A Millimeter-Wave Fully Differential Transformer-based Passive Reflective-Type Phase Shifter

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Outline

- Motivation
- Fundamentals of reflective-type phase shifter
- Our design and innovations
- Measurement
- Conclusion

Motivation

- **Why passive phase shifters (PS)?**
  - Zero DC power consumption
  - Excellent linearity

  (Essential in large-scaled and power-constrained phased array systems)
- **Why passive reflective-type phase shifter (RTPS) ?**
  - Continuous and dense phase shift (switch-filter and high/low-pass PS)
  - Moderate size (switched-line PS and traveling-wave PS)
  - Cascadable architecture (90°+90°=180°)
- **Challenges of mm-Wave RTPS nowadays:**
  - Phase shift range<360° (90°–180°)
  - High loss if multi-section RTPS in cascade (>15dB)
  - Figure-of-merit (FoM)<26°/dB

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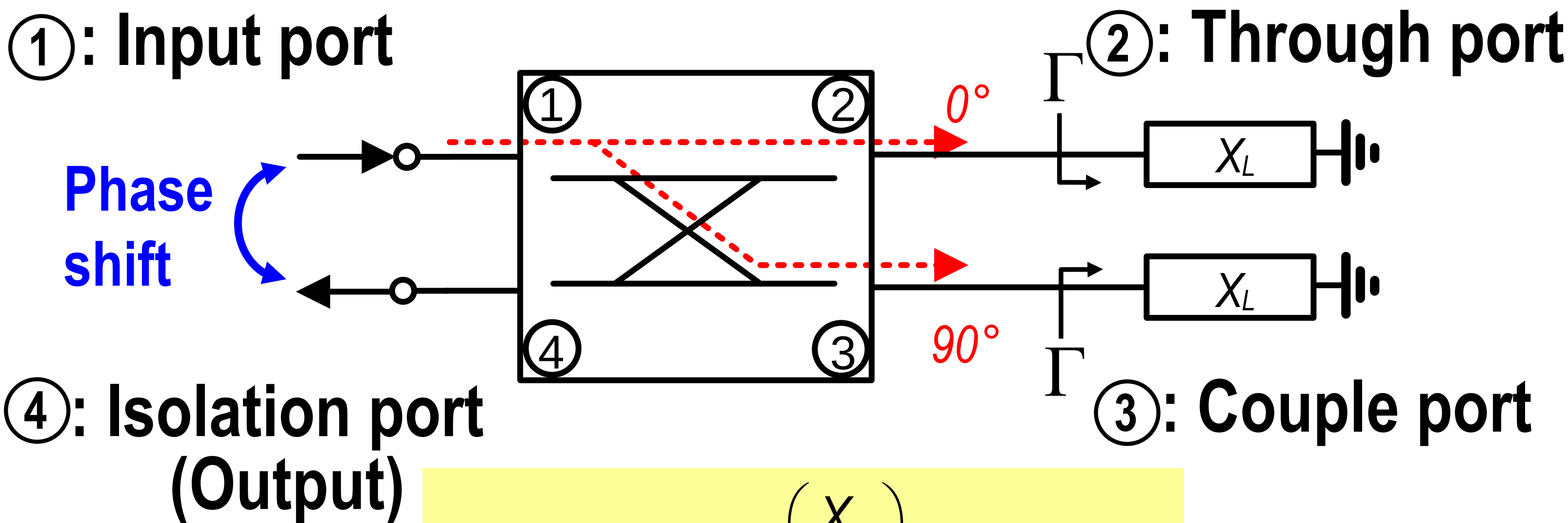
Fundamentals of RTPS

- **RTPS architecture:**
  - One 90° coupler (Characteristic impedance=Z_0)
  - Two identical reflective passive loads (X_L)

Total loss = 90° coupler loss + load loss



$$\theta = -90^\circ - 2\tan^{-1}\left(\frac{X_L}{Z_0}\right) = -90^\circ - \angle\Gamma$$

Phase shift between I/O is made by reflection coefficient of loads

Fundamentals of RTPS

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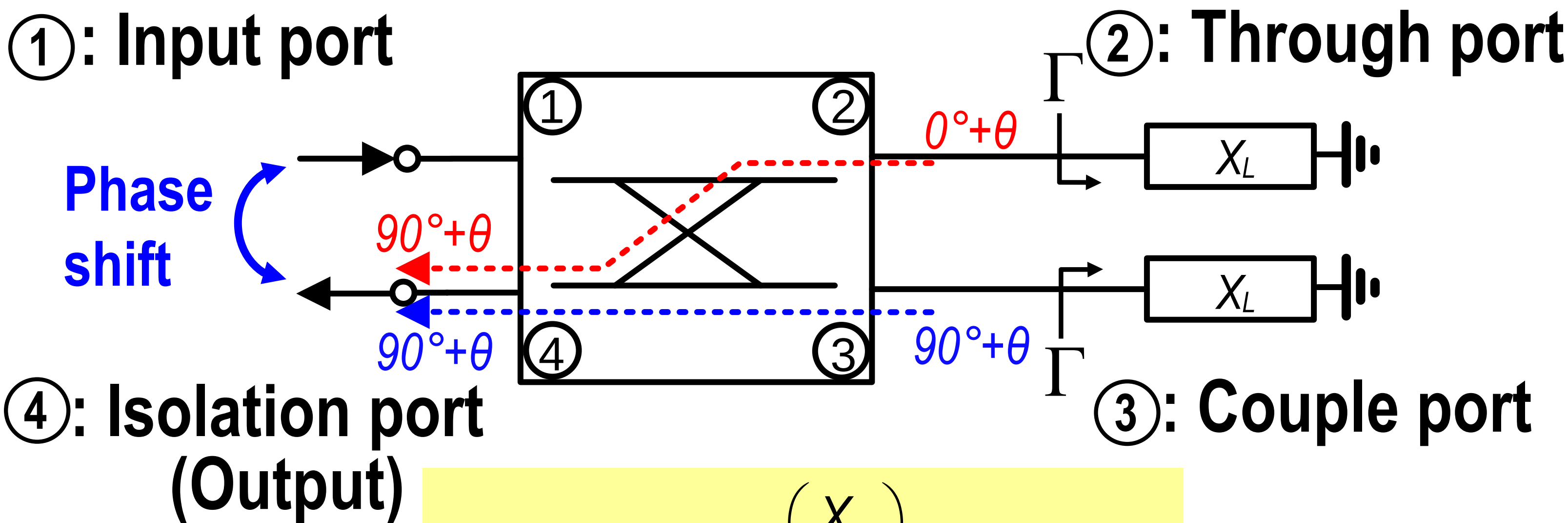


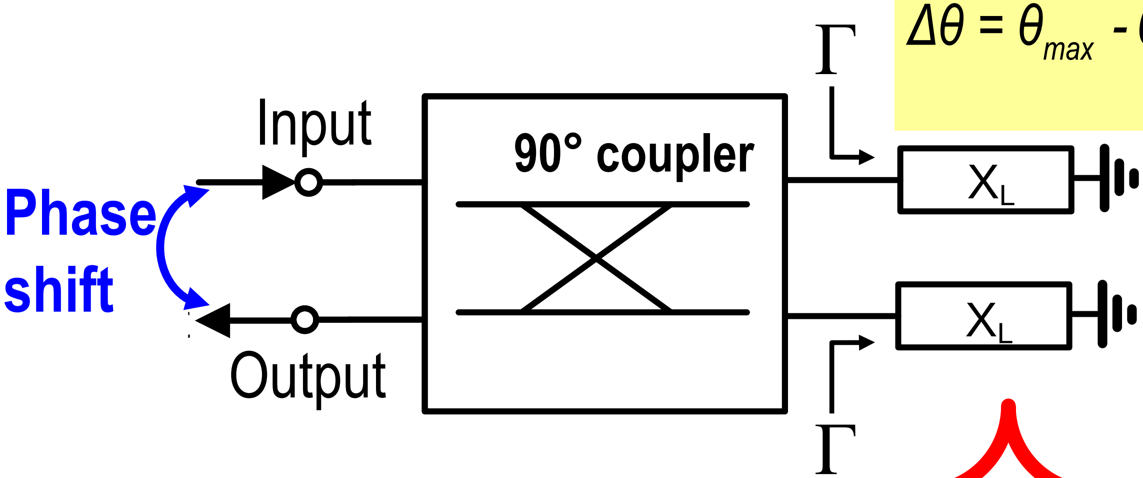
$$\theta = -90^\circ - 2\tan^{-1}\left(\frac{X_L}{Z_0}\right) = -90^\circ - \angle\Gamma$$

Phase shift between I/O is made by reflection coefficient of loads

Fundamentals of RTPS

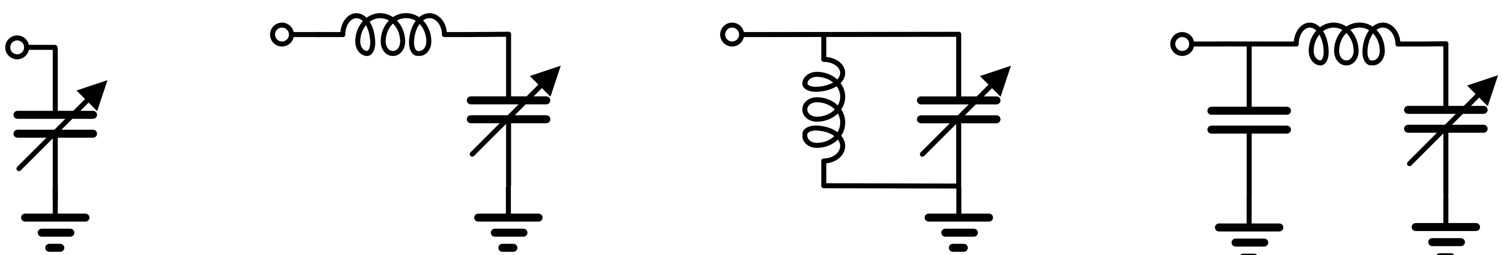
- **Reflective passive loads**

$$\Delta\theta = \theta_{max} - \theta_{min} = 2\left[\tan^{-1}\left(\frac{X_L^{max}}{Z_0}\right) - \tan^{-1}\left(\frac{X_L^{min}}{Z_0}\right)\right]$$



Reflective loads provide phase shift between input and output

Capacitive load (CL) | **Series LC resonator (SLC)** | **Parallel LC resonator (PLC)** | **CLC π-resonator (CLC)**



