A Single-chip Gaussian Monocycle Pulse Transmitter using 0.18 μm CMOS Technology for Intra/Interchip UWB Communication

Takamaro Kikkawa, Pran Kanai Saha, Nobuo Sasaki and Kentaro Kimoto

Research Center for Nanodevices and Systems, Hiroshima University

Outline

1. Introduction
2. Characteristics of Silicon On-chip Integrated antenna
3. Gaussian Monocycle Pulse (GMP) Generation
4. GMP Transmitter Circuits
5. Intra-/Inter-chip GMP Transmission
6. Conclusion

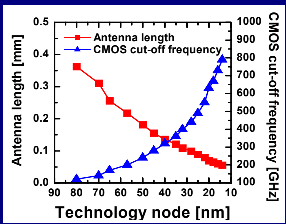
Introduction

Background

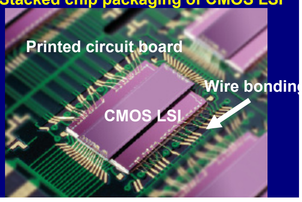
CMOS cut-off frequency increases up to 400 GHz for 32 nm technology node. However, data transmission frequency between CMOS LSI chips is limited below 4 GHz due to wire bonding between chip and printed circuit board.

Therefore, development of inter-chip wireless interconnection using on-chip antenna is necessary for high-speed data transmission to eliminate RC delay. Wireless interconnection enables much higher data rate than metal wire. Furthermore, the size of antenna can be scaled down to 150 μm.

Antenna length and CMOS cut-off frequency vs. CMOS technology node

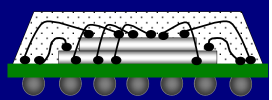


Stacked chip packaging of CMOS LSI

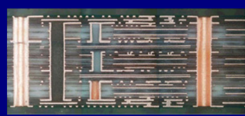


Requirements for LSI System Interconnection

1. Higher Chip Density : 3D packaging of LSI



LSI chips are connected by
Bonding wires, bumps and
Through Si Via Metal plugs,
which have RC delays (τ > 0.9 ns) .



2. Higher Data Rate > 100 Mbps

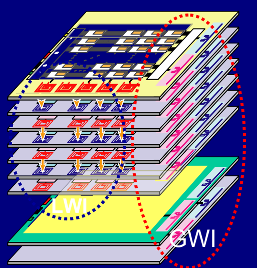
WLAN data rates are less than 100 Mbps.
802.11b: 11 Mbps @2.4GHz
802.11a: 54 Mbps @ 5.2GHz

Solution: 3D Integration with Wireless Interconnection

Motivation

To achieve 3D integration having more than 10 stacked LSI chips with data rates higher than 1Gbps for intra-/inter-chip communication,

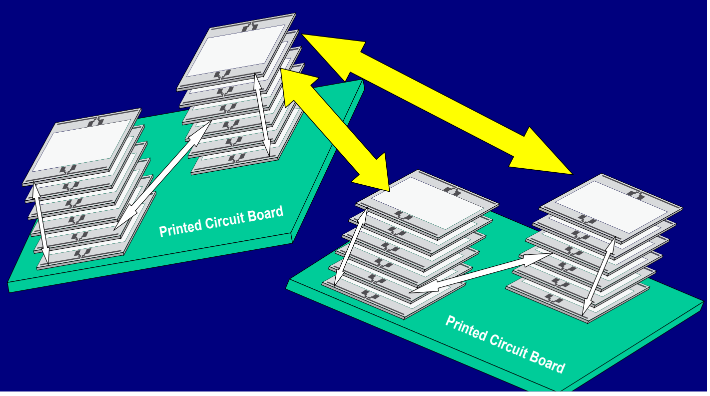
1. Local wireless interconnection (LWI)
   Inductive coupling
   for distances less than 300 μm
2. Global wireless interconnect (GWI)
   Electromagnetic wave transmission
   using integrated antennas
   for distances longer than 300 μm



3D Custom Stack System

International Solid-State Circuits Conference 2005

UWB Signal Transmission between LSI-chip Building Blocks



Ultra Wideband (UWB)

Why UWB?

