DesignCon® 2014

Reducing signal transmission loss by low surface roughness

Taka-aki Okubo[1)], Toshio sudo[1)],
Toshihiro Hosoi[2)], Hiroaki Tsuyoshi[2)], and Fujio Kuwako[2)]

[1)]Shibaura-institute of Technology
[2)]Mitsui- Mining & Smelting Co., Ltd.

January 28-31, 2014 | Santa Clara Convention Center | Santa Clara, CA

UBM Tech

Agenda

1. Introduction and research purpose
2. Signal transmission loss
3. Configuration of the evaluation board
4. Measurement and simulated results
5. Loss and surface roughness of copper foil
6. Summary

Agenda

1. Introduction and research purpose
2. Signal transmission loss
3. Configuration of the evaluation board
4. Measurement and simulated results
5. Loss and surface roughness of copper foil
6. Summary

Introduction and Research purpose

☐ Introduction

1. Higher-speed signal transmission is strongly required on a printed circuit board to handle massive data in electronic systems.
2. So, signal transmission loss of copper wiring on a printed circuit board has been studied.
3. First, total signal loss was divided into dielectric loss and conductor loss quantitatively based on electromagnetic theory.
4. In particular, the scattering loss due to surface roughness of copper foil has been examined in detail.

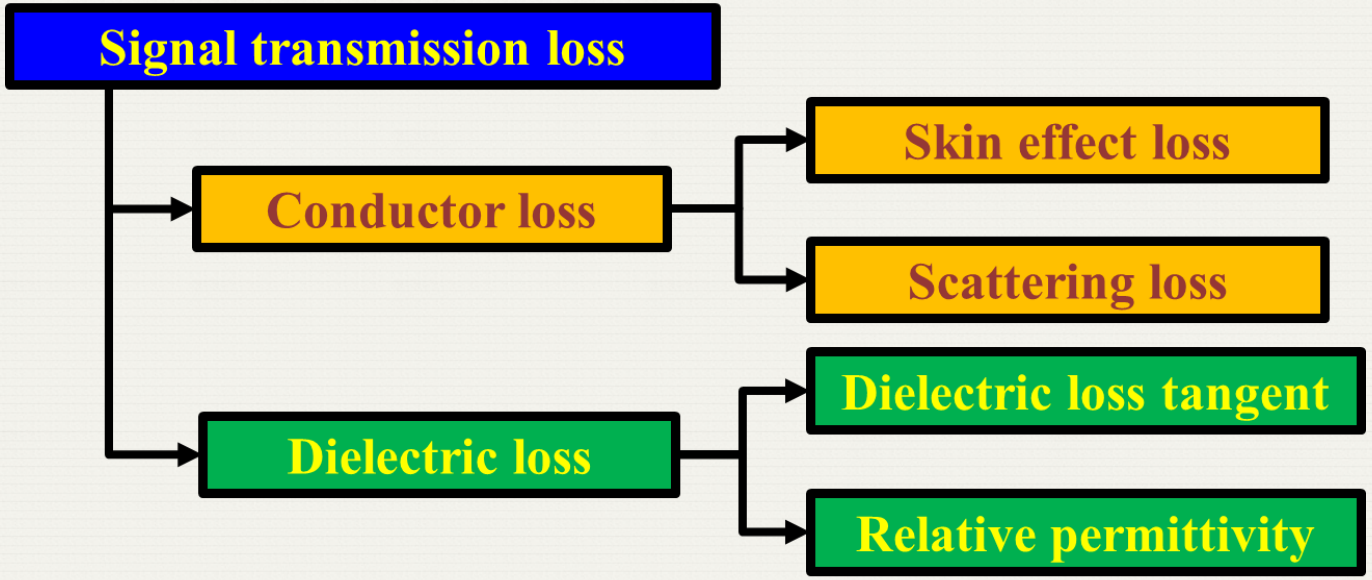
☐ Research purpose

◆ To demonstrate the usefulness of the copper foil with low surface roughness for higher-speed signal transmission.

Agenda

1. Introduction and research purpose
2. Signal transmission loss
3. Configuration of the evaluation board
4. Measurement and simulated results
5. Loss and surface roughness of copper foil
6. Summary

Signal transmission loss (1)



- Signal transmission loss on printed circuit boards can be classified into conductor loss and dielectric loss.
- Conductor loss can be classified into scattering loss caused by surface roughness and the skin effect loss.
- On the other hand, dielectric loss is due to dielectric loss tangent and relative permittivity.

Signal transmission loss (2)

Total loss

Total signal transmission loss can be expressed by two loss factors.

$$Loss = Loss_C + Loss_D$$

Where, $Loss_D$ is dielectric loss, $Loss_C$ is conductor loss.

