3D Integration of Ka-band RFIC by Inductive Inter-chip Wireless Communication Using Figure-8 Coils

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***Abstract*— Inter-chip communications using inductive coupling with figure-eight coils for a Ka-band RFIC is presented. Compared with a conventional rectangular coil, the figure-8 coil achieves 15dB better interference rejection while the signal transmission is inferior only by 1 dB. The minimum coil pitch can be set to 250 µm, which is 44 % smaller than that of the conventional rectangular coil, contributing to the miniaturization of Ka-band RFIC's.**

Keywords—3D integration, inductive-coupling, mm-wave

I. INTRODUCTION

Pitches between the elements of an array antenna is the half wavelength of the communication signal, and they become shorter as the communication frequency becomes higher. Therefore, RFICs must be designed to be smaller than the pitch, and the demand for miniaturization of RFICs is increasing. Stacking IC chips three-dimensionally and improving area efficiency are proposed to meet this demand.

For three-dimensional integration, it is necessary to connect signals between chips, and through-silicon vias (TSVs) drives up cost because of requiring additional manufacturing processes. A method of inter-chip wireless communication technology using inductive-coupling by on-chip coils, known as a ThruChip Interface (TCI), has been proposed. The coils are formed by standard CMOS process without additional processes unlike TSV. Therefore, TCI can suppress the increase in cost. TCI has been extensively researched for high-speed digital communications [1], [2].

In this paper, we propose to use TCI technology to transmit Ka-band analog signal and make the shape of the communication coil into figure-eight shape. It can improve the carrier-to-interference ratio better than a rectangular coil. We focus on 40 GHz in Ka-band. In this paper, Performance evaluation is performed using the maximum available gain, because the loss due to impedance matching of a figure-eight coil and a rectangular coil is considered to be about the same. In Section II, the theory of TCI using conventional rectangular coils and the concept of figure-eight coils are explained. In Section III, the performance of the Ka-band inter-chip wireless communications using figure-eight coils proposed in this paper is explained as compared with conventional rectangular coils. In Section IV, the conclusions are given.

II. THURUCHIP INTERFACE

A. Theory of ThuruChip Interface

TCI is a communication method that utilizes mutual induction of adjacent coils, as shown in Fig. 1. According to the Faraday's law of induction, an induced voltage is generated in the receiving coil by the change in the magnetic field

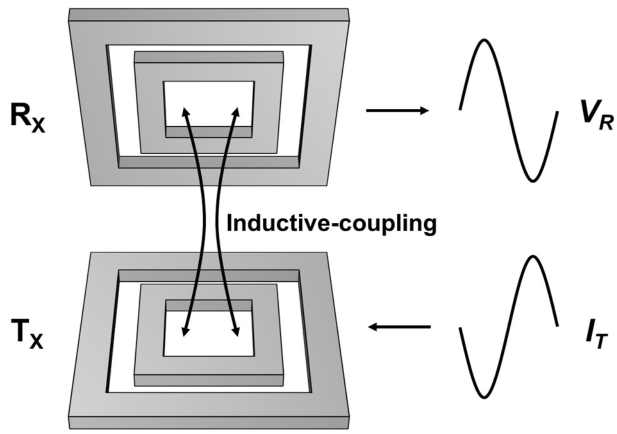

Fig. 1. The appearance of TCI.

generated from the transmit coil, and the relationship between the receiver voltage V_R and the transmit current I_T can be expressed as

$$V_R = k\sqrt{L_T L_R}\frac{dI_T}{dt} \tag{1}$$

where k is the coupling coefficient between transmit and receive coil, L_T and L_R are their inductance. However, in reality, the coil does not function as an inductor at a frequency higher than the self-resonant frequency, because a self-resonance phenomenon occurs due to the coil parasitic element. Fig. 2 shows the equivalent circuit of TCI when the same coil is used for transmit and receive coil. Inductance L and capacitance C, which are modeled on a rectangular coil, are given by

$$L = 1.62\times10^{-3} D_{out}^{-1.21} w^{-0.147} D_{avg}^{2.4} s^{-0.03} \tag{2}$$

