17.8 A Compact 130GHz Fully Packaged Point-to-Point Wireless System with 3D-Printed 26dBi Lens Antenna Achieving 12.5Gb/s at 1.55pJ/b/m

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Low-cost, energy efficient, high-capacity, scalable, and easy-to-deploy point-to-point wireless links at mm-waves find a variety of applications including data intensive systems (e.g., data centers), interactive kiosks, and many emerging applications requiring data pipelines. Operating above 100GHz enables compact low-footprint system solutions that can multiplex Tb/s aggregate rates for dense deployments; therefore competing with wired solution in many aspects including rate and efficiency, but much more flexible for deployment. The focus is on small-footprint fully integrated solutions, which overcome traditional packaging challenges imposed at >100GHz with commercial and low-cost solutions.

Traditional wireless systems use higher-order modulations to achieve spectral efficiency, often at the cost of energy efficiency. For point-to-point links we exploit the available spatial degrees of freedom (in form of multiplexing with narrow mm-wave beams and alternate polarizations) to relax spectral efficiency requirements and enable improved energy efficiency using an OOK system and duty-cycling the TX. The proposed compact and wideband system is fully packaged with a low-cost flip-chip IC on an organic substrate that includes an antenna-in-package (AiP) feeding an integrated 3D-printed high-gain lens.

Figure 17.8.1 shows the TRX IC block diagram and packaging solution. A wideband single-carrier OOK transmission combined with a non-coherent reception is chosen to drastically improve energy efficiency by eliminating power hungry blocks including synthesizers, quadrature mixers, and other modulator circuits.

Major circuit blocks are detailed in Fig. 17.8.2. The PA, as one of the main power bottlenecks, is cycled ON/OFF for OOK operation. Cycling the 130GHz oscillator for OOK modulation at >10Gb/s would lead to larger total power consumption due to fast settling constraints and is avoided. A single-stage differential standard cascode PA (diff-PA) is chosen to provide adequate mm-wave gain, bandwidth (BW), and output power while maintaining reliability margins for breakdown constraints. A P_{out} of ~10dBm is achieved with 21% efficiency under modulation. The 2:1 output balun provides both impedance transformation, which enhances the gain, and ESD protection. To create the OOK modulation, the PA tail current is switched by *M4-M5*, which bias or short out the current source (*M2*). Rise/fall times are maintained below 15ps. *M3* sustains a minimum trickle current path. The diff-PA consumes 30mA in ON and 1mA in OFF mode, which is optimized for transition speed and stability of the PA as well as the VCO loaded with the PA input.

The VCO is a common-collector Colpitts oscillator (Fig. 17.8.2) with a tank based on L_1 and NMOS varactors. $\lambda/4$ T-lines connect the collector to a 1.5V supply and the emitter to ground. R_b, in the common-mode (CM) bias path, suppresses CM gain and oscillation. A 12mA current bias ensures startup and sufficient drive amplitude under PVT, verified with measurement across multiple samples and packages.

The 130GHz LNA (Fig. 17.8.2) is designed for low NF, low power and achieving BW>15GHz. The first stage is biased at NF_{min}. A small gain-boosting inductor is placed in the base of Q_{1-B} whose size is determined as a trade-off between gain and stability considering PVT margins. The next stages are biased for maximum gain to drive the envelope detector (ED). Bandwidth extension is achieved with series cascode inductors between Q_{X-A} and Q_{X-B}. The simulated gain and NF of the LNA is respectively 26dB and 9.5 to 10dB. The nominal input P_{1dB} is -38dBm. The LNA consumes 24mW in nominal and 16.5mW in low-power (LP) mode, which has a gain of 15dB and a minimal effect on other metrics, as depicted in Fig. 17.8.2.

To further reduce the power consumption of the RX, while maintaining >15GHz BW, we opted for direct detection of 130GHz OOK signals using an ED, which is optimized for gain and NF. This was compared to heterodyne schemes, or direct detection using mixers, which are power hungry. With the choice of an optimum current density for maximum gain (enhanced nonlinearity regime), and device size to fulfill the NF requirement based on input power, the ED consumes only 750μW, with NF<15dB at input sensitivity levels.

To address the stringent link requirements, and also to utilize spatial degrees of freedom and to suppress interference, very-high-gain compact antennas with large BW, narrow beamwidth, and low leakage to the cross-polarization are needed. We target low-cost solutions with >30dBi gain and >20GHz BW at 130GHz.