H. Zarei, *et al.* "Reflective-Type Phase Shifters for Multiple-Antenna Transceivers", *TCAS-I* 07'

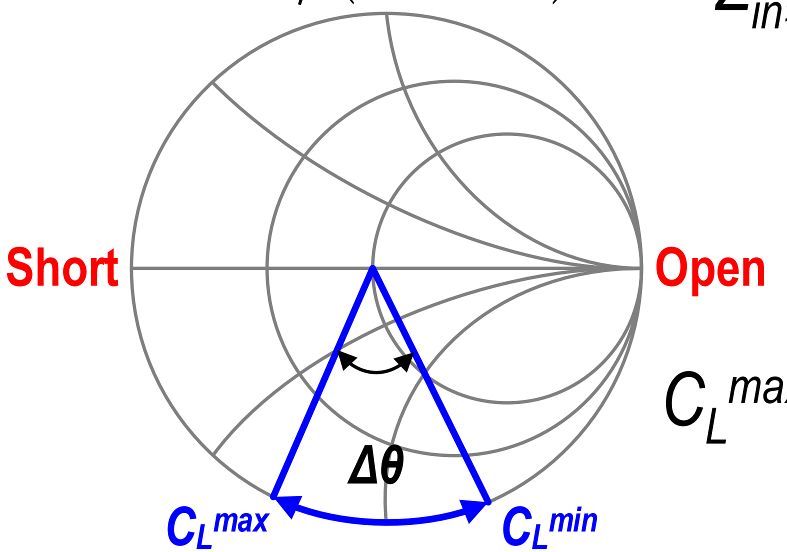
Fundamentals of RTPS

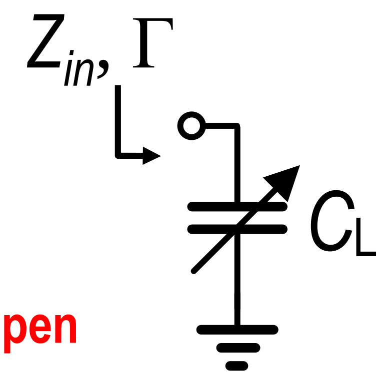
- **Capacitive load (CL)**

Assuming circuit is lossless

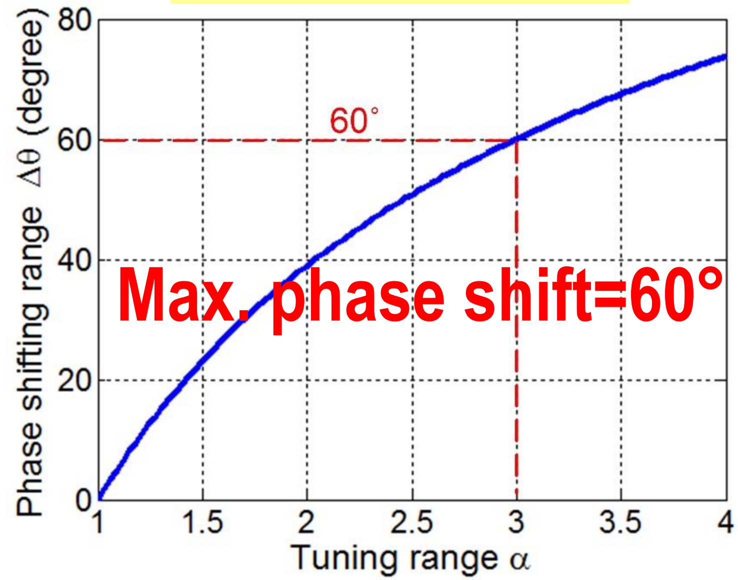
$$C_L^{min} = 1/\left(\sqrt{\alpha} Z_0 \omega_0\right)$$

$$\Delta\theta_{max} = 2\tan^{-1}\left(\frac{\alpha - 1}{2\sqrt{\alpha}}\right)$$





$$C_L^{max} \leq C_L \leq C_L^{min}$$

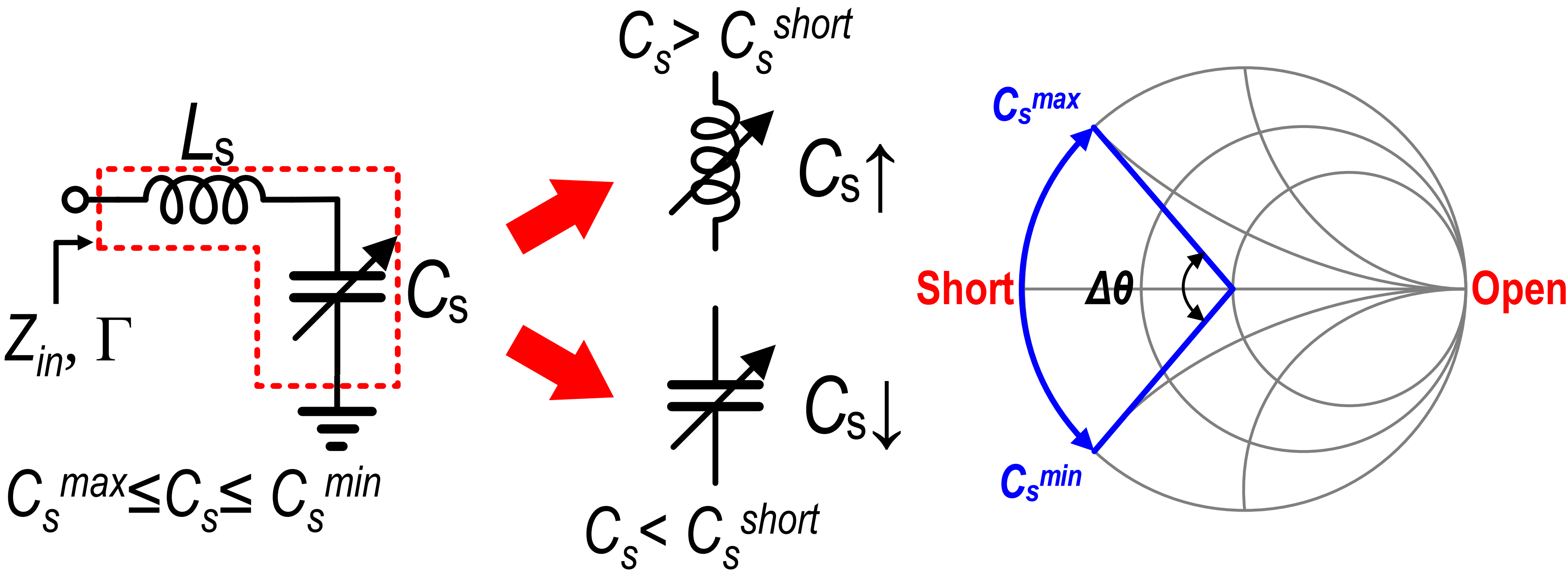


– Phase shift of CL RTPS strongly depends on tuning range ($\alpha = C_L^{max}/C_L^{min}$) of varactors. ($2 \leq \alpha \leq 4$)

H. Zarei, *et al.* “Reflective-Type Phase Shifters for Multiple-Antenna Transceivers”, *TCAS-I* 07’

Fundamentals of RTPS

- **Series LC resonator load (SLC)**



– L_s-C_s tank is inductive when C_s increases. ($C_s > C_s^{short}$)
– L_s-C_s tank is capacitive when C_s decreases. ($C_s < C_s^{short}$)

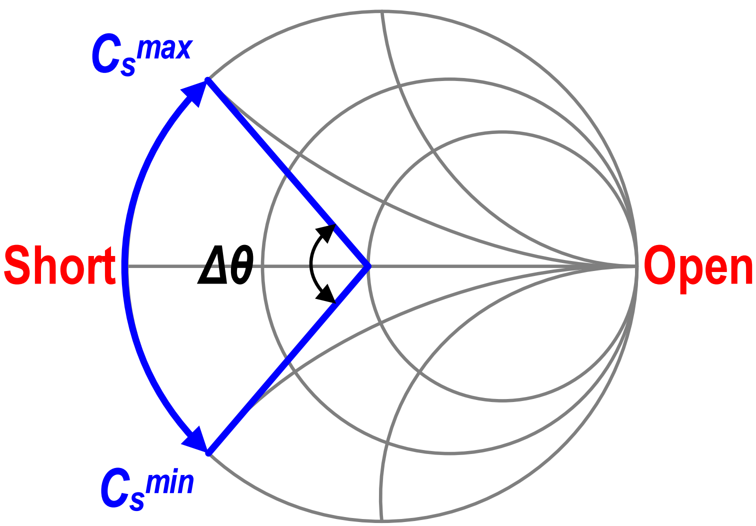
F. Ellinger, *et al.* "Compact reflective-type phase-shifter MMIC for C-band using a lumped-element coupler", *T-MTT* 01'

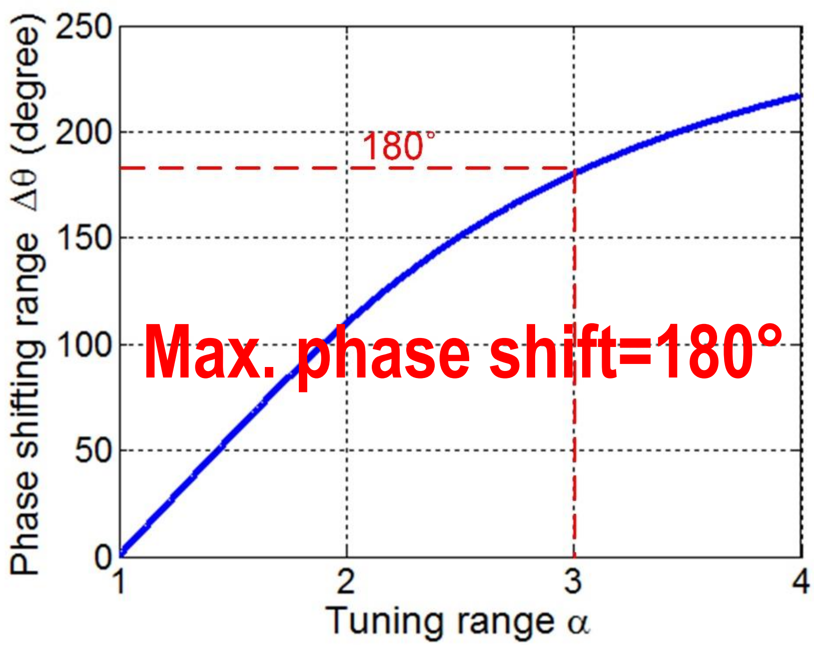
Fundamentals of RTPS

- **Series LC resonator load (SLC)**

$$\Delta\theta_{max} = 2\tan^{-1}\left(\frac{2}{\sqrt{\alpha}}\frac{\alpha-1}{\alpha-3}\right)$$

$$C_s^{min} = 1\Big/\left(\sqrt{\alpha}Z_0\omega_0\right)$$





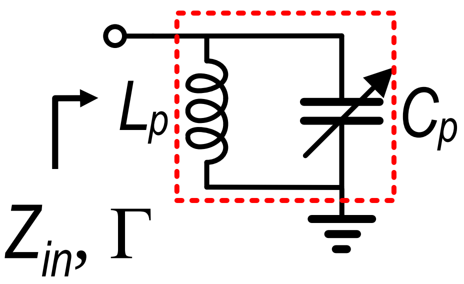
– Phase shift of SLC is wider than CL because SLC covers one resonance point.