$$C = C_G(D_{out}^2 - Din^2) + \frac{4C_c n D_{out}}{s} \tag{3}$$

[3] where D_{out} is the outer diameter of the coil, D_{in} is the inner diameter of the coil, D_{avg} is the average of the inner and outer diameter of coils, equal to $(D_{out}+D_{in})/2$, C_G is the bottom-plate capacitance, C_c is inter-winding capacitance, w is the line width, s is the line space, and n is the number of turns of coil. The self-resonant frequency of the transmit and receive coil that takes the effect of parasitic elements is given by

$$f_{SR} = \frac{1}{2\pi\sqrt{LC}} \tag{4}$$

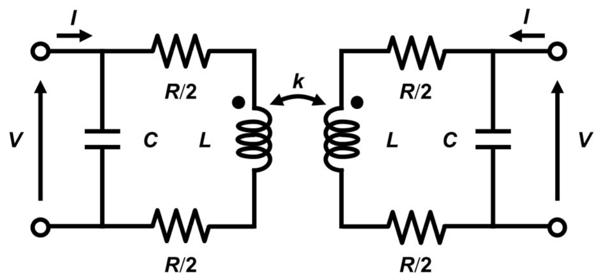

Fig. 2. The equivalent circuit of TCI.

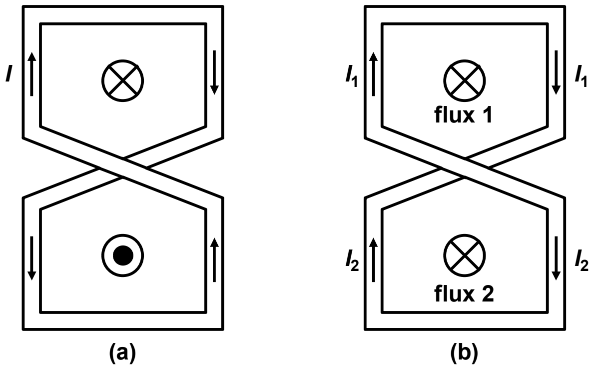

Fig. 3 The appearance of figure 8 coil and interference reduction function.

In order to communicate using inductive coupling of coils, it is necessary to design the coils so that the following relation is satisfied.

$$f_{\mathrm{R}} < f_{\mathrm{SR}} \tag{5}$$

Where f_R is the communication frequency.

B. *Figure-eight coil*

Using figure-eight coils for TCI has been proposed as a method of suppressing crosstalk interference between channels to improve channel density [4], [5]. Figure-eight coils obtain two rectangular coils turned inversely. As shown in Fig. 3 (a), magnetic fields in the opposite directions are generated, when source current *I* flows in a figure-eight coil. It is considered that the magnetic fields in opposite directions cancel each other at a distant place, and crosstalk interference becomes small. A figure-eight coil also has resistance to common mode noise. This is because, as shown in Fig.3 (b), currents in opposite directions I_1 and I_2 induced by identical flux 1 and flux 2 respectively cancel each other, when the magnetic flux in the same direction passes through a figure-eight coil.

III. Simulaiton Result

A. *Insertion loss of TCI*

Fig. 4 shows the appearance of TCI using figure-eight coils. The outer diameter of coils is 100 µm, the line width is 10 µm, the line space is 4 µm, and the length of the lead wiring is 10 µm. The communication distance X is changed to 10 µm, 20 µm, 30 µm, 40 µm, 50 µm, and the insertion loss is evaluated with the maximum available gain, and the simulation result is shown in Fig. 5. When X is 10 µm, the magnitude of impedance is shown in Fig.6, and the self-resonant frequency is 43.7 GHz. The maximum available gain

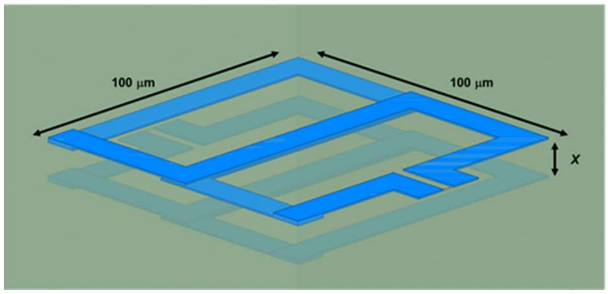

Fig. 4. The appearance of TCI using figure-eight coils.

