IEICE Society Conference

A 60-GHz Digitally-Controlled Phase Modulator with Phase Error Calibration

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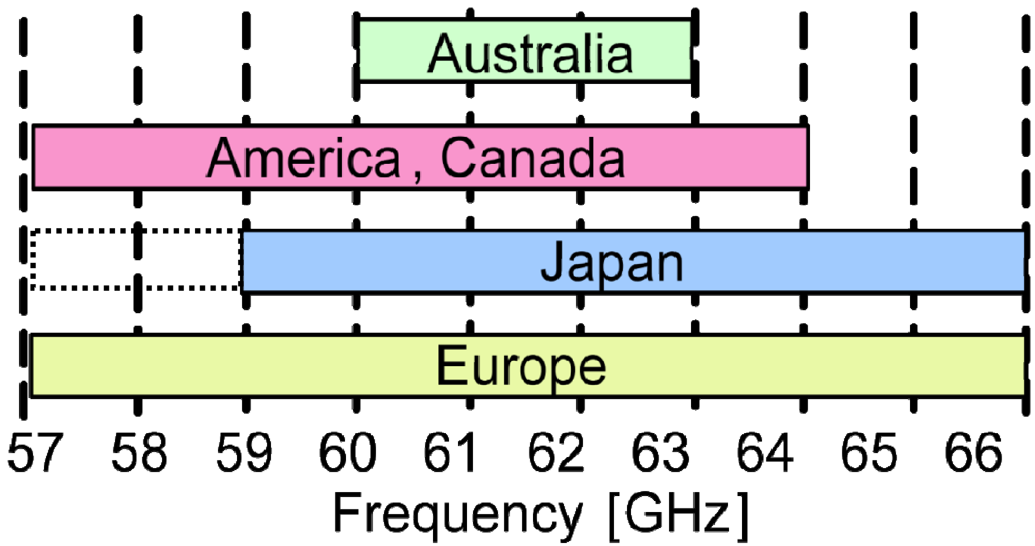
Background

- **9-GHz unlicensed bandwidth**
- **Several Gbps wireless communication**

  e.g. IEEE 802.15.3c

  QPSK→3.5 Gbps/ch

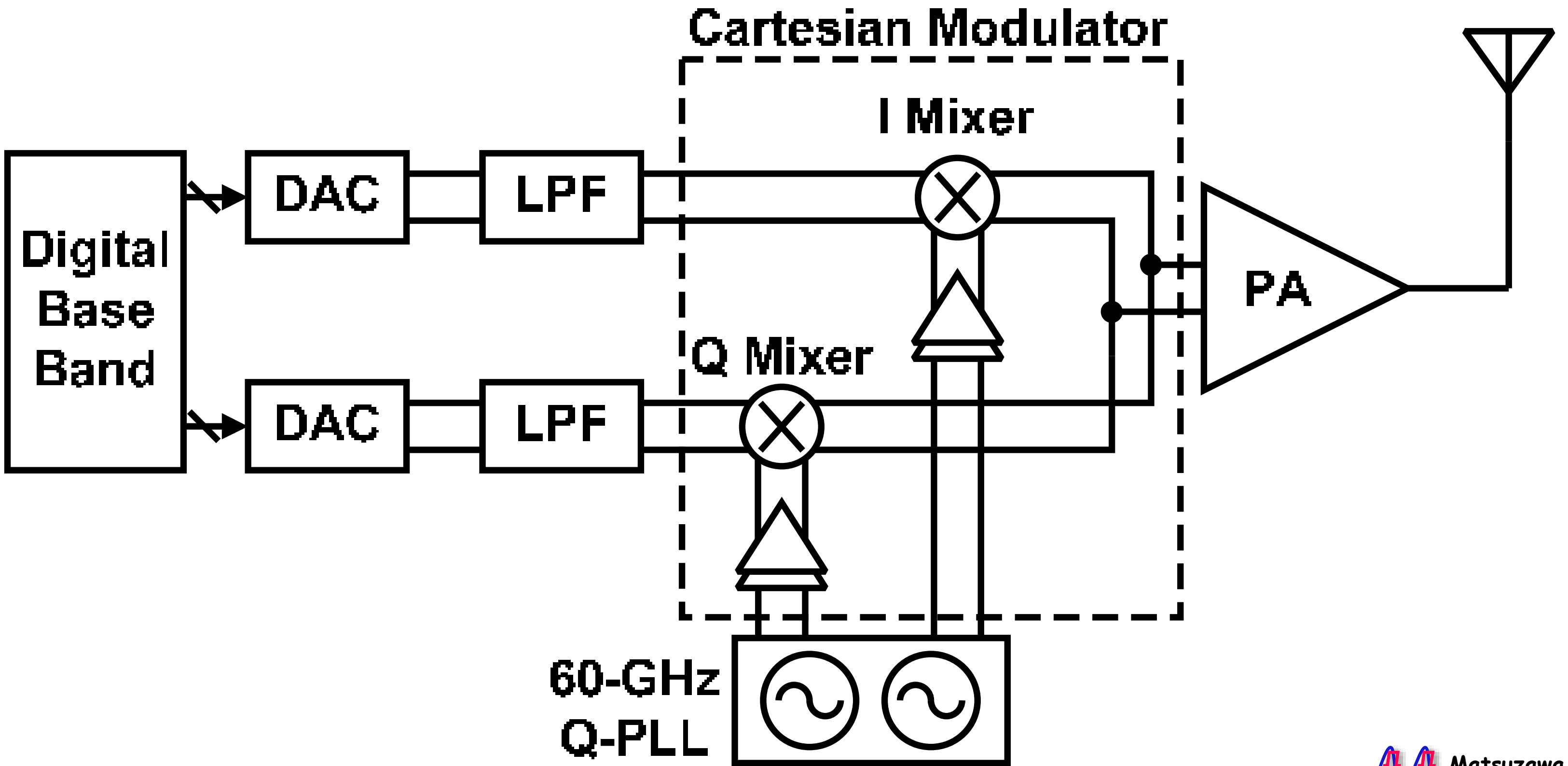
  16QAM→7 Gbps/ch



[1] http://www.tele.soumu.go.jp

Conventional 60-GHz Transmitter

- Direct-conversion architecture
  - Small area
  - Low power consumption
  - Free of imagine frequency issue



Cartesian Modulator Issues(1/2)

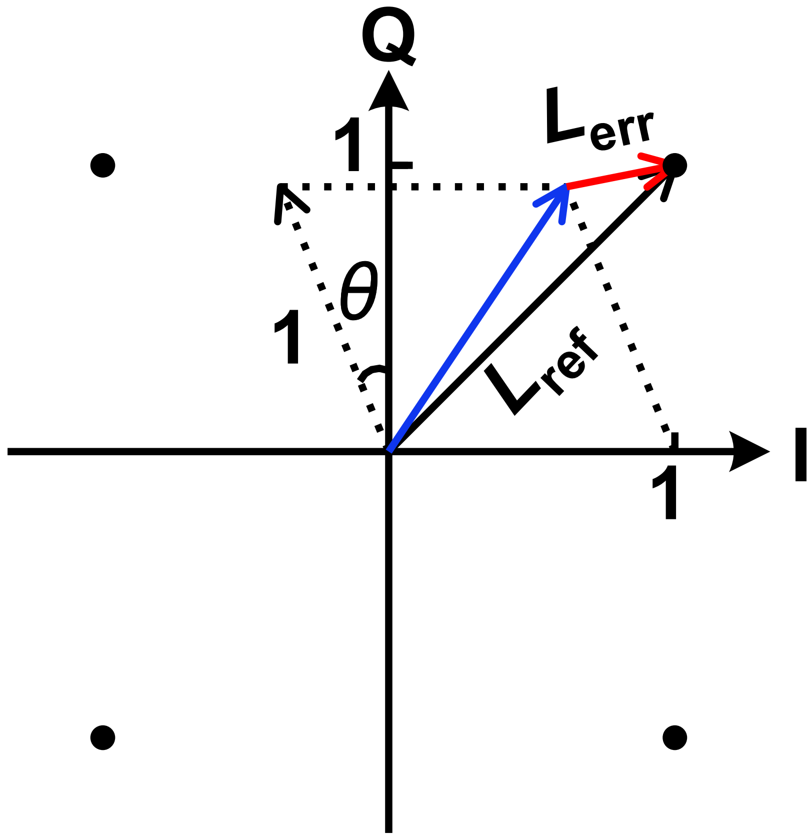
- **I/Q phase mismatch**

$$EVM(\%) = \frac{L_{err}}{L_{ref}} \times 100\%$$

For θ =10°

Phase error = 5°

***EVM*(%) ≈ 12.7%**



QPSK Constellation

Cartesian Modulator Issues(2/2)

