An Integrated 7-Gb/s 60-GHz Communication Link Over Single Conductor Wire using Sommerfeld Wave Propagation in 65-nm CMOS

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***Abstract*—The low loss and wide dispersion-free bandwidth of Sommerfeld-wave propagation on a single conductor wire (SCW) promises energy-efficient high data rate links. The first fully-integrated end-to-end wireline transceiver system on a SCW using Sommerfeld-wave propagation mode is demonstrated using a 60-GHz carrier frequency. Implemented in 65-nm CMOS, the proposed system includes on-chip radial-mode antennas as well as integrated serializers, 60-GHz OOK modulator, demodulator, deserializers and clocking. The link achieves 7 Gb/s data rate across 20-cm of 26AWG bare copper wire (diameter = 0.4 mm), while consuming 70.9 mW of power. Operating at 6 Gb/s and 7 Gb/s, this work achieves BER $< 10^{-12}$ and 10^{-5} respectively.**

***Index Terms*—Energy-efficient data links, millimeter wave, wireline, single wire waveguide, Sommerfeld wave, dispersion-free.**

I. Introduction

The need for high data rate, high density, and physically reconfigurable I/O links has led to wirelessly-coupled inter-chip links established through proximity coupling [1], guided-waves in low-cost waveguides [2], [3], and wireless links [4]. Wireless/guided-wave links are particularly attractive in CMOS technologies capable of high-speed digital processing to enable full integration. However, such links suffer from two critical challenges: (i) signal coupling between the TX/RX on the IC and the channel, and, (ii) signal propagation through the channel (waveguide/air). Weak signal coupling restricts fully-integrated capacitively-coupled proximity-coupling links to $<$ 2-mm range [1]. Although, hollow plastic-tube based links can achieve longer range, they require bond-wire/PCB antennas and have asymmetry between TX and RX antennas [2]. Furthermore, data rates over such hollow waveguides are ultimately limited by waveguide loss at high frequencies (2.5-dB/m@120-GHz), dispersion, and higher order modes [5]. Wireless links at sub-mmwave are conducive to antenna integration but are limited severely by free-space path loss.

Radial-mode Sommerfeld-wave propagation over a single-wire has long been known to have low loss ($<$ 1 dB/m@100 GHz) and almost no dispersion up to hundreds of GHz [6], [7]. However, exciting the radial wave in a single conductor wire (SCW) is challenging with typical linear/circular polarized antennas and has been accomplished using pico-second lasers exciting currents on a concentric two-electrode antenna fabricated on photoconductive material [7]. In this work, we present an approach for mm-wave excitation of the Sommerfeld-wave mode on a SCW using a radial on-chip antenna, demonstrating a fully-integrated end-to-end 7 Gb/s transceiver system over 60-GHz carrier (including serializers, mm-wave OOK modulators, on-chip antennas, demodulators and deserializers) across 20-cm of bare copper wire (diameter = 0.4 mm) with no off-chip components. This work presents not only the first fully-integrated system, but is also the first demonstration of a multi-Gb/s links over SCW using Sommerfeld waves.

