ULSI Wireless Interconnection Using Integrated Antennas for Ultra-Wide-Band Signal Transmission

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Abstract

Inter/intra-chip wireless interconnection technology using fractal antennas for ultra-wide-band (UWB) signal transmission in Si was demonstrated. Gaussian monocycle pulse whose pulse width was 100 ps and center frequency was 15 GHz could be transmitted horizontally and vertically in Si. Sierpinski carpet dipole antennas showed superior UWB characteristics for transmission of Gaussian monocycle pulse without distortion in 10 mm distance.

1. Introduction

In order to overcome signal delay time in global interconnects due to parasitic resistance and capacitance, a concept of wireless interconnection using Si integrated antennas operating at microwave frequency has been proposed. [1-4] The channel capacity of information is proportional to the bandwidth of the signal according to Shannon's theorem, indicating that ultra-wideband (UWB) communication is the most suitable technique to transmit a large amount of data from ULSI to ULSI.

In this study, the UWB characteristics of Si integrated antennas are investigated.

2. Experimental

A concept of inter/intra-chip wireless interconnects is shown in Fig. 1. P-type Si (100) wafers with resistivities from 10 Ω-cm to 2.29 k Ω-cm were used as substrates. The surface of Si was oxidized to form 0.3 μm thick field SiO_2. 1 μm thick aluminum was deposited on the SiO_2 layer by direct current magnetron sputtering and the antenna patterns were formed by electron beam lithography. 10 μm wide aluminum dipole antennas were fabricated on SiO_2 as shown in Fig. 2. Antenna lengths L of half wavelength dipole antennas changed from 1.0 to 6.0 mm and the distance between transmitter and receiver antennas changed from 1.0 to 10.0 mm. Fractal antennas such as Sierpinski carpet dipole antenna were fabricated as shown in Fig. 3. [5] The feature sizes W/L of the antennas are 1/1.9 mm, 2/3.8 mm and 4/7.6 mm, respectively. The gap of the dipole is 70 μm. Distances between transmitter and receiver antennas were ranging from 5.0 mm to 30.0 mm.

A wafer level measurement set-up for scattering parameter in frequency domain is shown in Fig. 4. S-parameter measurement was carried out in the frequency range from 6 to 26.5 GHz. A measurement set-up for the transient response of Gaussian monocycle pulses is shown in Fig. 5.

3. Results and Discussion

Dependence of Si substrate resitivity on measured return losses of dipole antennas as a function of frequency is shown in Fig. 6. The return losses of half wavelength dipole antennas with Si resistivities of 79.6 and 2290 Ωcm were larger than -10 dB in all frequency range except at 11 GHz which was a resonance frequency of antenna length of 6 mm as shown in Fig.6(a). On the other hand, Sierpinski carpet dipole antenna with Si resistivities of 79.6 and 2290 Ωcm showed larger return loss in the frequency range from 6 to 19 GHz but much lower return loss in the frequency range from 19 to 26 GHz as shown in Fig.6(b). As a result, optimum frequency spectrum of Gaussian monocycle pulse transmission was obtained as shown in Fig. 6(c).

Effect of horizontal distance between antennas on peak to peak voltage of Gaussian monocycle pulse for Sierpinski carpet dipole antennas is shown in Fig.7. The pulse amplitude is inversely proportional to the horizontal distance. Effect of Si substrate resistivity on Gaussian monocycle pulse amplitude of Sierpinski carpet dipole antenna is shown in Fig.8. The amplitude increases 5-6 times with increasing the resistivity from 10 Ωcm to 79 Ωcm. Effect of Si substrate thickness on the vertical transmission of Gaussian monocycle pulse for Sierpinski carpet dipole antennas is shown in Fig.9. The pulse amplitude decreased linearly with increasing the vertical distance to 3 mm in Si so that the vertical attenuation rate was -0.27 mV/mm. UWB transmitter and receiver circuits with integrated dipole antennas were designed and fabricated by use of 0.18 μm CMOS technology as shown in Figs. 10 (a) and (b).

4. Conclusion

Inter/intra-chip wireless interconnection in Si using fractal antennas for UWB signal transmission was demonstrated for the first time. Gaussian monocycle pulse whose pulse width was 100 ps and center frequency was 15 GHz could be transmitted horizontally and vertically in Si . The received pulse amplitude was improved 5-6 times by increasing the resitivity of Si from 10 Ωcm to 79 Ω cm. It is found that Sierpinski carpet dipole antenna showed superior UWB characteristics for transmitting and receiving Gaussian monocycle pulse without distortion.

References

[1] B.A. Floyd, C. Hung and Kenneth K.O, IEEE J. Solid-State Circuits, Vol. 37, May 2002, pp. 543-552.

[2] A.B.M. H. Rashid, S. Watanabe and T. Kikkawa, IEEE Electron Devices Lett. Vol. 23, Dec. 2002, pp.731-733.

[3] A.B.M. H. Rashid, S. Watanabe and T. Kikkawa, Japanese Journal of Applied Physics, Vol. 42, No. 4B, April 2003, pp. 2204-2209.

[4] T. Kikkawa, A.B.M. H. Rashid and S. Watanabe, Abstracts of IEEE Topical Conference on Wireless Communication Technology, Honolulu, Hawaii, Oct. 15-17, 2003.

[5] K. Kimoto, S. Watanabe and T. Kikkawa, P.S. Hall and Y. Yuan, Proc. 2004 IEEE Antennas and Propagation Society International Symposium and USNC/URSI National Radio Science Meeting, (Monterey, CA), Vol. 4, pp.3437-3440.

