Performance Improvement of Resonant Inductive Coupling for Wireless 3D IC Interconnect

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Introduction

As the demands on high performance and multi-function systems increase, System-in-Package (SIP) provides a method for increasing integration with a reasonable cost and short development time. SIP using vertically stacked (3D) ICs has the advantages of a small form-factor and short communication distance between chips, leading to increased data rate and efficiency. Several wired and wireless approaches for interconnect between 3D ICs have been proposed. Among them, wireless interconnect using inductive-coupling is very promising since it has achieved low power, high performance with small size, and operates across heterogeneous ICs and technologies as illustrated in Fig. 1 [1].

Prior wireless interconnect solutions rely on standard inductive coupling using air-core, planar spiral inductors. This results in poor efficiency (<5%) and a relatively short communication distance (~15μm) [2] since most of the flux is not linked between the coils. It has recently been shown that power can be wirelessly transferred using two resonant inductors for powering consumer electronics at relatively long distances, with efficiency up to 50% [3]. However, this has not been applied to 3D communication.

In this paper, we propose using resonant inductive-coupling for wireless interconnect between 3D ICs. First, a comparison of resonant inductive coupling (RIC) and standard inductive coupling (SIC) is discussed. Analytical models for signal coupling are derived for SIC and RIC links as they apply to 3D wireless interconnect, and verified through HFSS simulations using a 130nm CMOS process. Finally, a performance comparison between the two methods is presented.

Wireless Interconnects

Wireless 3D interconnect has the advantages that it is compatible with most conventional IC processes and therefore operates across heterogeneous dies, and it can eliminate the Known-Good-Die (KGD) issue that effects wired 3D ICs [2]. Among the wireless interconnect methods, inductive-coupling provides the best tradeoff between performance, distance, and cost [4].

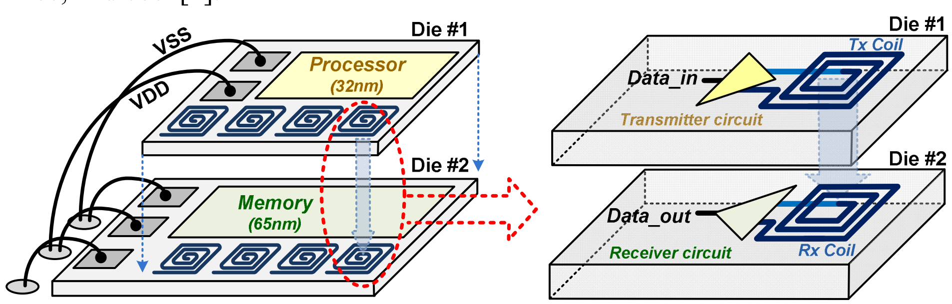

Fig. 1. Concept of wireless interconnects

A transmit-receive pair is illustrated in Fig. 1. Because the flux density, and therefore signal strength, in inductive links is directly proportional to current in the transmitting coil, the transmitter circuits should maximize current. On the receiver side, an amplifier optimized for low noise figure and power presents a high-impedance load on the receiver coil, therefore received voltage should ideally be maximized. SIC links operate well below the self-resonant frequency of the inductors, therefore the parasitic capacitances can be ignored and the SIC link is modeled as an equivalent circuit in Fig. 2(a). R_1 and R_2 model the losses in the coils. The transmitter is modeled as a current source operating at a fixed frequency. The receiver is modeled as a large resister R_L. The received voltage V_R for the SIC link is given by Eq. (1)

$$V_{R\_SIC} = j\omega k\sqrt{L_1 L_2} I_S = j\omega k L I_S \tag{1}$$

where k is the transformer coupling coefficient, L_1 and L_2 are the self-inductances of the transmitter and receiver coils, respectively. Since the transmitter and receiver coils are typically identical for SIC and RIC links, $L_1 = L_2 = L$. I_S is the transmitter current amplitude. The value of k is found from simulations, and is a strong function of the separation between coils ($k \propto \text{distance}^{-3}$), therefore its value determines the communication distance.

The RIC circuit is shown in Fig. 2(b). External capacitors C_1 and C_2 have been added to create resonant tanks at the transmitter and receiver sides. The resonant frequency can be tuned by adjusting the capacitor values. RIC links operate in two regimes, depending on the values of k and quality factor ($Q = \omega L/R$), where R is the loss in the inductor; the strongly coupled regime ($kQ \geq 0.1$) and the weakly coupled regime ($kQ < 0.1$). The link characteristics are different in each regime, as discussed in the following two sections.

