Tu3B-4

A Balun-Integrated On-Chip Differential Pad for Full-Multi-Band mmWave-THz Measurements

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Outline

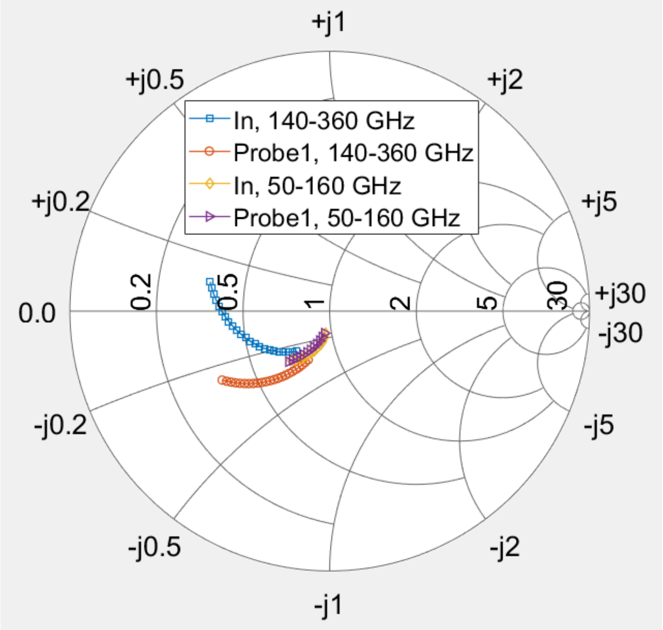
- Outline
- Motivation with problem statement and main objectives
- On-chip pad at mmWave/THz frequencies
- Planar Marchand balun: background with overview
- Balun-integrated differential pad: implementation details
- Measurement results
- Conclusions with comparison to the previous work

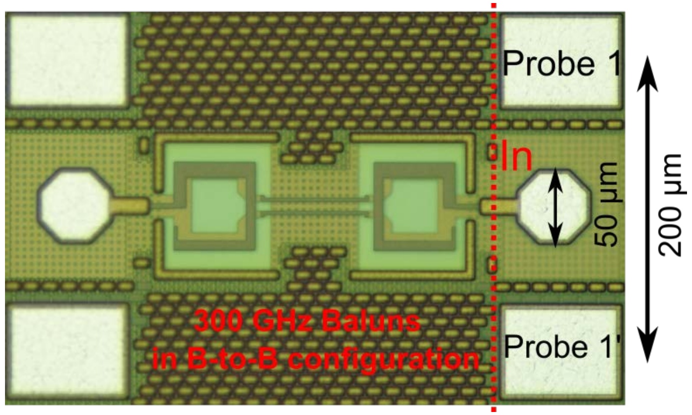
Motivation with problem statement

- **Motivation:** broadband characterization of differential on-chip active circuits in the upper mmWave/THz band
- **Requirements:**
  - Full/multi-band operation (nonlinear circuits with harmonic content)
  - RL around 20 dB for accurate characterization of large-signal operated circuits (load/pull effects hard to de-embed)
  - Very low imbalance for near-ideal differential excitation
- **Goal:** only 2nd-tier on-chip transmission calibration required after initial 2-port calibration with a standard cal substrate

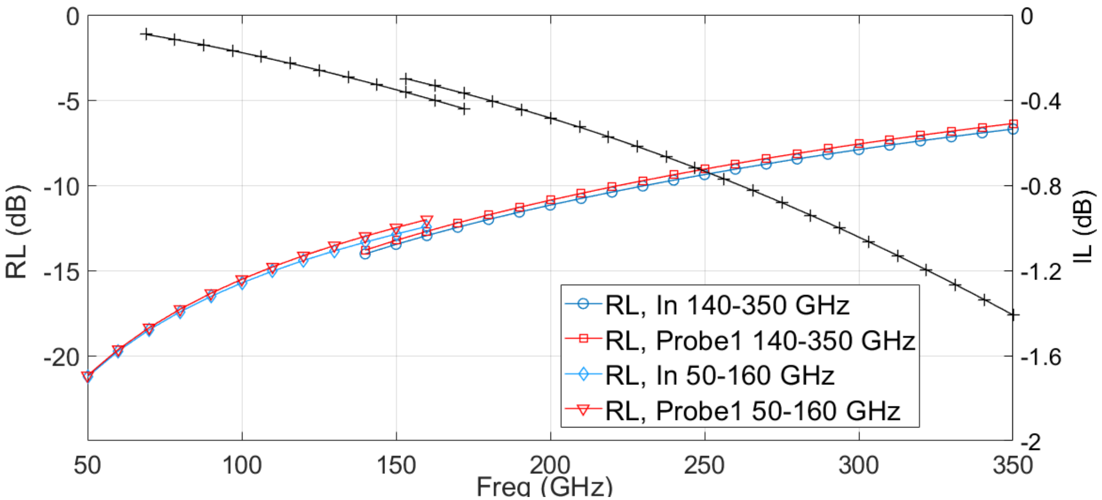
On-chip pad at THz frequencies

- On-chip 50Ω pads in 7-layer BEOL SiGe HBT
  - V-to-D band (TM2/M3) and J-band (TM2/M1)
  - Gnd below pad not removed (substrate coupling)
  - Poor RL/IL above 200 GHz
  - Up to D-band modeled by LC (21 pH/21fF)
  - J-band-> distributed 2-port with frequency-dependent Z_{out} scaled down to 20 Ω



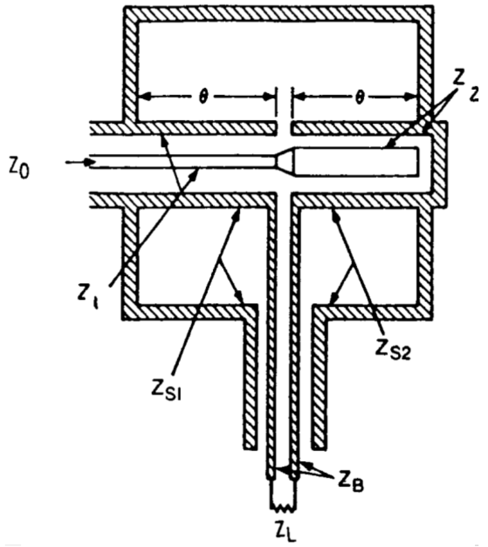


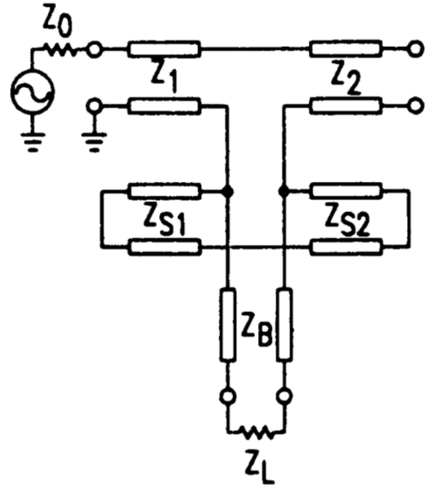
On-chip pad commonly compensated with a shunt stub at lower mmWave frequencies



Planar Marchand balun: overview

- Coaxial Marchand compensated balun
  - Multielement bandpass network of 4 different transmission lines in the general case (design flexibility)
  - Z_1/Z_2 completely shielded from Z_{s1} and Z_{s2}!
  - General design trends for broadband operation with an increase in Z_L/Z_o transformation ratio (filter synthesis)
    - Z_1,Z_2 increase, Z_{s1},Z_{s2} decrease
    - RL and bandwidth traded against each other
    - Bandwidth decreases with transformation ratio