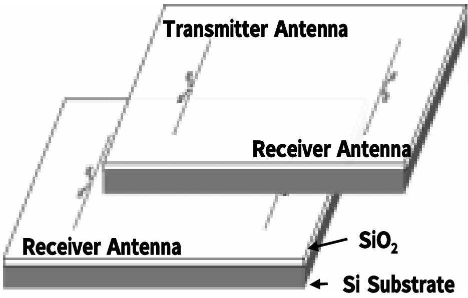


Fig. 1 A concept of inter-chip wireless signal transmission in stacked chip packaging.

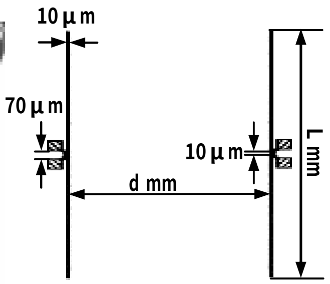


Fig.2. A plan-view of transmitting and receiving dipole antennas on a Si substrate.

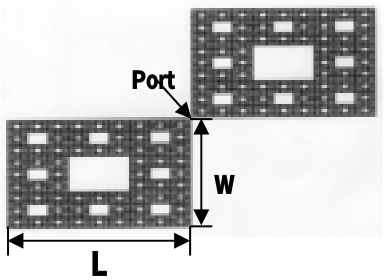


Fig.3. Configuration of Sierpinski carpet dipole antenna.W=1-4 mm, L=1.9-7.6 mm, Gap=70 μm.

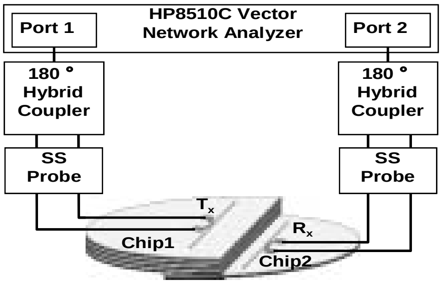


Fig.4. Wafer level frequency domain measurement set-up for dipole antennas fabricated on Si wafers.

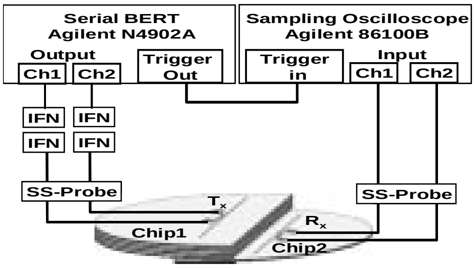
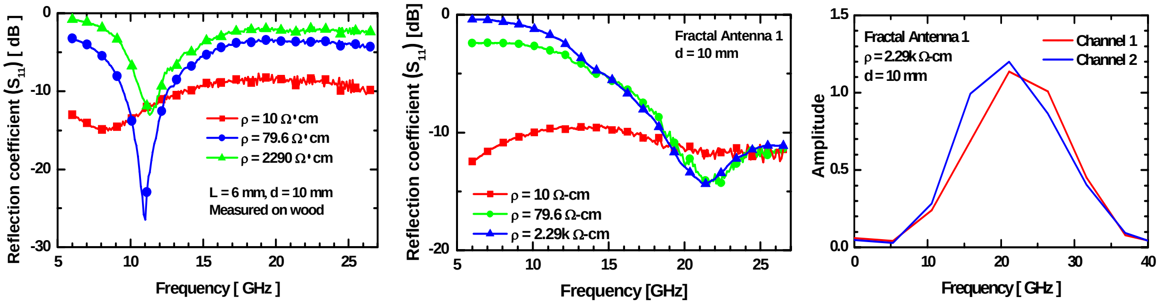


Fig. 5. Wafer level measurement set-up for inter-chip signal transmission characteristics in time domain. Gaussian monocycle pulse is formed by impulse forming networks



(a) (b) (c)

Fig. 6. Dependence of Si substrate resitivity on measured return losses (S_{11}) of dipole antennas fabricated on oxidized Si substrates as a function of frequency. (a) Half wavelength dipole antennas. (b) Sierpinski carpet dipole antennas. (c) Fourier transform of Gaussian monocycle pulse for Sierpinski carpet dipole antenna.

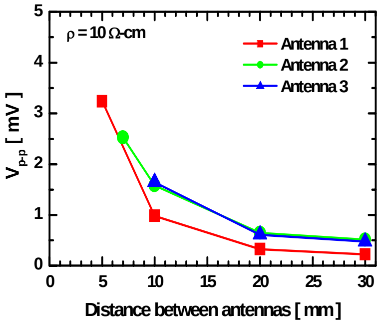


Fig.7 Effect of horizontal distance between antennas on peak to peak voltage of Gaussian monocycle pulse for Sierpinski carpet dipole antennas.

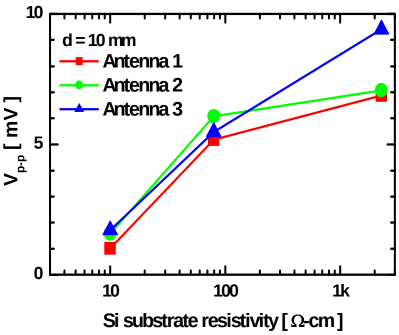


Fig.8. Effect of Si substrate resistivity on the horizontal transmission of Gaussian monocycle pulse in Si with Sierpinski carpet dipole antennas.

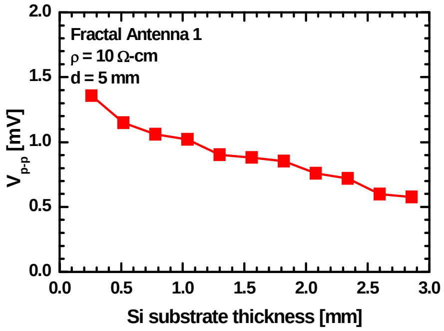
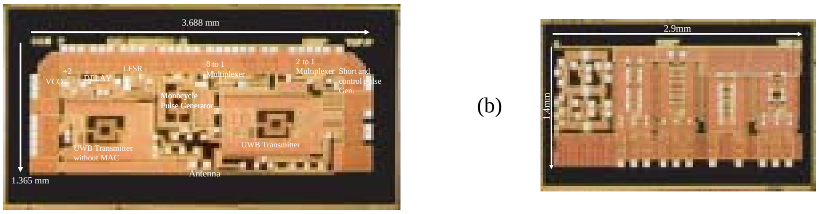


Fig.9. Effect of Si substrate thickness on the vertical transmission of Gaussian monocycle pulse in Si with Sierpinski carpet dipole antennas.



