PRINCETON UNIVERSITY

Dynamic Waveform Shaping for Reconfigurable Radiated Periodic Signal Generation with Picosecond Time-width

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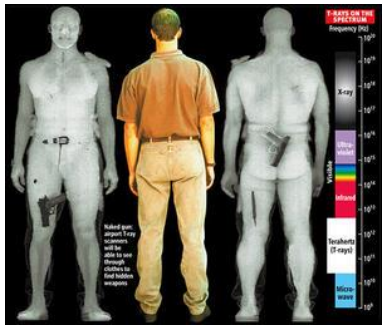
Outline

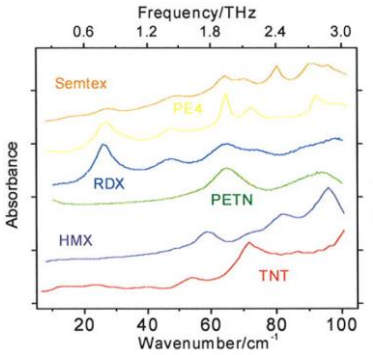
- Motivation and Background
- Architecture
- Circuit Blocks and Details
- Measurement
- Conclusions

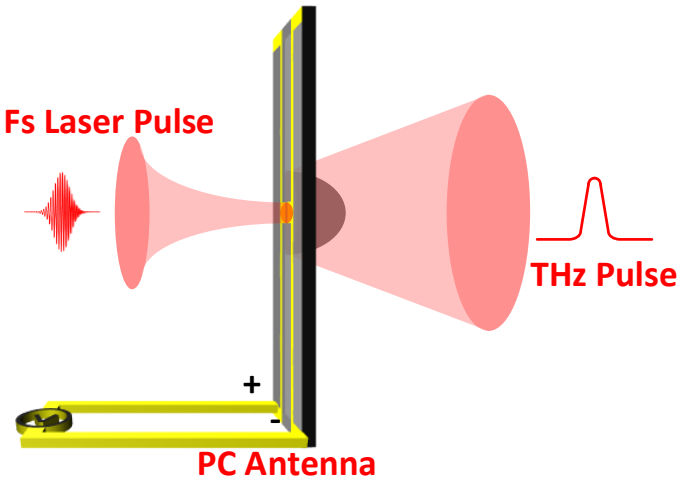
Picosecond Time-signatures

- **Applications:**
  - **High resolution imaging**
  - **Spectroscopy**
- **Generation:**
  - **Optical solution**
    - **Bulky and expensive**
    - **Low integration level**

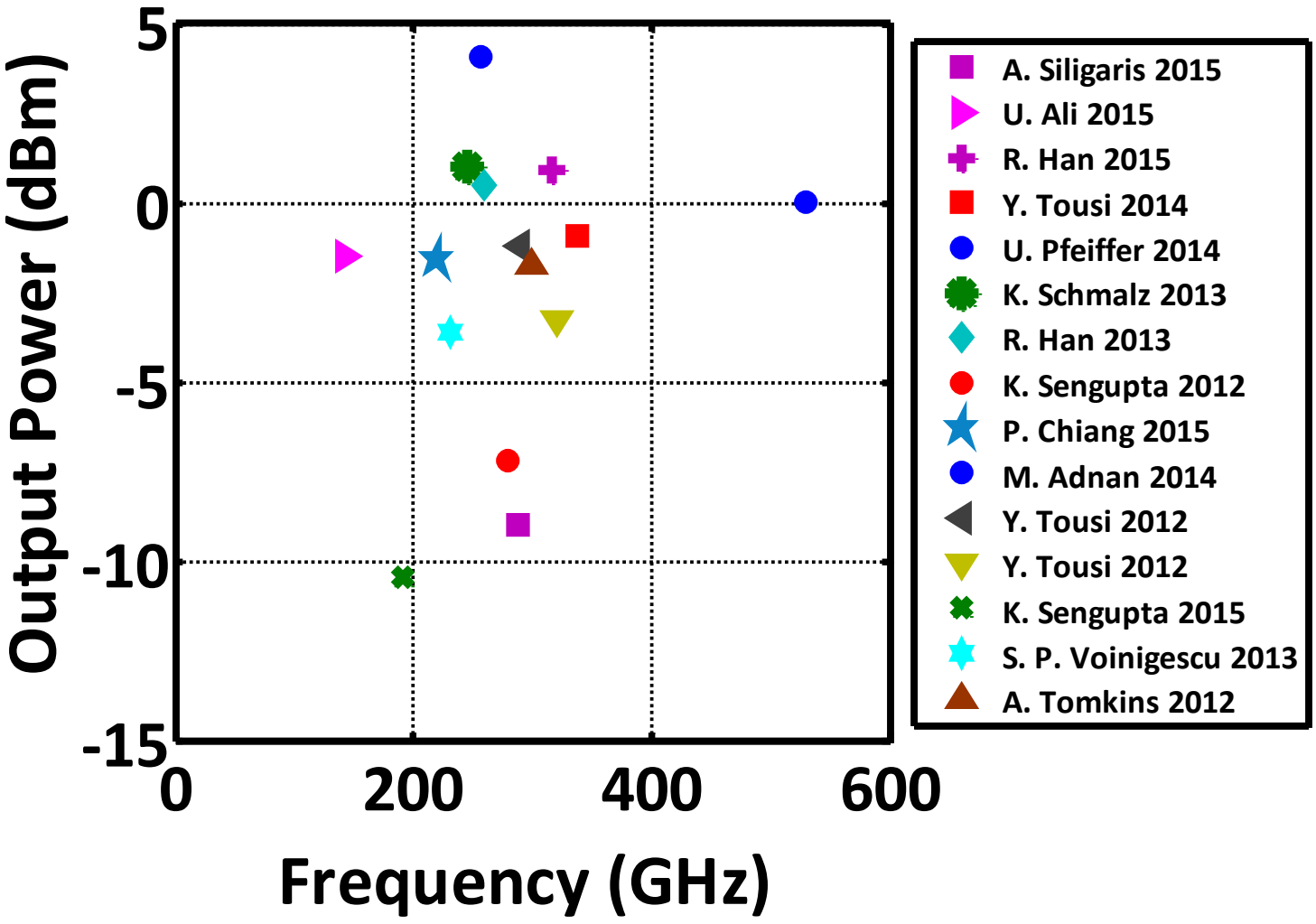


Terahertz scanner imagery // Source: dailymail.co.uk





Silicon-based Integrated Technology



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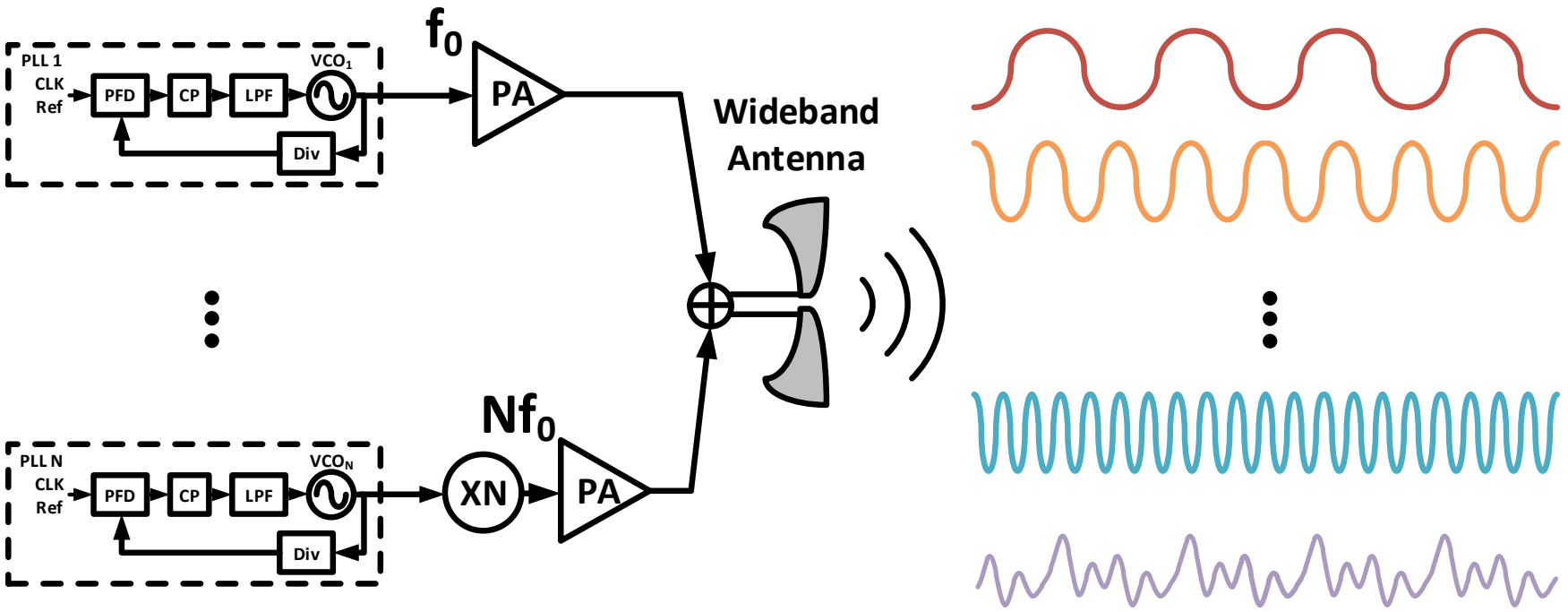
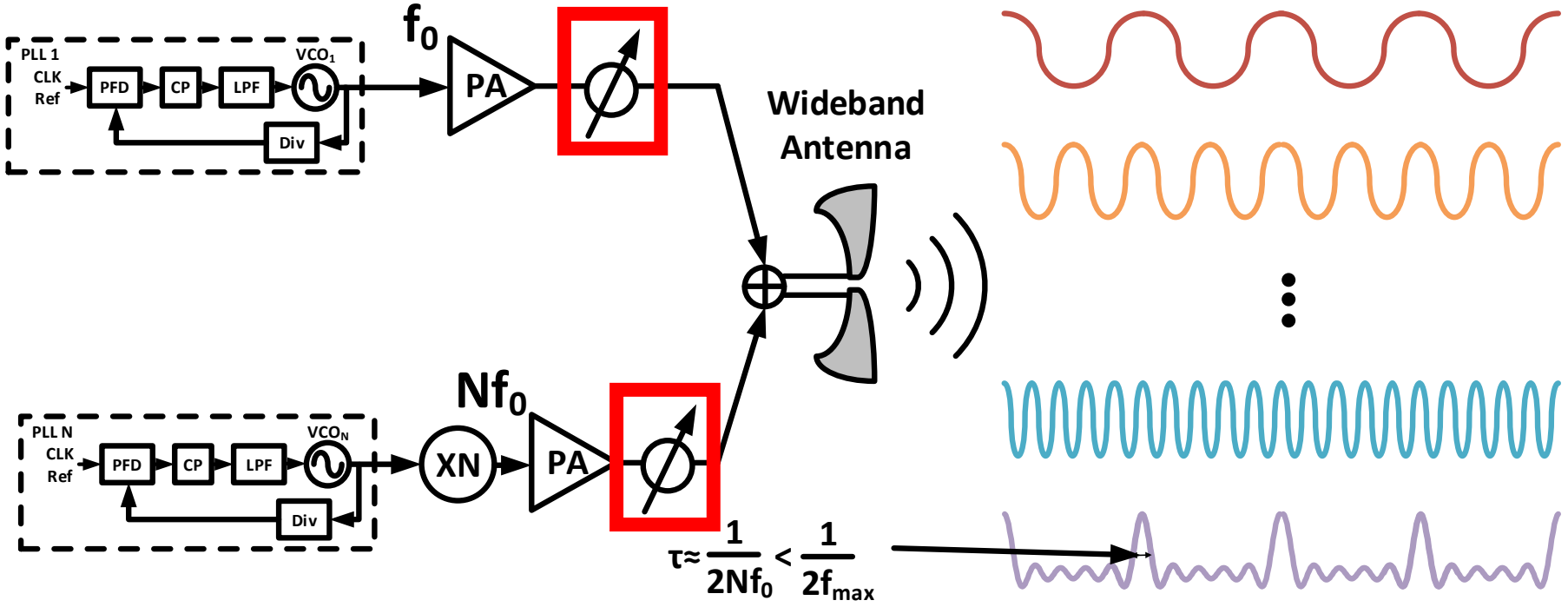
Waveform Synthesis (Harmonic Combining)



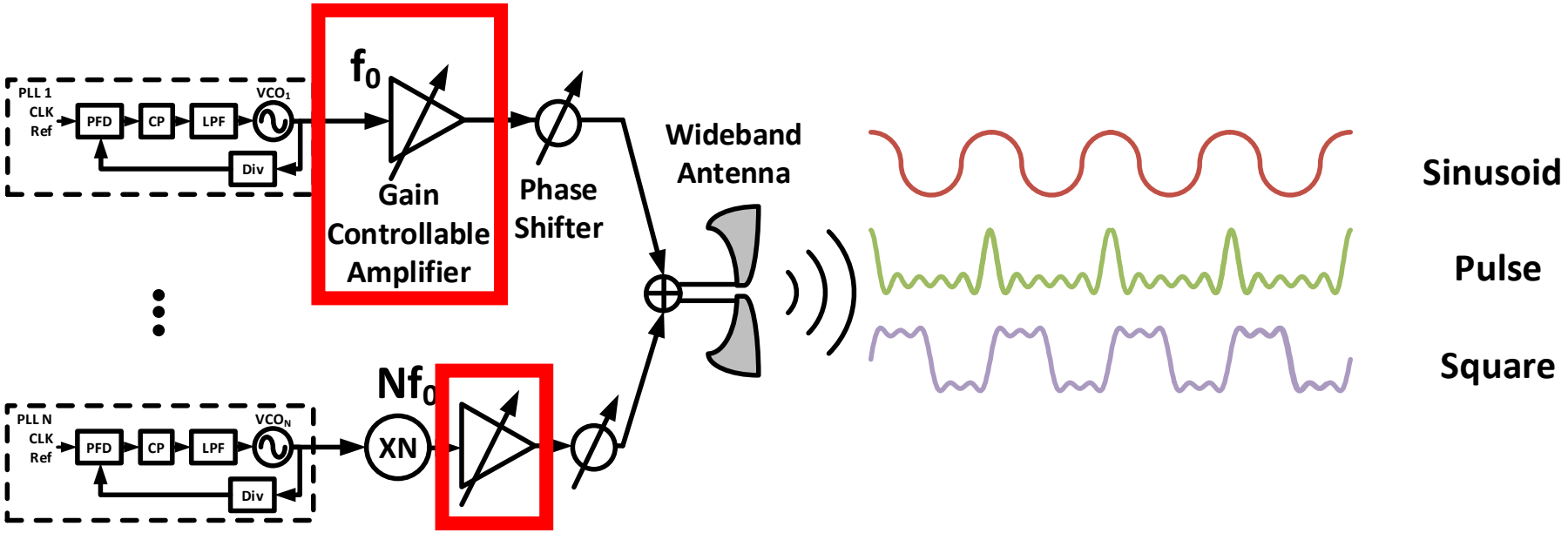
- Combine frequency synthesizers from f_0 up to Nf_0
- Same amplitude but random phases
- Power is distributed uniformly across time

Waveform Synthesis (Harmonic Combining)



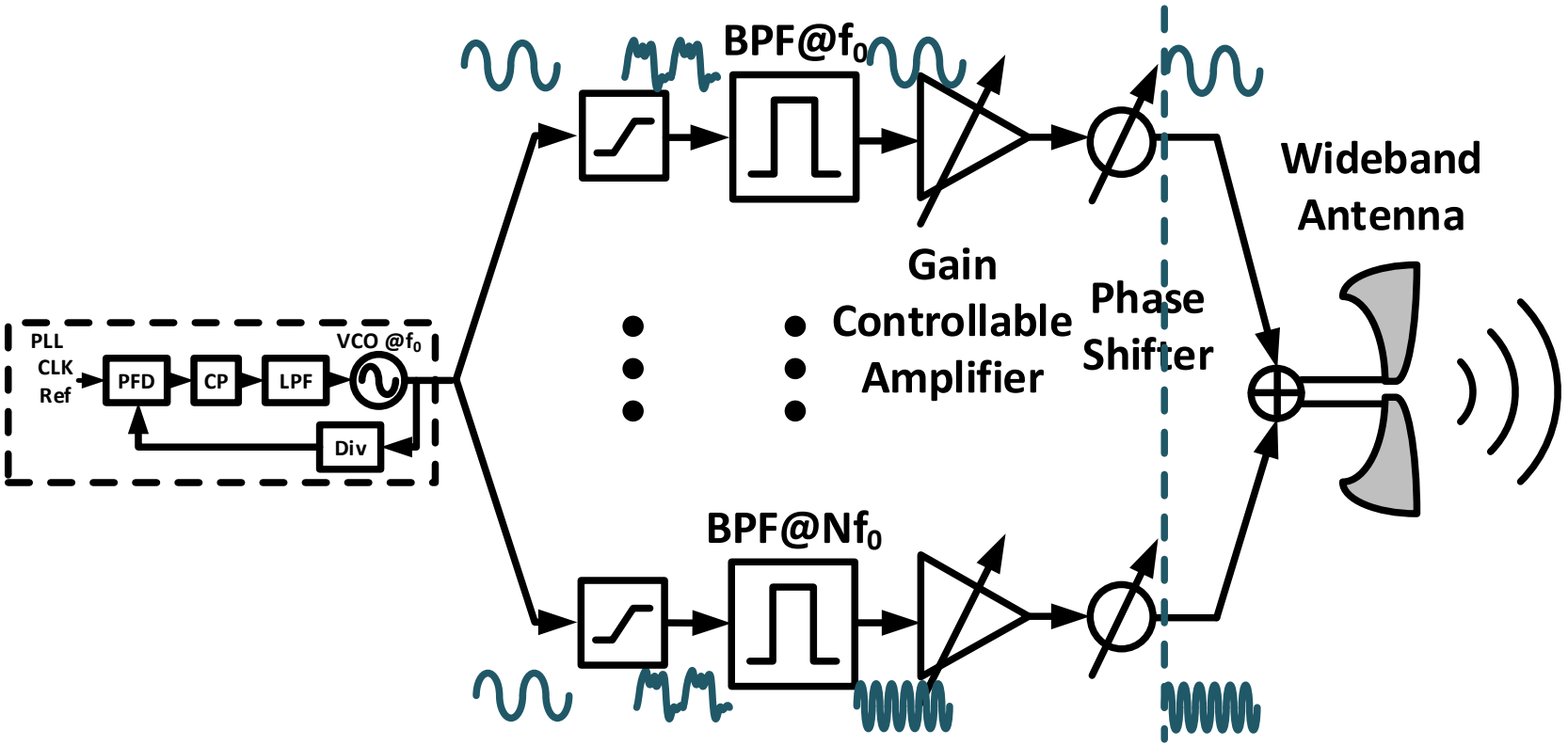
- Align phases of harmonics
- Bursts of energy in form of pulse train appear
- Pulse width is comparable to half of the period of the highest harmonic

Waveform Synthesis (Harmonic Combining)



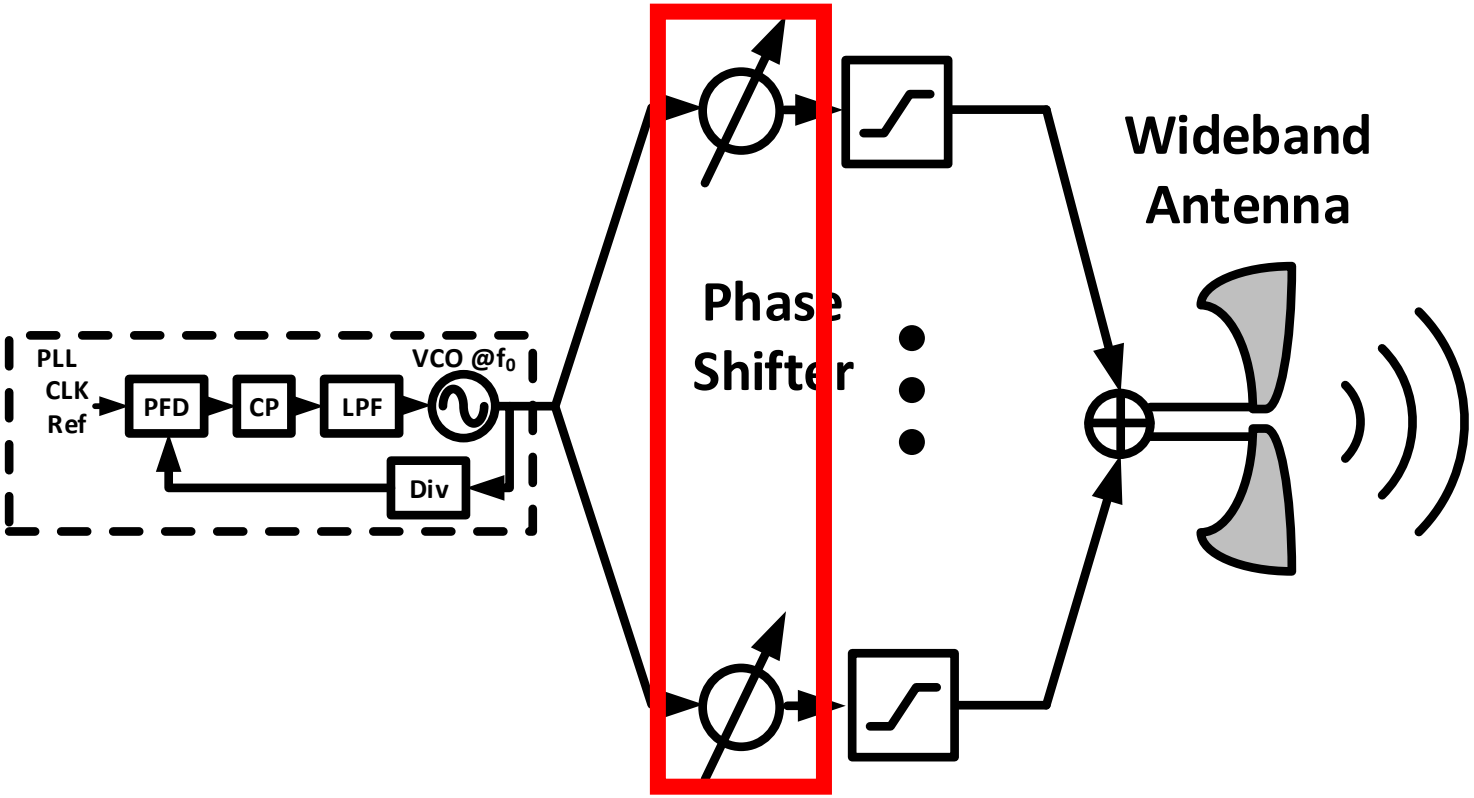
- Amplitude & phase controls above f_{max} are inefficient.
- Combiner with flat gain and group delay are difficult to achieve.