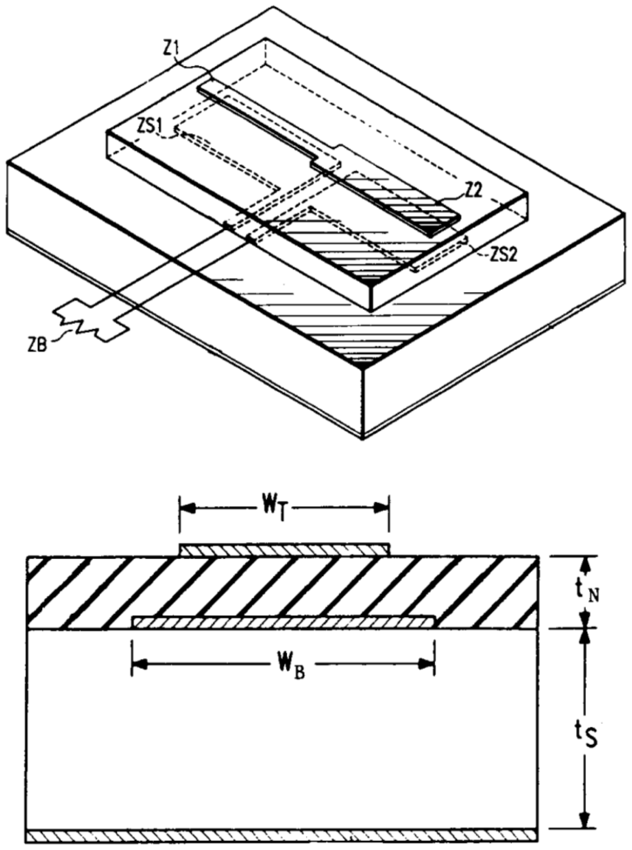


after [pavio1990]

[pavio1990] A. Pavio, A. Kikel, "A monolithic or hybrid broadband compensated balun," IEEE MTT-S Dig., May 1990, Dallas, TX, USA, pp. 483-486

Planar Marchand balun: overview

- Planar Marchand compensated balun
  - For sufficient isolation between Z1,Z2 and Zs1,Zs2 extremely tight coupling (t_n) ,large spacing to global ground (t_s), and high W_b/W_t ratio required
  - Practically unfeasible to fulfill for IC technologies with thin BEOL and close-proximity global ground
  - For 300 GHz operation, strip width further limited by physical implementation of a quarter-wavelength



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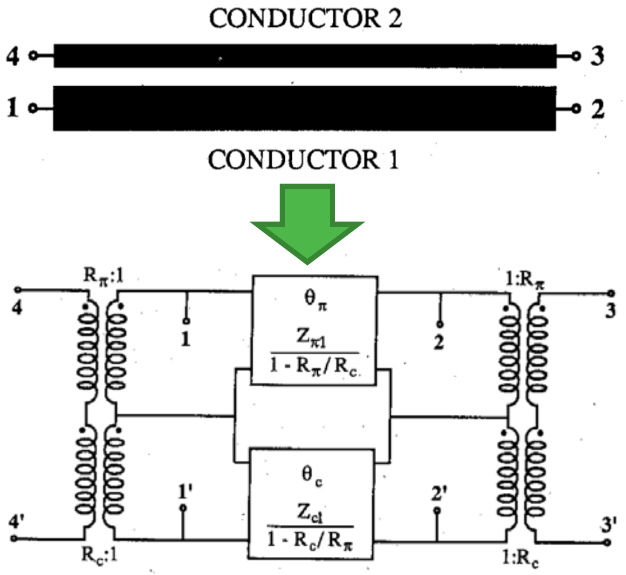
Planar Marchand balun: overview

- Planar Marchand compensated balun (analysis)
  - In general case, full modal analysis of the asymmetric coupled-lines in inhomogeneous medium required with 2 normal modes: 'c' and 'π'
  - Both modes relate to a combination of voltages on 2 lines with the corresponding voltage ratios Rc and Rπ
  - $Z_{c2}/Z_{c1}=Z_{\pi 2}/Z_{\pi 1}=-R_c \cdot R_\pi$
  - 4x4 Z-matrix representation with linear superposition of 'c' and 'π' terms (θc and θπ generally different)
  - Symmetrical lines: Rc=1 and Rπ=-1 (even/odd symmetry)
  - Asymmetric lines in homogeneous medium (TEM): Rc= -Rπ
  - Both capacitance and inductance matrix needed for normal mode parameters



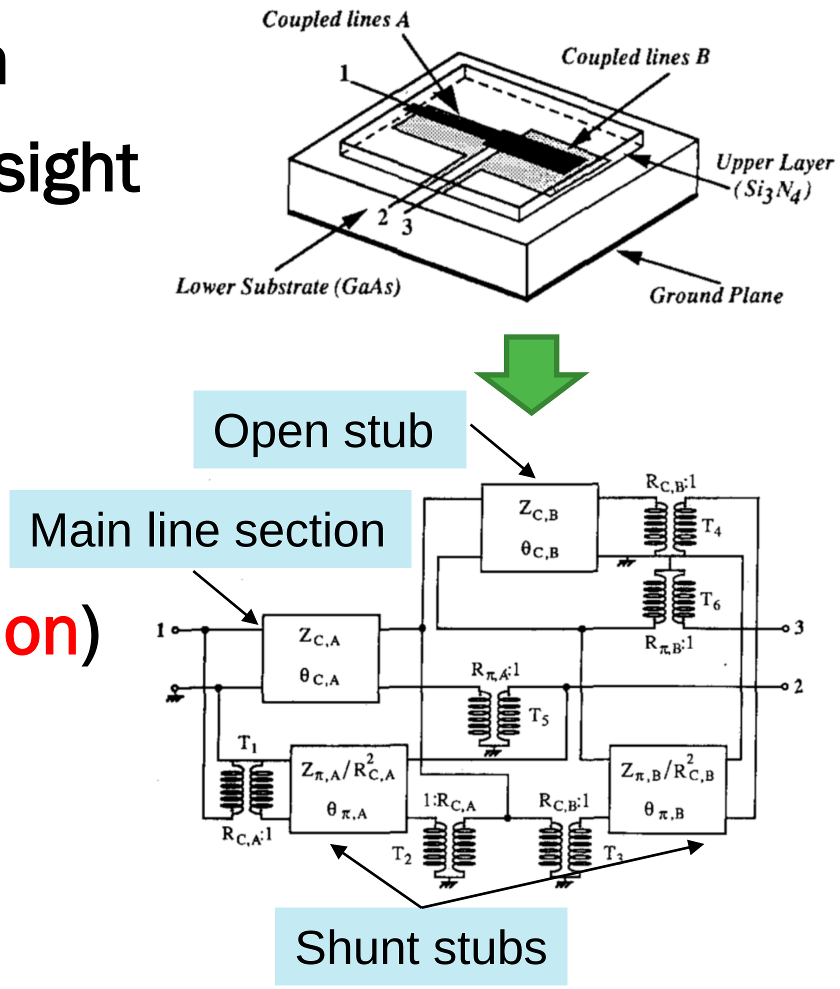
after [tsai1992]

[tsai1992] Ch. Tsai, and K.C. Gupta, "A generalized model for coupled lines and its applications to two-layer planar circuits," IEEE MTT., Dec. 1992, vol.40, no.12, pp. 2190-2199

Planar Marchand balun: overview

- Planar Marchand compensated balun (analysis)
  - Transmission line sections not isolated from each other -> complicated equivalent circuit without insight
  - Multiple transformers representing coupling between lines in each coupled-line section
  - Shunt stubs connected not only to the balanced output (both forward as well backward transmission)
  - Original Marchand balun for Rc=1 and Rπ=∞ (transformers disappear)

after [tsai1992]



[tsai1992] Ch. Tsai, and K.C. Gupta, "A generalized model for coupled lines and its applications to two-layer planar circuits," IEEE MTT., Dec. 1992, vol.40, no.12, pp. 2190-2199

Planar Marchand balun: overview

- Planar Marchand balun: overview of typical design strategies
  - Symmetric coupled lines (simple even/odd mode analysis)
    - Very restricted design space with closely related Zoe/Zoo (k), impedance transformation ratio, operation bandwidth, and RL
    - Large Zoe/Zoo required for sufficient balance and bandwidth -> tight coupling between lines with large separation to global ground
  - Asymmetric (typically broadside) coupled lines
    - Tight coupling feasible but not really exploited in detail
    - Finite isolation between lines ignored in the approximate design procedure
    - Large separation to global ground enforced to improve isolation (missing design parameter in terms of shunt stubs)