Conductor loss

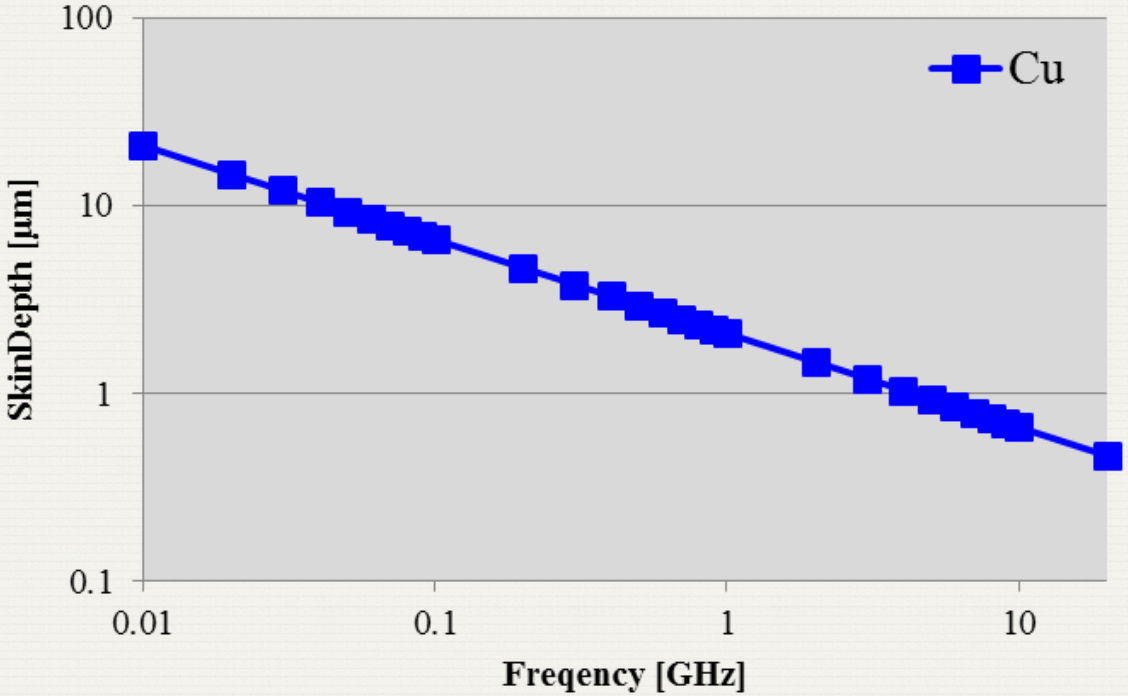
Conductor loss is represented by the following equation.

$$Loss_C = Loss_K + Loss_S$$

Where, $Loss_C$ is conductor loss, $Loss_K$ is skin effect loss and $Loss_S$ is scattering loss.

- Conductor loss is composed of scattering loss and skin effect loss.

Frequency dependency of skin depth in copper conductor



- Skin depth δ is defined by the distance where the current amplitude becomes 1/e times of the surface current amplitude in the conductor.
- In the frequency of 1GHz, the skin depth is about 2.1 µm.
- Current distribution is concentrated at the surface, or the edge of the conductor at high frequencies. This is the skin effect.

Skin effect loss

Skin effect

Skin effect is represented by following equation.

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} = \frac{1}{\sqrt{\pi f \mu\sigma}}$$

Where, δ is skin depth, ω is angular frequency, μ is permeability, σ is conductivity of copper and f is frequency.

- Skin effect δ is inversely proportional of the square root of the frequency.

Skin effect loss

The loss due to skin effect is represented by following equation.

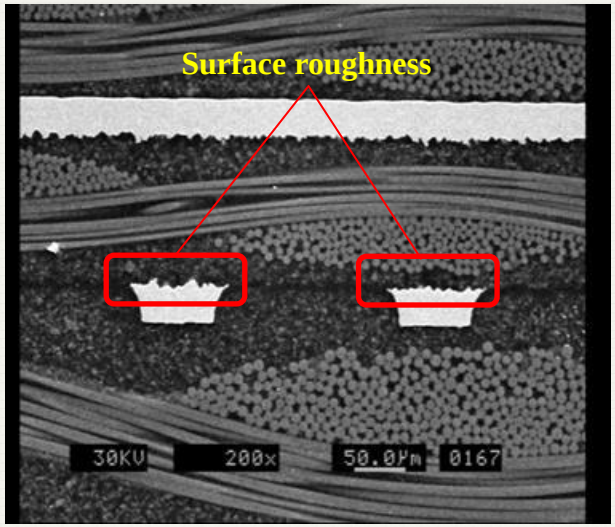
$$Loss_H = \frac{2.26 \times 10^{-8} \times \sqrt{f}}{w} \quad \text{[dB/m]}$$

Where, w is wiring width of copper.

- Skin effect loss is proportional to the square root of frequency.

Cross-section of copper conductor

Usually, the surface of the conductor in printed circuit boards is intentionally roughened to enhance the adhesion to the prepreg.



- Typical surface roughness of the copper foil commonly used in printed circuit boards was 6 μm.
- This is a value greater than 2.1 μm of the skin depth at 1GHz.
- Because skin depth becomes smaller than surface roughness at high frequency, the scattering loss becomes prominent.