Waveform Synthesis (Exploit Nonlinearity)



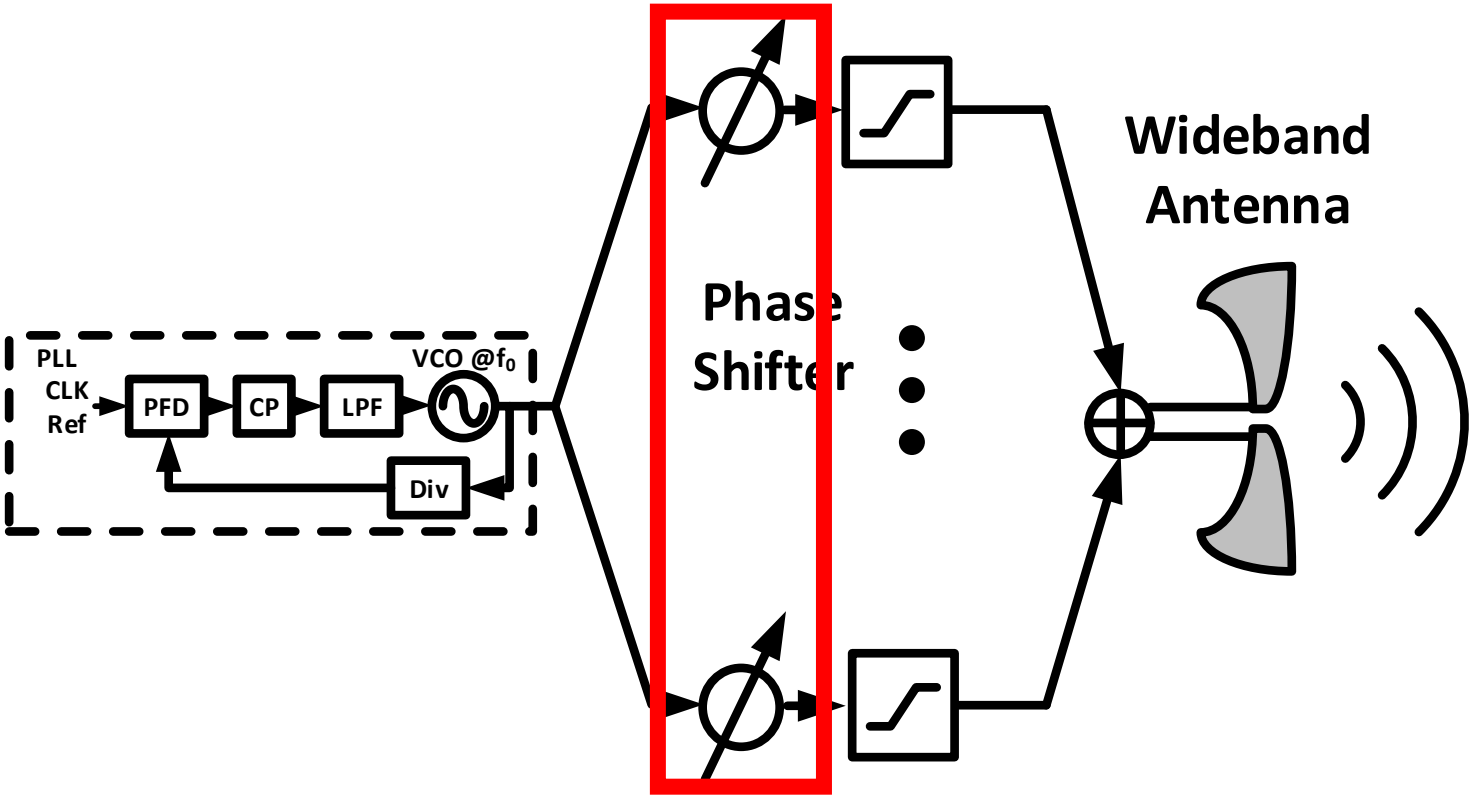
- Filtering harmonics at such high frequencies is very lossy and inefficient.
- Amplitude and phase controls are inefficient
- Combiner with flat gain and group delay are difficult to achieve.

Simultaneous Amplitude and Phase Control



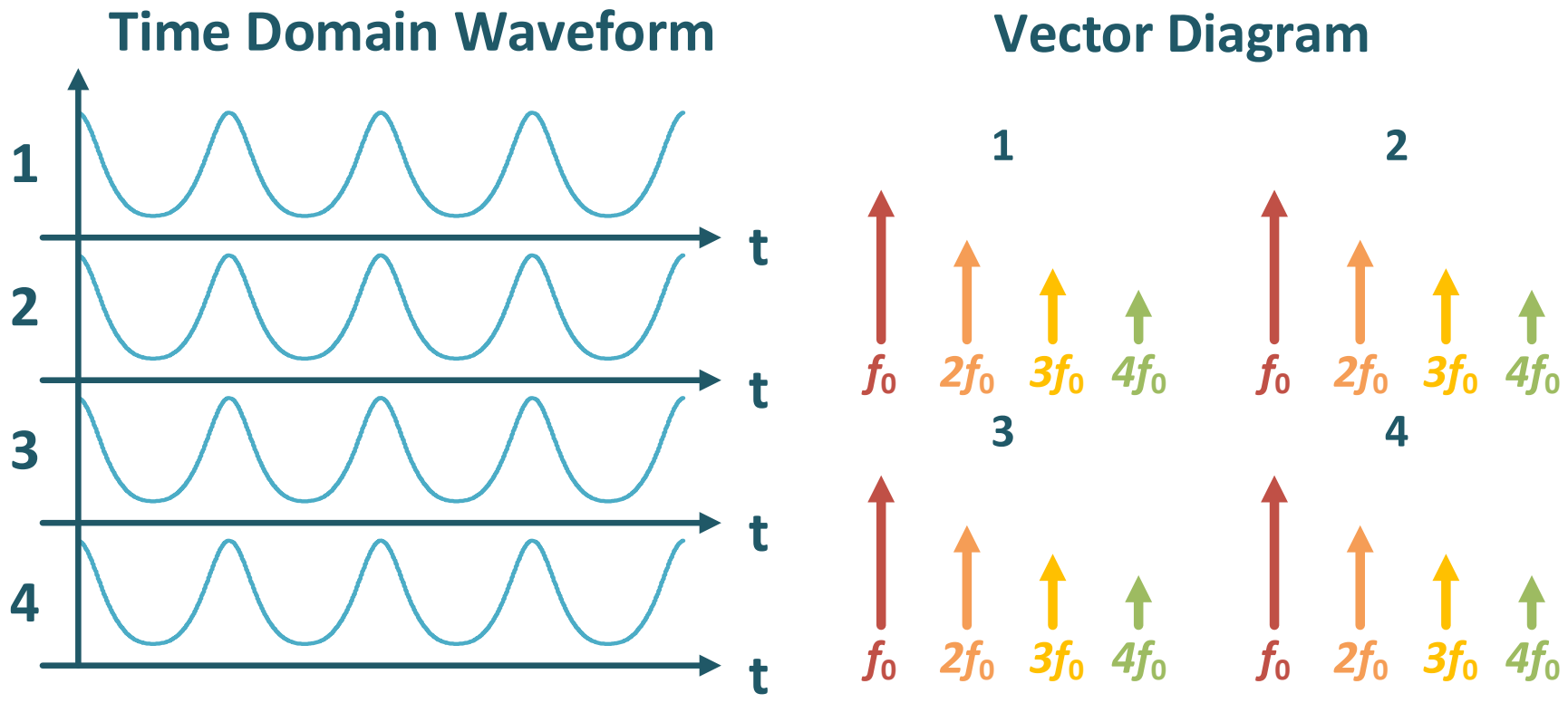
- Remove inefficient filtering
- Remove necessity of gain controllable amplifier
- Move the phase shifter before the nonlinear block

Simultaneous Amplitude and Phase Control

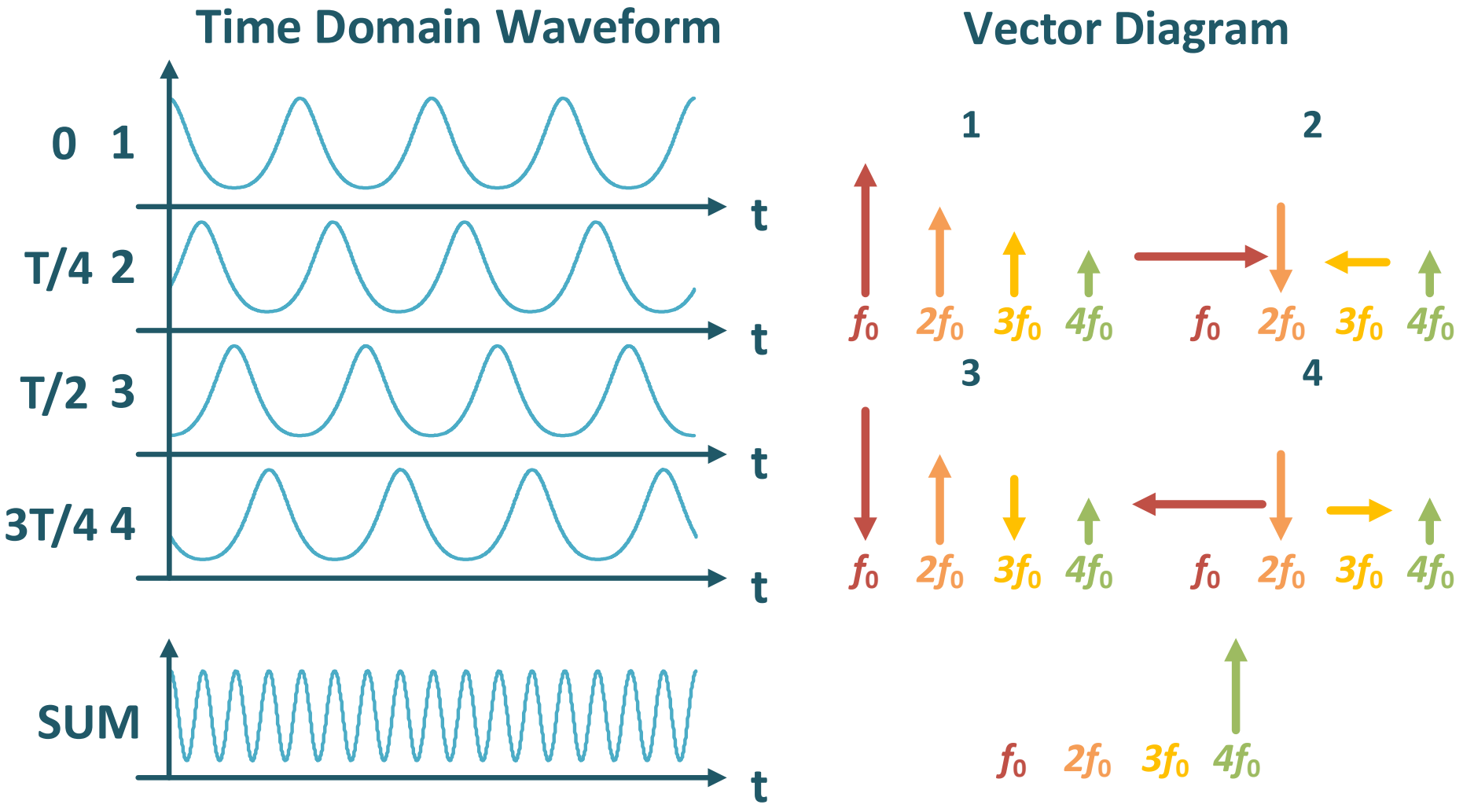


- Achieve simultaneous amplitude and phase control
- Phase shifters operate at f_0 before the nonlinear device
- Scalable both in power and frequency

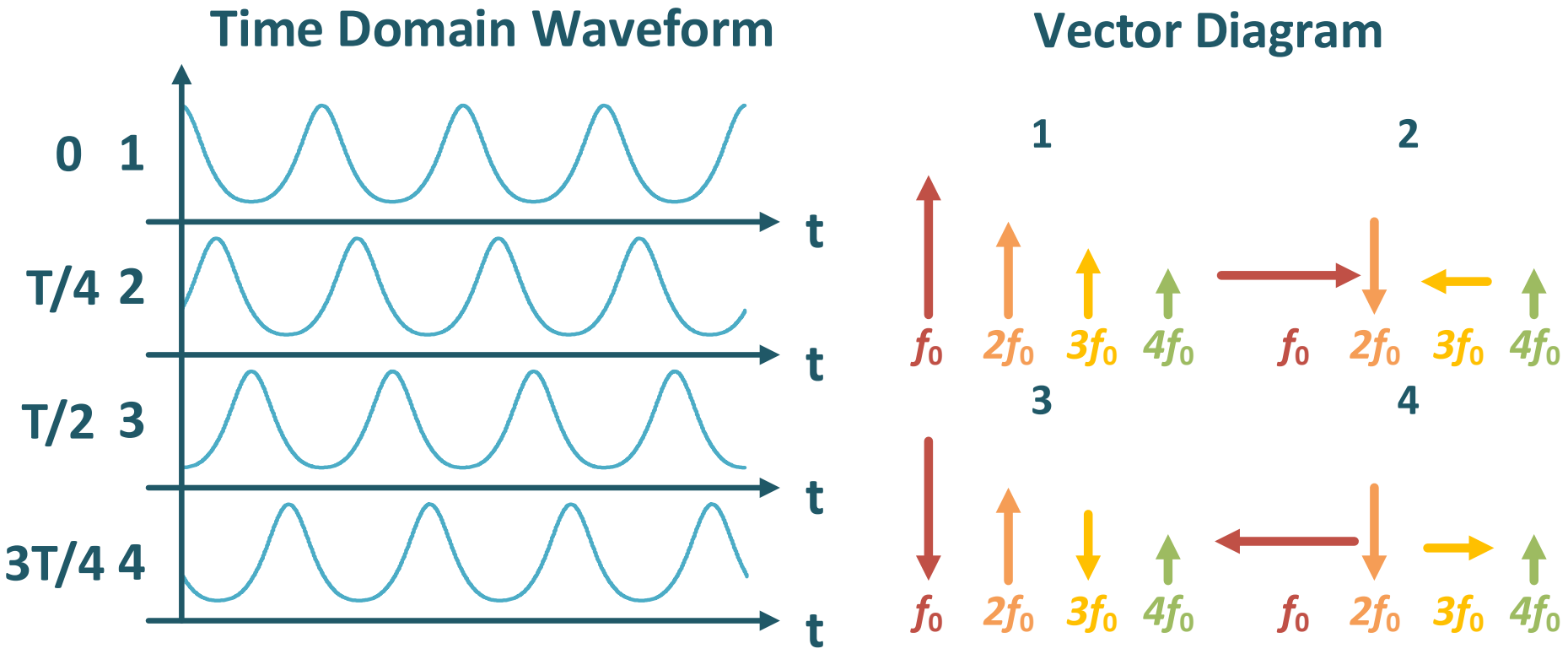
Reconfigurable Waveform Synthesis



Reconfigurable Waveform Synthesis

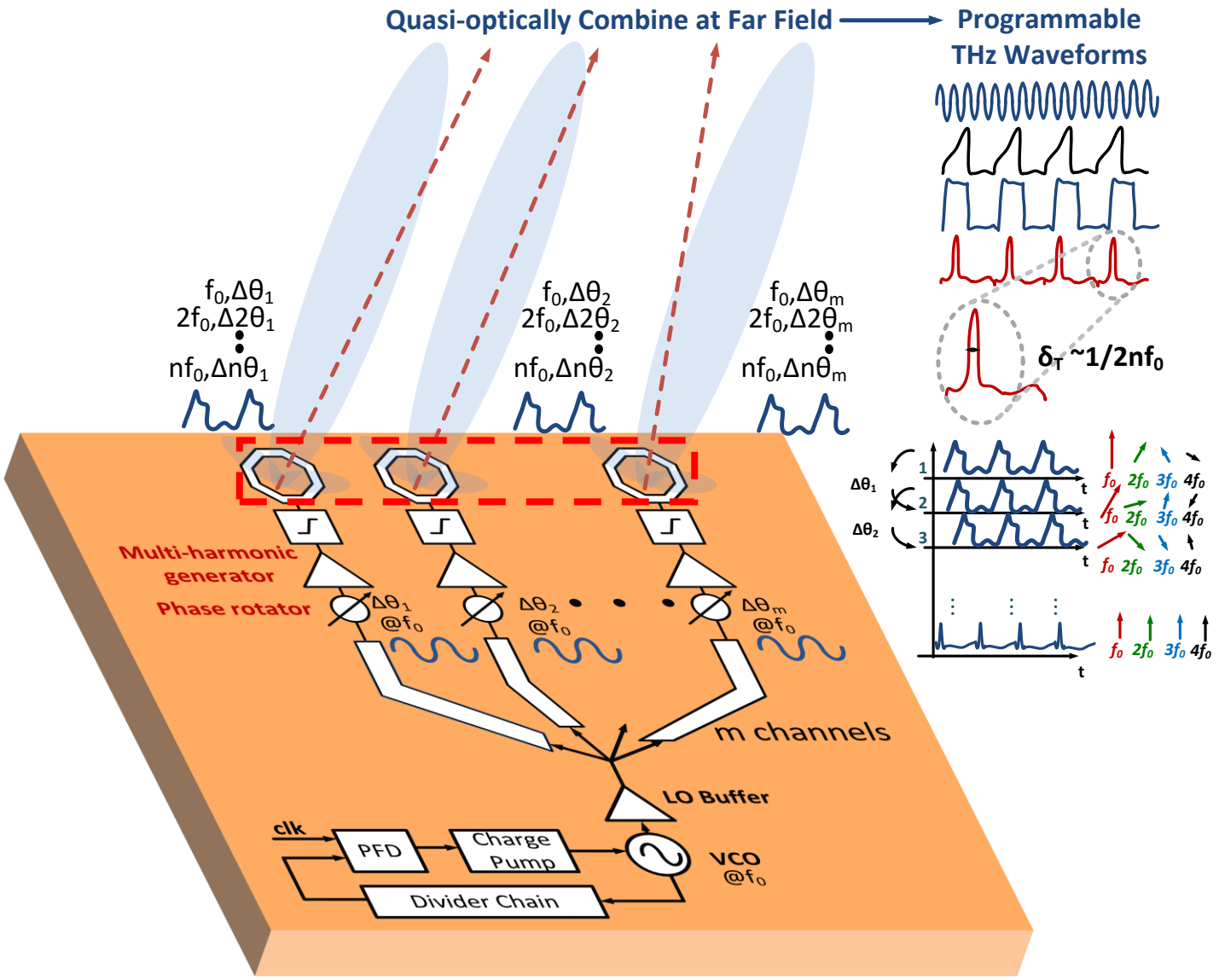


Reconfigurable Waveform Synthesis



- **The amplitudes of all the harmonic components are controlled by only controlling the phases at f_0.**

Quasi-Optical Waveform Synthesis



Architecture Analysis (Harmonic Generation)

Harmonic components

$\alpha_1 e^{j\phi_1}$

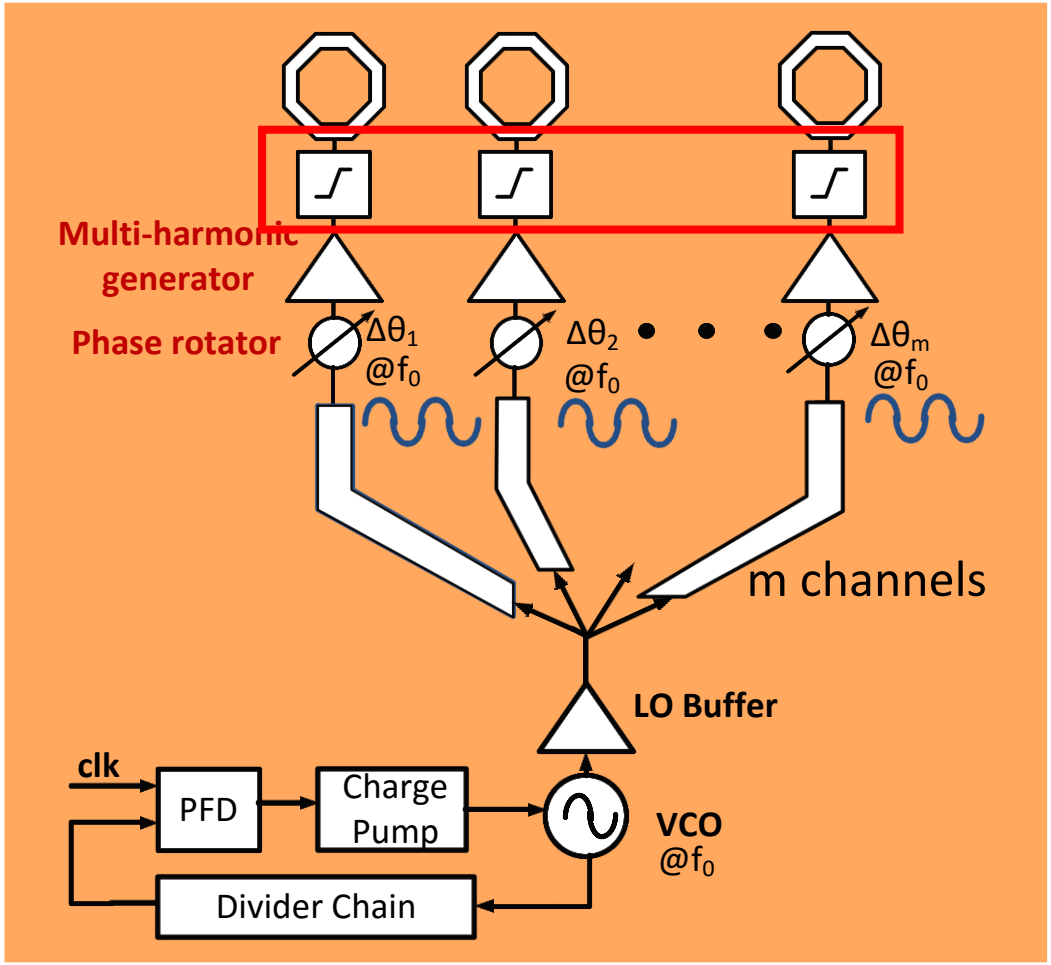
$\alpha_2 e^{j\phi_2}$

...

