Silicon integrated antennas for wirelcss interconnects

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1. Introduction

Parasitic resistance and capacitance of conventional interconnect remains the primary obstacle to increase clock frequency in Si ULSIs. Recently a revolutionary approach of intra-chip wireless clock signal transmission using integrated antenna have been proposed [1]-[2]. However, detail study of wireless clock transmission in Si is still in its infancy. In this paper basic characteristics of integrated antenna on Si, the interference effect of local interconnect metal lines on antenna transmission gain and various methods to improve transmission gain of integrated antenna have been reported. The measured characteristics are compared with simulated results obtained by using a high frequency structure simulator employing 3-D finite element method.

2. Fabrications and Measurement

Figure 1 shows the conceptual diagram of the clock distribution system. Antenna test structures were fabricated on 260 μm thick Si wafer with a resistivity of 10 Ω-cm using 500 nm field oxide and a 1 μm thick aluminum layer for antenna formation as shown in Fig. 2. The setup for S-parameter measurement is shown in Fig. 3. It consists of HP8510C Vector Network Analyzer, 180° Hybrid Couplers (6.0-26.5 GHz), Signal-Signal probes and a probe station. Wafers were measured on a block of wood (2.6 mm thick) on the metal chuck of the probe station. The relative dielectric constant of wood was measured as 2.15 at 1 GHz.

3. Results and Discussion

Figure 4 shows the measured return loss (S_{11}) of dipole antenna versus antenna length (L). A 3 mm long dipole antenna shows a resonance peak at around 22 GHz. The power transmitted to the receiving antenna is calculated from the scattering parameters using antenna transmission gain (G_a) as derived form *Frii's* transmission formula [1]. Figure 5 shows G_a versus frequency with antenna length as a parameter. At 20 GHz the 3 mm long dipole has 10 dB higher gain than the 2 mm dipole. The measured gain are compared with simulated values. Both measured and simulated data shows similar trend, however, the measured gain is about 5 dB less than the simulated gain at high frequency. This is due to the impedance mismatch between the antenna and the measuring instruments. Figure 6 shows transmission gain versus frequency with antenna distance (d) as a parameter. The measured and simulated gain are also compared. The transducer gain between two sets of pads separated by a distance of 10 mm is also shown. Very low pad to pad gain shows conclusively that the signal is transmitting from one antenna to the other by radiation. When separated by a distance of 1 cm, the 2 mm long and 10 μm wide antenna pair shows a transmission gain of −54 dB at 20 GHz. With the successful fabrication of integrated low noise amplifier (LNA) above 40 dB voltage gain in GHz frequency region [3] it is expected that such integrated dipole antennas can be used in the wireless clock/data transmission system in future ULSI chips. Figure 7 shows the effect of receiver rotation angle with respect to the transmitter on antenna gain. From the measured and simulated data we conclude that flexibility exist in orienting the receiver antenna with respect to the transmitting antenna up to an angle of 30° without any significant reduction of antenna transmission gain.

Figure 8 shows the effect of interference from local interconnect metal lines on the transmission gain of integrated antenna. As seen from the figure, when the interconnect metal lines area place normal to antenna radiation direction the antenna gain reduces by about 15 dB which does not depends on the number of interconnect metal lines. On the other hand, as shown in Fig. 9, when the metal lines are placed parallel to antenna radiation direction, the gain improves which is more prominent in the low frequency region. Fig. 10 shows that when the metal lines are placed in both normal and parallel to antenna radiation direction, due to their competing effect the reduction in transmission gain is minimized. The metal interconnect in a ULS chip can be approximated as a solid aluminum metal plate. As shown in Fig. 10, the existence of such a metal plate reduces the transmission gain by about 12 dB.

4. Future plan

To reduce the burden on circuit design it is necessary to improve the transmission gain of the antenna without increasing the antenna size. We plan to perform experimental investigation of the effect of Si substrate resistivity and other innovative process technique on antenna transmission gain in order to drastically improve integrated antenna performance. We would also like to investigate on the feasibility of inter-chip clock/data transmission as well.

We also plan to design and fabricate the analog/digital interface circuit along with the integrated antenna for the practical realization of the intra- and inter-chip wireless interconnect on Si ULSI.

5. Conclusion

Basic characteristics of integrated antenna on Si showed their feasibility to use for intra-chip wireless interconnections at frequencies ~20 GHz or higher. However, to reduce the burden on circuit design it is necessary to improve the transmission gain of the antenna without increasing the antenna size.