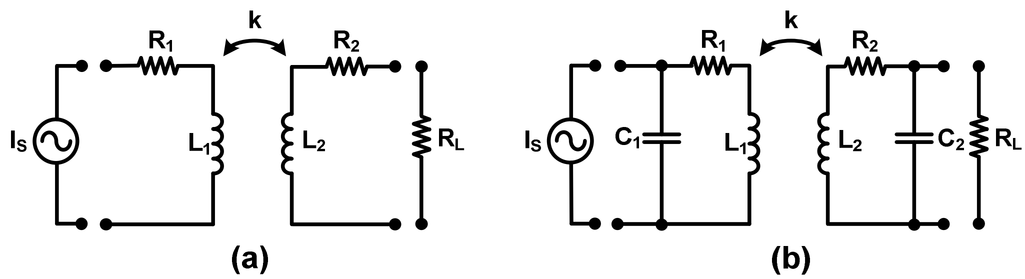

Fig. 2. (a) SIC equivalent circuit and (b) RIC equivalent circuit

Resonant Inductive Coupling in the Strongly Coupled Regime

The strongly-coupled regime is defined by $kQ \geq 0.1$, that is, when the coils are close together. In this regime, the coupling is strong enough that the loading on the receiver side effects the resonant frequency at the transmitter side when reflected through the transformer, and *vice versa*. This creates two resonant frequencies for the strongly-coupled RIC system, given by:

$$\omega_{0\_low} = \frac{\omega_0}{\sqrt{1+k}}, \qquad \omega_{0\_hi} = \frac{\omega_0}{\sqrt{1-k}} \tag{2}$$

where $\omega_0 = 1/\sqrt{L_1 C_1} = 1/\sqrt{L_2 C_2}$ is the unloaded resonant frequency. At each resonant frequency, the received voltage V_R for RIC with strong coupling is given by:

$$V_{R\_RIC\_low} = jQ^2\left(\frac{1+k}{1+kQ}\right)\omega_{0\_low}kLI_S \quad (3)$$

$$V_{R\_RIC\_hi} = jQ^2\left(\frac{1-k}{1+kQ}\right)\omega_{0\_hi}kLI_S \quad (4)$$

When k approaches 1, the advantage of RIC over SIC (Eq. 1) is an increase in received voltage by a factor of approximately $2Q$. As the coil separation increases, k reduces, and ω_{0_low} and ω_{0_hi} converge on a single resonant frequency ω_0. The RIC link then transitions from strongly-coupled into the weakly-coupled regime as described below.

Resonant Inductive Coupling in the Weakly Coupled Regime

The weakly-coupled regime is defined by $kQ < 0.1$, that is, when the coils are far apart. In this regime, the receiver load reflected to the transmitter side is negligibly small so that it has no impact on the transmitter circuit. Therefore, the system has one resonance frequency $\omega_0 = 1/\sqrt{L_1C_1} = 1/\sqrt{L_2C_2}$. At ω_0, the receiver voltage V_R is given by Eq. (5).

$$V_{R\_RIC} = jQ_1Q_2\omega_0 k\sqrt{L_1L_2}I_S = jQ^2\omega_0 kLI_S \quad (5)$$

In this regime, RIC significantly improves the received signal amplitude over SIC (Eq. 1) by a factor of Q^2, which is typically much greater than 1.

Simulations

To verify these models, we designed planar spiral coils for SIC and RIC using a Chartered 130nm CMOS process (Fig. 3). Two identical coils are vertically stacked to simulate communicating through stacked ICs. The distance between them is swept from 5μm to 95μm, and HFSS is used to extract the lumped-element models for the coils. These models are imported into Spectre to simulate the received voltage for a given transmitter current excitation. The results are shown in Fig. 4. The nominal value of Q is 3.1, and the boundary of the weakly/strongly coupled regimes is k = 0.03. In the weakly coupled regime, the RIC link has one resonant frequency, but as k increases, the frequency splits into ω_{0_hi} and ω_{0_low} (Fig. 4(a)). Fig. 4(b) shows V_{R_SIC}, V_{R_RIC} at ω_{0_low}, and the ratio of the two. RIC improves the coupling over SIC by a factor of 10 ($\approx Q^2$) in the weakly-coupled, and 5~10 ($\approx 2Q$) in the strongly-coupled regimes. As k increases, the stronger coupling increases V_{R_RIC}. However, the ratio V_{R_RIC}/V_{R_SIC} is decreasing, approaching $2Q$ for $k = 1$, and also with reducing Q as frequency ω_{0_low} decreases.