Dielectric loss

☐ Dielectric loss

Dielectric loss is represented by the following equation.

$$Loss_D = 90.9\sqrt{\varepsilon_\gamma} \times \tan\delta \times f$$

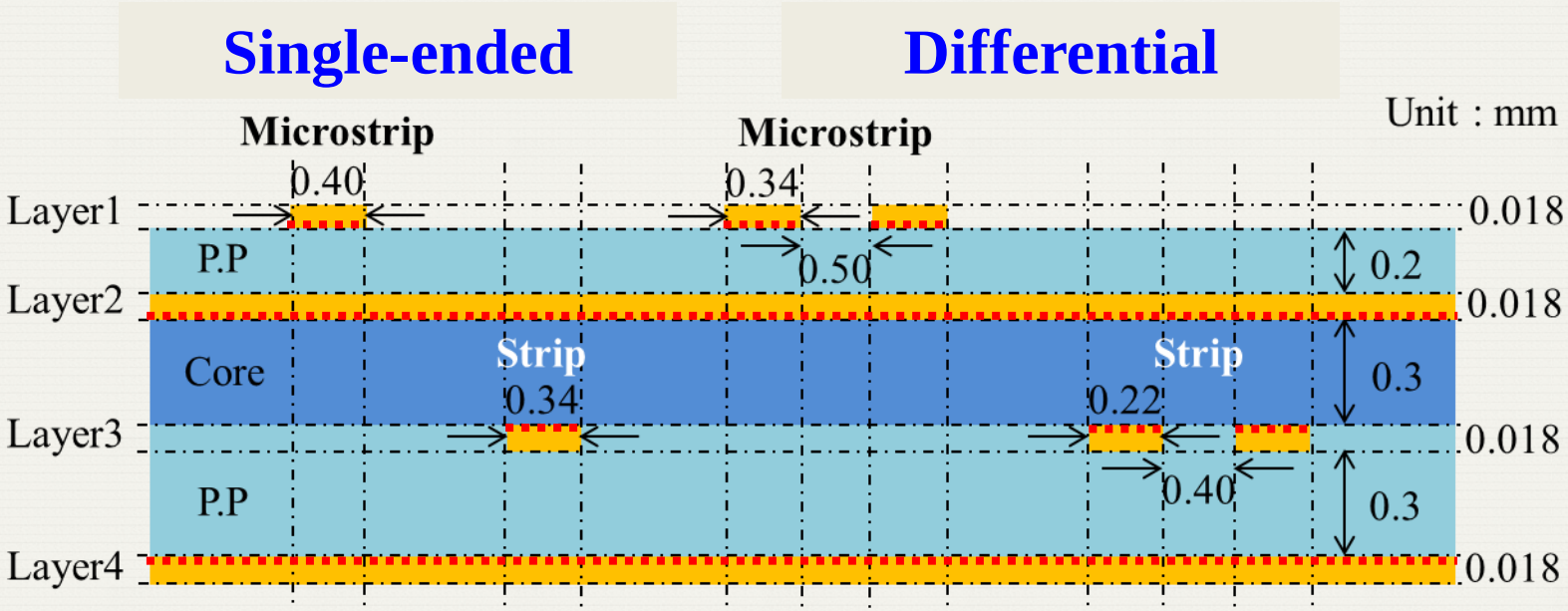
Where, ε_γ is relative permittivity, $\tan\delta$ is dielectric loss tangent and f is frequency.

- Dielectric loss is proportional to the frequency.
- Dielectric loss is affected by dielectric loss tangent and relative permittivity of the dielectric.

Agenda

1. Introduction and research purpose
2. Signal transmission loss
3. Configuration of the evaluation board
4. Measurement and simulated results
5. Loss and surface roughness of copper foil
6. Summary

Configuration of the evaluation board



- The evaluation boards included into the four types of transmission line structures.
- They are microstrip and strip structures for single-ended transmission line and there are those structures for differential transmission line.
- The dotted red lines on the conductors show mat faces of copper foils.
- The characteristic impedance for single-ended line was configured to 50 ohms and the differential impedance for differential line was configured to 100 ohms.