References

[1] K. Kim et al. IEDM Tech. Dig., pp. 485-488, December 2000.

[2] A.B.M. H. Rashid, S. Watanabe and T. Kikkawa, IITC Tech. Dig., June 2002, pp. 173-175

[3] F. Svelto et al., IEEE Trans. Very Large Scale Integr. Syst. 9 (2001) p. 100-105

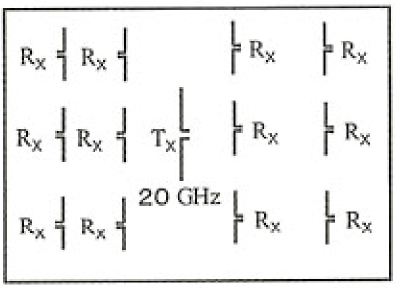

Fig. 1 Conceptual diagram of the wireless clock/data transmission system. T_X = Transmitter, R_X = Receiver.

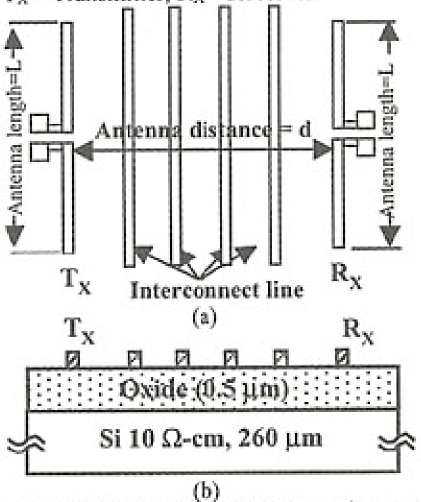

Fig. 2 (a) Layout and (b) Schematic cross-sectional diagram of dipole transmitter-receiver with interconnect metal lines in-between.

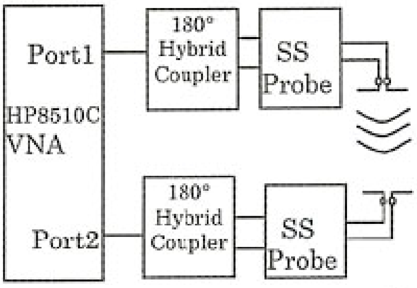

Fig. 3 Experimental set-up for on chip antenna characterization.

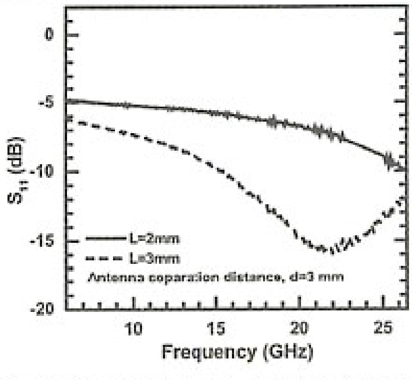

Fig. 4 Measured return loss (S_{11}) versus frequency with antenna length (L) as a parameter.

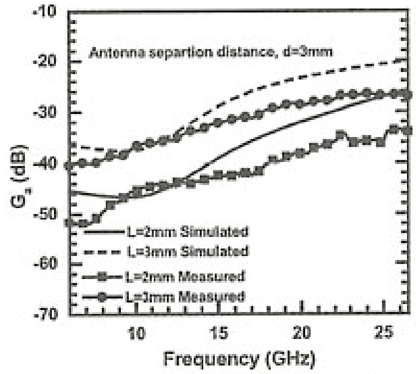

Fig. 5 Transmission gain (G_a) versus frequency with antenna length (L) as a parameter. Measured and Simulated data are compared.

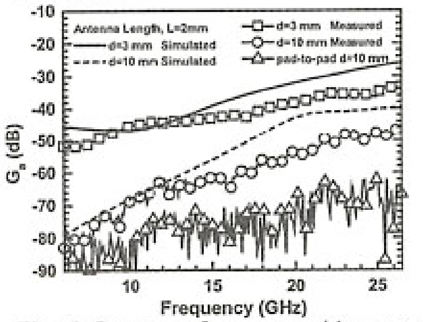

Fig. 6 G_a versus frequency with antenna separation distance (d) as a parameter. Measured and simulated data are compared. A dummy pad to pad gain is also shown.