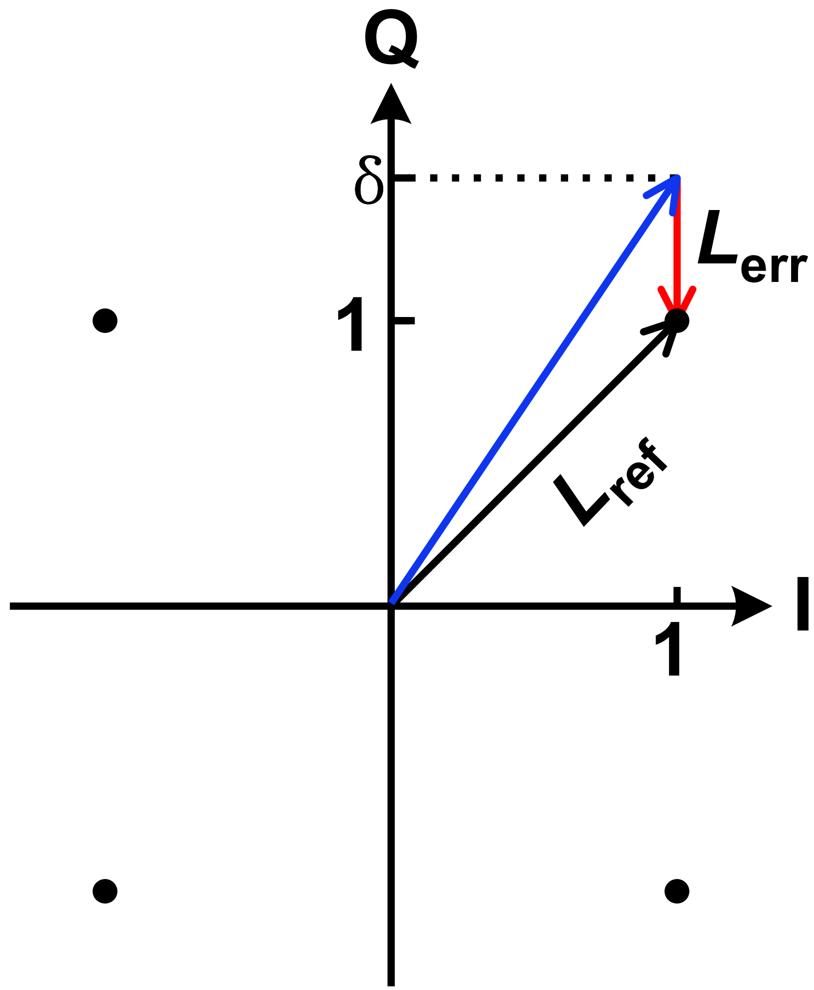
- **I/Q gain mismatch**

$$EVM(\%) = \frac{L_{err}}{L_{ref}} \times 100\%$$

For $20log_{10}\delta = 1$ dB

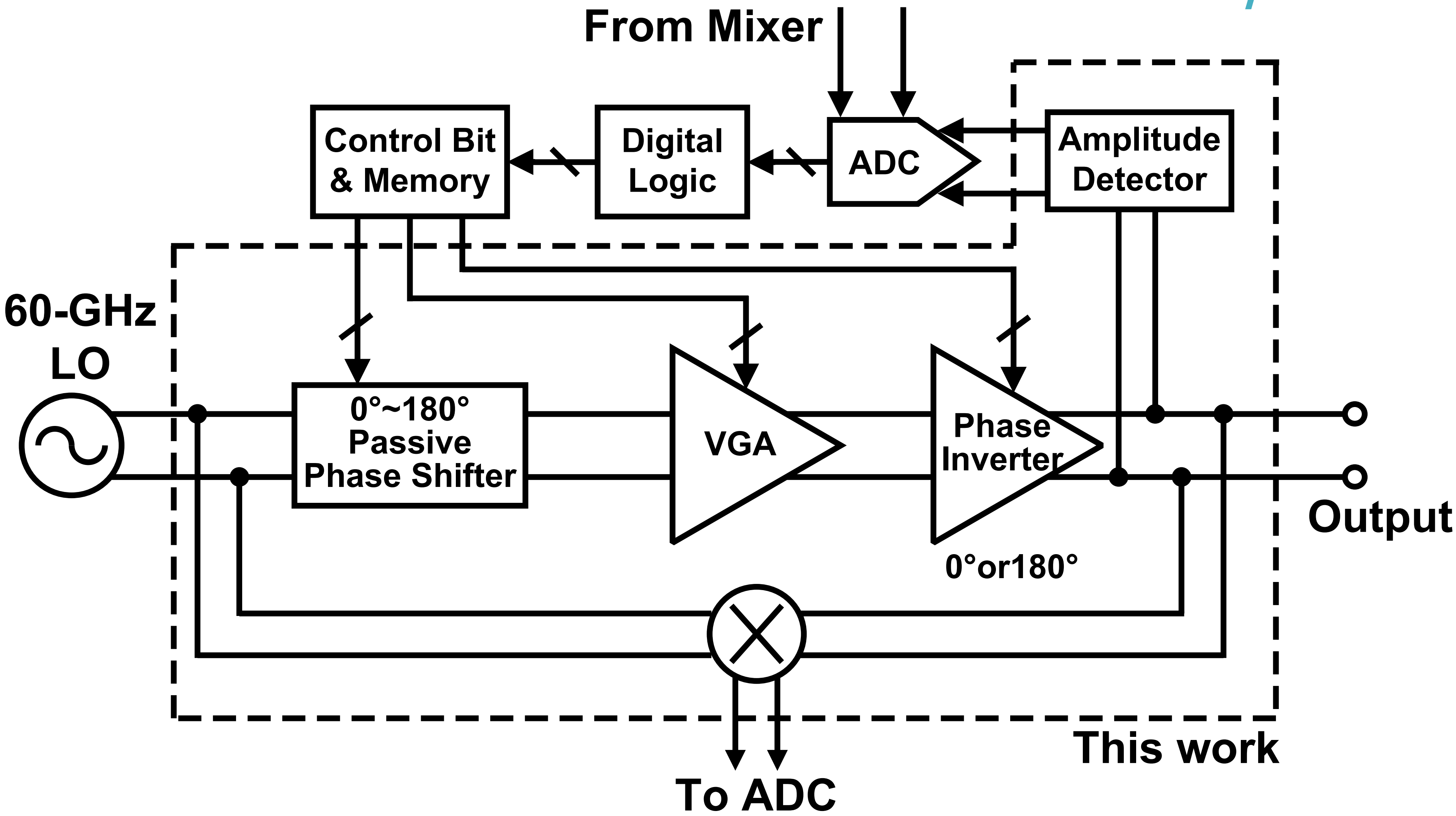
Phase error ≈ 3°

***EVM*(%) ≈ 8.6%**

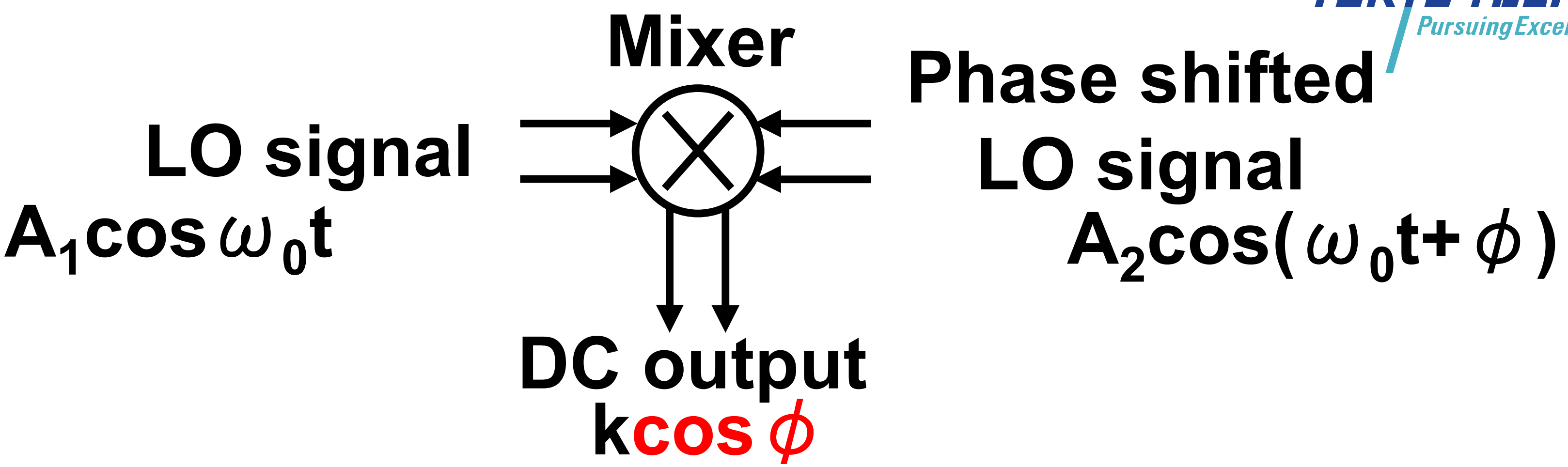


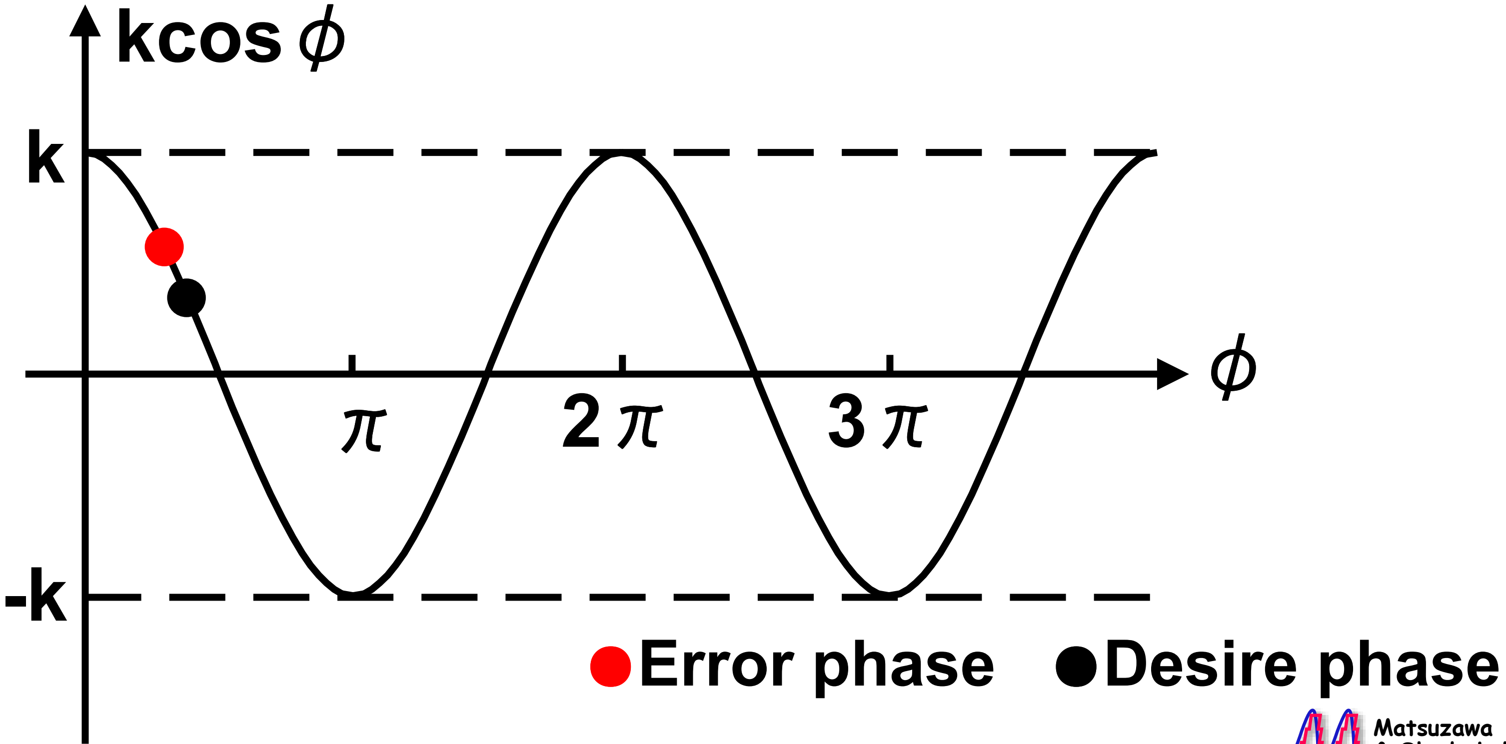
QPSK Constellation

Proposed Phase Modulator



Phase Calibration Principle (1/2)





Phase Calibration Principle (2/2)