Properties of dielectric materials

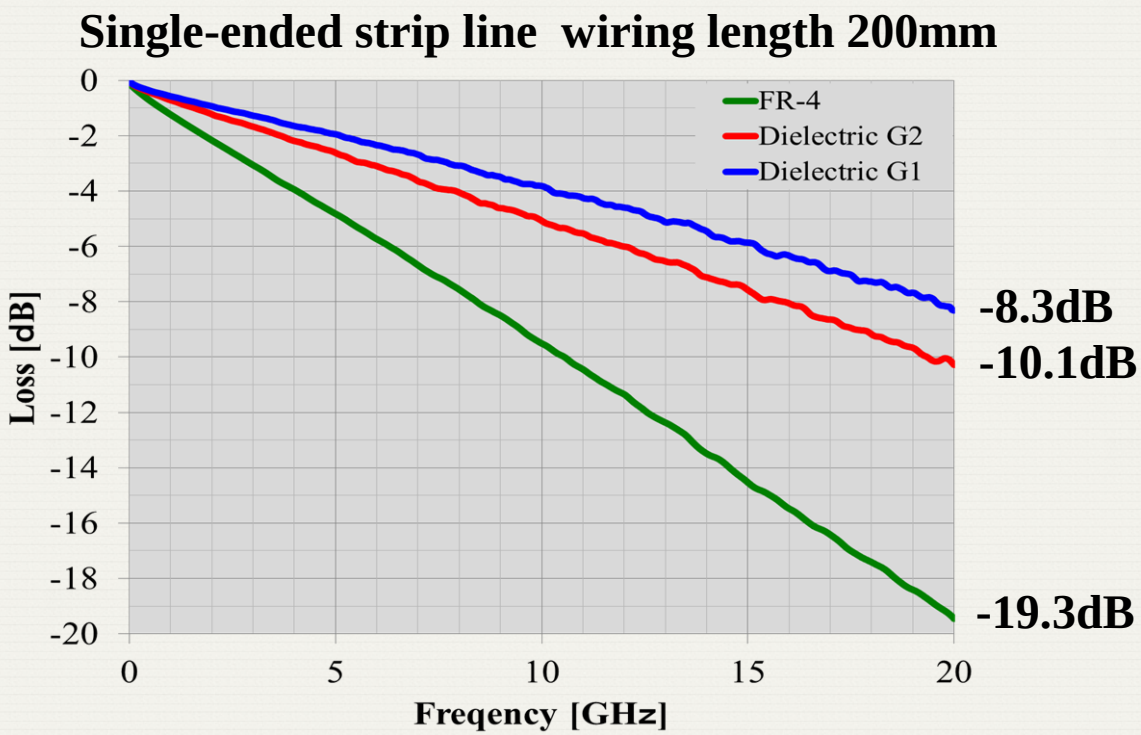
	Relative permittivity	Dielectric loss tangent
G1	3.6	0.002
G2	3.8	0.005
FR-4	4.4	0.02

- The evaluation boards have been provided with three types of the dielectric materials.
- They are low dielectric material G1, G2 and commonly used dielectric material, FR-4.
- This table shows relative permittivity and dielectric loss tangent of each materials.

Agenda

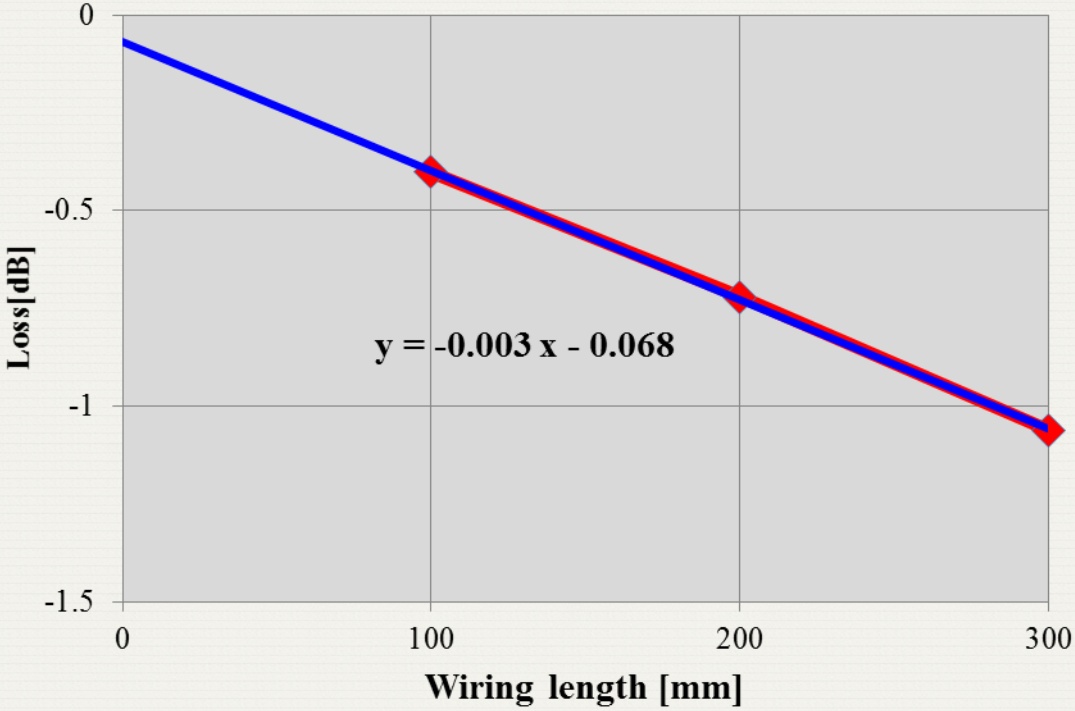
1. Introduction and research purpose
2. Signal transmission loss
3. Configuration of the evaluation board
4. Measurement and simulated results
5. Loss and surface roughness of copper foil
6. Summary