Balun-integrated differential pad

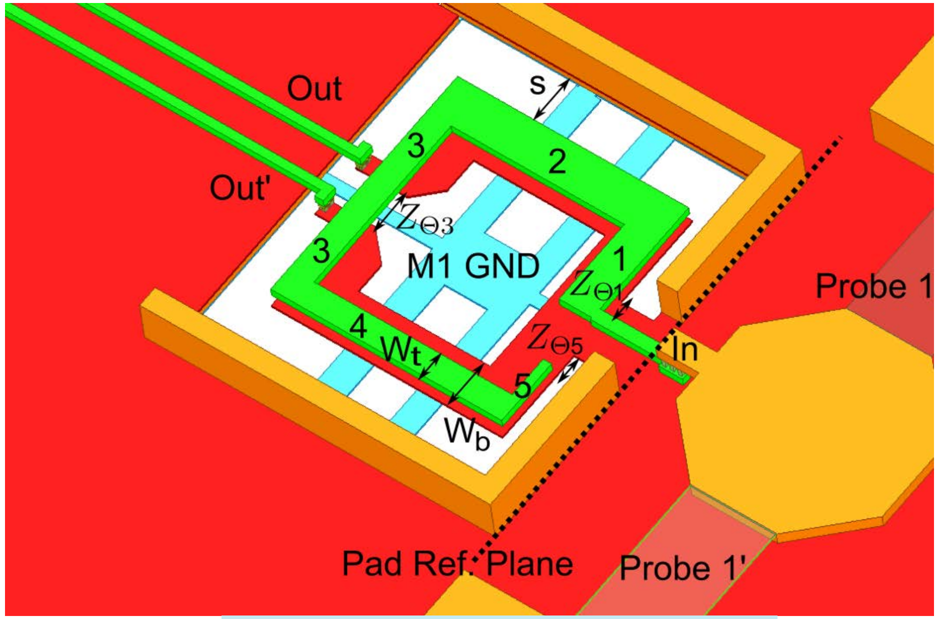
- Main request:

  More accurate and rigorous analysis to better understand design trade-offs

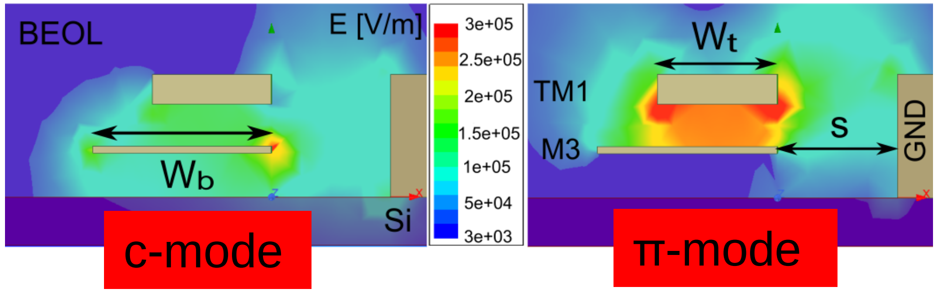
  – Imperfect isolation between lines due to the close-proximity ground
  – Impedance transformation with imperfectly isolated lines
  – Layer choice in view of the imbalance and operation bandwidth
  – Broadband compensation methods with the close-proximity ground
  – Link between impedance transformation, modal line parameters, and physical line cross-sections (multi-conductor analysis)

Balun-integrated differential pad

- Main implementation details
  - Buried line sections TM1/M3 in SiO_2 BEOL stack (5µm overlay, 2.8µm vertical spacing)
  - Velocity mismatch between 'c' and 'π' modes < 5%
  - Operated in the proximity of critical point
    - -> $k_c \sim k_l$, R_c and R_π in-phase
    - -> 2 modal impedances become negative
    - -> near ideal backward-coupling directional coupler
  - Gnd plane underneath the lines removed to improve coupling, close-proximity side gnd present
  - The assumption of high line isolation violated: $R_c<1$, R_π far below infinity

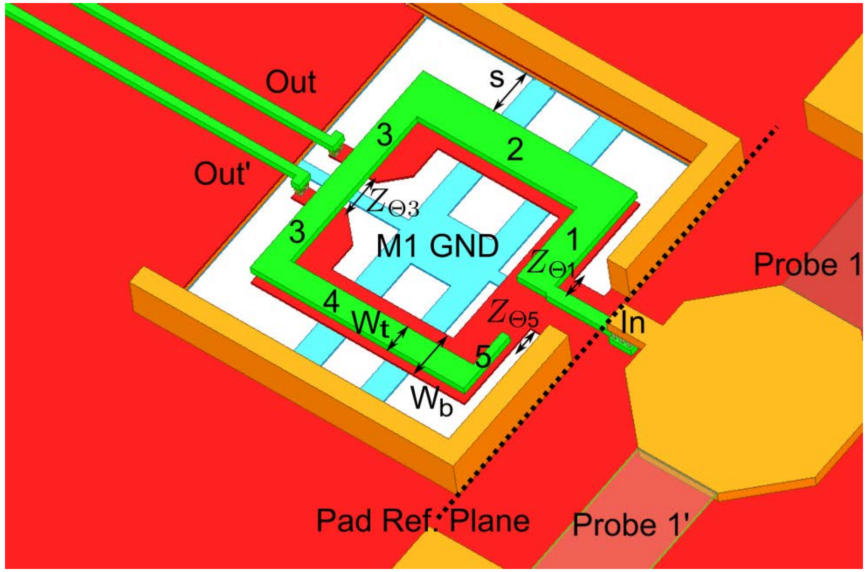


300 GHz differential pad

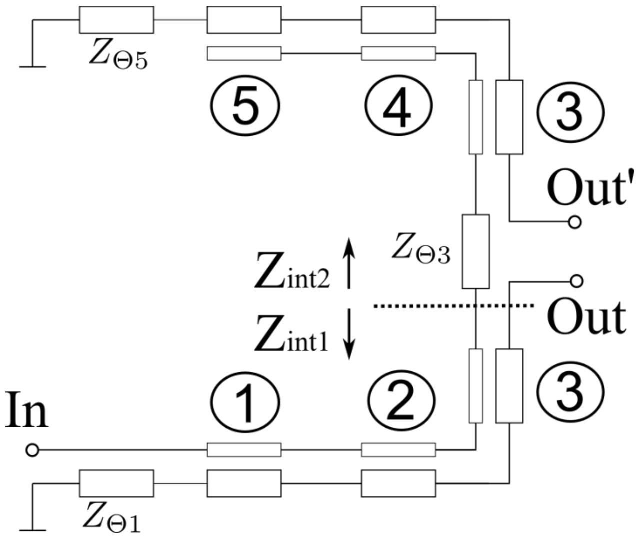


Balun-integrated differential pad

- Impedance transformation ratio (I_n -> Z_{int1})
  - Provided by the cascaded sub-λ/4 long nonuniformly-sized line sections '1-2-3' in view of the frequency-dependent pad impedance
  - Initial guess: '1-2-3' uniform λ/4 long line section
    - Assumptions
      1. matched phase velocity for 'c' and 'π' modes
      2. perfect ac short at a center tap of the top strip '3'



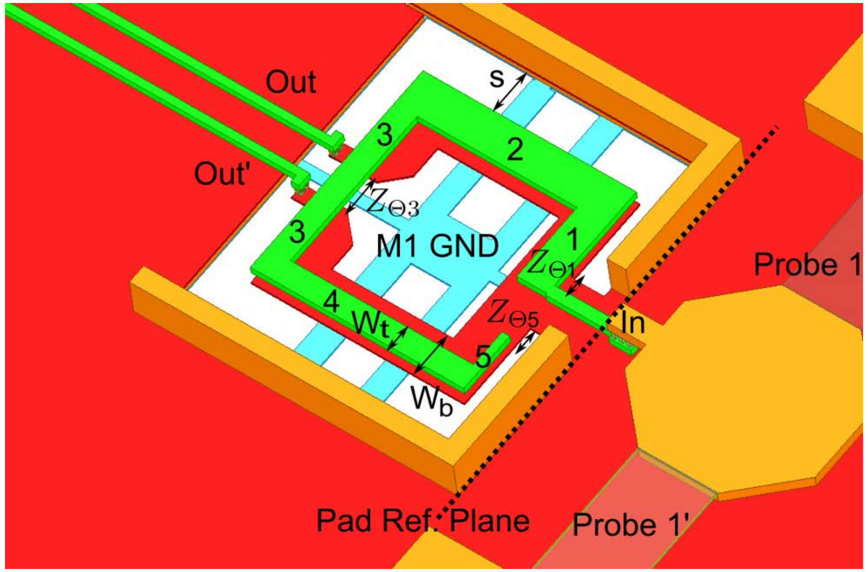
$$Z_{eff} = \frac{Z_{c,b} \cdot Z_{\pi,t} \cdot (R_\pi - R_c)}{Z_{\pi,t} + Z_{c,b} \cdot R_\pi \cdot R_c}$$