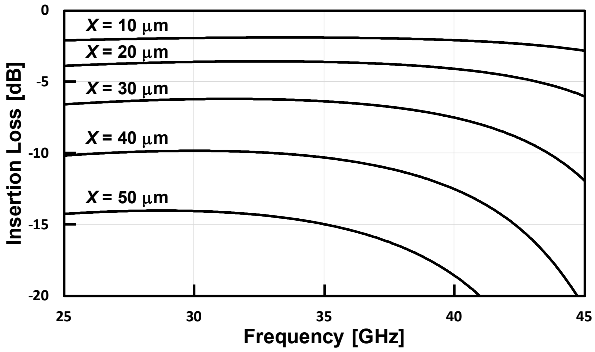

Fig. 5. The relationship between the communication distance X and the insertion loss using figure-eight coils.

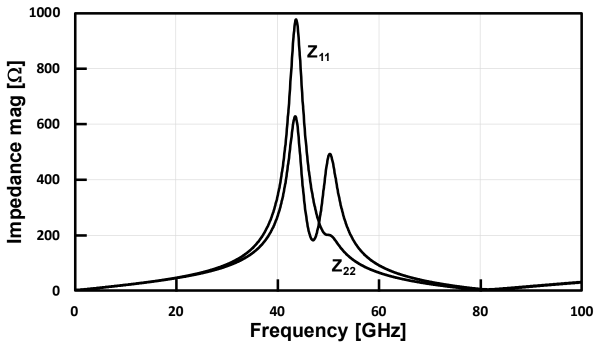

Fig. 6. The magnitude of impedance of figure-eight coils.

of the insertion loss is -2.1 dB at 40 GHz when the communication distance is 10 µm, and The insertion loss improves as the communication distance becomes shorter.

In [6], digital signal inter-chip communication using TCI was confirmed between stacked, 10 µm-thick chips. Therefore, we employed the communication distance of 10 µm in this paper.

Fig. 7 shows the appearance of TCI using conventional rectangular coils. In order to match the conditions with the figure-eight coil, the outer diameter of coils is 100 µm, the line width is 10 µm, the line space is 4 µm, and the length of the lead wiring is 10 µm. Fig. 8 compares the maximum available gains of the insertion loss when the communication distance is 10 µm. The insertion loss of the rectangular coils is about 1 dB better than that of the figure-eight coils. It is considered this is because the area inside the coil is reduced due to the overlap of wiring in the figure-eight coils, and the opposite magnetic fields generated in the figure-eight transmit coil weaken each other before reaching the receive coil.

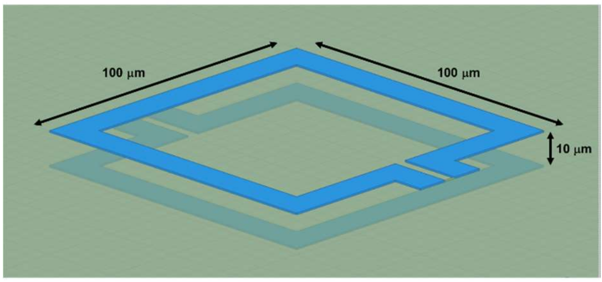

Fig. 7. The appearance of TCI using rectangular coils.

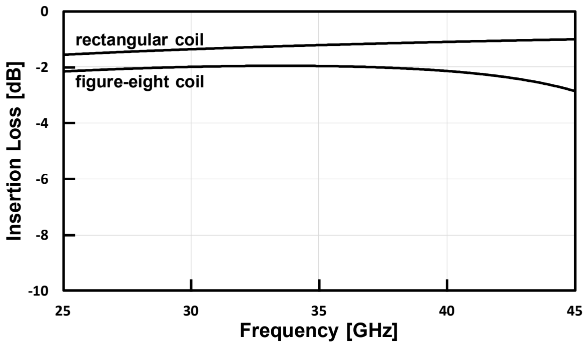

Fig. 8. The insertion loss of TCI using the figure-eight coils and the rectangular coils.