- **Insensitivity to the phase shift of mixer.**

$$P = k\cos(\phi + \Delta\theta)$$

Phase 1: $\phi_1 + \Delta\theta = \arccos(P_1/k)$

Phase 2: $\phi_2 + \Delta\theta = \arccos(P_2/k)$

Phase 2-Phase 1:

$$\phi_2 - \phi_1 = \arccos(P_2/k) - \arccos(P_1/k)$$

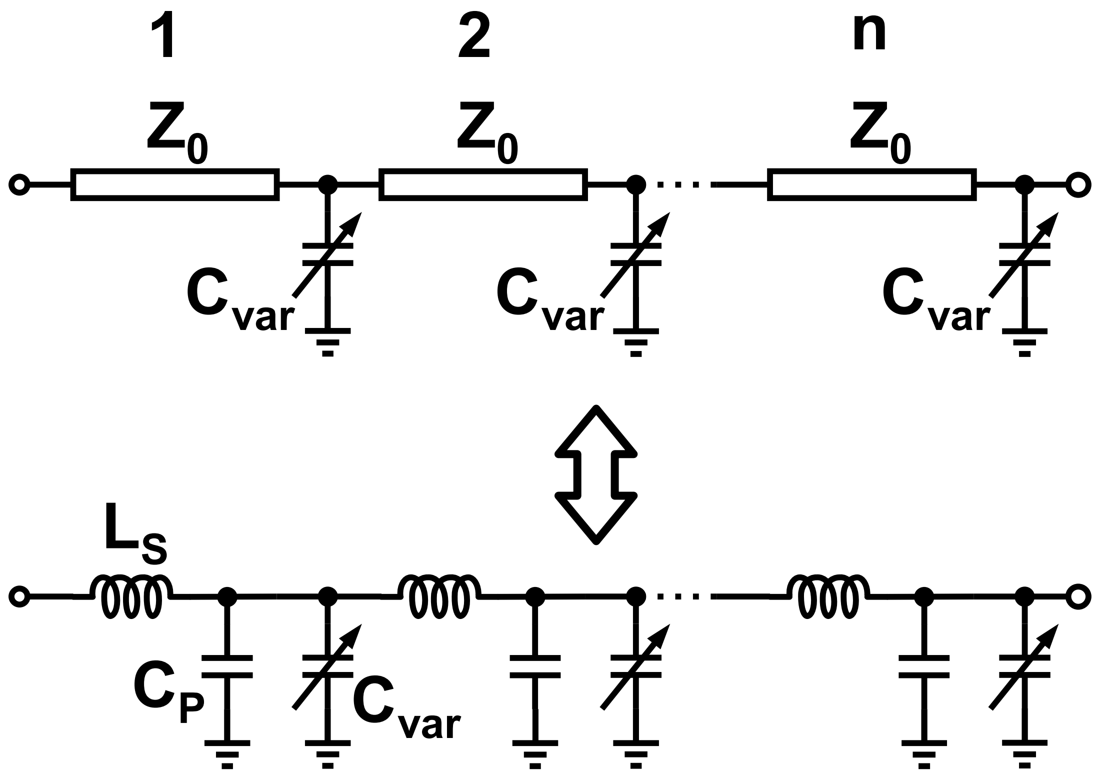
Varactor-Loaded TL

$$\varphi = \tan^{-1}\left[\frac{Y_C^2 X_L - 2Y_C - X_L}{2(1 - Y_C X_L)}\right]$$

