In-Phase Resonant Inductive Coupling for Multi-Layer Vertical Communication in 3D-ICs

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Abstract— **A signal boosting scheme for wireless inductive interconnects in 3D-ICs is proposed. It enables longer distance communication through multiple-stacked layers without increasing coil size by using in-phase resonant inductive coupling and regenerative oscillation. Measurement results show the received signal is improved by 16dB compared to a conventional standard inductive coupling method with and aspect ratio of 4:1.**

I. Introduction

3D integration achieves a smaller form-factor and lower-latency interconnect between ICs by vertically stacking multiple die. Inductive coupling is one technique used to create through-die-interconnect between stacked layers as depicted in Fig. 1(a) [1-4]. In this application, the aspect ratio (*communication distance / coil diameter*) limits the area-efficiency of the link, and the number of layers that can be communicated through.

Fig. 1(b) shows the simulated coupling coefficient k between planar spiral inductors vs. aspect ratio [5]. Since k decreases rapidly for aspect ratios larger than 1, conventional wireless inductive data links usually have aspect ratios less than 1. For this reason, prior inductive links for multiple die stacking send data only to the adjacent layer, and relay data to communicate through multiple dies as shown in Fig. 1(c) [1][2]. This relay method takes a number of cycles to transmit data to the destination. While direct communication through multiple-stacked dies resolves this latency problem [3][4], prior work uses large coils to do so due to the limited aspect ratio.

This paper analyzes a technique termed multi-layer signal boosting (MLSB) intended for inductive data links in 3D-IC applications. By exploiting resonant inductive coupling, it enables a larger aspect ratio, which means direct transmission through multiple dies with relatively small coils.

II. Theoretical Analysis

Consider four vertically stacked planar coils as shown in Fig. 2. When an AC current is applied in the bottom coil, it induces out-of-phase AC current in the second and fourth coils and in-phase AC current in the third coil when the coil terminals are all shorted, according to Faraday's law of induction (Fig. 2(a)). If the coils are instead loaded by a large impedance, an AC current close to in-phase is induced in all coils (Fig. 2(b)). As shown in Fig. 2(c), if regeneration is added to the coils, the magnitude of the induced current is amplified. This roughly explains the operation of MLSB.

The two major elements of MLSB are the in-phase strongly-coupled resonant inductive coupling (RIC) and the regeneration of the oscillations. RIC provides signal gain depending on the product of kQ of the inductors [6], and in this paper we show that the phase difference is affected by the kQ value as well.

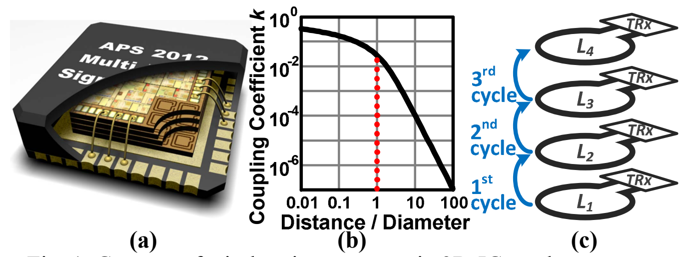

Fig. 1. Concept of wireless interconnect in 3D-ICs and conventional inductive coupling for multiple-stacked layers.

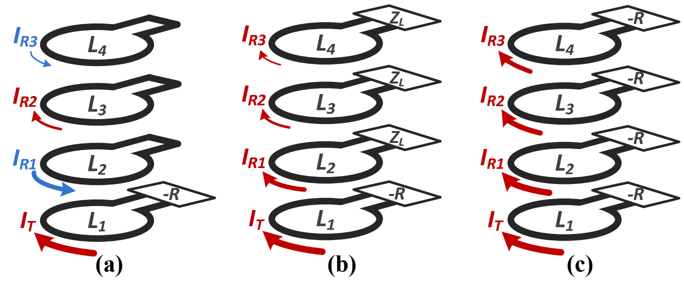

Fig. 2. Concept of multi-layer signal boosting.

