A 0.31THz CMOS Uniform Circular Antenna Array Enabling Generation/Detection of Waves with Orbital-Angular Momentum

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Outline

- **Introduction**
- **Applications and Prior Works**
- **0.31THz OAM CMOS Generation/Detection**
  - System architecture
  - 0.31THz Reconfigurable Pixel
  - 0.31THz Amplifier-Multiplier Chain
  - Controller and Key-to-OAM mapping
- **Measurement Results**
- **Conclusion**

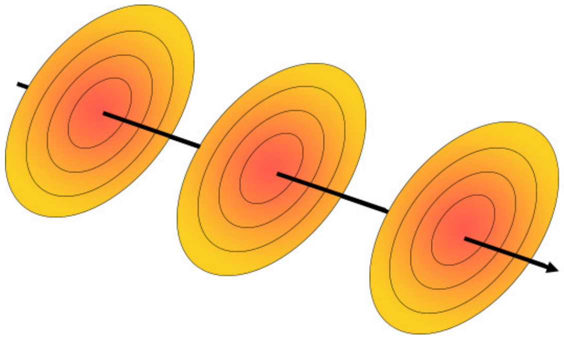
Introduction

- **Orbital Angular Momentum (OAM)**

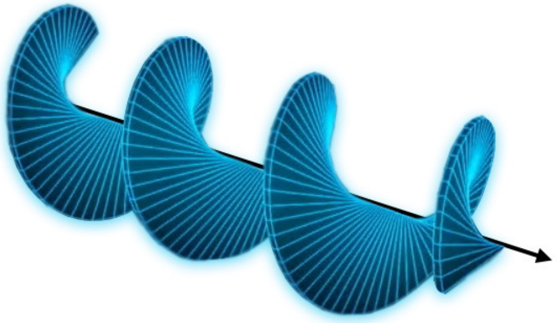
An OAM-based wave possesses a wavefront with a helical phase distribution around the central axis of the beam

$$|E| = A_o J_l(k_t\rho)e^{\left(\frac{-\rho^2}{w_{BG}^2}\right)} e^{(-jm\phi)} e^{(-jkz)}$$ Ref. [1]

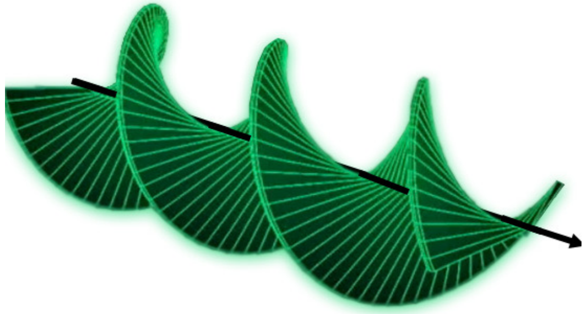
$m = 0, \pm1, \pm2, \ldots$ represents OAM modes



$m = 0$



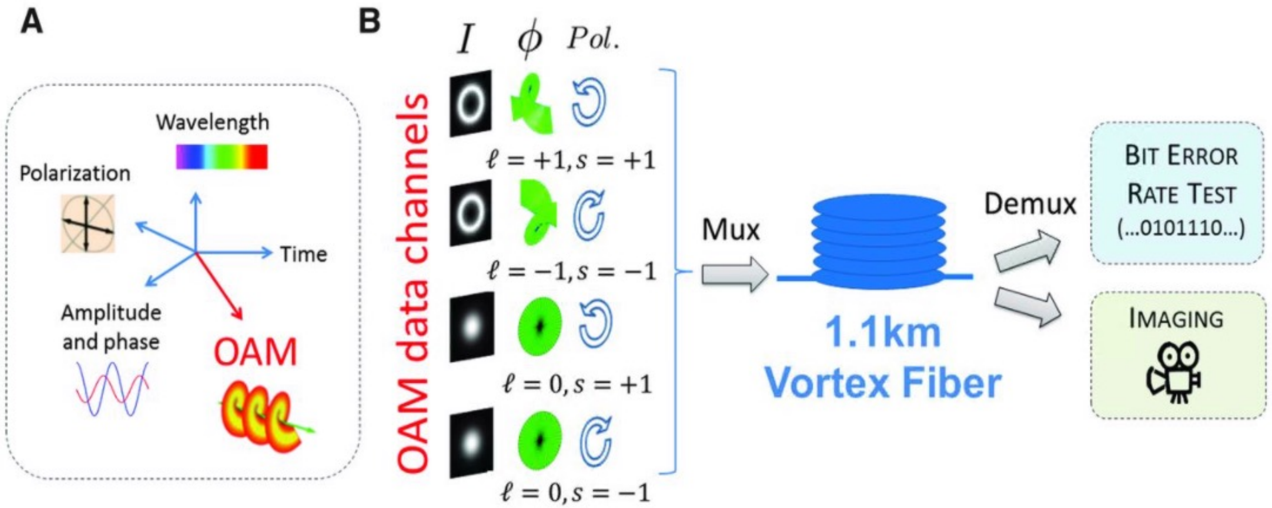
$m = -1$



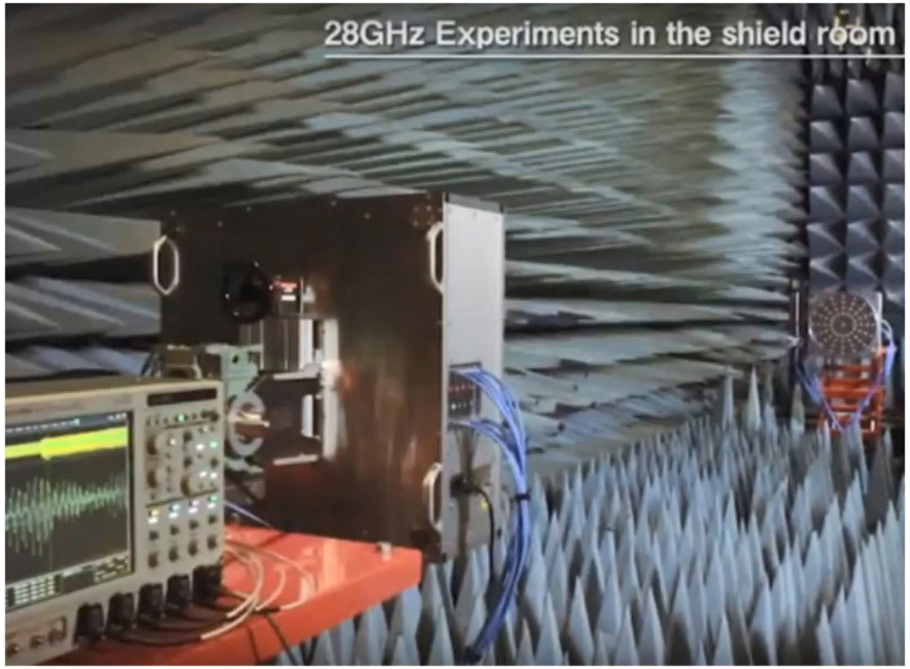
$m = -2$

Applications

- **Enhanced spectral efficiency**
  - Orthogonal modes support spatial multiplexing/demultiplexing



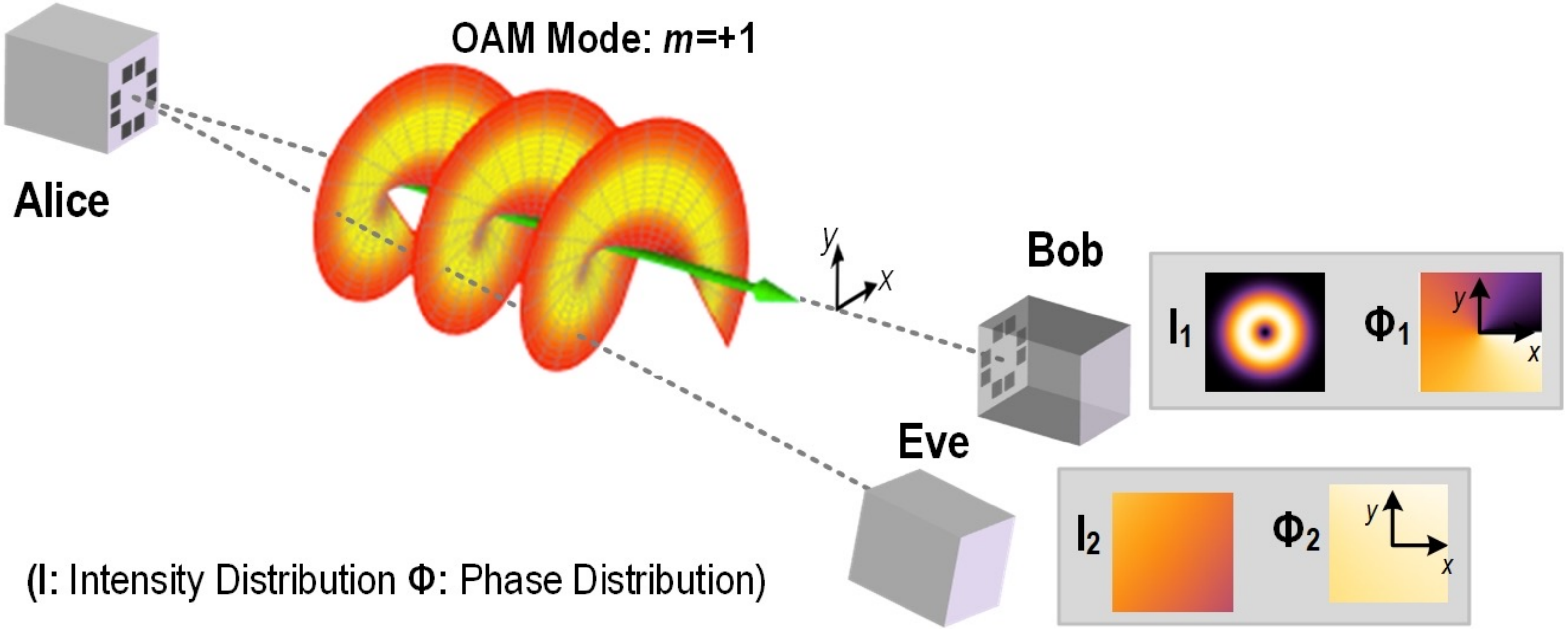
400Gbps using 4-OAM modes at single wavelength
[2] Science 2013



100Gbps using 5-OAM modes at 28GHz
[3] Microwave Journal 2018

Applications

- **Physical-layer security for wireless channels**
  - Require multiple phase-comparing antennas or colluding eavesdroppers