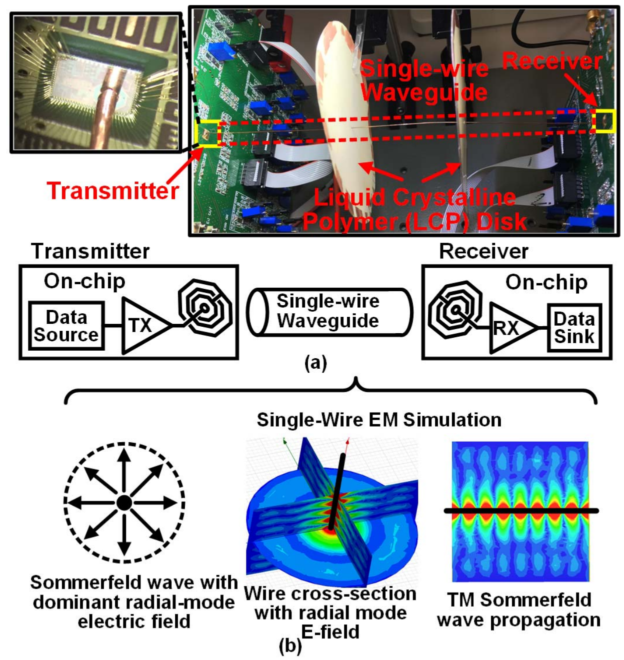

Fig. 1. (a) System overview of communication link with a modulated 60-GHz carrier using low-loss and flat dispersion Sommerfeld-wave propagation in a single conductor wire (SCW) (bare copper wire, 400 μm diameter), (b) EM simulations of dominant radial-mode E-field and TM propagation in SCW.

II. Fully-Integrated Communication Link Over Single Wave Conductor

A. System Overview

Fig. 1 outlines the link concept. A high-speed multiplexer serializes incoming data and drives an on-chip mm-wave TX that generates an OOK-modulated 60-GHz signal. The TX output is coupled to the Sommerfeld radially-polarized propagation mode in a single conductor wire (SCW) using an on-chip antenna. The weakly-guided Sommerfeld wave occurs due to the finite conductivity of the bare-copper SCW and propagates along the SCW as a TM wave. The electric field is largely radial as shown in Fig. 1 but has a longitudinal component along the wire. The SCW is supported mechanically using $\sim$100 μm-width Liquid Crystal Polymer (LCP) disks

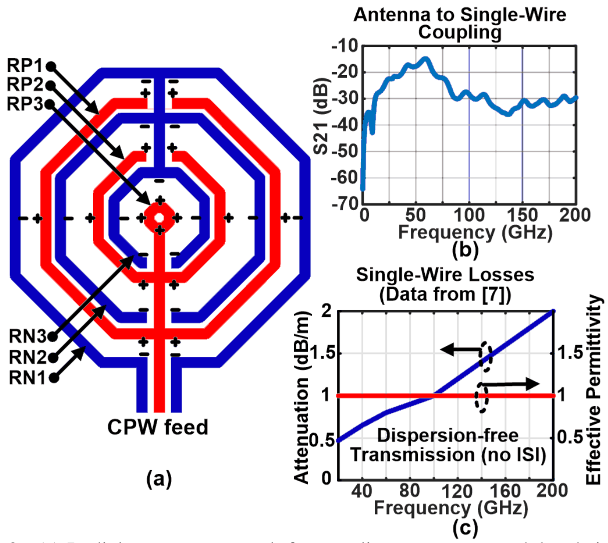

Fig. 2. (a) Radial antenna approach for coupling mm-wave modulated signal on the IC to the radial Sommerfeld-wave mode on the SCW, (b) The concentric rings in the antenna increase coupling from on-chip antenna to SCW, (c) The Sommerfeld-wave mode is low-loss and has flat delay across frequency and hence coupling loss dominates link performance.

(ϵ_R= 2.9, tan δ = 0.0025@10 GHz). The supporting structure ensures radial symmetry around the SCW up to $\sim$5λ (λ = 5 mm @ 60 GHz) to maintain radial-mode propagation. On the RX, a similar antenna couples the 60-GHz Sommerfeld wave from the SCW into the IC where an OOK demodulator drives on-chip samplers and deserializers. The wide bandwidth of the SCW propagation channel implies that simple modulation schemes such as OOK are adequate with wideband mm-wave circuits, and efficient coupling into SCW ensures that the link does not require equalization.