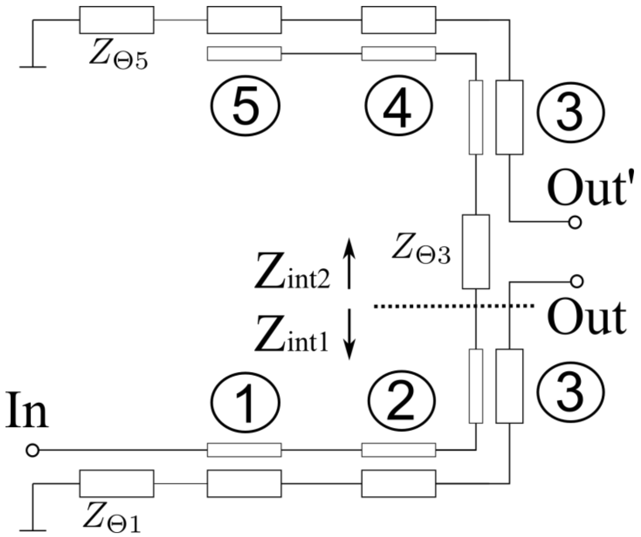


- $Z_{eff} = Z_{\pi,t}/R_c$ if $R_\pi >> R_c$, in particular $Z_{eff} = Z_{\pi,t}$ if $R_c=1$, where 't' and 'b' stand for top and bottom line, respectively
- *The condition from above not true for the presented design*

Balun-integrated differential pad

- Close-proximity ground (separation 's')
  - Impact on the balun transformation ratio accounted for accurately from a general multi-conductor analysis of the line cross-section (Ansys 2D extractor)
  - Separation 's' between coupled-line section and side ground-plane creates a 'shunt stub' equivalent in the original Marchand balun
    - Matching at the balanced output
    - Broadband balun compensation with different slot lengths along line sections '1-2-3' and '3-4-5' ($Z_{\theta 1}$, $Z_{\theta 5}$) (more efficient than line section '3-4-5')





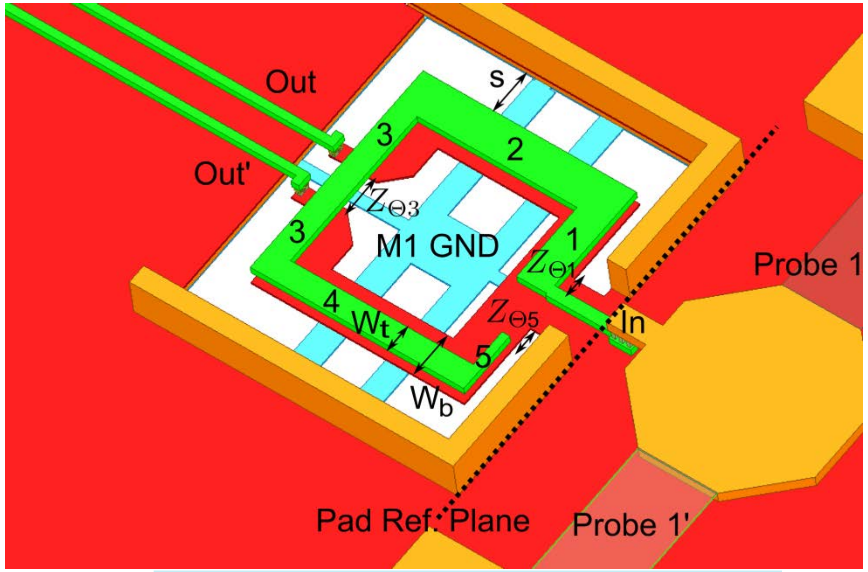
Balun-integrated differential pad

- Main implementation details (cd)
  - Open stub '3-4-5' exploited for the bandwidth extending off-center design (2 in-band RL minima) by different length and impedance profile as compared to '1-2-3'
  - $Z_{\theta 3}$ further exploited for balancing the balun output
  - Line sections optimized numerically

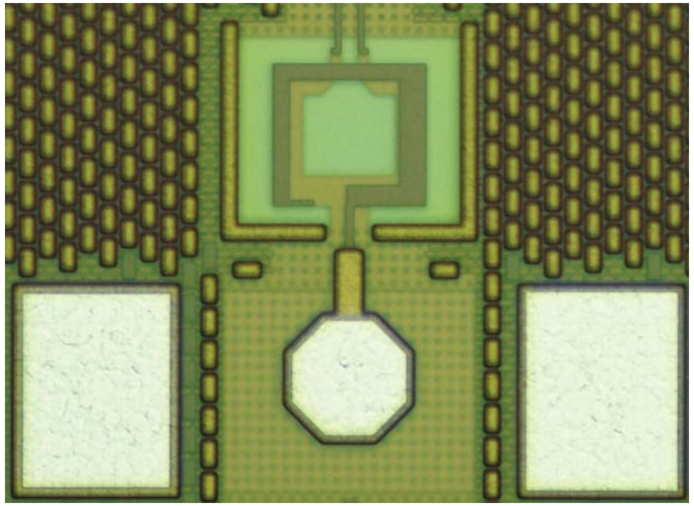
Sec.	$w_t/w_b/s$ [μm]	K –	$\theta_{0.3THz}$ [deg]	$\lvert R_c\rvert/\lvert R_\pi\rvert$ –	$\lvert Z_{c,b}\rvert/\lvert Z_{\pi,t}\rvert$ [Ω]	$\lvert Z_{eff}\rvert$ [Ω]	
1	8/12/8	0.7	19.5	0.61/3.8	57/46	47	← cntr f
2	10/12/11	0.77	36.5	0.65/3	59/46	41	← high f
3	6/12/10	0.69	15.5	0.62/3.92	62/53	56	← low f
4	6/12/12	0.72	38	0.63/3.63	64/54	53	
5	2/12/8	0.56	10	0.55/5.85	64/71	90	

Imperfect isolation ↗ (the $\lvert R_c\rvert/\lvert R_\pi\rvert$ column)

↖ Comparable $Z_{c,b}$ and $Z_{\pi,t}$ (the $\lvert Z_{c,b}\rvert/\lvert Z_{\pi,t}\rvert$ column)