Applications

- **Physical-layer security for wireless channels**
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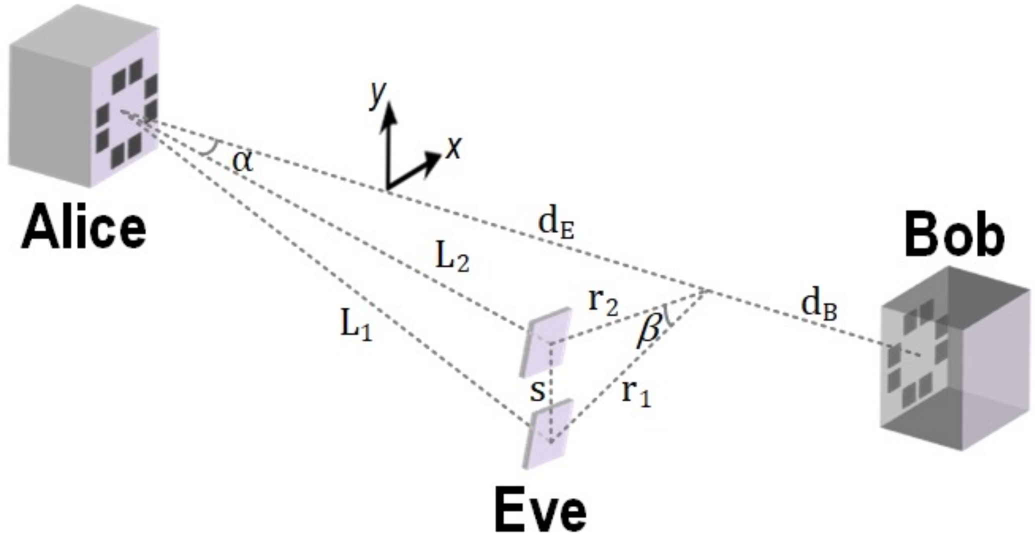
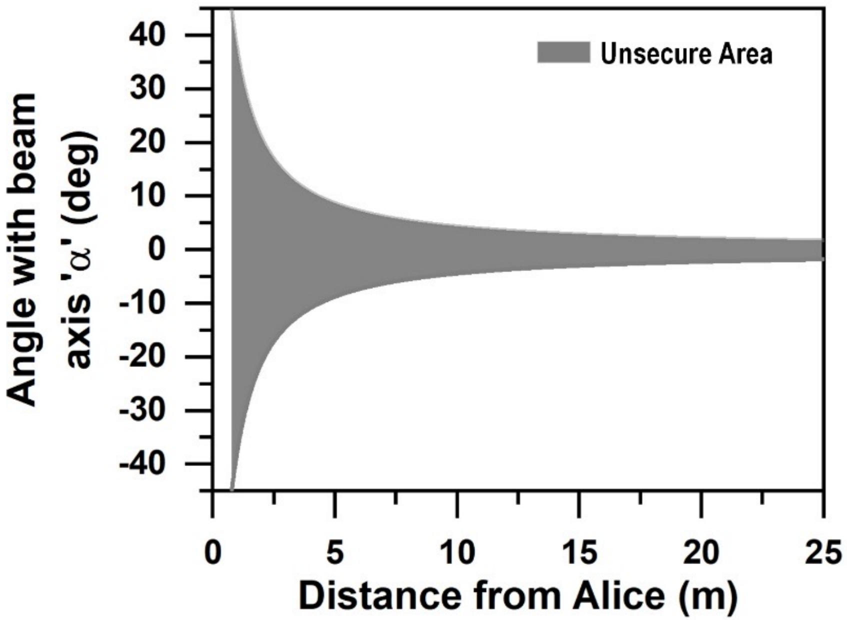


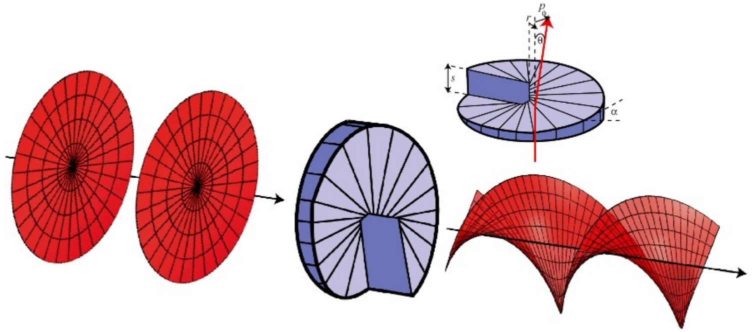
Eve with two phase-comparing antennas



Unsecure area with $L_1 = L_2$, $r_1 = r_2$, $\beta = 15°$

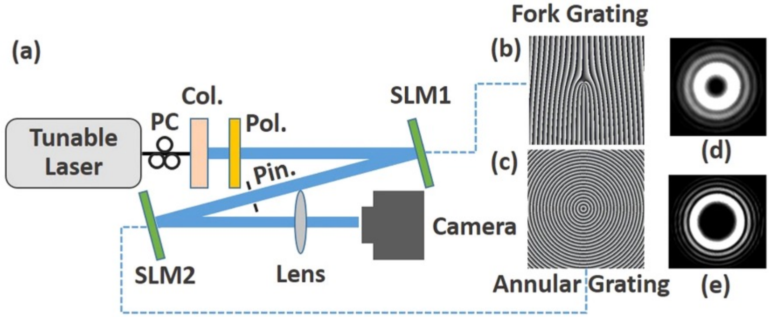
Discrete Systems for Generation/Detection of OAM