$\alpha_N e^{j\phi_N}$

$\alpha_i \rightarrow$ **Amplitude of ith harmonic**

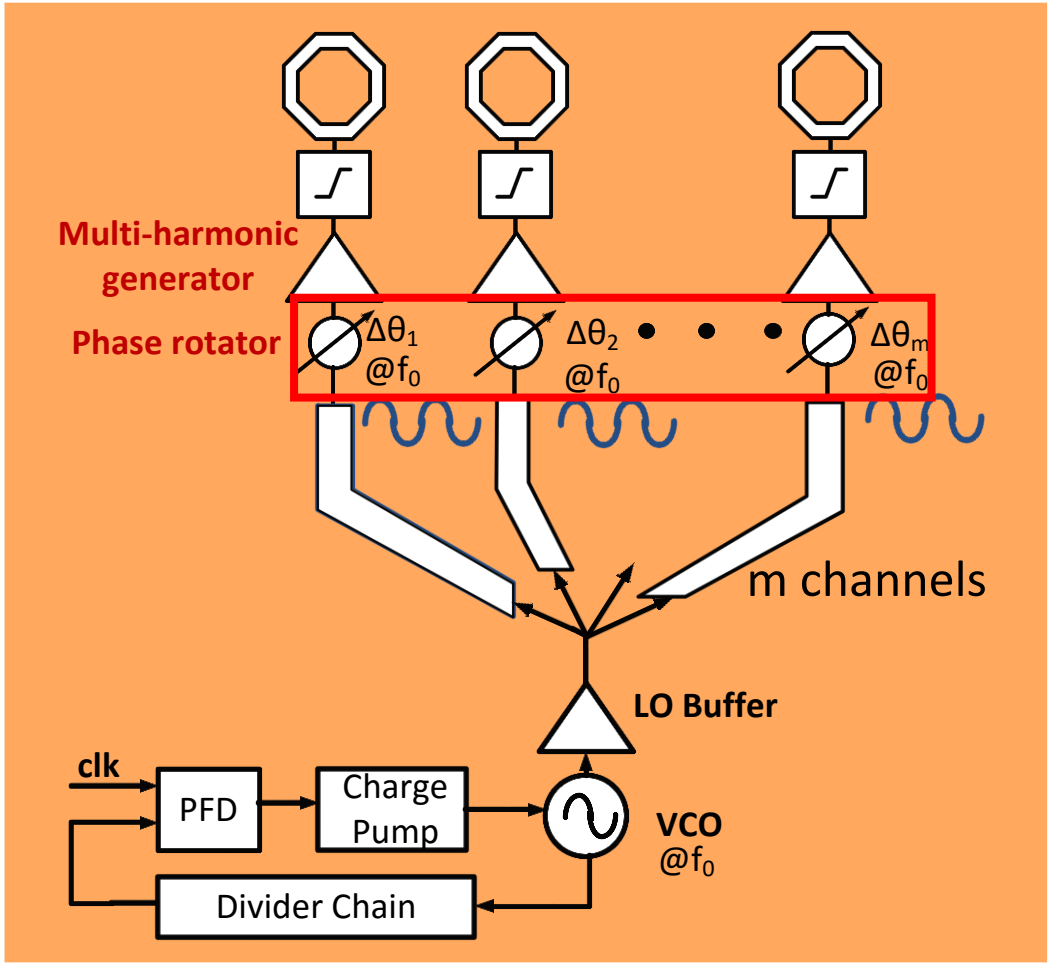
$\phi_i \rightarrow$ **Phase of ith harmonic**



Architecture Analysis (Phase Rotation)

Phase Control in m Channels

1st Channel		m th Channel
$\alpha_1 e^{j(\phi_1+\Delta\theta_1)}$	…	$\alpha_1 e^{j(\phi_1+\Delta\theta_m)}$
$\alpha_2 e^{j(\phi_2+2\Delta\theta_1)}$	…	$\alpha_2 e^{j(\phi_2+2\Delta\theta_m)}$
…		
$\alpha_N e^{j(\phi_N+N\Delta\theta_1)}$	…	$\alpha_N e^{j(\phi_N+N\Delta\theta_m)}$



$\Delta\theta_k$ → **Phase shift at f_0 in k th channel**

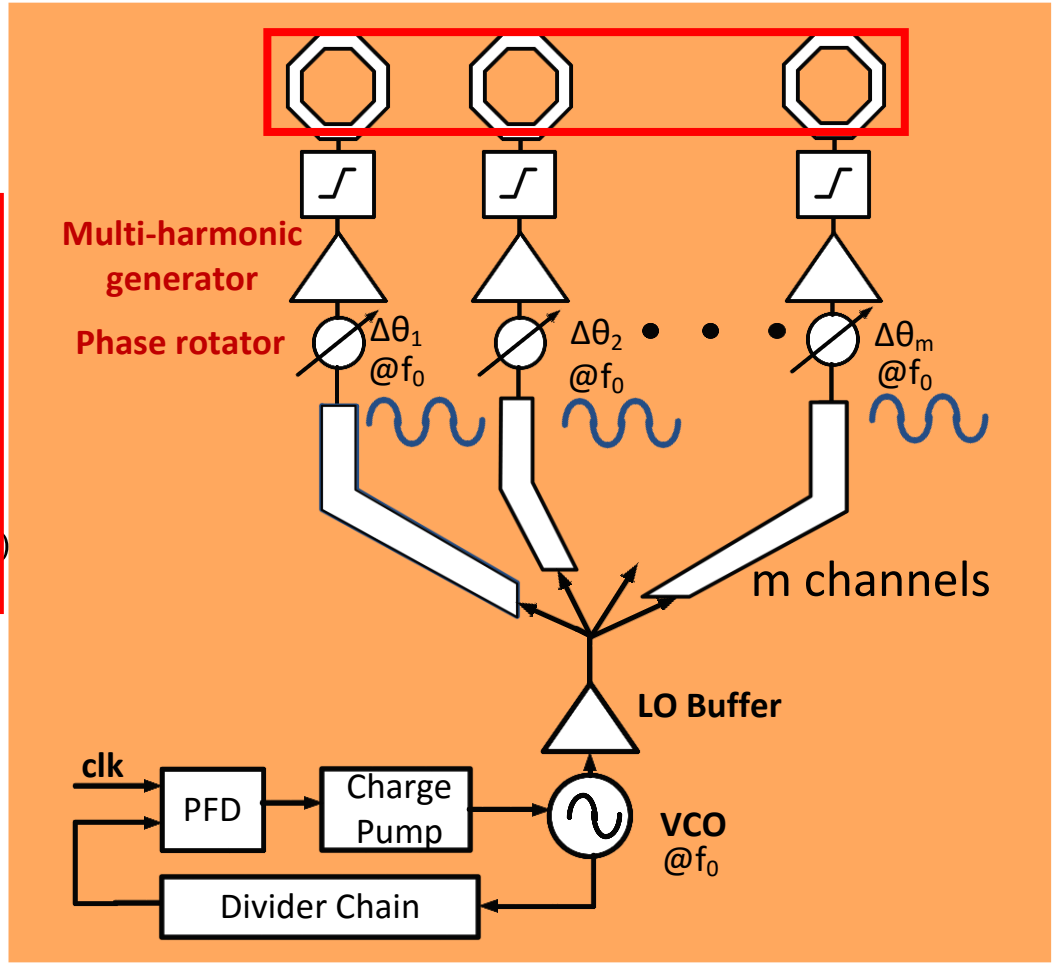
$i\Delta\theta_k$ → **Phase shift at if_0 in k th channel**

Architecture Analysis (Antenna)

Phase Control in m Channels

1st Channel **mth Channel**

$$\begin{matrix} E_1 e^{j(\phi_1+\Delta\theta_1+\psi_1)} & +\cdots & E_1 e^{j(\phi_1+\Delta\theta_m+\psi_1)} \\ E_2 e^{j(\phi_2+2\Delta\theta_1+\psi_2)} & +\cdots & E_2 e^{j(\phi_2+2\Delta\theta_m+\psi_2)} \\ \cdots & & \\ E_N e^{j(\phi_N+N\Delta\theta_1+\psi_N)} & +\cdots & E_N e^{j(\phi_N+N\Delta\theta_m+\psi_N)} \end{matrix}$$



$\psi_i \rightarrow$ **Phase shift at *if*$_0$ induced by antenna**

$E_i \rightarrow$ **Scaled amplitude at *if*$_0$ after radiation**

Number of Channels Required

	Desirable Signal		1st Channel		mth Channel
1st Harmonic	$A_1 e^{j\theta_1}$	$=$	$E_1\, e^{\mathrm{j}(\phi_1+\Delta\theta_1+\psi_1)}$	$+ \cdots$	$E_1\, e^{\mathrm{j}(\phi_1+\Delta\theta_m+\psi_1)}$
2nd Harmonic	$A_2 e^{j\theta_2}$	$=$	$E_2\, e^{\mathrm{j}(\phi_2+2\Delta\theta_1+\psi_2)}$	$+ \cdots$	$E_2 e^{\mathrm{j}(\phi_2+2\Delta\theta_m+\psi_2)}$
	...				
Nth Harmonic	$A_N e^{j\theta_N}$	$=$	$E_N\, e^{\mathrm{j}(\phi_N+N\Delta\theta_1+\psi_N)}$	$+ \cdots$	$E_N e^{\mathrm{j}(\phi_N+N\Delta\theta_m+\psi_N)}$

$A_i, \theta_i \rightarrow$ **Amplitude and phase of ith harmonic in desirable signal**

- **If m=2N, it is possible to arrive at a solution for $\Delta\theta_i$ for any desirable (A_i, θ_i).**

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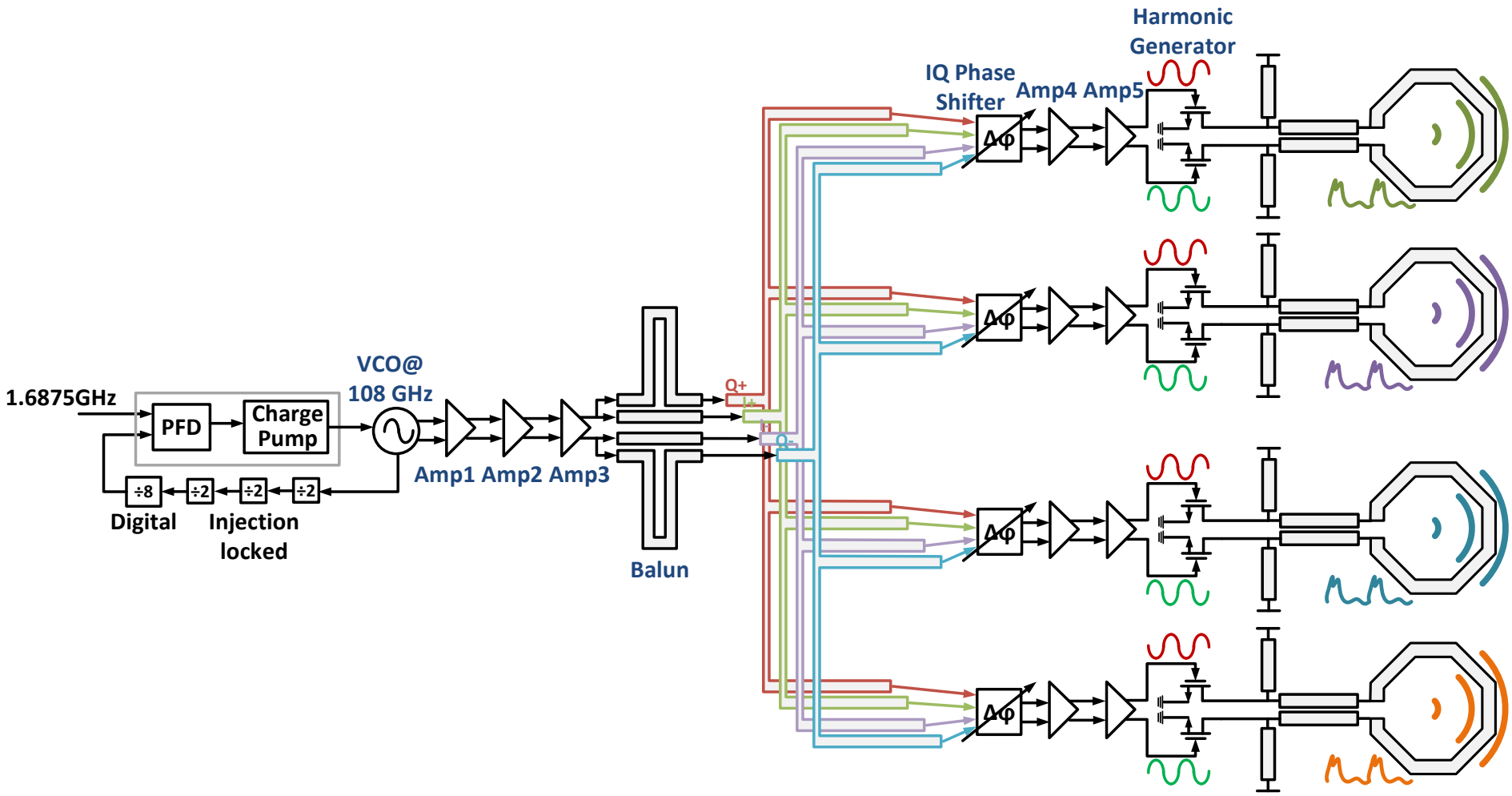
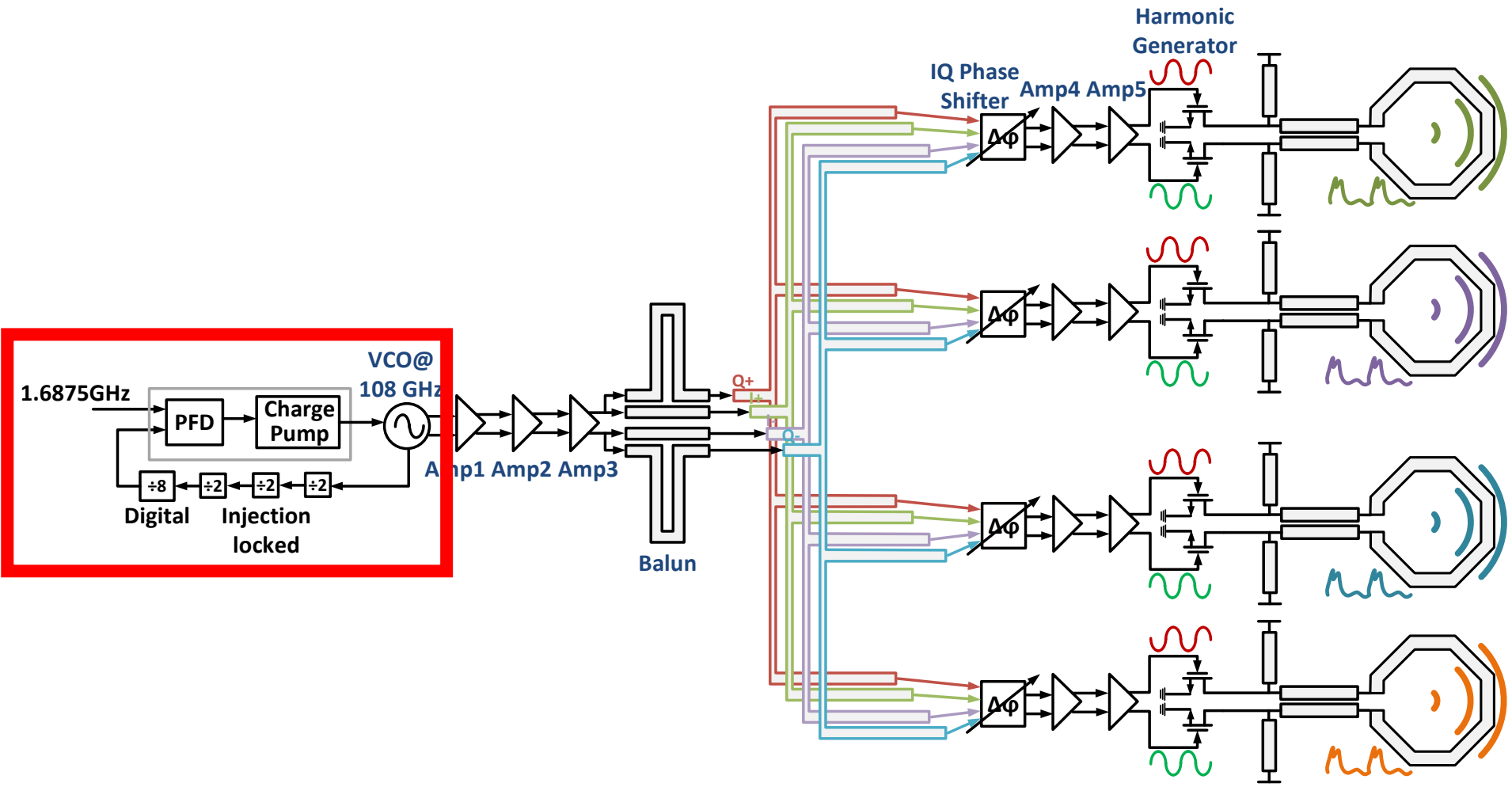
Reconfigurable Periodic Waveform Radiator

