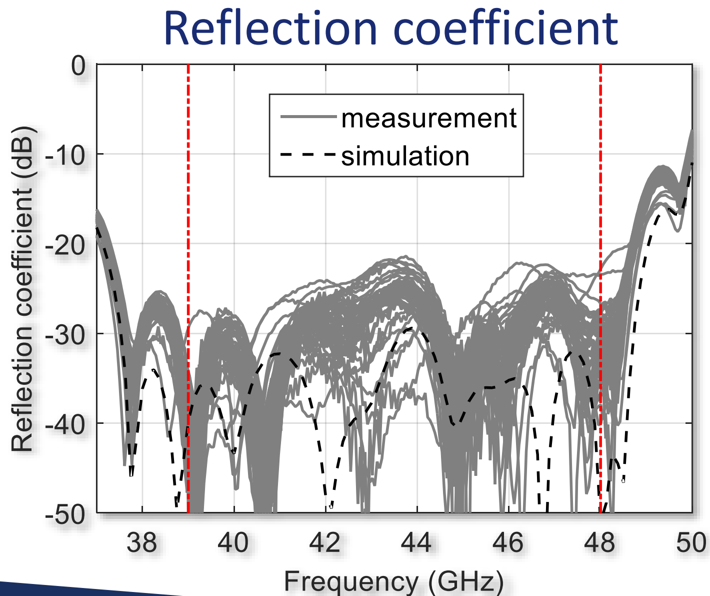


Q-band OMTs

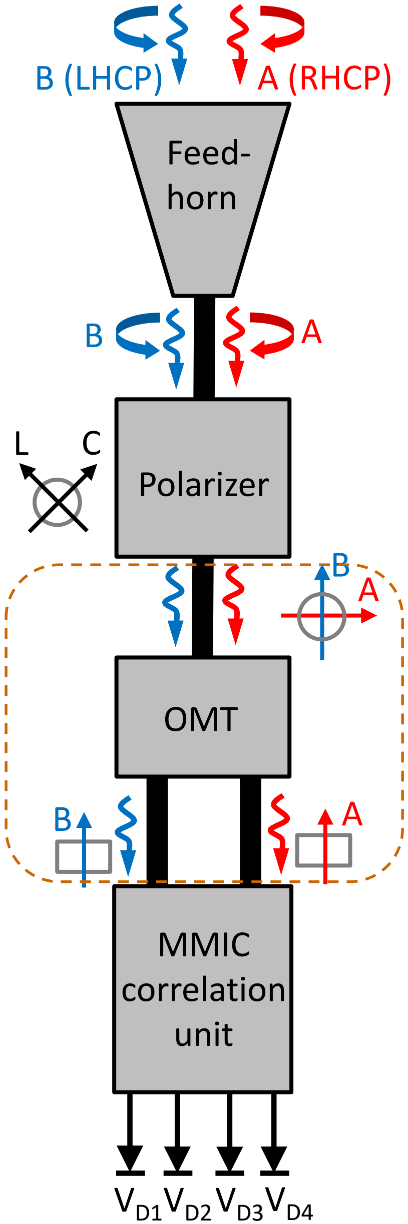


Measured performances	
Band (GHz)	39 – 48 (nominal) (21%) 29 – 50 (enlarged) (53%)
Return loss (dB)	> 22 (> 5)
Insertion loss(dB)	< 0.6 (< 0.3 silver-plated)
Cross-coupling (dB)	< -50
Isolation (dB)	50