1. Spiral Phase Plate (SPP)



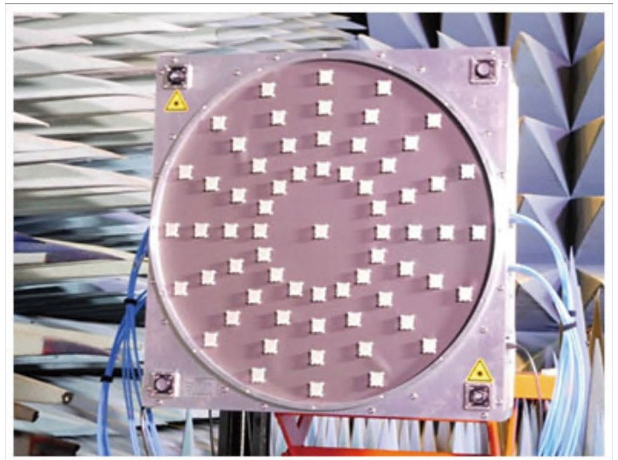
[4] Adv. Optics and Photonics 2011

2. Holographic Gratings

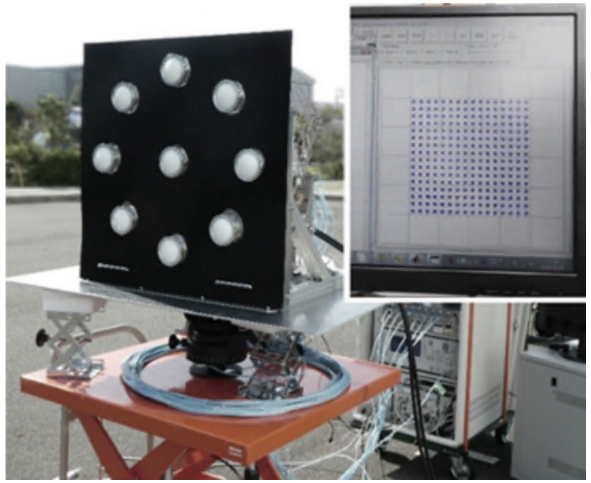


[5] Science Report 2017

3. Circular Antenna Array



[6] NTT Technical Review 2018



[7] NEC News 2020

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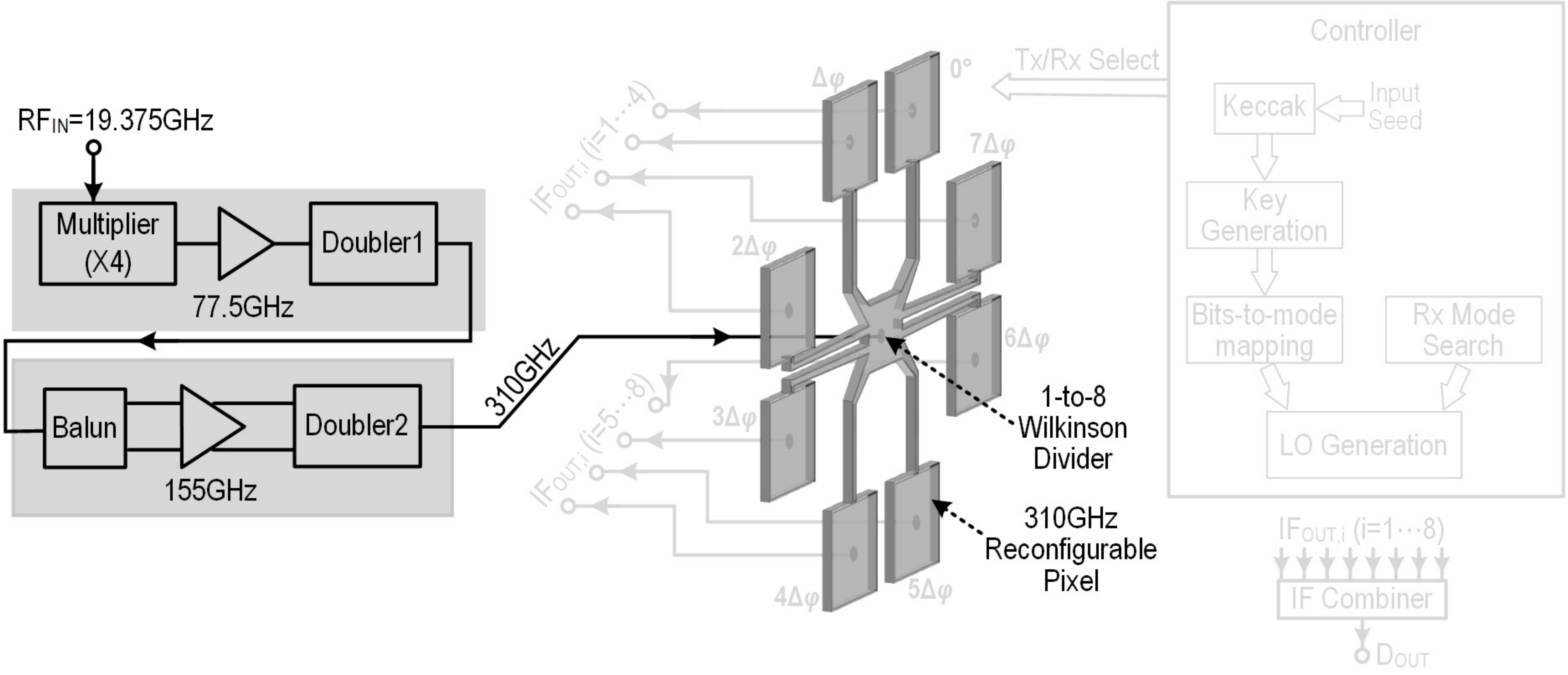
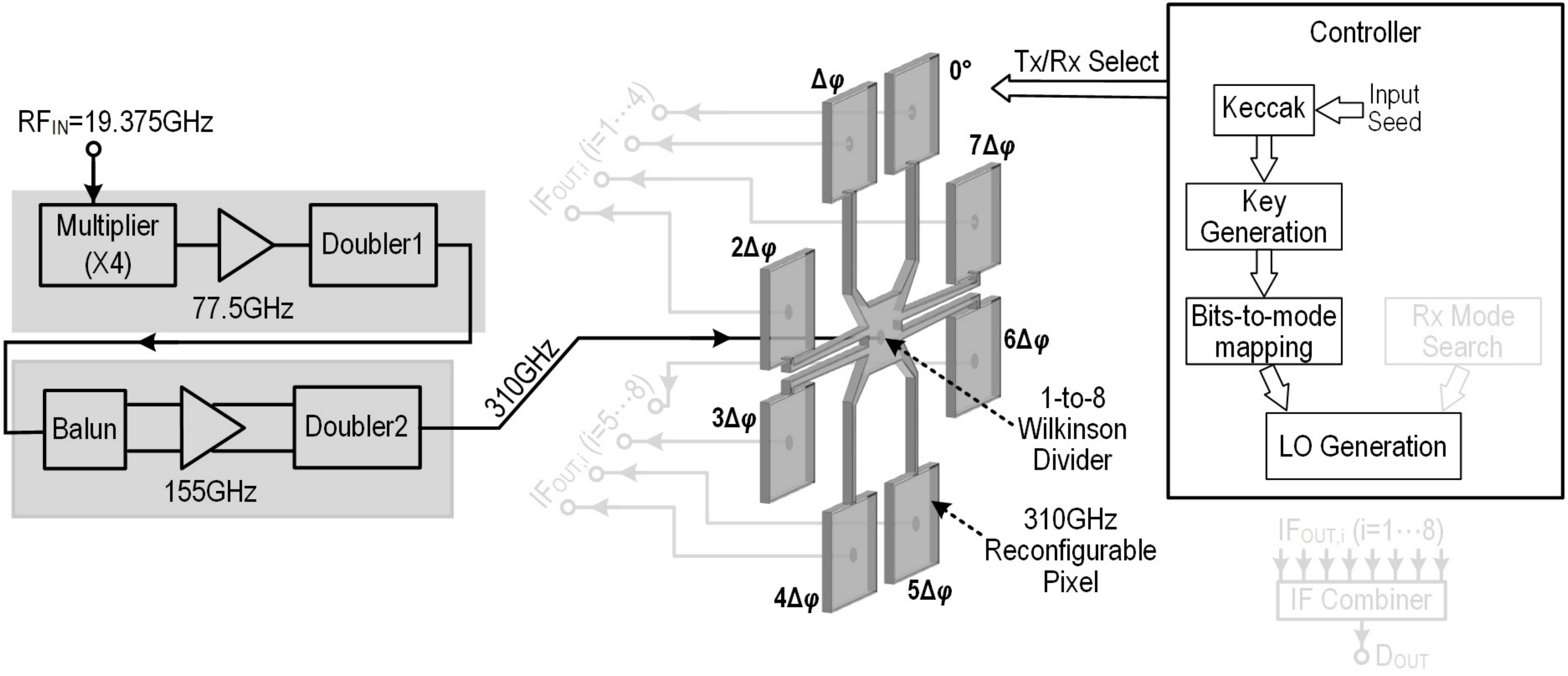
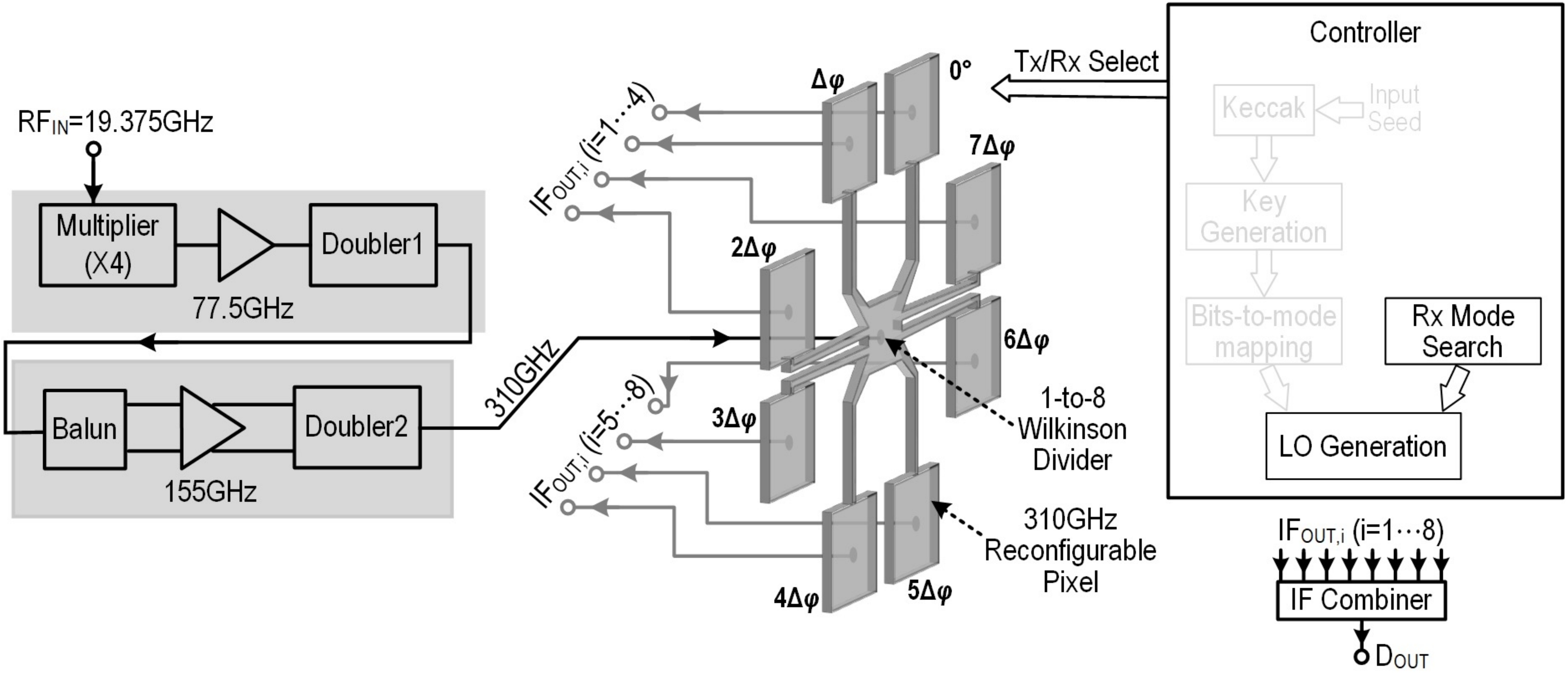
System Architecture



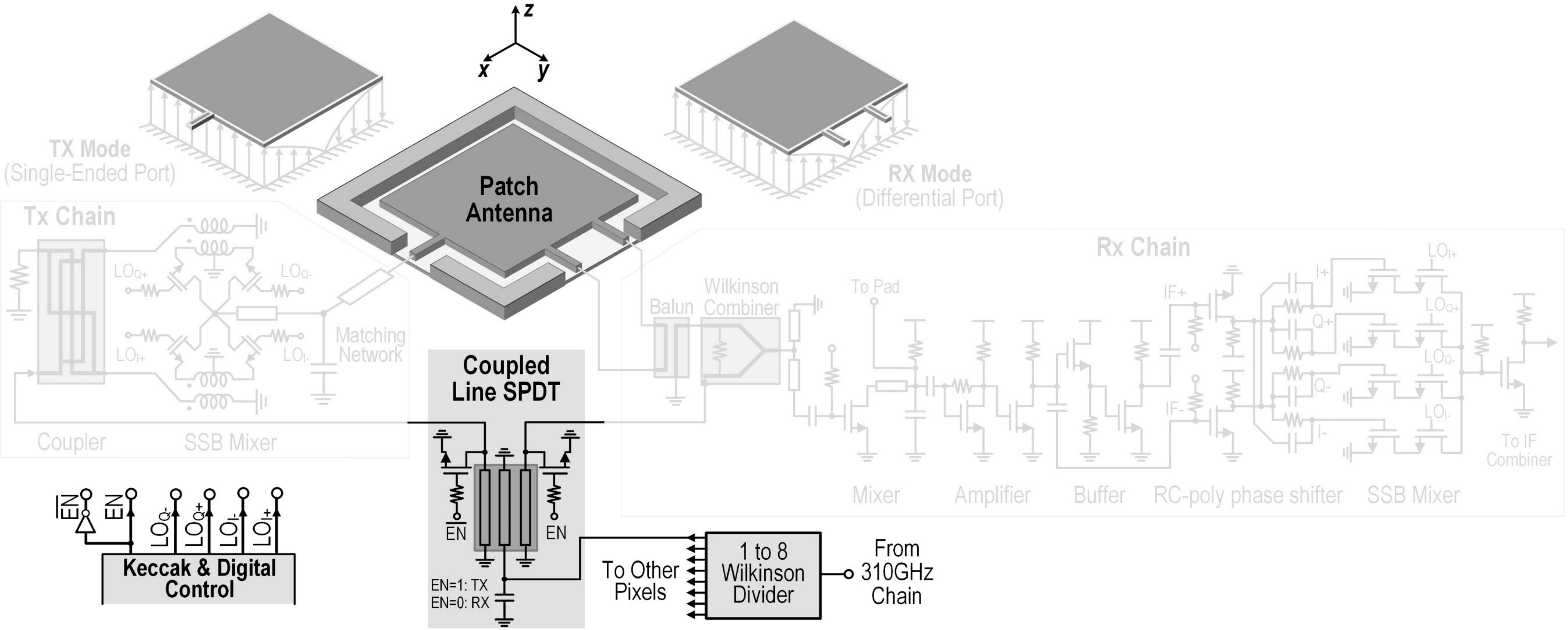
System Architecture (Tx Mode)



