High-Speed mm-Wave Data-Link Based on Hollow Plastic Cable and CMOS Transceiver

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***Abstract*—A multi-Giga-bit/s (up to 6 Gbps) and energy-efficient ($<$1 pJ/bit/m) data link is formed by using hollow plastic cable and CMOS transceivers for short distance ($<$8 m) digital communications. The demonstrated link couples/de-couples 60 GHz carried digital signals with roughly 6 dB loss per coupling into/from a hollow plastic cable made of relatively low-loss ($\sim$1.5 dB/m) Teflon, which is widely used for various home appliances. The CMOS transceivers are designed and implemented in 65 nm Foundry CMOS to support the intended 60 GHz operation with 28 mW power consumption under a 1 V supply.**

***Index Terms*—Amplitude shift keying (ASK) modulation, hollow plastic waveguide, millimeter wave integrated circuits, RF-interconnect.**

I. INTRODUCTION

GLOBAL Data Centers continue to demand better energy efficiency (in terms of pJ/bit/m) data links for short range (1–100 m) inter-server/container communications. Optical fiber links dominate current markets for high data rates and flexible deployment. However, they are hardly energy-efficient because they necessitate electrical-to-optical (E2O) and optical-to-electrical (O2E) operations by using discrete and temperature-constrained III-V compound lasers and detectors [1]. Copper-based active cable standards, such as Thunderbolt and 10GBASE-T, are rapidly replacing optical fibers for short distance communications by eliminating E2O/O2E in such markets, but still dissipate from hundreds of milli-watts to a few watts by adapting power-hungry DSP with pre-distortion/equalization [2], [3]. On the other hand, dielectric waveguides have been investigated in the past for mm-Wave communications even before the invention of fiber-optical communications [9]. However, those investigations did not lead to any useful data link development due to the following reasons: 1) the cut-off frequency of electronic devices (especially the silicon-based technologies) was too low to reach the required mm-wave transceiver implementation with sufficiently wide communication bandwidth; 2) the dielectric loss for mm-Wave transmission was substantially higher than that of optical fiber for long haul communications. However, such disadvantages no longer hold true due to the rapid development of mm-Wave CMOS transceiver technology in recent years and the fast market growth of Data Centers which require vastly on inter-server/container communications mostly within 100 meters. In this work, we propose an energy/cost-efficient ($<$1 pJ/bit/m) data link by using low-power mm-Wave transceivers and low-cost hollow plastic cable (or "Wave Cable"). Such data link would eliminate O2E/E2O conversion processes and pave the road for greener and fully silicon based data links for short distance (1–100 meter) inter-server/container communications within fast growing worldwide Data Centers.

II. PROPOSED SYSTEM ARCHITECTURE

The revival of mm-Wave communications through wires (or waveguides) originated from the development of very short distance (up to 30 cm for example) RF-Interconnect (RFI) [5]–[8]. Although previous works mainly focused on communications over copper wires, which exhibit a low-pass characteristic, the carrier-modulated communication is better-suited for transmission media with high-pass channel characteristics. Consequently, Sony researchers have started the use of solid plastic waveguide for very short distance interconnects on board (up to 30 cm) for multiband mm-Wave communications [4]. Nevertheless, their proposed solid plastic waveguide was rectangular which was not intended for the single-mode operation and was limited in link-distance due to the high dielectric loss of polyethylene at mm-Wave frequencies. To alleviate such disadvantages, we propose to 1) replace the solid rectangular waveguide with a hollow plastic cable to transmit energy mostly within the air-core; 2) maintain mm-Wave signal through a cylindrical cable under a circular HE11 single-mode operation [9], [10]. The proposed data link via a hollow plastic cable is explained in Fig. 1. It contains 60 GHz CMOS transceivers based on non-coherent amplitude shift keying (ASK) with off-chip but in-package wire-bonded dipole antenna as part of the signal coupling device (Fig. 1). The antenna is designed with emphasis on efficient near-field coupling. Due to the lower dielectric loss/dispersion of the air-core, the Wave Cable can achieve a longer communication range with substantially improved link efficiency.