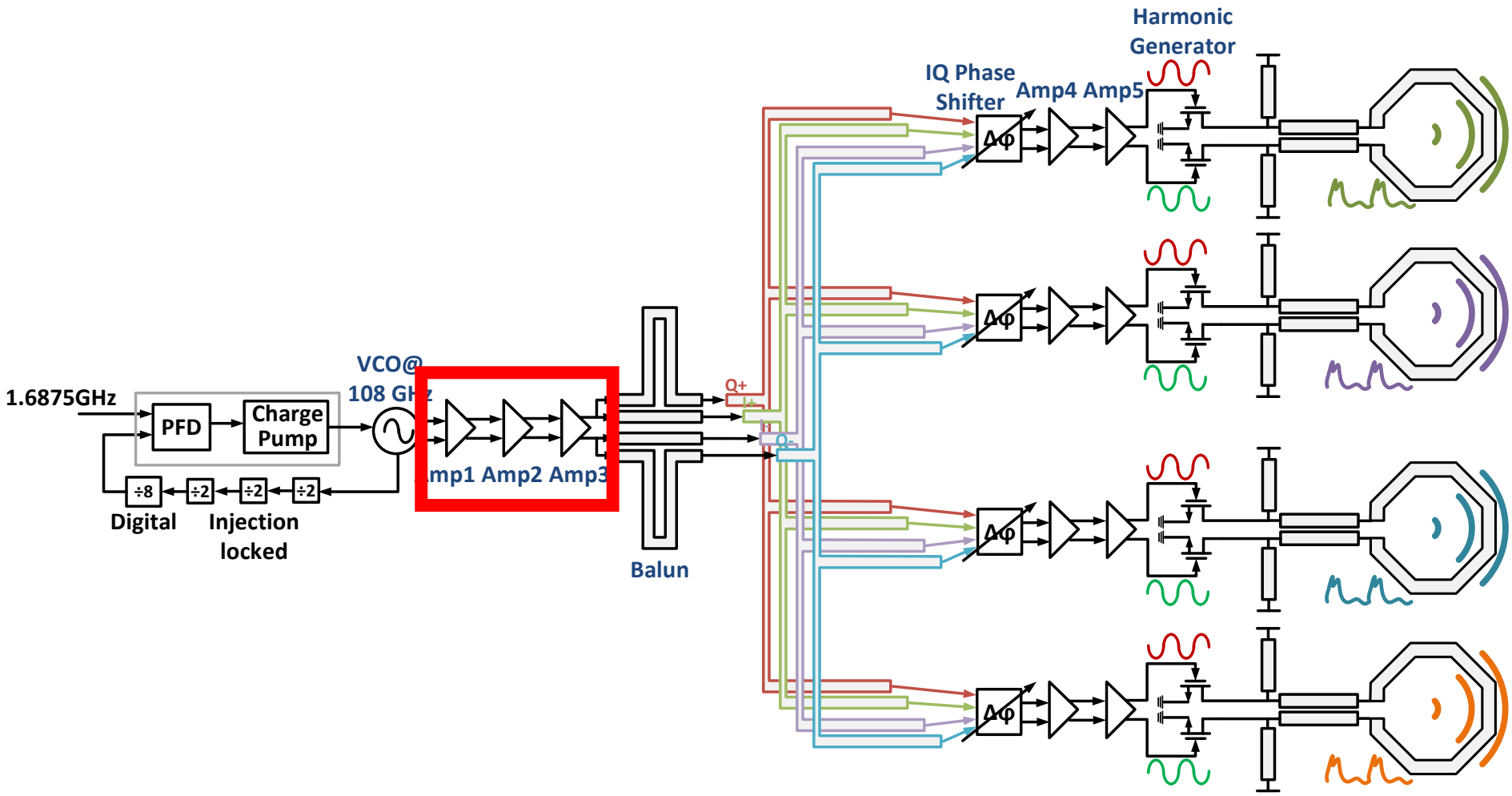


Reconfigurable Periodic Waveform Radiator



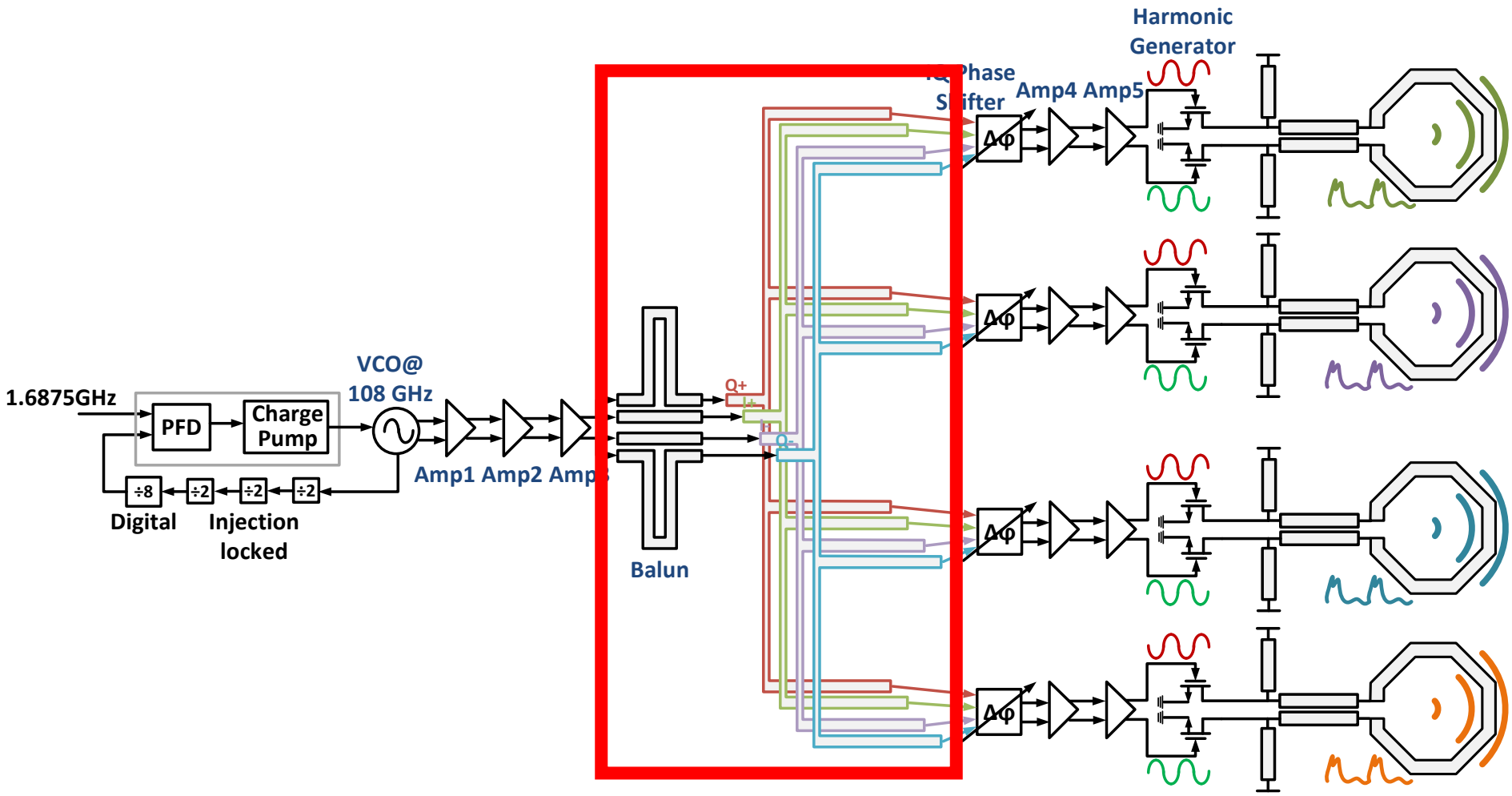
- VCO @ 108GHz

Reconfigurable Periodic Waveform Radiator



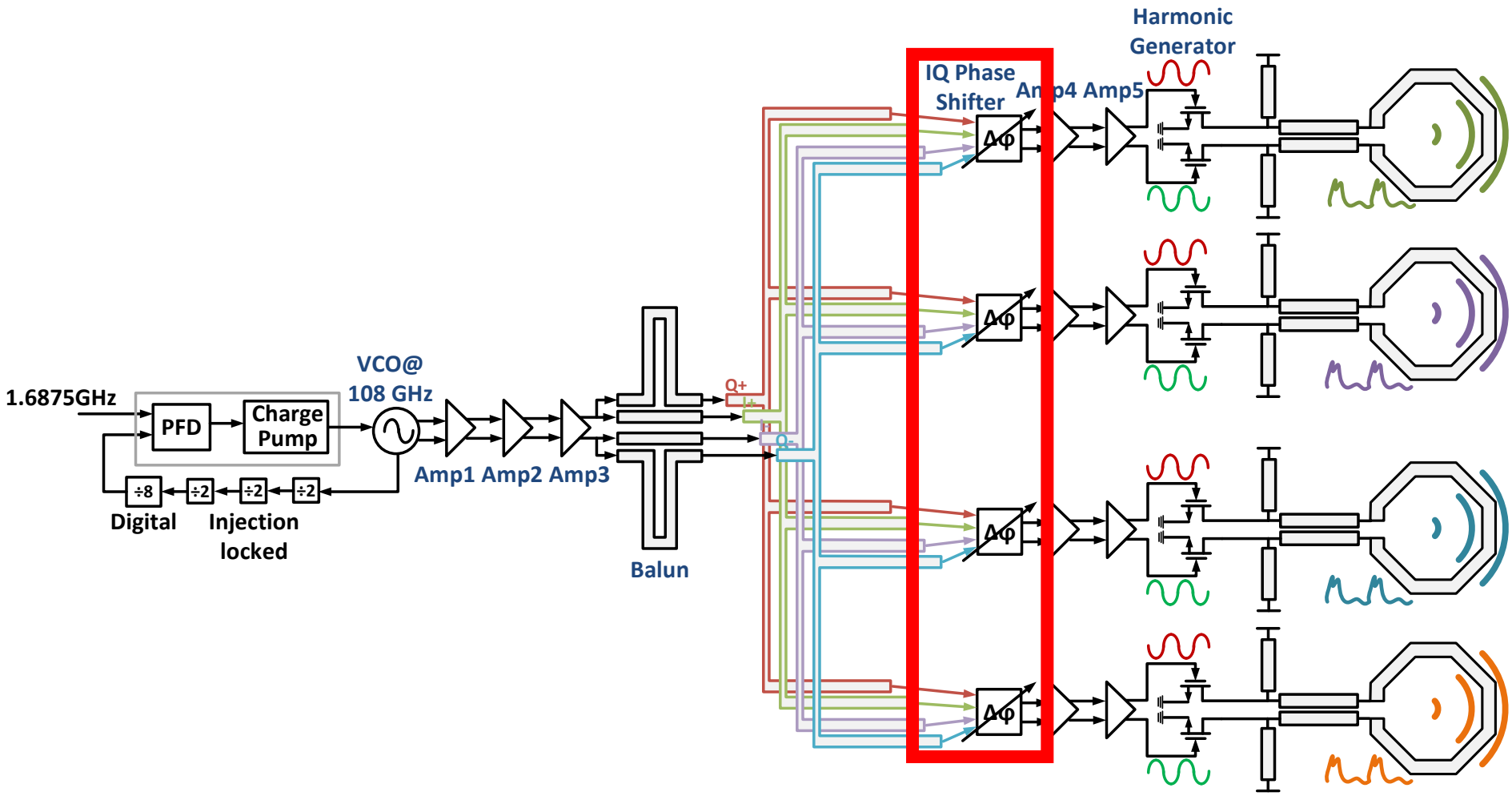
- **Amplified by three cascaded amplifiers**

Reconfigurable Periodic Waveform Radiator



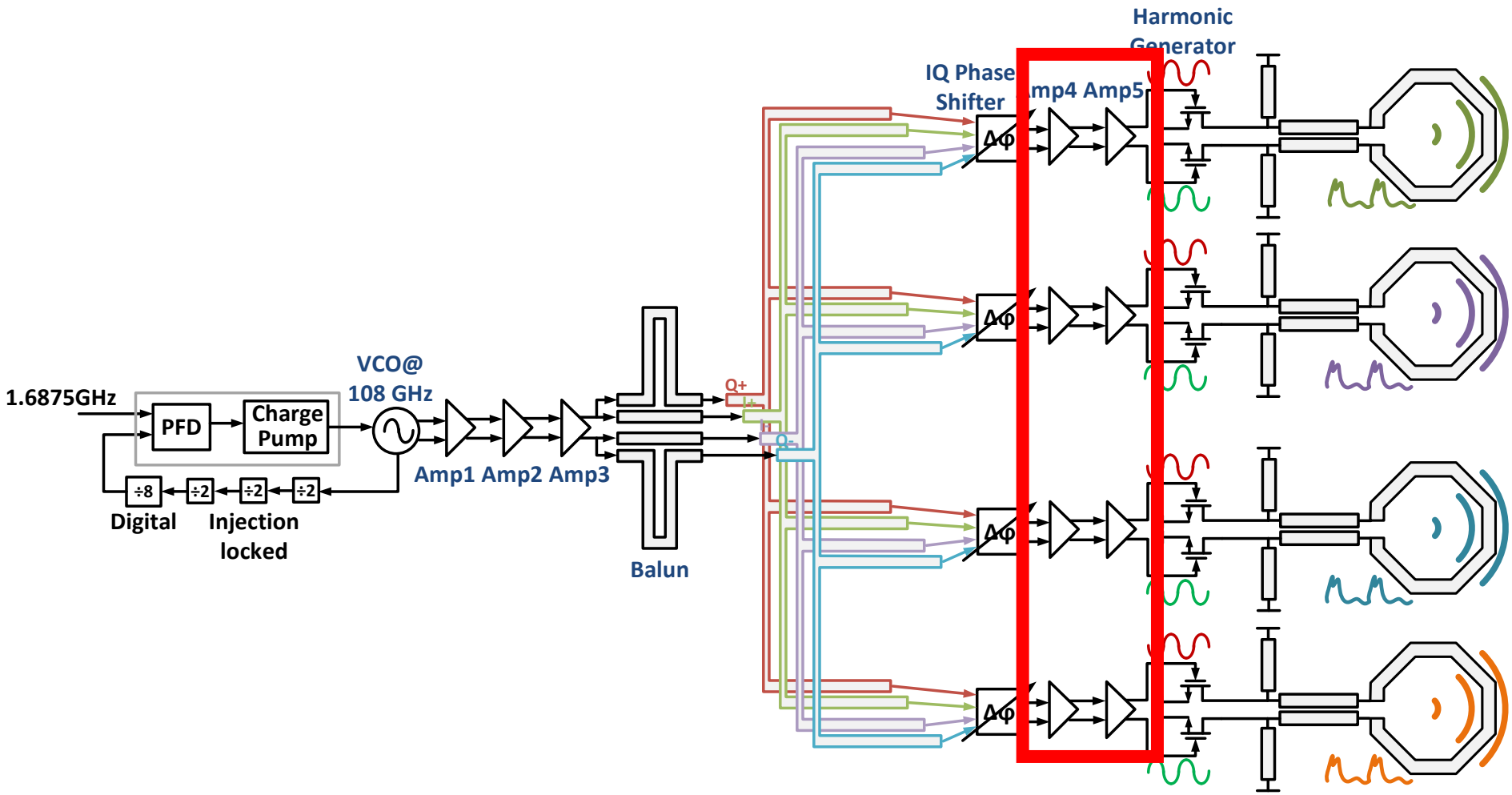
- **Generate quadrature signals for distribution**

Reconfigurable Periodic Waveform Radiator



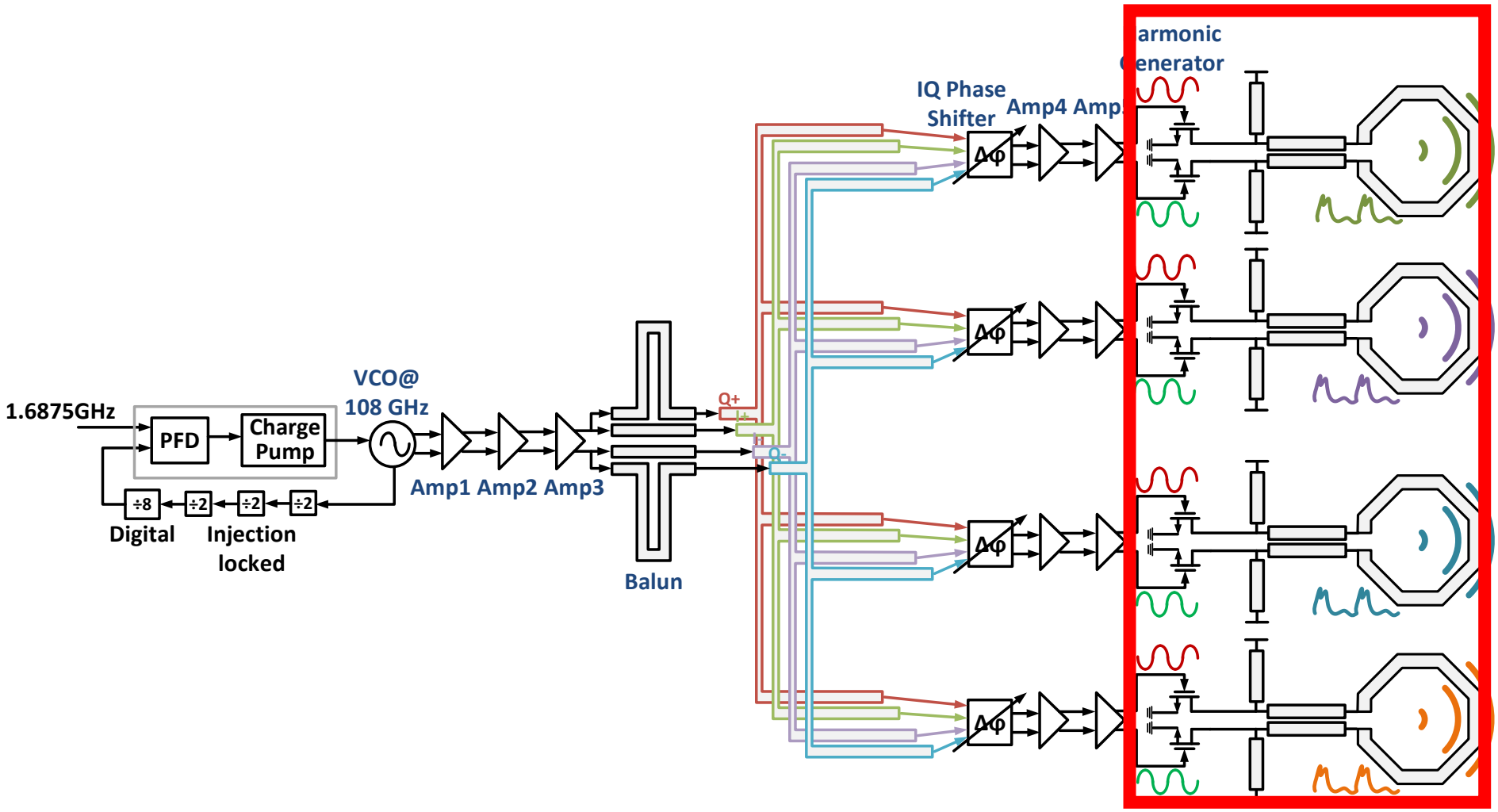
- **Phase rotated by an IQ phase shifter**

Reconfigurable Periodic Waveform Radiator



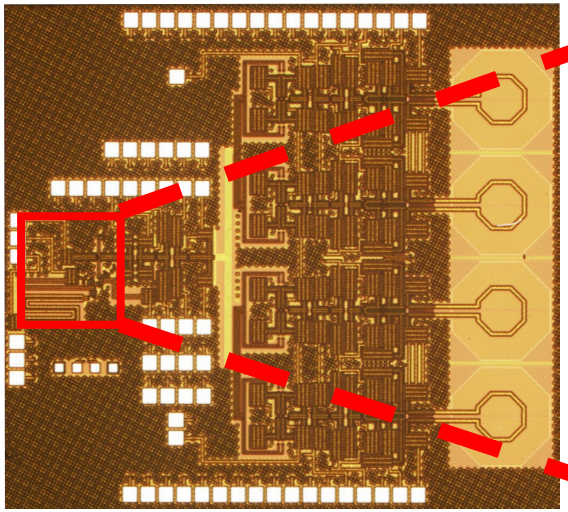
- **Amplified by two cascaded amplifiers**

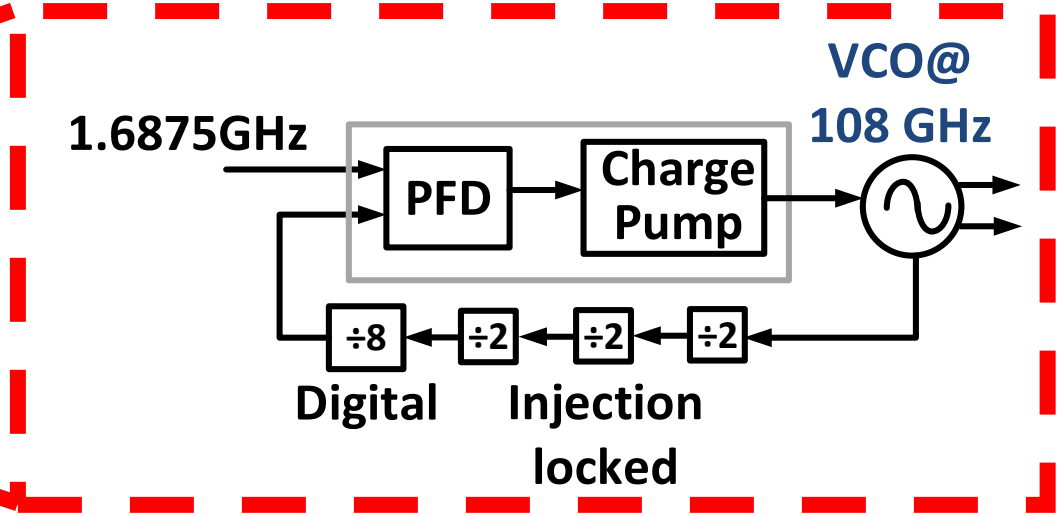
Reconfigurable Periodic Waveform Radiator