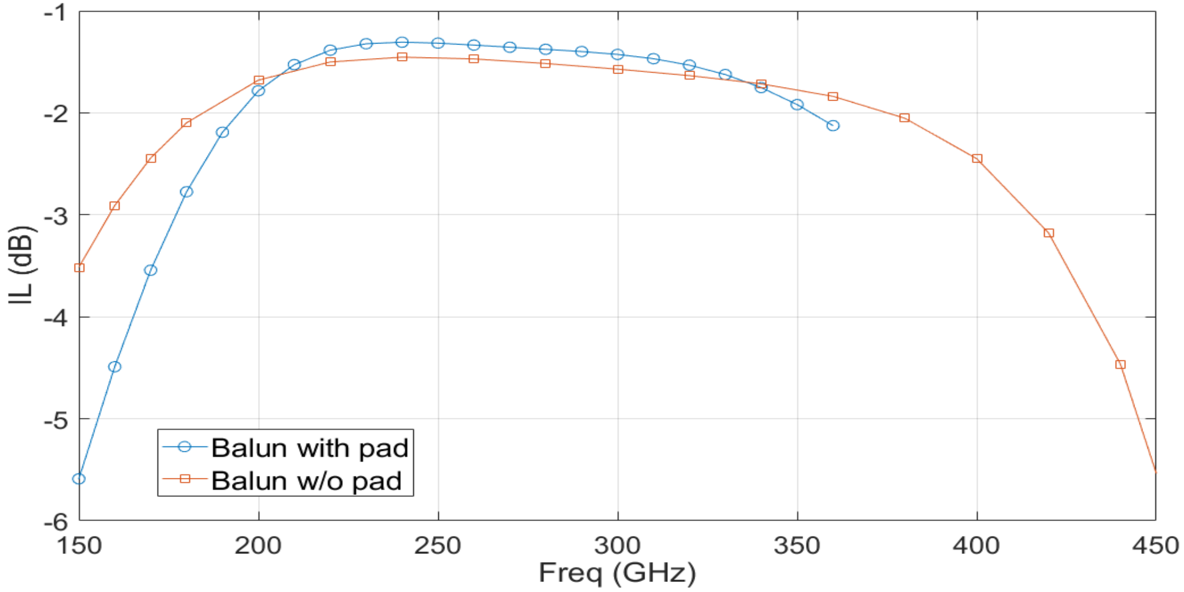


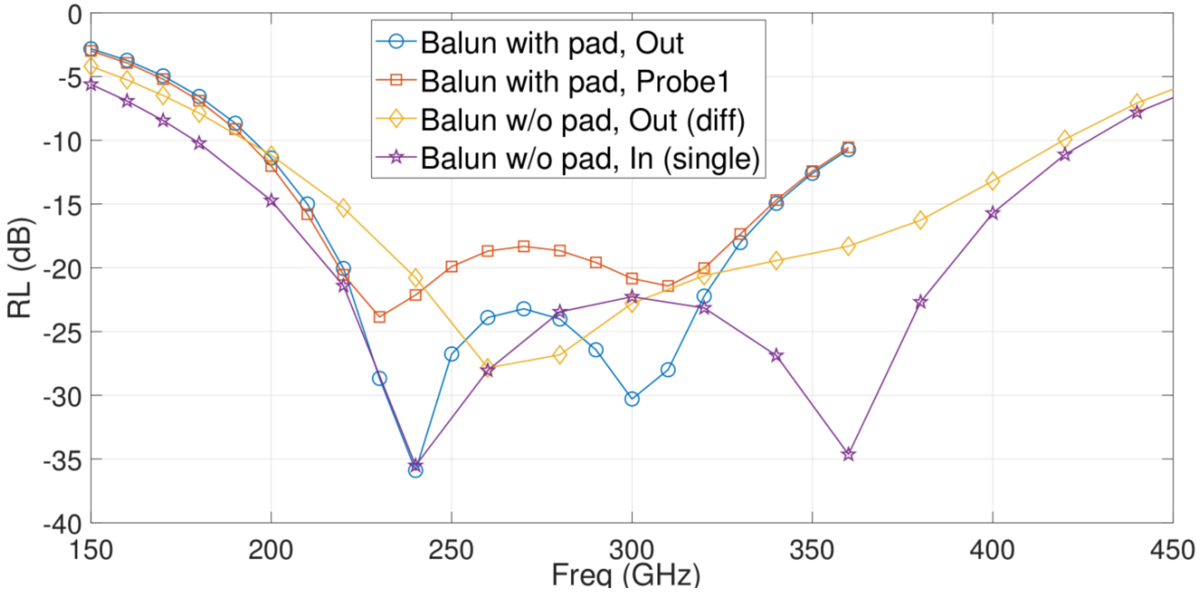
300 GHz differential pad



Balun-integrated differential pad

- Simulation results: balun with pad vs. balun w/o pad

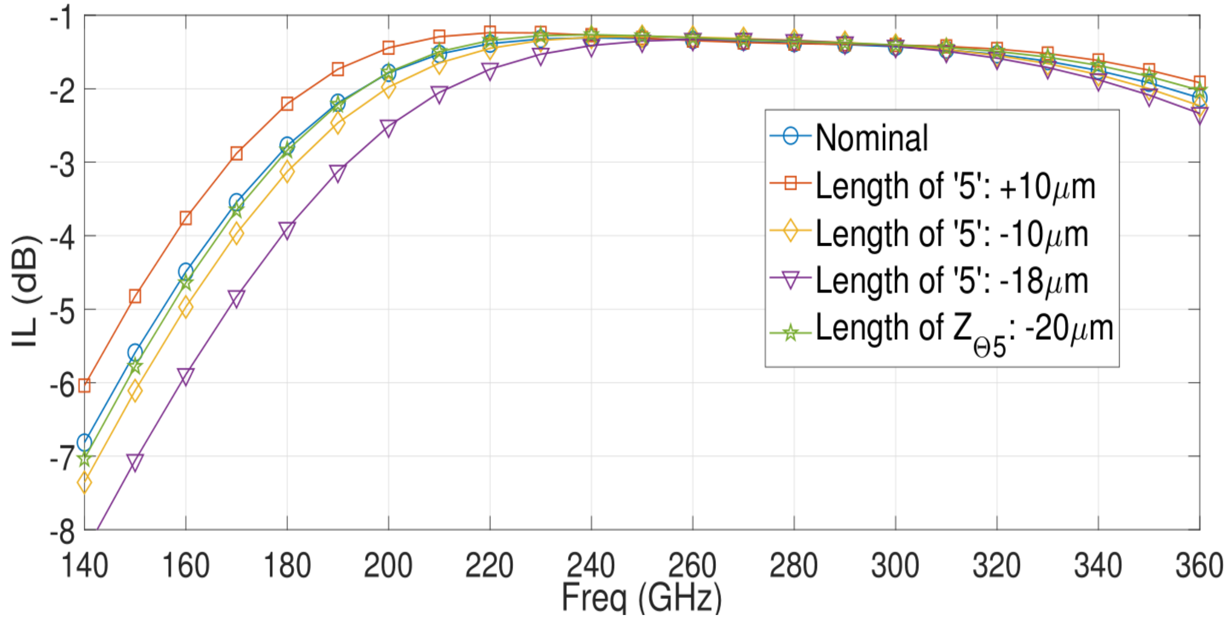


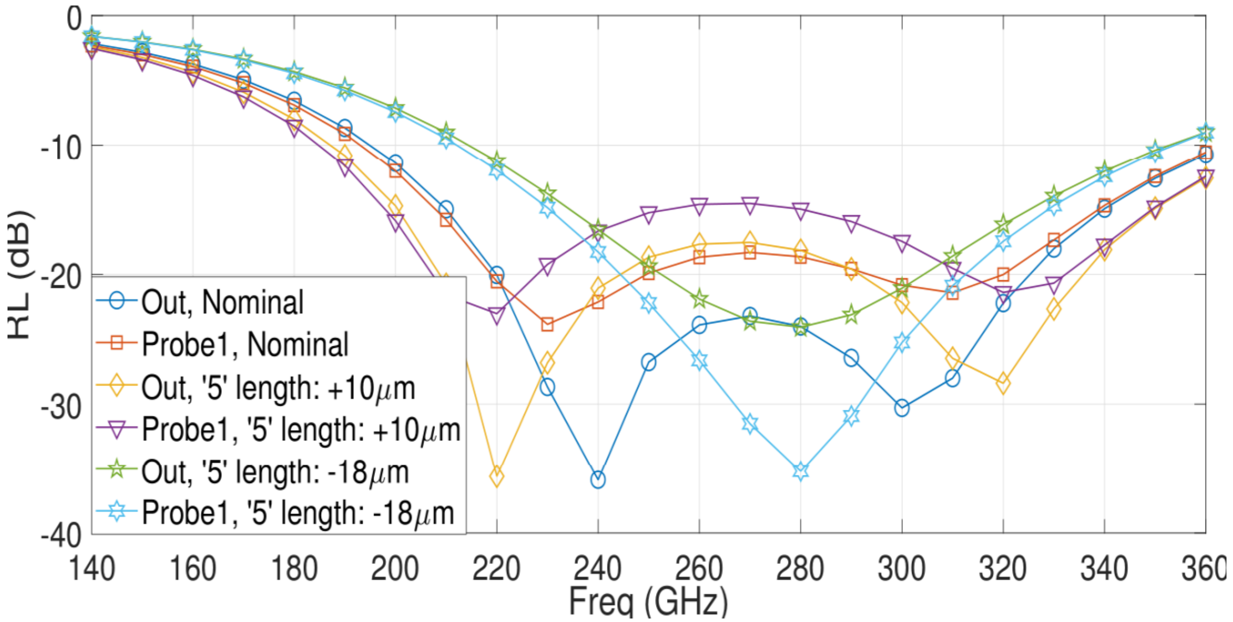


- ❑ Pad-integrated balun: 220 - 320 GHz -> IL=1.25 - 1.4dB, RL<20 dB !, 10dB RL bandwidth=180 GHz, 3-dB IL bandwidth 260 GHz, Pad IL=0.6dB @ 160 GHz, $\lambda/4$-long 50Ω u-strip IL=0.6 dB @ 300 GHz
- ❑ Pad-integrated balun vs. 50-to-100 Ω balun:
  - lower IL -> shorter implementation, tighter line coupling, co-design (bandpass network)
  - lower bandwidth -> complex load with higher impedance transformation ratio (20-to-100 Ω)