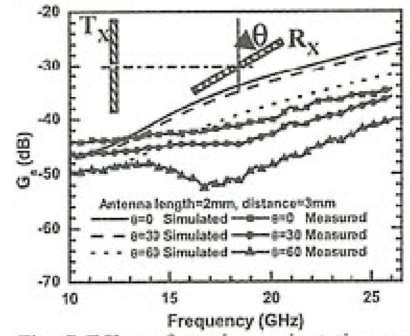

Fig. 7 Effect of receiver orientation angel on antenna transmission gain (Ga).

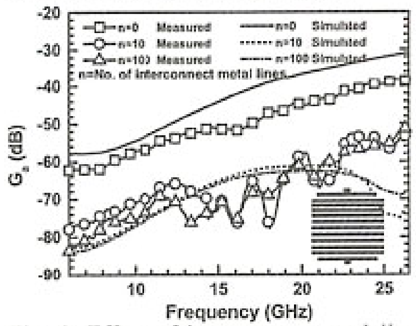

Fig. 8. Effect of interconnect metal lines on transmission gain (Ga). For metal lines placed normal to the antenna radiation direction Ga decreases by about 15 dB.

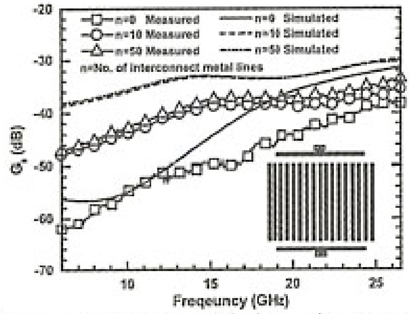

Fig. 9 Antenna transmission gain versus frequency with interconnect metal lines placed parallel to antenna radiation direction.

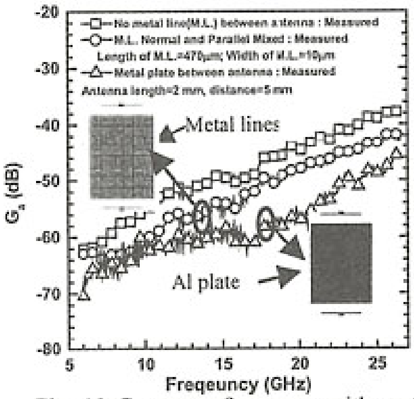

Fig. 10 G_a versus frequency with metal lines placed both normal and parallel direction. Bottom line shows the effect of a solid metal plate.

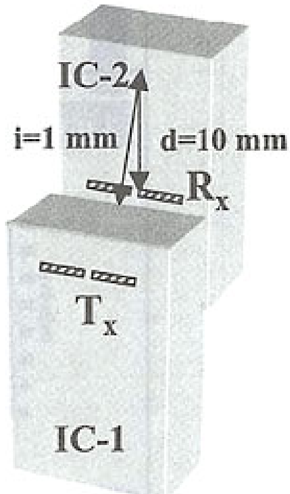

Fig. 11 Conceptual diagram of inter-chip clock and data transmission using integrated antenna. Tx= transmitter, Rx=receiver.

Si Integrated Antenna for Wireless Interconnects

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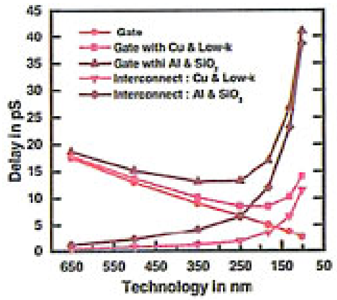
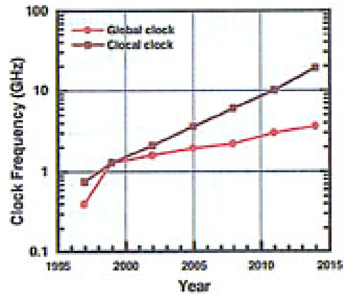
Motivation

Limitation of Maximum Clock Frequency in conventional ULSI





- Interconnect delay far exceeds the gate delay at present technology
- Parasitic R, C and L is the primary obstacle for high frequency clock and data transmission in ULSI.

Objective

New revolutionary approach

- Signal transmission via microstrip transmission line
- Signal transmission using optical interconnect
- Wireless signal transmission using integrated antenna.

Advantage of Wireless Interconnect

- High speed signal transmission is possible by eliminating RC interconnect delay
- Signal skew due to parasitic RC effect is eliminated
- Reconfigurable type interconnect is possible

Target : On chip wireless interconnect at around 15~20 GHz clock frequency.