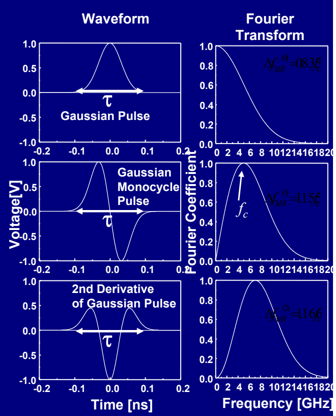
Shannon's Channel Capacity Theorem

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

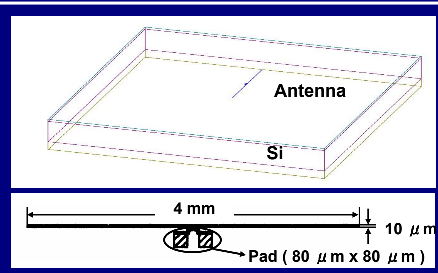
C: Channel capacity, B: bandwidth

Gaussian Monocycle Pulse
is a promising candidate
for Impulse-radio-based UWB Signal

Advantages:
- High data rate
- Carrier-free transmission
- Multiple accessibility



Characteristics of Si Integrated Dipole Antennas

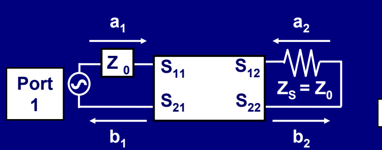


CMOS fabrication process

1. Oxidation	Thermal oxide (thickness : 0.3 μm)
2. Aluminum sputtering	DC magnetron sputtering (thickness : 1.0 μm)
3. Lithography	Electron beam lithography (HL-700)
4. Patterning	Wet etching
5. Photoresist stripping	Remover

Measurement of Antenna Parameters

Scattering – Parameter (S – Parameter)

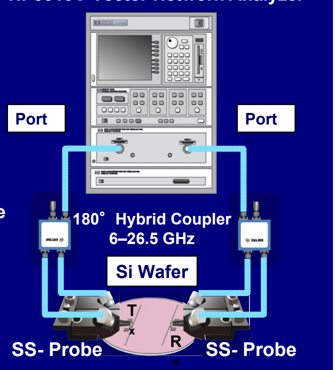


$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

a_i - Incident wave
b_j - Reflected wave

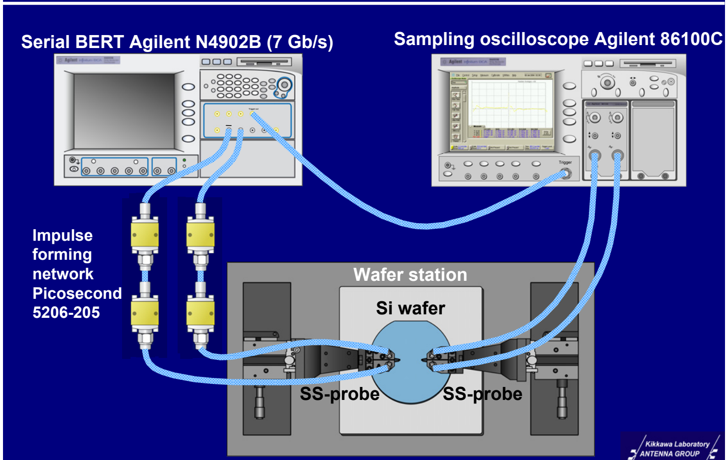
$$S_{ii} = \left. \frac{b_i}{a_i} \right|_{a_j = 0} \qquad S_{ij} = \left. \frac{b_i}{a_j} \right|_{a_i = 0}$$