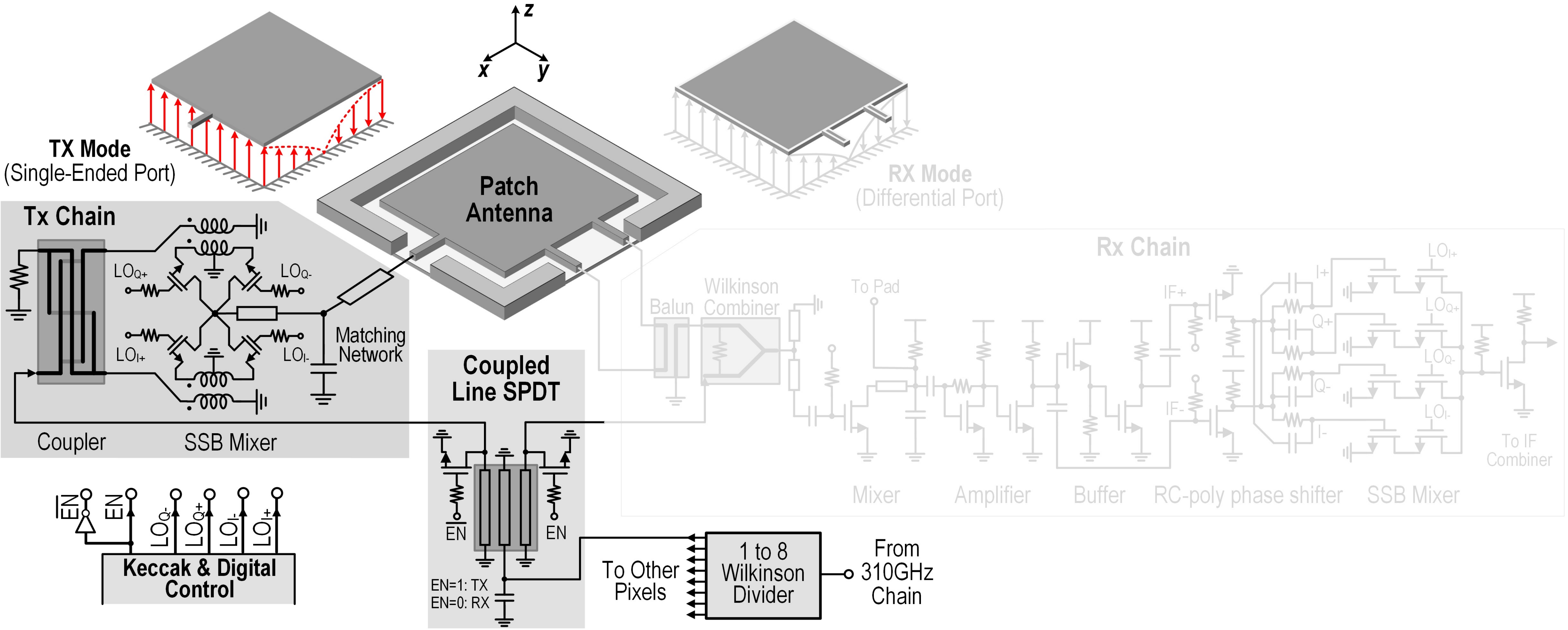
System Architecture (Rx Mode)



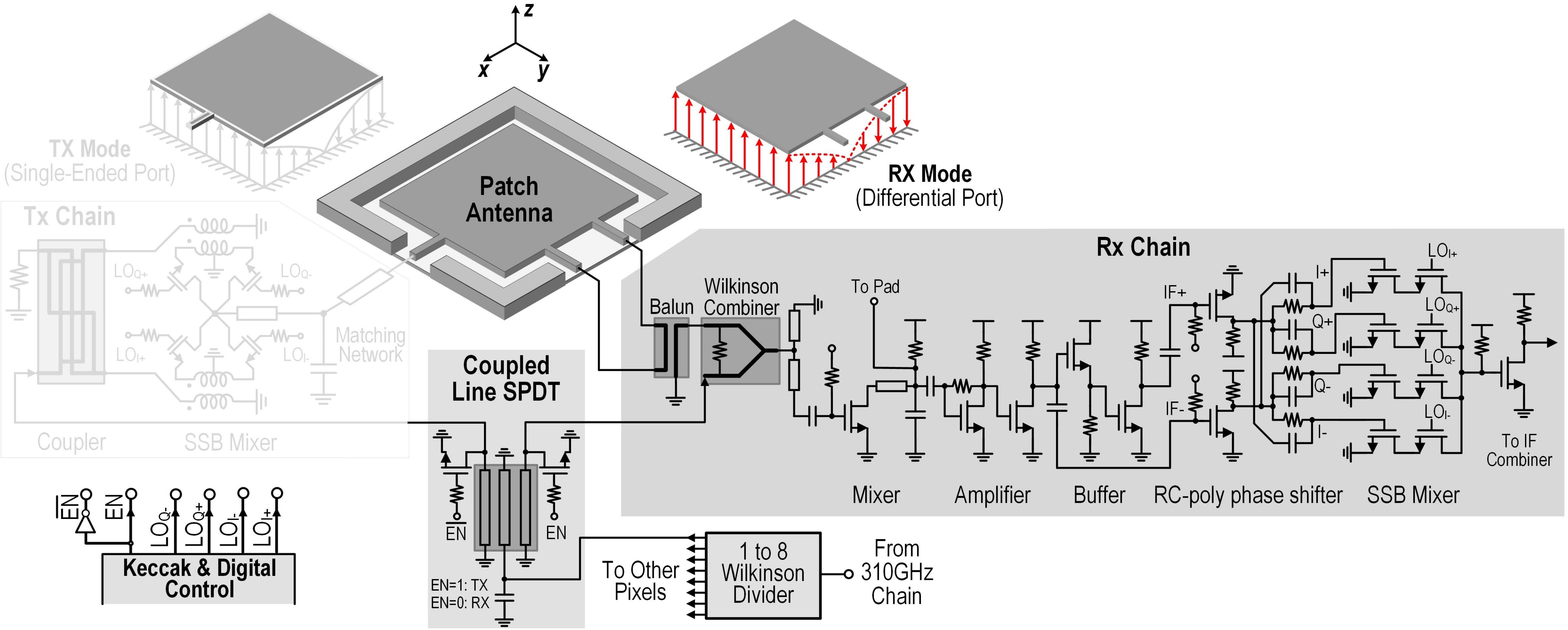
310GHz Reconfigurable Pixel



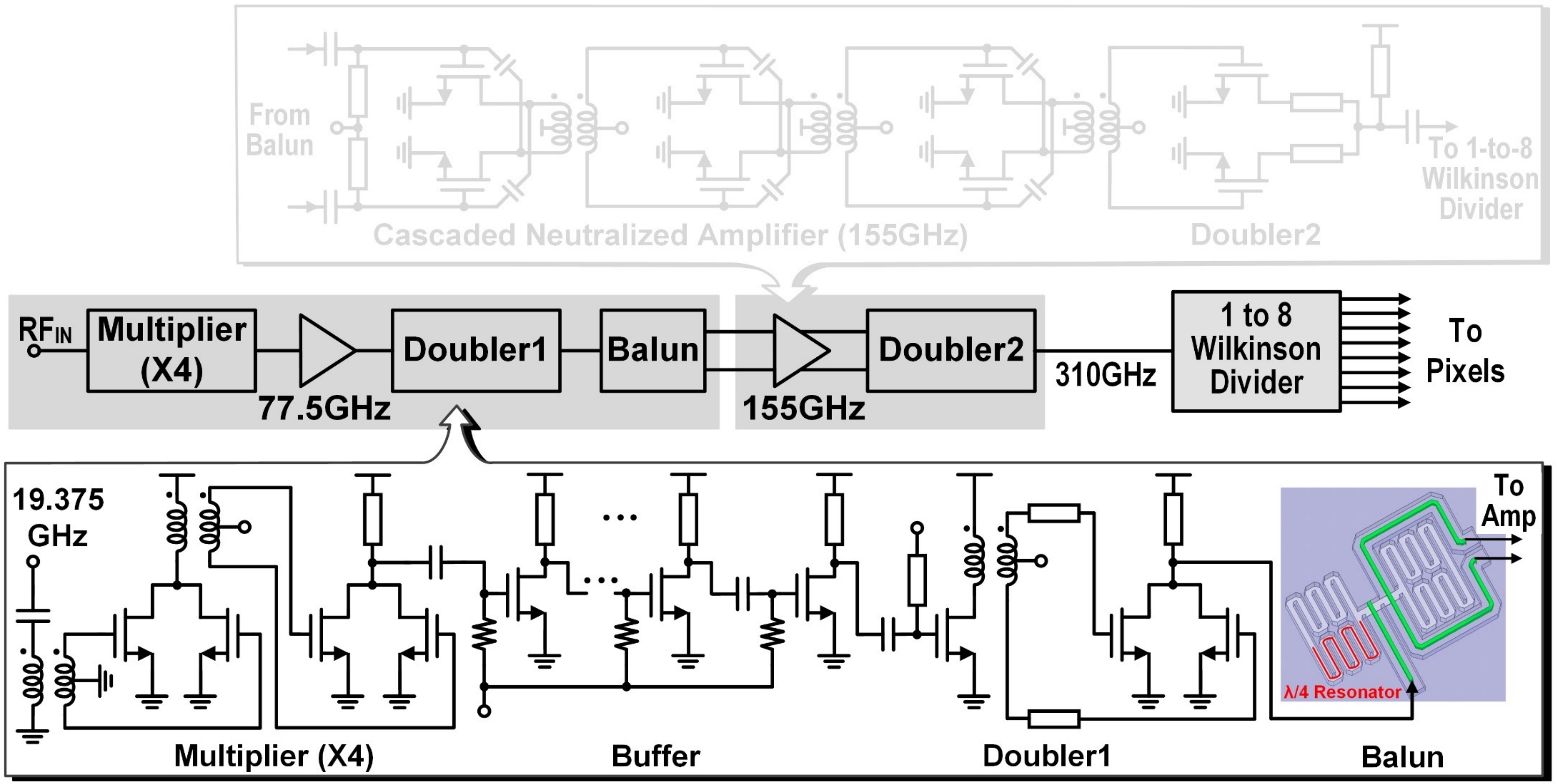
310GHz Reconfigurable Pixel (Tx Mode)



