Application of Generalized Scattering Matrix for Prediction of Power Supply Noise

System Level Interconnect Prediction 2010
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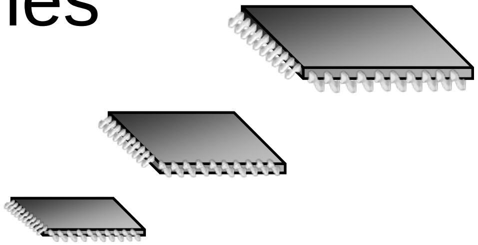
Background



Progress of LSI fabrication technologies

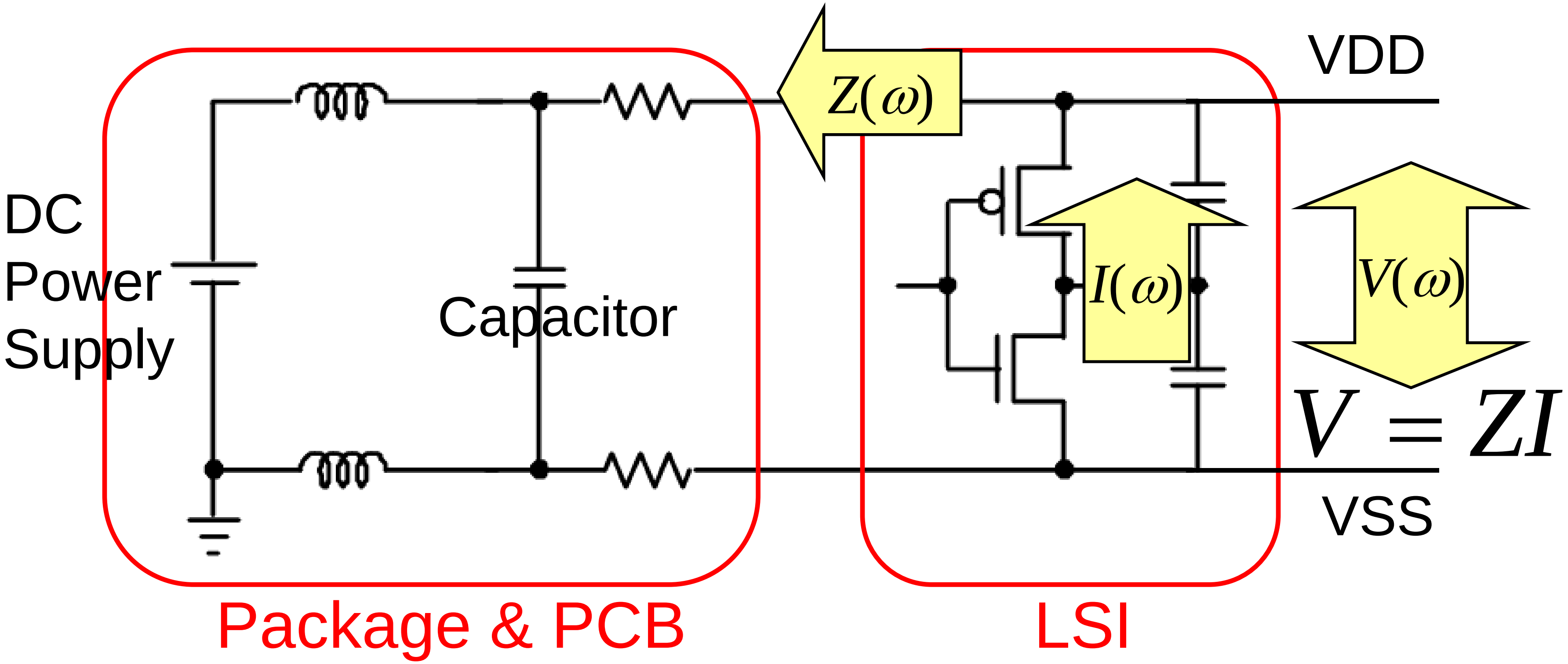
- Low power supply voltage
- High power consumption

Issues caused by power supply noise

- Deteriorate Signal Integrity (SI)
- Interference to another circuits, such as RF