HP8510C Vector Network Analyzer

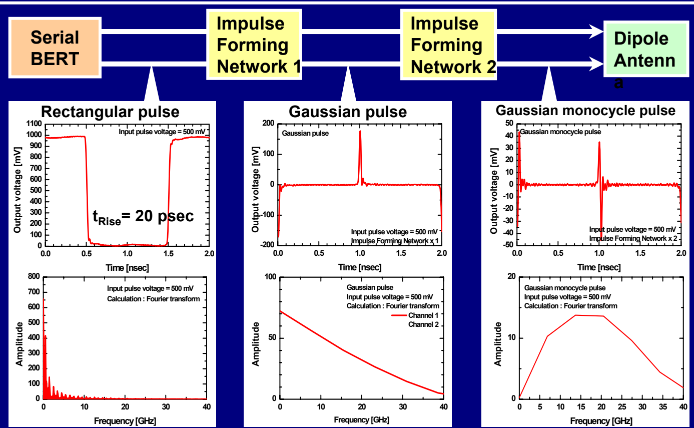


T_x:Transmitting antenna, R_x:Receiving antenna

Measurement of UWB Waveform

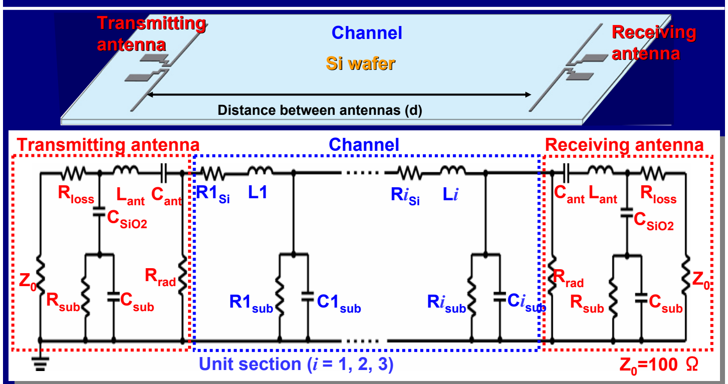


Characteristics of Gaussian Monocycle Pulse



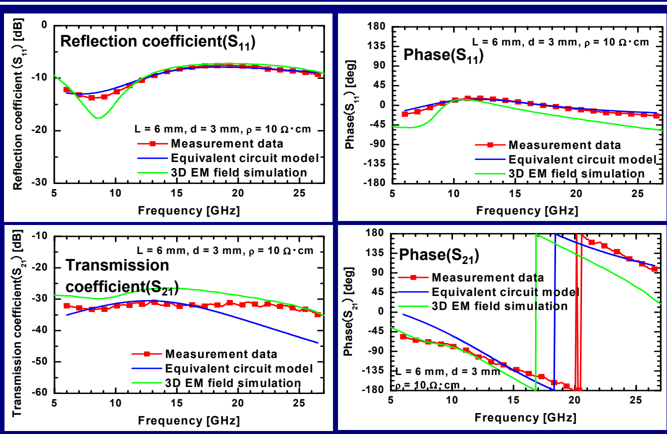
Characteristics of Gaussian monocycle pulse
Pulse width = 70 psec, Center frequency = 15 GHz, Bandwidth = 20 GHz

Equivalent Circuit Model for Intra-chip Si Integrated Antenna



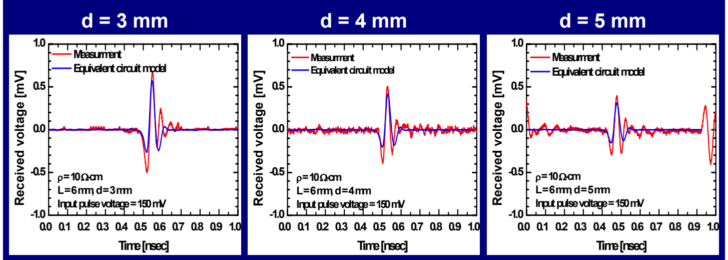
Transmitting and receiving antennas consist of RLC (R_{rad}, C_{ant}, L_{ant}) series resonant circuits.
Channel is modeled by a transmission line (R_{Si}, L, R_{sub}, C_{sub}).
Distance between antennas changed from 3 to 5 mm.

Comparison of Equivalent Circuit Model with Measurement



Parameter fitting of equivalent circuit was carried out.
Equivalent circuit model fits well with measurement data of S_{11} and S_{21}.

Dependence of Received Waveform on Distance



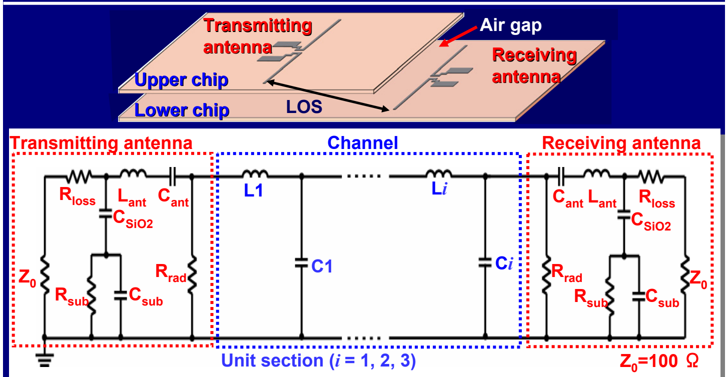
Intra-chip linear dipole antenna (L = 6 mm)

Using extracted RLC parameters, received waveform of Gaussian monocycle pulse was simulated by HSPICE circuit simulator in time domain.

Received waveforms were the first derivatives of the transmitted waveforms.

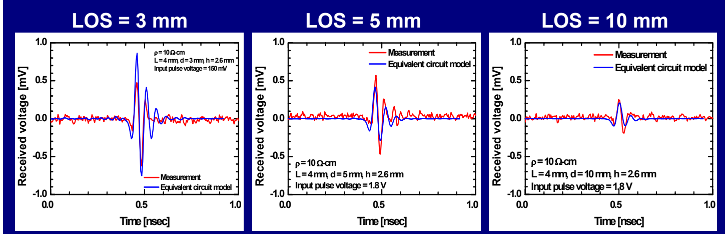
Simulation results can reproduce measurement data.