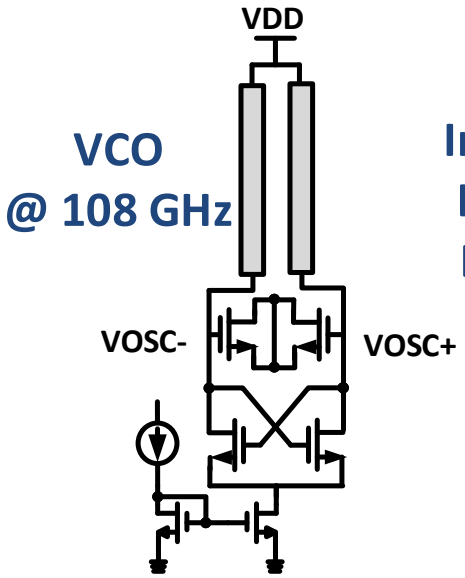


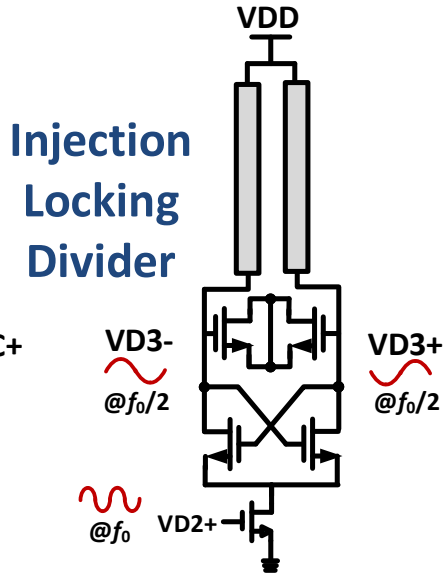
- Send to harmonic generator to generate harmonic for radiation (@108GHz and its harmonics)

