A 125GHz Transceiver in 65nm CMOS Assembled with FR4 PCB Antenna for Contactless Wave-Connectors

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Abstract — This paper presents a millimeter-wave (125GHz) based ultra-short distance (~2mm) contactless wave-connector (CWC) for consumer interconnect applications. Conventional high-speed connectors in interconnect standard such as USB, HDMI, DP, and Thunderbolt are not only expensive, but also suffer poor performance in both mechanical reliability and signal integrity often becoming a bottleneck in high-performance computing systems. The proposed CWC exploits a 125GHz CMOS transmitter (TX), receiver (RX), and compact FR4 PCB antenna to realize high-speed (>10Gb/s), low-cost, and energyefficient connector solutions. An on-off keying (OOK) modulation is utilized for a non-coherent transceiver (TRX) architecture. In addition, antennas are designed on an FR4HR substrate for a compatibility with an existing infrastructure. The CMOS TX and RX is assembled with the antenna through a flipchip process. The demonstrated CWC draws a total of 60mW of power under 1.1V supply while transferring 14Gb/s of data rate, achieving 4.28pJ/bit energy efficiency.

Index Terms — 125GHz Transceiver, FR4 PCB Antenna, Flip-Chip, OOK modulation, Contactless Wave-Connector (CWC).

I. INTRODUCTION

Because of the increasing demand in the data bandwidth for multimedia applications, the industry has come up with new interconnect solutions such as Thunderbolt, USB3.0, Display Port, HDMI, and Gigabit Ethernet. The data rate of 10Gb/s per channel is no longer uncommon in the consumer market. However, as each interconnect standard evolves, serious challenges remain in its bandwidth scalability, power, and other fundamental physical limitations such as mechanical reliability, thermal constraints, and overall system form-factor. Often times, connectors play important role in each generation because of its non-scalable nature and inherent discontinuities between physical layers. The non-ideal behavior makes the high-speed signal undergoing distortion, inter-symbol interference (ISI), and reduced signal-to-noise ratio (SNR). Although, one can invest more resource in packaging and connector technologies [1], much effort is focused on the digital signal processing based pre-emphasis and equalization, which leads to a complicated transceiver architecture requiring calibration, software, and more power.

Meanwhile, a recent research suggested to remove the physical connection and replace it with short-distance wireless



Fig. 1. Conceptual diagram of conventional connector, contactless waveconnector, and block diagram of overall system where the contactless waveconnectors can replace conventional mechanical connectors.

connectors [2]. The fundamental advantage comes from an available wide fractional bandwidth around a carrier frequency and its non-contacting air-interface. The contactless wave-connector (CWC) can be installed essentially anywhere in a given network topology as illustrated in Fig. 1, for instance, between network port and LAN/WAN cables, USB port and mobile devices, and HDMI port and display monitors. In the proposed approach, the CMOS TX chipset generates an OOK modulated 125GHz carrier signal, and the TX PCB antenna radiates electromagnetic energy to the reciprocal RX PCB antenna. Then, similar to [3], the CMOS RX chipset amplifies the modulated signal and down-converts to the baseband signal through a self-mixer without using frequency-synthesizer/carrier-synchronization.

II. 125GHz ANTENNA DESIGN ON FR4 PCB AND CHIP-TO-ANTENNA FLIP-CHIP ASSEMBLY

Before designing the antenna structure, we first characterized the FR4HR substrate by designing transmission line (TL) calibration structure [4]. By measuring scattering parameters of different length of TL through a vector network analyzer, we extracted the dielectric constant of 3mil and



Fig. 2. (a) Measured and extrapolated dielectric constant of FR4HR substrate used for simulation. (b) Manufacturer provided and extrapolated loss tangent of FR4HR substrate.



Fig. 3. (a) Side view of TX to RX air-coupling, chip-to-antenna flip-chip assembly, and illustration of ground plane for impedance matching. (b) Top view of assembled module. (c) Simulated S11 looking into the antenna port. (d) Simulated one antenna to the other side of antenna air-coupling loss performance.