(a) (b)

Fig.10. Photomicrographs of UWB circuits integrated with dipole antennas. (a) Transmitter. (b) Receiver.

ULSI Wireless Interconnection using Integrated Antennas for UWB Signal Transmission

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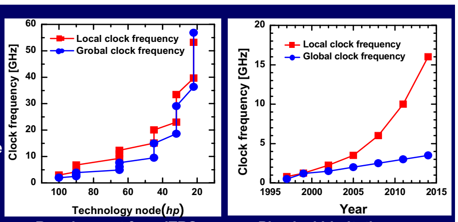
Outline

1. Issues of conventional interconnects
2. Structure of Si integrated antenna
3. Measurement set-up for antenna characteristics
    - Frequency domain; cosine wave
    - Time domain; Gaussian monocycle pulse
4. Transmission characteristics of antenna
    - Linear dipole antenna
    - Fractal antenna
    - Effect of substrate resistivity
5. UWB transmitter and receiver cirucuits
6. Summary

Issues of Conventional Interconnects

(1) Physical Limit of
Global Clock Frequency
in ULSI
due to parasitic
resistance and capacitance
of metal interconnects



Requirement from ITRS   Physical Limitation

(2) Channel Capacity
Theorem

$$C = B\log_2\left(1+\frac{S}{N}\right)$$

C: channel capacity,
B: bandwidth
S: signal
N: noise

Solution

(1) Ultra-high-frequency clock distribution by electromagnetic wave
(2) Ultra-wide-band signal transmission by Gaussian monocycle pulse

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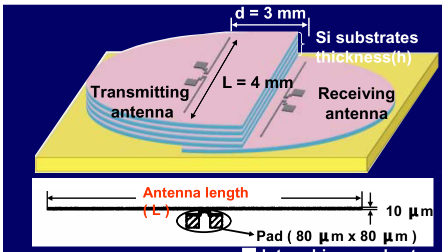
Si Integrated Dipole Antenna and Fabrication Process



🟪 : SiO_2 = 0.3 μm
🟦 : Si = 260 μm
🟨 : Wood = 2.6±0.1 mm

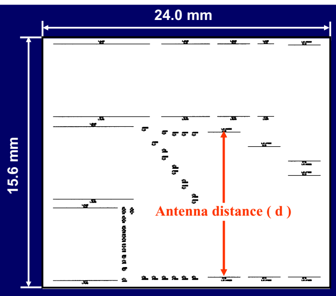
L : Antenna length
d : Horizontal distance between antennas
h : Inter-chip vertical distance
ρ : Si substrate resistivity

■ Inter-chip sample structure

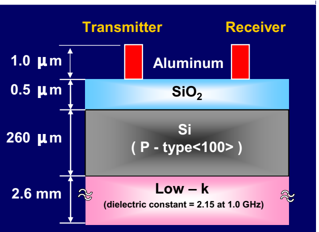
Fabrication Process

1. Oxidation	Thermal oxide (thickness : 0.3 μm)
2. Aluminum sputtering	DC magnetron sputtering (thickness : 1.0 μm)
3. Lithography	Electron beam lithography (HL700)
4. Patterning	Wet etching
5. Photoresist stripping	Remover

Structure of Si Integrated Dipole Antenna

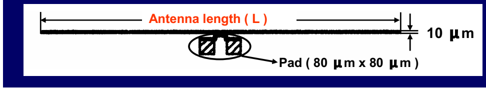


Layout pattern of integrated antenna on Si.
Chip size is 24 mm × 15.6 mm

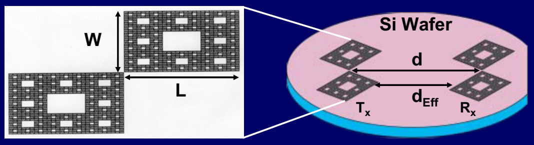


Cross-sectional schematic diagram

Fabrication Process:
Si-LSI Process Technology



Fractal Dipole Antenna Integrated on Si



🟪 : SiO_2 = 0.3 μm
🟦 : Si = 260 μm

W : Antenna width
L : Antenna length

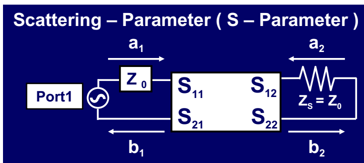
d : Distance between antennas
T_x:Transmitting antenna, R_x:Receiving antenna

■ Fractal dipole antenna   ■ Measurement structure

- ◆ Fractal antenna 1 : W/L = 1.89675/0.999 [mm]
- ◆ Fractal antenna 2 : W/L = 3.7935/1.998 [mm]
- ◆ Fractal antenna 3 : W/L = 7.587/3.996 [mm]

Measurement for Frequency Domain Characteristics of Antenna

Scattering – Parameter (S – Parameter)



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

a_i - Incident wave

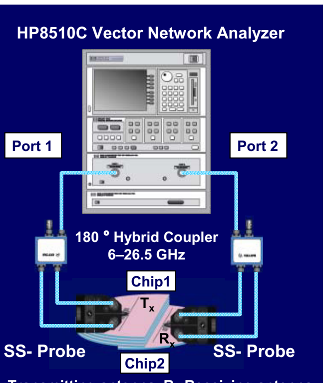
b_j - Reflected wave

$$S_{ii} = \frac{b_i}{a_i}\bigg|_{a_j = 0} \qquad S_{ij} = \frac{b_i}{a_j}\bigg|_{a_i = 0}$$