Our design relies on 3D printing and low-loss-organic BGA-packaging techniques (Fig. 17.8.3). A 2×2 aperture-coupled patch-antenna array with a large BW illuminates the elliptical lens for maximum directivity. The additional substrate-integrated grounded cavity minimizes unwanted TM_0 surface waves. The array is optimized to achieve a directivity of 10 to 11dBi necessary for appropriate illumination of the lens. The input match covers 96 to 142GHz and 10.9dBi (±0.4) directivity is measured at 116 to 140GHz. An extended hemispherical lens, made of basic low-cost ABS-M30 plastic material (used extensively in classic 3D printers), is chosen for achieving a high gain in a small form factor. In order to reduce the dielectric losses and minimize the sensitivity to manufacturing imperfections, the lens is designed as a hollow shell with optimized removal of internal volume (Fig. 17.8.3). Measurements with the lens show S_{11}<-10dB, antenna gain >26dBi and polarization purity >25dB above 114GHz. The small discrepancies between measured and simulated gain is mainly due to a 1° residual misalignment in measurements setup in addition to not being entirely in far-field (at 80cm) due to setup limitations.

Figure 17.8.4 shows the setup for measurement of the TX spectrum and EIRP. The VCO tunability range is 123 to 131GHz (Fig. 17.8.4), and the EIRP of 16.3dBm (9.3dBm P_{out}, 8dBi measured BGA gain, 1dB flip-chip loss) and 32.5dBm (2.8dB lower than expected due to likely residual misalignments) is measured without and with lens, respectively. In order to perform measurements using a single BERT and also observe the performance in complex mm-wave channels, a metal reflector is used to close the TX-RX loop when transceivers are placed side by side with an absorber in between to avoid direct feedthrough paths (Fig. 17.8.5). Even in the complex/non-ideal extended channel formed by the reflector, 12.5Gb/s data transmission with 10^{-6} BER is measured at 5m. At short-range (50cm LoS) and LP mode, 11.5Gb/s with 10^{-6} BER is achieved with 25% lower power consumption (Fig. 17.8.7).

Figure 17.8.6 shows the comparison table with state-of-the-art high-speed TRXs. FOM_1 (energy/bit/range) is improved by >40× compared to [1-6] owing to the high gain yet compact antenna that together with the efficient TRX places this system in competition with wired solutions. FOM_2 represents the maximum achieved EIRP for a given power consumption at TX and achieves 131× improvement. Figure 17.8.7 shows the pad-limited 1.62×1.98mm² die micrograph in 55nm BiCMOS (active area of 0.4mm²).

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References:
[1] C. Byeon, et al., "A 67mW 10.7Gb/s 60GHz OOK CMOS Transceiver for Short-Range Wireless Communications," *IEEE TMTT*, vol. 61, no. 9, pp. 648-650, Sept. 2013.
[2] Z. Wang, et al., "A CMOS 210-GHz Fundamental Transceiver with OOK Modulation," *IEEE JSSC*, vol. 49, no. 3, pp. 564-580, Mar. 2014.
[3] S. Shahramian, et al., "A 16-Element W-Band Phased Array Transceiver Chipset with Flip-Chip PCB Integrated Antennas for Multi-Gigabit Data Links," *IEEE RFIC*, pp. 27-30, May 2015.
[4] S. Thyagarajan, et al., "A 240GHz Fully Integrated Wideband QPSK Receiver in 65nm CMOS," *IEEE JSSC*, vol. 50, no. 10, pp. 2268-2280, Oct. 2015.
[5] R. Wu, et al., "A 42Gb/s 60GHz CMOS Transceiver for IEEE 802.11ay," *ISSCC*, pp. 248–249, Feb. 2016.
[6] K. Tokgoz, et al., "A 56Gb/s W-Band CMOS Wireless Transceiver," *ISSCC*, pp. 242-243, Feb. 2016.
[7] G. Mangraviti, et al., "A 4-Antenna-Path Beamforming Transceiver for 60GHz Multi-Gb/s Communication in 28nm CMOS," *ISSCC*, pp. 246-247, Feb. 2016.

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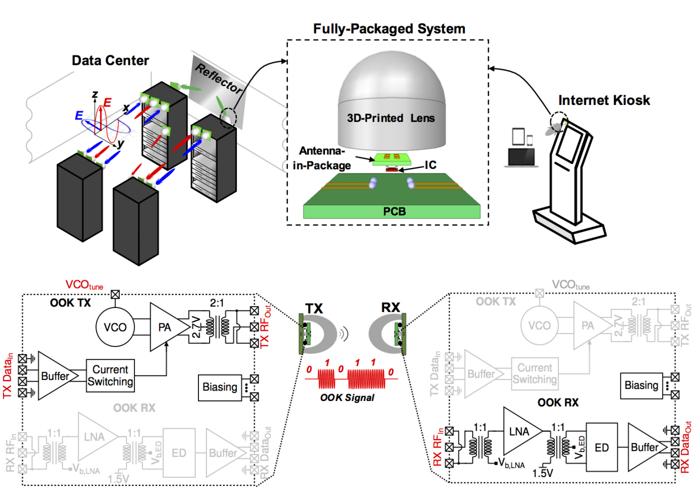

Figure 17.8.1: Low-cost, energy-efficient, high-capacity, scalable and easy-to-deploy point-to-point wireless links: applications (top), block diagram of the TRX (bottom).