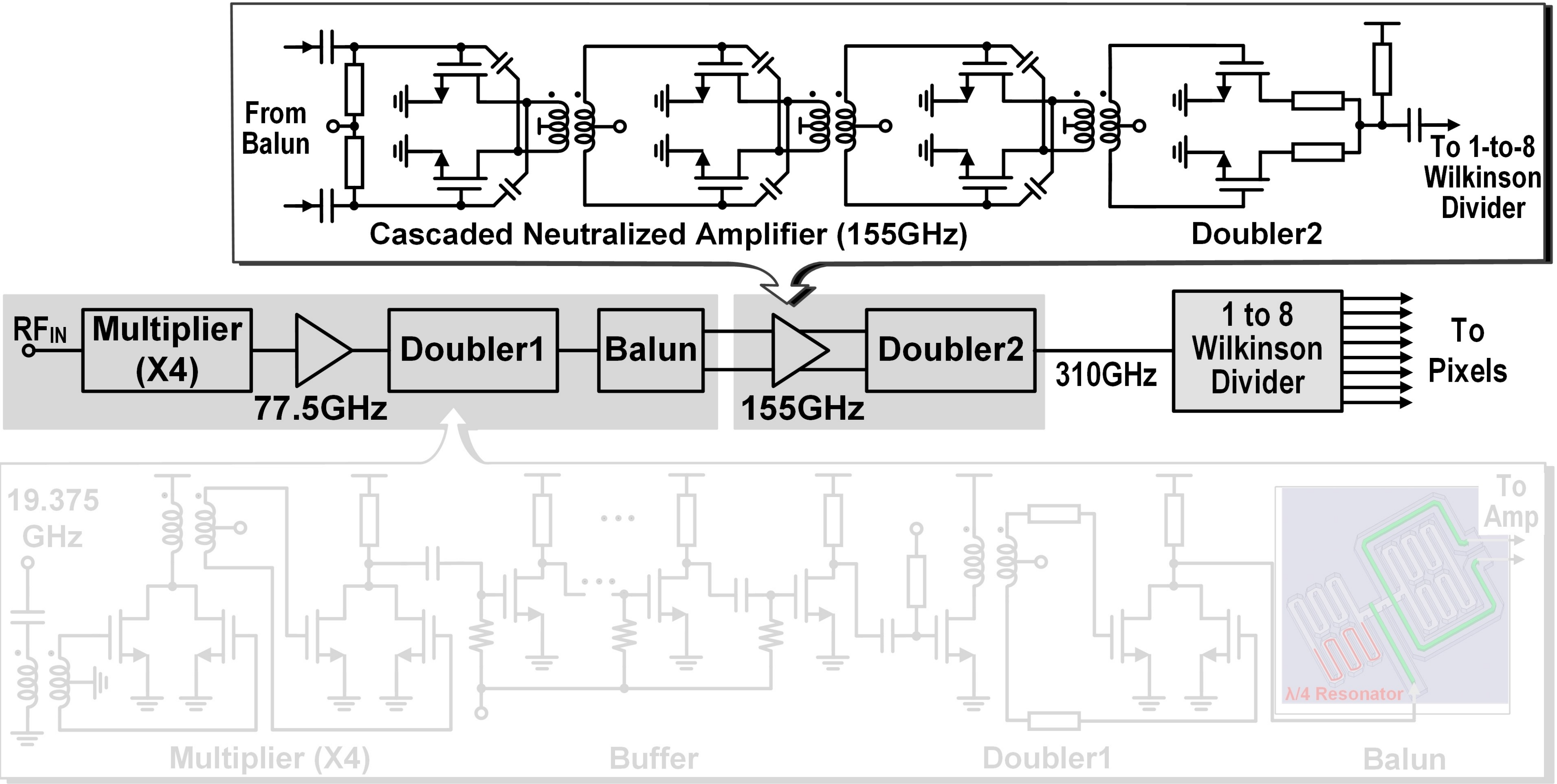
310GHz Reconfigurable Pixel (Rx Mode)



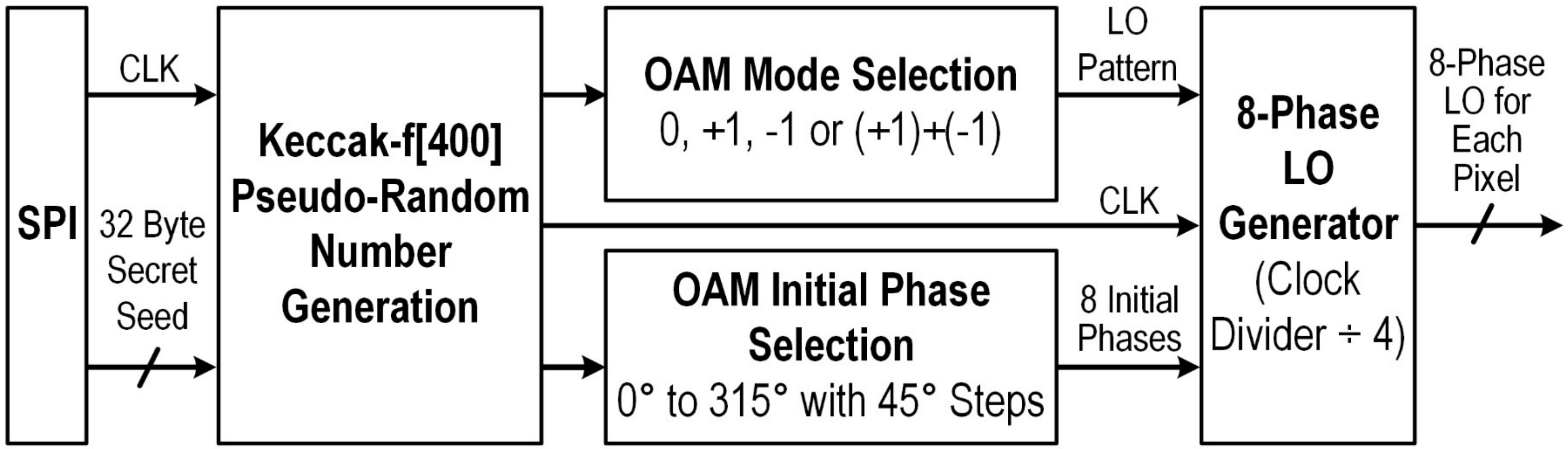
310GHz Amplifier-Multiplier Chain



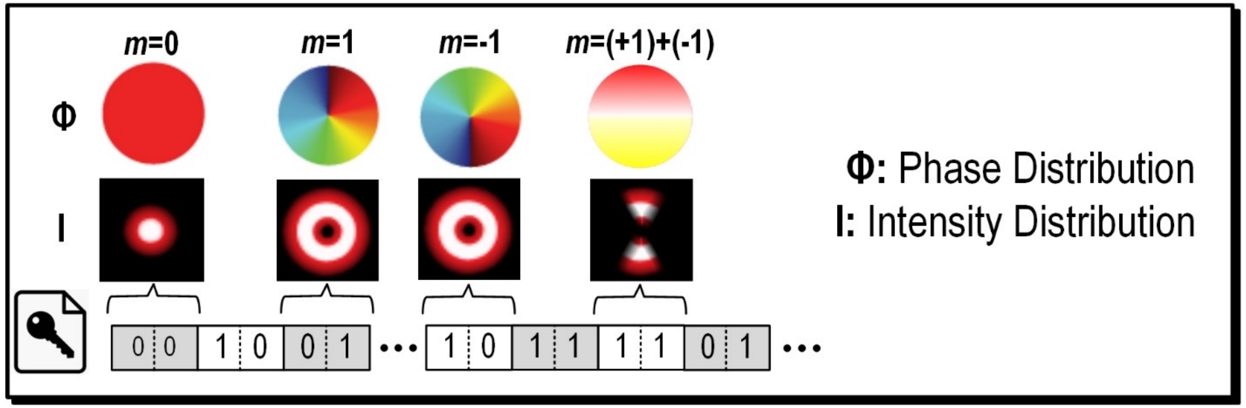
310GHz Amplifier-Multiplier Chain



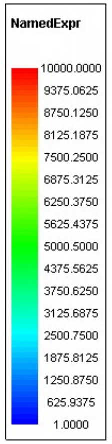
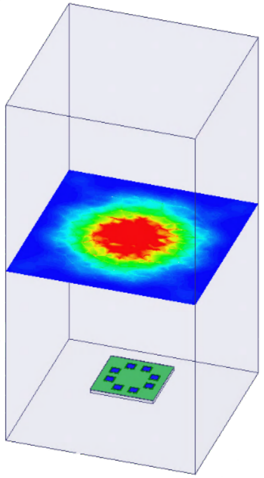
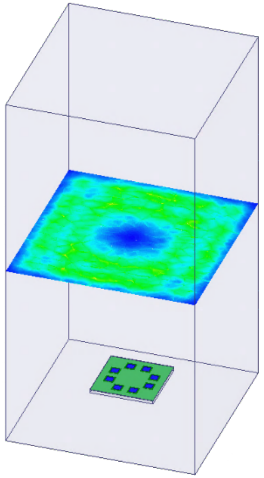
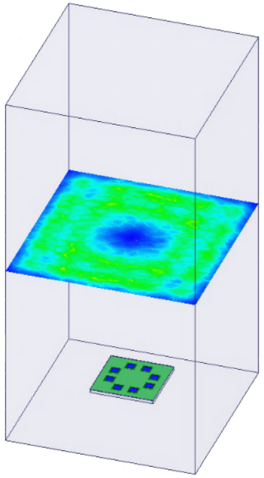
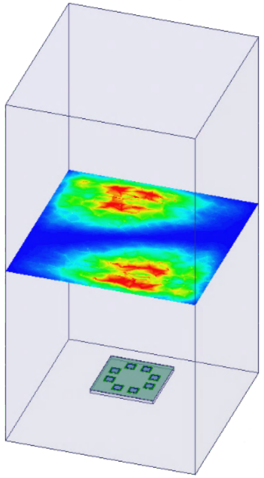
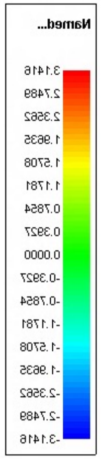
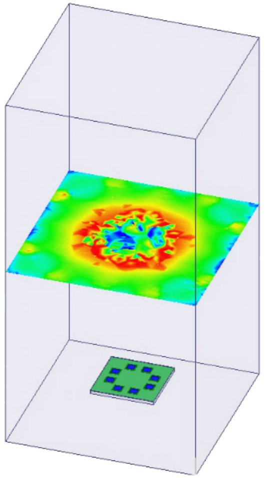
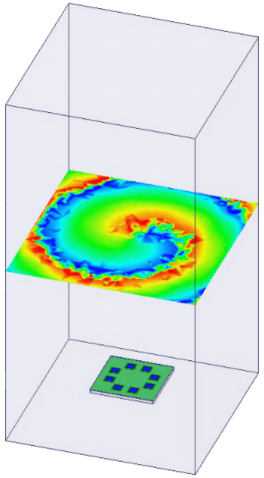
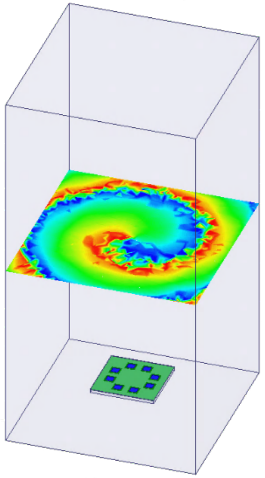
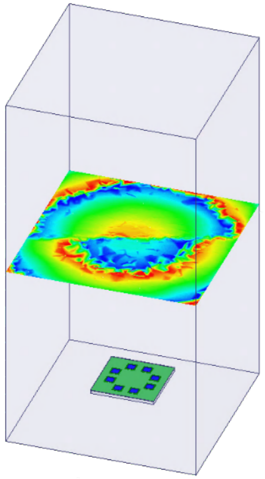
Controller and Key-to-OAM Mapping