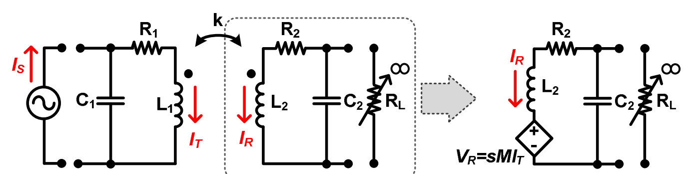

Fig. 3. Equivalent circuit of an inductively coupled circuit.

A. In-phase Resonant Inductive Coupling

Fig. 3 shows the equivalent circuit of an inductively coupled data link across two layers. The transmitter is simplified to current source I_S, and R_L is a model of the receiver circuits loading the coils. Because R_L is generally large for data links, it can be ignored to simplify the circuit. This results in the following equation for current gain across the coils:

$$\frac{I_R}{I_T} = -\frac{sM}{sL+R+\frac{1}{sC}} = \frac{\omega^2 MC}{1+j\omega RC-\omega^2 LC} \tag{1}$$

By substituting the resonant frequencies of a strongly-coupled RIC system, the ratios are concisely written as follows.

$$\left(\frac{I_R}{I_T}\right)_{Strongly\ Coupled\ RIC, low\ res.freq.} = \frac{kQ}{kQ+j} \tag{2}$$

$$\left(\frac{I_R}{I_T}\right)_{Strongly\ Coupled\ RIC, high\ res.freq.} = \frac{-kQ}{kQ-j} \tag{3}$$

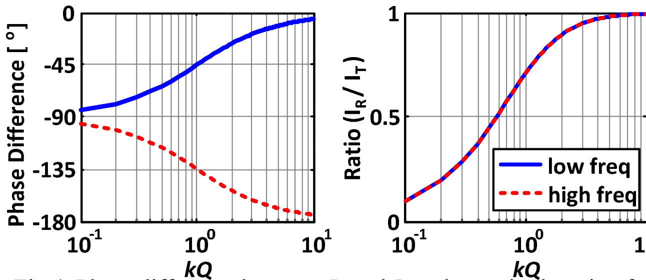

Fig.4. Phase difference between I_R and I_T and magnitude ratio of strongly coupled RIC.

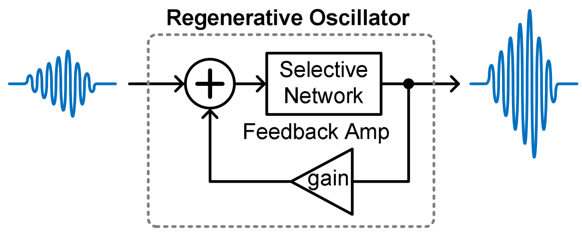

Fig.5. Diagram of regenerative oscillator.

The phase difference between I_R and I_T is a function of kQ as shown as Fig. 4. As the kQ value increases, the phase at the lower resonant frequency converges to 0^0 (in-phase) and at the higher frequency converges to 180^0 (out-of-phase). The amplitude of the induced current is increasing as the kQ value increases for both cases. By operating the link at the lower resonant frequency and in the strongly-coupled regime, the induced current has a similar phase to the inducing current.

B. Regenerative Oscillation

The larger kQ value results in a smaller phase difference and a larger induced current. In practice, it is difficult to increase kQ because k is limited by the coil size and die thickness, and an on-chip inductor has a relatively small Q-factor. Because of the kQ limitation, in-phase RIC cannot increase the induced current amount significantly by itself. Regenerative oscillation is able to amplify the current amount in company with in-phase RIC. The regenerative oscillator has a feedback whose loop gain is slightly less than one as shown in Fig. 5. When the induced signal is applied to a regenerative oscillator, it triggers sustained oscillations and amplifies the induced in-phase current. Since this oscillation is in phase with original transmitter current, they sum to induce a stronger signal in the next layer. This process then repeats at each layer.

III. MAESUREMENT RESULTS

To verify the theory, a prototype system is designed with a planar coil on PCB and discrete components to implement the regeneration.