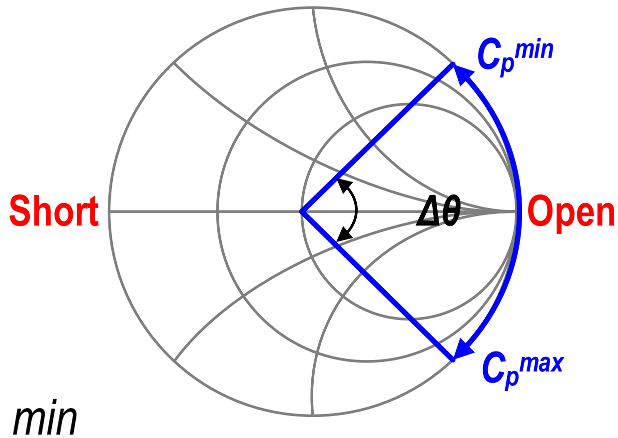
F. Ellinger, *et al*. "Compact reflective-type phase-shifter MMIC for C-band using a lumped-element coupler", *T-MTT* 01'

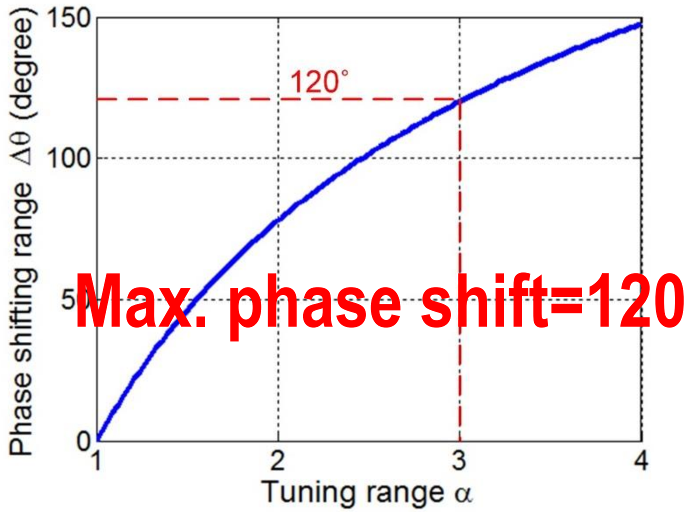
Fundamentals of RTPS

- **Parallel LC resonator load (PLC)**

$$C_p^{min} = 1/\left(\sqrt{\alpha} Z_0 \omega_0\right)$$







Max. phase shift=120°

$$C_p^{max} \leq C_p \leq C_p^{min}$$

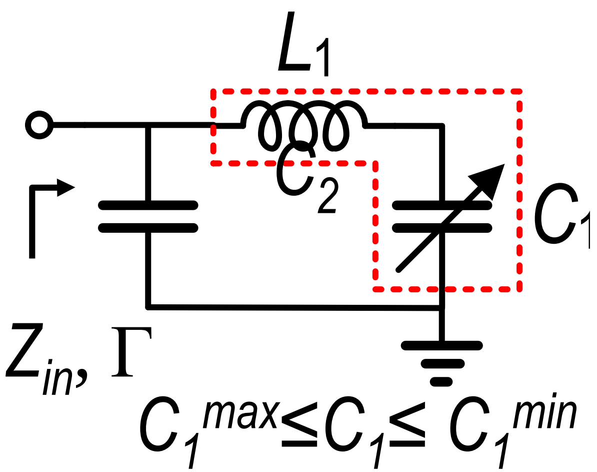
- Phase shift of PLC is wider than CL because PLC covers one resonance point.

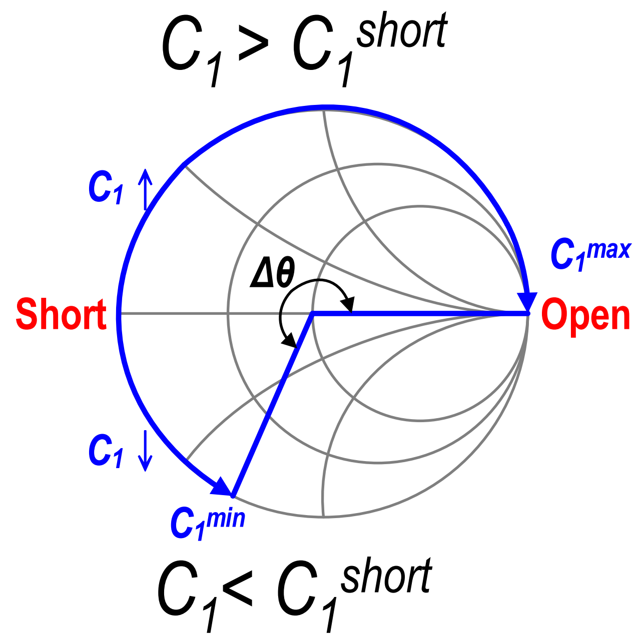
H. Krishnaswamy, *et al*. "A Silicon-based, All-Passive, 60GHz, 4-Element, Phased-Array Beam former Featuring a Differential, Reflection-Type Phase Shifter", *ARRAY* 10'.

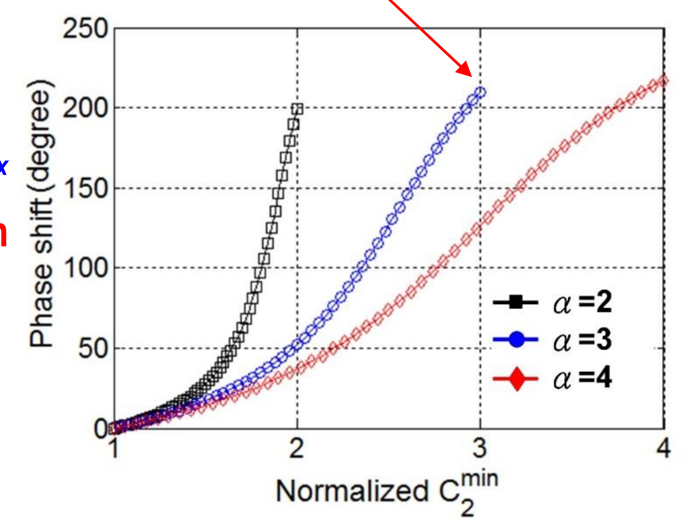
Fundamentals of RTPS

- **CLC π-resonator load (CLC)**

Max. phase shift=210°







- L_1-C_1 tank resonates at S.C → $Z_{in}=0$
- L_1-C_1 tank is inductive when C_1 increases. ($C_1 > C_1^{short}$)
- L_1-C_1 tank is capacitive when C_1 decreases. ($C_1 < C_1^{short}$)

H. Zarei, *et al.* "Reflective-Type Phase Shifters for Multiple-Antenna Transceivers", *TCAS-I* 07'

Fundamentals of RTPS

- **Summary of reported reflective loads of RTPS**

Reflective load type	Resonance point	Maximum phase shift* (°)
Capacitive Load	0	60
Series LC resonator	1	180
Parallel LC resonator	1	120
CLC π resonator	2	210

Assuming the tunable capacitance $C^{min}=1/(\sqrt{\alpha}Z_0\omega_0)$

More resonance points achieved, wider phase shift obtained

– How to increase phase shifting range?

1) Enhancing tuning range of varactors → limited by process
2) Cascading RTPSs→ loss also increasing
3) Multi-resonance reflective load → complexity↑, loss ↑

*Tuning range=3

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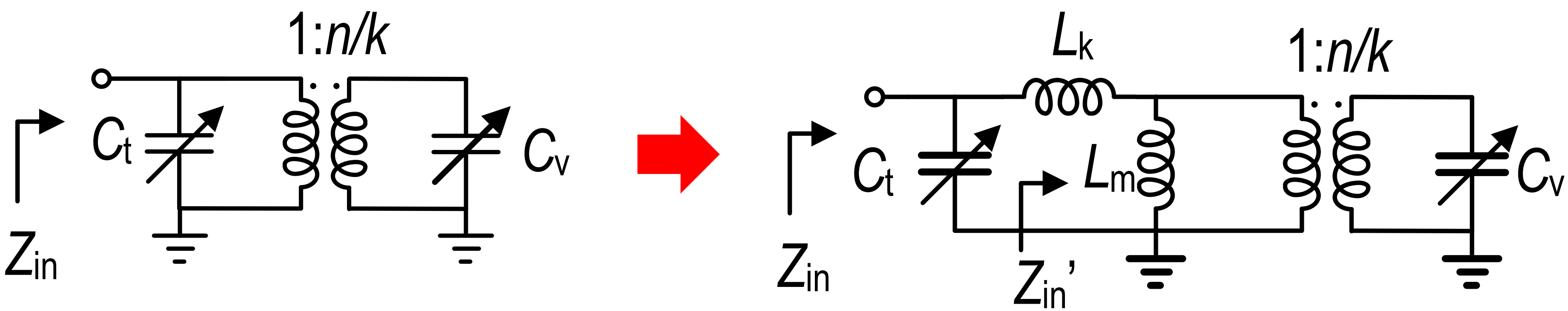
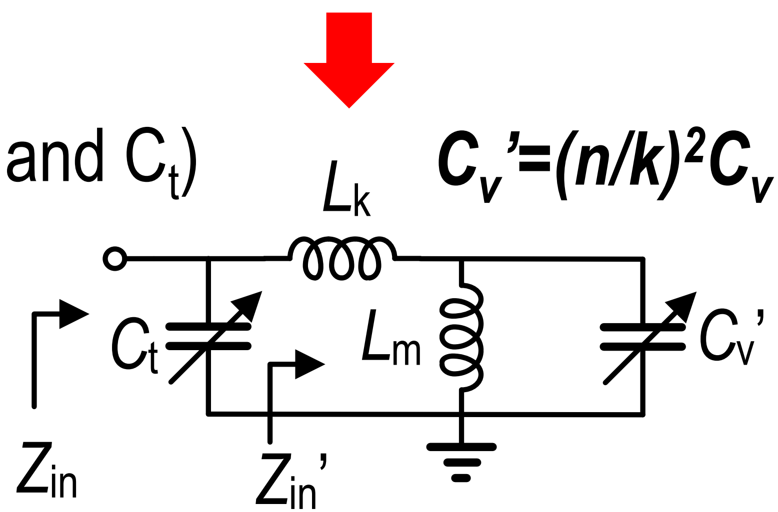
- **Our design and innovations**
- Measurement
- Conclusion

Our design and innovations

- **Transformer-based multi-resonance load (single-end)**



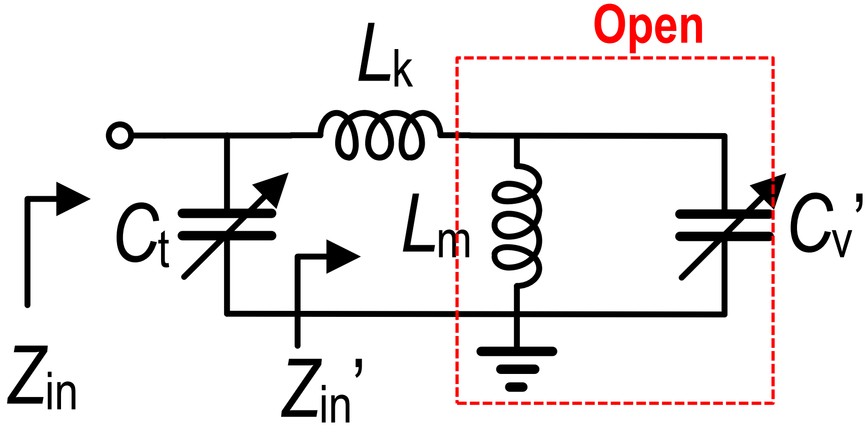
– Multi-resonance load:
one transformer + two varactors (C_v and C_t)
– Leakage inductance: $L_k=(1-k^2)L_t$
– Magnetizing inductance: $L_m=k^2L_t$
– Magnetic coupling coefficient: k
– Self-inductances of primary side: L_t

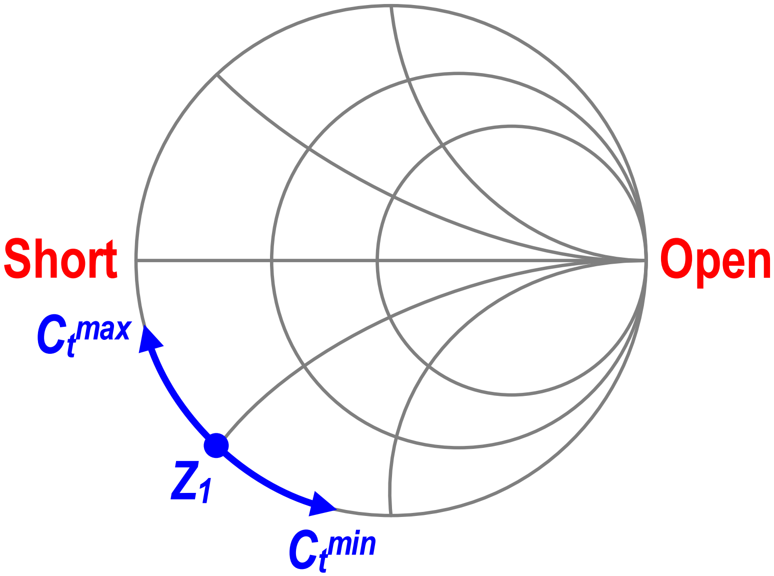


John Long, "Monolithic transformers for silicon RFIC design" *JSSC* 00'