III. POWER BUDGET AND IMPLEMENTATION

Fig. 2 describes the system power budget and corresponding Tx/Rx schematics. For the first prototype, we aim for the communication distance within 10 m. First of all, the Tx delivers 0 dBm of output power, and the receiver senses -21 dBm assuming the channel undergoes 1.5 dB loss per meter. Significant part of the channel loss is caused by Tx-to-cable and cable-to-Rx

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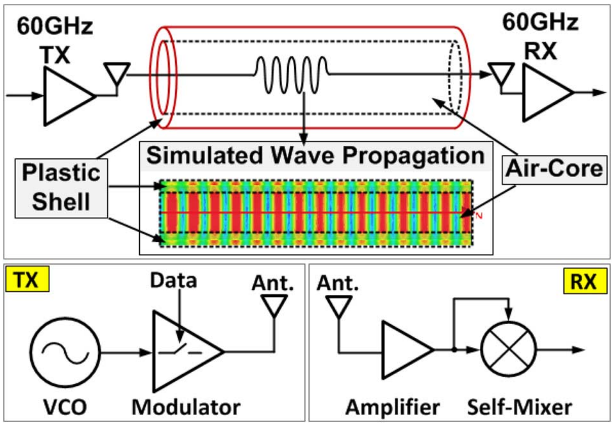

Fig. 1. Wave Cable transceiver diagrams with an air-core hollow plastic waveguide.

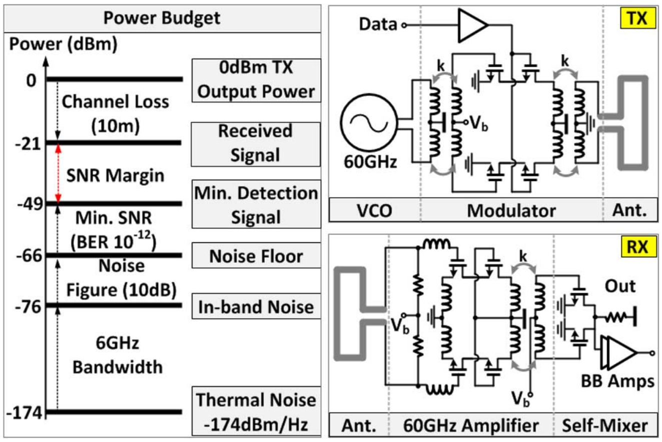

Fig. 2. Wave Cable system power budget and transceiver schematics.

couplings, primarily due to Omni-directional Tx/Rx antenna designs. With 6 GHz of system bandwidth and 10 dB of noise figure, the Rx in-band thermal noise floor is -66 dBm. To acquire the bit error rate (BER) of less than 10^{-12}, the non-coherent ASK Rx requires a minimum 17 dB of signal-to-noise ratio (SNR). The minimum detectable power is now -49 dBm. Therefore, the SNR margin becomes 28 dB, which indicates that the system is not limited by the thermal noise. The Tx contains an LC-based oscillator free-running at 60 GHz, an ASK modulator, an on-chip transformer, and an off-chip coupling antenna. The oscillator drives the current generating device via an on-chip transformer, and the switch device turns the current flow on and off to complete the ASK modulation. The Rx begins with a reciprocal antenna as a coupling device with the measured return loss of -10 dB within the bandwidth, and the 60 GHz amplifier provides the voltage gain of 18 dB. Next, the self-mixer cancels the carrier signal to extract the envelope of the modulated signal, and baseband amplifiers boost up the demodulated signal before the output driver.