Comparison with loss difference caused by dielectric materials



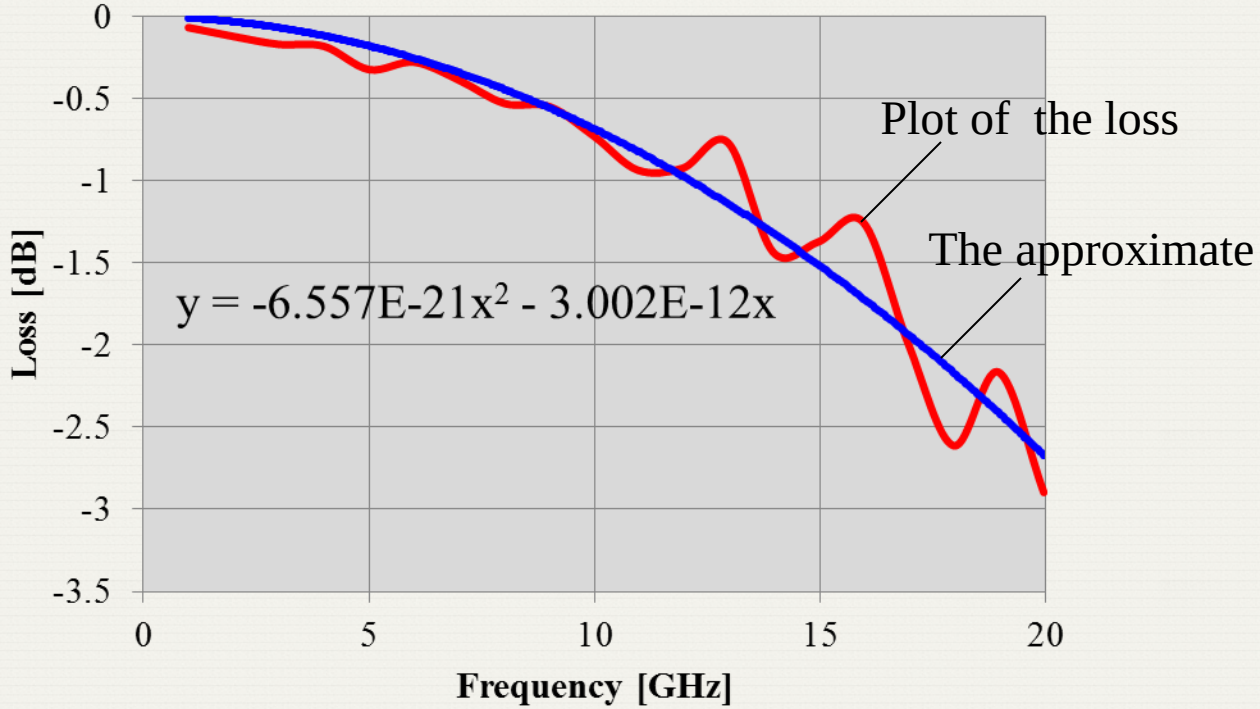
- S parameters were measured with a vector network analyzer. The frequency range is from 300 KHz to 20GHz. This measurement results includes the signal loss due to vias.
- The losses were reduced to more than half by adopting dielectric G1 and G2 as compared with the loss for FR-4.

How to deduce the loss due to vias?



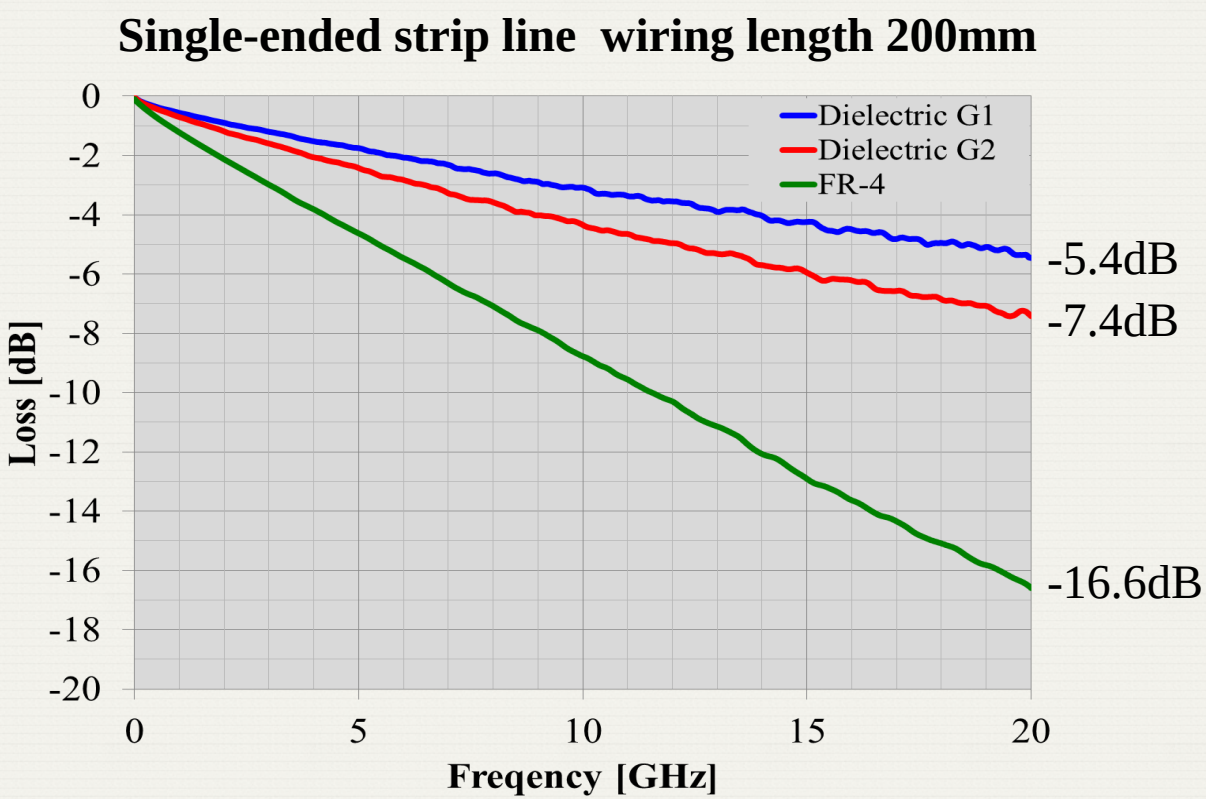
- This figure shows the losses for three wiring lengths at 1GHz.
- The red plots indicate the measured losses in each wiring length and the blue line is the regression line of them.
- The intercept of the blue line shows the via loss value. The value of the via loss was -0.00679dB at 1GHz.