Reduction of power supply noise is important for interconnect and RF circuits

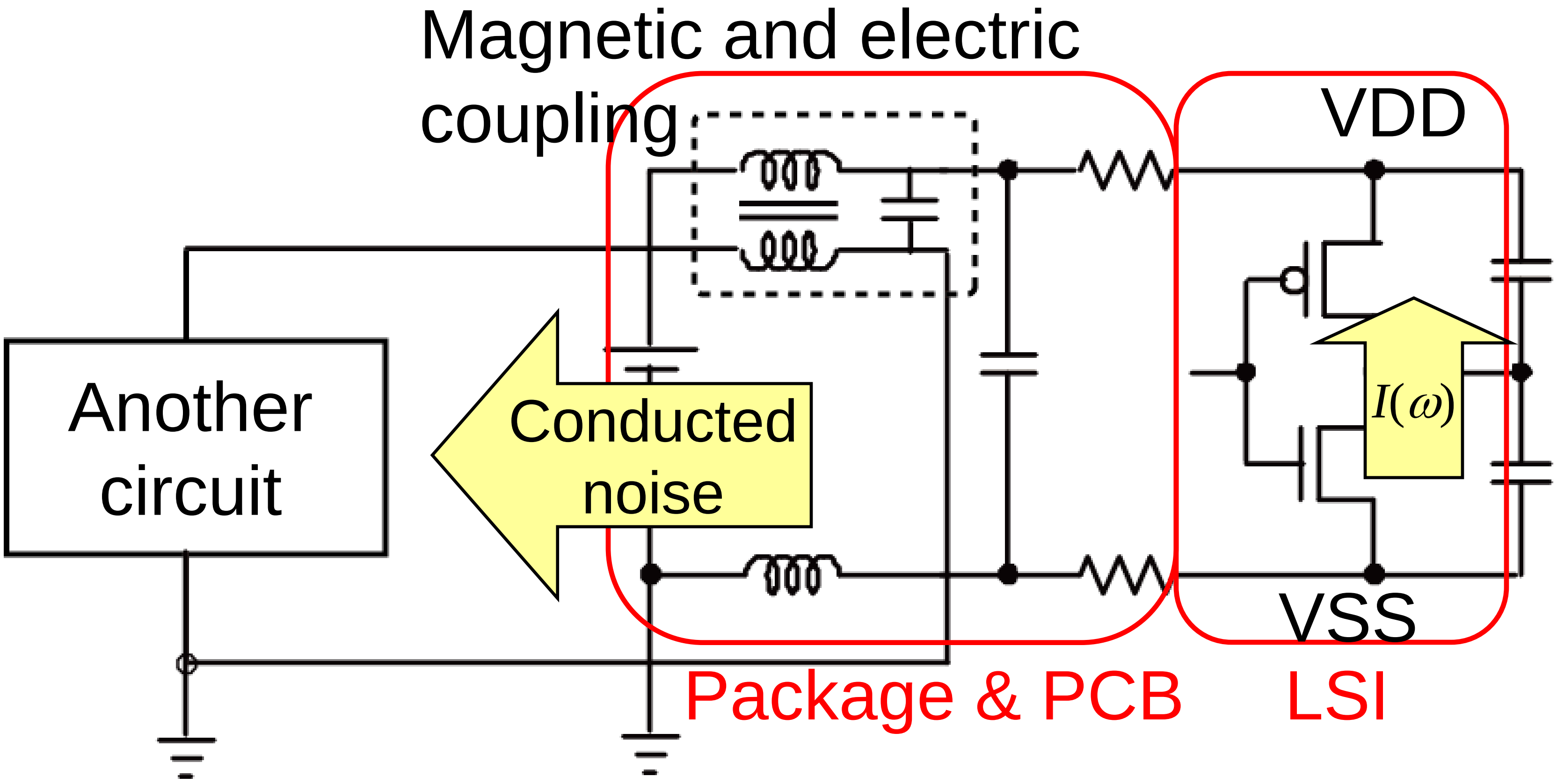
Power supply noise: voltage fluctuation



*PCB: Printed Circuit Board

Deteriorate signal timing and integrity
of noise source LSI

Power supply noise: conducted noise


Magnetic and electric coupling

Ramifications on another circuit through AC coupling or parasitic antenna

Purpose of this work

Issues

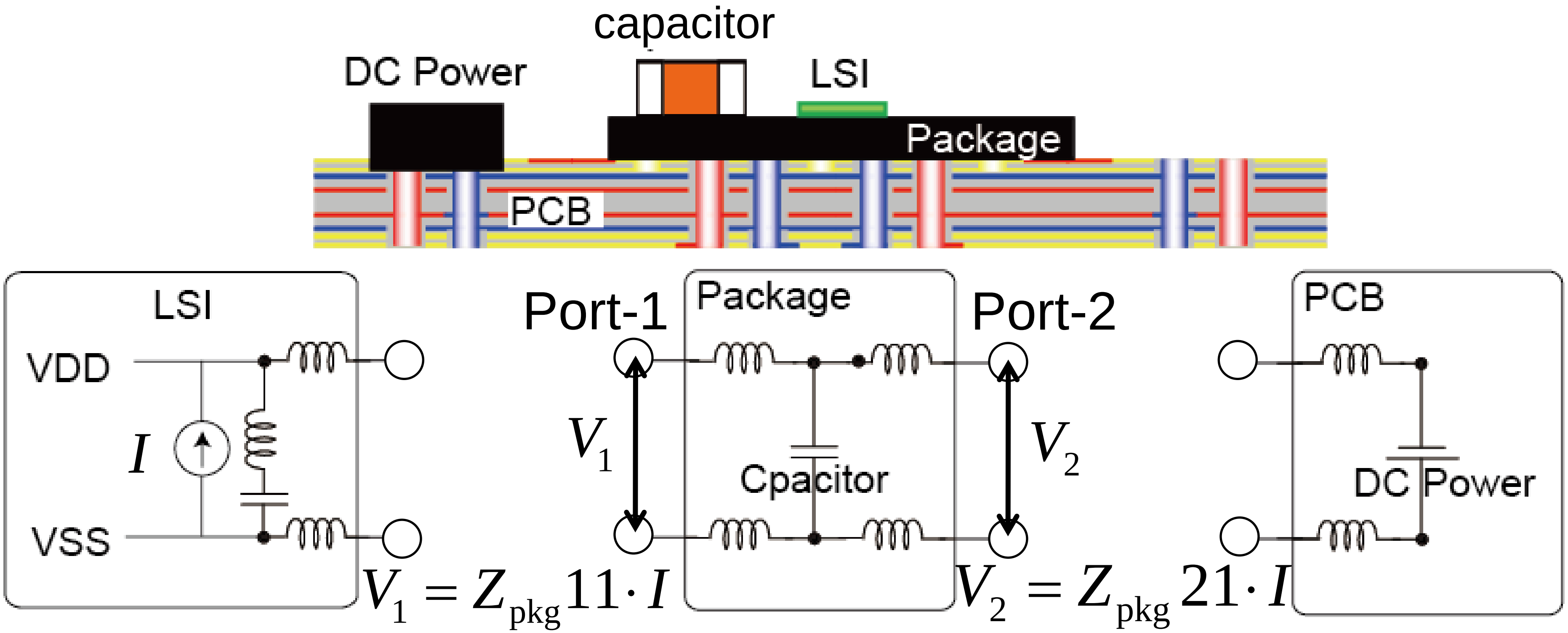
- Noise analysis is inaccurate and takes too much time
- Noise measurements are difficult

Purpose

- Propose a simple but accurate method for predicting power supply noise
  - generalized scattering matrix
- Validate the proposed method through test-chip measurements

Prediction method of power supply noise

Conventional method: Z-parameter of interposer



$$V_1 = Z_{\mathrm{pkg}}11 \cdot I \qquad V_2 = Z_{\mathrm{pkg}}21 \cdot I$$

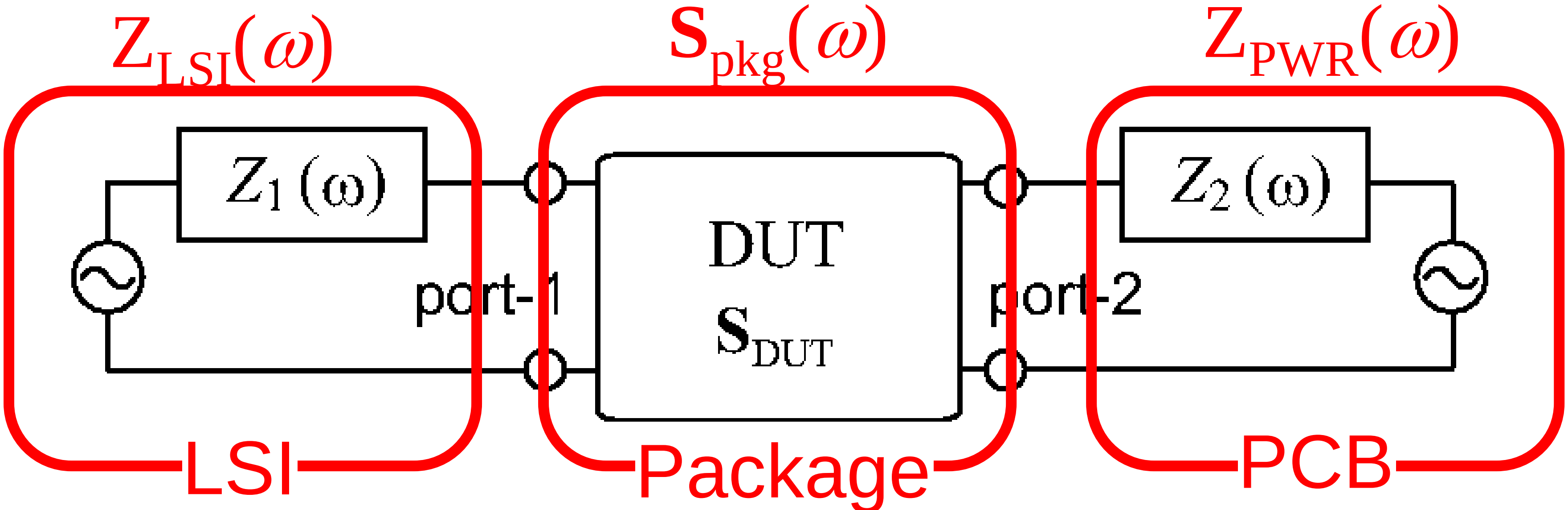
Voltage fluctuation : $Z_{\mathrm{pkg}}11$

Conducted noise : $Z_{\mathrm{pkg}}21$

Effect of complex input/output impedance has not been considered

Generalized scattering matrix

(K. Kurokawa. Power waves and the scattering matrix. m*icrowave Theory and Techniques, IEEE Transactions on, 13(2):194–202, Mar 1965*)



$$\mathbf{S}_{DUT} = \mathbf{F}(\mathbf{Z}_{DUT} - \mathbf{G}^{*})(\mathbf{Z}_{DUT} + \mathbf{G})^{-1}\mathbf{F}^{-1}$$

$$F_{ii} = \frac{1}{2\sqrt{\mathrm{Re}(Z_i)}}, \quad G_{ii} = Z_i$$

$\mathbf{Z}_{\mathrm{DUT}}$: Impedance matrix of DUT

Correction of an S parameter when reference impedances are complex

Proposed prediction method

Indicator of voltage fluctuation

$$Z_{\mathrm{sys}} = Z_{\mathrm{LSI}} \,//\, Z_{\mathrm{pkg}}11$$

Impedance calculated by reflection parameter $S_{\mathrm{pkg}}11$

Prediction parameter of conducted noise

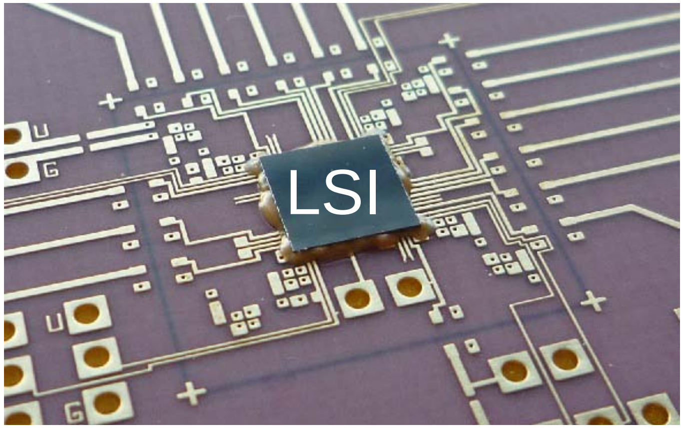
$$S_{\mathrm{pkg}}21$$

Transmission parameter of generalized S parameter

- Exact amplitude of power supply noise is not known
- Useful when evaluating frequency characteristics of different designs (design changes)