A. Measuremt Setup

The coil on each PCB has an octagon shape, is a single turn, and has a 23mm diameter. Each PCB layer has a cross-coupled oscillator for regeneration, using discrete FETs, a bias current of 30mA, and a supply voltage of 3V. Four layers are stacked as shown in Fig. 6, and the separation between layers is changed to sweep k from 0.01 to 0.1. Since the coil Q-factor is 150, the links operate in the strongly coupled regime. The resonant frequency of the system is tuned to 75MHz.

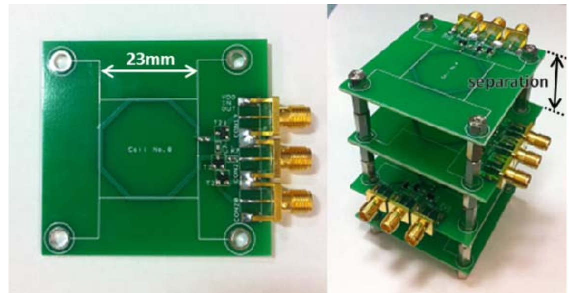

Fig.6. Prototype system

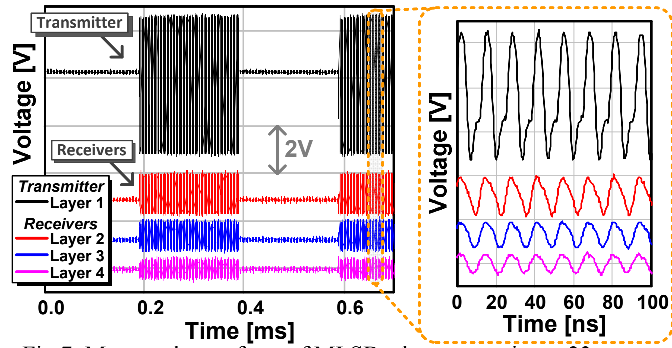

Fig.7. Measured waveform of MLSB when separation = 23mm.

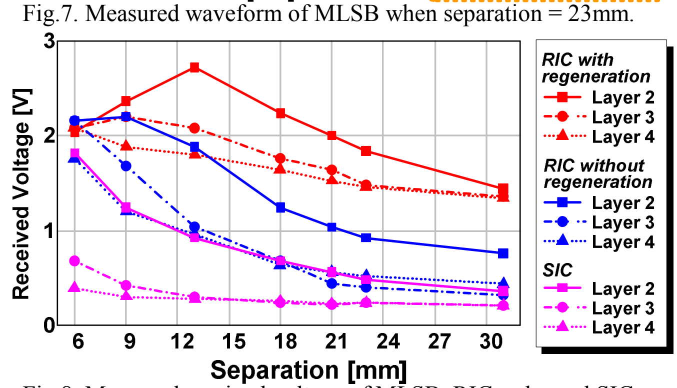

Fig.8. Measured received voltage of MLSB, RIC-only, and SIC

B. Measurement Results

Fig. 7 shows signal transmission from layer 1 to layer 4 with 23mm separation per layer. The source signal at layer 1 and the induced signal at layers 2-4 are almost in-phase, with the phase difference ranges from 0º to 24º. The comparison between MLSB, RIC without regeneration and standard inductive coupling (SIC) is shown in Fig. 8. As the separation increases, the SIC signals reduce, eventually becoming too small to sense. RIC alone induces larger signals than SIC, but fails to deliver sufficient signals to layers 3 and 4 when the distance is long. However, if regeneration is used with RIC, communication distance is significantly enhanced. When the aspect ratio is 4:1 (the separation = 31mm), the received signal at layer 4 is 9.8dB larger than RIC-only and 16.2dB larger than SIC.

REFERENCES

[1] N. Miura, *et al*., IEEE JSSC, Vol. 41, No. 1, pp. 23-34, Jan., 2006.
[2] N. Miura, *et al*. IEEE ISSCC, pp. 490-491, Feb. 2011.
[3] Y. Sugimori, *et al*., IEEE ISSCC, pp. 244-245, Feb. 2009.
[4] M. Saito, *et al*., IEEE ISSCC, pp.440-441, Feb. 2010.
[5] C. M. Zierhofer, *et al*., IEEE T-BME, Vol. 43, No. 7, Jul. 1996.
[6] S. Han, *et al*., IEEE AP-S Jul. 2010.