Our design and innovations

- **Transformer-based multi-resonance load (single-end)**

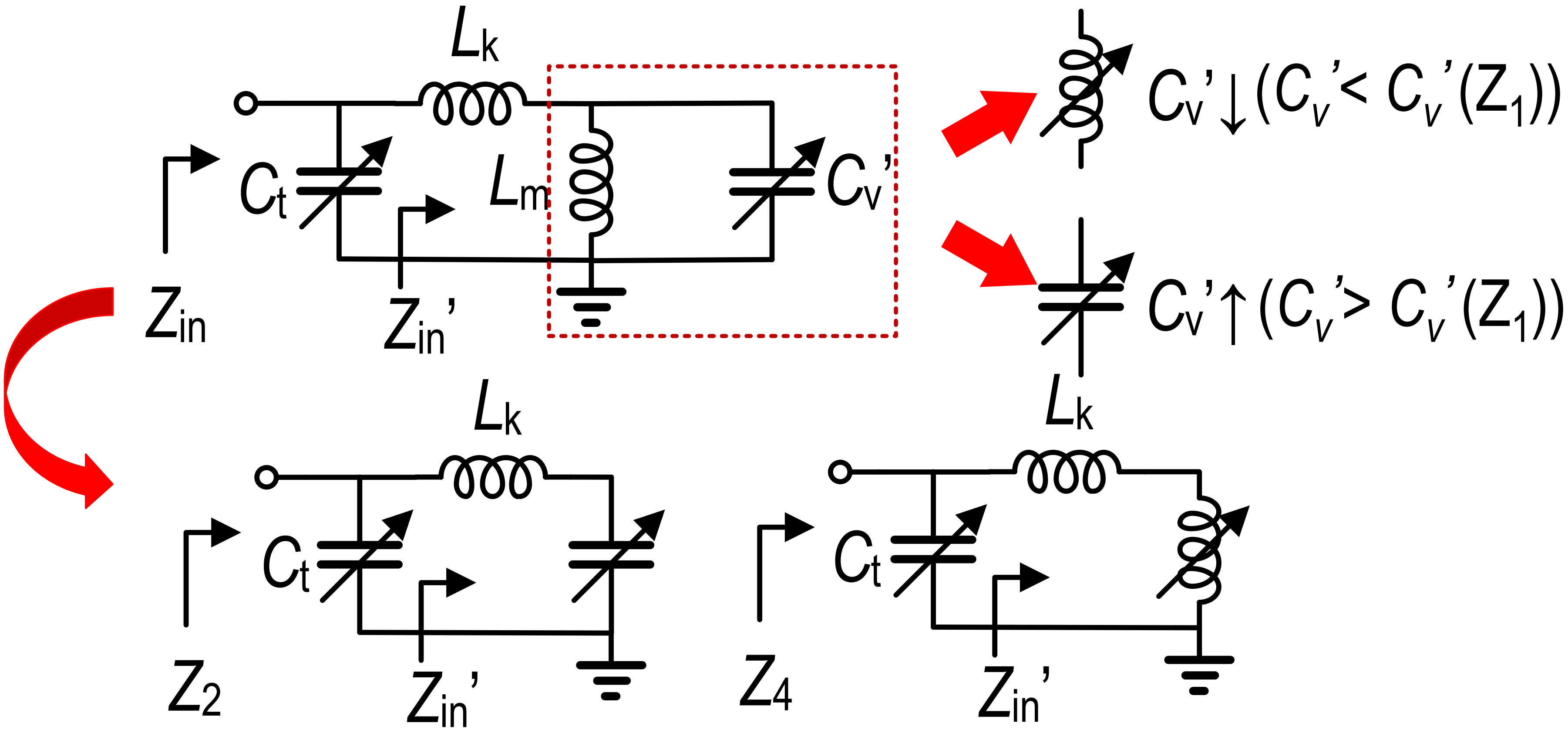




- Assume all components are lossless to simplify analysis.
- Tuning range: (in this analysis) $\alpha = C_t^{max}/C_t^{min} = C_t^{max}/C_t^{min}$
- *Lm-C_v' tank resonates at open* $\rightarrow Z_{in}' = \infty$
- Input impedance is determined by $C_t \rightarrow Z_{in} = Z_1 = 1/j\omega_o C_t$

Our design and innovations

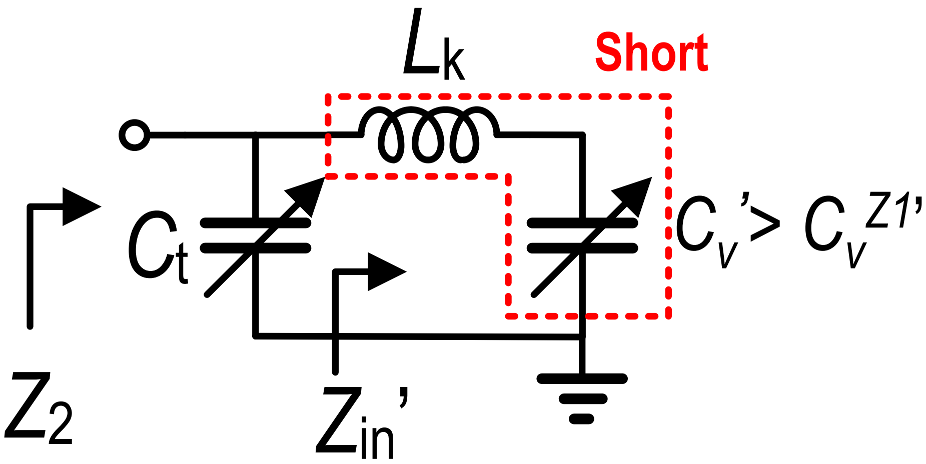
- **Transformer-based multi-resonance load (single-end)**

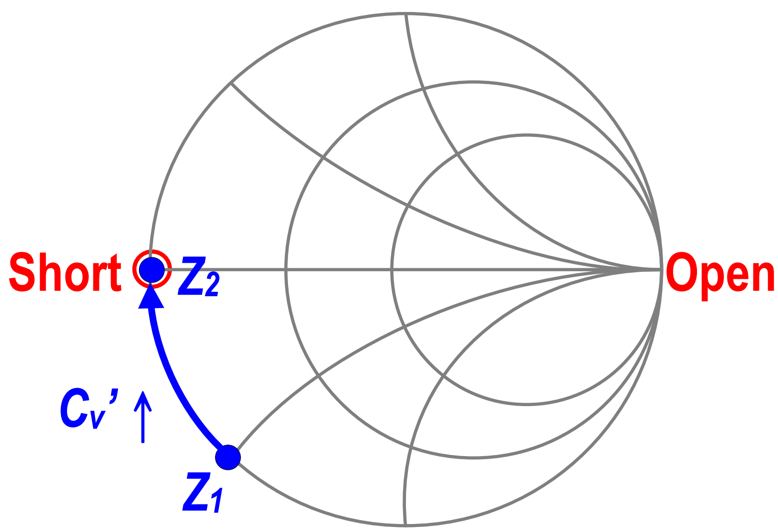


– L_m-C_v' tank shows inductive or capacitive behaviors when C_v' is away from the resonance point.

Our design and innovations

- **Transformer-based multi-resonance load (single-end)**

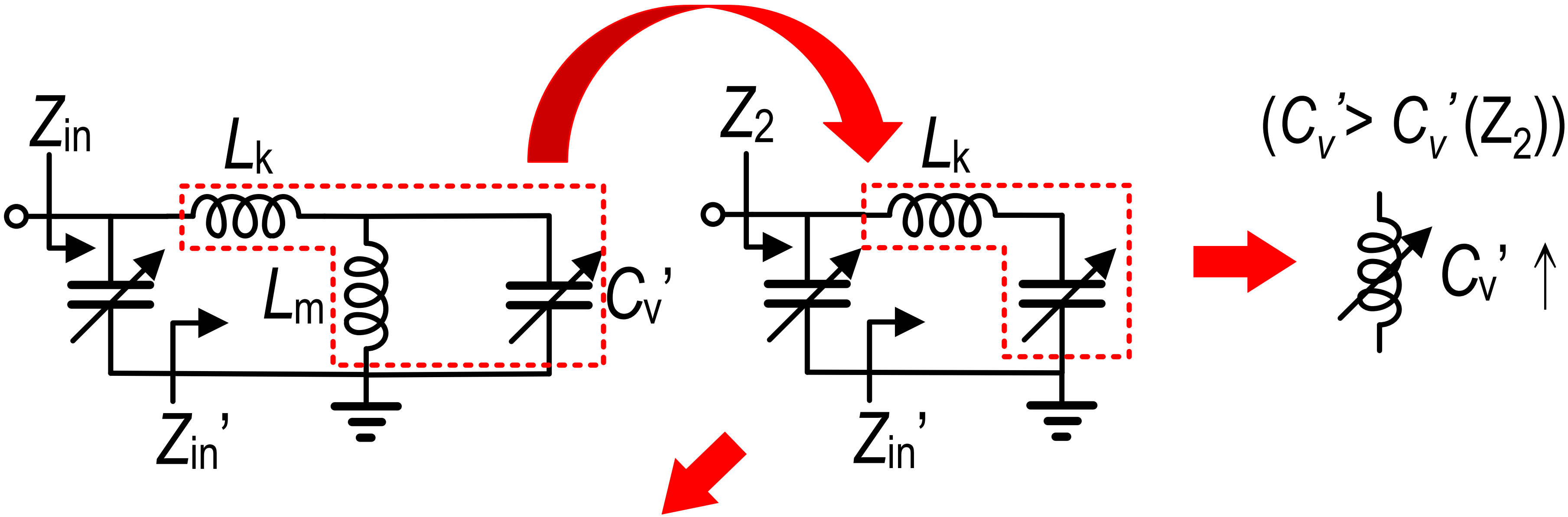


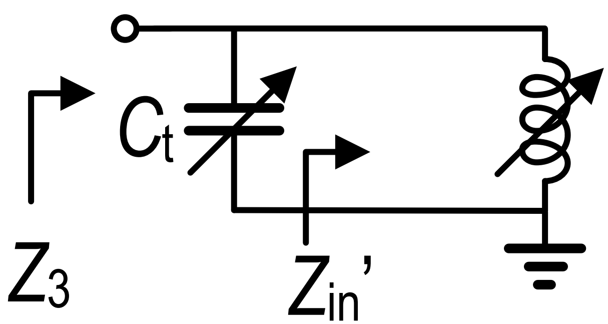


- L_m-C_v' tank is capacitive when C_v' increases ($C_v' > C_v'(Z_1)$) .
- L_k-L_m-C_v' tank resonates at short $\rightarrow Z_{in}'=0 \rightarrow Z_{in}=Z_2=0$.
- 1st resonance point achieved (similar to SLC)