Key-to-OAM Mapping



EM Simulation of OAM Modes

OAM Modes	$m = 0$	$m = +1$	$m = -1$	$m = \pm 1$
Intensity Distribution 				
Phase Distribution 				

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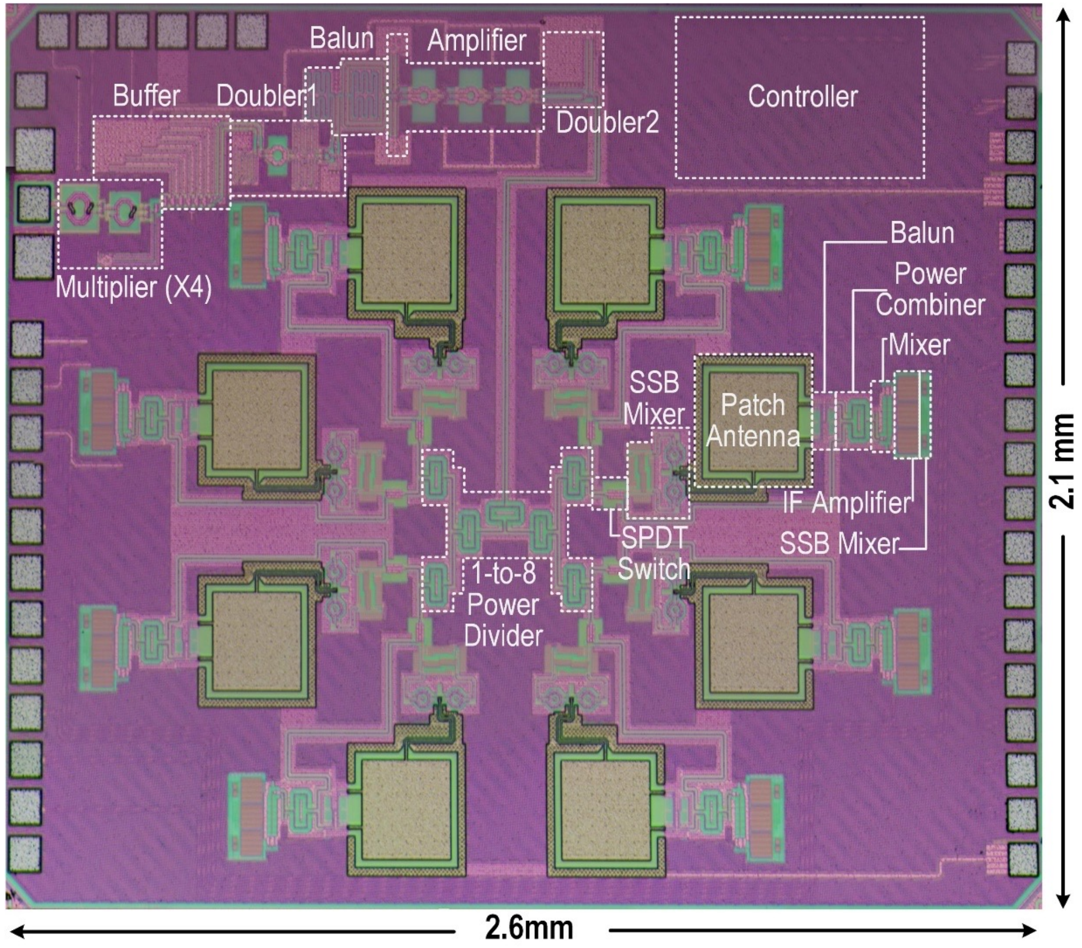
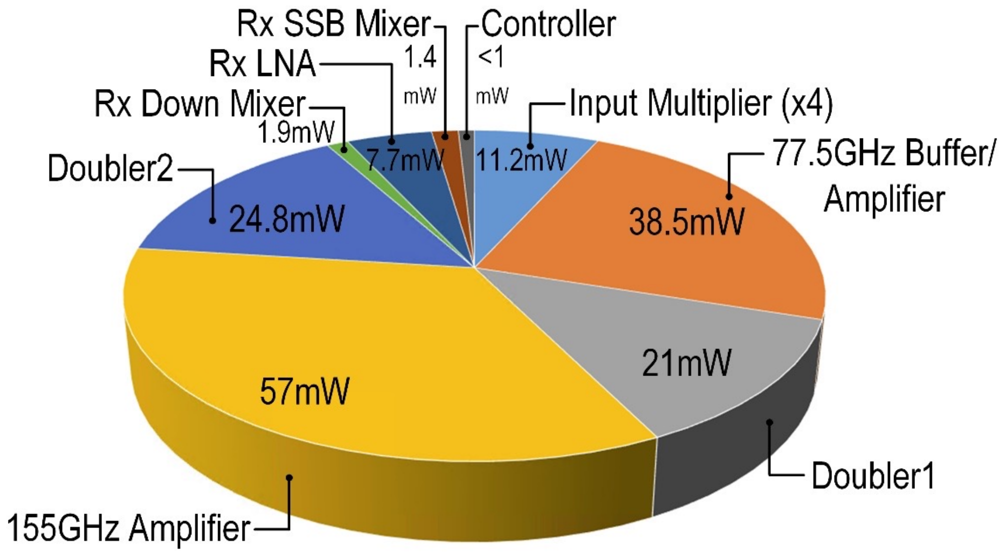
Chip Micrograph and Power Consumption