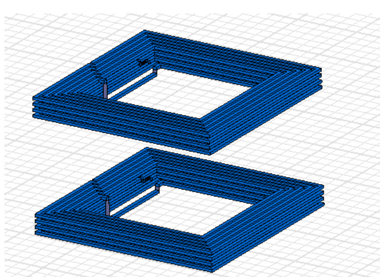

Fig. 3. HFSS coils design

TABLE I
DETAILS OF COILS

Parameter	Value
diameter	30μm
Width	0.65μm
space	0.35μm
Number of turns	5
Number of layers	4
L	22nH
C	40fF
R	240Ω

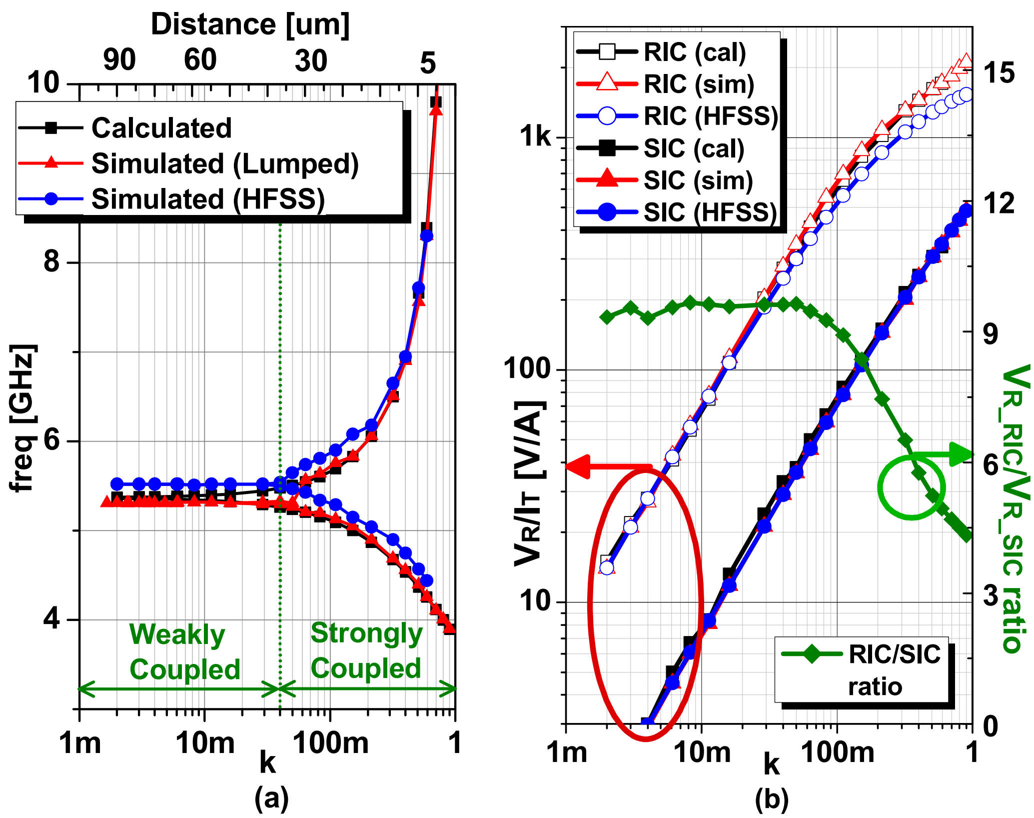

Fig. 4. (a) Resonant frequency depending on k and (b) received voltage depending on k

Conclusion

The performance of inductive links for 3D wireless interconnects in a package can be improved by using resonant inductive coupling over standard inductive coupling. Without increasing the size of the coils or power consumption, RIC can increase the received voltage by factors of Q^2 (weakly coupled) and $2Q$ (strongly coupled) compared to SIC. The improvement of RIC is the highest in the weakly-coupled regime when the received signal is smallest. Therefore, RIC can be exploited for small k to increase the communication distance and separation between coils, enabling communication through thicker die or multiple die, as well as wireless testing and verification.

References

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