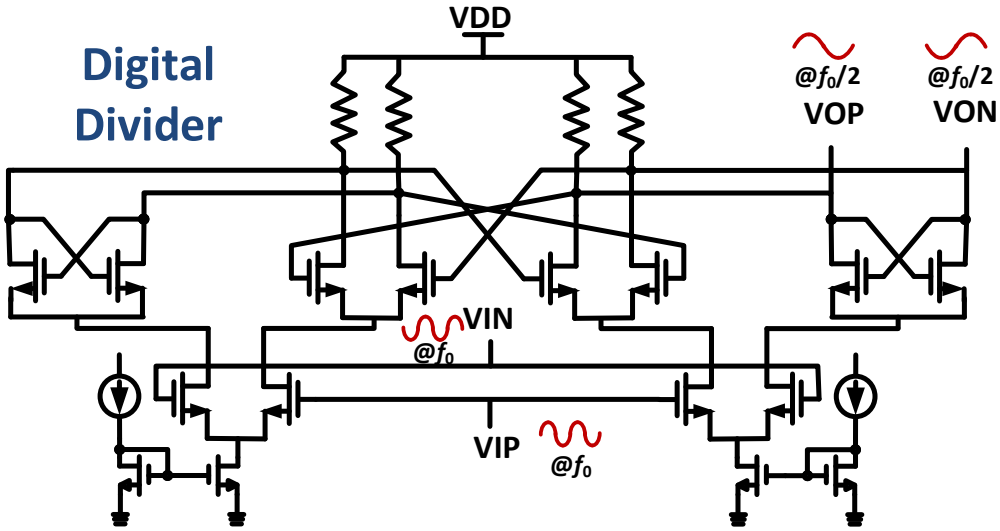
Central Frequency Synthesizer



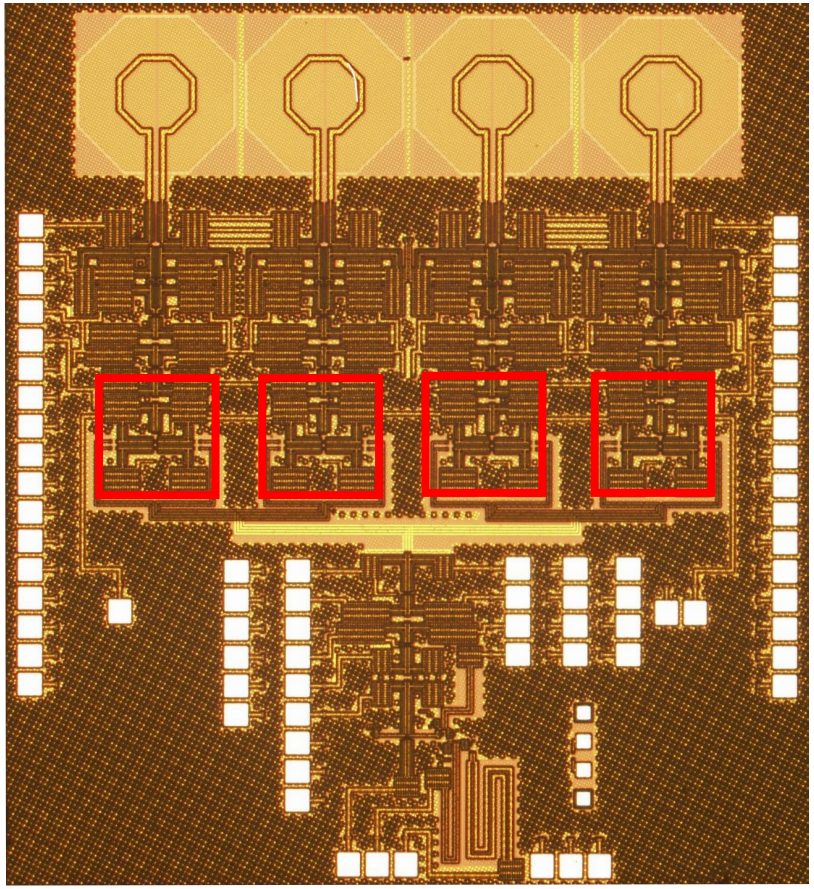






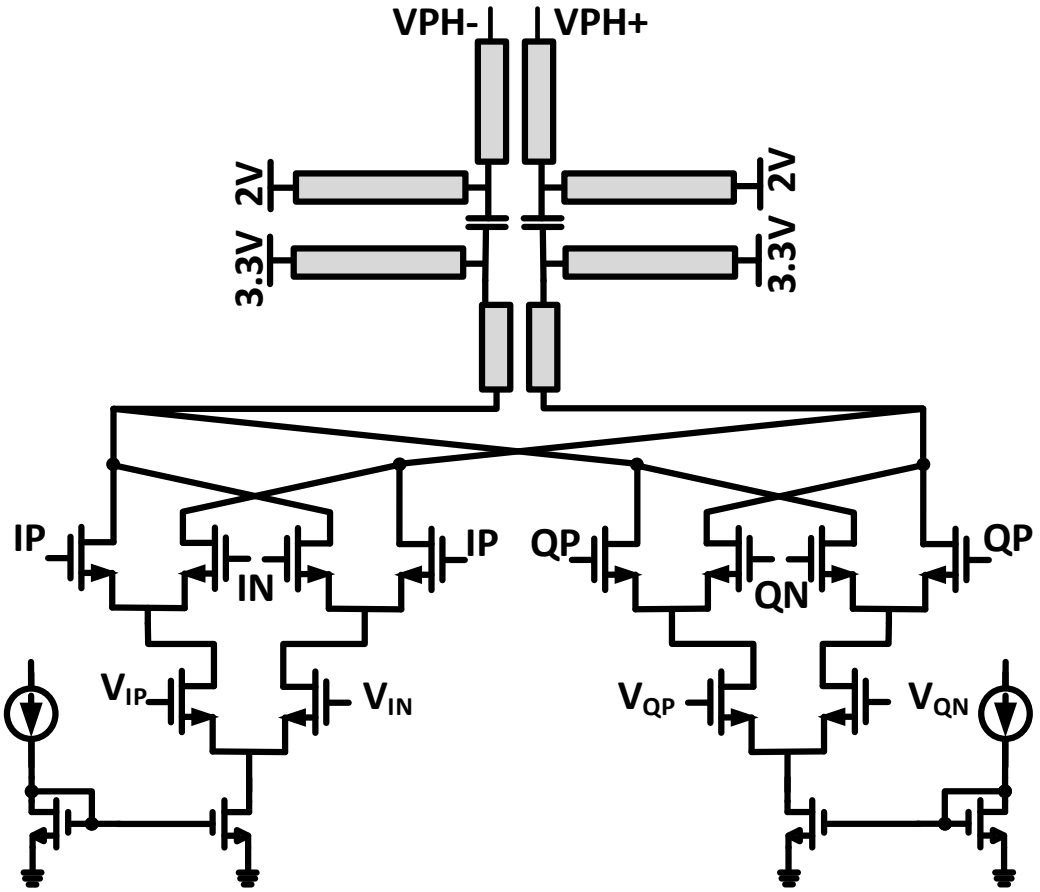


IQ Phase Shifters



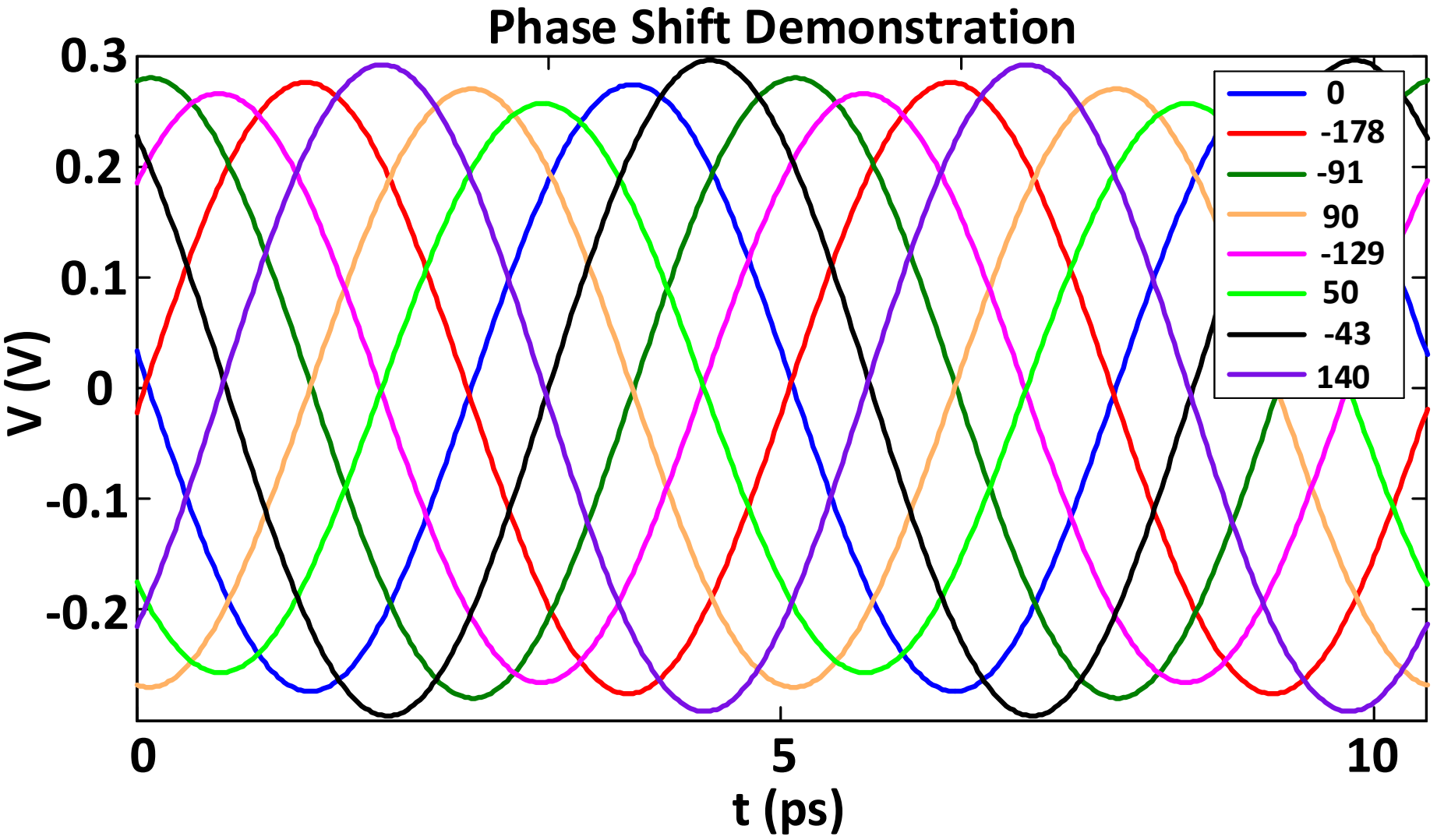
Location of IQ Phase Shifter

IQ Phase Shifter

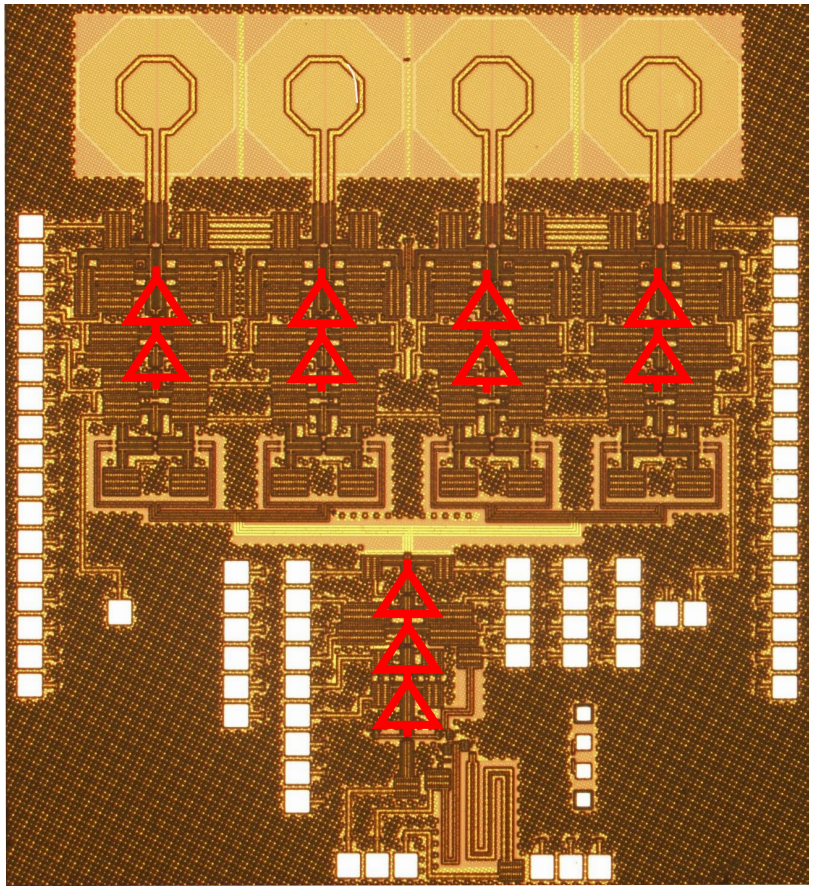


Circuit of IQ Phase Shifter

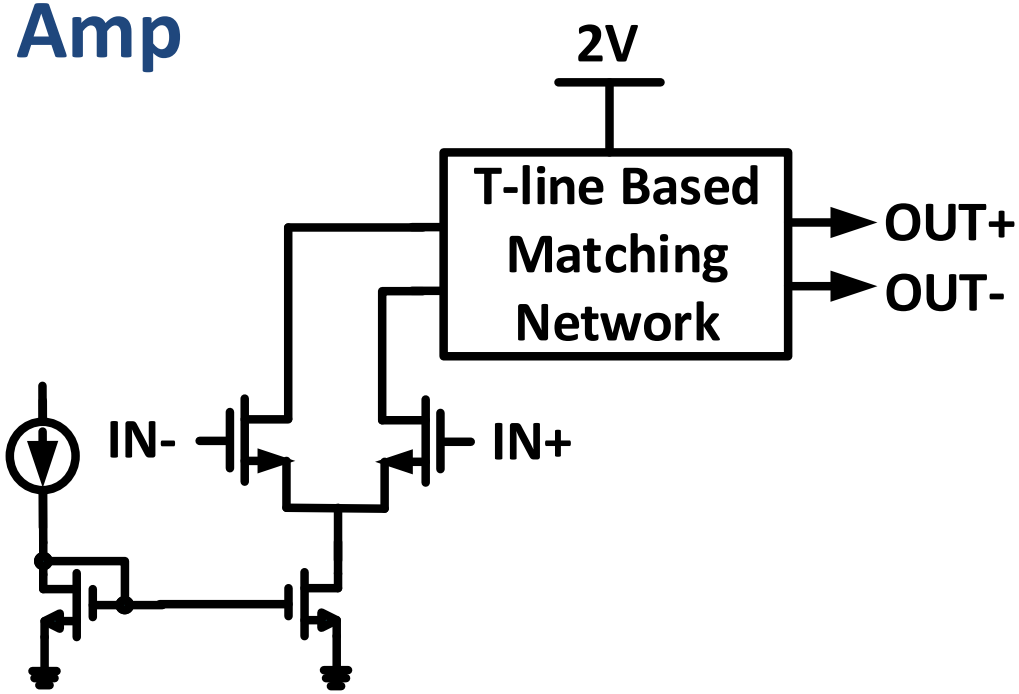
Simulation of IQ Phase Shifters



Amplifier Chain

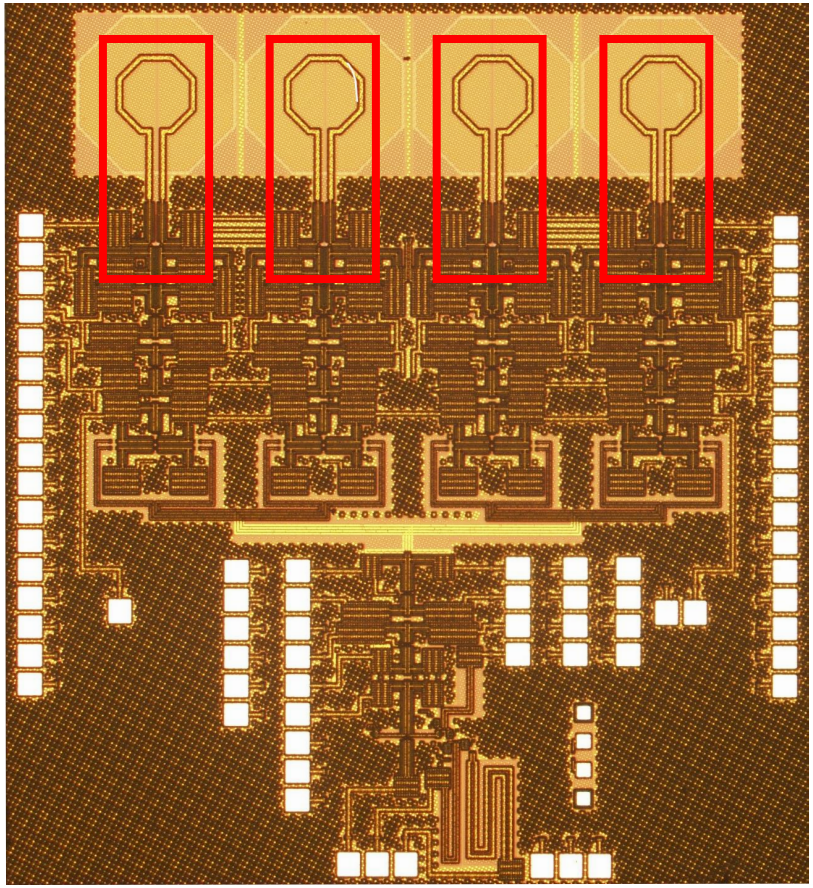


Location of Amplifiers

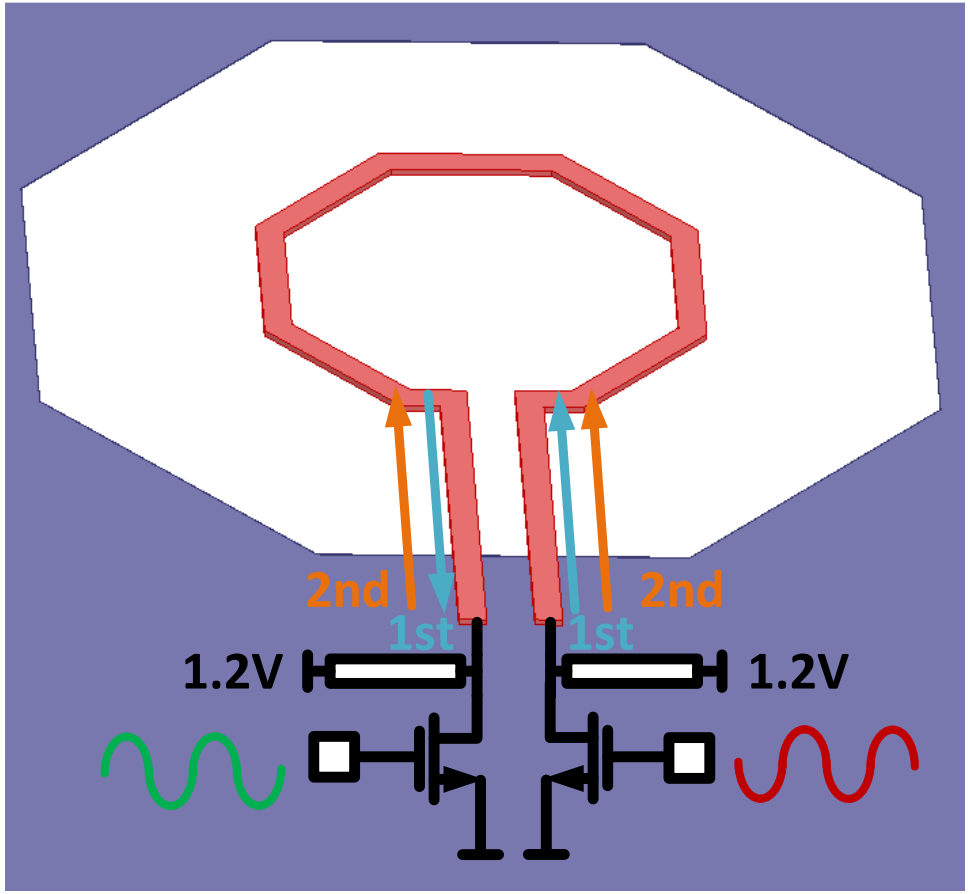


Circuit of Amplifiers

Harmonic Generator and Antenna Design



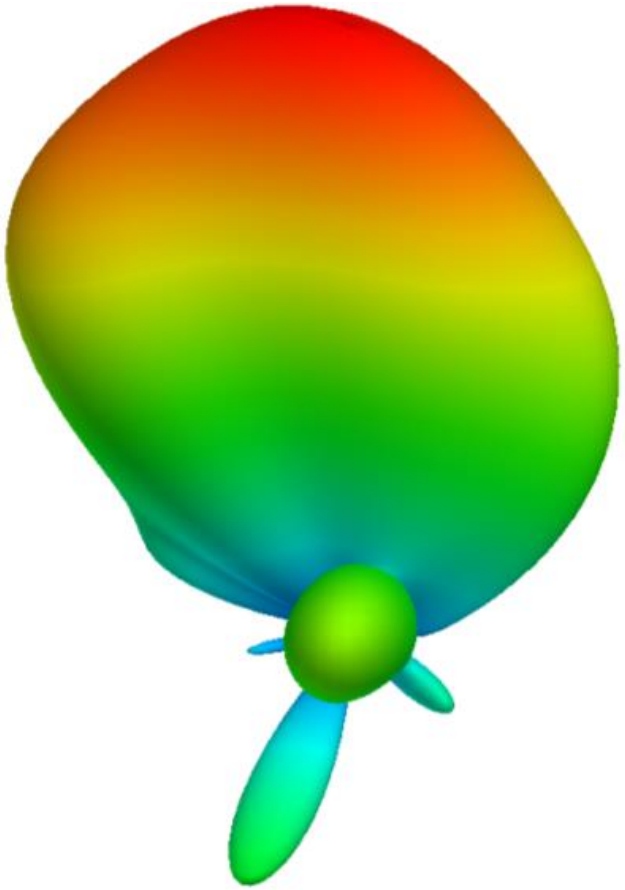
Location of Harmonic Generator



Circuit of Harmonic Generator

- Antenna provides proper impedance for optimal harmonic generation

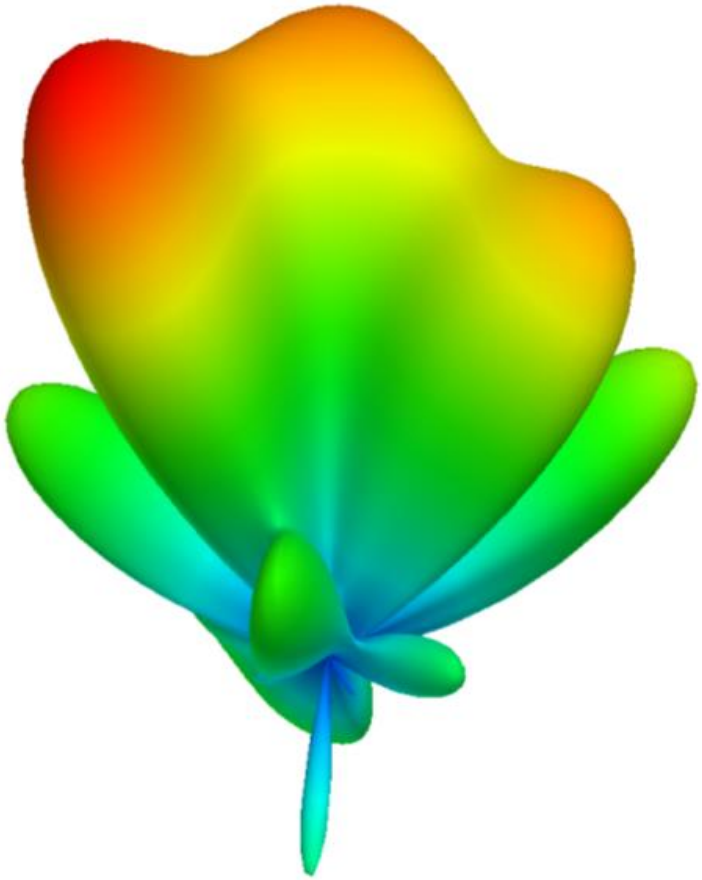
Simulated Radiation Pattern



108GHz

D_{MAX}=8.0 dB

EFF=12.3%



216GHz

D_{MAX}=7.2 dB

EFF=11%

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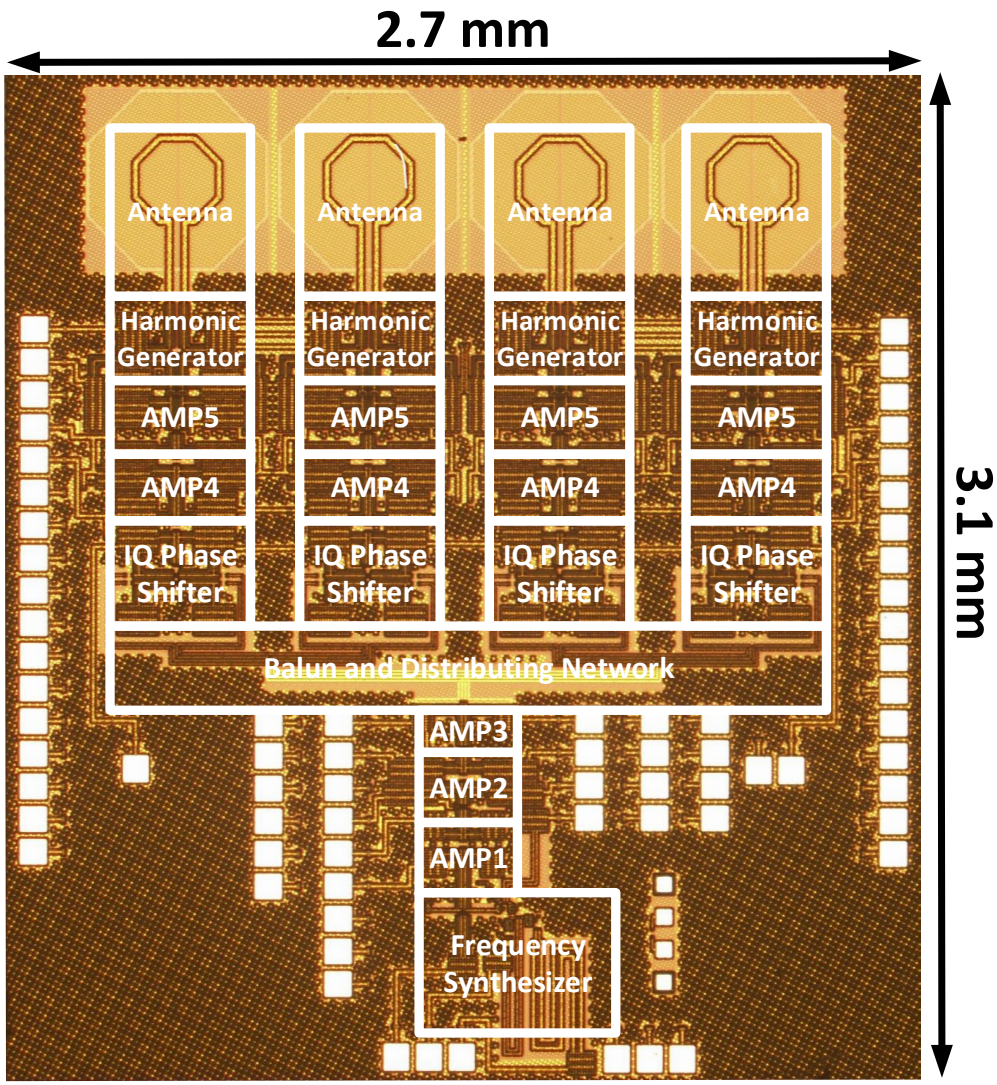
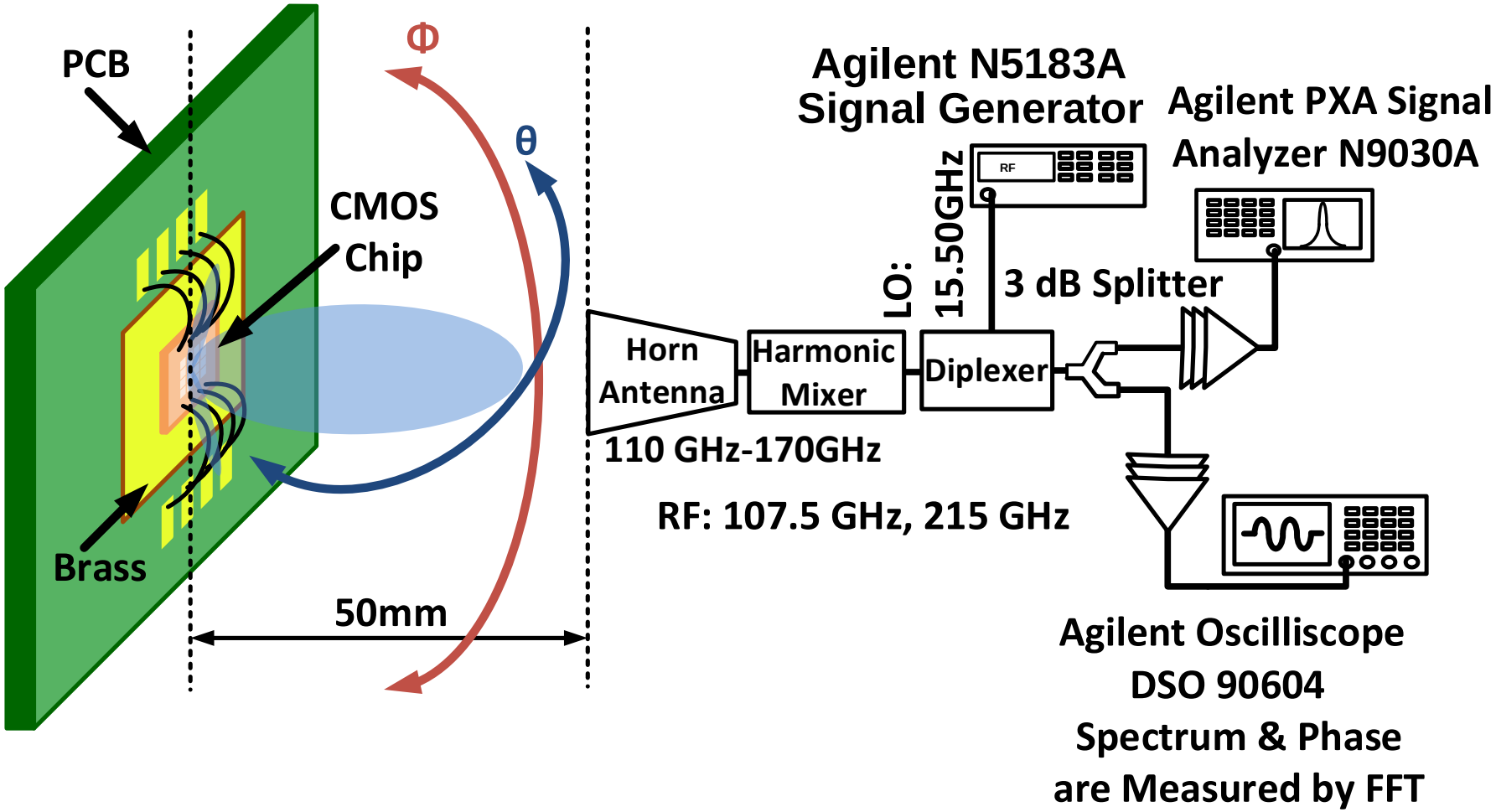
Technology and Die Photo



- The chip is fabricated in 65nm LP-CMOS

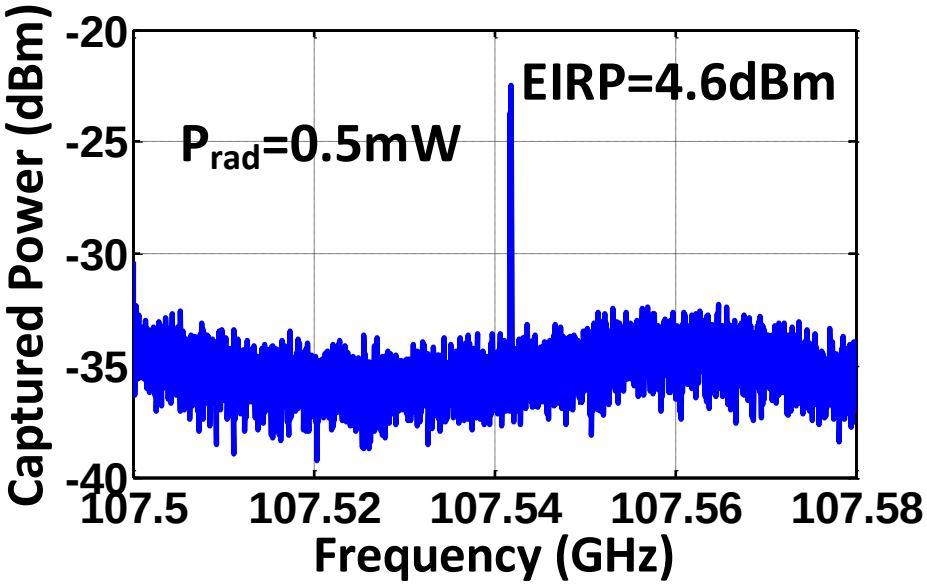
Measurement Setup



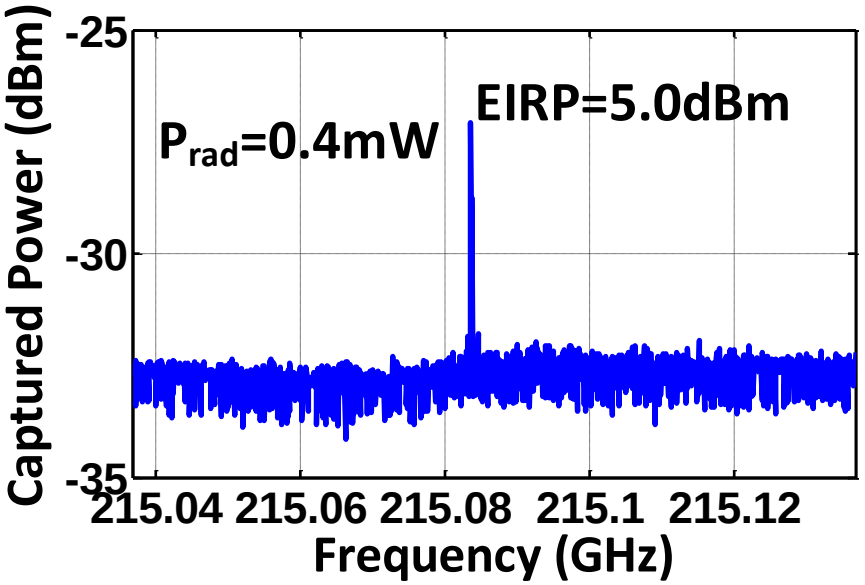
- The whole path is calibrated for both amplitude and phase

Measured Radiated Spectrum

Spectrum of Fundamental Frequency

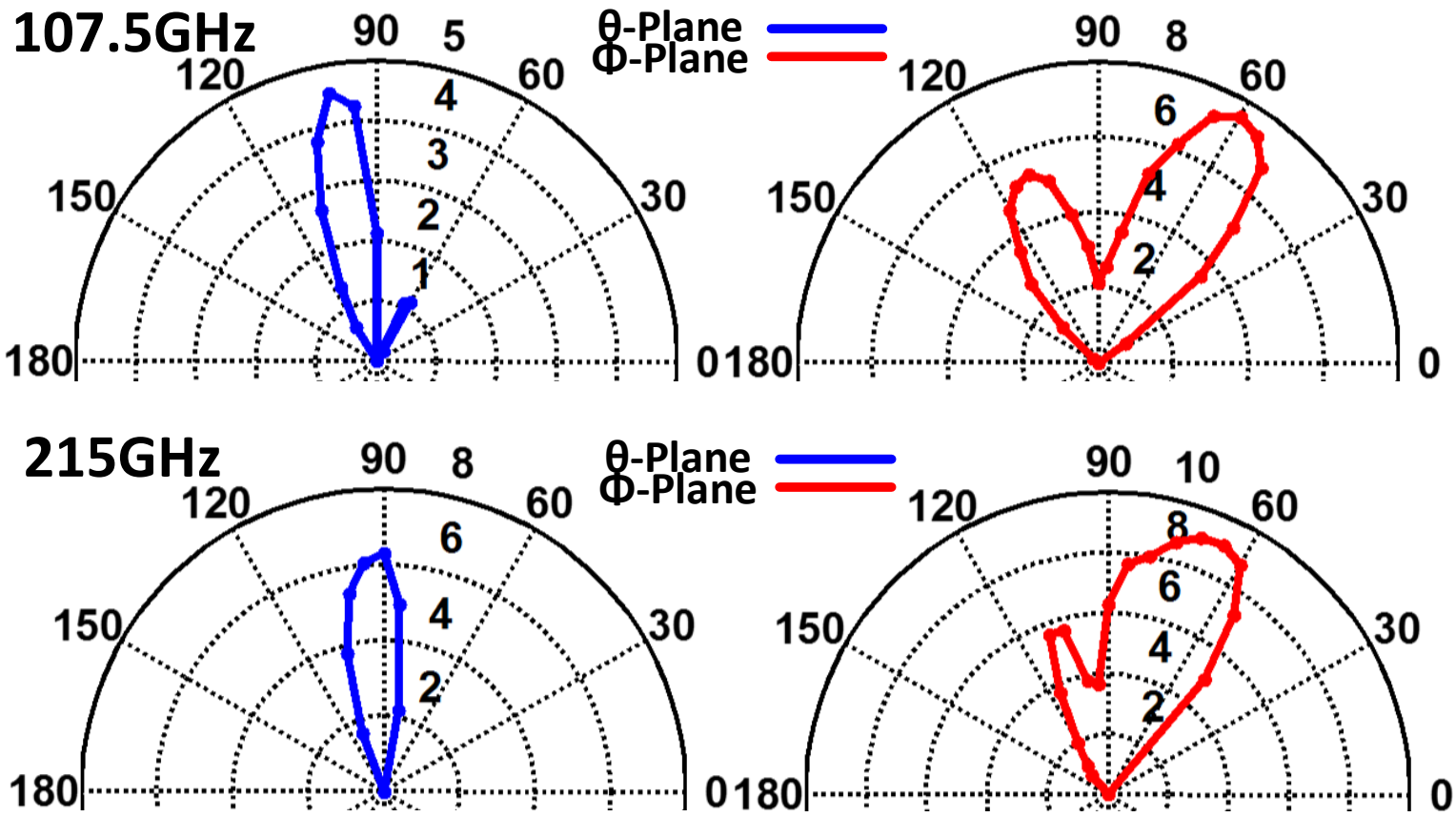


Spectrum of 2nd Harmonic



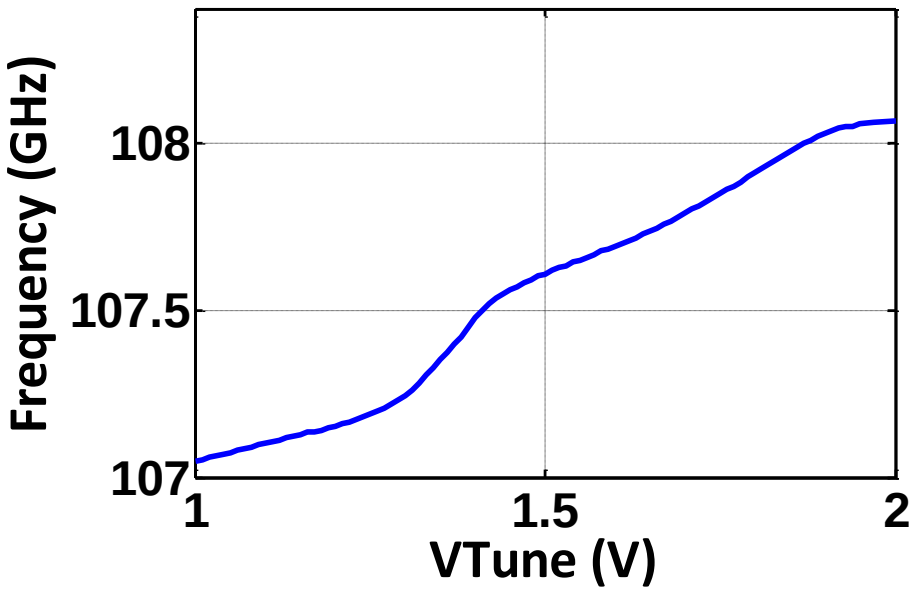
- Fundamental Frequency, Radiated Power: 0.5mW EIRP: 4.6dBm
- 2nd Harmonic, Radiated Power: 0.4mW EIRP: 5 dBm