Q-band OMTs



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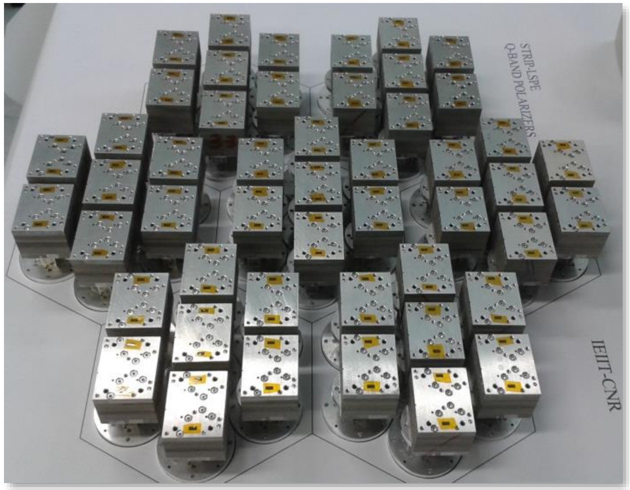
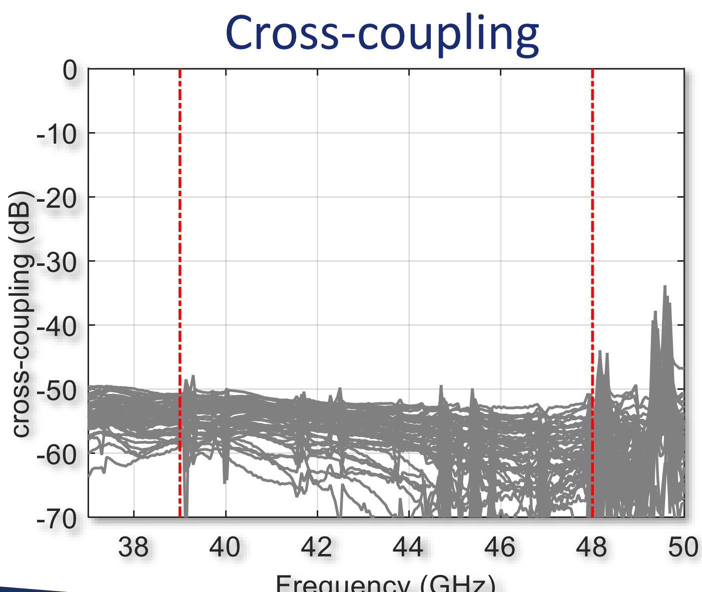
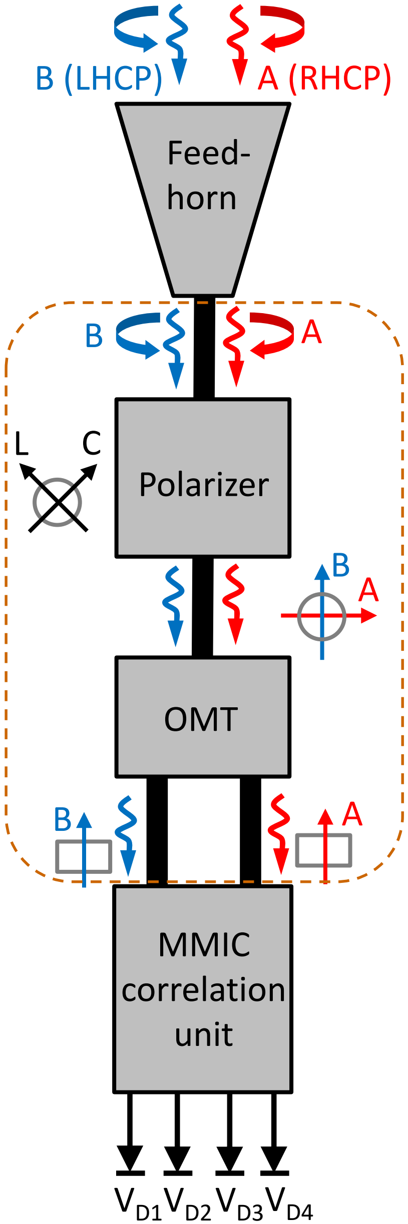
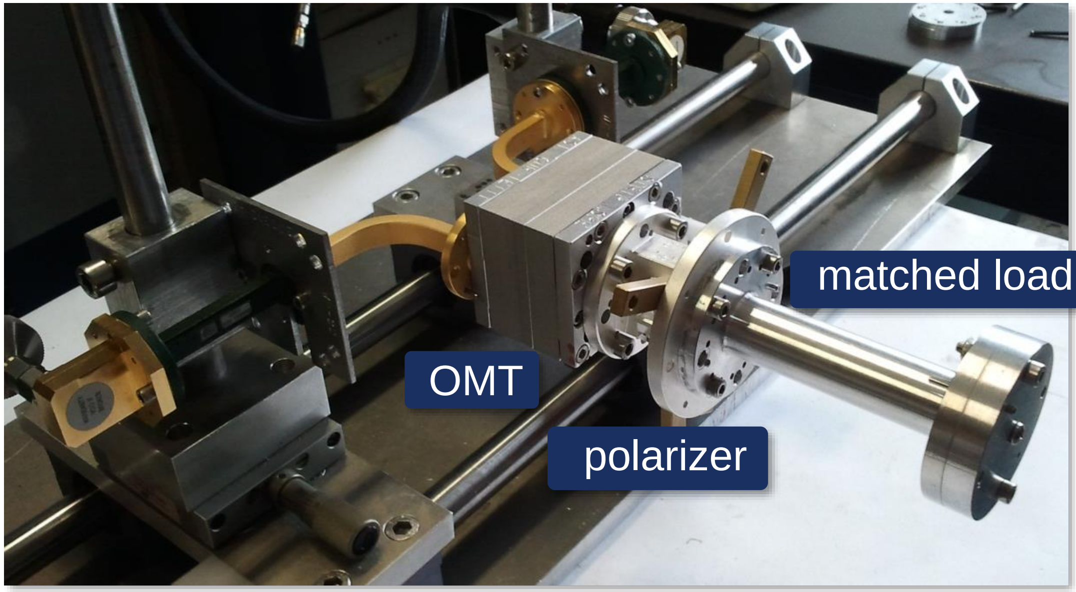