Experimental validation

Test fixture

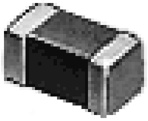


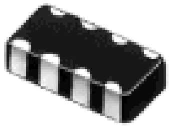
- 180-nm CMOS buffer
- Flip-chip mount on FR-4 PCB
  - – Mimics a package interposer

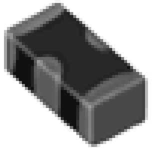
Z_{SYS} → Voltage fluctuation

$S_{pkg}21$ → Conducted noise

Evaluate the change of above parameters for different ceramic capacitors


2-terminal

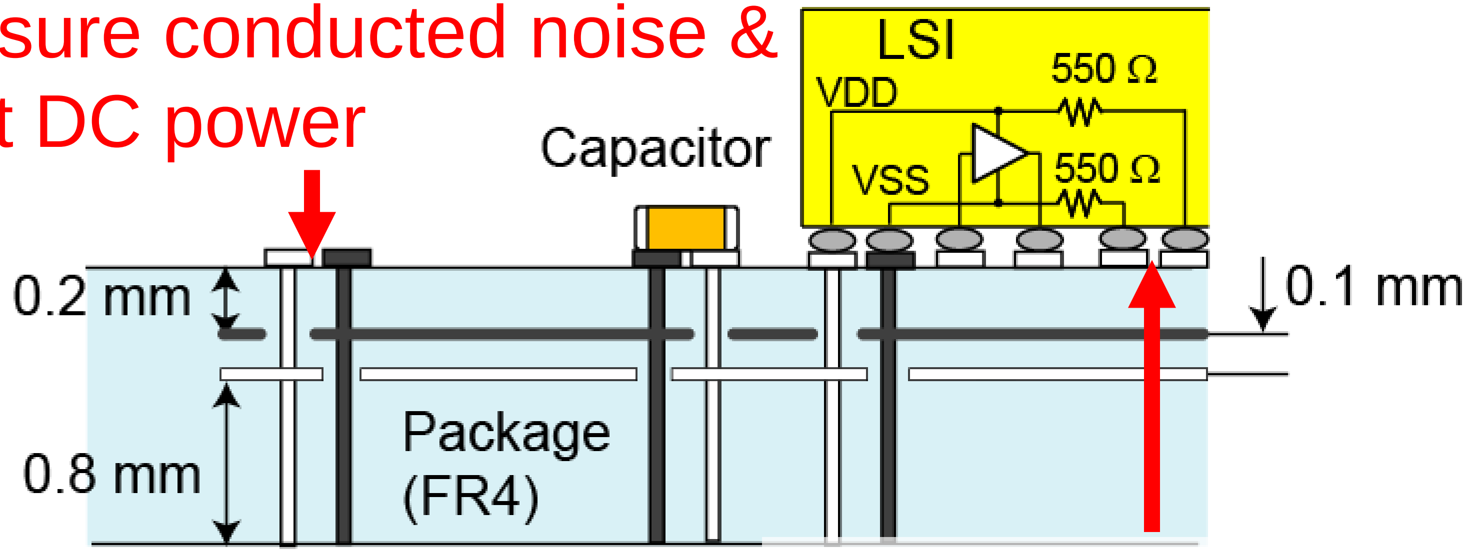

Multi-terminal


Feed-through

Measurement configuration

50MHz pulse

Measure conducted noise & input DC power

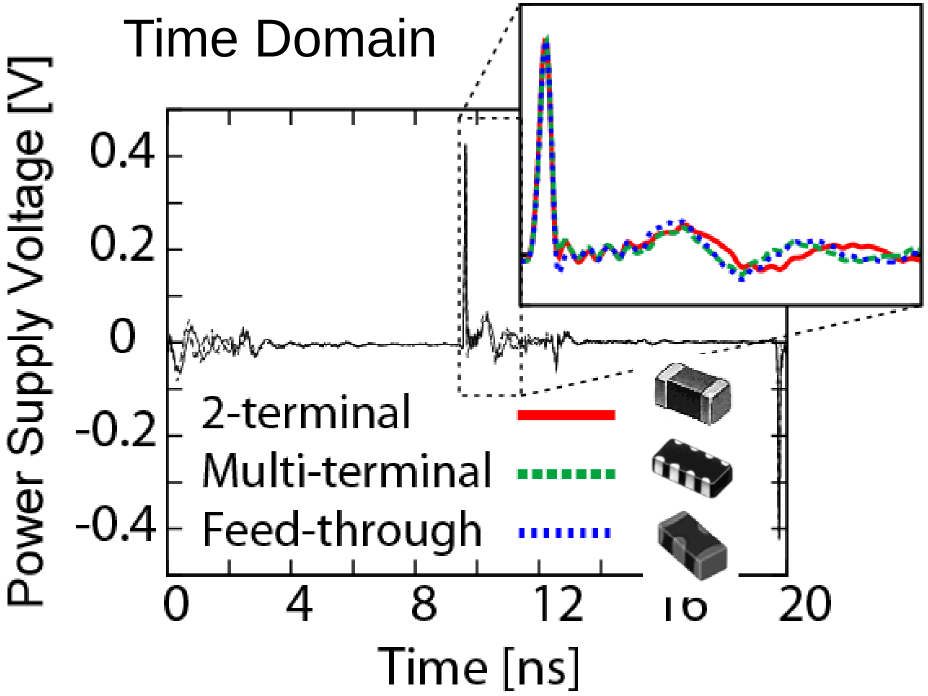


Measure voltage fluctuation through direct probing

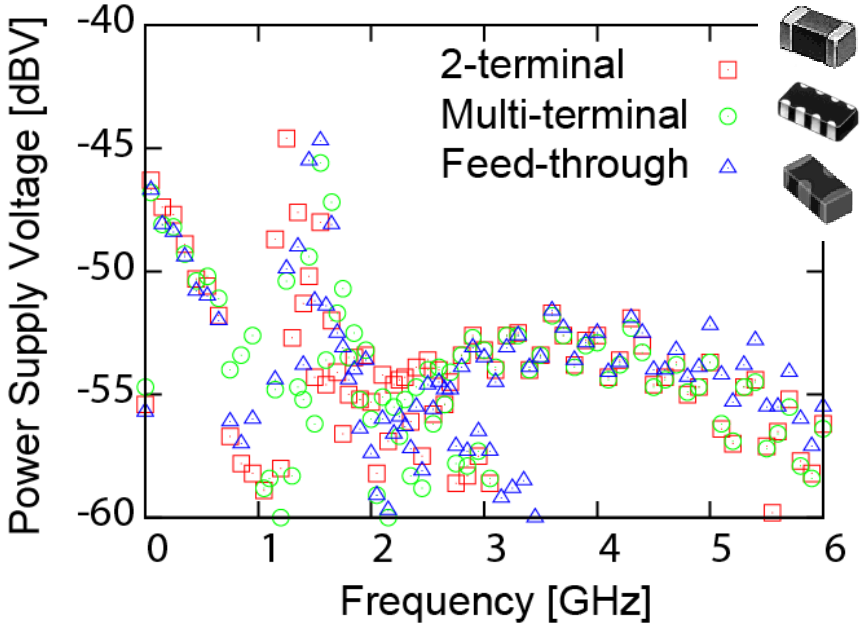
Z_{SYS} and $S_{pkg}21$ are individually measured by VNA