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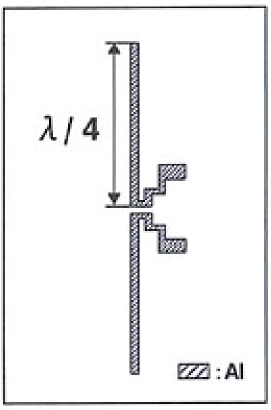
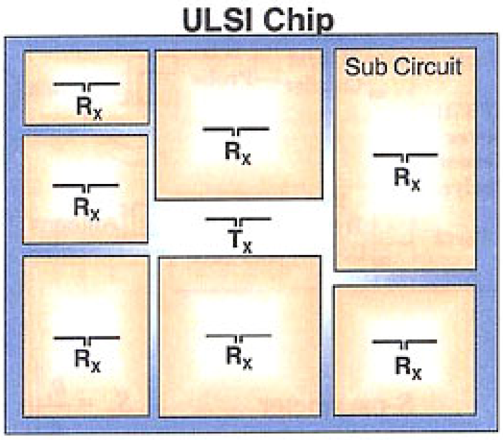
Wireless signal transmission - Concept

Integrated Antenna





T_x : Transmitting Antenna

R_x : Receiving Antenna

Conceptual diagram of wireless clock and data transmission System

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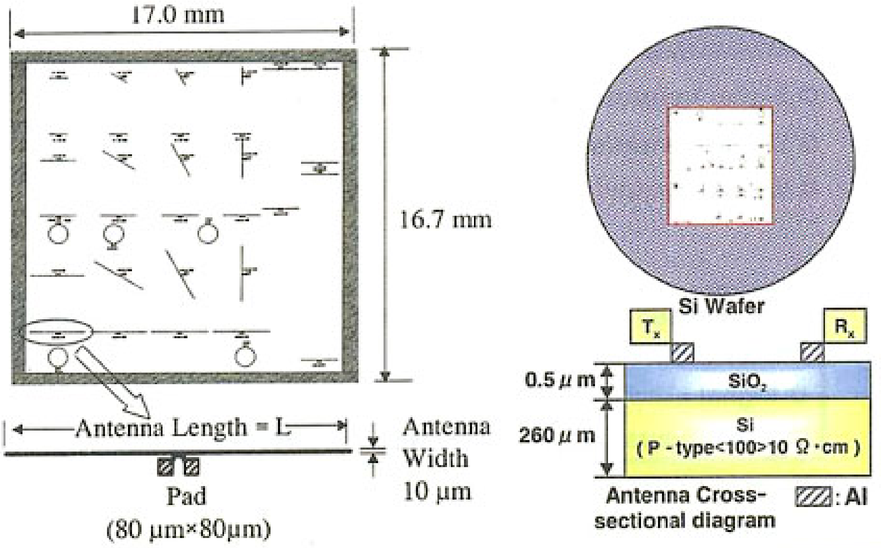
Sample Fabrication – Evaluation of Basic Characteristics



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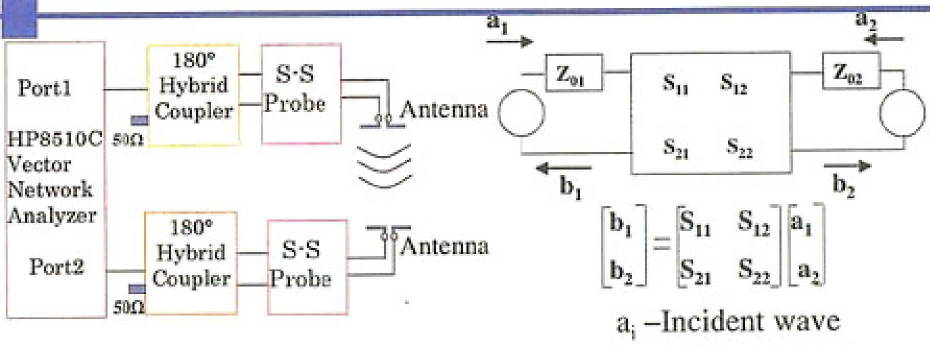
Measurement Technique



$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

a_i –Incident wave

b_i– Reflected wave

S-parameter $S_{ii} = \left.\frac{b_i}{a_i}\right|_{a_j = 0}$ $S_{ij} = \left.\frac{b_i}{a_j}\right|_{a_i = 0}$

Antenna Transmission Gain (G_a) $G_a = G_r \cdot G_t \cdot \left(\frac{\lambda}{4\pi R}\right)^2 = \frac{|S_{21}|^2}{(1-|S_{11}|^2)(1-|S_{22}|^2)}$