B. *Crosstalk interference between channels*

The communication distance is fixed at 10 µm and the interference between adjacent channels is simulated. The distance *D* between the two sets of TCIs is varied from 50 µm to 400 µm at intervals of 50 µm, and the crosstalk to the coil of the adjacent channel is simulated. Fig. 9 shows the appearance using figure-eight coils and Fig. 10 shows the appearance using rectangular coils.

Fig. 11 shows the results of the carrier-to-interference ratio using the maximum available gain with respect to the pitch, where the pitch of the TCI is the summation of the length of the distance *D* and the outer diameter of the coil. The carrier-to-interference ratio improves as the pitch becomes larger, because the influence of the magnetic fields from the coil of the adjacent channel is reduced by increasing the distance. Moreover, using figure-eight coils improves the carrier-to-interference ratio by about 15 dB. It is considered that this is because the opposite magnetic fields generated by the figure-eight coils cancel out each other at a distance. Furthermore, assuming a system that requires the carrier-to-interference ratio of 60 dB, the pitch of TCI using the figure-eight coils is 250 µm, while that of the rectangular coils is 450 µm, so the pitch can be 56 %.

IV. Conclusion

We propose TCI using figure-eight coils for the Ka-band analog signal, and the evaluation was performed using the maximum available gain. Compared to the conventional rectangular coils, the insertion loss is inferior by about 1 dB, but the carrier-to-interference ratio improves by about 15 dB. Assuming a system that requires the carrier-to-interference ratio of 60 dB, the pitch can be set to 250 µm, which is 56 % of the conventional rectangular coils. Therefore, TCI using figure-eight coils can contribute to downsizing of the RFIC.

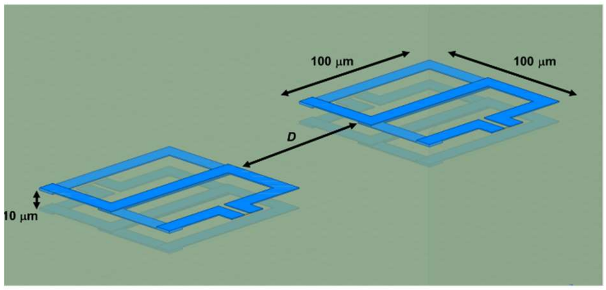

Fig. 9. The appearance of the simulation of crosstalk interference between two channels using figure-eight coils.

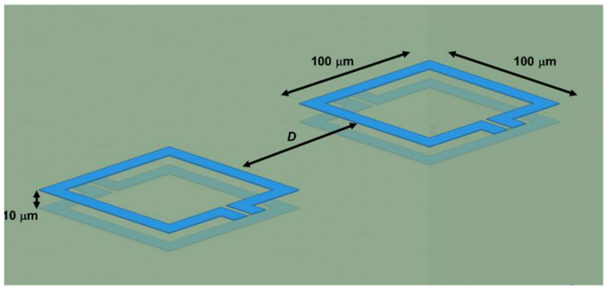

Fig. 10. The appearance of the simulation of crosstalk interference between two channels using rectangular coils.

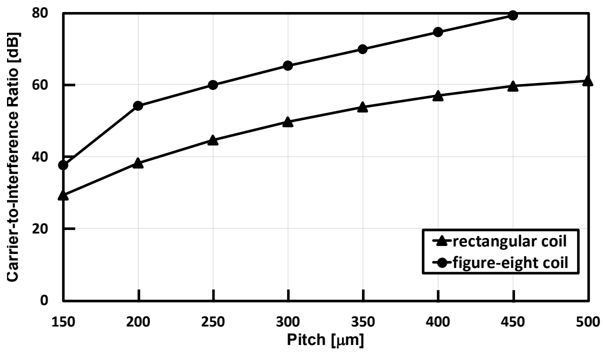

Fig. 11. The relationship between the pitch of TCIs and the carrier-to-interference ratio.

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