Equivalent Circuit Model for Inter-chip Signal Transmission with Air-gap



Line of sight (LOS) distance was changed from 3 to 10 mm.
The antenna length was fixed to 4 mm.
Electromagnetic wave radiated from transmitting antenna propagates through air-gap, so that LC transmission line model was used for channel.

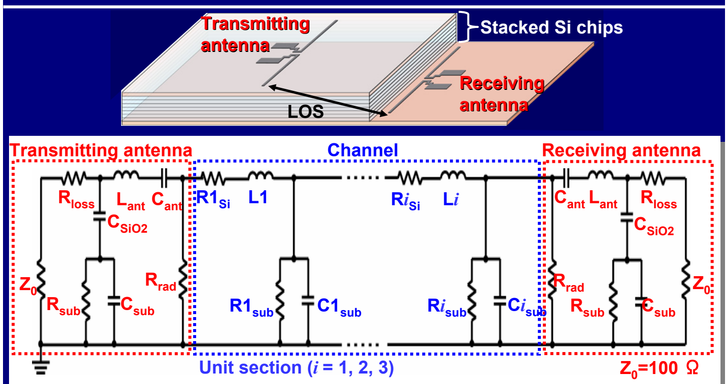
Dependence of Received Waveform on LOS Distance



HSPICE simulation results were matched well with the measurement data for various LOS distances.

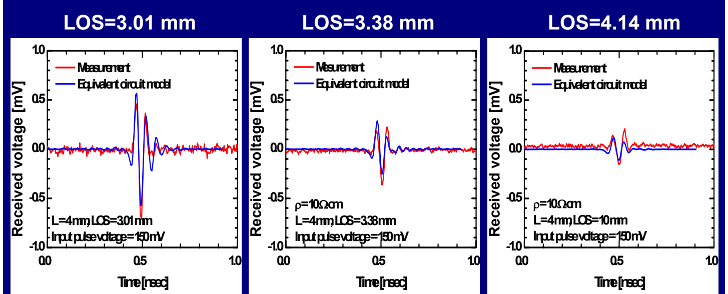
Received waveforms were distorted due to band-pass characteristics of the air-gap.

Stacked Inter-chip Equivalent Circuit Model



Line of sight (LOS) distance was changed from 3.01 to 4.14 mm by increasing number of Si chips.
The antenna length was fixed to 4 mm. Electromagnetic wave radiated from transmitting antenna propagates through stacked lossy Si chips.

Dependence of Received Waveform on LOS Distance



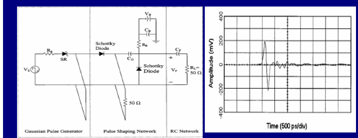
The received waveforms were the first derivatives of transmitting Gaussian monocycle pulse.

Simulation results can reproduce the measurement data.

Previous Works in GMP Generation

OFF-CHIP

Step Recovery Diode (SRD)
Monocycle Pulse Generator



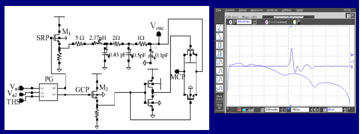
Ref. Jeongwoo et al. IEEE Microwave and wireless Components letters Vol. 12 No. 6, June 2002 p. 206 .

Problem:

Difficulty of SRD integration in CMOS technology

ON-CHIP

RLC network with pass gate

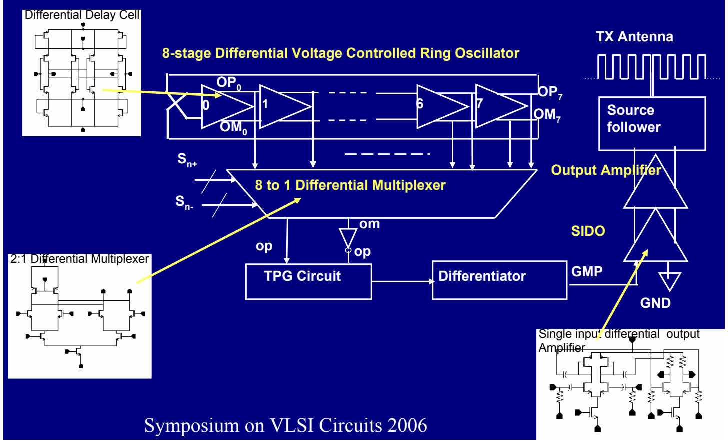


Ref.: P. K. Saha, T. Kikkawa, JJAP, vol.44 No. 4B, 2005 p. 2104.