10mil thickness substrate up to 67GHz and extrapolated up to 200GHz as shown in Fig. 2(a). For the loss tangent, we used a manufacturer provided data up to 10GHz and again extrapolated up to 200GHz shown in Fig. 2(b).

The TX to RX air-coupling scheme is depicted in Fig 3(a). A 125GHz folded-dipole antenna is designed on the substrate that was measured above. A ground plane (GND2) is placed 13mil underneath the antenna to act as a reflecting surface (close to the quarter lambda at 125GHz). With the ground plane specified, the antenna dimension is designed to match with 100 Ω differential impedance. Then, a 1.7mm by 0.8mm rectangular cavity is formed by a via-wall to provide a higher directivity.

The CMOS chips are directly mounted by a flip-chip process, and a 0.5mm length of TL connects the chip and antenna with a 3mil-depth ground plane (GND1) to maintain 1000hm differential characteristic impedance. The top view of assembled module is shown in Fig. 3(b) emphasizing the chip and antenna together can fit within 1mm by 3mm area. Looking into the antenna port, the return loss (S11) maintains below -8dB over 40GHz bandwidth. In addition, the transmission performance (S21) between the TX antenna to the RX antenna through 2mm air-coupling experiences no worse than 12dB loss over 40GHz bandwidth. Notice how the amplitude variation is confined within 4dB as opposed to the



Fig. 4. (a) Schematic of proposed transmitter and flip-chip 3D model. (b) Flip-chip transmission loss, and complete link transmission performance including TX and RX side of flip-chip/antenna and 2mm air-coupling channel. (c) Transmitter die-photo.

conventional mechanical connector may induce more than 30dB of notch in frequency response [5]. The above study indicates that the proposed air-coupling channel can transmit more than 20Gb/s of baseband data without requiring power hungry equalization or pre-emphasis.

III. 125GHz CMOS TRANSMITTER

The TX adapts an OOK modulation to enable an energyefficient architecture. An on-chip Pseudo Random Bit Sequence (PRBS) (2⁷-1) generates 14Gb/s data stream, which is clocked by an on-chip 14GHz phase-locked loop (PLL), and drives a mixer's tail current device. In order to perform the upconversion, a free-running oscillator first generates 125GHz carrier signal and drives the mixer's differential pair through a transformer. After the up-conversion, the mixer directly drives the off-chip feed-line and antenna through a transformer without using an additional power amplifier (PA) as shown in Fig. 4 (a). From the link budget study explained in the next section, we intentionally avoided designing PA. That is, the oscillator generates enough power to transfer energy to the RX through an air-coupling channel. For the CMOS-to-PCB flipchip assembly, we had to increase the on-chip pad size to 100µm diameter, in return adding significant amount of capacitance compared to a design library based pad. To perform an output matching with this constraint, we implemented a pad-tapped shunt inductor. From the HFSS simulation, CMOS-pad/flip-chip-bump (80um diameter)/PCBpad contributes 2.8dB loss. Adding from the result of TX antenna to RX antenna in Fig. 3(d), the final end-to-end transmission efficiency becomes 16dB at 125GHz. Here again, the amplitude of S21 maintains within 4dB variation over 40GHz span. The TX generates 0dBm output power at



Fig. 5. (a) Schematic of proposed receiver including 1-stage low-noise amplifier and feedback based self-mixer. (b) Link budget analysis. (c) LNA gain. (d) Self-mixer conversion loss. (e) Receiver die-photo.

the input of on-chip pad while consuming 35mW of power. A die-photo is taken in Fig. 4(c).