TSMC 65nm CMOS Process



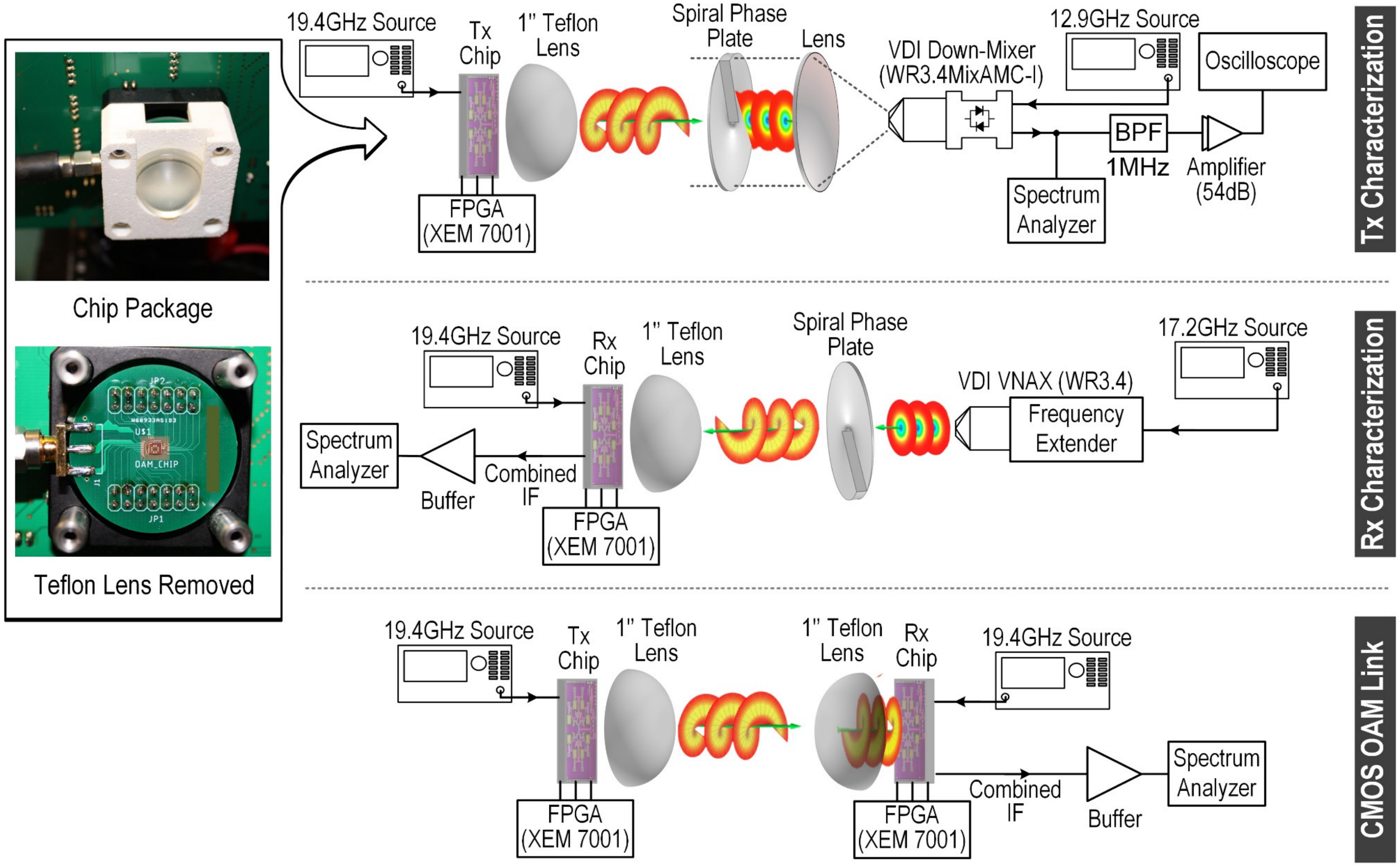
Power Consumption Breakdown



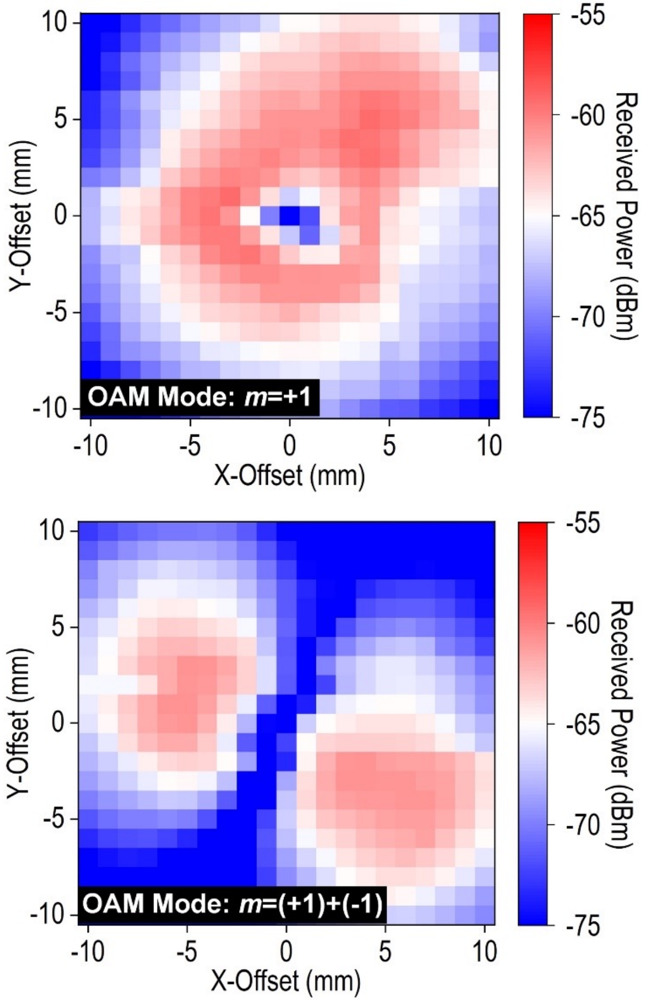
Tx Mode → 154mW

Rx Mode → 166mW

Measurement Setups

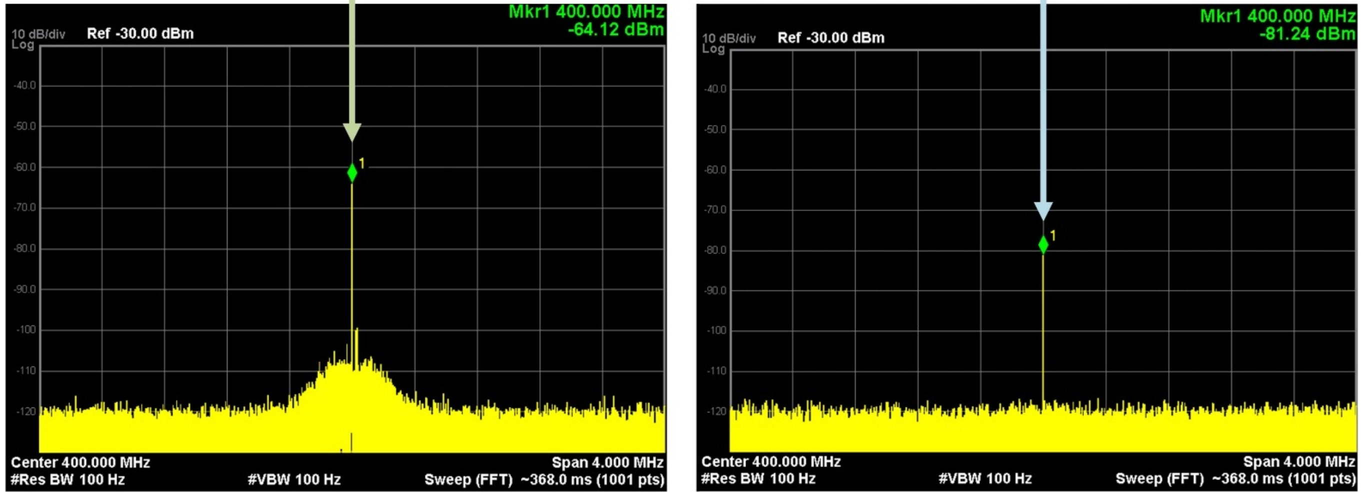


Intensity Profiles and Tx Mode-checking



Measured intensity distribution for m=+1 and m=(+1)+(-1) OAM modes

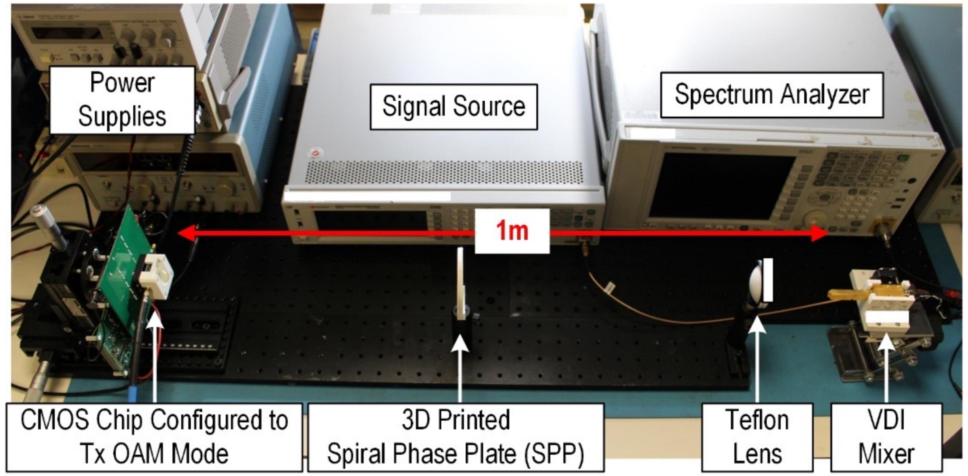
Tx Mode	Rx SPP	P_{RX} (dBm)
0	No SPP	-50
0	+1	-69
0	-1	-70
+1	No SPP	-58
+1	+1	-64
+1	-1	-81
-1	No SPP	-58
-1	+1	-80
-1	-1	-64
±1	No SPP	-76
±1	+1	-68
±1	-1	-67



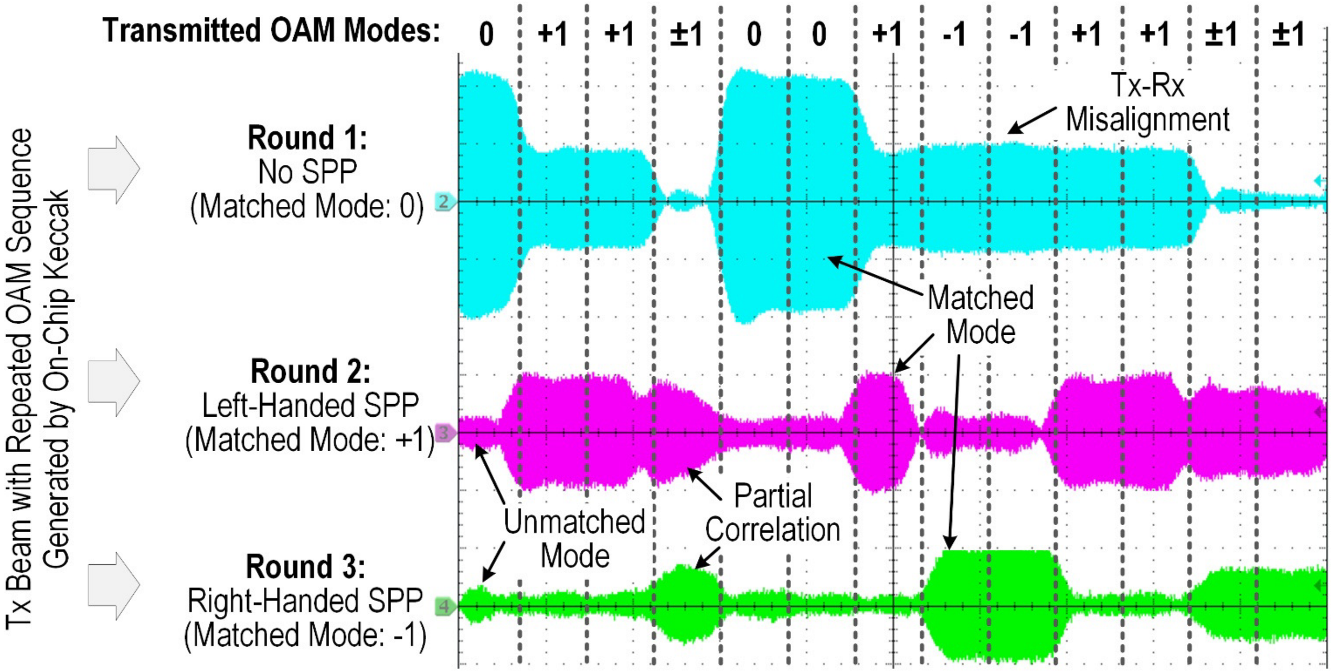
Tx OAM mode-checking

Measured spectrums when Tx chip is m=+1 and Rx SPP is m=+1 and -1

Time-domain Tx OAM Mode-checking

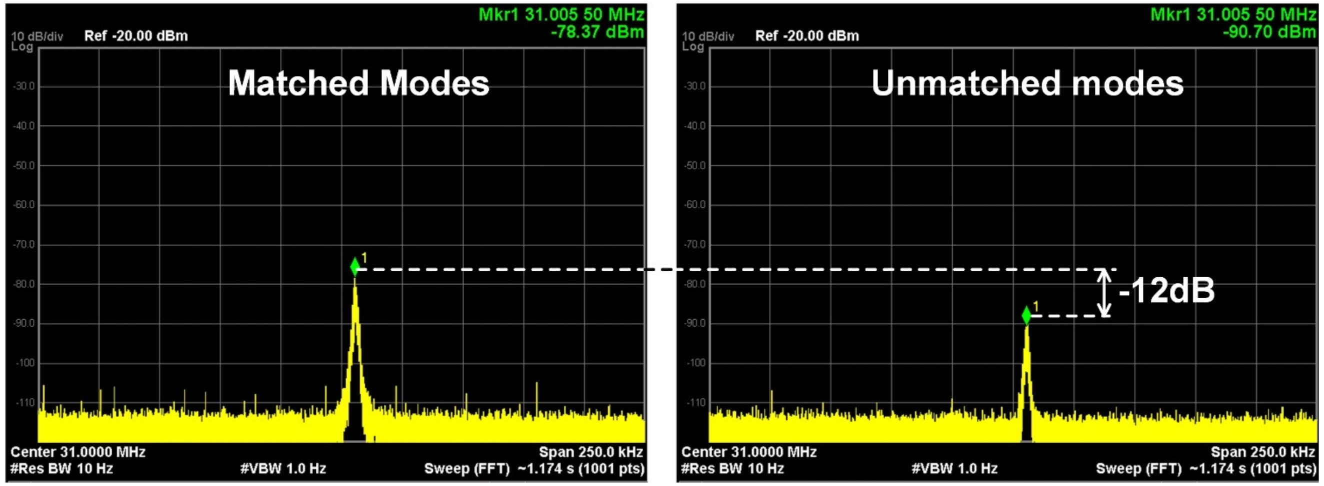


Time-domain OAM mode-checking setup
with 1m Tx-Rx distance

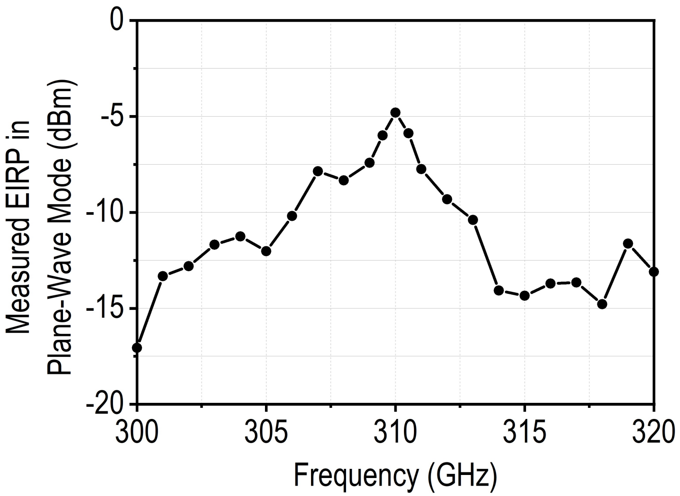


Time-domain output of the Rx configured to respond
to different OAM modes, when it is illuminated by the same
OAM sequence (1Mbps) generated by on-chip Keccak