Our design and innovations

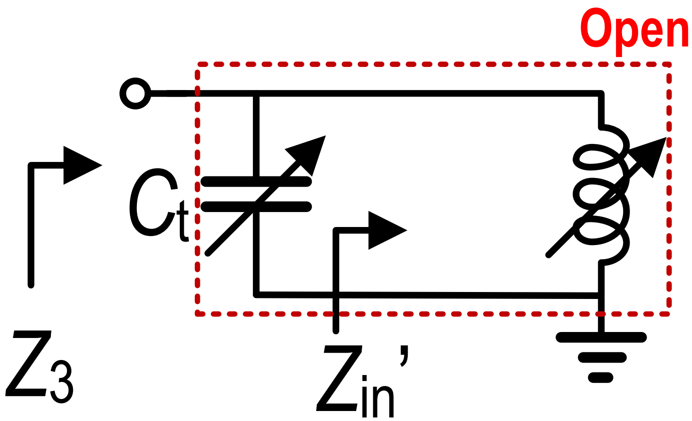
- **Transformer-based multi-resonance load (single-end)**

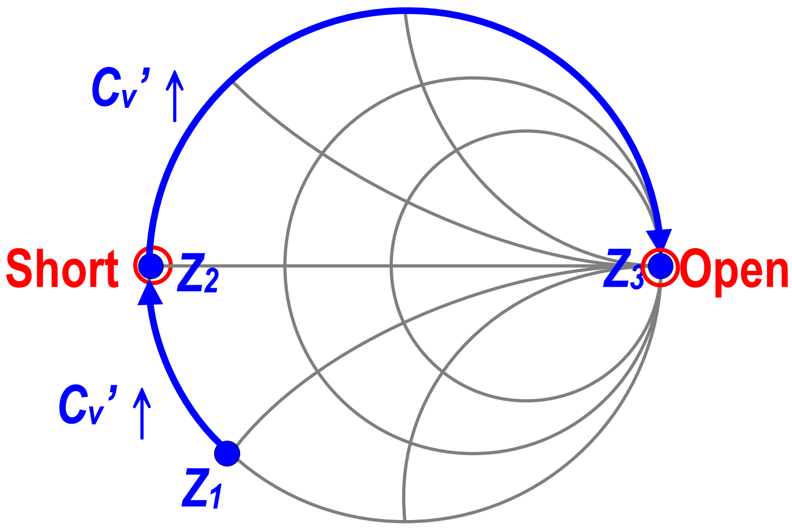




- If C_v' is keeping increasing, L_k-L_m-C_v' tank will be inductive (C_v'> $C_v'(Z_2)$) > $C_v'(Z_1)$).

- **Transformer-based multi-resonance load (single-end)**





– L_k-L_m-$C_v^{max'}$ tank resonates with C_t^{max} at open $\longrightarrow Z_{in}=Z_3=\infty$.

– 2nd resonance point achieved (similar to CLC).

Our design and innovations

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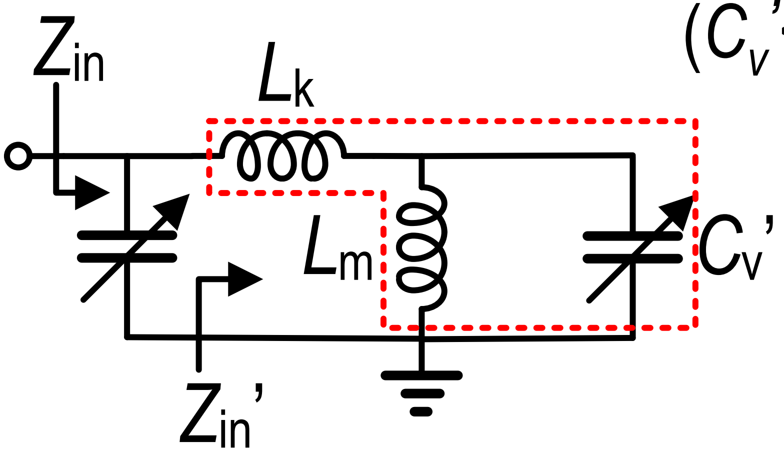
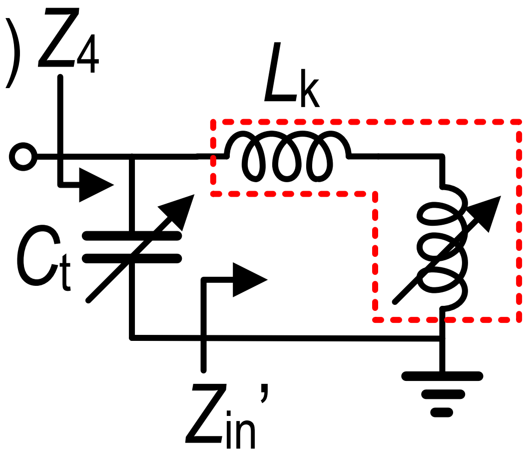
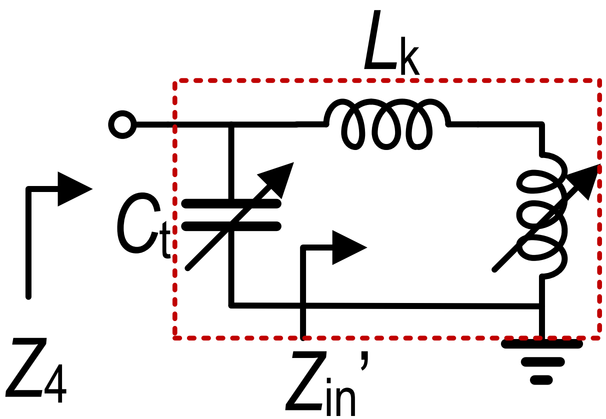
- **Transformer-based multi-resonance load (single-end)**



$(C_v' < C_v'(Z_1))$

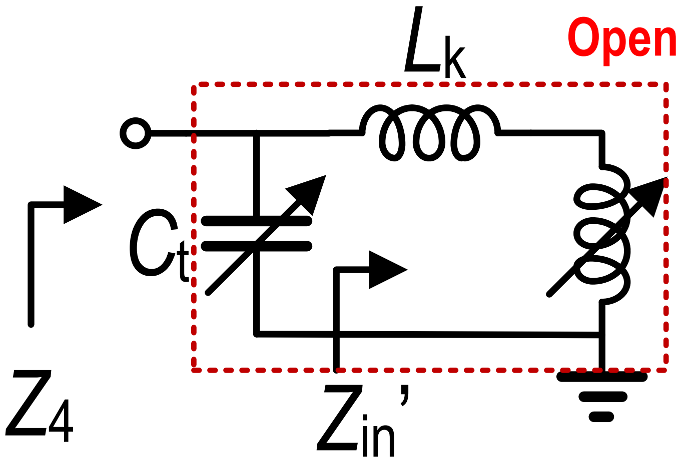


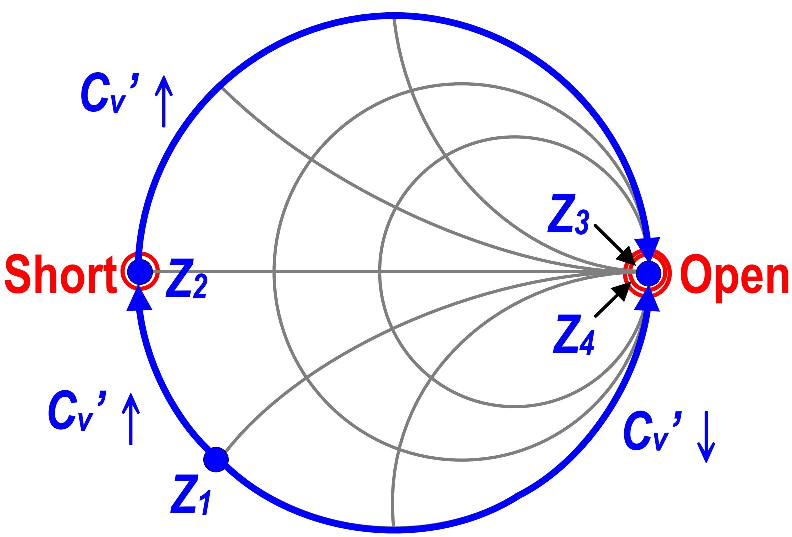


– L_m-C_v' tank is inductive when C_v' decreases ($C_v' < C_v'(Z_1)$)

Our design and innovations

- **Transformer-based multi-resonance load (single-end)**





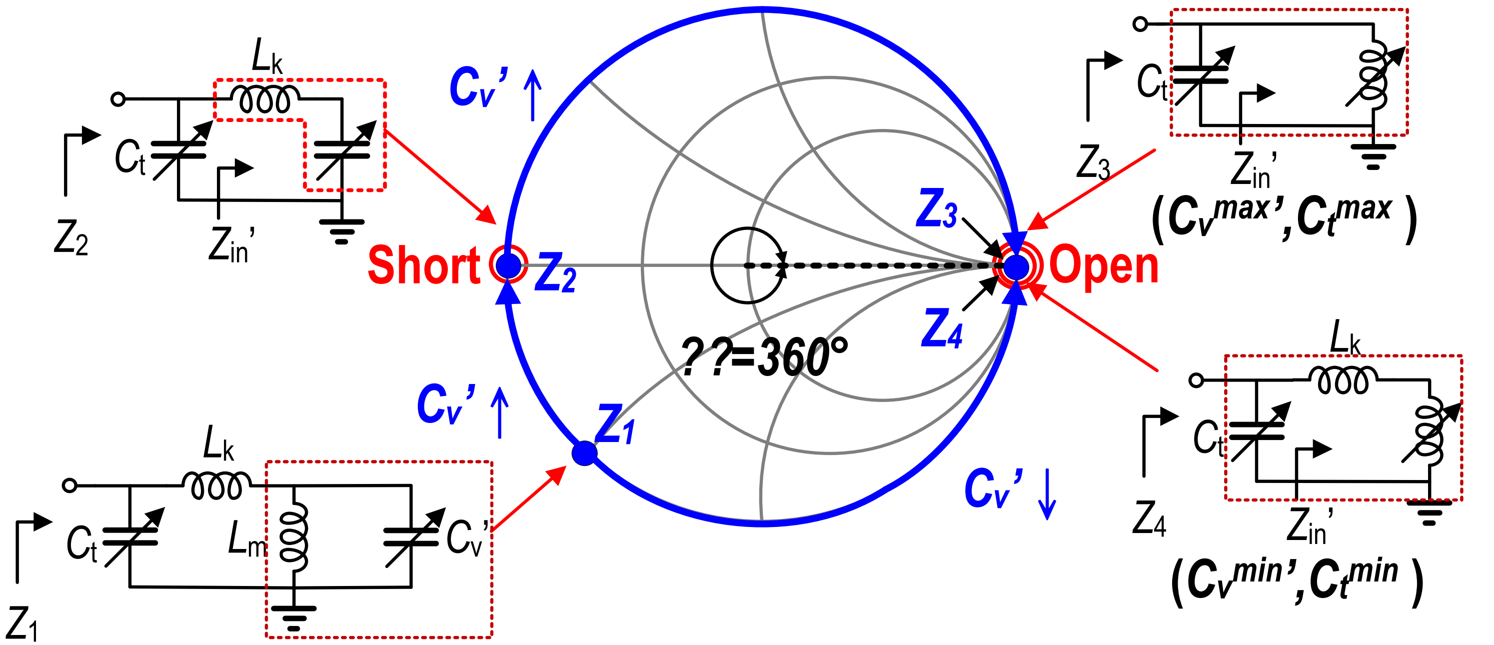
– L_m-C_v' tank is inductive when C_v' decreases ($C_v' < C_v'(Z_1)$).