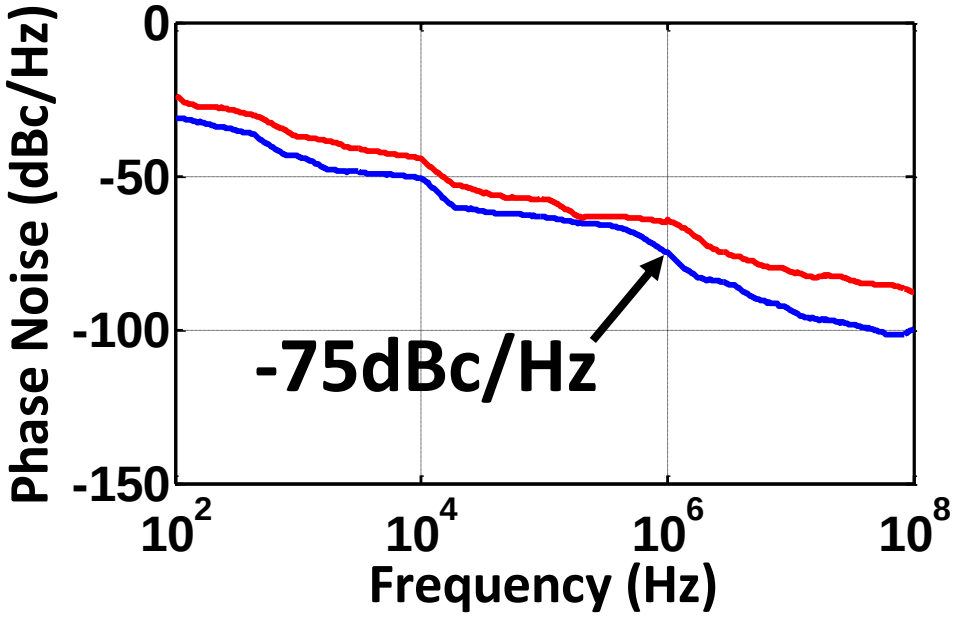
Measured Radiation Pattern



- **Fundamental Frequency: maximum directivity is 7.6 dB**
- **2nd Harmonic: maximum directivity is 9 dB.**

Measured Tuning Range and Phase Noise

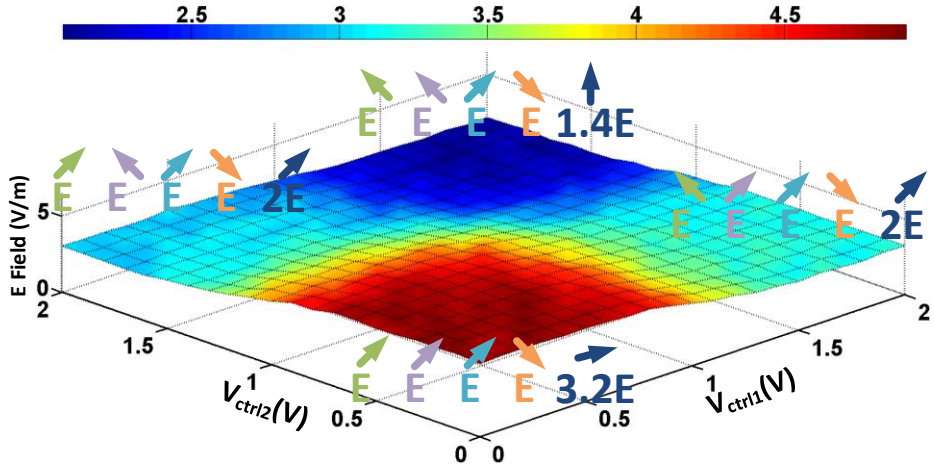




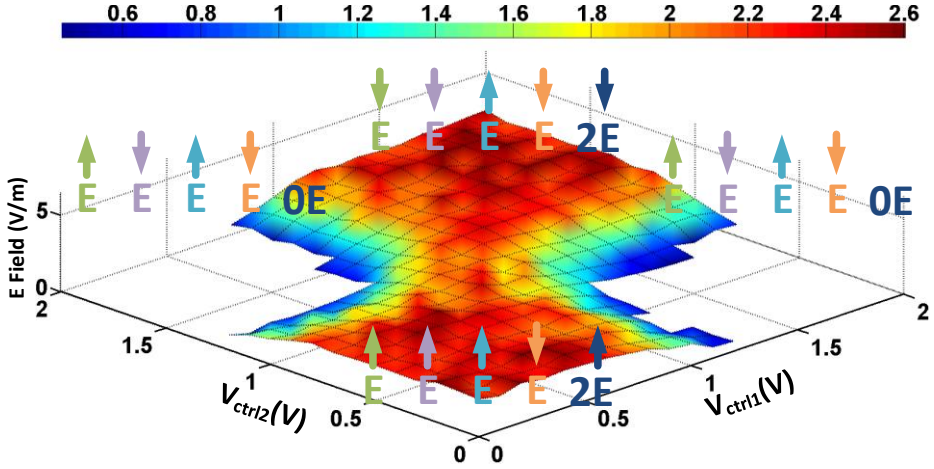
- VCO Tuning Range: 107-108.1GHz
- Phase noise of fundamental frequency is ~-75dBc/Hz @ 1MHz
- Phase noises of both harmonics are 6 dB apart as expected

Measured Radiated Waveform

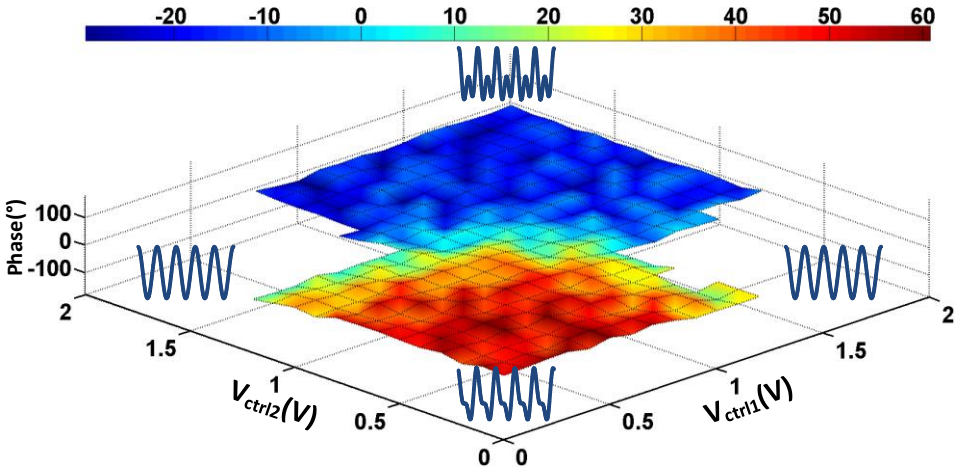
V_{ctrl3}=0, V_{ctrl4}=-2V



1st Harmonic Magnitude



2nd Harmonic Magnitude



Phase Offset ($2\theta_{f0}$-θ_{2f0})

$V_{ctrli}=V_{IP}-V_{IN}-(V_{QP}-V_{QN})$

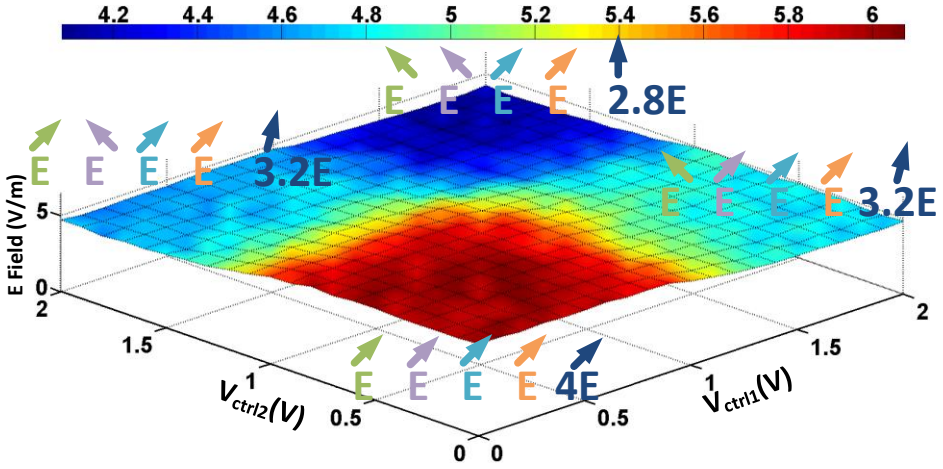
V_{IP}, V_{IN}, V_{QP} and V_{QN}: DC Current Control in IQ Phase Shifter

V_{ctrli}>0, I: constant Q: variable
V_{ctrli}<0, I: variable Q:constant

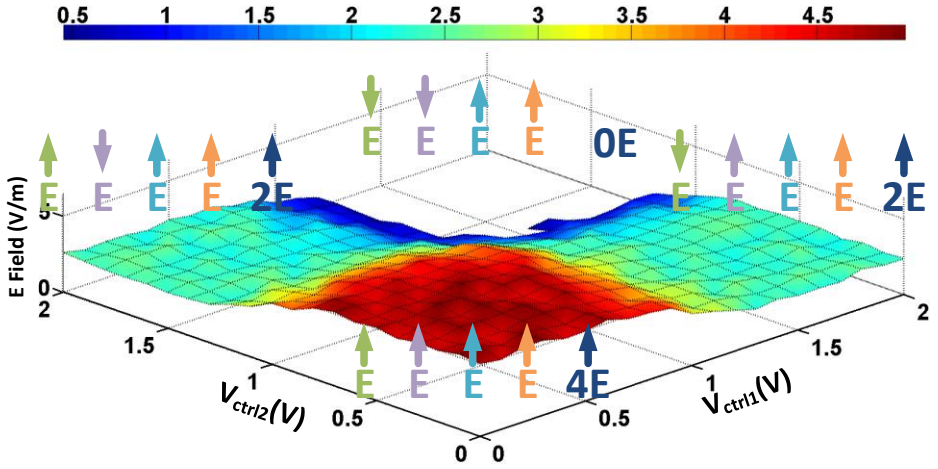
↗: 1st Antenna ↗: 2nd Antenna ↗: 3rd Antenna ↗: 4th Antenna ↗: Combined

Measured Radiated Waveform

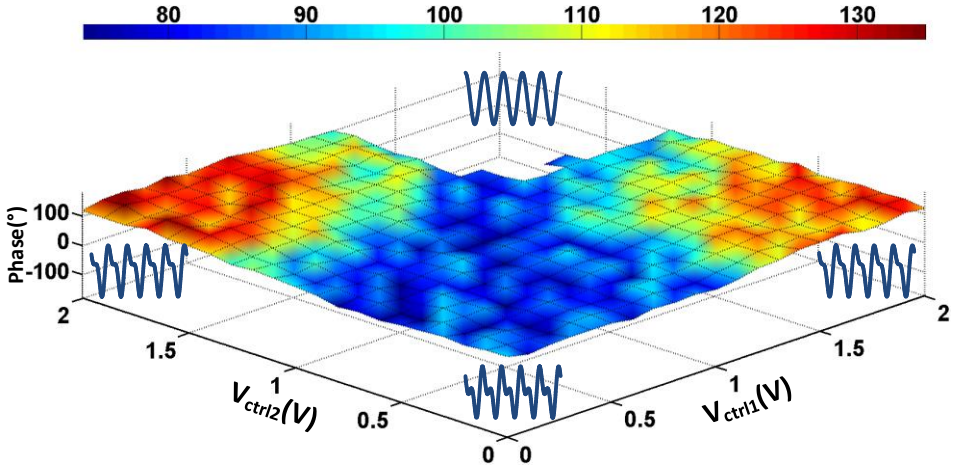
V_{ctrl3}=0, V_{ctrl4}=0V



1st Harmonic Magnitude



2nd Harmonic Magnitude



Phase Offset ($2\theta_{f0}$-θ_{2f0})

$V_{ctrli}=V_{IP}-V_{IN}-(V_{QP}-V_{QN})$

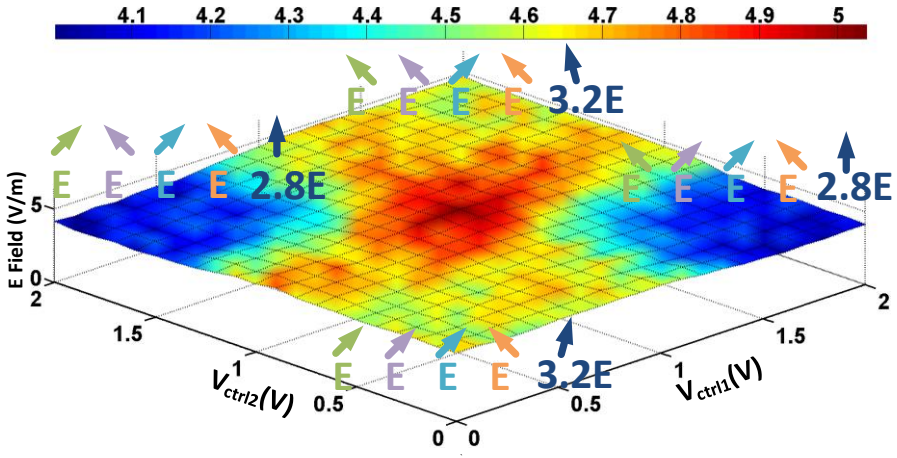
V_{IP}, V_{IN}, V_{QP} and V_{QN}: DC Current Control in IQ Phase Shifter

V_{ctrli}>0, I: constant Q: variable
V_{ctrli}<0, I: variable Q:constant

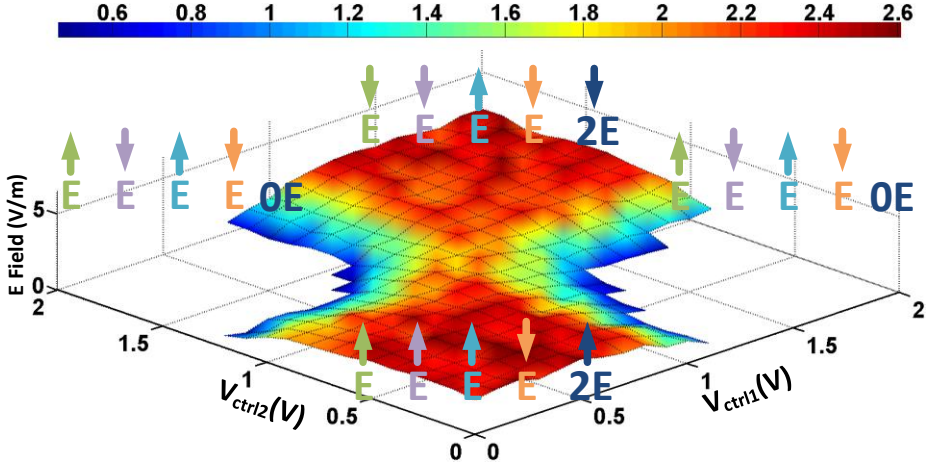
↗: 1st Antenna ↗: 2nd Antenna ↗: 3rd Antenna ↗: 4th Antenna ↗: Combined

Measured Radiated Waveform

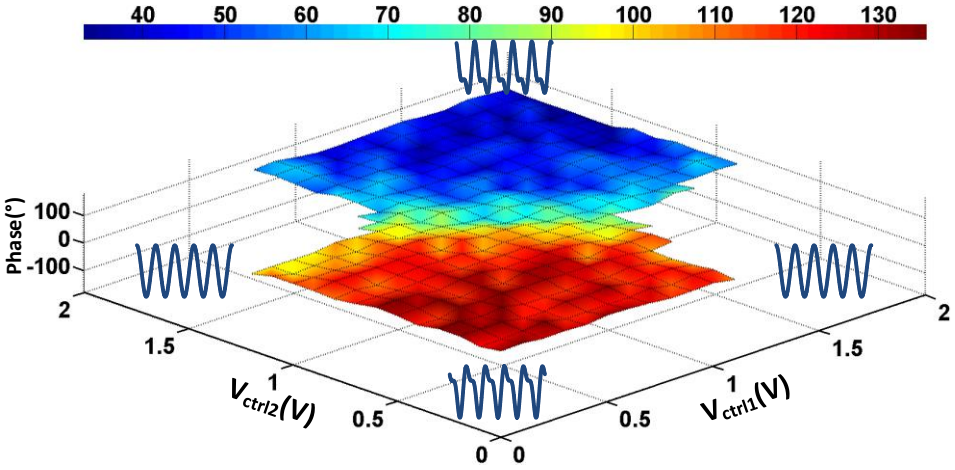
V_{ctrl3}=0, V_{ctrl4}=2V



1st Harmonic Magnitude



2nd Harmonic Magnitude



Phase Offset ($2\theta_{f0}$-θ_{2f0})

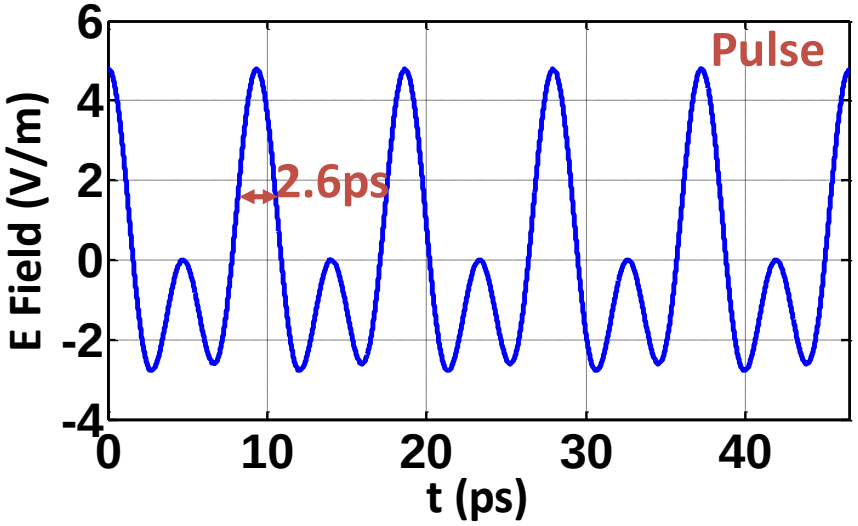
$V_{ctrli}=V_{IP}-V_{IN}-(V_{QP}-V_{QN})$

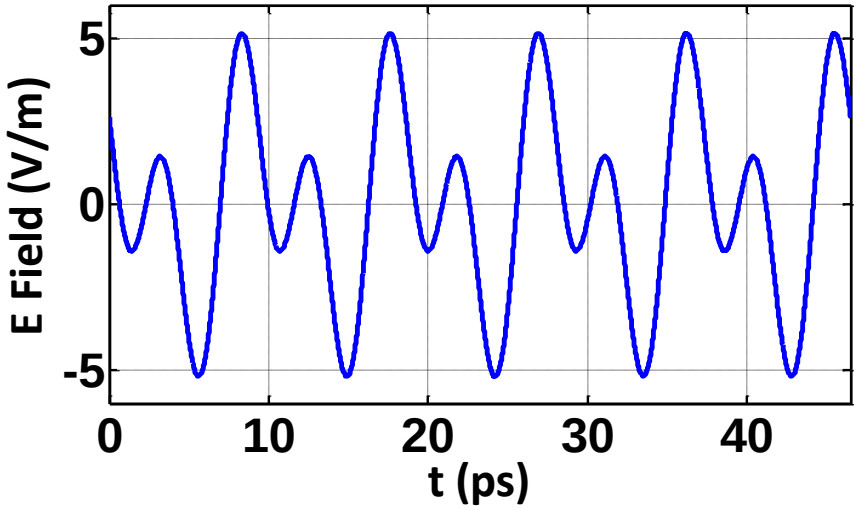
V_{IP}, V_{IN}, V_{QP} and V_{QN}: DC Current Control in IQ Phase Shifter

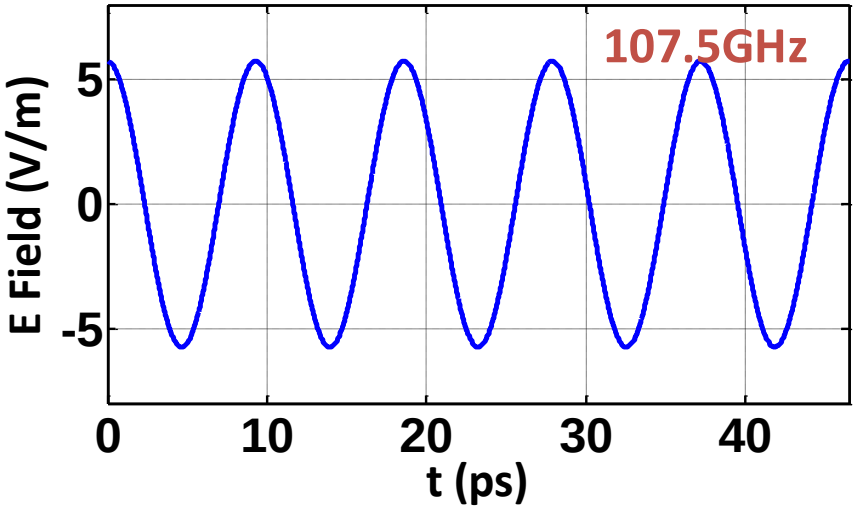
V_{ctrli}>0, I: constant Q: variable
V_{ctrli}<0, I: variable Q:constant