Measured on-chip voltage fluctuation

Time Domain

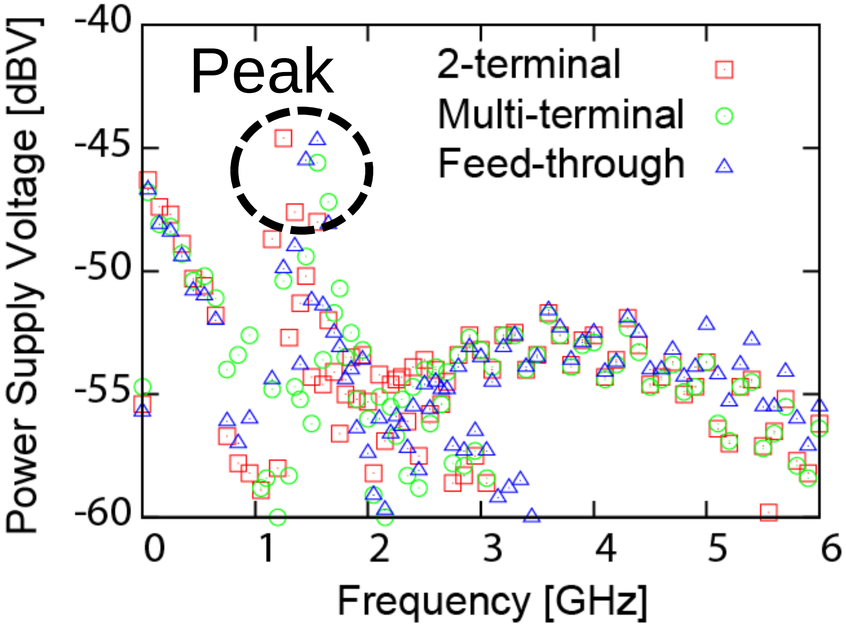


Frequency Domain

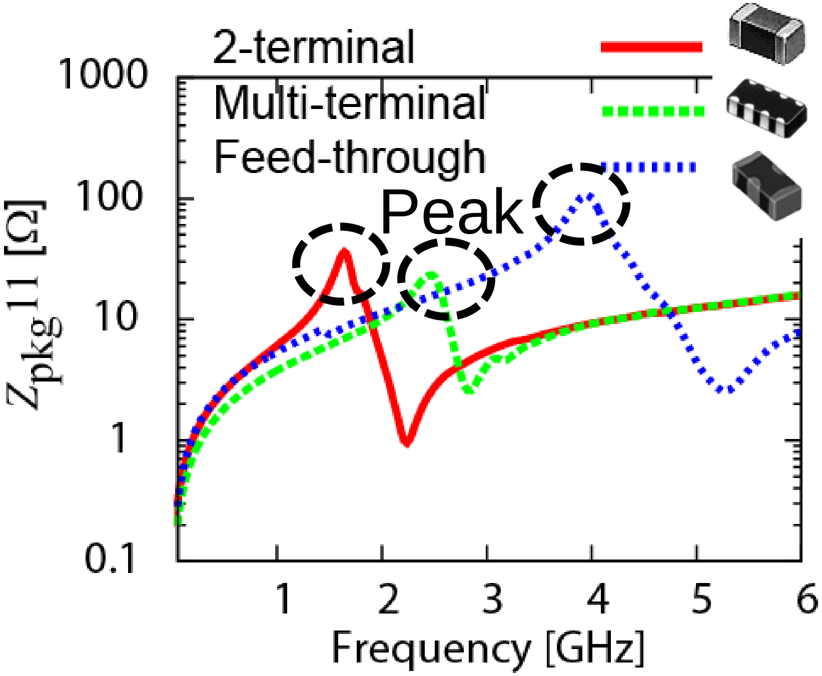


- Peak voltages are almost equal
- Peak frequencies are different depending on the type of capacitors

On-chip voltage fluctuation prediction by a conventional method



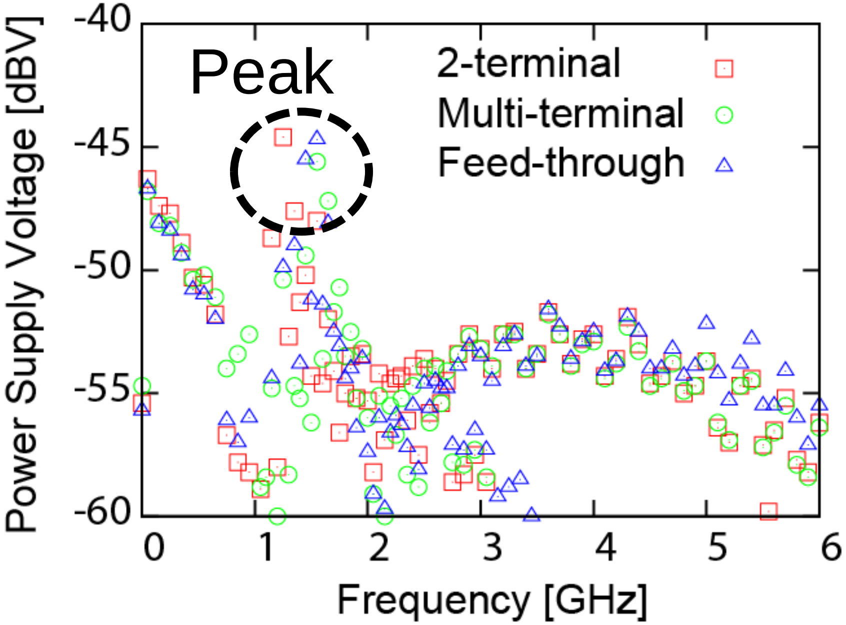
Voltage fluctuation
(measurement)



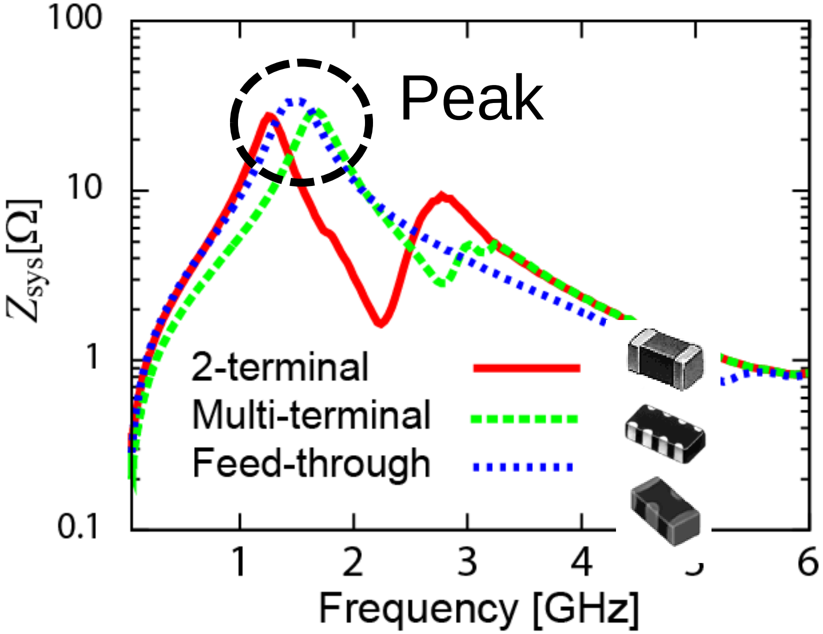
Conventional $Z_{pkg}11$
(prediction)

Peak frequencies of $Z_{pkg}11$ are mis-predicted, which leads to ineffective capacitor placement

On-chip voltage fluctuation prediction by the proposed parameter



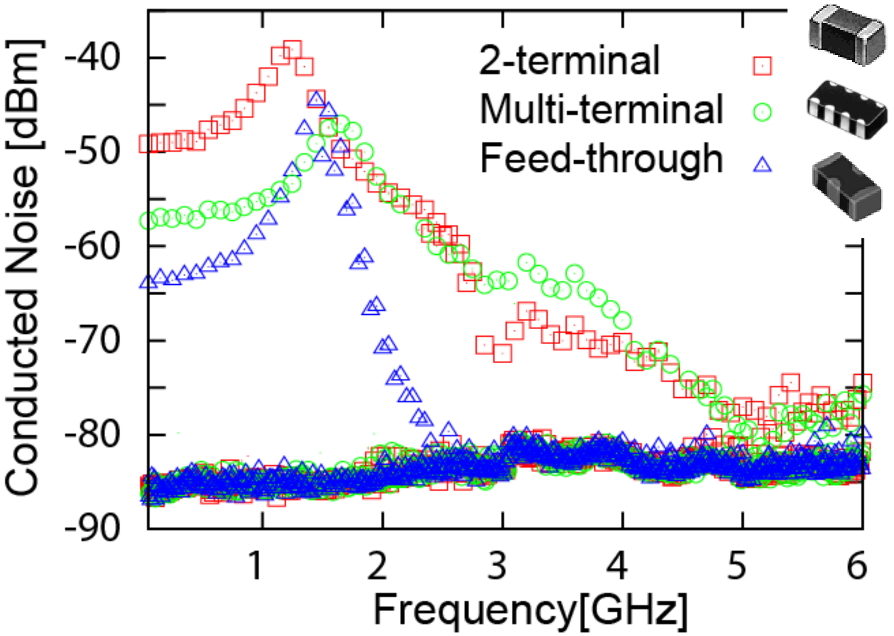
Voltage fluctuation
(measurement)