– L_k-L_m-$C_v^{min}{}'$ tank resonates with C_t^{min} at open $\rightarrow Z_{in}=Z_4=\infty$.

– 3rd resonance point achieved (similar to PLC).

Our design and innovations

- **Transformer-based multi-resonance load (single-end)**



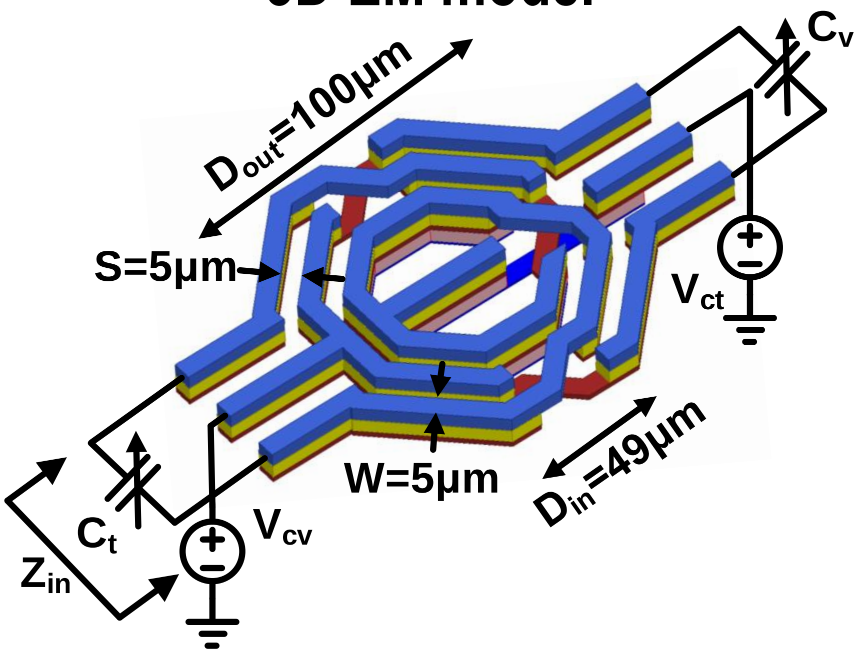
$$\frac{C_t^{\max}}{C_t^{\min}} = \alpha = \frac{\left(1-k^2\right)+k^2\Big/\left(1-\omega_0^2 n^2 L_t C_v^{min}\right)}{\left(1-k^2\right)+k^2\Big/\left(1-\omega_0^2 n^2 L_t \alpha C_v^{min}\right)}$$

Three resonance points made →ensure phase shift ≥ 360°

Our design and innovations

- **Transformer-based multi-resonance reflective load**

3D EM model

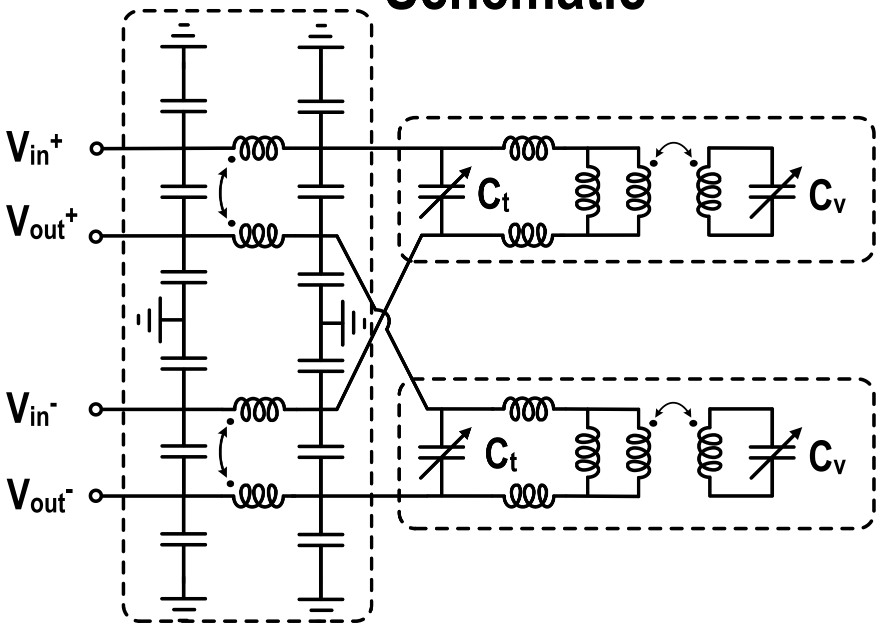


- 2-to-1 transformer with optimum k=0.63.
- 130nm BiCMOS
- $46fF \le C_v \le 125fF$ $(-1V \le V_{cv} \le 0.45V)$
- $21fF \le C_t \le 57fF$ $(-1V \le V_{ct} \le 0.45V)$

Our design and innovations

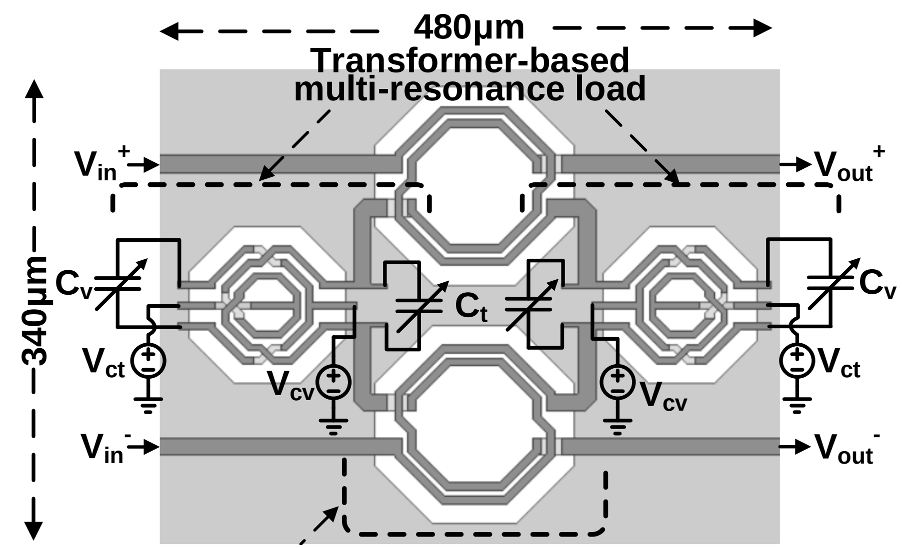
- **Fully differential transformer-based RTPS**

Schematic



Differential 90° coupler

3D EM model



Transformer-based 90° coupler

  - Standard 130nm SiGe BiCMOS process with a core area of 340µm×480µm
  - Fully differential and symmetric layout

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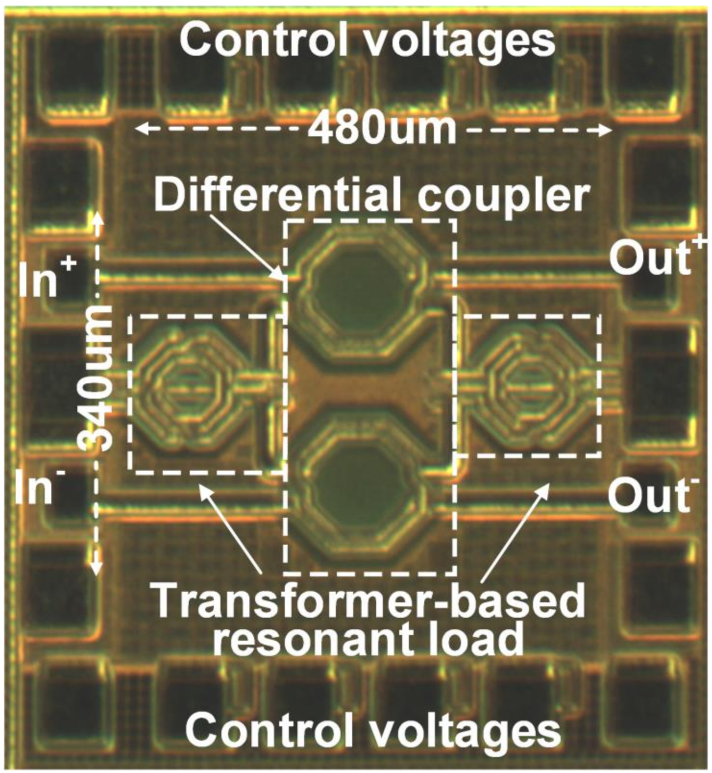
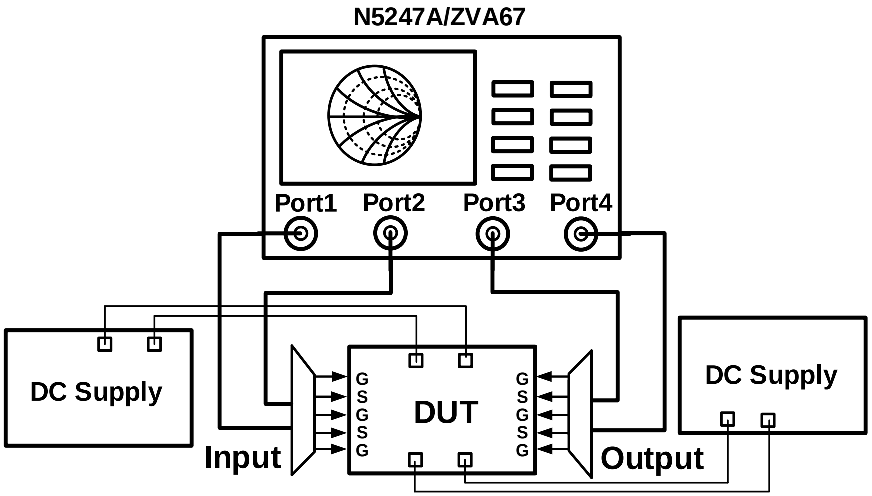
Measurement

- Chip microphotograph and test set-up



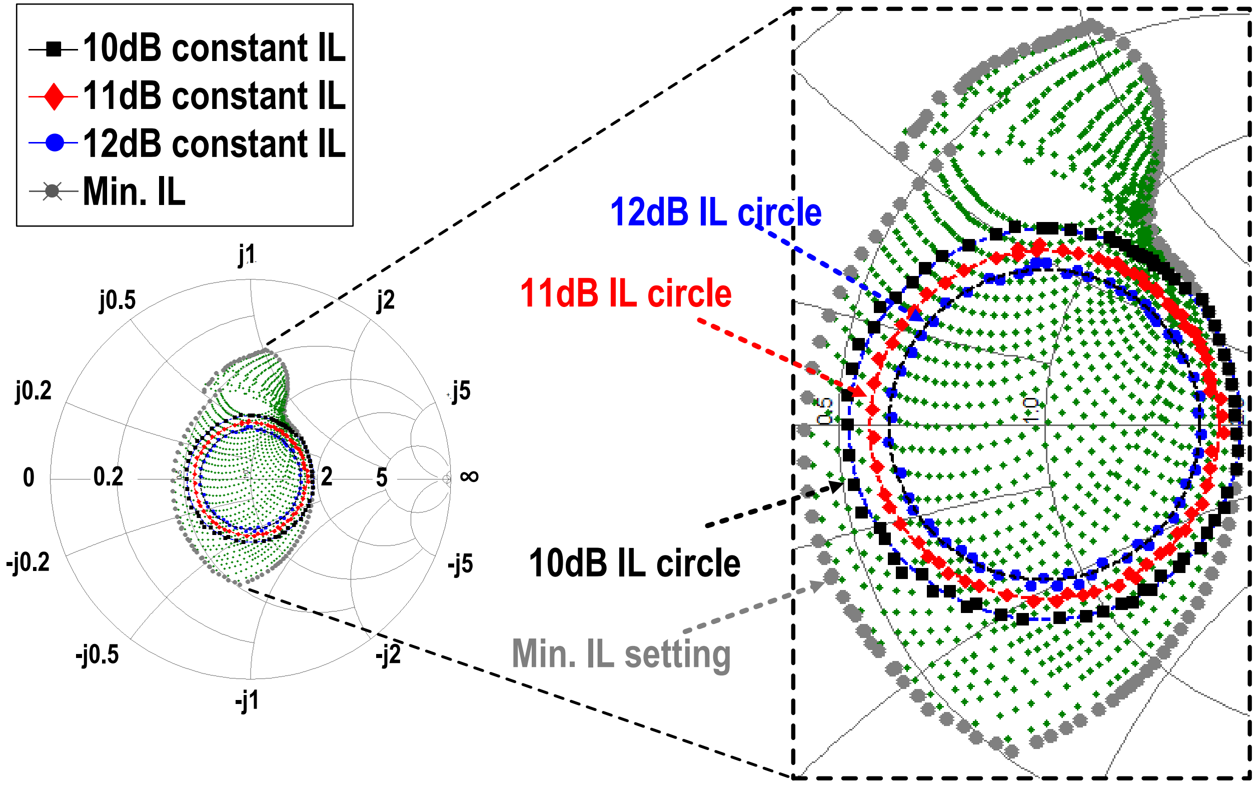
Fully symmetric layout



- Chips are tested by using probing
- A 4-port network analyzer for differential S-parameter measurement (Keysight and R&S)