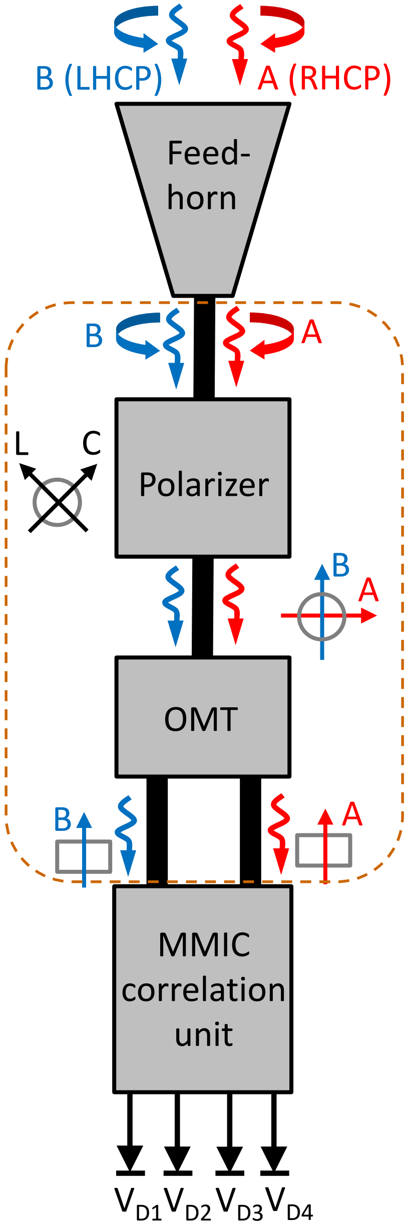




Dual-Mode Short Delay Reactive Load (DM-SDRL)

- Reflection measurement @ rectangular ports
- Five standard loads
- Complete dual-polarization characterization
- Extendible to over-moded waveguide devices (MM-SDRL)