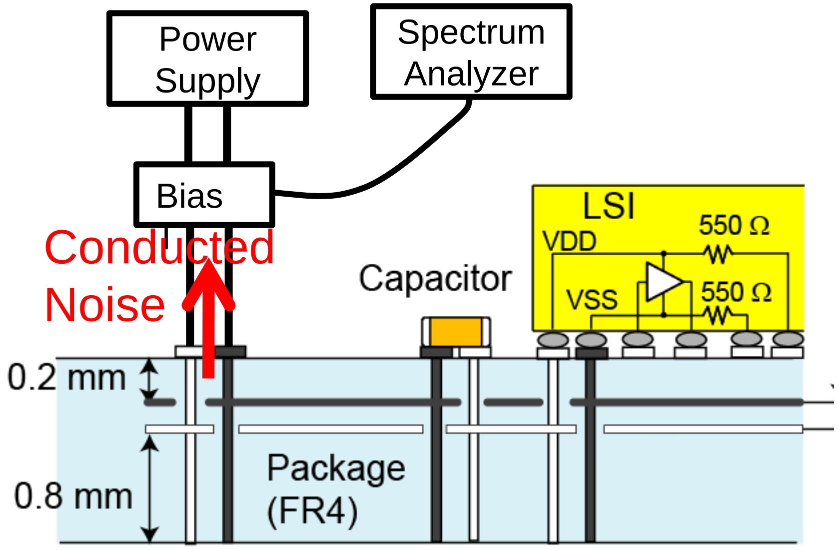


Proposed Z_{SYS}
(prediction)

Peak frequencies of Z_{sys} match with those of voltage fluctuation

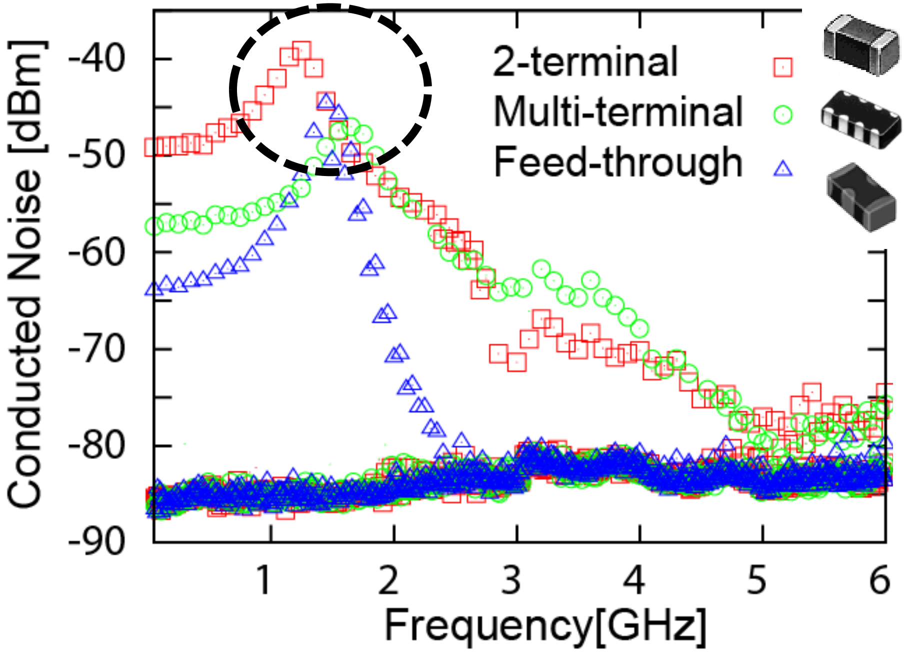
Measured conducted noise



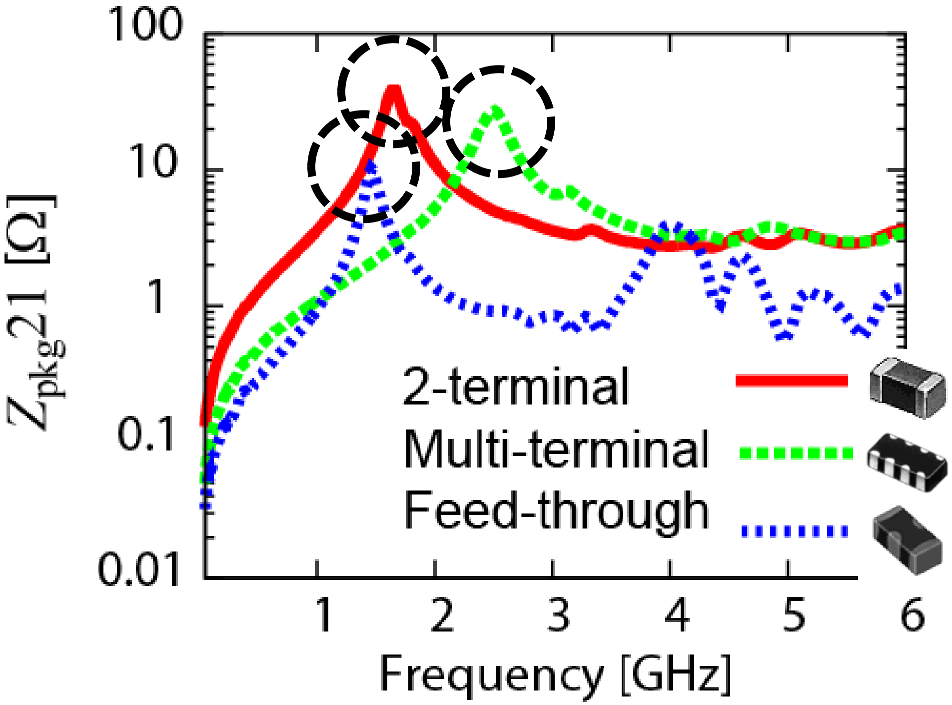


- Peak frequencies and amplitude are different depending on the type of capacitors
- Feed-through(blue) capacitor drastically reduce conducted noise

Conducted noise prediction by a conventional method



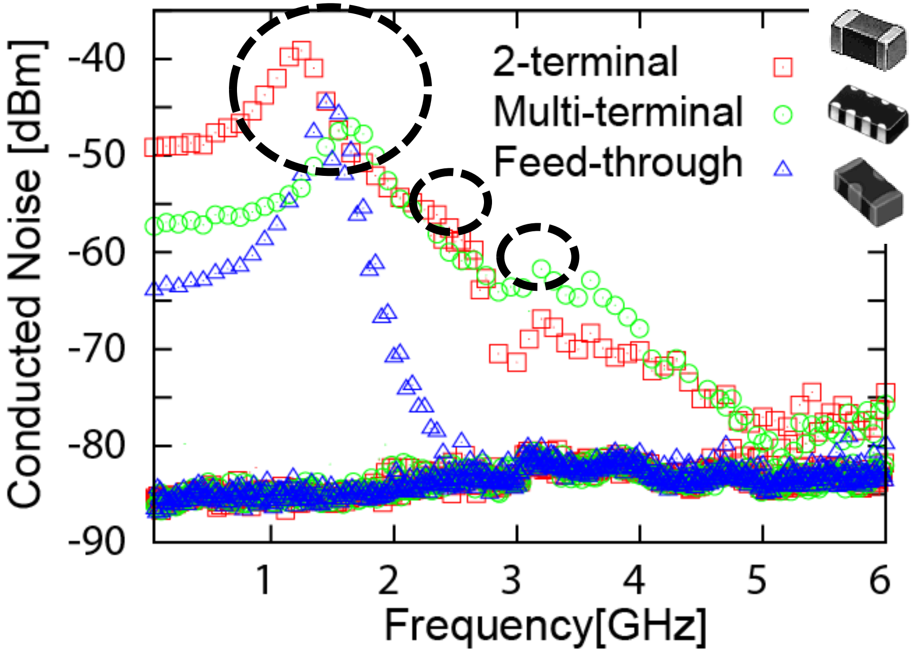
Conducted noise
(measurement)