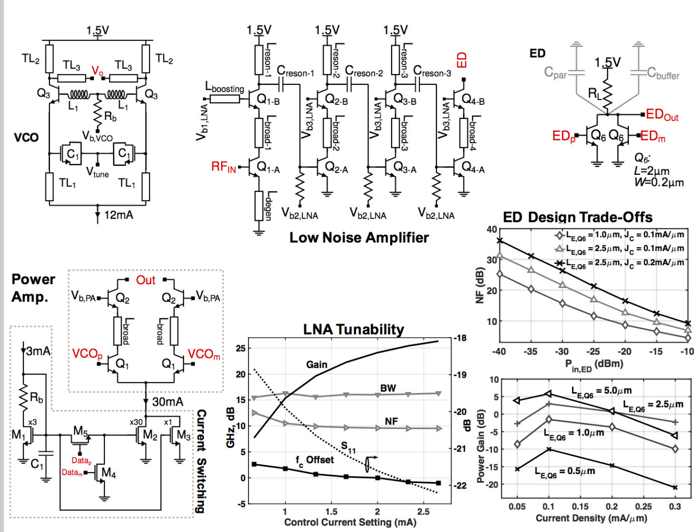

Figure 17.8.2: Detailed schematics of the OOK TRX with design trade-offs.

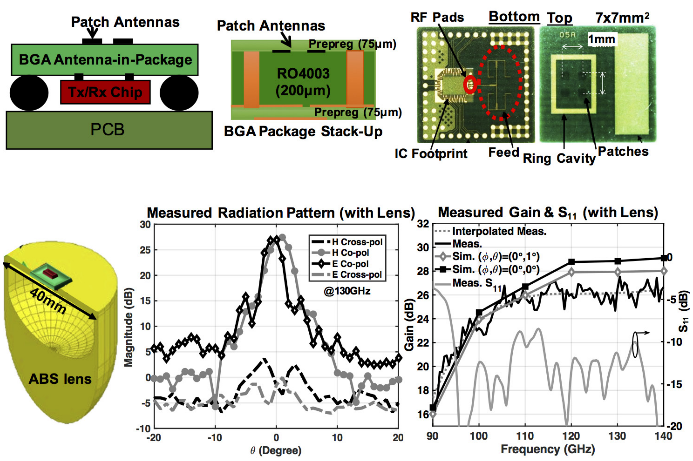

Figure 17.8.3: Antenna-in-package, BGA stack-up, fabricated BGA, cross-sectional view of the lens, E/H-plane radiation patterns at 130GHz, gain vs frequency, and input match.

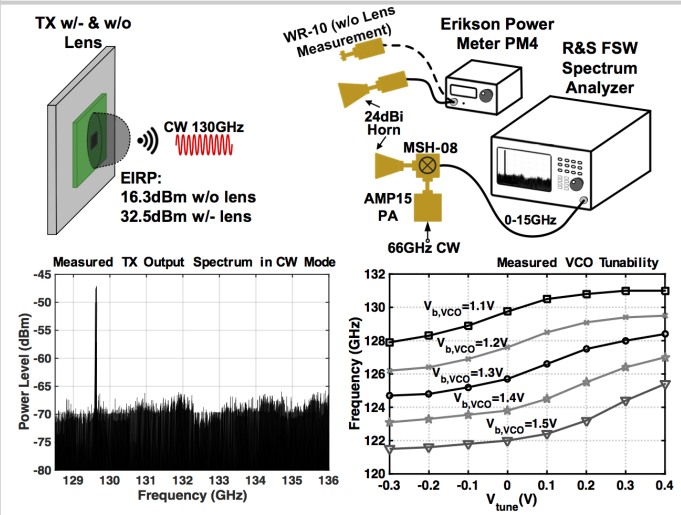

Figure 17.8.4: Transmitter characterization (top), measurements of CW output spectrum and VCO tunability (bottom). This measurement setup is also used to measure output power and EIRP w/- and w/o the lens.

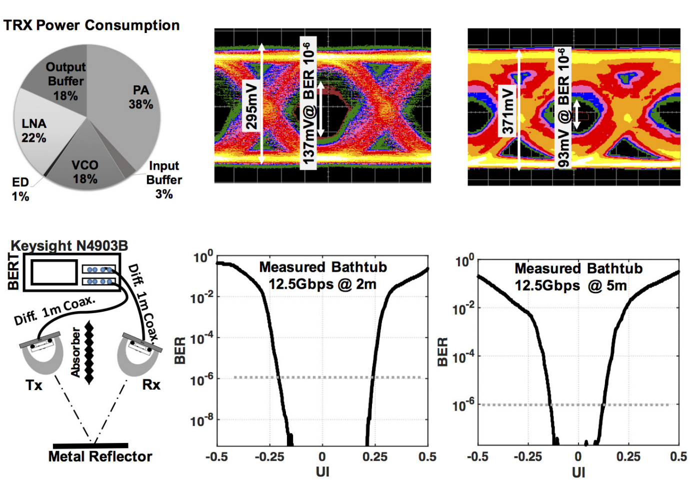

Figure 17.8.5: Transceiver power consumption breakdown, TRX end-to-end measurement setup with the reflector, eye diagram and bathtub curves for data transmission at 2m and 5m.