where

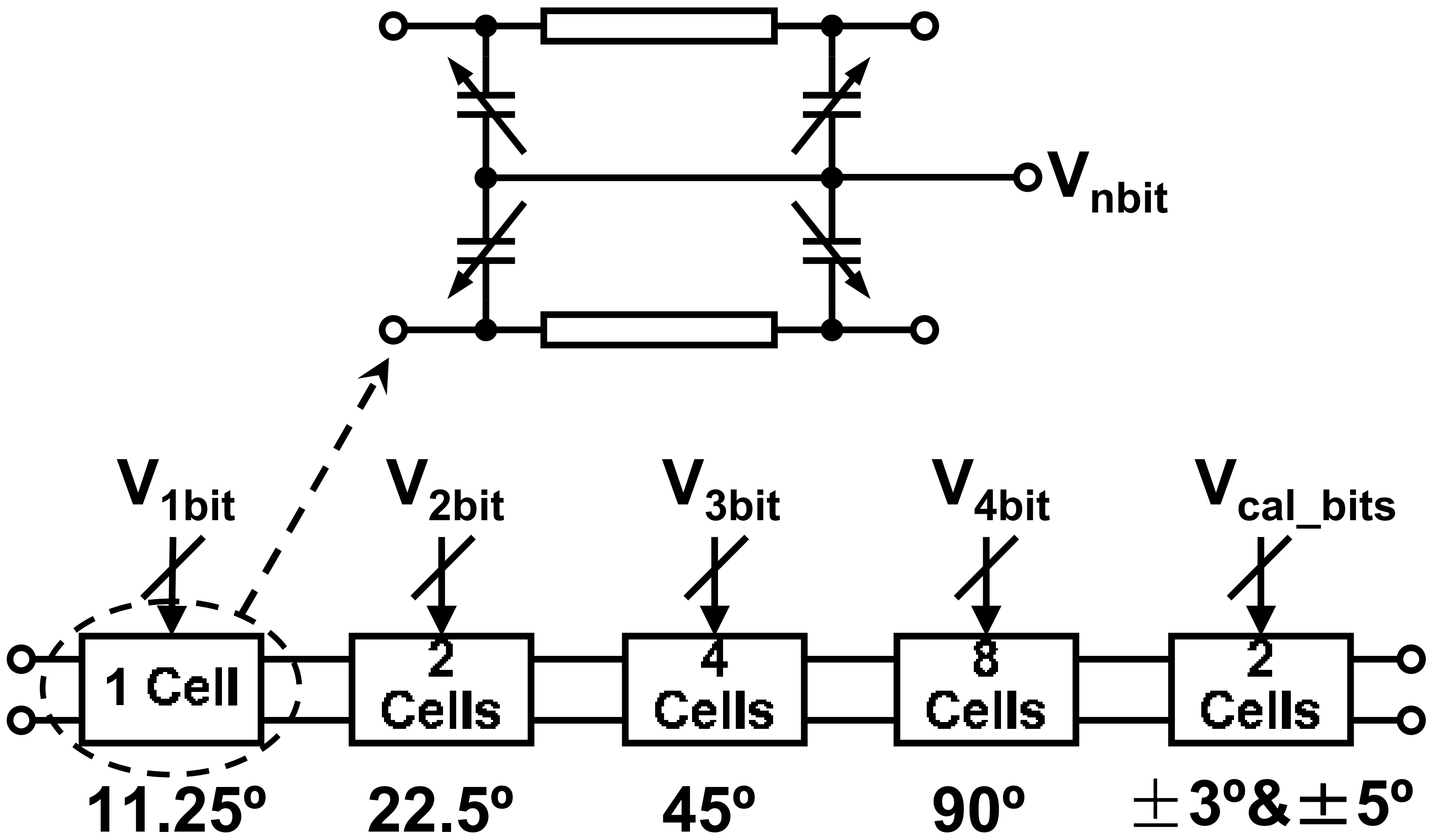
$$Y_C = \frac{1}{2}\omega\left(C_P + C_{\mathrm{var}}\right)Z_0$$

$$X_L = \frac{\omega L_S}{Z_0}$$

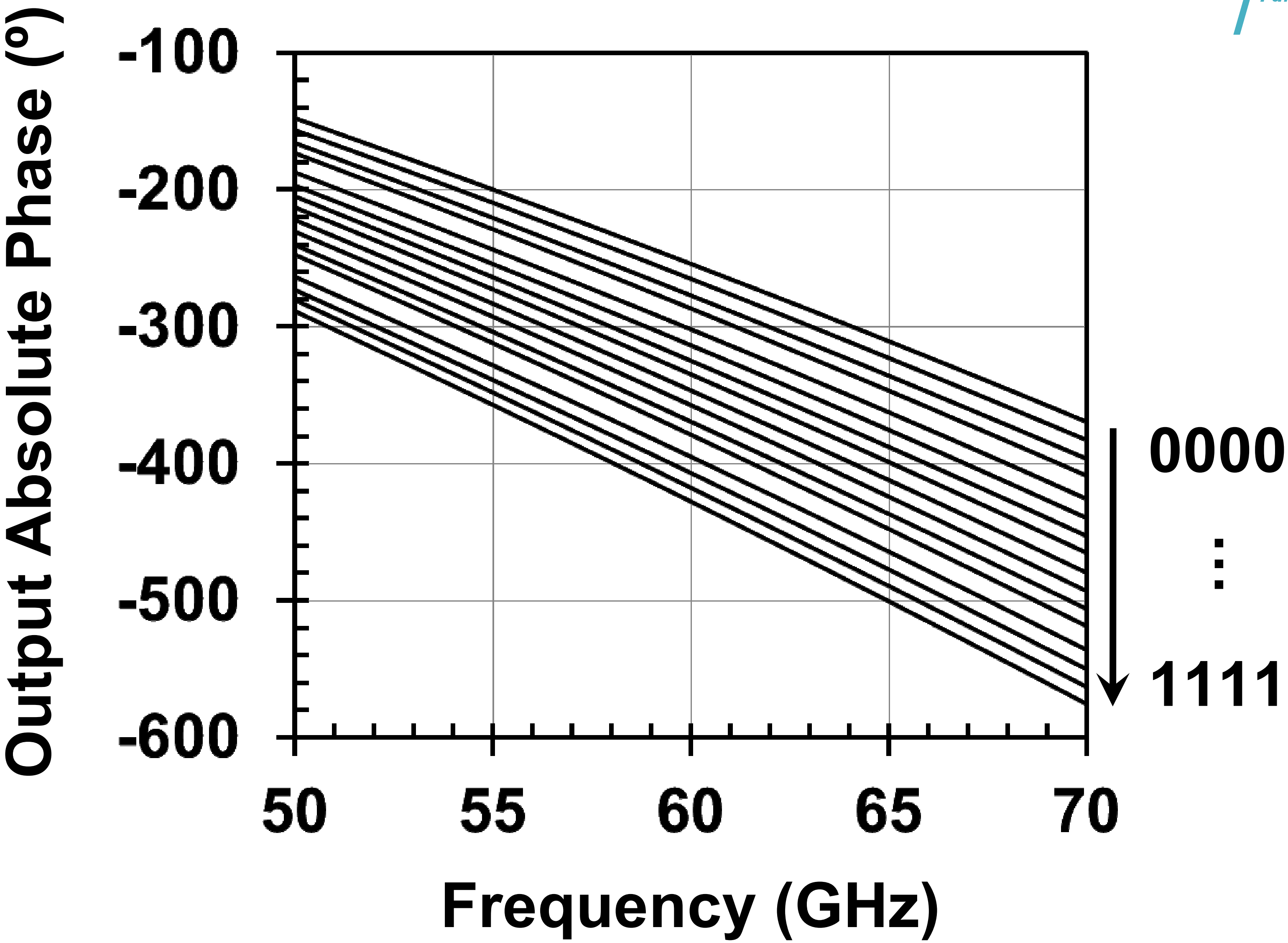


[2] F. Ellinger et. al, TMTT 2003.