Antenna Transmission Gain (G_a)

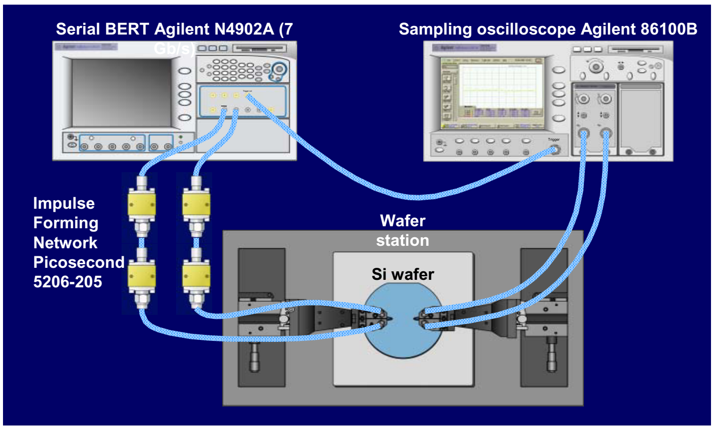
$$G_a = \frac{|S_{21}|^2}{(1 - |S_{11}|^2)(1 - |S_{22}|^2)}$$

HP8510C Vector Network Analyzer



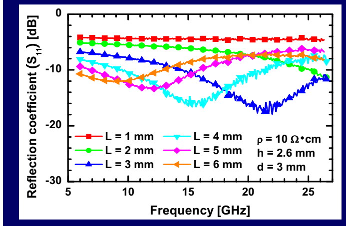
T_x:Transmitting antenna, R_x:Receiving antenna

Measurement for Time Domain Characteristics of Antenna

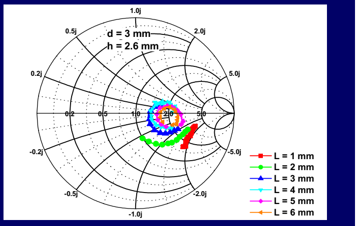


Effect of Antenna Length on Return Loss and Impedance of Linear Dipole Antenna

Return Loss



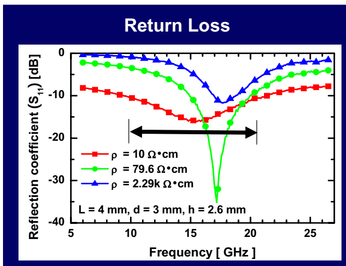
Antenna Impedance



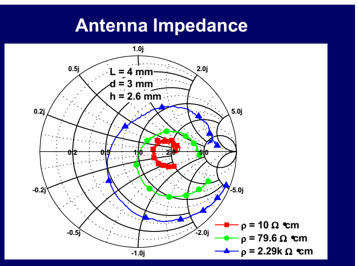
S_{11} is less than -10 dB for antenna lengths of 3, 4 and 5 mm in the frequency range from 10 to 26 GHz.
Resonance frequency is about 15 GHz for 4 mm antenna length.

Effect of Si Substrate Resistivity on Return Loss and Antenna Impedance

Return Loss

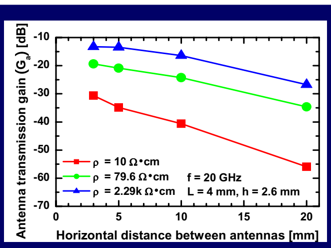


Antenna Impedance



S_{11} is less than -10 dB for antenna lengths of 4 mm in the frequency range from 10 to 20 GHz.
Resonance frequencies are 15 - 18 GHz for the resistivities of 10, 79.6 and 2.29 k Ω·cm, respectively.

Effect of Si Substrate Resistivity on Antenna Gain versus Distance



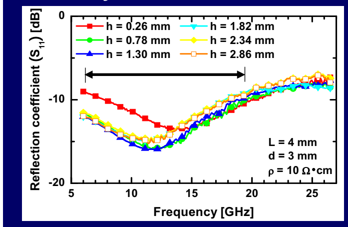
Antenna gain decreases with increasing the distance between antennas.
Attenuation rates per unit distance for antennas on the Si substrates improved with increasing the Si substrates resistivities.

Attenuation rate :

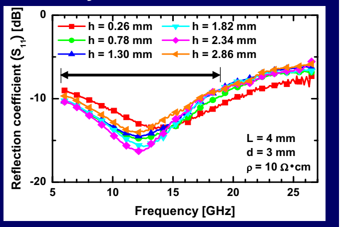
- 1.5 dB/mm (ρ = 10 Ω·cm)
- 0.9 dB/mm (ρ = 79.6 Ω·cm)
- 0.8 dB/mm (ρ = 2.29k Ω·cm)

Effect of Si Substrates Thickness on Return Loss

Resistivity of inserted Si = 10 Ω·cm

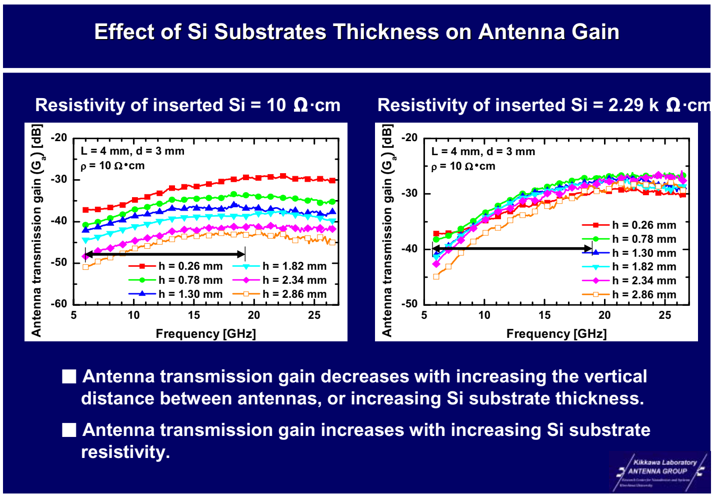


Resistivity of inserted Si = 2.29 k Ω·cm



Return loss < -10 dB @ 6-19 GHz for
Si substrates of 10 Ω·cm and 2.29 k Ω·cm

■ Return loss was not affected very much by either thickness or resistivity of Si substrates.