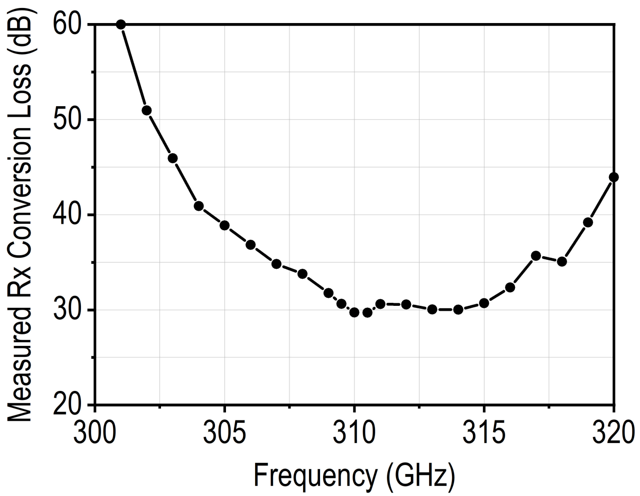
Rx Mode-checking and Tx-Rx Characterization



Measured spectrum of combined IF when OAM modes are matched and unmatched

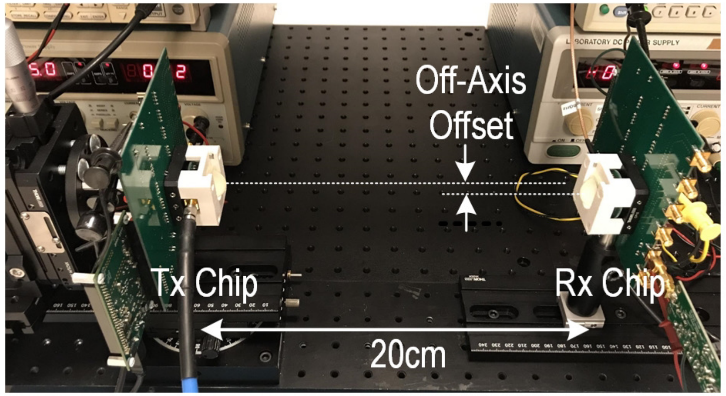


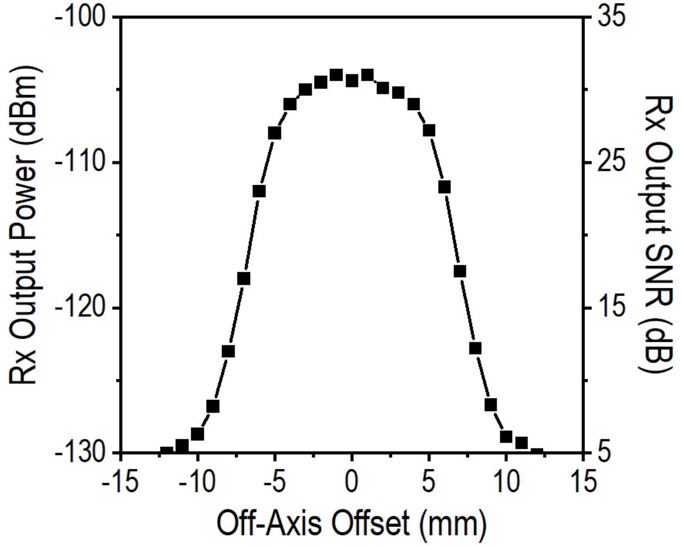
Measured Tx EIRP $(m = 0)$

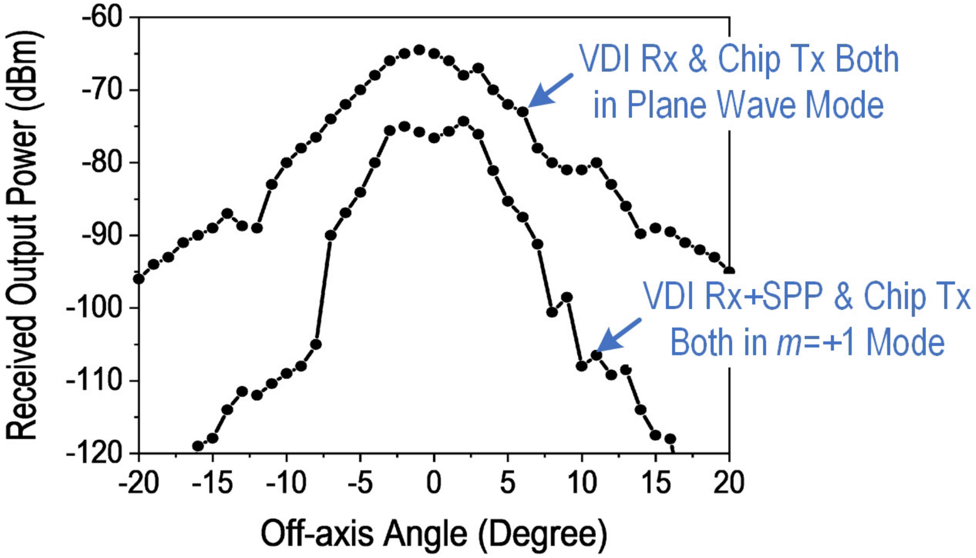


Measured Rx pixel conversion loss

CMOS Tx-Rx OAM Link







Full-silicon OAM link and sensitivity to co-axial alignment

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Comparison with RF and mm-Wave OAM Prototypes

	Nature Comm. '14 [8]	Wireless Comm. '17 [9]	IICCW '20 [10]	This work
Implementation	Discrete Transceivers + SPP + Quasi-Optical Beam Combiner	Active-Driven Antenna Arrays + Parabolic Reflectors	Active-Driven Antenna Arrays	Active-Driven Antenna Array on a 65nm CMOS Chip + Teflon Lens
Frequency (GHz)	28	10	40	310
OAM Modes	±1, ±3	±2, ±3	0, ±1, ±2, ±3	0, +1, -1, ±1
Data Modulation	16QAM/Mode Dual Polarization	32QAM on each mode, Full Duplex	256QAM/Mode Dual Polarization	Bit-to-Mode OAM Hopping
Radiated Power (dBm)	8	0	11.5	-4.8 (EIRP)
Antenna Aperture Diameter (cm)	30	60	120	1.35
Application	Enhanced Spectral Efficiency	Enhanced Spectral Efficiency	Enhanced Spectral Efficiency	Physical-Layer Security
DC Power (mW)	N/A	N/A	N/A	154 (Tx), 166 (Rx)

Acknowledgement

- This work is supported by National Science Foundation EAGER SARE award

- Prof. Yang Yang at University of Technology, Sydney for the spiral phase plates

This work will be presented at RFIC 2021

M. I. W. Khan, J. Woo, X. Yi, M. I. Ibrahim, R. T. Yazicigil, A. P. Chandrakasan and R. Han, "A 0.31THz CMOS Uniform Circular Antenna Array Enabling Generation/Detection of Waves with Orbital-Angular Momentum," 2021 IEEE Radio Frequency Integrated Circuits Symposium (RFIC), Atlanta, GA, USA, 2021 (Best Student Paper Award)

References

1. L. Allen, M. Padgett, and M. Babiker, “The orbital angular momentum of light,” ser. Progress in Optics, E. Wolf, Ed. Elsevier, 1999, vol. 39, pp. 291–372.
2. N. Bozinovic, Y. Yue, Y. Ren, M. Tur, P. Kristensen, H. Huang, A. E. Willner, and S. Ramachandran, “Terabit-scale orbital angular momentum mode division multiplexing in fibers,” Science, vol. 340, no. 6140, pp. 1545–1548, 2013.
3. https://www.microwavejournal.com/articles/30341-ntt-successfully-demonstrates-100-gbps-wireless-transmission-using-oam-multiplexing-for-the-first-time
4. Alison M. Yao and Miles J. Padgett, "Orbital angular momentum: origins, behavior and applications," Adv. Opt. Photon. 3, 161-204 (2011)
5. Zheng, S., Wang, J. "Measuring Orbital Angular Momentum (OAM) States of Vortex Beams with Annular Gratings," Sci Rep 7, 40781 (2017)
6. https://www.ntt-review.jp/archive/ntttechnical.php?contents=ntr201905fa5.html
7. https://www.nec.com/en/press/202003/global_20200310_01.html
8. Y. Yan, X. Guodong, L. Martin P. J., H. Hao, A. Nisar, B. Changjing, R. Yongxiong, C. Yinwen, L. Long, Z. Zhe, M. A. T. Moshe, P. Miles J., and W. Alan E., “High-capacity millimetre-wave communications with orbital angular momentum multiplexing,” Nature Comm., Sep. 2014.
9. W. Zhang, S. Zheng, X. Hui, R. Dong, X. Jin, H. Chi, and X. Zhang, “Mode division multiplexing communication using microwave orbital angular momentum: An experimental study,” IEEE Transactions on Wireless Communications, vol. 16, no. 2, pp. 1308–1318, 2017.
10. H. Sasaki, Y. Yagi, T. Yamada, T. Semoto, and D. Lee, “An experimental demonstration of over 100 Gbit/s OAM multiplexing transmission at a distance of 100 m on 40 GHz band,” in 2020 IEEE International Conference on Communications Workshops, 2020, pp. 1–6.

Thank you!