B. Radial Mode Antenna Design

Fig. 2 shows the proposed on-chip radial mode antenna which is discussed here in the context of the TX, where a radial electric field is desirable to couple effectively to the radial propagation mode on the SCW. An on-chip co-planar waveguide feeds the antenna, which consists of the concentric rings R_{P1}, R_{P2}, R_{P3} (in red) connected to the signal, and R_{N1}, R_{N2} and R_{N3} (in blue) connected to the RF ground. Since the signal is connected to R_{P1} and the ground is connected to R_{N1} (see Fig. 2) - electric dipoles are created between $R_{P,k}$ and $R_{N,k}$ as well as between $R_{P,k}$ and $R_{N,k+1}$. However, the dipoles between R_P and R_N rings that are placed close together do not couple to the wire whereas dipoles created between rings such as $R_{P,k}$ and $R_{N,k}$ result in signal coupling to the wire. Since these dipoles are created all along the antenna, a radial electric field is created that couples to the radial mode when the single-wire conductor is placed close to the antenna. Additional rings enhance coupling, however, EM simulations suggest little benefit beyond the three ring structure. The proposed antenna can tolerate off-center SCW placement to within $\pm$100 μm. Passivation layer on top of the IC ensures no electrical contact between the wire and the antenna. Notably, the proposed antenna requires the absence

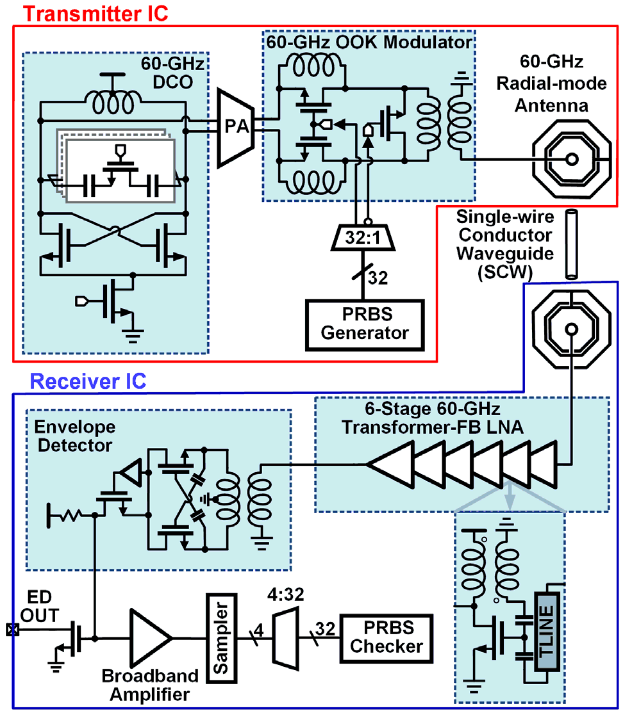

Fig. 3. Block diagram of the proposed 60-GHz 7 Gb/s transceiver IC with OOK modulator/demodulator and radial-mode antenna.

of a ground plane underneath - to prevent electrical field lines from the antenna rings to the ground. The IC was packaged using chip-on-board and the ground plane of the PCB is 450 μm away from the part of the IC with the antenna. Fig. 2 shows s-parameters based on EM simulations, demonstrating $\sim$-15dB coupling between the IC and the antenna. Coupling loss is dominated by losses in the silicon substrate (10 Ω-cm in this implementation) and hence thinning the substrate and/or using high-resistivity substrate technologies will lead to higher efficiency. The single wire itself has $<$ 1-dB/m loss implying that all signal loss occurs when coupling to/from the IC. The antenna presents an impedance of 25 Ω at 60 GHz.

C. Fully-Integrated 60GHz TX/RX Design

The CMOS TX/RX implementation is shown in Fig. 3. The mm-wave TX consists of a low-power digitally-controlled oscillator (DCO) (tuning range: 57 GHz to 62 GHz) that drives a 60-GHz buffer. OOK modulation is accomplished by a mm-wave switch driven by buffered data. The DCO and buffer are differential and a transformer at the output of the switch drives the single-ended antenna. The transformer is also sized to resonate with the switch to provide a 25-Ω match at 60 GHz and switch transistors are sized to balance the trade-off between power required for data buffers to drive the switch and mm-wave loss. In simulation, the 60-GHz OOK modulator delivers a 0-dBm 60-GHz signal at the radial mode antenna.