Deduction of via loss from measurement



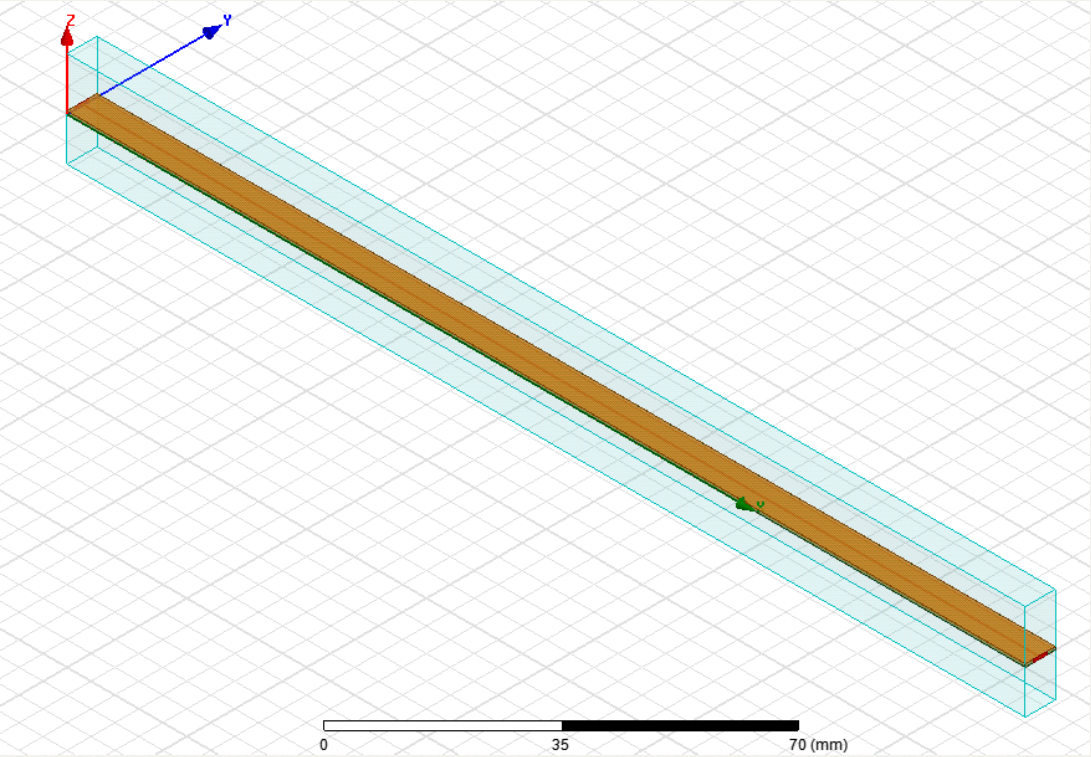
- This figure shows the deduced via loss from 1GHz to 20 GHz.
- The red line shows plots of loss due to vias in each frequency. The blue line shows approximated curved line for the red line.
- The deduced via loss was approximately -2.8 dB at 20 GHz.