Balun-integrated differential pad

- Simulation results: RL/IL, bandwidth trade-offs

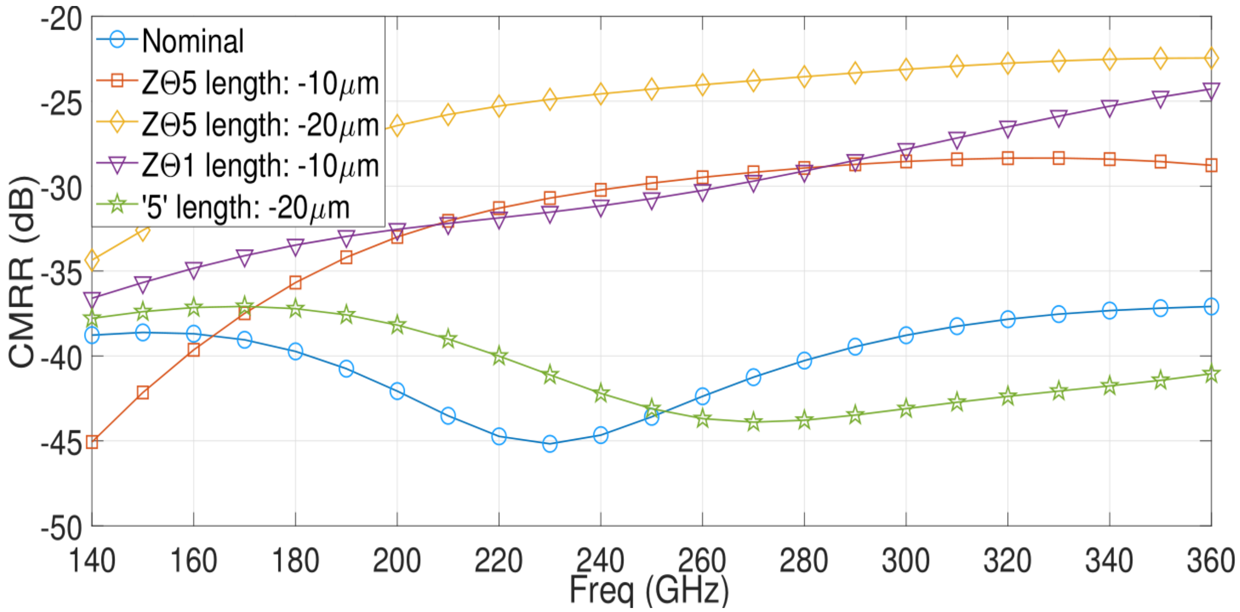


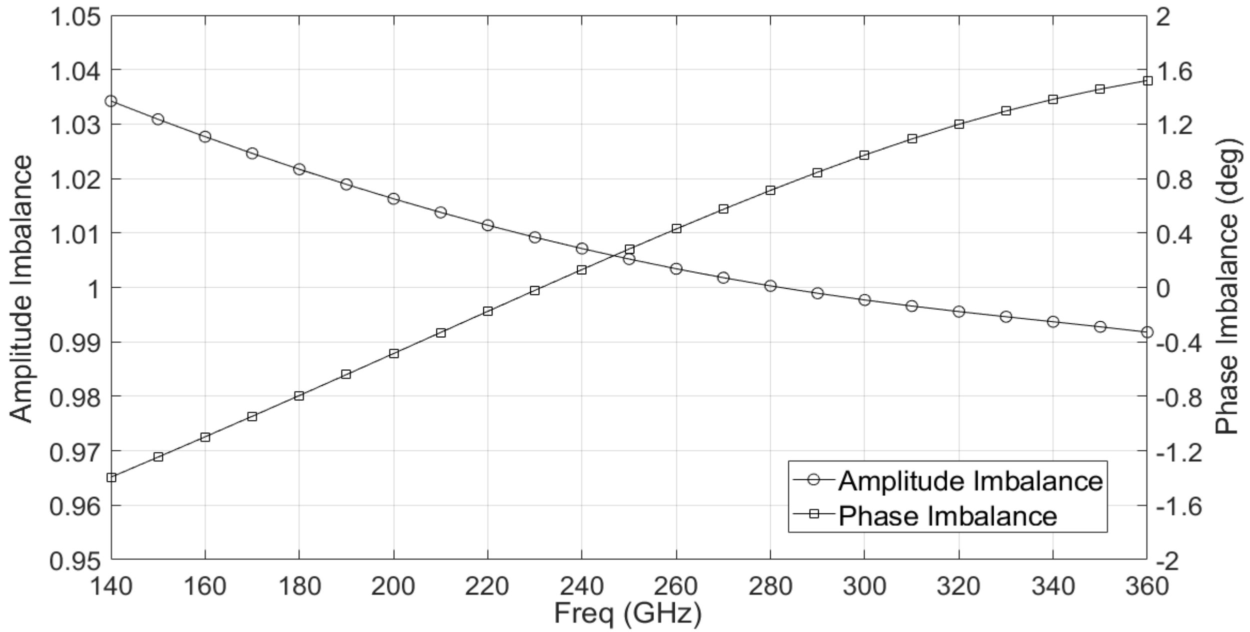


- ❑ Open stub '3-4-5' exploited for bandwidth extending off-center design (2 in-band RL minima)
- ❑ Length of '3-4-5' can be further changed to improve bandwidth at the cost of RL
- ❑ Length of shunt stubs ($Z_{\theta 1}$,$Z_{\theta 5}$) less critical for RL/bandwidth compared to open stub '3-4-5'
- ❑ Length of '3-4-5' less critical for output balance (see next slide)