Problem:

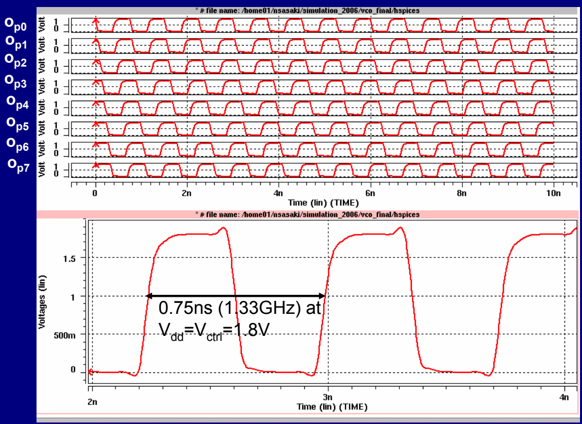
Large area (0.19 mm²) is occupied due to inductance

Block Diagram of GMP Transmitter Circuits

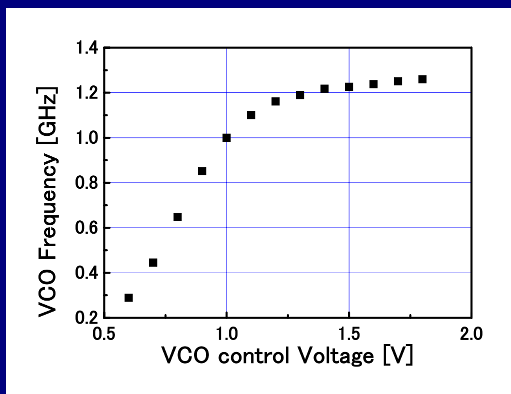


Symposium on VLSI Circuits 2006

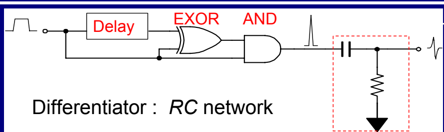
Timing Chart of VCO (Simulation)



VCO Control Voltage versus Frequency



Gaussian Monocycle Pulse Generation



The transfer function $G(s)$ of *RC* network

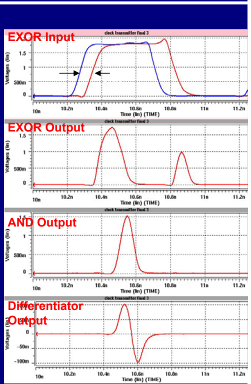
$$G(s) = \frac{v_{GMP}}{v_{triang}} = \frac{RCs}{1+RCs}$$

$$s = j\omega \cdot \frac{d}{dt}$$

v_{triang} = triangular pulse as differentiator input,
v_{GMP} = differentiator output (Gaussian monocycle pulse) .
$RCs << 1$,

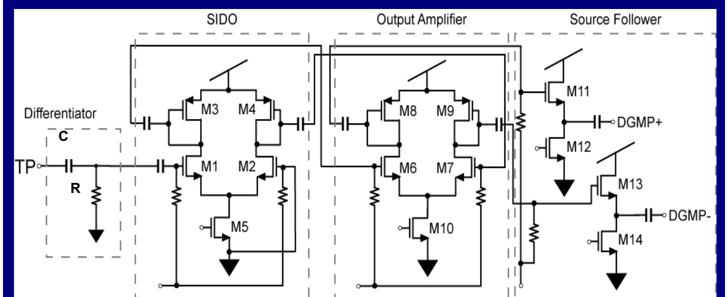
$$v_{GMP} = T_c \frac{dv_{triang}}{dt}$$

T_c = Derivative time coefficients=*RC*.
The *RC* values are to be chosen to generate GMP from triangular shaped pulse.



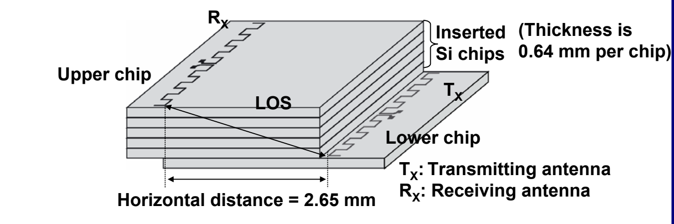
Triangular pulse is formed by rising edges of rectangular pulses of NMOS with and without delay. Symmetrical Gaussian monocycle pulse with short pulse width is formed.