Calibrated S21 without via loss



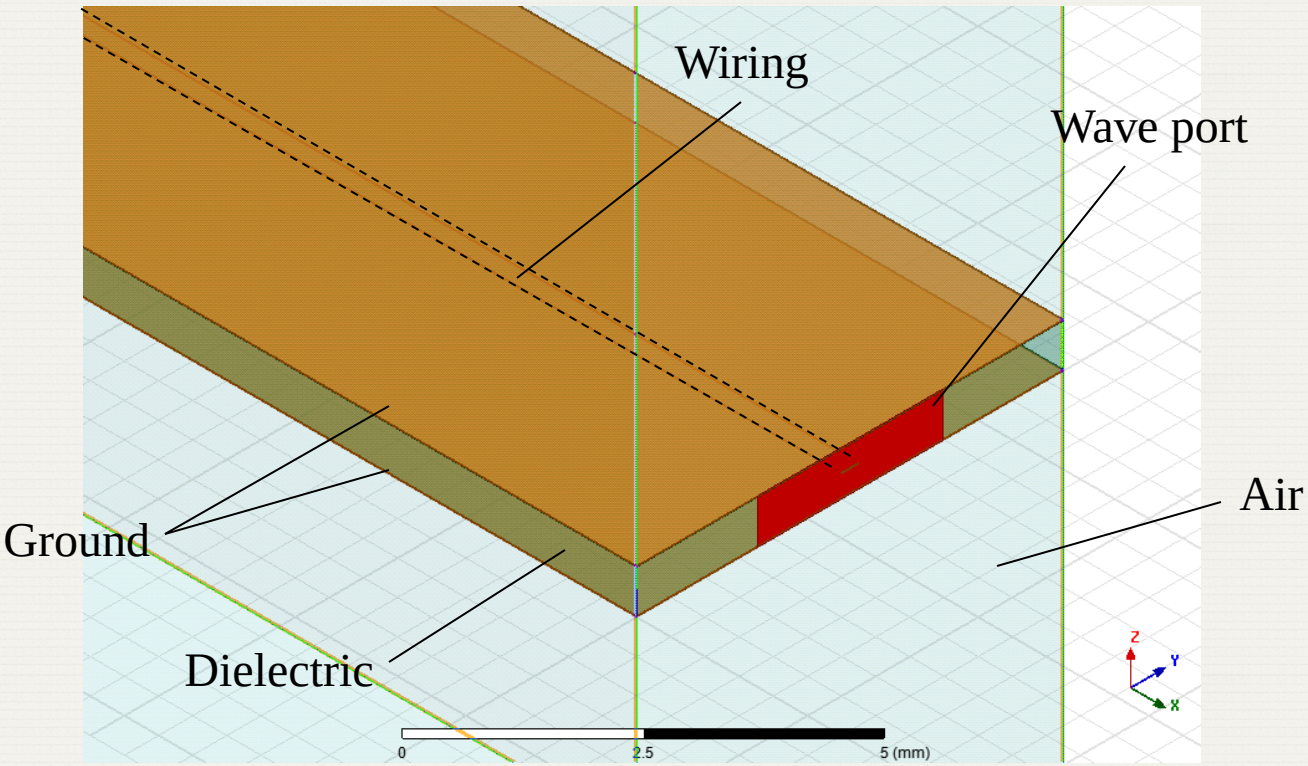
- This figure shows calibrated S21 that does not include the loss due to vias.
- In case of dielectric G1, the loss value was about -5.4 dB at 20 GHz.
- On the other hand, the loss value for FR-4 was about -16.6 dB at 20 GHz.

Simulated S21 by HFSS model



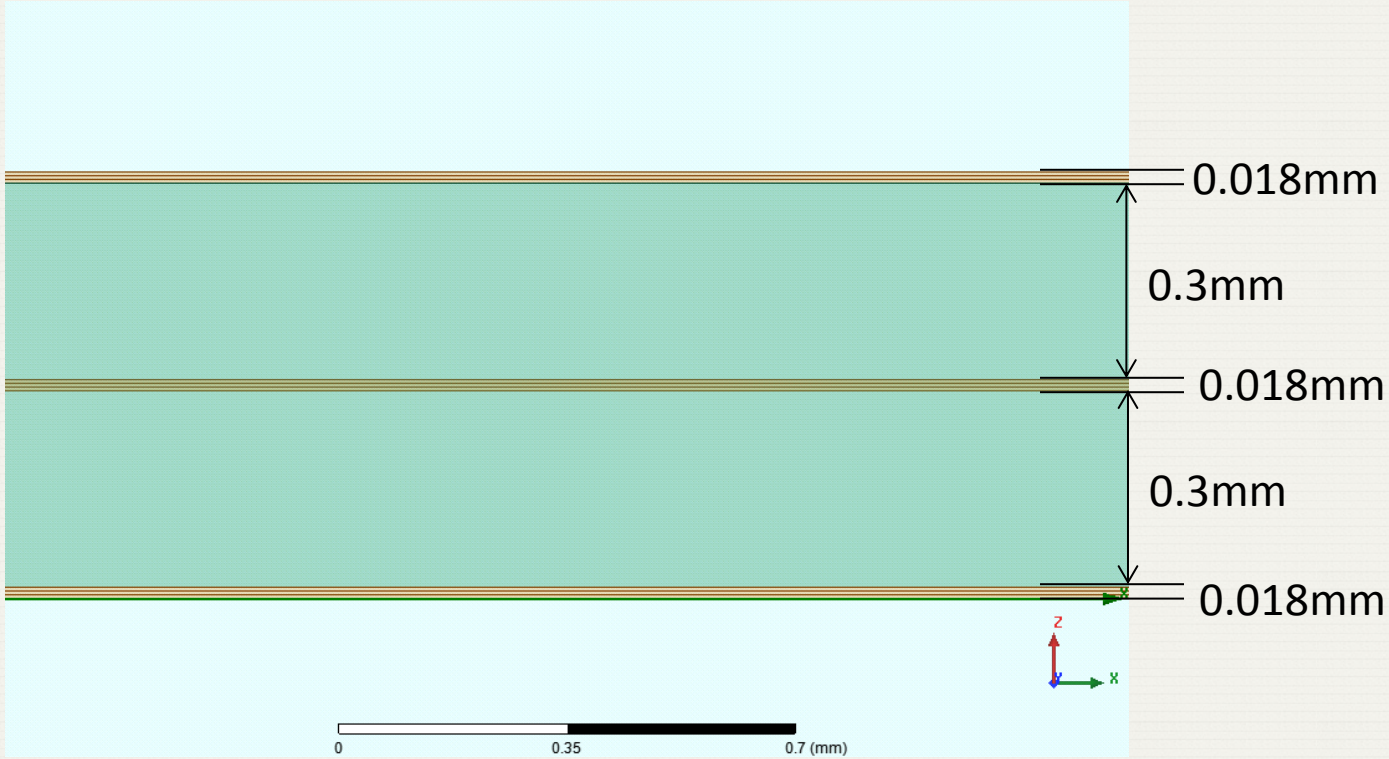
- The signal loss was analyzed with 3D electromagnetic solver, HFSS.
- This figure shows the analysis model of wiring on a printed circuit board.
- The model was single-ended strip structure and wiring length was 200mm.