The 60-GHz LNA uses a transformer-based neutralization scheme that provides higher gain than common-source stages for same power consumption. The 6-stage LNA provides 24-dB gain and 6.2-dB noise figure (NF) in simulation while consuming $\sim$21 mW and is also matched to 25-Ω antenna

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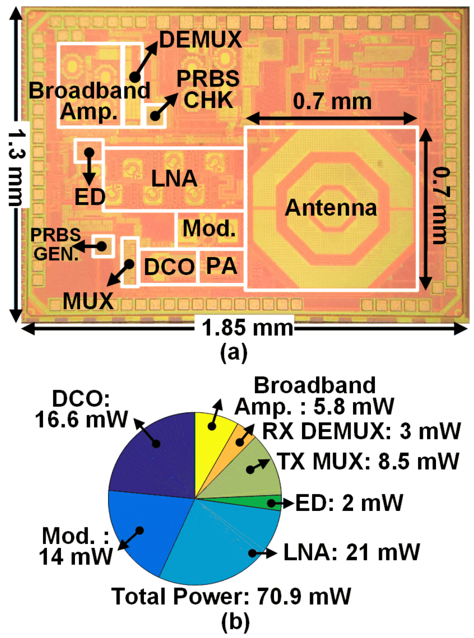

Fig. 4. (a) Die photograph of the proposed transceiver in 65-nm CMOS; (b) Summary of transceiver power consumption.

input. The LNA output is provided to a 60-GHz envelop detector (ED) for OOK signal demodulation, amplification and sampling. In addition, the ED output drives an open-drain buffer for direct measurement.

III. Measured Performance

The die micrograph of the 65-nm CMOS implementation of the concept and block level power consumption are shown in Fig. 4. The test setup for the SCW link measurements closely follows Fig. 1. Bare Cu wire with 400 μm diameter (26AWG) is used as the SCW and is placed in proximity to the antenna on the TX and RX. The 20-cm long wire has an intrinsic bend in the current setup with a radius of $\sim$28 cm. Fig. 5 shows the measured pulse response of the entire transceiver including the wire for 10-cm and 20-cm wire lengths and 5 Gb/s and 6 Gb/s pulse widths. For this measurement, 166.67-ps and 200-ps pulses were up-converted in the modulator to 60-GHz carrier, amplified by LNAs and finally received by the envelop detector output. Despite increasing the wire length by 2x, the measured pulse response shows no change in the pre and post-cursor ISI. This measurement demonstrates the low loss and wideband nature of the proposed communication channel and the TX-RX 60-GHz front end.

Fig. 6 shows the measured buffered ED output for 6 Gb/s and 7 Gb/s data rates and the bathtub plot of the sampled data for 20-cm channel. Even though the open-drain buffered output has lower bandwidth than the internal ED output node, the eye opening can still be seen at 7 Gb/s for the buffered ED output. The proposed transceiver achieves 7 Gb/s data rate for BER $< 10^{-5}$ and 6 Gb/s for BER $< 10^{-12}$. The measured bathtub curves at 6 Gb/s and 7 Gb/s are shown in Fig. 7. At 6 Gb/s, the received eye opening is 36 ps. The proposed transceiver is compared with the state-of-the-art guided-wave/wireless link approaches in Table I. Notably, the SCW link in this work is fully integrated and does not require any off-chip/bondwire components while achieving comparable energy efficiency even with 65-nm CMOS.