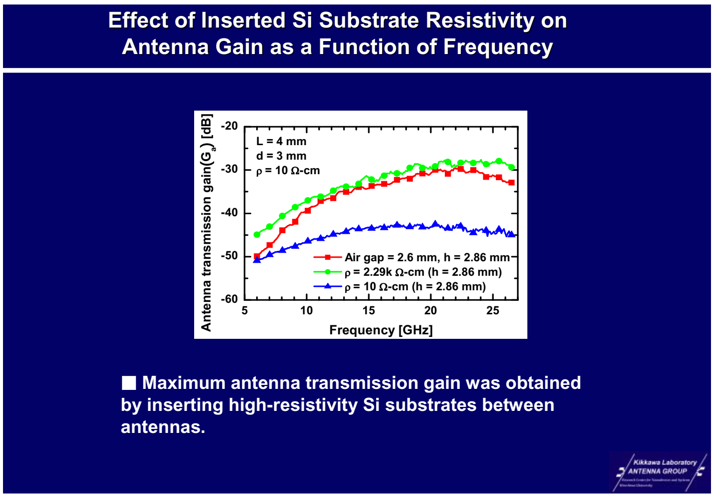


Effect of Si Substrates Thickness on Antenna Gain

Resistivity of inserted Si = 10 Ω·cm

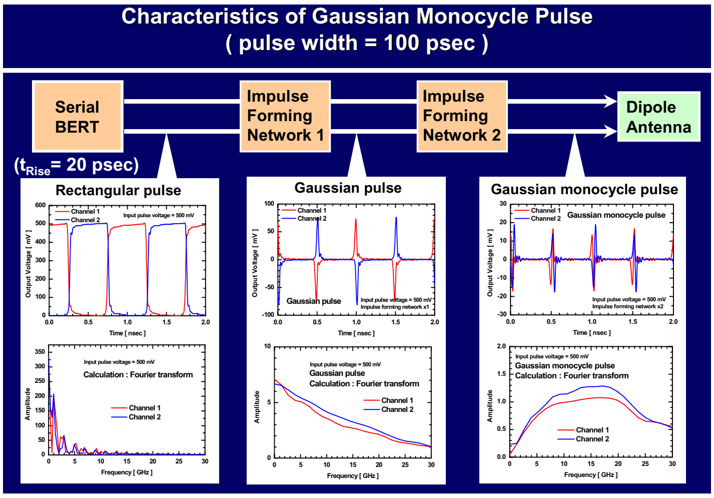
Resistivity of inserted Si = 2.29 k Ω·cm

- Antenna transmission gain decreases with increasing the vertical distance between antennas, or increasing Si substrate thickness.
- Antenna transmission gain increases with increasing Si substrate resistivity.



Effect of Inserted Si Substrate Resistivity on Antenna Gain as a Function of Frequency

- Maximum antenna transmission gain was obtained by inserting high-resistivity Si substrates between antennas.



Characteristics of Gaussian Monocycle Pulse (pulse width = 100 psec)

Serial BERT

Impulse Forming Network 1

Impulse Forming Network 2

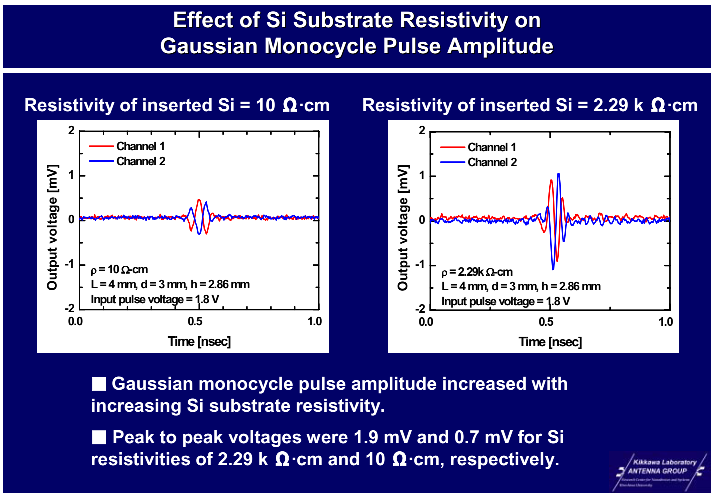
Dipole Antenna

(t_{Rise}= 20 psec)

Rectangular pulse

Gaussian pulse

Gaussian monocycle pulse

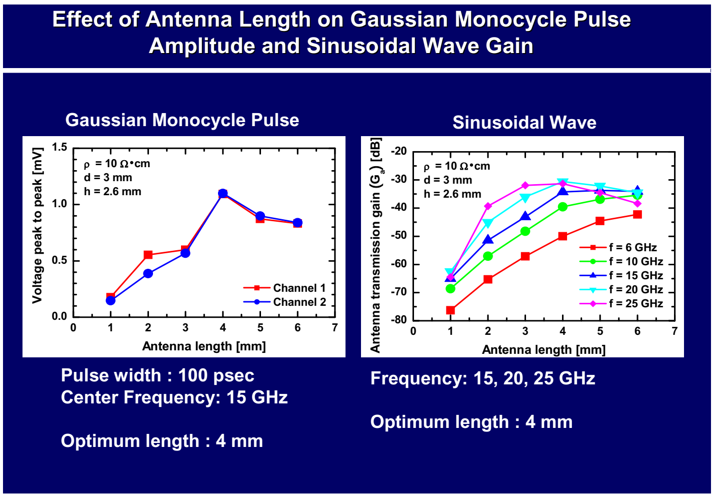


Effect of Si Substrate Resistivity on Gaussian Monocycle Pulse Amplitude

Resistivity of inserted Si = 10 Ω·cm

Resistivity of inserted Si = 2.29 k Ω·cm

- Gaussian monocycle pulse amplitude increased with increasing Si substrate resistivity.
- Peak to peak voltages were 1.9 mV and 0.7 mV for Si resistivities of 2.29 k Ω·cm and 10 Ω·cm, respectively.