IV. CHARACTERISTICS OF HOLLOW PLASTIC WAVEGUIDE

To understand the channel behavior, the dispersion relation and power loss are discussed. As shown in Fig. 3(a), from the

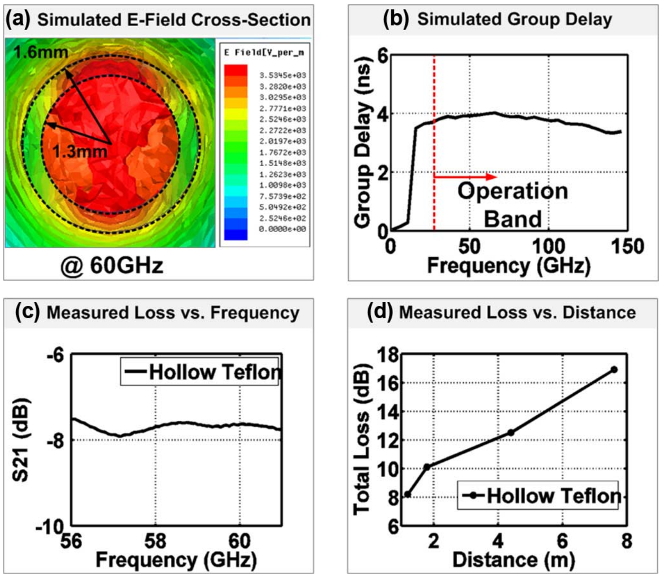

Fig. 3. (a) Simulated cross-section E-Field. (b) Attenuation factor ratio versus inner/outer radius ratio. (c) Measured insertion loss comparison. (d) Measured total loss for incrementing distance.

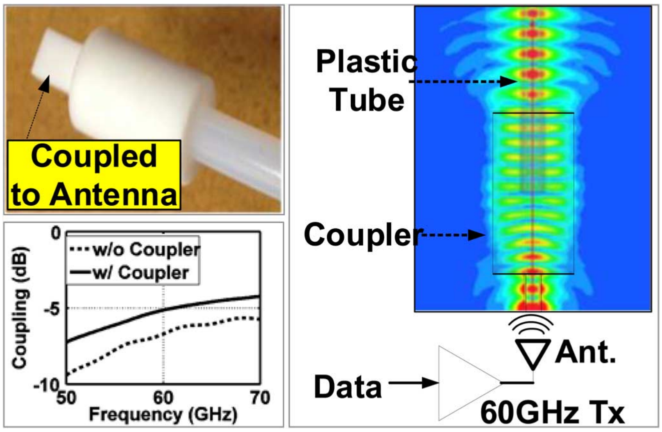

Fig. 4. Hollow tube transition-coupler design, simulated coupler loss, and transition diagram with simulated E-field result.

cross-section view, the boundaries are divided into 3 regions; a hollow air-core (radius of 1.3 mm), a plastic shell (radius of 1.6 mm), and an outermost side of air. We examined the property of field propagation using a 3D full-wave simulator. With the diameter of $\sim \lambda/2$ at 60 GHz, the hollow plastic fiber can guide the most energy through the center air-core area. The cable's dispersion behavior is implicated by its group delay as shown in Fig. 3(b). As the frequency of operation increases beyond 30 GHz, the group velocity becomes relatively constant and suits broadband communications well. Fig. 3(c) and (d) summarize the signal transmission characteristics of hollow Teflon cable. We first measure the insertion loss of a 1.2 m cable with a network analyzer. Including the calibrated 6 dB antenna coupling loss, the cable exhibits a total loss of 7.5 dB at the frequency of 60 GHz, and the in-band ripple is measured to be less than 1 dB. We also estimate the power loss for various cable distances, and data shows total 17 dB loss for 7.6 m long cable.

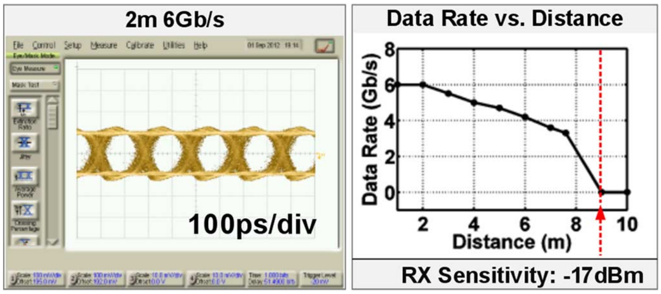

Fig. 5. Measured eye-diagram and Rx sensitivity under $2^{15}-1$ PRBS with BER $< 10^{-12}$.