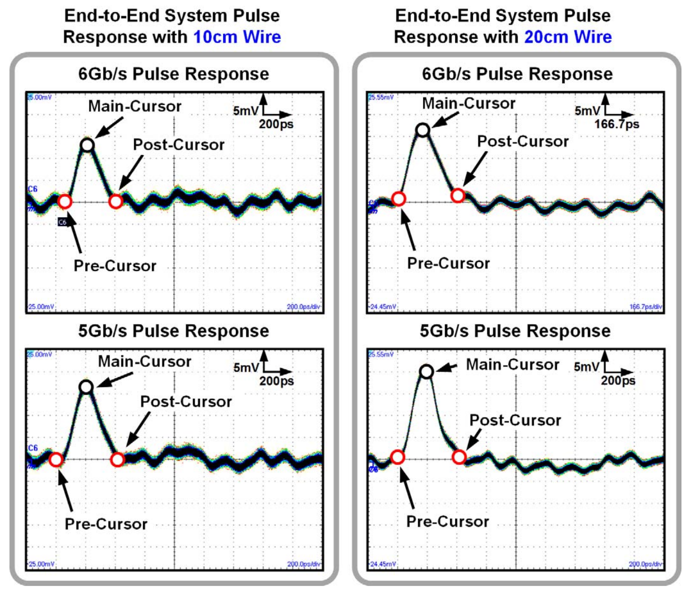

Fig. 5. Measured end-to-end system pulse response for 10-cm wire and 20-cm wire lengths demonstrating a low-loss and dispersion free channel.

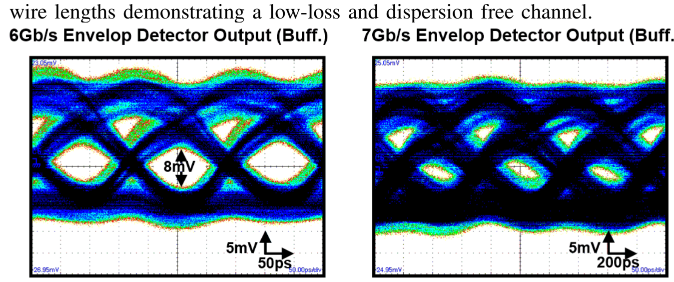

Fig. 6. Measured eye diagrams using buffered envelop-detector (ED) output in Fig. 3. Bandwidth is limited by wirebond from chip to PCB trace.

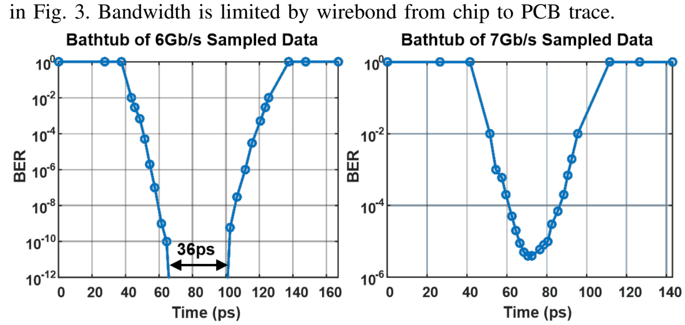

Fig. 7. Measured bathtub curves at the internal sampler input for 6 Gb/s and 7 Gb/s data rates.

IV. Conclusion

The paper presents the first demonstration of a mm-wave data link using Sommerfeld-wave propagation on a single conductor wire. A fully-integrated end-to-end prototype is presented to demonstrate the feasibility of energy-efficient high data rate links over the low-loss and low-dispersion waveguide. The 65-nm CMOS prototype achieves 7 Gb/s data rate over 20-cm channel length with energy efficiency of $\sim$10 pJ/bit. Future

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TABLE I
COMPARISION TO STATE-OF-THE-ART