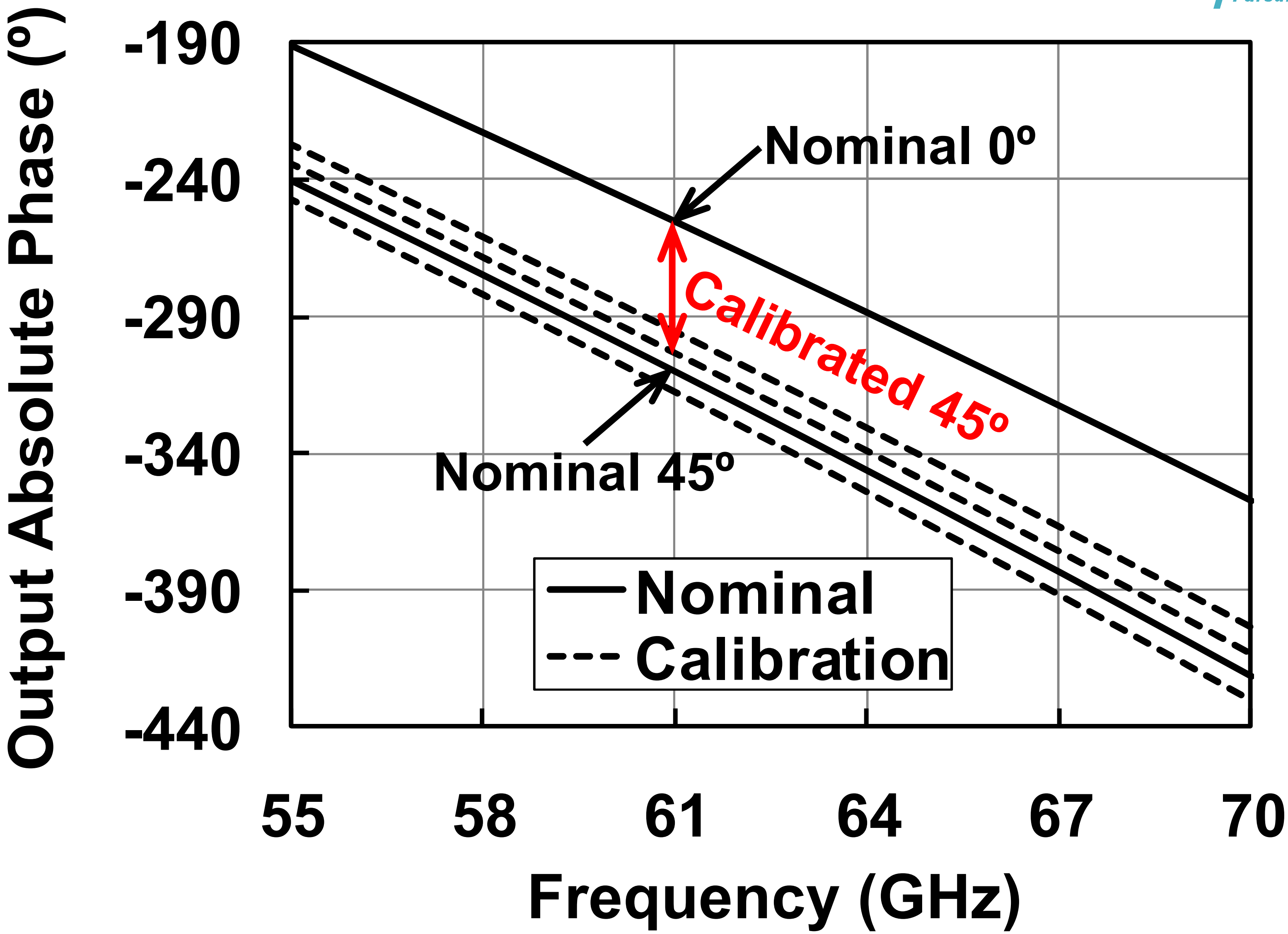
Phase Shifter Architecture



Phase Shifter Sim. Result



Phase Shifter Sim. Result

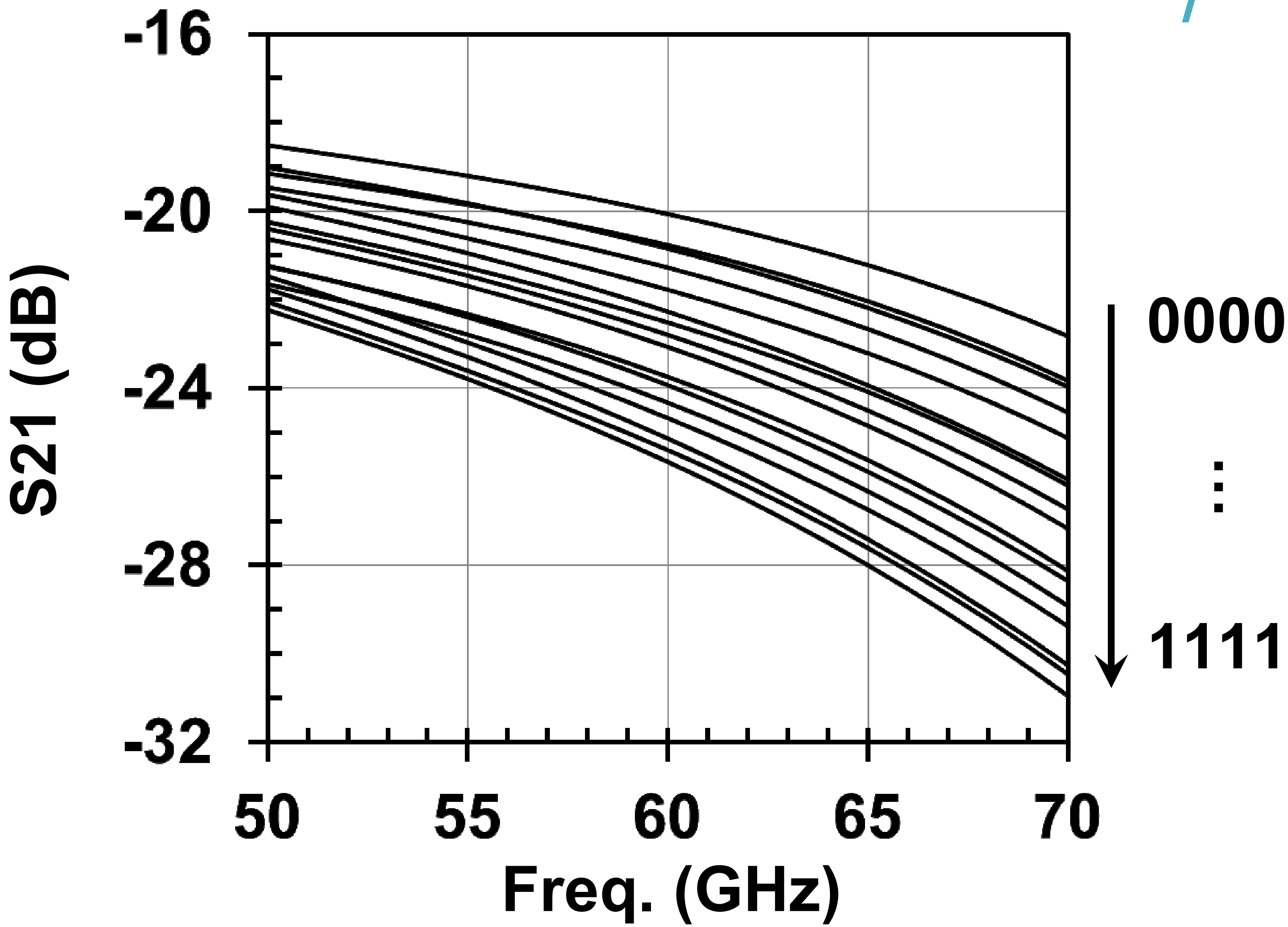


Conclusion

- **The phase accuracy of the modulator will be greatly improved over PVT variations by using the proposed technique.**

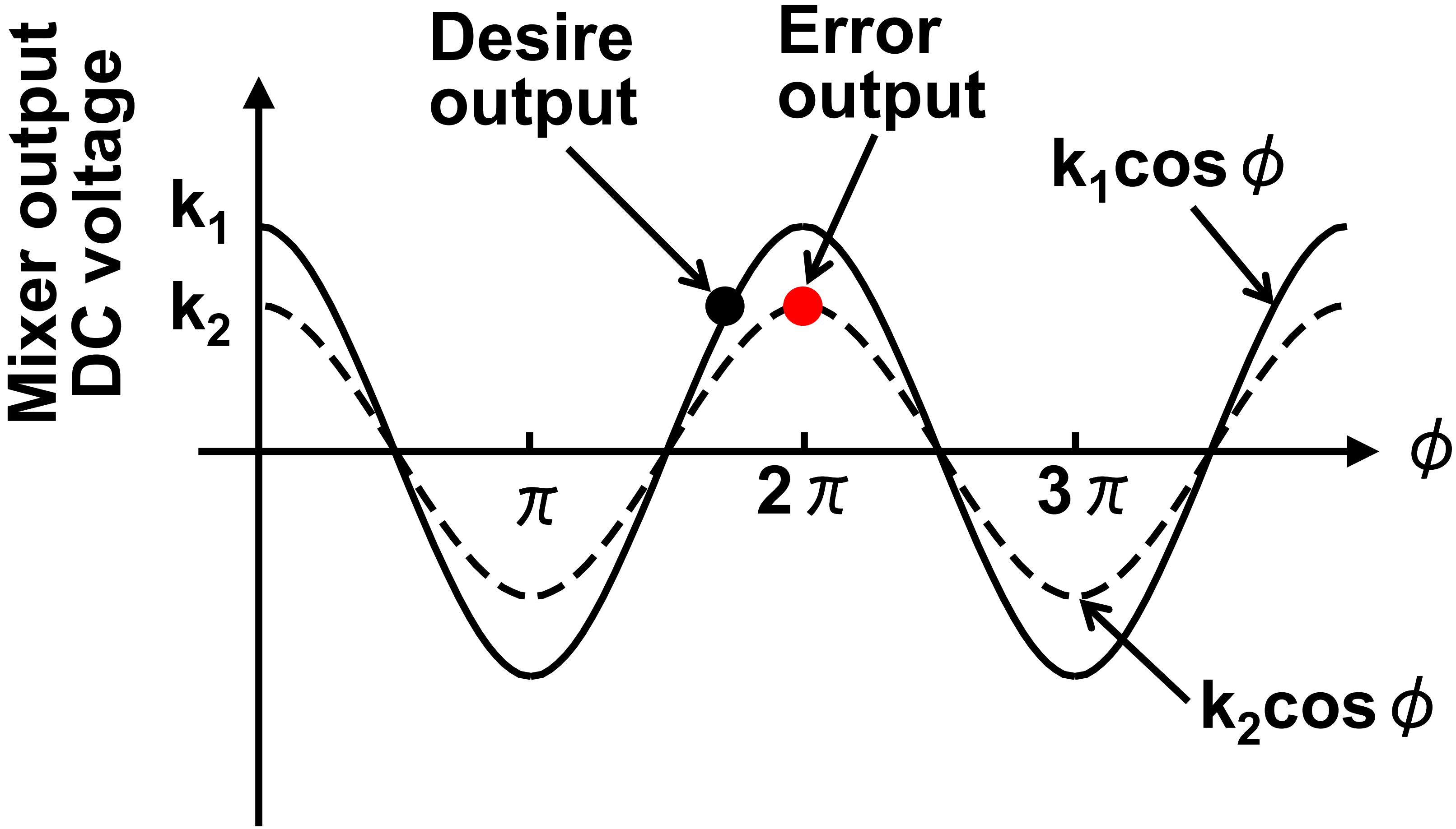
Thank you for your attention!

