A single phase modulation for pulse-based inductive-coupling connection in 3D stacked chip

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Abstract: This paper proposes an efficient modulation in high-speed inter-chip data communication with inductive-coupling wireless connection for 3D-stacked system in package (SiP). In this modulation, signal is generated only in one polarity of the digital signal transmission. Compared with BPM and NRZ modulation, it has a 50% power reduction and better crosstalk immunity.

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1 Introduction

Inductive-coupling wireless connection is a promising interconnect technology for 3D stacked chips package. Compared with through silicon via (TSV) [1] connection, micro-bump connection [2] and capacitive-coupling connection [3], it has advantages such as: 1) this technology leads to low cost, high reliability and high yield without additional processes; 2) ESD protection is unnecessary, as its a non-contact interface; 3) the connection is current-driven, which means it can work under various supply voltages and processes; 4) There is no limitation in the number of stacked chips.

The power dissipation is a critical issue of inductive-coupling wireless connection. A lot of technologies has been developed to reduce the power consumption. Ref. [4] proposes a bi-phase modulation (BPM), gets 3 pJ/bit power dissipation. Based on the BPM, some techniques have been developed for reducing the power furtherly. A Digitally-Controlled Precise Pulse Shaping technology is reported in ref. [5], got the power of 0.14 pJ/bit. In ref. [6], a charge recycling technique is adopted, power is reduced to 65 fJ/bit. In ref. [7], a dual-coil transmission scheme under low operating voltage reduced the power to 20 fJ/bit. Ref. [8] proposed a non-return-to-zero (NRZ) modulation, gets 6 pJ/bit power dissipation with 0.25 um CMOS process. There are two types of NRZ modulation, the synchronous type [8] and the asynchronous type [9]. The synchronous type NRZ modulation and BPM are pulse based modulation. They have a lower power dissipation comparing with non-pulse-based modulation, but their data rate is not high because of the requirement of precise timing control. This paper only discusses the pulse-based modulation.

This paper proposes a single-phase modulation (SPM), its transceiver scheme is presented in section 2. Performance analysis and comparison with BPM and NRZ modulation are in the section 3. Section 4 gives a conclusion.

2 Single phase modulation

Fig. 1 shows the schematic diagram and simulation waveform of the proposed SPM signaling transceiver. In the transmitter, a pulse generator produces pulse voltages whose pulsewidth is determined by the delay of the inverter chain. A pulse voltages is generated in every positive edge of $T_X clk$. These pulse voltages do AND operation with $T_X data$, pulse voltages can pass the AND gate only when the $T_X data$ is HIGH. Then the AND gate drives a NMOS transistor to convert the pulse voltages to pulse current I_T. When the pulse current flows through the T_X inductor,

induced voltage V_R is produced in the R_X inductor. The R_Xclk samples the V_R in the first half of V_R, and recovers it to $Rxdata$.
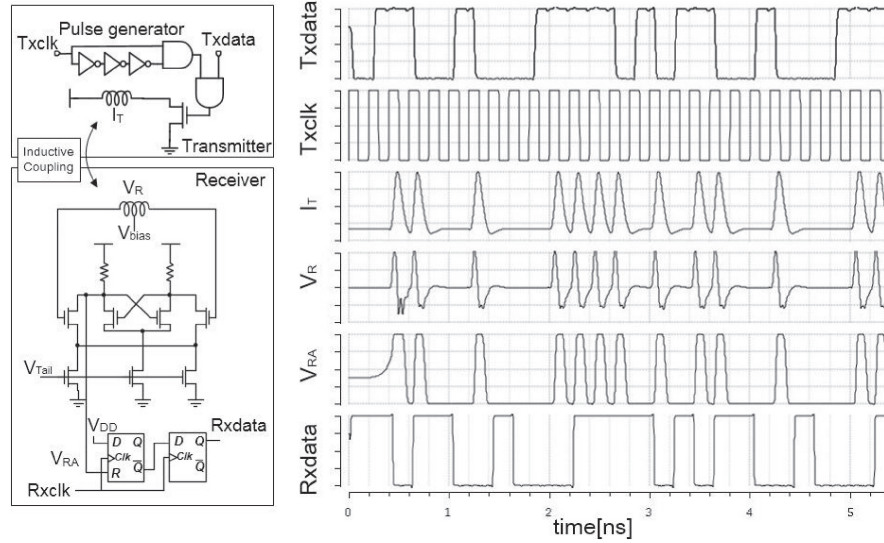