Here, G_r= Receiver Gain, G_t=Transmitter Gain

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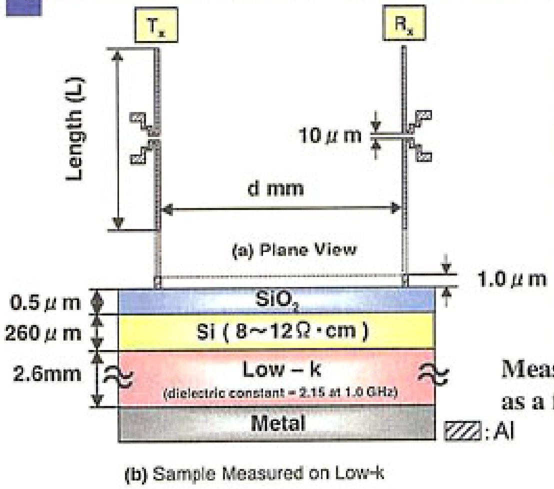
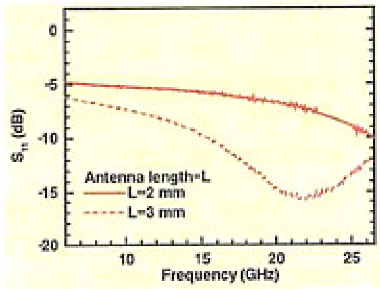
Basic Characteristics – Return Loss





Measured return loss versus frequency as a function of antenna length

◎ 3 mm long dipole antenna shows resonance peak at around the target frequency of 20 GHz.

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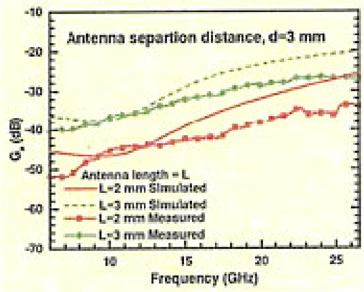
Basic Characteristics – Transmission Gain vs. Antenna Length

◎ 3 mm long dipole has 10 dB higher gain than the 2 mm long dipole.

◎ Measured gain is lower than the simulated gain because of the impedance mismatch between the antenna and measuring equipments.



Transmission Gain versus Antenna Length

SIMULATION : 3-D Finite element method using Ansoft HFSS

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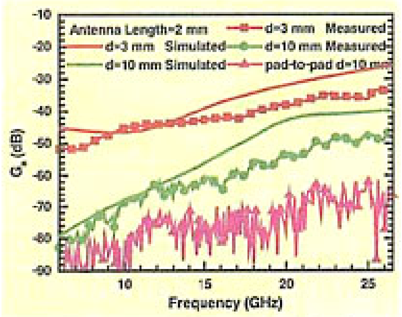
Basic Characteristics – Transmission Gain vs. Antenna distance

◎ Dipole antenna with L=2 mm, W=10 μm (area 0.02 mm^2) shows a transmission gain of -54 dB at 20 GHz and at a distance of 1cm.

◎ Very Low pad-to-pad gain shows that signal is propagating from one antenna to the other by radiation.

◎ Integrated dipole antenna is promising for on-chip wireless clock and data transmission on Si.



Transmission gain (Ga) versus frequency

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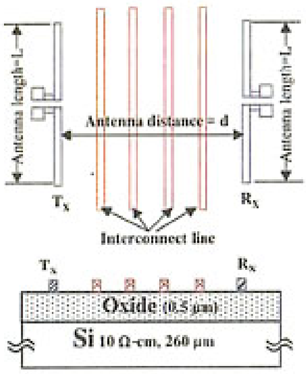
Sample Fabrication – Evaluation of Interference



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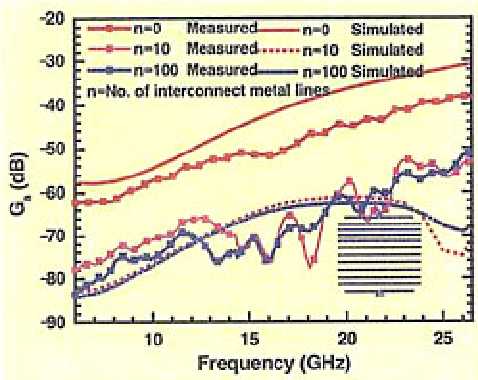
Interference – Metal Line Normal to Radiation Direction



◎ When metal lines are placed normal to antenna radiation direction, the transmission gain decreases by about 15 dB at 20 GHz. The decrease in gain does not depends on the number of metal lines placed between the transmitting and the receiving antenna.