	This Work	JSSC 2014	ISSCC 2015	JSSC 2011	ISSCC 2016
Technology	**65-nm CMOS**	32-nm SOI	40-nm CMOS	40-nm CMOS	14-nm CMOS
Area (mm^2)	**0.95(tot.)/0.77(Mod/Demod,TRX,Ant)**	4.62	0.48	0.21	9.6/38.4
Channel	**0.4 mm Bare Copper Single wire**	Air	2mm×1mm PTFE Tube	1mm×8mm PS Tube	Air
Coupling	**On-chip Radial Antenna**	On-chip Dipole	On-chip dipole (TX), bondwire ant.(RX)	Off-chip Quasi-Yagi	Capacitive
Freq./Mod.	**60-GHz OOK**	210-GHz OOK	120-GHz CPFSK	57-GHz OOK	NA
Data Rate/Range	**7 Gb/s@1e-5, 6 Gb/s@1e-12, 20 cm**	10 Gb/s (NA)	12.7 Gb/s, 1 m	15 Gb/s, 10 cm	8 Gb/s×4, 0.8 mm
Integration	**Serializer, TX, RX, Sampler, Deserializer, Clocking**	TX, RX	TX/RX	TX/RX	Serializer, TX/RX, Deserializer, Clocking
Power (mW)	**70.9 (total), 54 (Mod, TRX, Demod) @7 Gb/s**	308	61	71	32×4
Efficiency (pJ/b)	**10.1 (total) / 7.7 (Mod, TRX, Demod) @7 Gb/s**	30	4.8	4.7	4

work includes achieving higher data rates using the SCW by increasing carrier frequency and investigating multi-lane mm-wave data links using parallel SCW.

ACKNOWLEDGMENT

Graduate students working on this project were supported by Intel and by the National Science Foundation (NSF Award No. 1554720). The authors would also like to thank Professor Hossein Hashemi and Alireza Imani of University of Southern California for providing assistance with laser trimming of IC and Tektronix Inc. for assistance with test equipment.

REFERENCES

[1] C. Thakkar, S. Sen, J. E. Jaussi, and B. Casper, “A 32Gb/s bidirectional 4-channel 4pJ/b capacitively coupled link in 14nm CMOS for proximity communication,” in *Proc. IEEE Int. Solid-State Circuits Conf. (ISSCC)*, Jan. 2016, pp. 400–401.

[2] W. Volkaerts, N. V. Thienen, and P. Reynaert, “An FSK plastic waveguide communication link in 40nm CMOS,” in *Proc. IEEE Int. Solid-State Circuits Conf. - (ISSCC) Digest of Technical Papers*, Feb. 2015, pp. 1–3.

[3] S. Fukuda, Y. Hino, S. Ohashi, T. Takeda, H. Yamagishi, S. Shinke, K. Komori, M. Uno, Y. Akiyama, K. Kawasaki, and A. Hajimiri, “A 12.5+12.5 Gb/s full-duplex plastic waveguide interconnect,” *IEEE Journal of Solid-State Circuits*, vol. 46, no. 12, pp. 3113–3125, Dec. 2011.

[4] Z. Wang, P. Y. Chiang, P. Nazari, C. C. Wang, Z. Chen, and P. Heydari, “A CMOS 210-GHz fundamental transceiver with OOK modulation,” *IEEE Journal of Solid-State Circuits*, vol. 49, no. 3, pp. 564–580, Mar. 2014.

[5] N. Dolatsha, C. Chen, and A. Arbabian, “Loss and dispersion limitations in mm-wave dielectric waveguides for high-speed links,” *IEEE Transactions on Terahertz Science and Technology*, vol. 6, no. 4, pp. 637–640, Jul. 2016.

[6] M. King and J. Wiltse, “Surface-wave propagation on coated or uncoated metal wires at millimeter wavelengths,” *IRE Transactions on Antennas and Propagation*, vol. 10, no. 3, pp. 246–254, May 1962.

[7] M. Wåchter, M. Nagel, and H. Kurz, “Frequency-dependent characterization of THz Sommerfeld wave propagation on single-wires,” *Opt. Express*, vol. 13, no. 26, pp. 10 815–10 822, Dec 2005. [Online]. Available: http://www.opticsexpress.org/abstract.cfm?URI=oe-13-26-10815

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