Reference	[1] MTT'13	[2] JSSC'14	[3] RFIC'15	[4] JSSC'15	[5] ISSCC'16	[6] ISSCC'16	[7] ISSCC'16	This Work Nom. Mode	This Work LP Mode
Technology	90nm CMOS	32nm SOI	180nm BiCMOS	65nm CMOS	65nm CMOS	65nm CMOS	28nm CMOS	55nm BiCMOS	
f_c / BW (GHz)	60/14	210/14	90/20	240/7.6	60/9	77/9-94/8	60/2	130/15	
Data Rate (Gbps) / Modulation	10.7 OOK	10■ OOK	4.8 QPSK	16▲ QPSK	42.24 64QAM	56 16QAM	10.5● 64QAM	12.5★ OOK	11.5★ OOK
Range (m)	0.1	0.035	20	0.02	0.03	0.1	1	5	0.5
Power Consumption (mW)	TX: 31 RX:36	TX: 240 RX: 68	TX: 5500 RX: 4500	TX: 220 RX:260	TX: 544 RX: 432	TX: 260 RX: 300	TX: 670 RX: 431	TX: 59 RX: 38	TX: 49 RX: 24
Energy Efficiency (pJ/bit)	6.26	30.8	2083	30	23.1	10	105	7.76	6.3
TX P_{out} / element (dBm)	4.4	4.6	8	0	7	-8.4	7.5	9.5 (Nom.)	
TX Eff. / element ($P_{out}/P_{dc,TX}$)	8.90%	4.8%	1.8%	0.45%	1.80%	0.06%	3.7%	15% (Nom.)	
Integration Level	Fully-Packaged	Chip (On-chip Ant.)	Fully-Packaged	Chip (On-chip Ant.)	Chip+ Ext. Horn Ant.	Chip+ Ext. Horn Ant.	Fully-Packaged	Fully-Packaged w/ Lens	
Die / Active Area (mm²)	1.92/0.44	4.62/-	24.5/-	2/-	17.64/7.18	6/-	7.9/-	3.2/0.4	
Total System Area▽ (mm²)	35.92	4.62	-	2	NA	NA	44✦	1256 (R_{lens}=20mm)	
FoM_1 (pJ/bit/m)	62.6	880	104.1	1500	770	100	105	1.55	12.6
FoM_2 ($EIRP/P_{dc,TX}$)	0.455	0.138	0.457	0.006	NA	NA	0.37	60 (w/- lens Nom.) 1.12 (w/o lens Nom.)	
FoM_3 ($Range/\sqrt{Total\ Area}$)	16.7	16.3	-	14.2	NA	NA	150.7	141.1	14.1

■ No wireless OOK data transfer at this rate. ▲ BER = 10^{-4} ● BER = 10^{-3}
✦ Approximated. ★ BER = 10^{-6} ▽ Total area including antenna and chip.

Figure 17.8.6: Performance comparison to state-of-the-art mm-wave transceivers.

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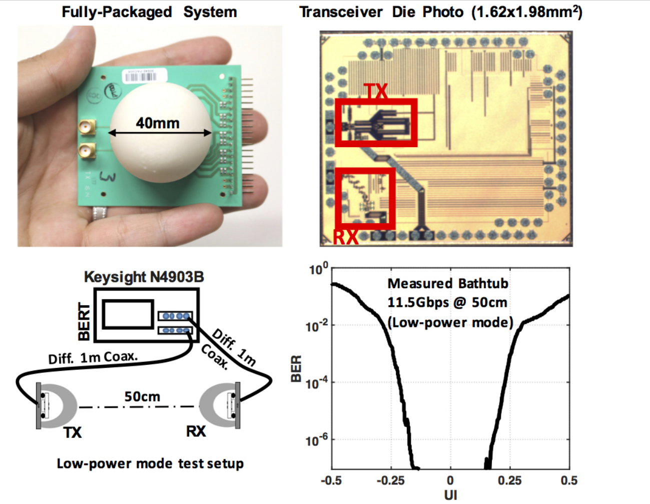

Figure 17.8.7: Fully packaged transceiver and die micrograph (top), short-range (50cm) LoS measurement set-up for low-power mode operation and its bathtub curve (bottom).

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