Fig. 1.   Transceiver adopted SPM signaling and its simulation waveform

Fig. 2 shows the I_T and V_R waveform of NRZ, BPM and SPM signaling. In the BPM, every bit of data generates one current pulse. In the SPM, a pulse is produced only when the data "1" is transmitted. In the NRZ, the pulses are produced when the data changes. When the data turns from "0" to "1", a positive pulse is produced. When the signal voltage turns to "0", a negative pulse is produced.
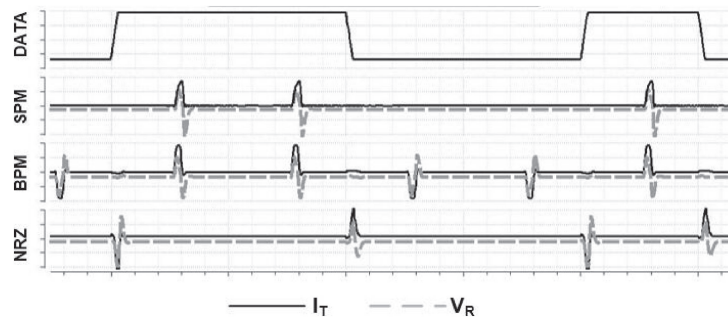

Fig. 2.   Waveform comparison of SPM, BPM and NRZ

3   Performance analysis and comparison

Power dissipation

In the pulse based modulation for inductive coupling connection, energy is consumed by every current pulse. Fig. 3 shows the pulse shape of I_T and the induced voltage V_R. τ is the width of I_T, I_P is the peak current. S_P is the slew rate of I_T. The energy consumed by the current pulse is approximately calculated by

$$E_{pulse} = \frac{1}{2} V_{DD} \cdot I_P \cdot \tau = \frac{1}{2} V_{DD} \cdot S_P \cdot \tau^2 \tag{1}$$

The induced voltage is given by

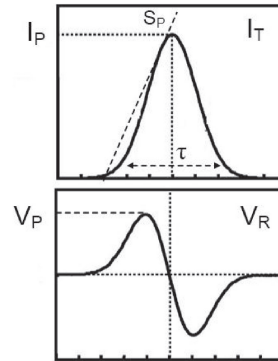$$V_P = M \cdot \frac{dI_T}{dt} \approx M \cdot S_P = M \cdot \frac{I_P}{\tau} \tag{2}$$

Fig. 3. Waveform of I_T and V_R

M is the mutual inductance between two inductors. From eq. 1, 2, reducing the τ can not only lower the E_{pulse}, but also increase the V_R. τ is limited by requirement of bit error rate (BER). The too narrow pulsewidth will increase the probability of sampling errors. In the previous reports, τ should be larger than 120 ps. E_{pulse} in ref. [4] is 0.11 pJ/bit with 1 Gb/s data rate.

In the BPM, energy consuming occurs in every bit of data. In the SPM, it only occurs when the data is "1". The power dissipation of SPM $P_{SPM} = P1 * P_{BPM}$, $P1$ is the proportion of "1" in the data. In a pseudo random binary sequence (PRBS), the quantity of "1" in the data is equal to that of "0", the power dissipation of SPM is 50% of BPM. In the NRZ modulation, the power dissipates when data changes. The power dissipation of NRZ is $P_{NRZ} = RR * P_{BPM}$, RR is repeat rate of the data. In the PRBS, $RR = 0.5$, the power dissipation of SPM is also 50% of BPM.

Crosstalk immunity

To obtain high bandwidth in a limited chip area, inductive-coupling connection channels are usually arranged in array with small spacing. The electromagnetic field of an inductor effects its adjoining inductors, mutual inductance are produced between inductors, which causes crosstalk. The received voltage with crosstalk is given by

$$V_{Ri} = Z_{ind}\left(k_{ii}I_T + \sum_{j \neq i} k_{ij}I_T\right) \tag{3}$$

where Z_{ind} is the trans-impedance of inductive coupling, k_{ii} is the coupling coefficient between a R_X inductor and its corresponding T_X inductor. k_{ij} is the coupling coefficient between the R_X inductor and the non-corresponding T_X inductor around it. Therefore, crosstalk-signal-ratio (CSR) is given by

$$CSR = \frac{k_{ii}I_T}{k_{ij}I_T} = \frac{k_{ii}}{k_{ij}} \tag{4}$$

It can be seen in eq. 4 that CSR is only related to the coupling coefficient. The coupling coefficient can be calculated by methods in ref. [10]. It noteworthy that