Balun-integrated differential pad

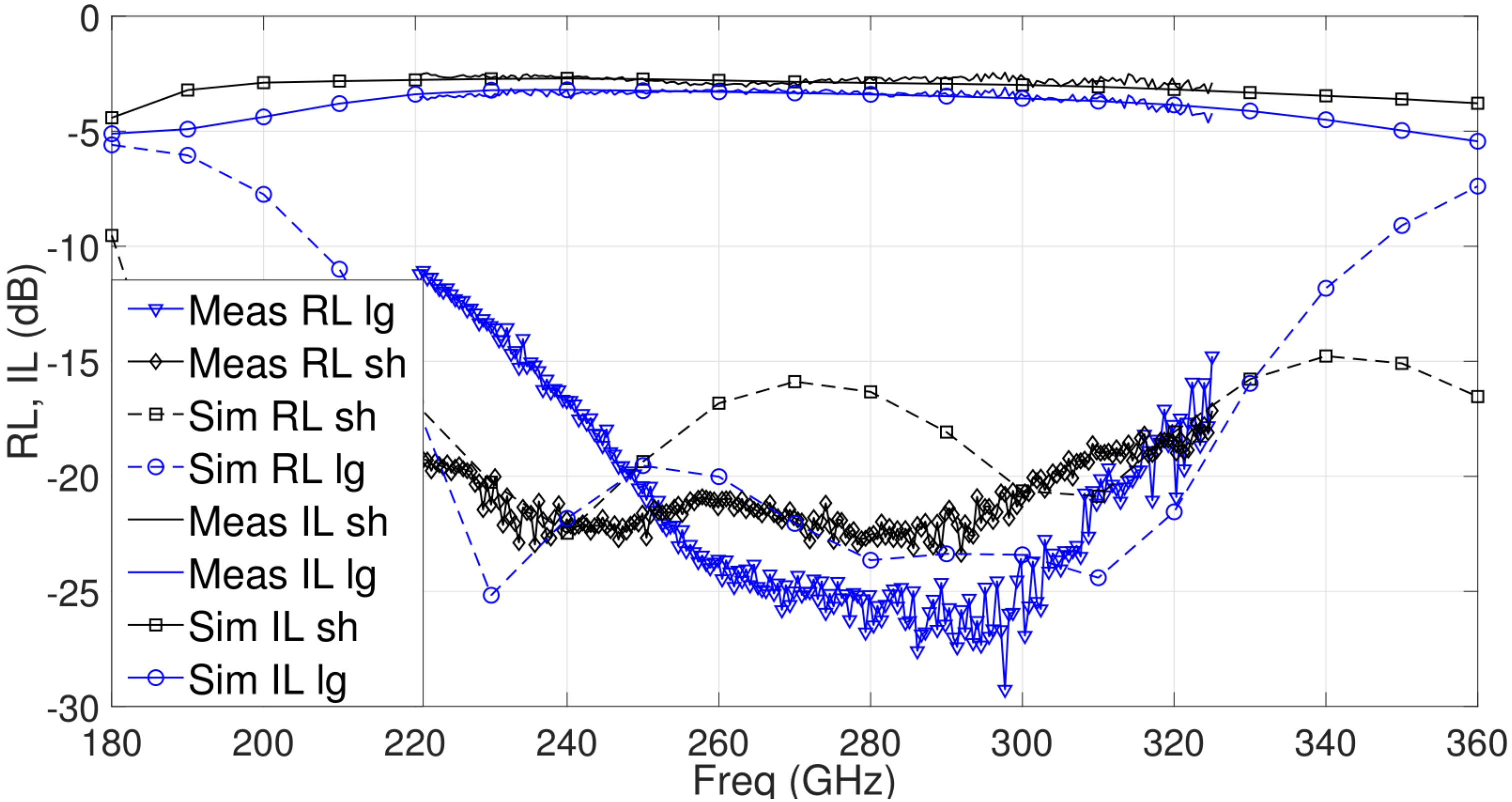
- Simulation results: output balance

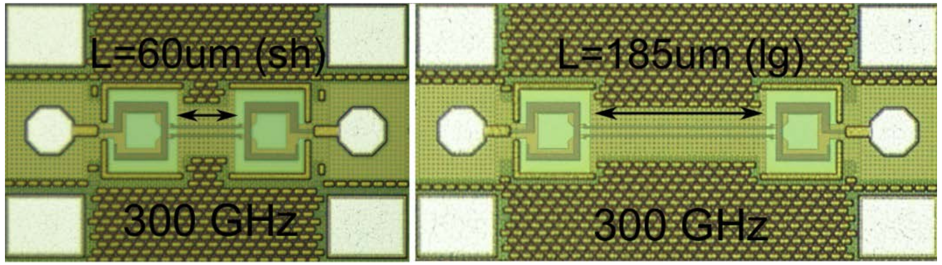




- ❑ Length of shunt stubs ($Z_{\theta1}$,$Z_{\theta5}$) used to adjust balance with low sensitivity to RL variation
- ❑ Length of open stub '3-4-5' less critical for output balance
- ❑ Space 's' to side gnd not very sensitive to broadband balance compensation
- ❑ Very good broadband balance (even out-of-band): Amplitude <0.3 dB, Phase <1.6 deg

Measurement results (220-320 GHz)

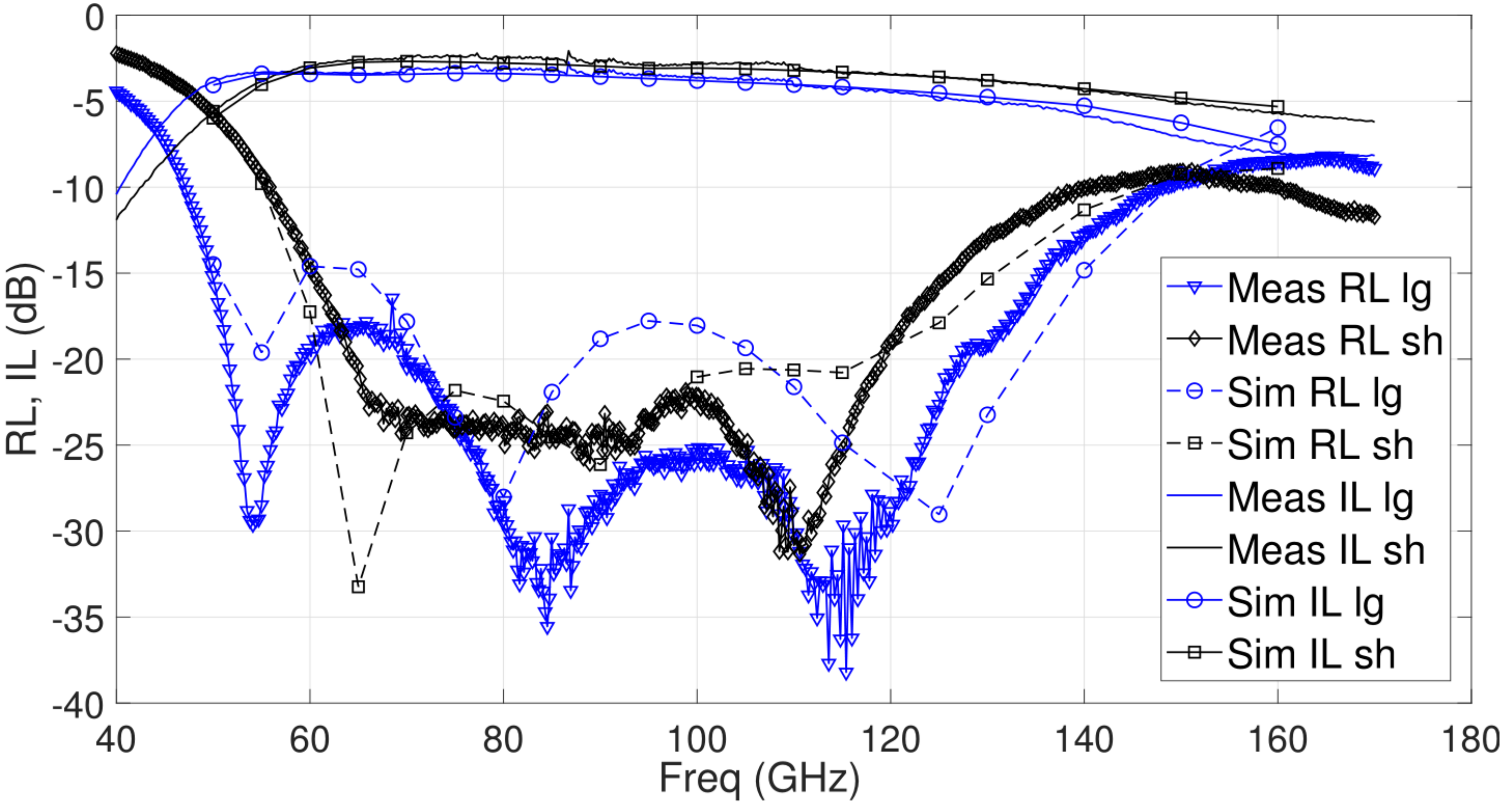


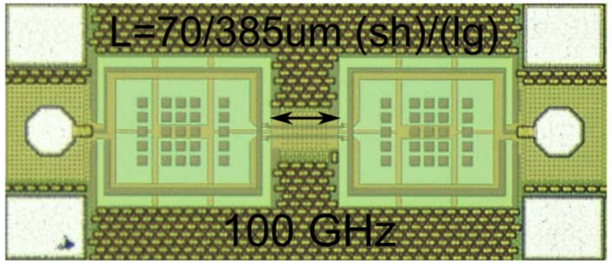


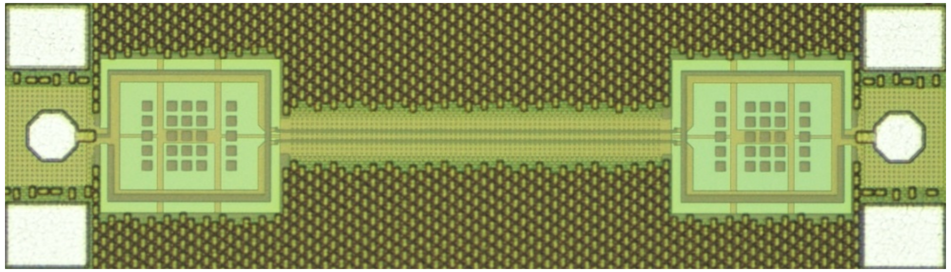
- Initial TRL calibration with cal substrate
- Missing equipment for WR5/WR2.2 band
- Full-band covered with very good RL
- IL= 1.3-1.5 dB / balun-integrated pad