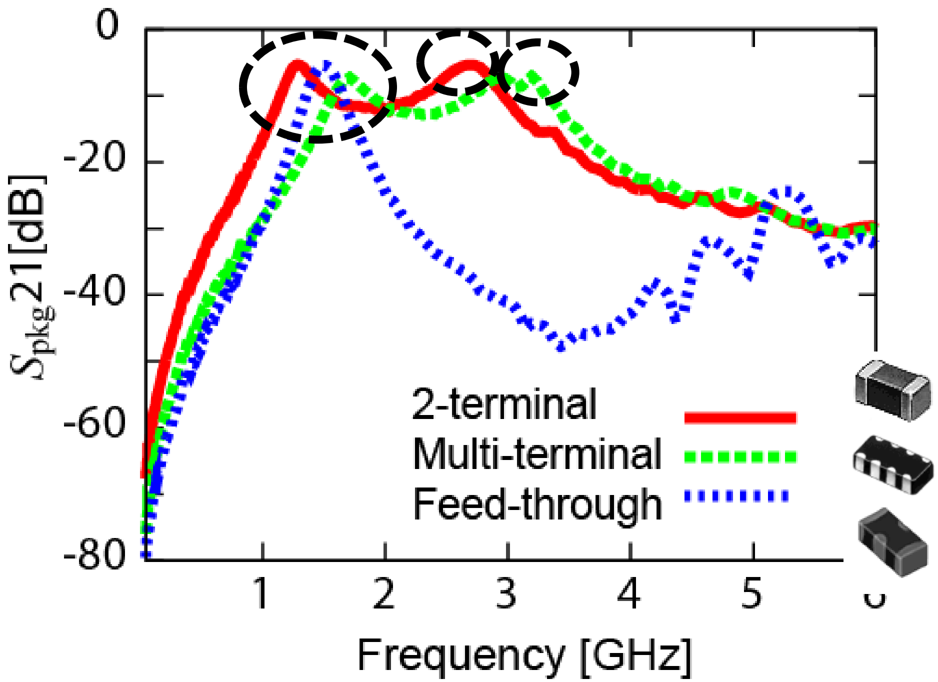
Conventional $Z_{pkg}21$
(prediction)

Inaccurate noise peak frequencies of $Z_{pkg}21$, which leads to ineffective noise-filter placement

Conducted noise prediction by the proposed parameter



Conducted noise (measurement)



Proposed S_{pkg21} (prediction)

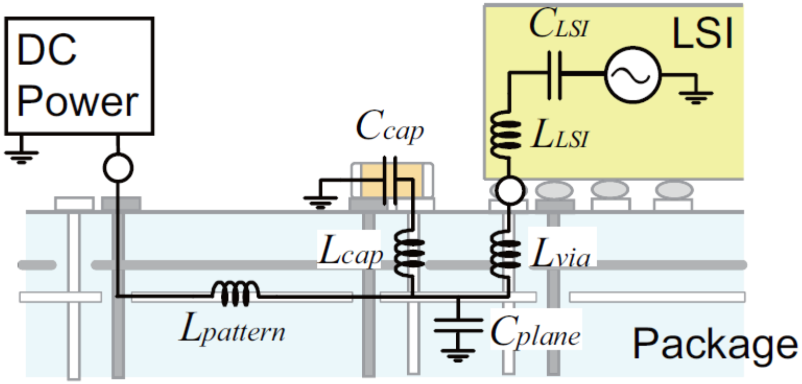
Peak frequencies of $S_{pkg}21$ match with that of conducted noise

Conclusions

- An application of generalized scattering matrix for prediction of power supply noise has been presented
- Prediction with the proposed parameter matches better with the measurements compared to the vanilla Z parameter
- The proposed method contributes to the evaluation of power supply noise in early stage of design flow

Equivalent circuit of test fixture

2 and Multi-terminal

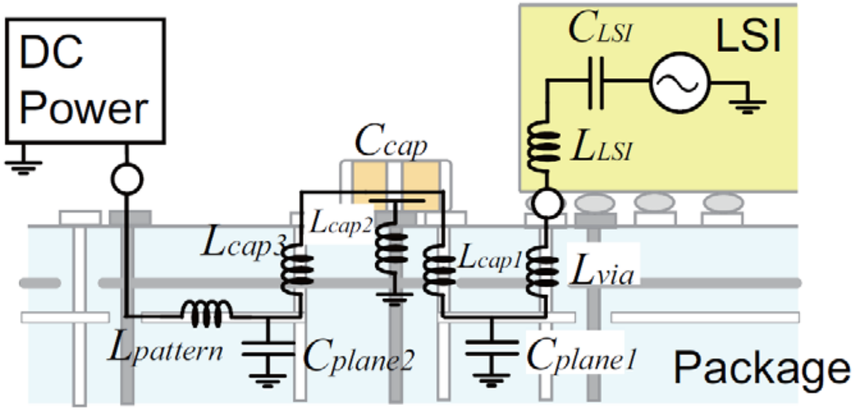


C_{LSI}	C_{cap}	C_{plane}
12.6pF	0.47μF	24.5pF

L_{LSI}	L_{via}	$L_{pattern}$	R_{LSI}	R_{via}	$R_{pattern}$
60pH	450pH	1.8nH	0.87Ω	0.07Ω	1.9Ω

	L_{cap}	R_{cap}
2-terminal	324pH	0.39Ω
4-terminal	144pH	0.23Ω

Feed-through



C_{LSI}	C_{cap}	C_{plane1}	C_{plane2}
12.6pF	0.47μF	5pF	17.5pF

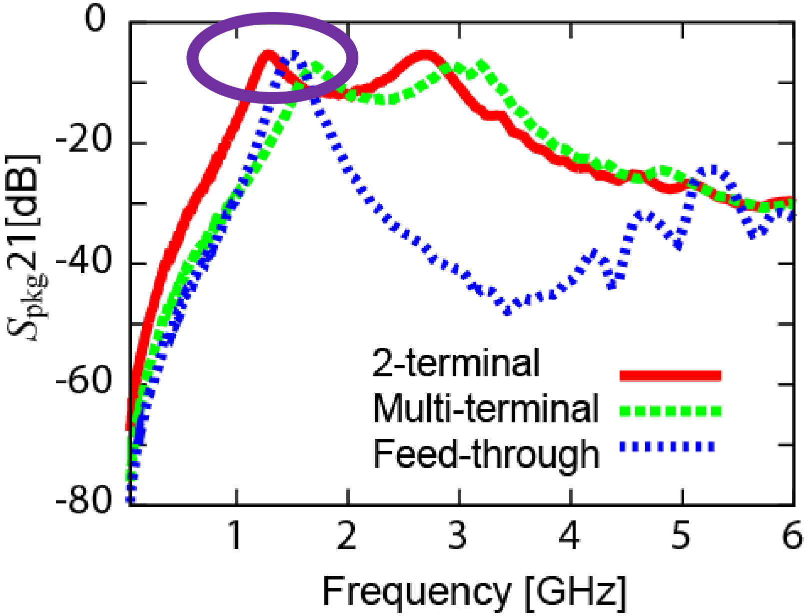
L_{LSI}	L_{cap1}	L_{cap2}	L_{cap3}	L_{via}	$L_{pattern}$
60pH	277pH	61pH	606pH	450pH	1.73nH

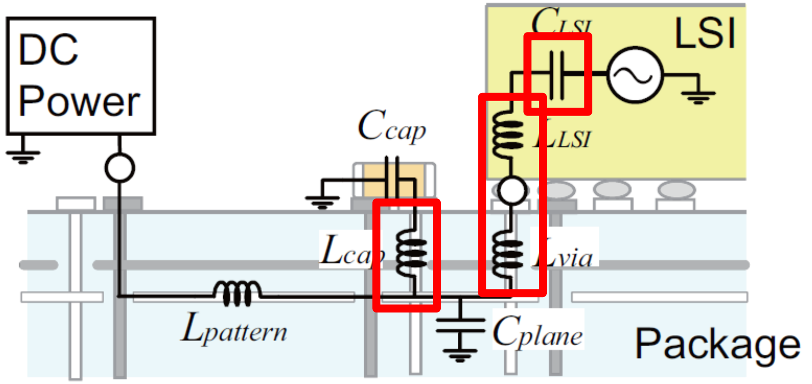
R_{LSI}	R_{cap1}	R_{cap2}	R_{cap3}	R_{via}	$R_{pattern}$
0.87Ω	0.62Ω	0.08Ω	0.38Ω	0.07Ω	1.67Ω