IV. 125GHz CMOS RECEIVER

The RX starts with a matching transformer and provides 10dB of gain via a 1-stage low-noise amplifier (LNA) as shown in Fig. 5(a). The link budget analysis in Fig. 5(b) reveals that the noise floor of RX begins at -70dBm considering the 28GHz bandwidth (double-side band of 14Gb/s data). Going through 15~19dB transmission loss, -20dBm signal arrives at the RX front-end. The LNA amplifies the signal up at -10dBm, and the front-end adds 10dB of noise figure. In addition, a 15dB of minimum SNR is added to the floor to achieve a bit-error-rate (BER) of 10⁻¹² for the noncoherent OOK de-modulation. Although the -10dBm modulated signal further undergoes 21dB of self-mixing conversion loss (Fig. 5(d)), with the updated noise floor at -45dBm, the system has room for another 14dB of SNR margin. Unlike the resistor loaded self-mixer design in [3], we employed a feedback amplifier based self-mixer in order to deliver a wider down-conversion bandwidth. Lastly, highspeed buffers amplify the down-converted 14Gb/s baseband signal and drive a scope for an eye-diagram measurement. The RX consumes 25mW, and its die-photo is shown in Fig. 5(e).

V. TX 125GHZ OUTPUT SPECTRUM AND TRANSCEIVER DATA LINK MEASUREMENT RESULTS

To demonstrate the radiated power from the TX, first we measured the modulated output spectrum using W-band horn



Fig. 6. (a) TX output spectrum measurement setup. (b) Captured TX output spectrum. (c) TX and RX data link setup with 2mm air-gap. (d) Measured 14Gb/s eye-diagram.

antenna and harmonic mixer shown in Fig. 6(a). Although, 125GHz is actually not within the W-band region, given the output power from the TX and the conversion loss from the harmonic mixer, we were able to capture the TX output spectrum and confirmed that indeed there is carrier signal power at 124.7GHz and modulated sideband as shown in Fig. 6(b). After confirming radiated power with modulation, we setup the TX and RX data link as shown in Fig. 6(c). First, 55MHz reference clock is provided for the 14GHz PLL to be locked. The same 55MHz reference clock is used for triggering an oscilloscope. Then, the RX is placed underneath the TX with a 2mm air-gap. The down-converted and amplified signal is fed into the scope to measure the 14Gb/s of eye-diagram as shown in Fig. 6(d). As the wide-opened eye-diagram indicates, there is a margin to go beyond 14Gb/s.

VI. CONCLUSION

In this paper, we have demonstrated a contactless waveconnector for consumer oriented interconnect solutions to provide wide-bandwidth and reduce form factor and power consumption. The demonstrated 125GHz TX and RX module combined with a PCB antenna achieves 14Gb/s of data rate without using complex and power hungry equalization circuits. The TX and RX chips are implemented in TSMC 65nm CMOS technology and occupies 0.5mm x 0.3mm of TX and 0.5mm x 0.4mm of RX silicon area. The TX and RX consumes 35mW and 25mW of DC power, respectively, achieving 4.28pJ/bit energy efficiency.

REFERENCES

- [1] D. G. Kam and J. Kim, "40-Gb/s Package Design Using Wire-Bonded Plastic Ball Grid Array," *IEEE Transactions on*
- Bonded Plastic Ball Grid Afray, *IEEE Transactions on Advanced Packaging*, vol. 31, no. 2, pp. 258-266, 2008.
 [2] K. Kawasaki, *et al.*, "A Millimeter-Wave Intra-Connect Solution," *IEEE Journal of Solid-State Circuits*, vol. 45, no. 12, pp. 2655-2664 2010.
 [3] Y. Kim, *et al.*, "High-Speed mm-Wave Data-Link based on Hollow Plastic Cable and CMOS Transceiver," *IEEE*
- Hollow Plastic Cable and CMOS Transceiver, *IEEE Microwave and Components Letters*, vol. 23, no. 12, 2013.
 [4] N. K. Das, *et al.*, "Two Methods for the Measurement of Substrate Dielectric Constant," *IEEE Transactions on Microwave Theory and Techniques*, vol. 35, no. 7, 1987
 [5] Y. Du, *et al.*, "A 16Gb/s 14.7mW Tri-Band Cognitive Serial Lieb, Terrupticate Original Clash and Clash and
- Link Transmitter with Forwarded Clock to Enable PAM-16/256-QAM and Channel Response Detection in 28nm CMOS," IEEE Symposium on VLSI Circuits, 2016