UWB Differential Amplifiers



Si On-chip Integrated Meander Dipole Antenna

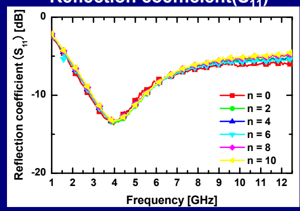
Total dipole antenna length = 22.32 mm, Antenna width = 10 µm



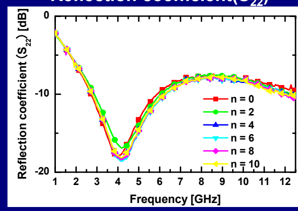
Resistivity of inserted Si substrate = 50 kΩ·cm

Transmission Characteristics of Meander Dipole Antenna

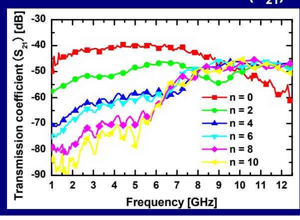
Reflection coefficient(S_{11})



Reflection coefficient(S_{22})



Transmission coefficient(S_{21})

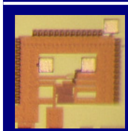


The thickness of the Si substrates was increased from 2.8 mm to 7.2 mm by increasing the number of inserted Si substrates.

Return loss was not affected very much by thickness of Si substrates.

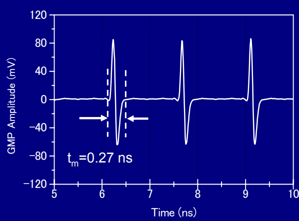
Antenna transmission gain decreases with increasing the LOS distance between antennas, or increasing Si substrate thickness.

GMP Transmitter Simulation

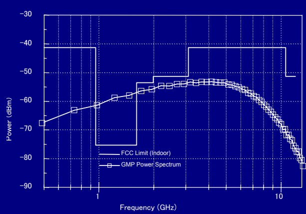


VCO + MUX → TPG → Differentiator → GMP

GMP



GMP FFT and FCC Limit



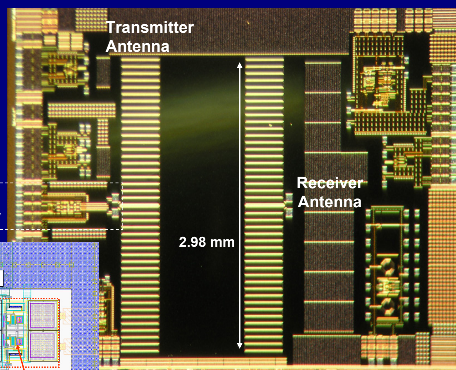
GMP pulse width =0.27 ns
GMP center frequency=3.7 GHz
3 dB bandwidth= 4.29 GHz

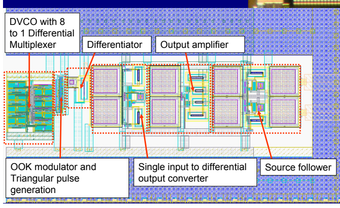
GMP power is less below FCC limit in frequency band 3.1 –10.6 GHz.
Due to high pass characteristics of antennas the spectral parts below 1.6 GHz do not harm the permitted emission limits.

CMOS Transmitter with Integrated Antennas

Technology : 0.18 µm CMOS
GMP Generator Area: 0.03 mm²
Transmitter Area: 0.1387 mm²

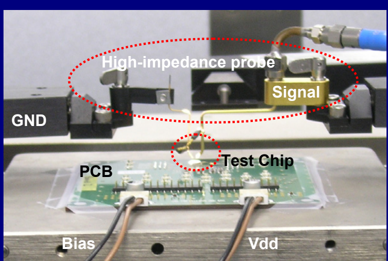
Antenna total length = 22.33 mm





0.45 mm

GMP Measurement Set-up



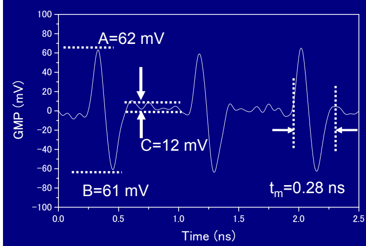
Oscilloscope

DC Power Supply

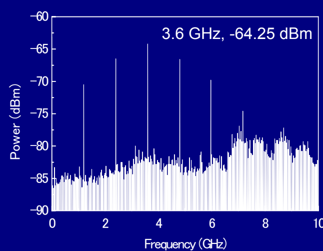
A test chip is fabricated in 0.18 µm CMOS technology and bonded on PCB for wiring of DC bias voltages. GMP measurement is carried out by fine-pitch high-impedance microprobe.