Effect of Antenna Length on Gaussian Monocycle Pulse Amplitude and Sinusoidal Wave Gain

Gaussian Monocycle Pulse

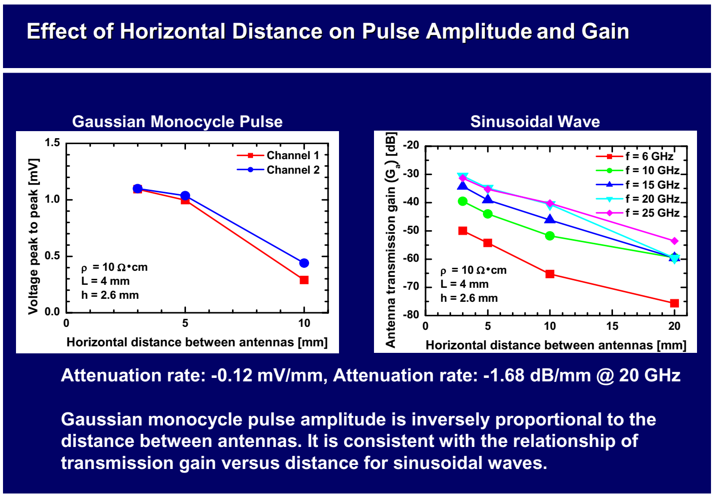
Sinusoidal Wave

Pulse width : 100 psec
Center Frequency: 15 GHz

Optimum length : 4 mm

Frequency: 15, 20, 25 GHz

Optimum length : 4 mm



Effect of Horizontal Distance on Pulse Amplitude and Gain

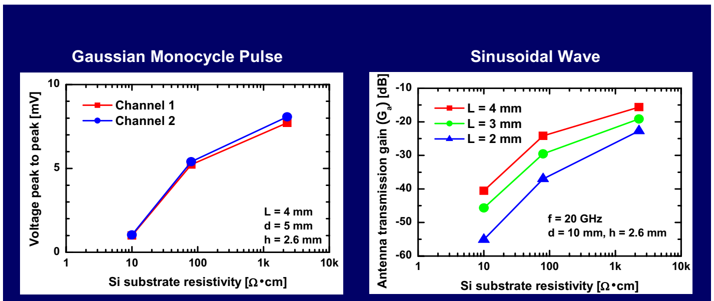
Gaussian Monocycle Pulse

Sinusoidal Wave

Attenuation rate: -0.12 mV/mm, Attenuation rate: -1.68 dB/mm @ 20 GHz

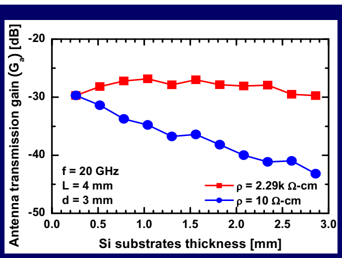
Gaussian monocycle pulse amplitude is inversely proportional to the distance between antennas. It is consistent with the relationship of transmission gain versus distance for sinusoidal waves.

Effect of Si Substrate Resistivity on Gaussian Monocycle Pulse Amplitude and Sinusoidal Wave Gain



V_{p-p} was improved by using high resistivity Si substrate.

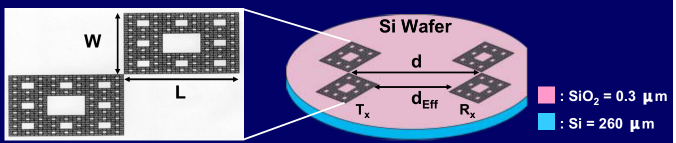
Effect of Si Substrates Thickness on Antenna Transmission Gain



- ■ Antenna transmission gain of –30 dB was obtained for for vertical distance of 2.86 mm with 2.29k Ω·cm Si substrates.
- ■ Attenuation rates of antenna gain per unit vertical distance in the Si substrates were improved by increasing Si substrates resistivity.

Attenuation rate :
- 4.9 dB/mm (ρ = 10 Ω·cm)
- 0.4 dB/mm (ρ = 2.29k Ω·cm)

Fractal Dipole Antenna Integrated on Si



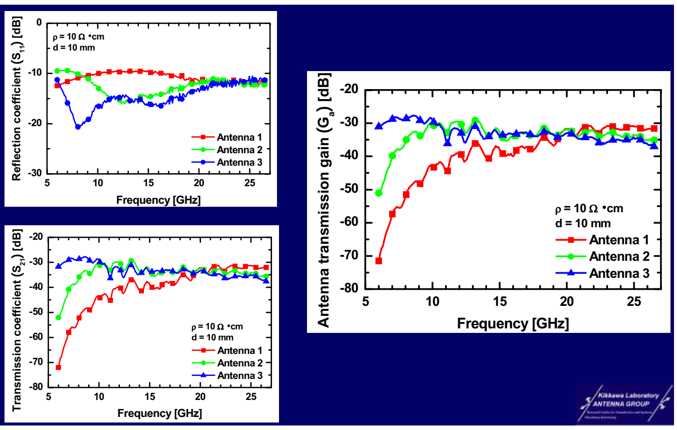
W : Antenna width
L : Antenna length

d : Distance between antennas
T_x:Transmitting antenna, R_x:Receiving antenna

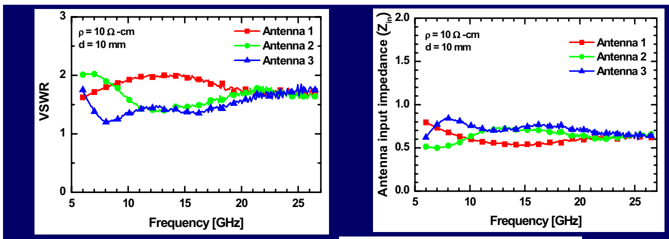
■ Fractal dipole antenna
■ Measurement structure