Measurement

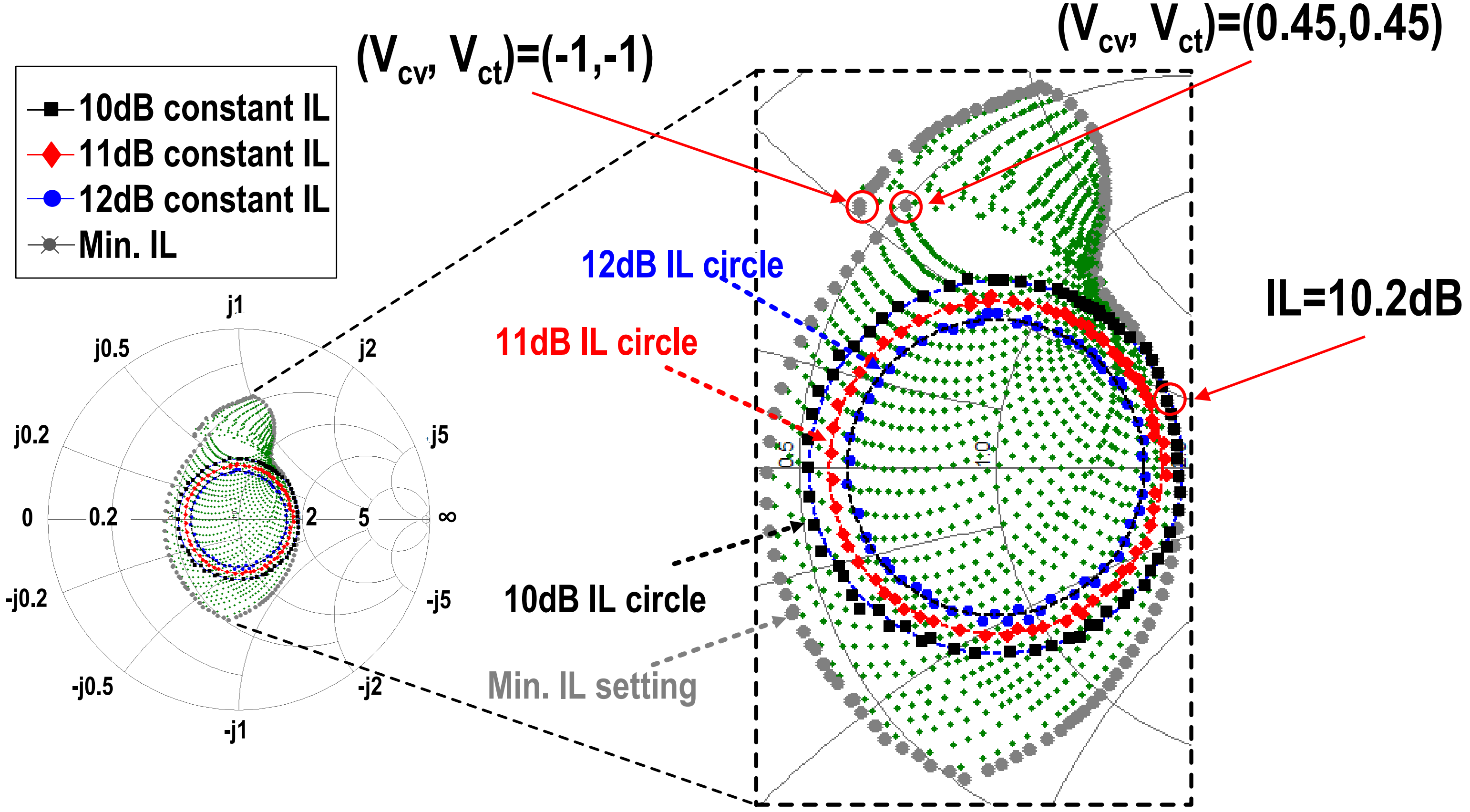
- **Measured complex insertion loss at 62GHz**



- Two control varactors→2D complex IL plot (phase and loss)
- Analog continuous tuning: discrete voltage step of 50mV

Measurement

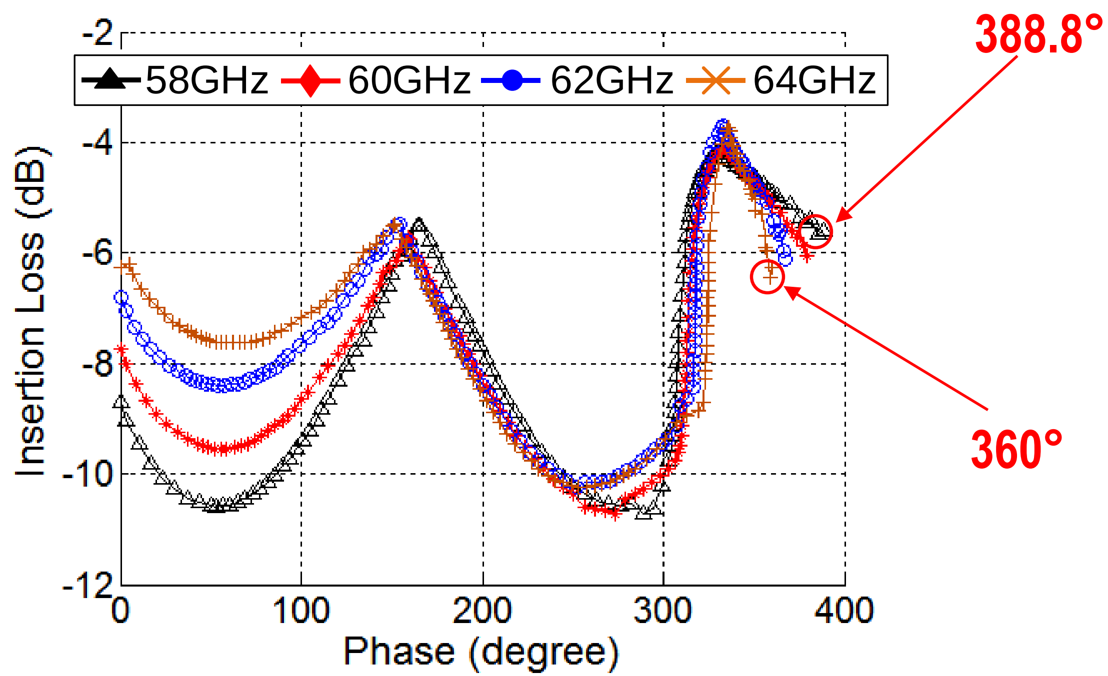
- **Measured complex insertion loss at 62GHz**



  - Minimum IL contour covers phase shift = 367°
  - Worst-case IL at minimum IL contour = 10.2dB

Measurement

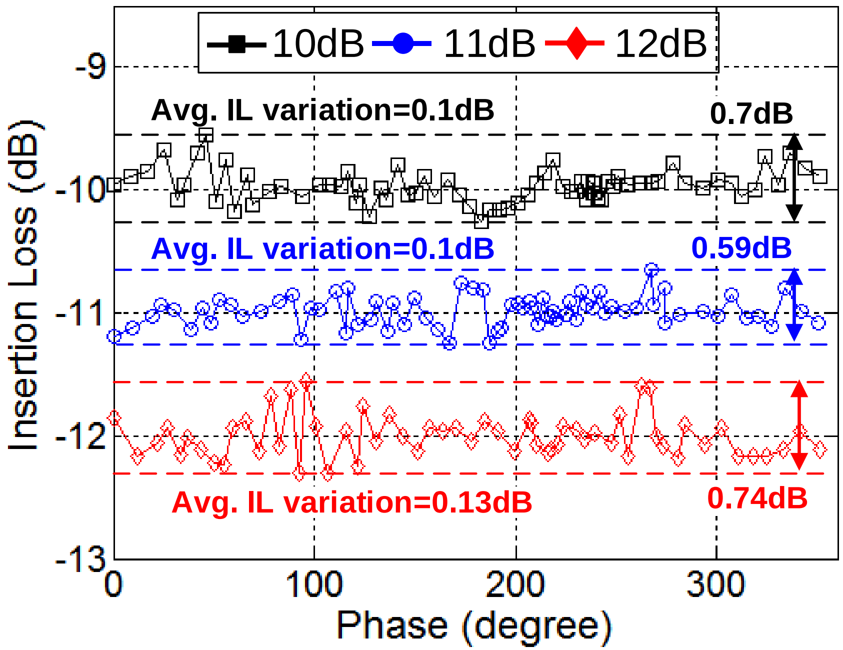
- Measured min. IL vs. phase shift for various frequencies



– BW=58GHz-64GHz under the condition (IL<11dB and phase shift≥360°) with min. IL settings

Measurement

- Measured IL variation vs. phase shift for different constant IL circles at 62GHz