- Measured back-to-back in view of the challenges for balanced port characterization
- 2 different lengths (‘sh’/‘lg’) for constructive/destructive reflections at balanced ports
- Good simulation/measurement correlation -> good balance/low RL at the balanced port
- Discrepancy: calibration/probe positioning accuracy, differences in physical BEOL constants

Measurement results (50-160 GHz)







- Measured back-to-back with 2 different lengths (‘sh’/‘lg’)
- Very good simulation/measurement correlation with broadband low RL
- Multi-band operation (only 14GHz bandwidth reduction compared to 50-100 Ω balun)
- IL of 1.25-2.15 dB per single balun-integrated pad (improved IL with narrowband operation)

Conclusions/comparison

- Balun-integrated differential on-chip pads for mmWave/THz operation
  - Full-band/multi-band operation with low RL around 20 dB
  - Particularly dedicated to large-signal characterization of active circuits
- A general theory of asymmetric coupled-lines in inhomogeneous medium applied for design flexibility and performance improvement
  - Rigorous analysis with the impact of a close-proximity ground accounted for in the design process
  - Co-design with frequency-dependent pad impedance (bandpass filter)
- IL=1.3-1.5 dB, RL around 20dB with very good balance for 220-320 GHz

[ahmed2015] – IL=2.3-3.3dB, RL=15dB, amplitude/phase imbalance of 1.5dB/20deg for 200-325 GHz

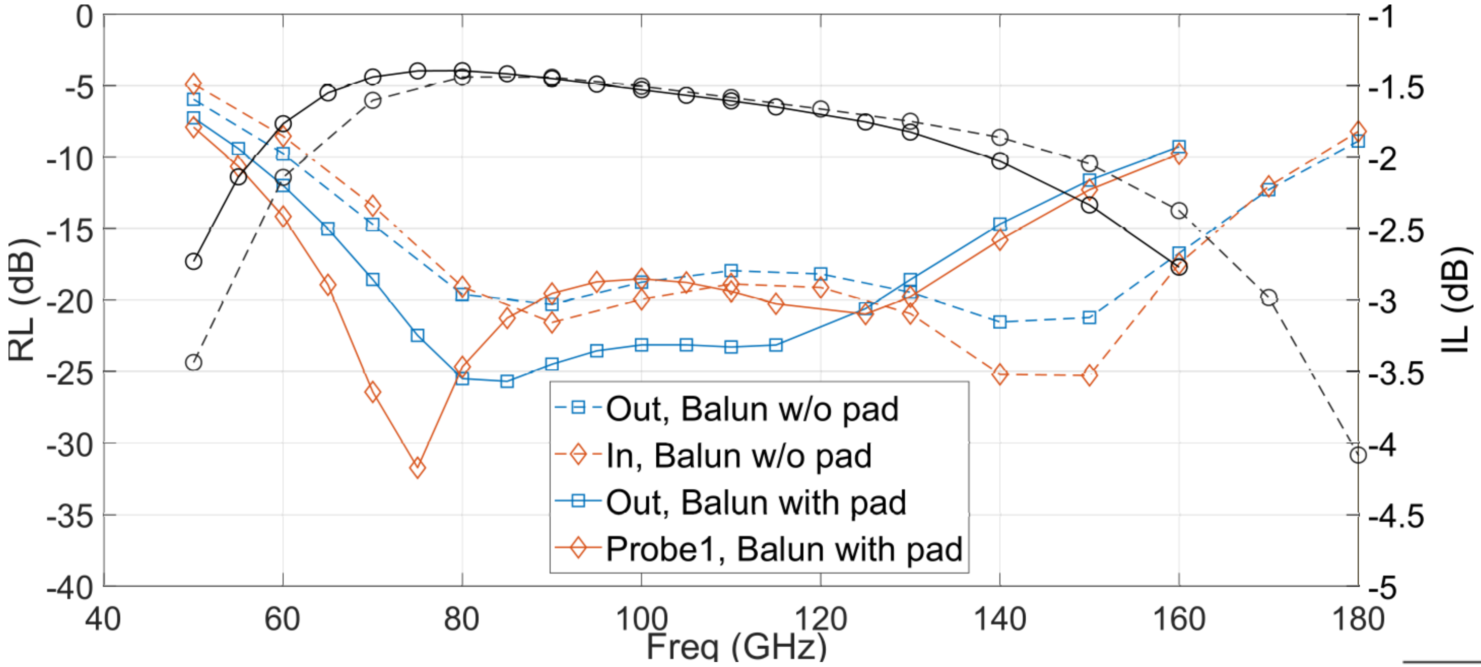
[ali2019] – IL=1.2-2.1dB, RL=15dB, amplitude/phase imbalance of 1.8dB/6deg for 110-220 GHz (simul. w/o pad)

[song2014] – IL=1.7-4.7dB, RL=5-20dB, amplitude/phase imbalance of 1.5dB/7deg for 34-110 GHz

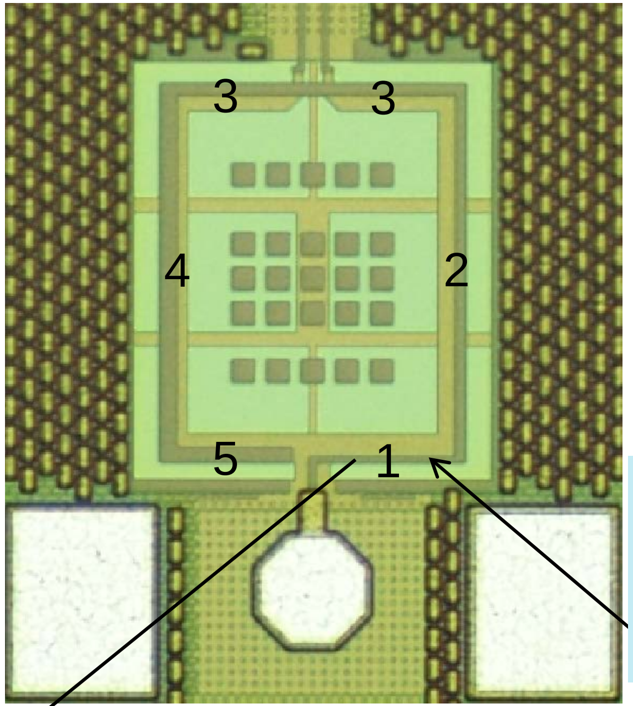
Thank you

Back-up

- Simulation/design details (50-160 GHz)



Simulation results: balun-integrated pad vs. 50-100Ω balun



High Z_{eff} for compensation of capacitive pad

Sec.	$w_t/w_b/s$ [μm]	K –	$\theta_{0.1THz}$ [deg]	$\|R_c\|/\|R_\pi\|$ –	$\|Z_{c,b}\|/\|Z_{\pi,t}\|$ [Ω]	$\|Z_{eff}\|$ [Ω]
1	2/12/8	0.61	17	0.52/4.66	63/71	90
2	4/12/11	0.71	41	0.58/3.41	65/67	67
3	5/12/10	0.71	15	0.57/3.38	61/61	62
4	7/12/11	0.76	40	0.62/2.92	60/54	49
5	6/12/8	0.7	14	0.57/3.53	56/55	57

Back-up

[ahmed2015] – F. Ahmed, M. Furqan, and A. Stelzer, "A 200-325-GHz Wideband, Low-Loss Modified Marchand Balun in SiGe BiCMOS Technology," Proc. 45th European Microwave Conf. Sep. 2015, Paris, France, pp.40-43;

[ali2019] – A. Ali, J. Yun, H. J. Ng, D. Kissinger, F. Giannini, P. Colantonio, " High Performance Asymmetric Coupled Line Balun at Sub-THz Frequency," Appl. Sci., 2019,9, 1907;

[song2014] – I. Song, et.al., "A 34-110 GHz Wideband, Asymmetric, Broadside-Coupled Marchand Balun in 180 nm SiGe BiCMOS Technology," IEEE MTT-S Int. Microwave Symp. (IMS), June 2014, Tampa, FL, USA, pp. 1-4;