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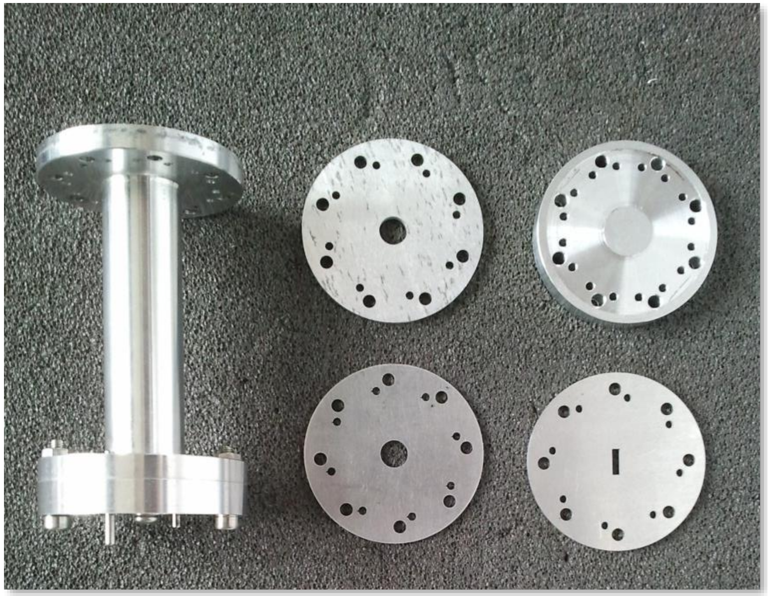
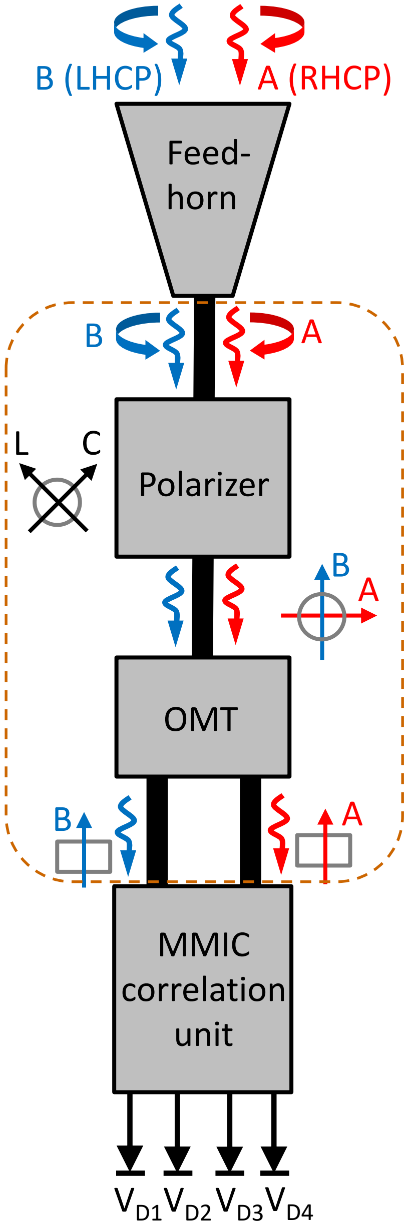
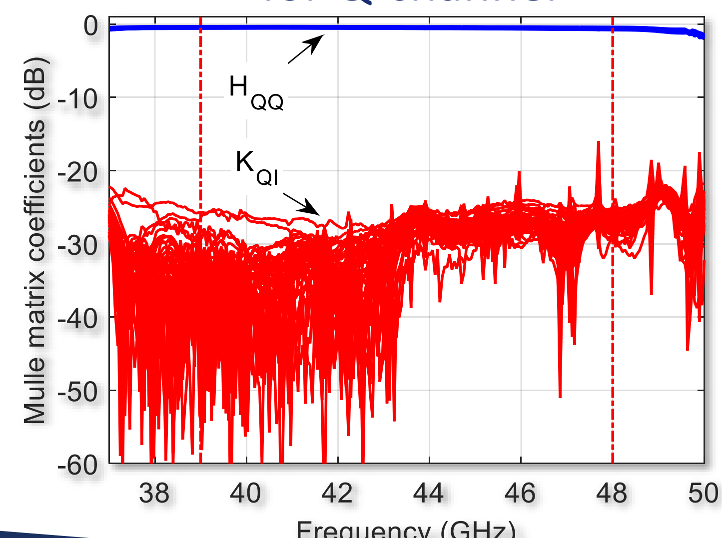