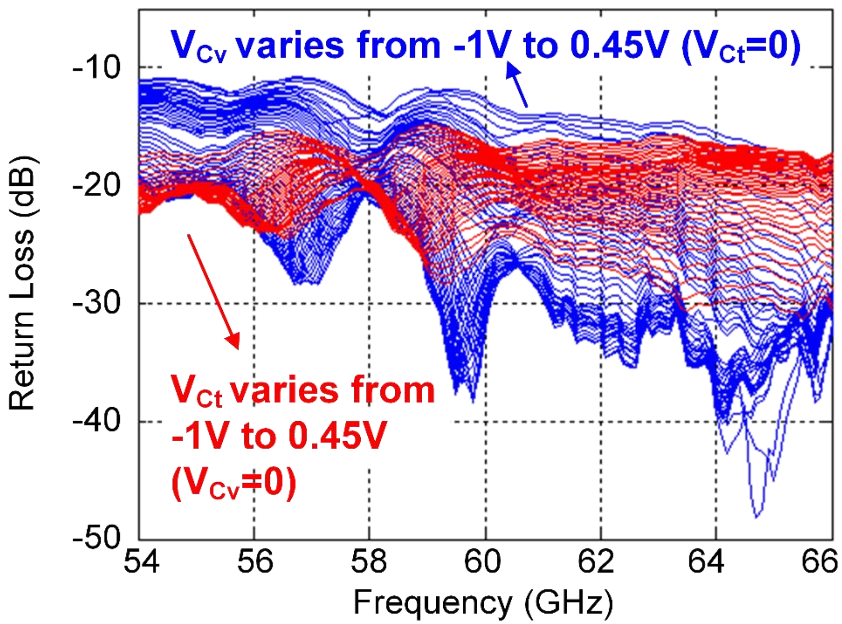


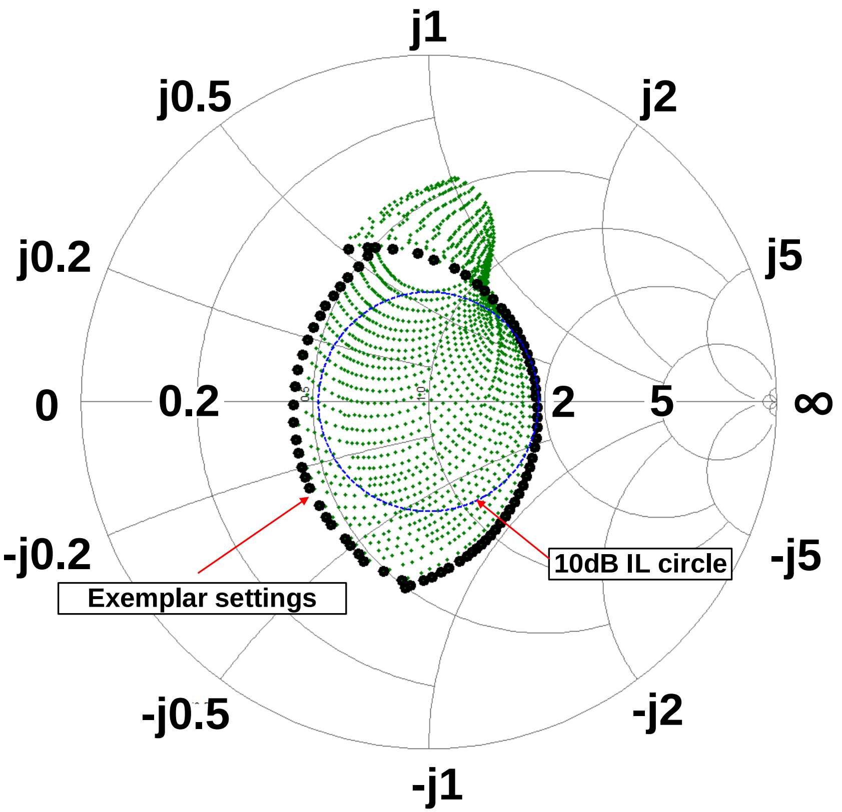
– IL variation:
  10dB circle: 0.7dB
  11dB circle: 0.59dB
  12dB circle: 0.74dB

– IL variations are suppressed under constant IL circle settings

Measurement

- Return loss (RL) of exemplar settings





– RL>11.2dB from 54GHz to 66GHz for exemplar settings

Measurement

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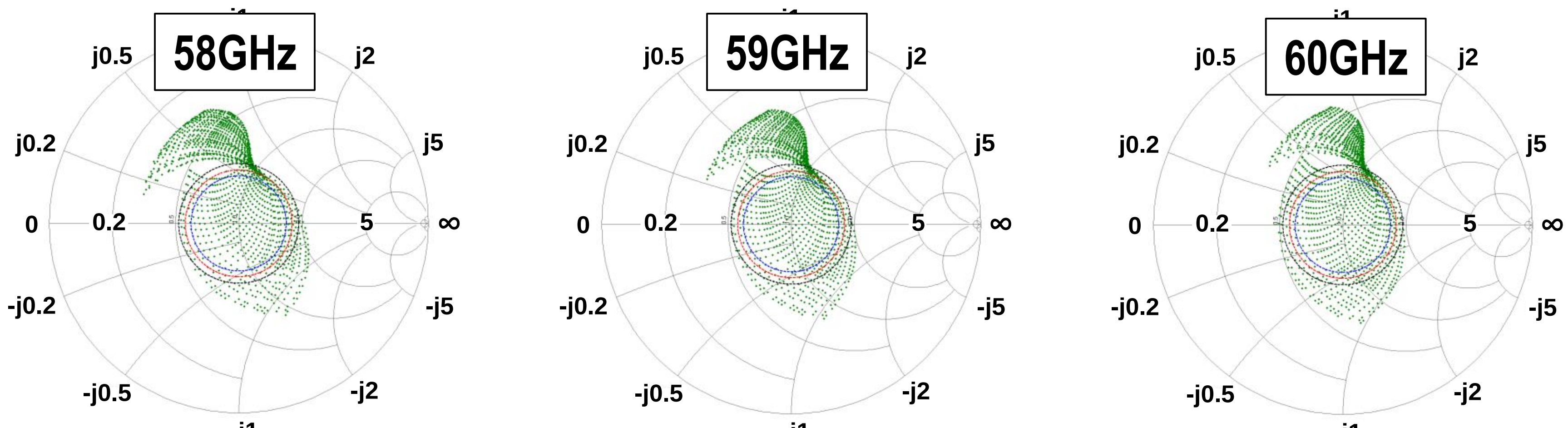
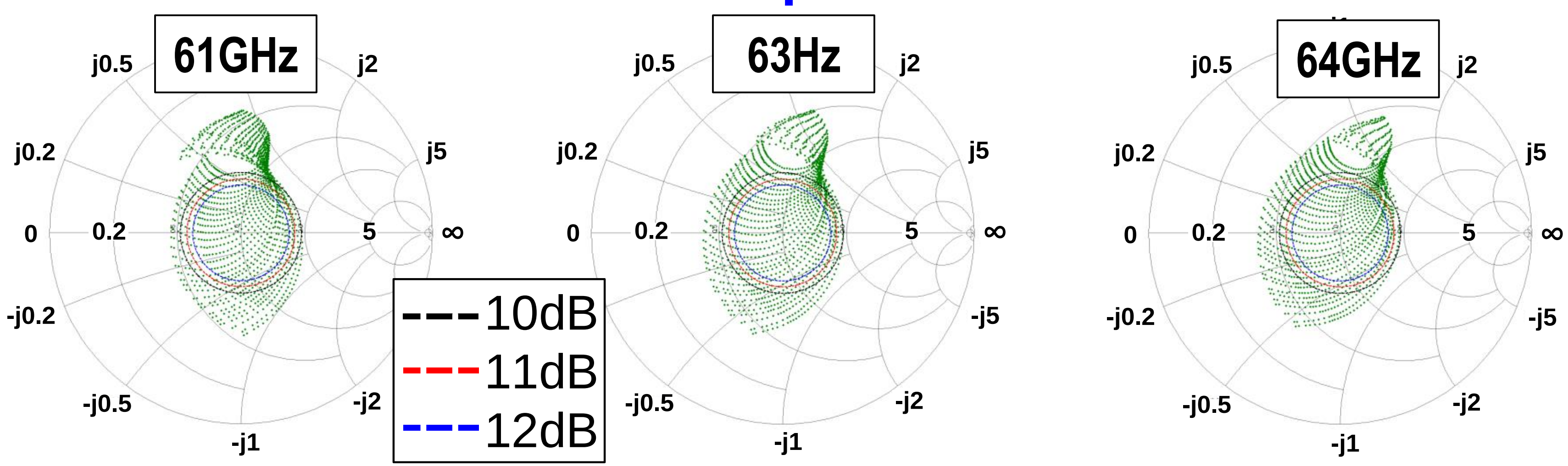
CICC

- Measured complex IL at various frequencies



All circles maintain full-span 360° from 58 to 64GHz

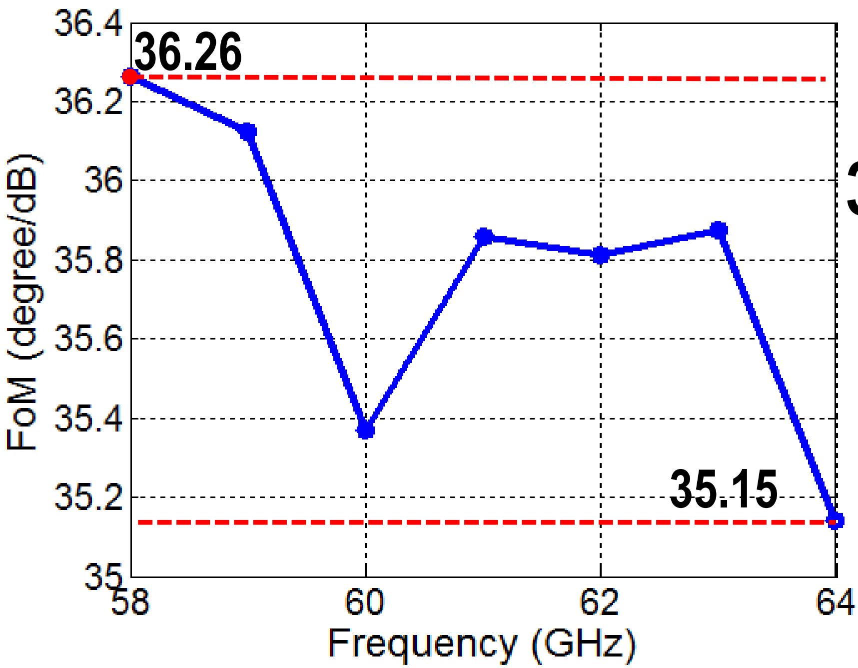


Measurement

- **Figure-of-merit (FoM):**
  - A quantitative metric to evaluate the performance of RTPS.

$$FoM\left(^{\circ}/dB\right) = \Delta\theta_{max}/IL_{max}$$

  - Maximum phase shift $\Delta\theta_{max}$ divided by the worst-case IL.



35.15≤ FoM ≤ 36.26

Measurement

- **Comparison of fully integrated mm-Wave RTPS in silicon**

Reference	This work	RFIC 09'	CICC 11'		ARRAY 10'	MWCL 13'
Frequency (GHz)	**58-64**	60	60		60	60
Max. phase shift (°)	**367**	180	180	147	156	90
Insertion Loss (dB)	**3.7-10.2(1)** **9.6-10.3(2)**	4.2-7.5 (8.6-15)(3)	5-8.3 (10-16.6)(3)	3.3-5.7	4-6.2	4.5-6.9 (18-27.6)(4)
Max. IL variation (dB)	**6.5** **0.7**	3.3	3.3	2.4	2.2	1.4
Return Loss (dB)	**>11.2**	-	9	13	5	12
Best FoM (°/dB)	**36.3**	24	21.7	25.8	25	13
Chip area (mm^2)	**0.16**	0.18	0.031	0.048	0.33	0.25
Process	**130nm BiCMOS**	130nm BiCMOS	65nm CMOS		130nm BiCMOS	130nm BiCMOS

(1)Min. IL settings; (2)Constant 10dB IL circle settings; (3)Two RTPS in cascade for 360°; (4)Four RTPS in cascade for 360°.

Outline

- Motivation
- Fundamentals of reflective-type phase shifter
- Our design and innovations
- Measurement
- **Conclusion**

Conclusion

- The first mm-Wave full-span 360° fully differential integrated RTPS in silicon (BW: 58-64GHz).
- Our design performs low loss (10.2dB) and compact chip size (340μm×480μm).
- The IL variations are suppressed under the constant IL circle settings (10dB, 11dB and 12dB), only up to 0.74dB.
- The best FoM of 36.26°/dB compared with other reported integrated mm-Wave RTPS in silicon.