- ◆ Fractal antenna 1 : W/L = 1.89675/0.999 [mm]
- ◆ Fractal antenna 2 : W/L = 3.7935/1.998 [mm]
- ◆ Fractal antenna 3 : W/L = 7.587/3.996 [mm]

S_{11}, S_{21} and Gain of Fractal Dipole Antenna

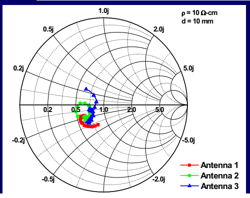


Voltage Standing Wave Ratio and impedance of Fractal Antenna

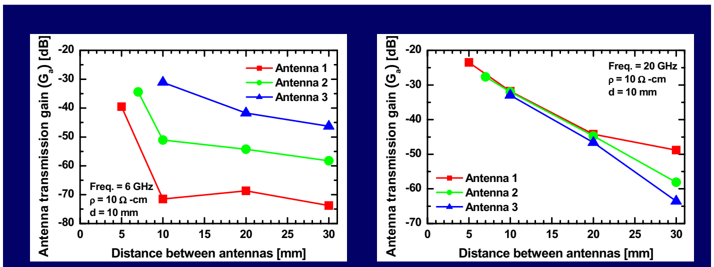


VSWR<2
$0.5<Z_{in}/Z_0<1.0$

in
6<Frequency<26.5 GHz

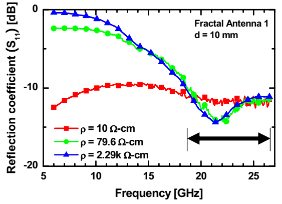


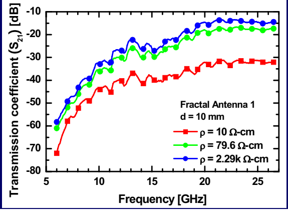
Transmission Gain vs Distance for Fractal Dipole Antenna

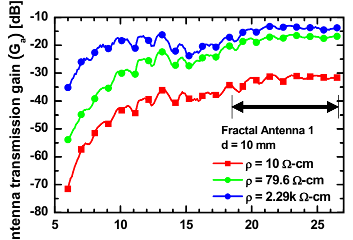


Attenuation @ 20 GHz
Antenna1: -1.01 dB/mm
Antenna2: -1.31 dB/mm
Antenna3: -1.53 dB/mm

Effect of Si Substrate Resistivity on S_{11}, S_{21} and Gain for Fractal Antenna







Return loss S_{11}< -10 dB @ 18-26 GHz

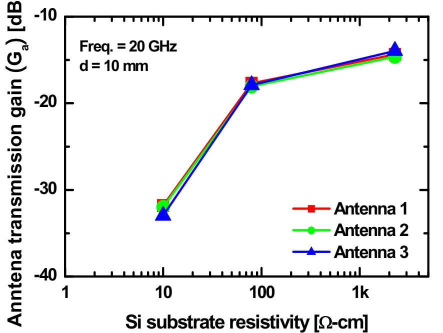
Gain @ 18-26 GHz

-15 dB : 2.29 kΩcm

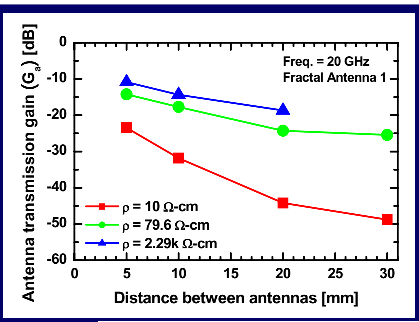
-20 dB : 79.6 Ωcm

-35 dB : 10Ωcm

Effect of Si Substrate Resistivity on Transmission gain of Fractal Antennas



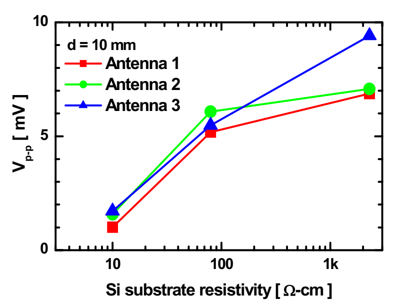
Effect of Si Substrate Resistivity on Transmission Gain as a Function of Distance



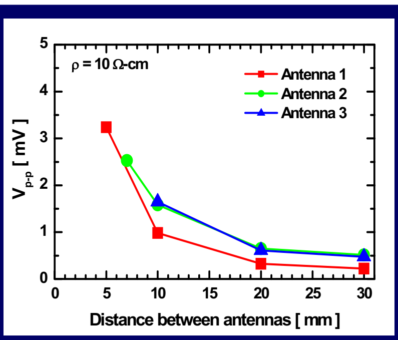
Attenuation @ 20 GHz

- 1.01 dB/mm (ρ = 10 Ω·cm)
- 0.46 dB/mm (ρ = 79.6 Ω·cm)
- 0.51 dB/mm (ρ = 2.29k Ω·cm)