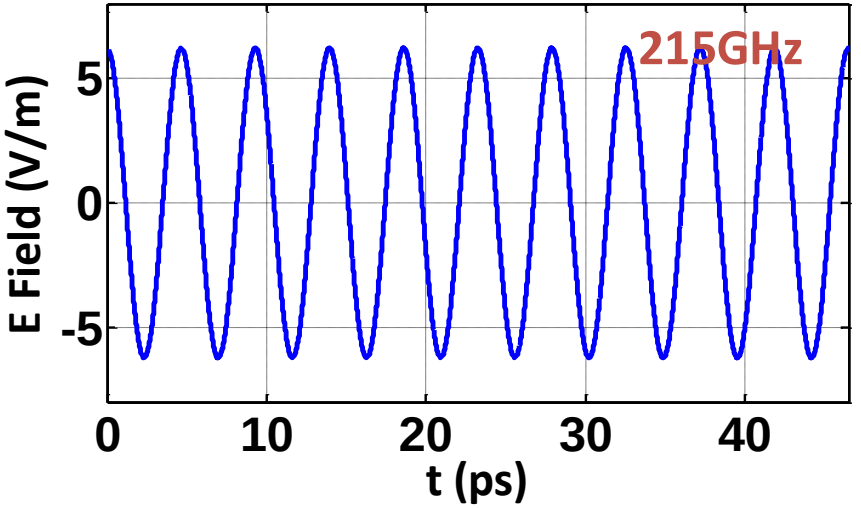
↗: 1st Antenna ↗: 2nd Antenna ↗: 3rd Antenna ↗: 4th Antenna ↗: Combined

Measured Radiated Waveform Examples

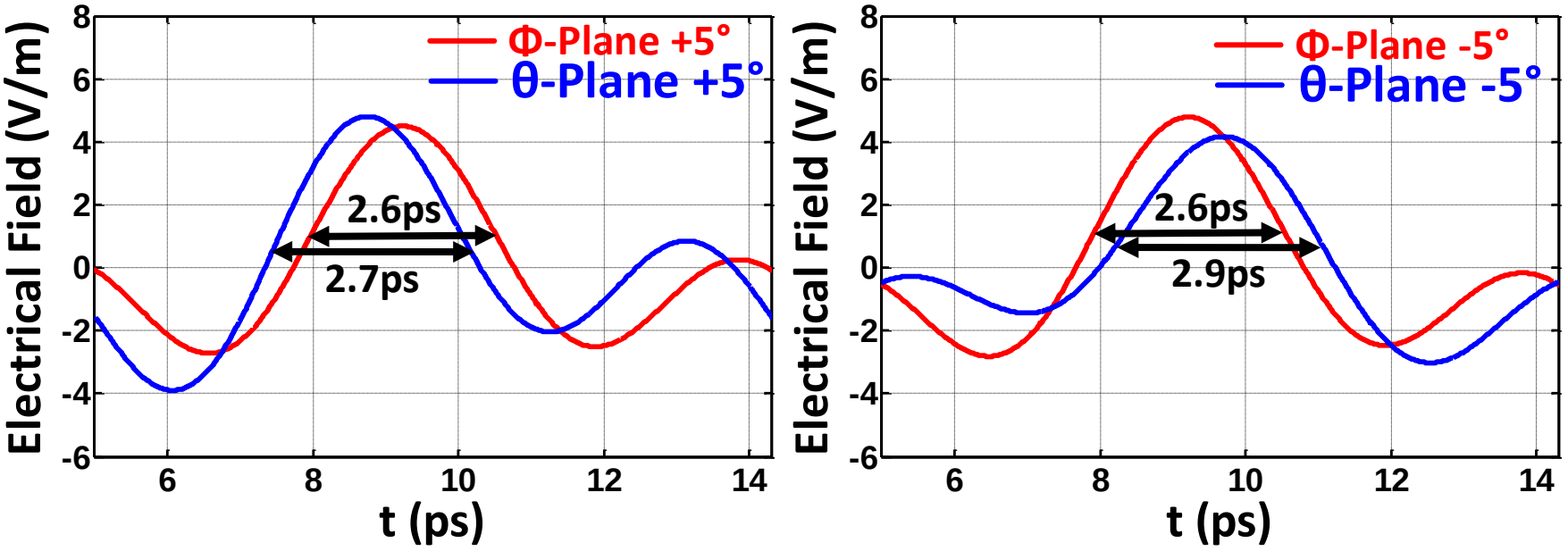








Pulse Degradation from Broadside Axis



- **Robust to radiation angle variations within -5°~5°, Δt≤0.3ps**

Comparison Table

	This work	A. Ababian (JSSC 2013)	R. Han (ISSCC 2013)	M. M. Assefzadeh (IMS 2014)
Pulse width (ps)	2.6	26	45	8
Reconfigurable	Yes	No	No	No
Measured Signal	Radiated	Radiated	Radiated	Radiated
Pulse Generation Method	Quasi-optical	Oscillator-based	Oscillator-based	Digital Pulse
Technology	65nm-LPCMOS	0.13µm SiGe	65nm CMOS	0.13µm SiGe

- Radiate pulse train with 2.6 pulse width
- The radiated waveform is reconfigurable

Outline

- Motivation and Background
- Architecture
- Circuit Blocks and Details
- Measurement
- Conclusions

Conclusion

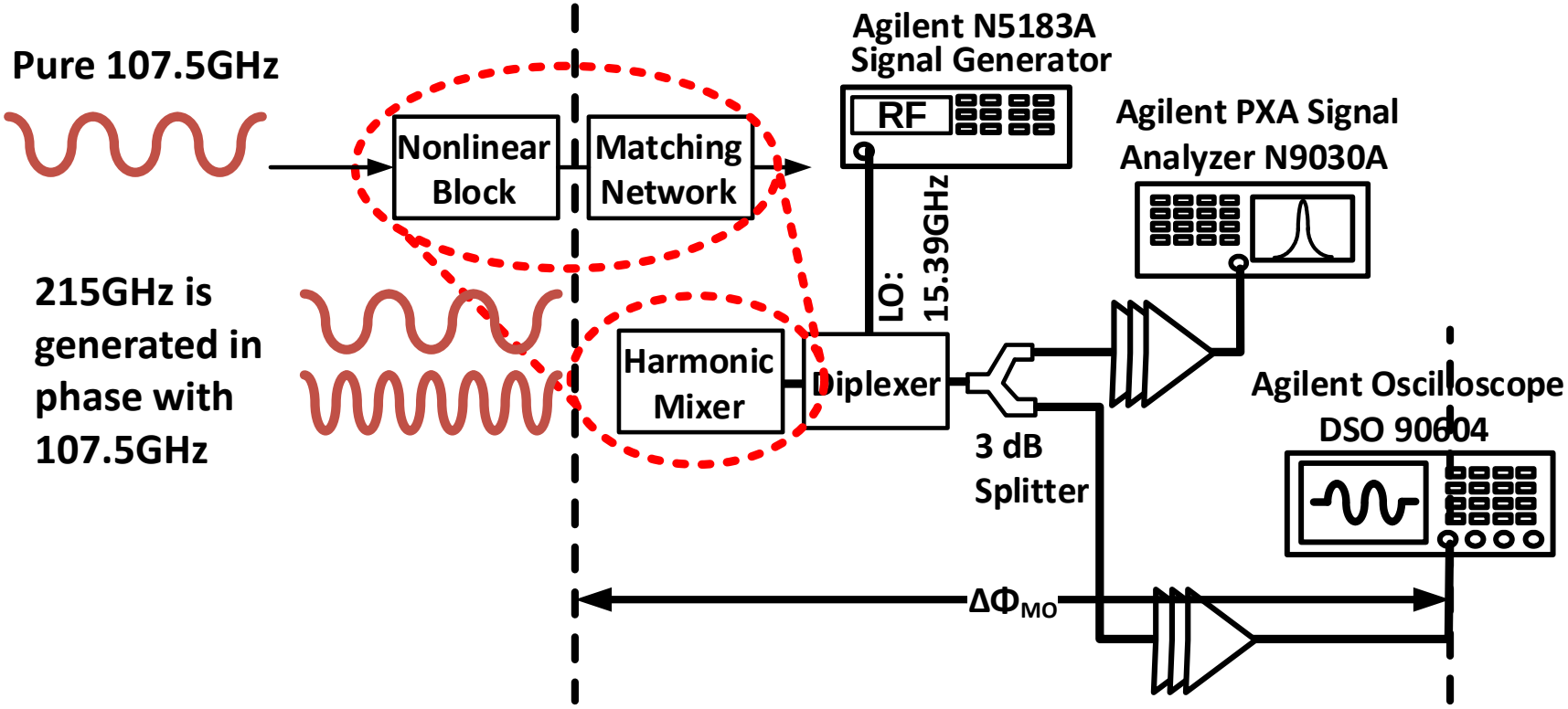
- **Architecture**
  - **Scalable and reconfigurable**
  - **Radiate periodic waveform with ps time-width**
  - **Simultaneous control on amplitudes and phases**
- **Reconfigurable Periodic Waveform Radiator**
  - **2.6 ps pulses radiation**
  - **Pure tone radiation at 107.5 and 215 GHz**
  - **Reconfigurability enable any arbitrary combination of the two harmoics**

Acknowledgement

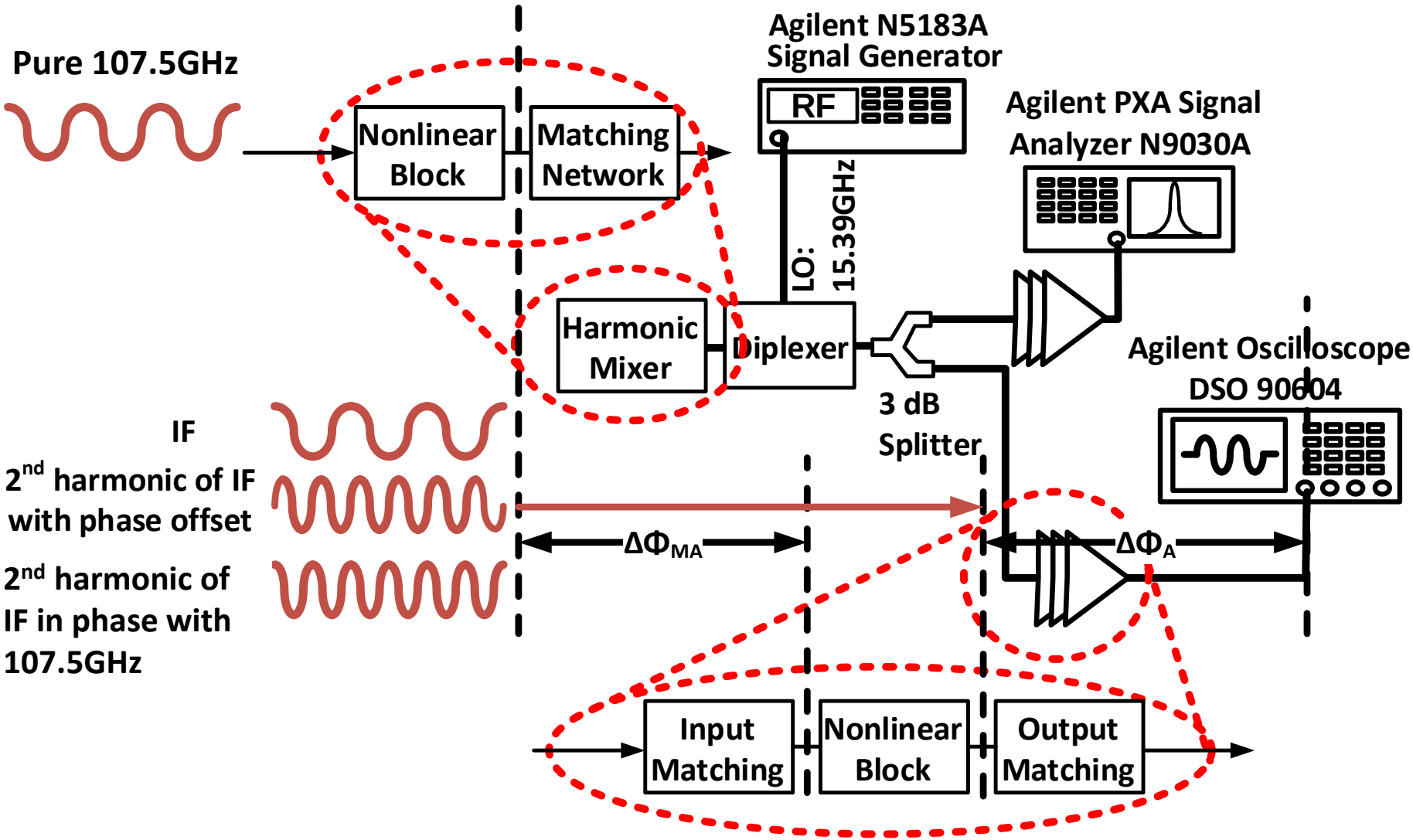
- **IBM**
- **All researchers in Integrated Micro-systems Research Lab (IMRL) of Princeton University**
- **Micro/Nano Fabrication Laboratory (MNFL) of Princeton University**

Thank you!

Calibration of Phase



Nonlinearity of Amplifier

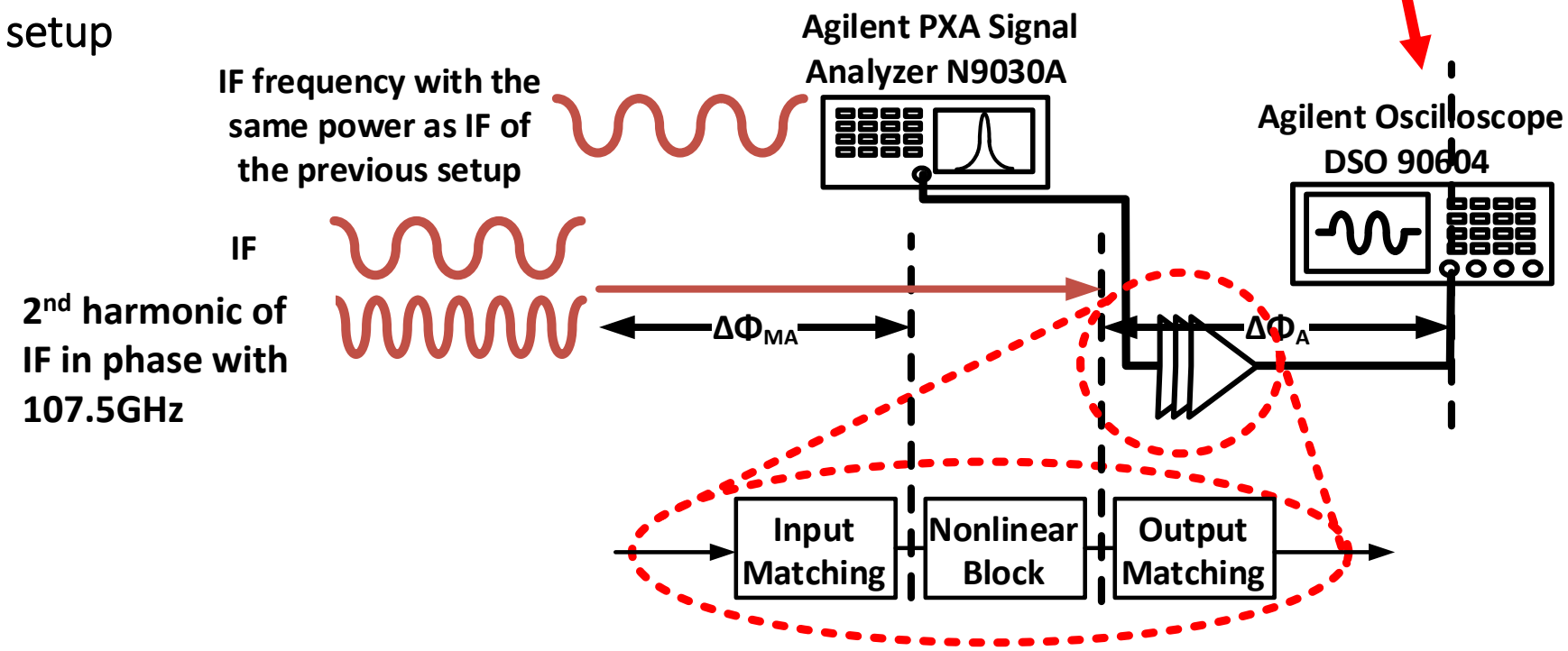


Nonlinearity of Amplifier

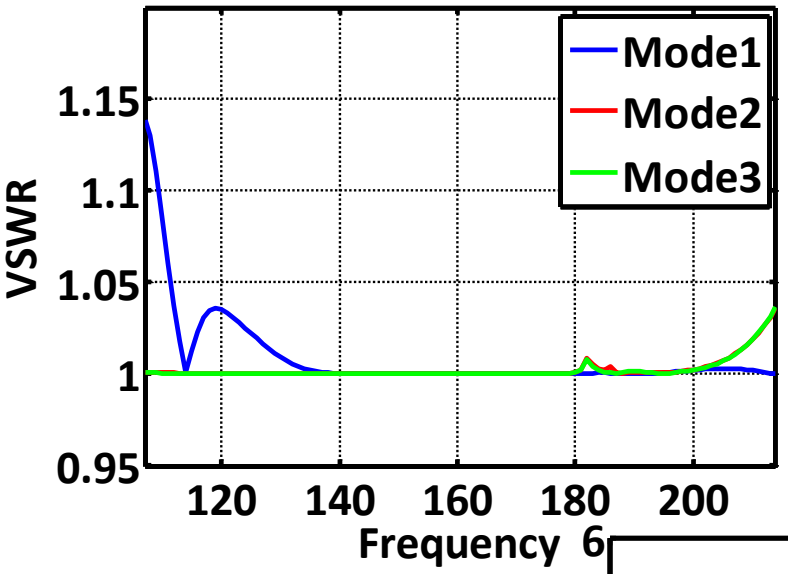
$$A_{total2}\cos(2\omega t + \phi_{MO}) = A_{M2}\cos(2\omega t + \phi_{MA} + \phi_A) + A_{A2}\cos(2\omega t + \phi_A)$$

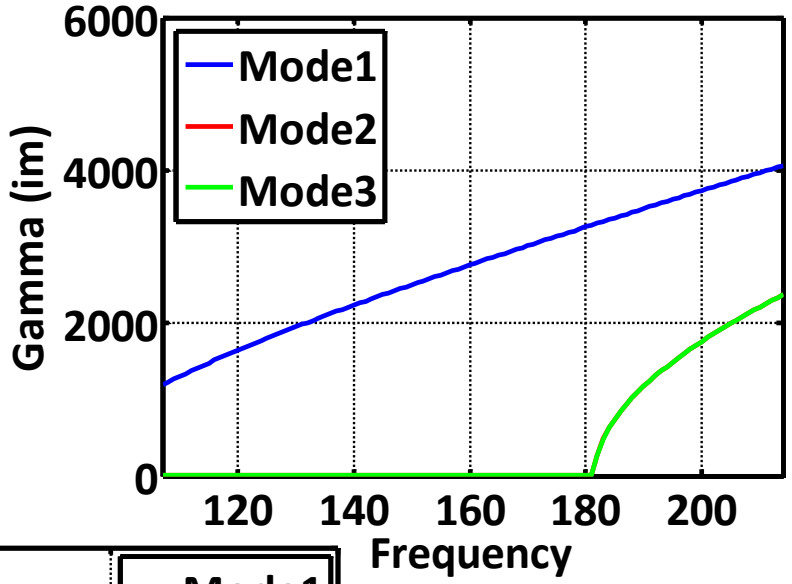
Spectrum and phase of 2nd harmonic are measured in oscilloscope from previous setup

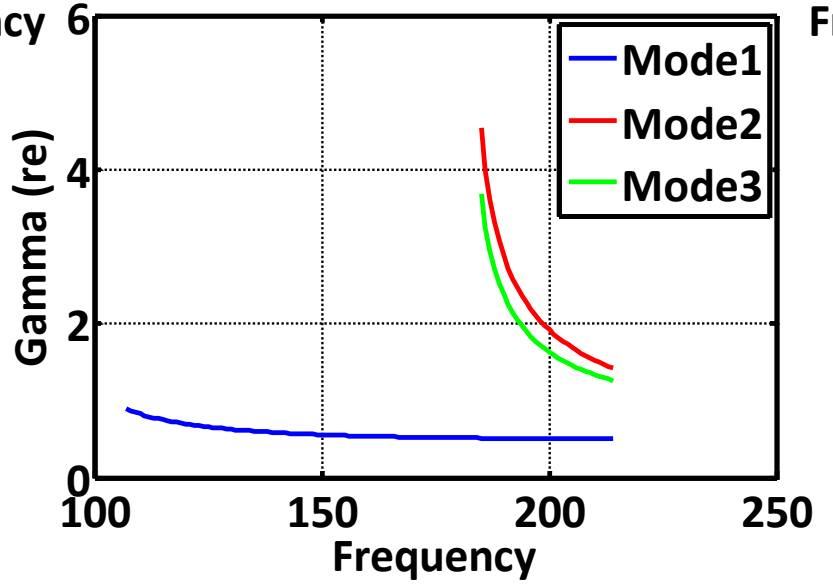
Calculate amplitude and phase of the signal due to mixer's nonlinearity



Multi-mode Operation







Phase Noise of LO