	This Work	ISSCC 2012 [1]	Thunderbolt (Intersil) [2]	ISSCC 2012 [3]	ISSCC 2012 [4]
Distance (m)	7.6	N/A	3	100	0.12
Channel	Plastic (Hollow)	Fiber	Copper	UTP	Plastic (Solid Rect.)
Data Rate (Gb/s)	3.3	23	10	10	26
Link Type	P2P	P2P	P2P	P2P	P2P
Power (mW)	28	1830	450	2000	137
FoM (pJ/b/m)	1.11	N/A	15	2	43.9
Technology	65nm CMOS	40nm CMOS	40nm CMOS	40nm CMOS	40nm CMOS
Technology Scaled FoM	0.69	N/A	15	2	43.9

Fig. 6. Performance summary and comparison with prior arts.

V. COUPLER DESIGN AND MEASUREMENT

Fig. 4 illustrates the physical structure of the chip-to-cable transition-coupler made of the same plastics (Teflon) as that of the hollow cable. On the transmitter side, its rectangular tip would receive electromagnetic energy from the Tx-antenna via the near-field coupling and then pass that to the Teflon cable. On the receiver side, it would work reciprocally to convey energy from the cable to Rx-antenna. Such EM-energy transition behavior is clearly depicted through Ansoft HFSS simulations. Since the chip-to-cable (or cable-to-chip) transition occurs via the near-field coupling, the coupler can be simply placed atop in-package antenna as indicated in Fig. 4. The simulated coupler loss is 5∼6 dB. It is due to the use of Omni-directional antenna and can be further reduced with more directional designs. Unlike the optical fiber, the chip to coupler alignment can be conducted straightforwardly without using special equipment. The data link prototype exhibits a data rate of 6 Gb/s at the distance of 2 m, and degrades to 3.3 Gb/s at the distance of 7.6 m. This is validated according to received eye-diagrams of $2^{15}-1$ PRBS data with measured Rx sensitivity (-17 dBm) in Fig. 5. The data rate reduction primarily comes from 1) additional signal dispersion caused by longer transmission distance; 2) long plastic cable needed to be bent with extra 1∼2 dB power loss for the convenience of BER testing. The aforementioned issues can be further improved by implementing Tx signal pre-distortion and/or surrounding the Teflon cable shell with cladding dielectric structures for better focused energy within the air-core.

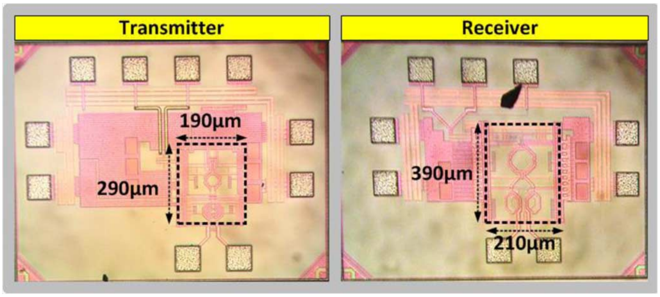

Fig. 7. Die photo of (a) Wave Cable transmitter and (b) Wave Cable receiver.

VI. CONCLUSION

We have designed and characterized the Wave Cable transceiver systems for short distance data links. The entire transceiver and channel characteristics have been simulated and agrees well with the measurement results. We have achieved the maximum data throughput of 6 Gb/s at 2 m and the maximum communication distance of 7.6 m with 3.3 Gb/s while the BER is less than 10^{-12}. The TRX consumes 28 mW (Tx:12 mW, Rx:16 mW), and have accomplished a Figure-of-Merit (energy per bit per meter) by a factor of 2.9∼63 better than that of prior arts, as compared in Fig. 6. The die-photos for both Tx and Rx are shown in Fig. 7(a) and (b), respectively. The demonstrated silicon-only CMOS transceiver is also more adaptable for green data center operations due to its wider temperature tolerance (in contrast to $< 5^{\circ}\mathrm{C}$ operation window for typical III-V lasers) and higher system integration which lead to more compact link systems.

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