Clarify the effect of 3 capacitors to conducted noise

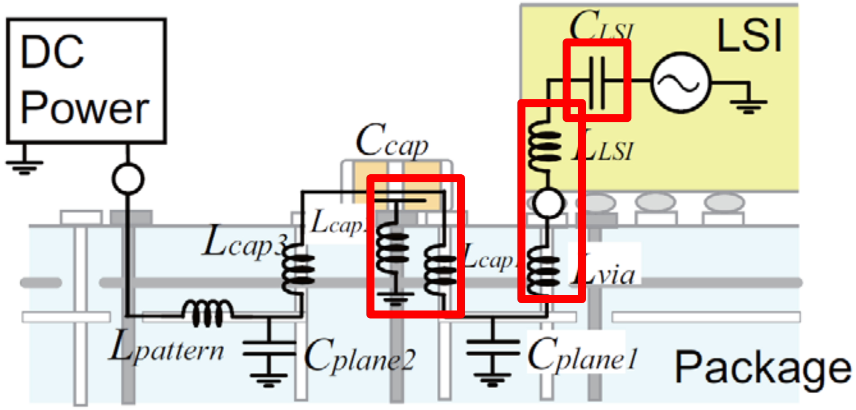
Cause of the first resonance

First resonance





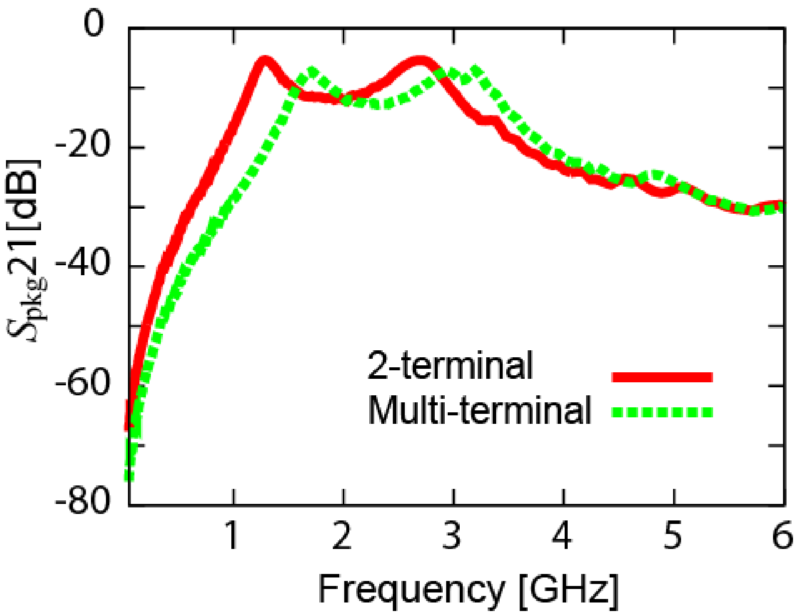
2 and Multi-terminal

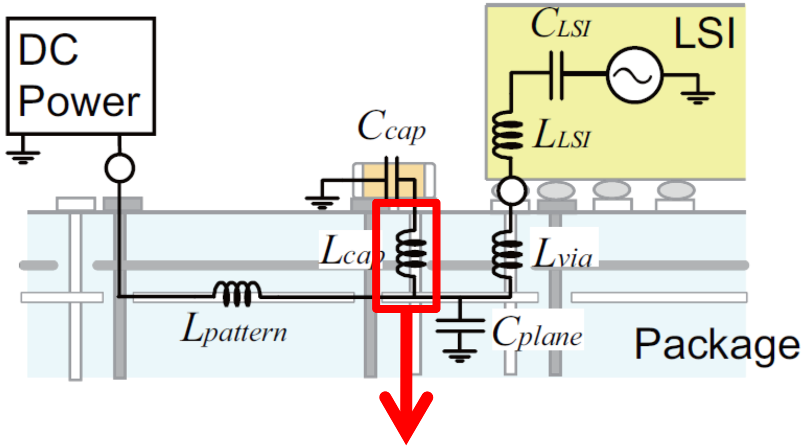


Feed-through

Series resonance between LSI capacitance and board inductance

Cause of the difference between 2 and multi-terminal



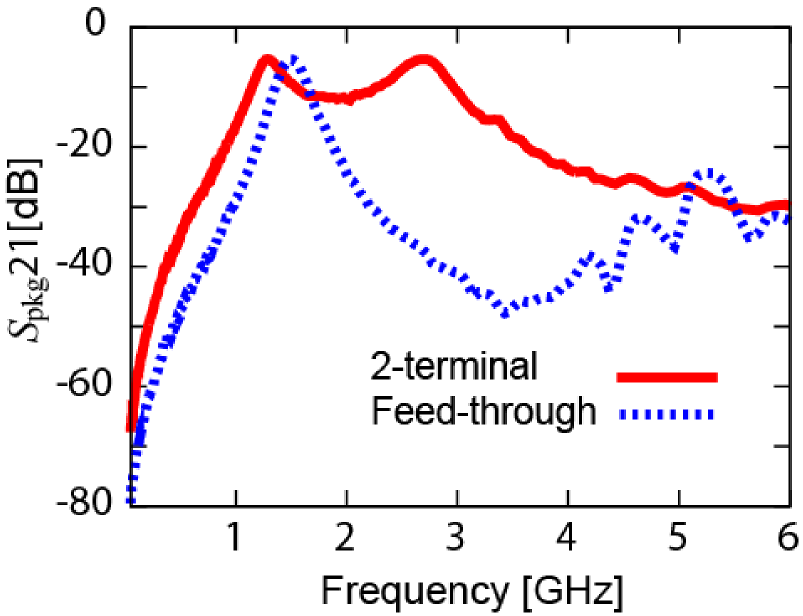


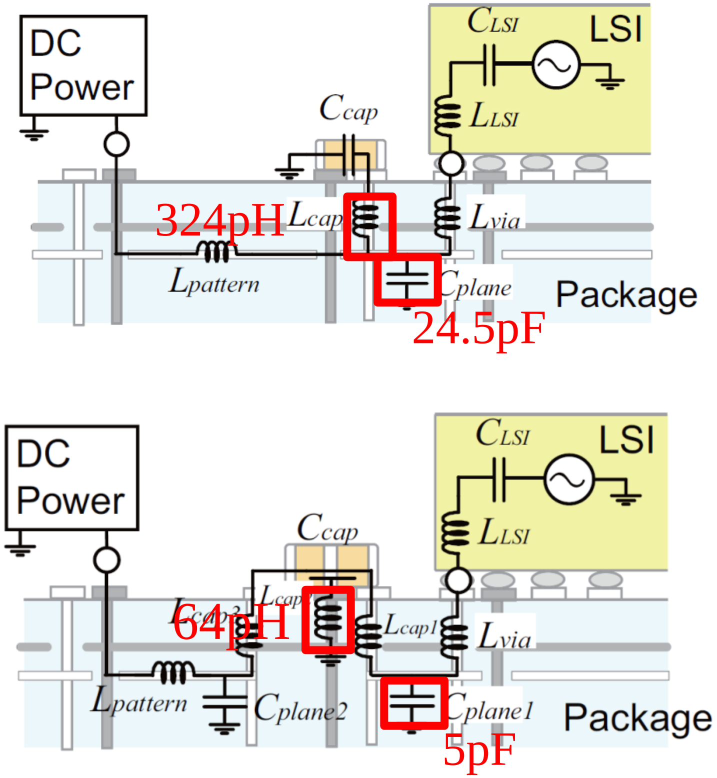
2-terminal: 324 pH

Multi-terminal: 144 pH

- Parasitic Inductance of capacitor only is different
- Resonance frequencies are shifted due to the different

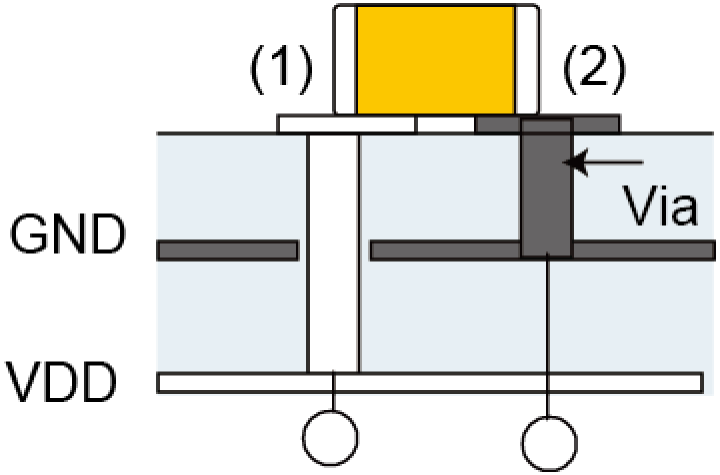
Cause of the difference between 2-terminal and feed-through