Phase Shifter Loss Variation

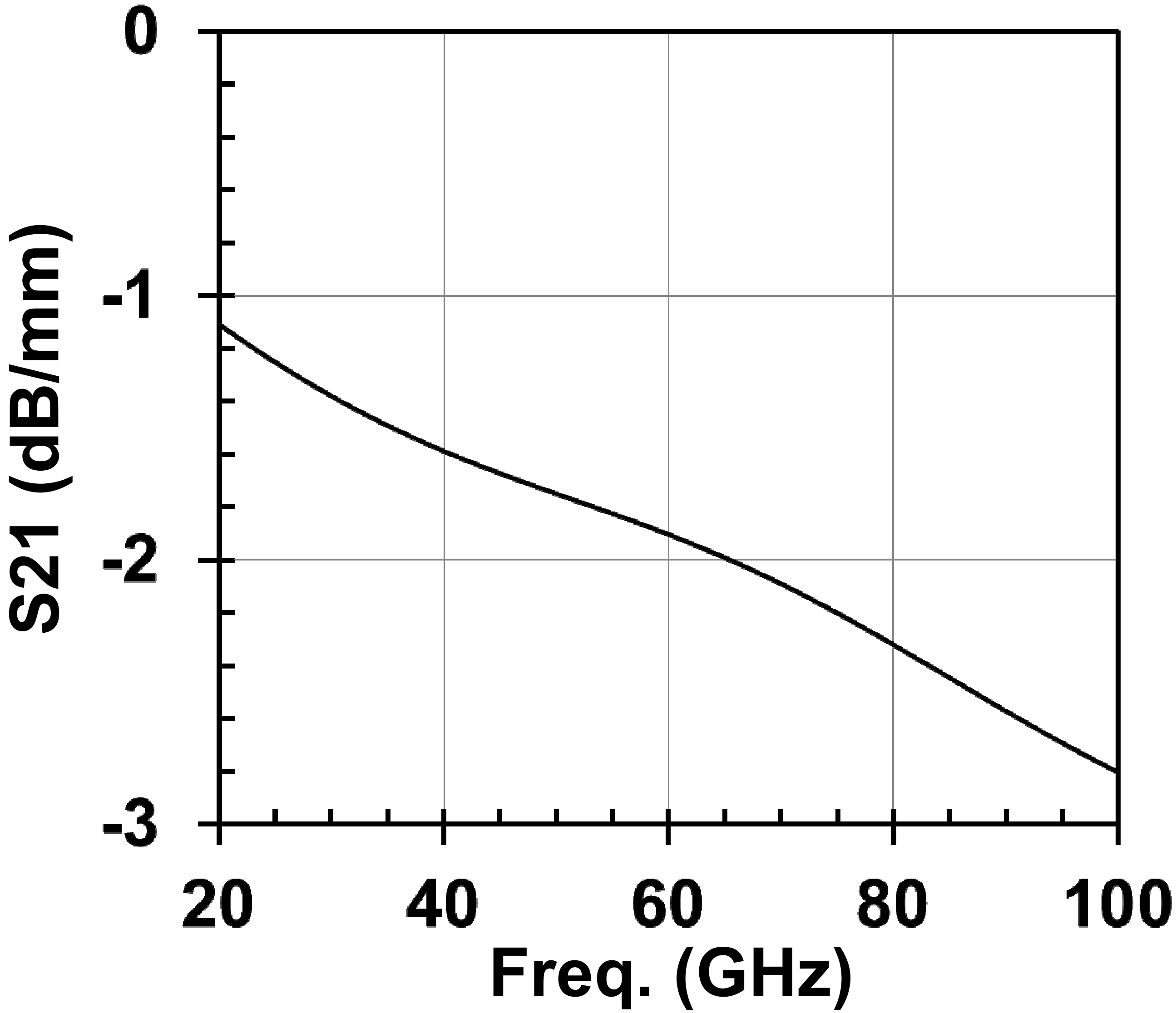


Loss Variation Issue

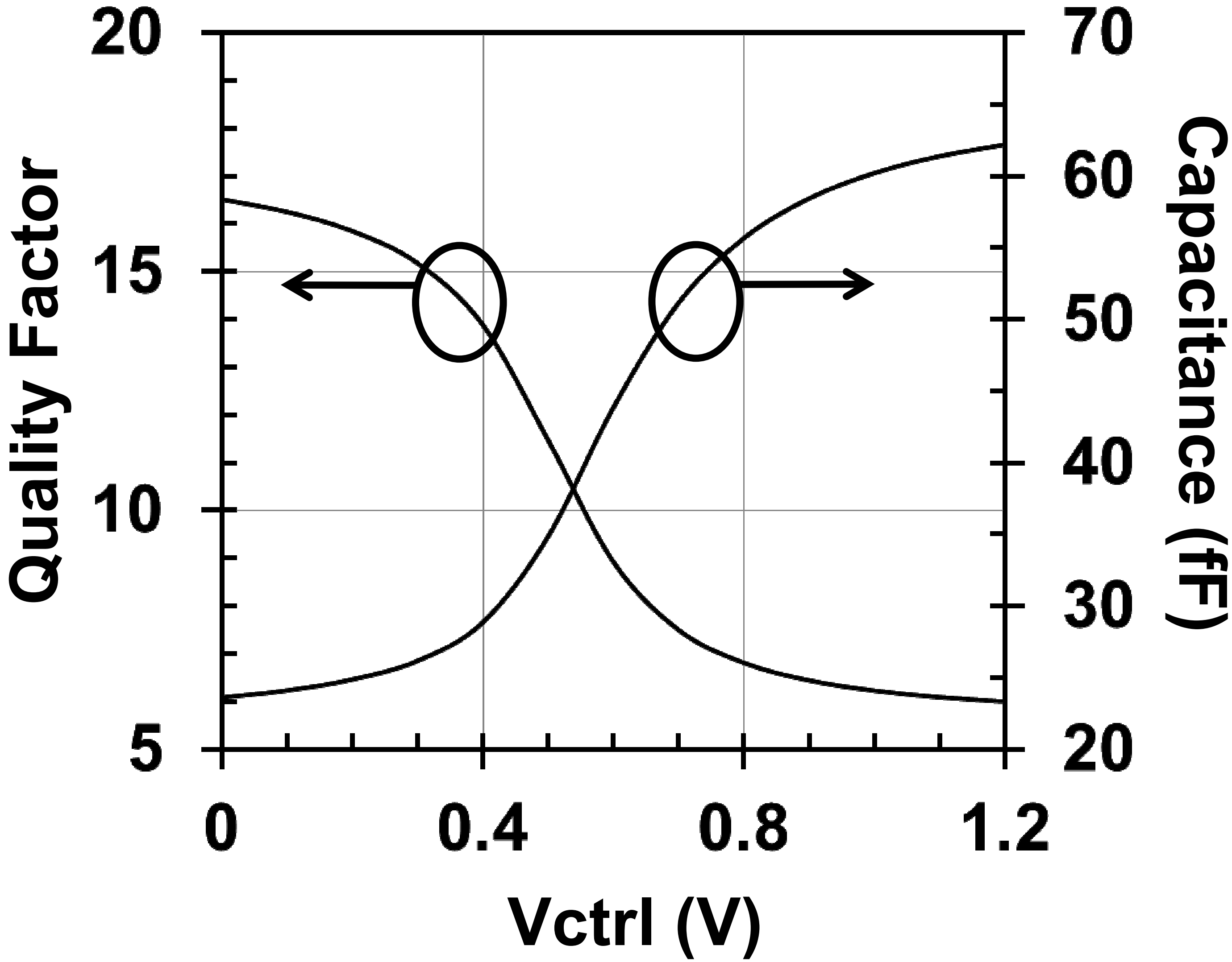
- **Calibration error**



Transmission Line Loss



Varactor Quality Factor



Attenuation Constant:

$$\alpha \propto \frac{1}{Q^2}$$

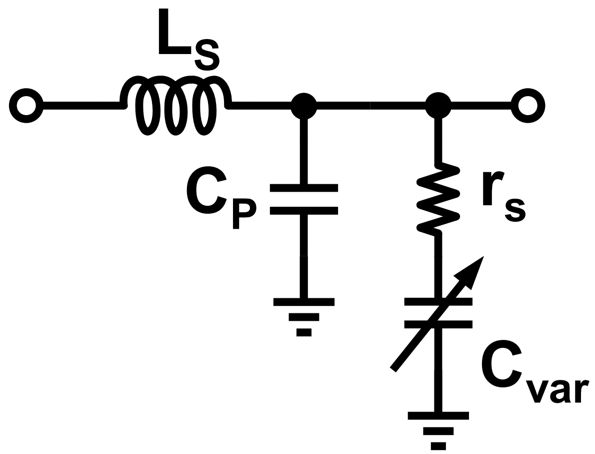
[3] A. S. Nagra et. al, TMTT 1999.

Loss from Varactor

$$\alpha = (2\pi f)\frac{L_S}{2r_s Q^2 \sqrt{1-\cos(\beta)^2}}$$

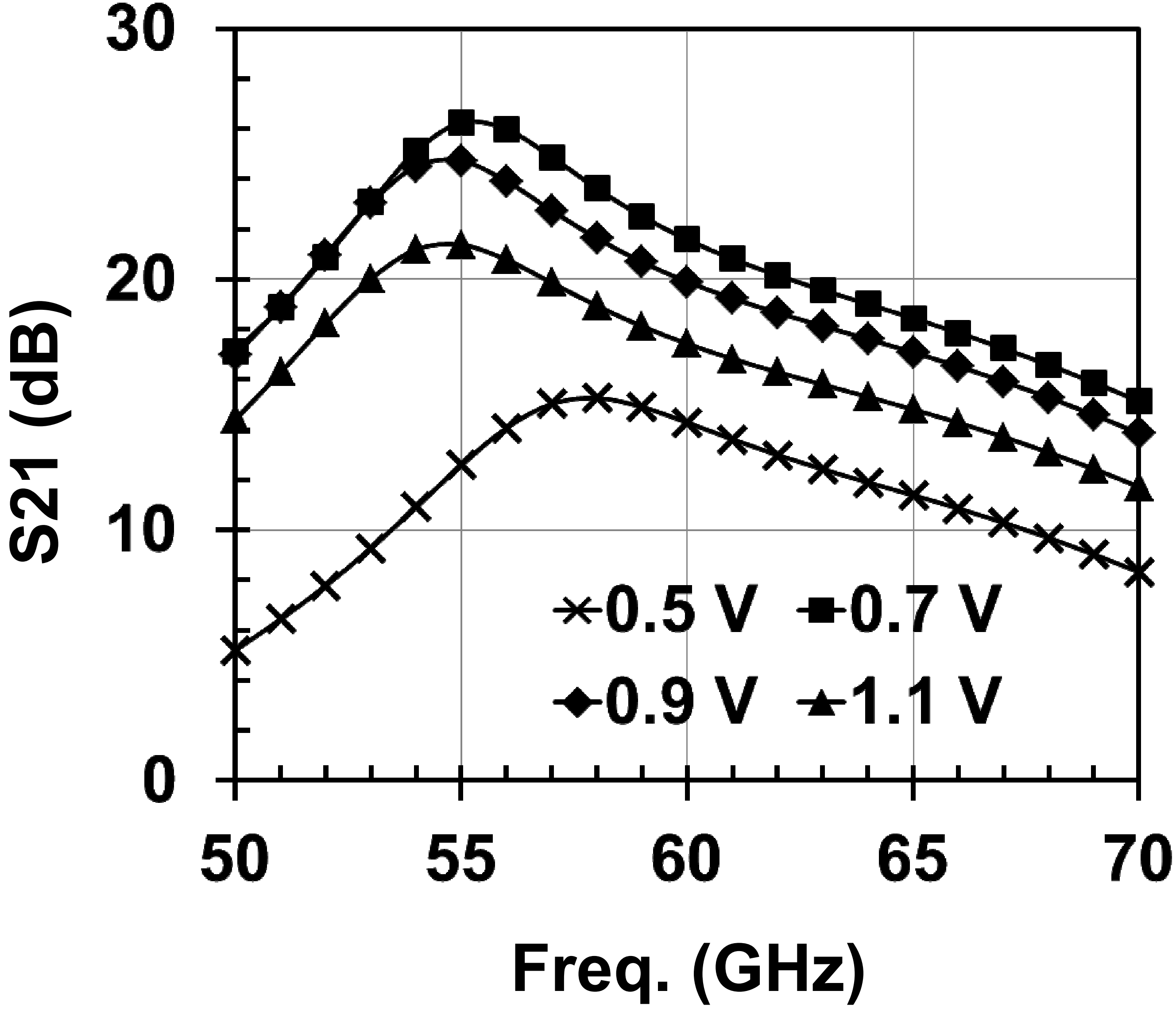
where

$$\cos(\beta) = 1-(2\pi f)^2 \frac{L_S (C_P + C_{var})}{2}$$



[3]A. S. Nagra et. al, TMTT 1999.

Variable Gain Amplifier (Sim.)



IEEE 802.15.3c

- **High Speed Interface Mode**

Data rate	EVM (dB)	EVM (%)
Up to 1.5Gb/s	-7	45%
2.1Gb/s to 2.7 Gb/s	-14	20%
2.8 Gb/s to 5.3 Gb/s	-21	9%
Above 5.4 Gb/s	-23	7%

Performance Comparison

60 GHz	[4]	[5]	[6]	This work (Aim)
EVM	9.5%	6%	12%	6%
Modulation	π/4 DQPSK	QPSK	QPSK	QPSK
Bandwidth	20 MHz	20 MHz	1 MHz	1.7 GHz
Topology	Modified Gilbert-cell	Sub-harmonic Gilbert-cell	Fundamental Reflection-type	Direct Phase Shifting
Process	CMOS	CMOS	GaAs HBT	CMOS

[4] J.-H. Tsai, TMTT 2011.

[5] J.-H. Tsai et. al, TMTT 2007.

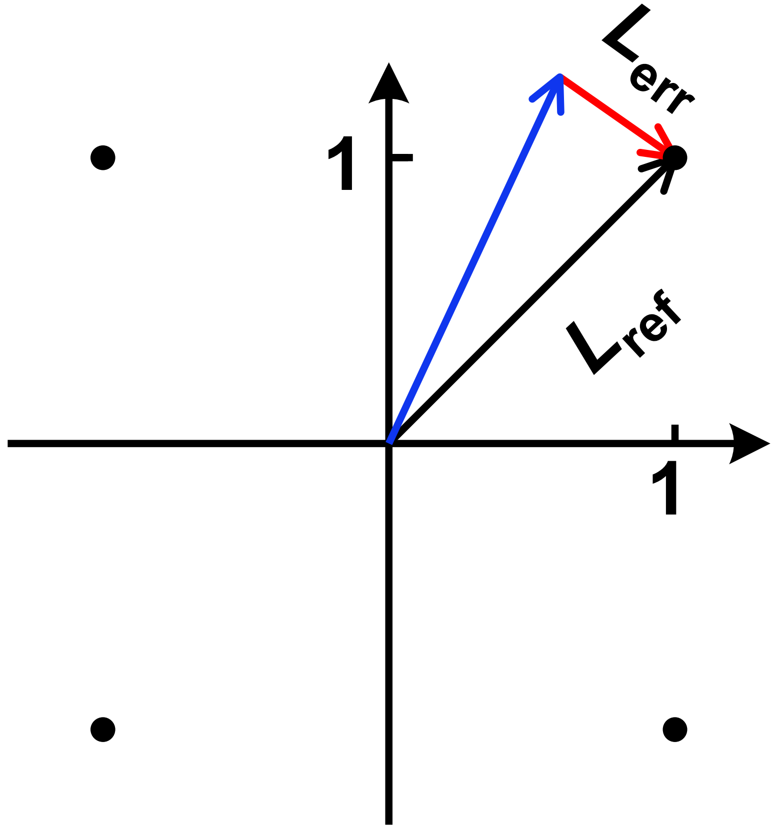
[6] H.-Y. Chang, TMTT 2004.