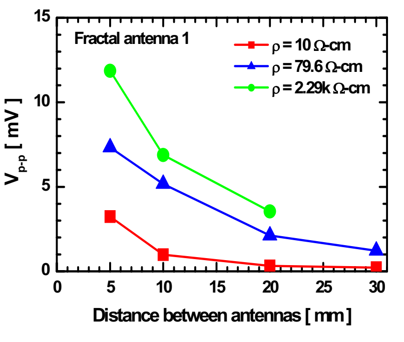
Dependence of Si Resistivity on Vp-p of Gaussian Monocycle Pulse for Different Antenna Sizes



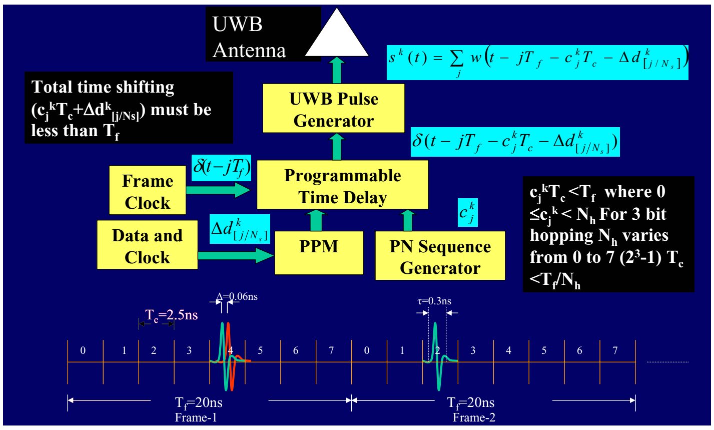
Dependence of Distance on Vp-p of Gaussian Monocycle Pulse



Dependence of Distance on Vp-p of Gaussian Monocycle Pulse for Different Si Substrate Resistivity



UWB Transmitter System Diagram



UWB Antenna

$s^k(t) = \sum_j w\left(t - jT_f - c_j^k T_c - \Delta d^k_{[j/N_s]}\right)$

Total time shifting ($c_j^k T_c + \Delta d^k_{[j/Ns]}$) must be less than T_f

UWB Pulse Generator

$\delta(t - jT_f - c_j^k T_c - \Delta d^k_{[j/N_s]})$

Frame Clock

$\delta(t - jT_f)$

Programmable Time Delay

Data and Clock

$\Delta d^k_{[j/N_s]}$

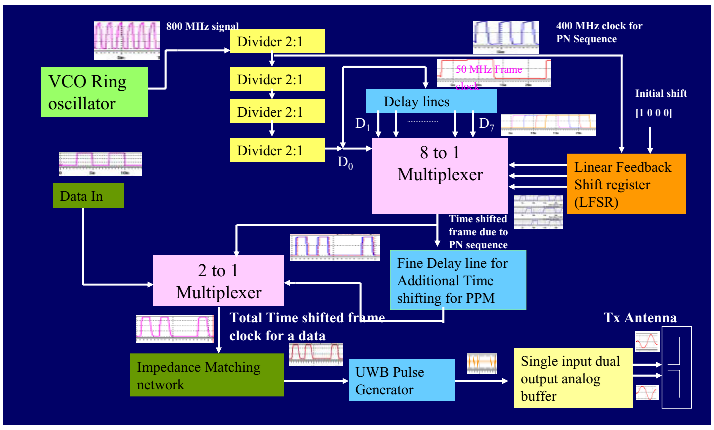
PPM

c_j^k

PN Sequence Generator

$c_j^k T_c < T_f$ where $0 \le c_j^k < N_h$ For 3 bit hopping N_h varies from 0 to 7 (2^3-1) $T_c < T_f/N_h$

UWB Transmitter Circuits Block Diagram



800 MHz signal

VCO Ring oscillator

Divider 2:1

Divider 2:1

Divider 2:1

Divider 2:1

400 MHz clock for PN Sequence

50 MHz Frame clock

Delay lines

Initial shift [1 0 0 0]

D_1 ……… D_7

D_0

8 to 1 Multiplexer

Linear Feedback Shift register (LFSR)

Data In

Time shifted frame due to PN sequence

2 to 1 Multiplexer

Fine Delay line for Additional Time shifting for PPM

Total Time shifted frame clock for a data

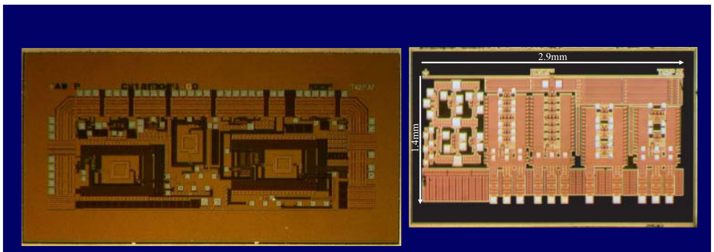
Tx Antenna

Impedance Matching network

UWB Pulse Generator

Single input dual output analog buffer

UWB Transmitter and Receiver Circuits



Technology: TSMC 0.18 μm CMOS Mixed signal process .

Operating voltage: 1.8 V

Summary

1. **Intra- and inter-chip characteristics of Si integrated linear dipole and fractal antennas for use in ULSI were demonstrated.**
2. **Gaussian monocycle pulses as well as sinusoidal wave signals can be transmitted between Si chips separated by a spacer and through Si substrates.**
3. **Inter-chip transmission gain of -26 dB was obtained for vertical distance of 2.86 mm through 2.29 kΩ·cm Si substrates and horizontal distance of 3 mm by use of 4 mm long dipole antenna.**
4. **Return loss of Sierpinski carpet dipole antenna was below -10 dB in the frequency range from 6 GHz to 26.5 GHz.**
5. **Transmission gains of Sierpinski carpet dipole antennas did not depend on the antenna size but on Si substrate resistivity. Antenna transmission gains for 10 mm apart Sierpinski carpet antennas were approximately -15 dB and -30 dB for Si resistivities of 79.6 Ω·cm and 10 Ω·cm, respectively.**