Generated GMP Signal

Measured GMP



Measured Spectrum



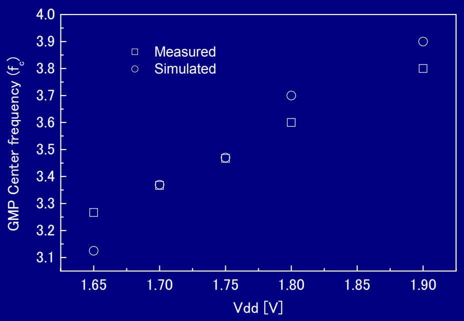
Upper and lower parts of GMP have good symmetry in shape and amplitude (B/A>98%)

Ringing level (C/(A+B))<0.1) = -20.2 dB

GMP pulse width= 0.28 ns

Peak to peak amplitude= 123 mV

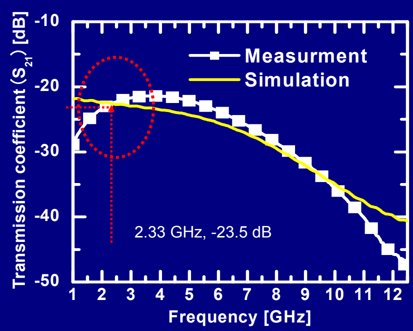
Dependence of GMP Center Frequency on V_{dd}



Change of ±5% variation of V_{dd} from 1.8 V changes GMP center frequency (3.6GHz) ± 5-6 %.
Change of GMP center frequency with change of V_{dd} should be controlled.

Total power dissipation is 21.6 mW at 1.8 V.

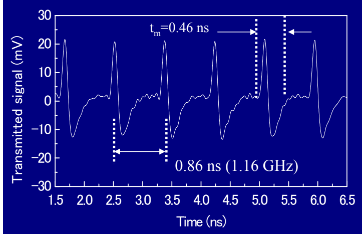
Intra-chip GMP Transmission Coefficient



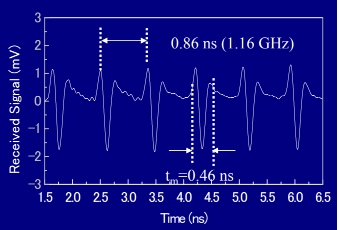
Transmission loss is –24 dB as computed from transmitted and received power at 2.33GHz, which is nearly the same as the simulated transmission coefficient of Tx-Rx antenna pair.

Intra-chip GMP Transmission (Time Domain)

Transmitted Signal



Received Signal



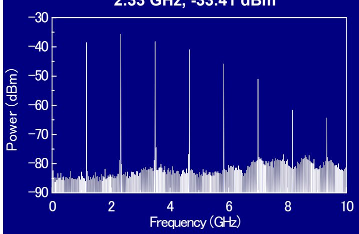
Transmission rate : 1.16Gbps

Transmitted GMP pulse width changed from 0.28 ns to 0.46 ns
due to SIDO and output amplifier's output capacitance and resistance.

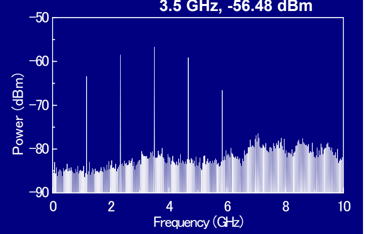
Received signal is the first derivative of the transmitted GMP due to antenna.

Intra-chip GMP Transmission (Frequency domain)

Transmitted GMP Spectrum



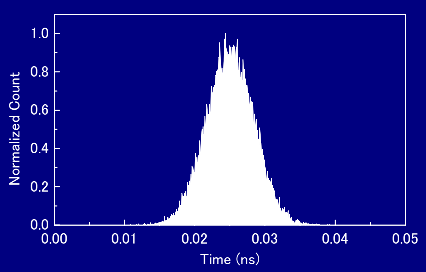
Received GMP Spectrum



Transmitted signal center frequency (f_c) is 2.33 GHz, which is lower than that of generated GMP (3.6 GHz) because the transmitted GMP pulse width changed from 0.28 ns to 0.46 ns due to SIDO and output amplifier's output capacitance and resistance.

Received signal center frequency (3.5 GHz) is approximately 1.41 times of transmitted f_c (2.33GHz).