Q-band polarizers + OMTs

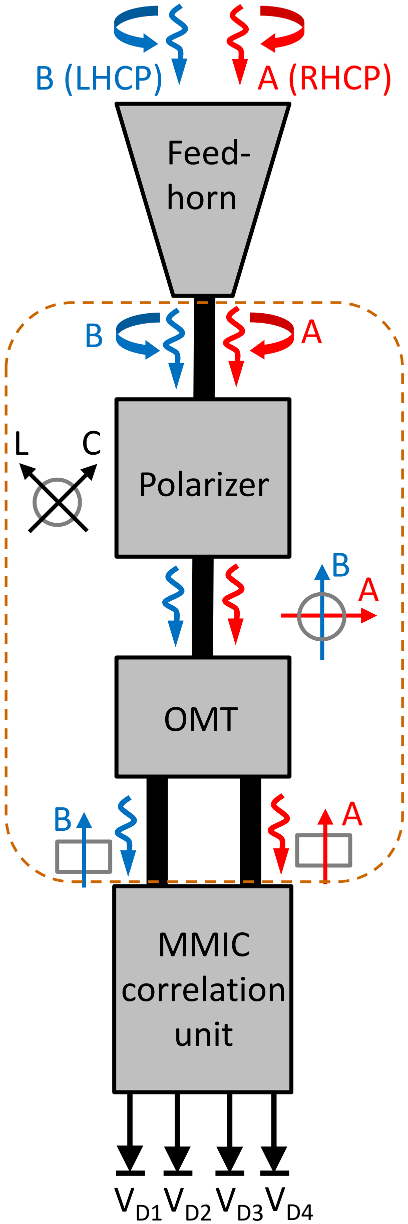


Measured performances	
Band (GHz)	39 – 48 (nominal) (21%) 29 – 50 (enlarged) (53%)
Return loss (dB)	> 22 (> 5)
Insertion loss(dB)	< 0.7
Cross-coupling (dB)	< -35
Isolation (dB)	40