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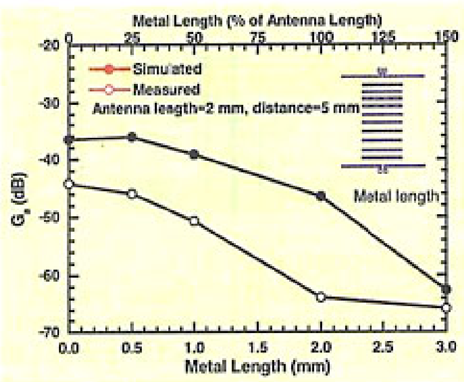
Interference – Length of Metal Line Normal to Radiation Direction



◎ When metal lines are placed normal to antenna radiation direction, the decrease in transmission gain depends on the length of interconnect metal lines.

◎ For length of metal lines one fourth of antenna length, the decrease in gain is negligible.

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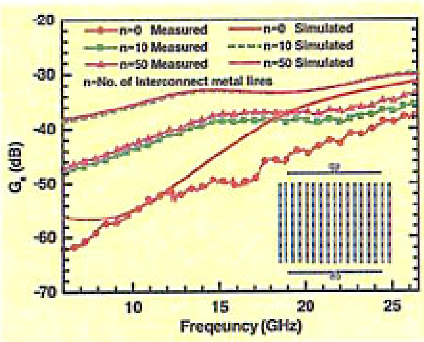
Interference – Metal Line Parallel to Radiation Direction



◎ **When metal lines are placed parallel to antenna radiation direction, the transmission gain increases which is more visible at the lower frequency region.**

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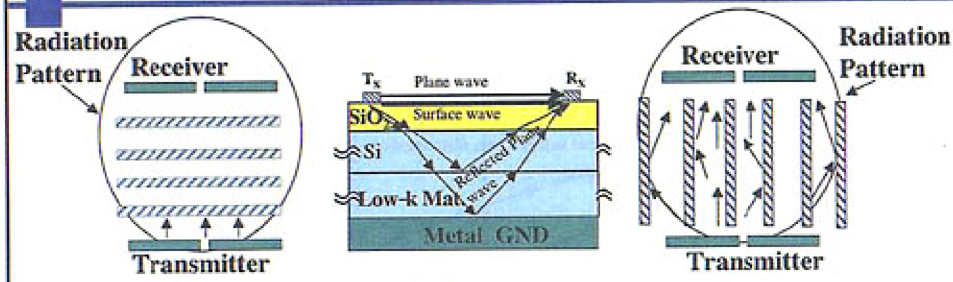
Interference – Plane Wave Model



EM wave propagating through the plane of the antenna (plane wave) get reflected back and can not reach the receiver antenna.

◎**Transmission gain reduces and the reduction in transmission gain does not depends on the number of interconnect lines but on the length of the metal lines.**

Plane wave can propagate through metal spacing. Also metal lines at the sides acts as a reflector and direct the outgoing plane waves towards the receiver.

◎ **Transmission gain increases**

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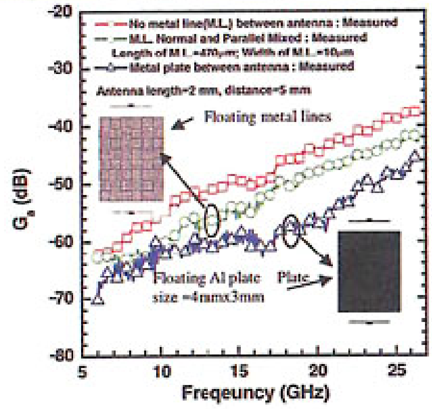
Interference — Effect of Metal Line both in Parallel and Normal direction and Effect of Solid Metal plate



◎ Due to the competing effect of interconnect lines placed both normal and parallel to antenna radiation direction, reduction in transmission gain is minimized for such layout.

◎ A floating Al plate reduces the gain by about 10 dB.

Conclusion

◎ Small size dipole antenna (0.02 ˜ 0.03 mm^2) on Si shows feasibility to be used in intra-chip wireless interconnection at frequencies around ˜ 20 GHz.

◎ To reduce the burden on circuit design it is necessary to improve the transmission gain of the antenna without increasing the antenna size.