Received Signal Jitter Measurement

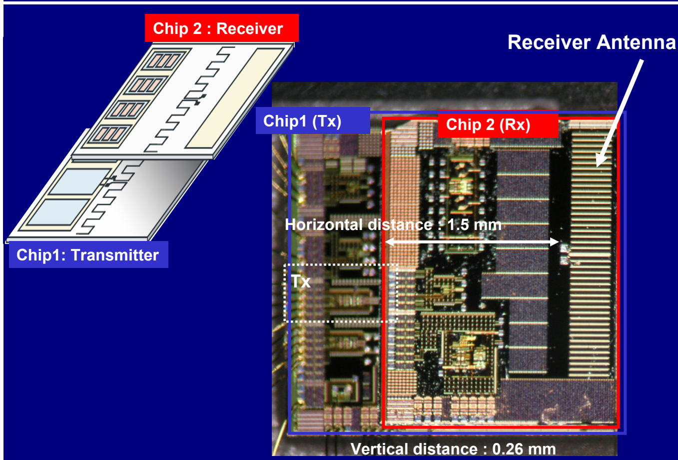


Mean period of received signal: 0.857 ns (1.166 GHz)

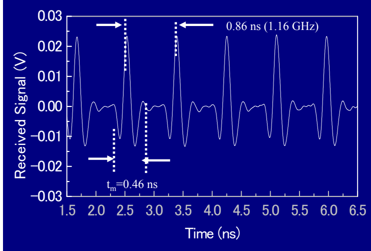
Standard deviation =3.38 ps

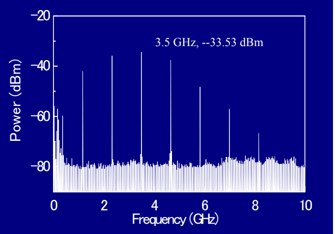
Low periodic jitter confirms reliable reception of transmitted signal.

Inter-chip GMP Transmission



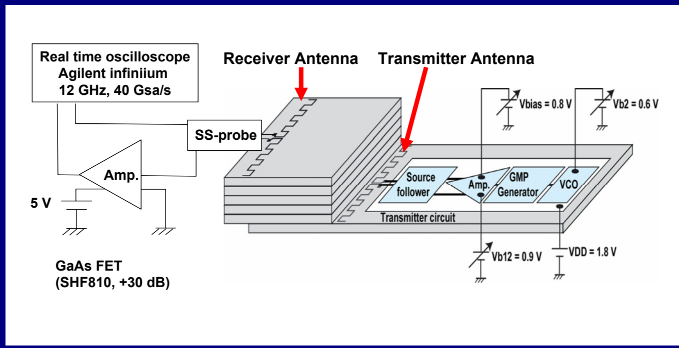
Inter-chip GMP Transmission



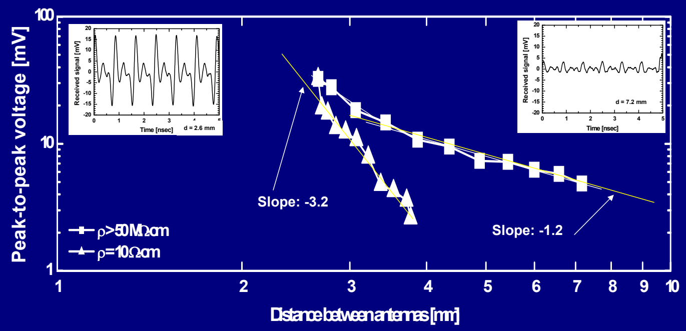


Received signal was measured after an amplifier having a gain of 30 dB in frequency band from 30 kHz to 40 GHz.
Received signal pulse duration center frequency and repetition rate are the same as those of intra-chip.
Phase shifting of the received signal is due to the amplifier.
Transmission loss is –30.12 dB.

GMP Transmission for 3D Integration



GMP Transmission versus Distance



Comparison of GMP Performance

	Step recovery diode based circuit [2]	This work (measurement)
Pulse duration	300 ps	280 ps
Peak to peak amplitude	200 mV	123 mV
Center Frequency	-------------	3.6 GHz
3 dB bandwidth	Wide bandwidth	4.14 GHz
Ringing level	-17 dB	-20.2 dB
Implementation	Board level	Integrated in 0.18 μm CMOS technology
Area	Large Area	0.03 mm^2
Power dissipation	----------	12.6 mW at 1.2 V

[2] J. Han and C. Nguyen,"A new ultra–wideband, ultra short monocycle pulse generator with reduced ringing," IEEE Microwave and Wireless Components Lett., vol. 12, no. 6, pp. 206-208 June 2002.

Conclusion

1. **Generation of ultra short Gaussian monocycle pulse (280 ps) using 0.18 μm CMOS technology has been demonstrated for the first time .**
2. **Transmission and reception of generated GMP at the rate of 1.16 Gbps by meander dipole antennas integrated in the same Si-LSI chips are also demonstrated successfully for intra-/inter-chip communication .**
3. **Simple circuits and sufficient performance make attractive for other impulse based UWB communication.**

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