when the horizon distance between two inductors is larger than their diameter, the coupling coefficient between them is lower than zero. So k_{ij} is a negative number. Which means that the crosstalk voltage produced by a positive current pulse is a negative pulse, as shown in Fig. 4.
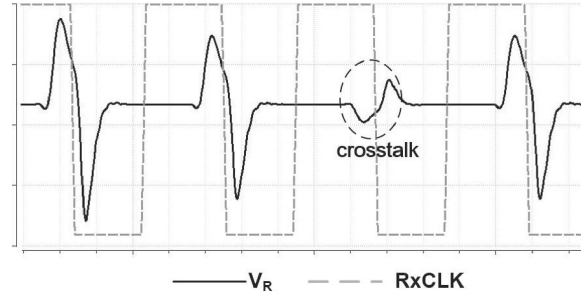

Fig. 4. Waveform of crosstalk

In BPM and NRZ modulation, there are two kinds of crosstalk pulse, the positive pulse and the negative pulse. In the worst condition, the crosstalk and noise always attenuate the signal, or produces a pulse in the place where there was no signal. The highest BER of NRZ, BPM are calculated by eq. 5, 6, respectively [4].

$$BER_{NRZ} = \frac{1}{2} erfc \left(\frac{\tau}{4\sqrt{2}\tau_{jitter}} \sqrt{ln \frac{1 - NSR - CSR}{NSR + CSR}} \right) \quad (5)$$

$$BER_{BPM} = \frac{1}{2} erfc \left(\frac{\tau}{4\sqrt{2}\tau_{jitter}} \sqrt{ln \frac{1 - NSR - CSR}{NSR}} \right) \quad (6)$$

Where $erfc()$ is the error function complement, τ is the V_R pulsewidth, τ_{jitter} is the jitter of sample clock, and NSR is the noise-to-signal ratio. NSR can be reduced by increasing transmit pulse energy. However, CSR remains constant because when the signal energy is increased, the crosstalk energy is increased simultaneously.

In SPM, there is only negative crosstalk pulse. That makes the condition of crosstalk in SPM more uncomplicated. In the signal "1", crosstalk attenuates the signal. In the signal "0", the crosstalk produces a sag in the waveform (shown in Fig. 4), which makes the signal "0" safer. So the BER of SPM when signal "1" and "0" are calculated by eq. 7, 8, respectively.

$$BER_{SPM(1 \to 0)} = \frac{1}{2} erfc \left(\frac{\tau}{4\sqrt{2}\tau_{jitter}} \sqrt{ln \frac{1 - NSR - CSR}{NSR}} \right) \quad (7)$$

$$BER_{SPM(0 \to 1)} = \frac{1}{2} erfc \left(\frac{\tau}{4\sqrt{2}\tau_{jitter}} \sqrt{ln \frac{1 - NSR}{NSR}} \right) \quad (8)$$

The highest BER of SPM, BPM and NRZ depending on transmit pulse energy are calculated with same parameters. The result is shown in Fig. 5, assuming the quantity of data "0" is equal to that of data "1". It can be seen that the BER of SPM is a slight lower than that of BPM, and the BER of NRZ is much higher than that of other two modulation. Because the uncertainty of the crosstalk in the NRZ makes the bit error happen easily, it needs some times higher power to get the same BER of SPM and BPM.
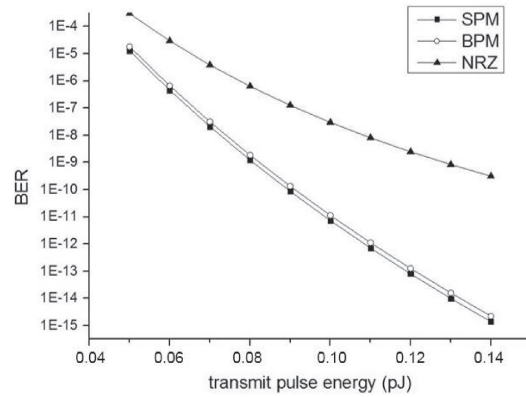
Fig. 5. Calculated BER of SPM, BPM and NRZ in the worst condition respectively ($CSR = 0.2$, $Noise = 0.01\,\text{pJ}$, $\tau = 125\,\text{ps}$, $\tau_{jitter} = 25\,\text{ps}$)

4   Conclusions

A single phase modulation for inductive-coupling connection has been introduced. This modulation reduces power dissipation significantly comparing with the BPM. Not be able to carry a clock is as a sacrifice. But when inductive-coupling connection channels are arranged by array, it's not necessary for each channel to carry a clock, and its advantage of good crosstalk immunity is shown up.

Acknowledgments