Muller matrix coefficients for Q-channel

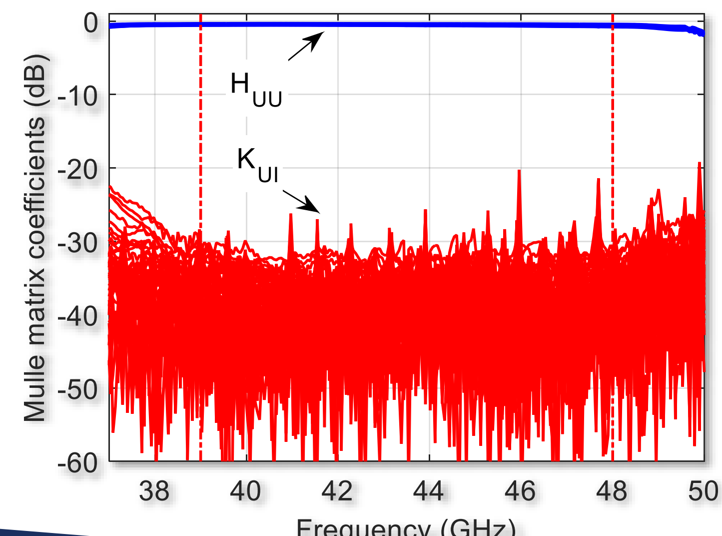


Q-band polarizers + OMTs

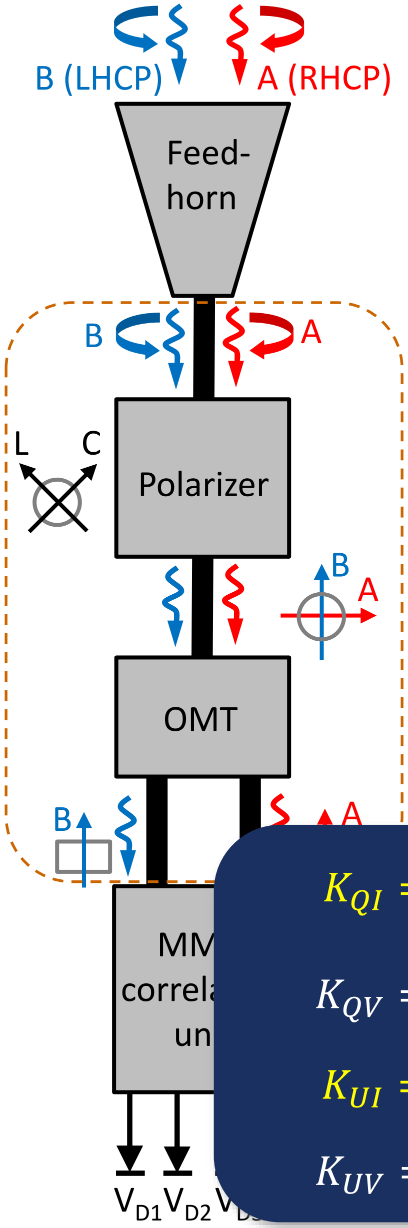


Measured performances	
Band (GHz)	39 – 48 (nominal) (21%) 29 – 50 (enlarged) (53%)
Return loss (dB)	> 22 (> 5)
Insertion loss(dB)	< 0.7 (< 0.4 silver-plated)
Cross-coupling (dB)	< -35
Isolation (dB)	40

Muller matrix coefficients for U-channel



Q-band polarizers + OMTs



Measured performances	
Band (GHz)	39 – 48 (nominal) (21%) 29 – 50 (enlarged) (53%)
Return loss (dB)	> 22 (> 5)
Insertion loss(dB)	< 0.7 (< 0.4 silver-plated)
Cross-coupling (dB)	< -35
Isolation (dB)	40

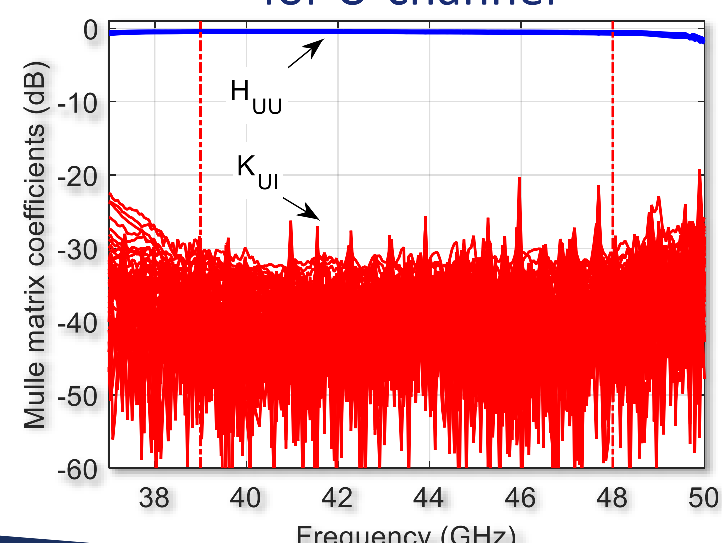
$$K_{QI} = \mathrm{Re}\{T_{AA}T_{BA}^{*} + T_{AB}T_{BB}^{*}\}$$

$$K_{QV} = -\mathrm{Re}\{T_{AA}T_{BA}^{*} - T_{AB}T_{BB}^{*}\}$$

$$K_{UI} = \mathrm{Im}\{T_{AA}T_{BA}^{*} + T_{AB}T_{BB}^{*}\}$$

$$K_{UV} = -\mathrm{Im}\{T_{AA}T_{BA}^{*} - T_{AB}T_{BB}^{*}\}.$$

Muller matrix coefficients for U-channel



Thank you for your attention