Direct Phase Modulation

$$EVM(\%) = \frac{L_{err}}{L_{ref}} \times 100\%$$

Phase error = 3°

***EVM*(%) ≈ 5.2%**



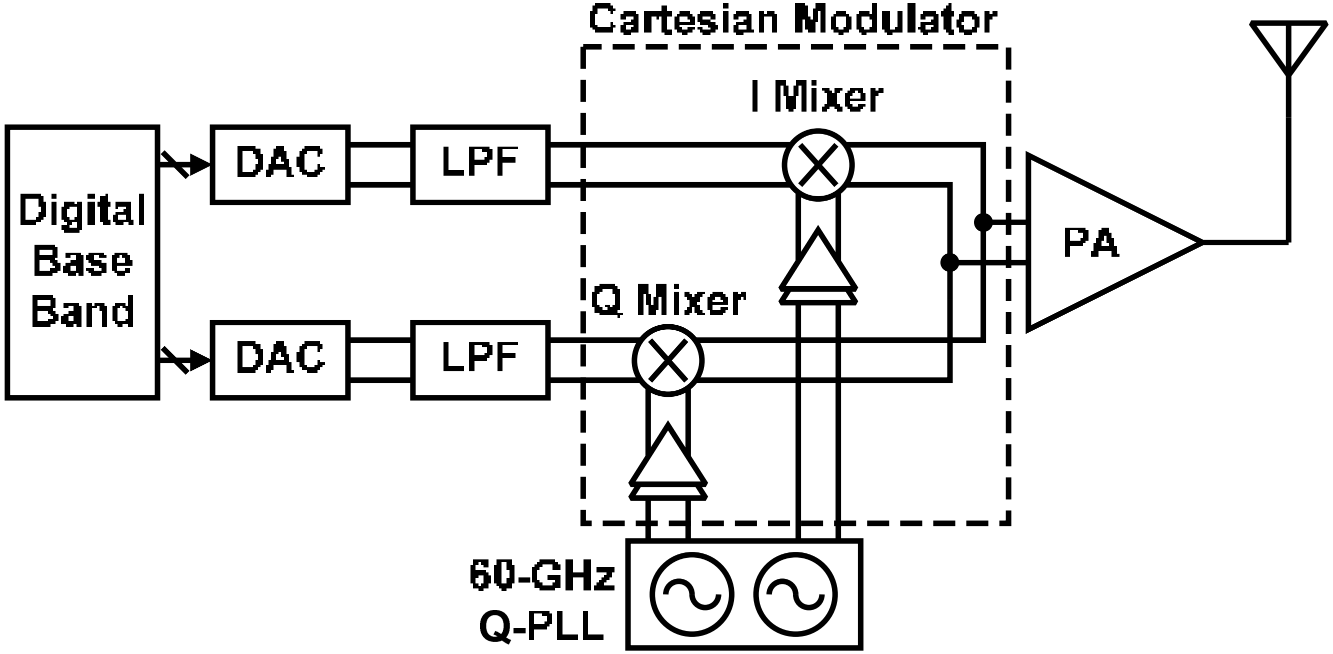
QPSK Constellation

Power Consumption

	Phase shifter	Phase inverter	Mixer + Amplitude detector
This work	0 mW	11.5 mW	7.7 mW

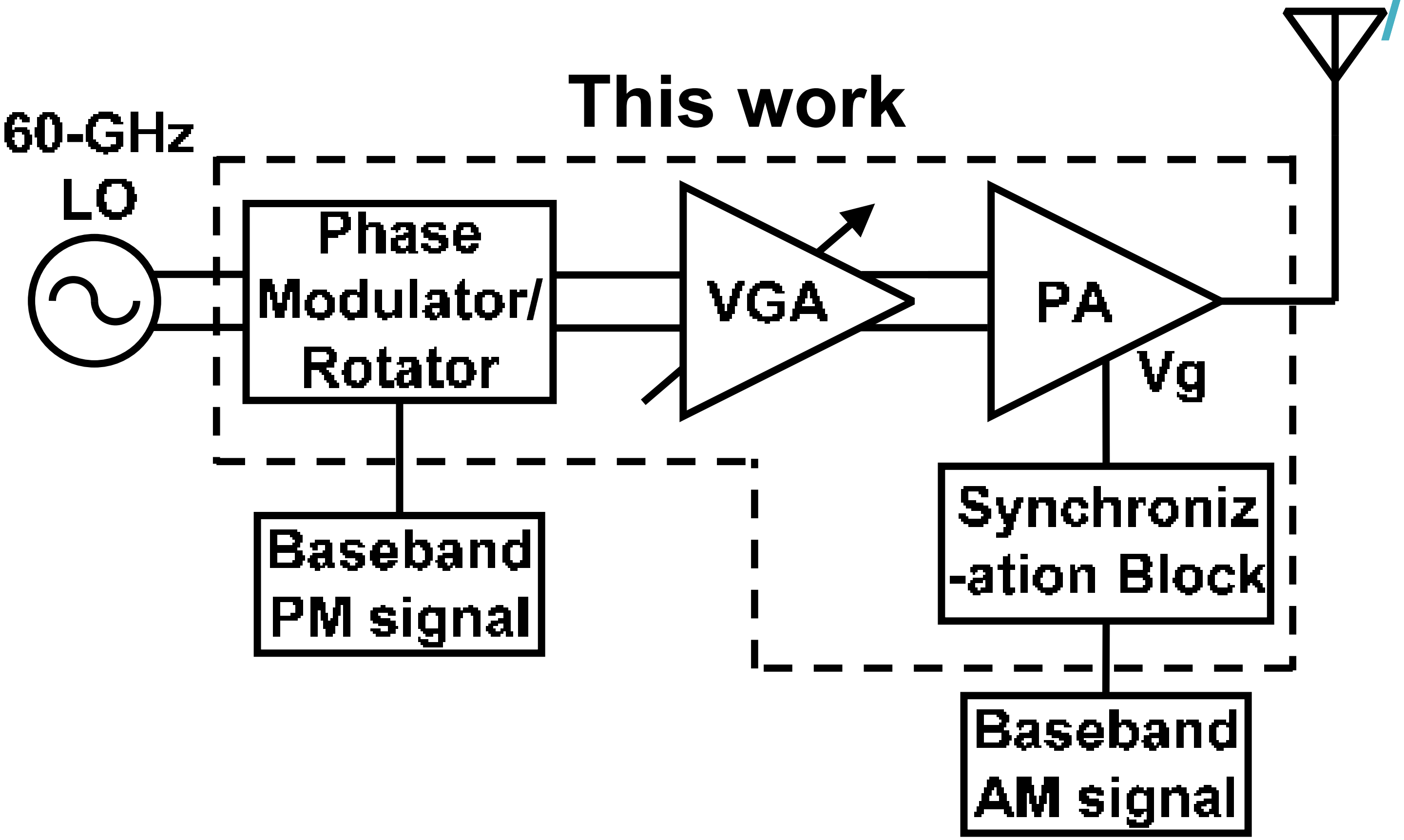
Conventional 60-GHz Transmitter

Pros	Cons
➢Small area ➢Low power consumption ➢Free of imagine frequency issue	➢High linearity PA is required ➢Low Power Added Efficiency (PAE) ➢High performance 60-GHz Q-PLL is needed



Direct-Conversion Architecture

Proposed Polar Tx Block Diagram



☺PAE can be improved for a wide output power range

☺Gate injection is suitable for wideband (several GHz) AM signal

Design Considerations for Blocks

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Blocks (state)	Design Considerations
PA (designing)	➢ Capable for wideband AM injection ➢ High peak PAE (> 15%) ➢ Saturation output power > 10 dBm
VGA (designing)	➢ Gain tuning range of 5dB~10dB ➢ Small phase shift variation with gain tuning
Phase Modulator (designing)	➢ Broadband characteristic for all ports ➢ Phase calibration capability
Synchronization Block (unsolved)	➢ Compensation for the delay difference between AM and PM signals

Phase Shifter S11 and S22