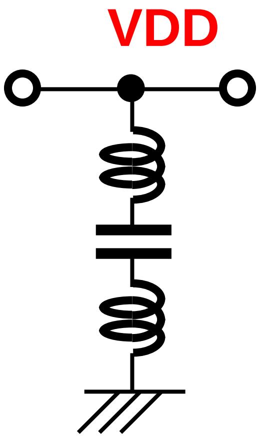


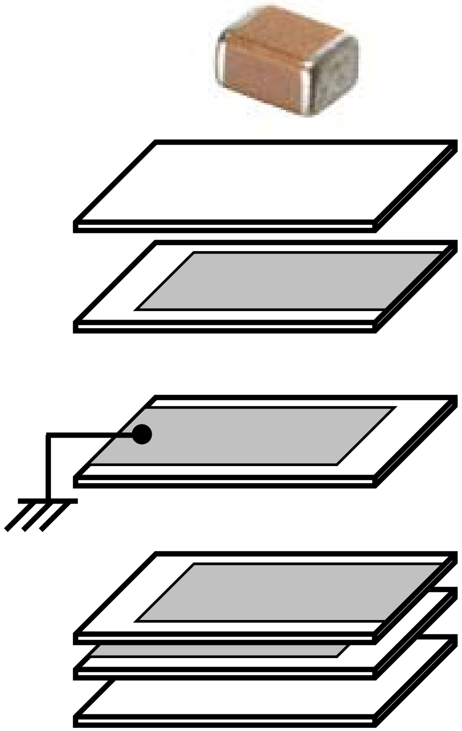


- Parasitic inductance and capacitance becomes small due to insertion in series of feed-through capacitor
- Second resonance frequency is shifted higher and insertion loss becomes large for feed-through capacitor

2-terminal ceramic capacitor

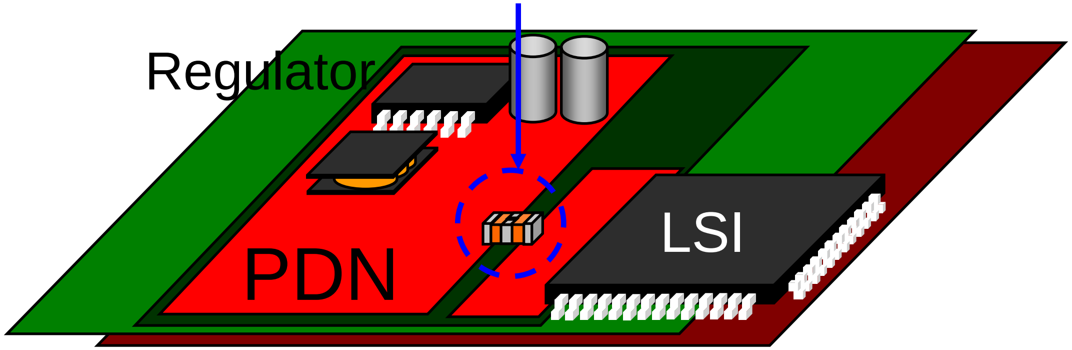


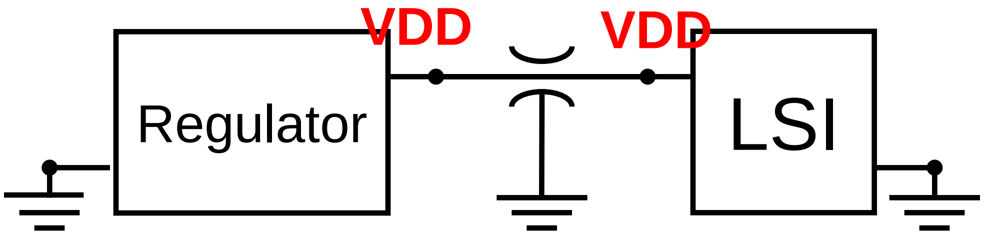


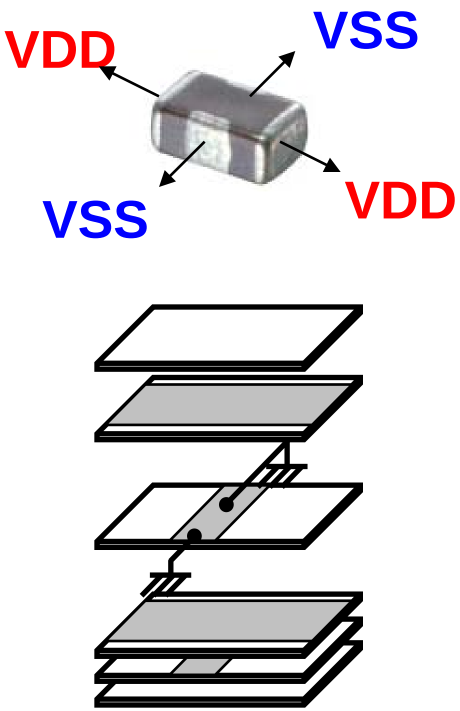


- The most commonly used capacitor
- Behave as short component and minify current loop at high frequency

Feed-through ceramic capacitor

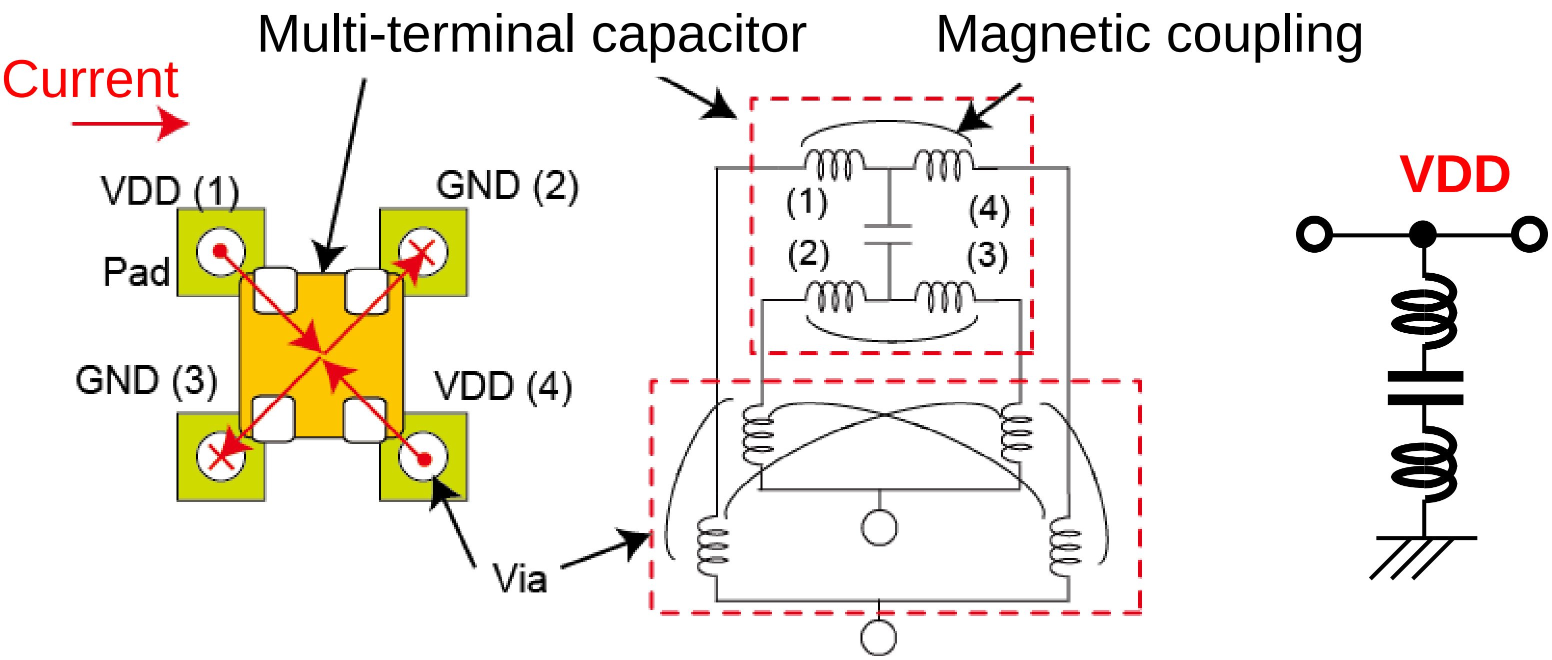






- Insert between LSI and regulator in series
- Drastically reduce conducted noise
- Behave as normal capacitor at the same time

Multi-terminal ceramic capacitor



Current

Multi-terminal capacitor

Magnetic coupling

VDD (1)

GND (2)

Pad

GND (3)

VDD (4)

Via

(1)

(4)

(2)

(3)

VDD

- Alternately put VDD and VSS electrodes
- Drastically reduce inductance using magnetic coupling
- Structure is the same as feed-through capacitor