HFSS model without via



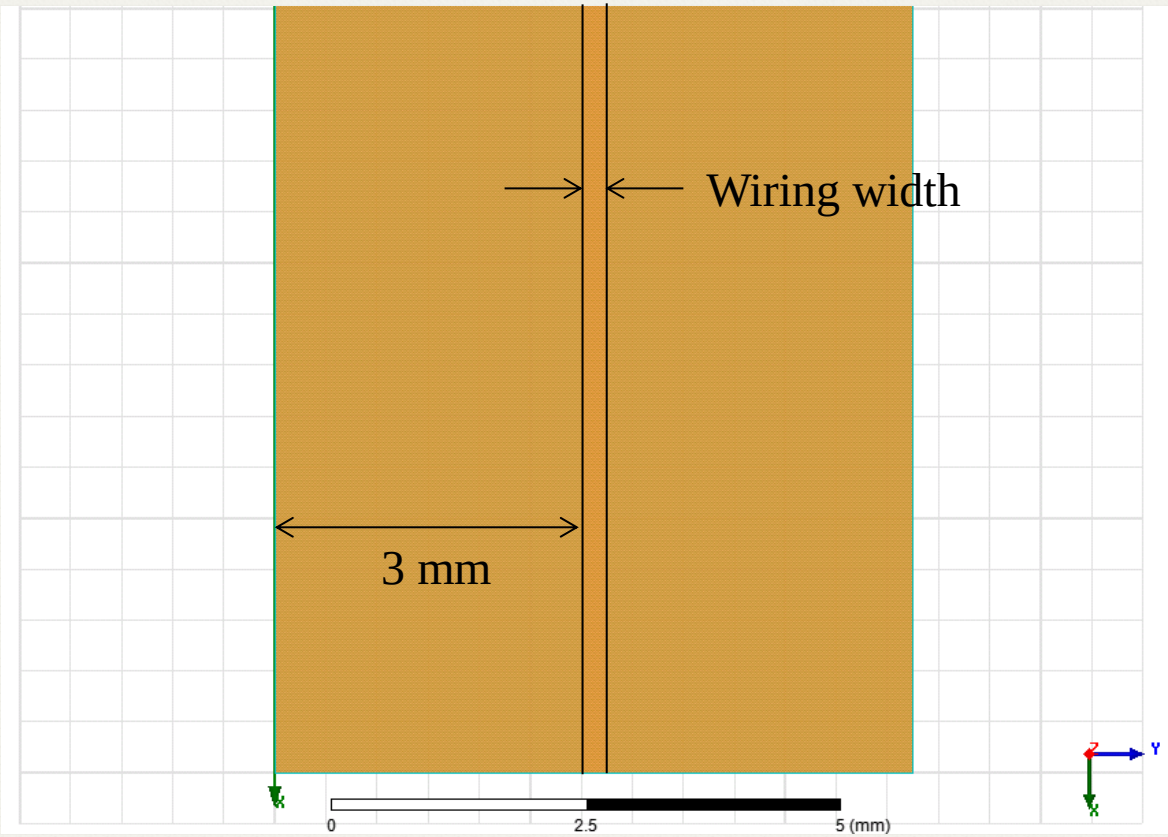
- This figure shows a port of HFSS model without via.
- The ports were set to wave port. This wave port is the ideal port.

Cross-section in HFSS model



- This figure shows the cross-section of the HFSS model. The thickness of conductors was set to 18 μm.

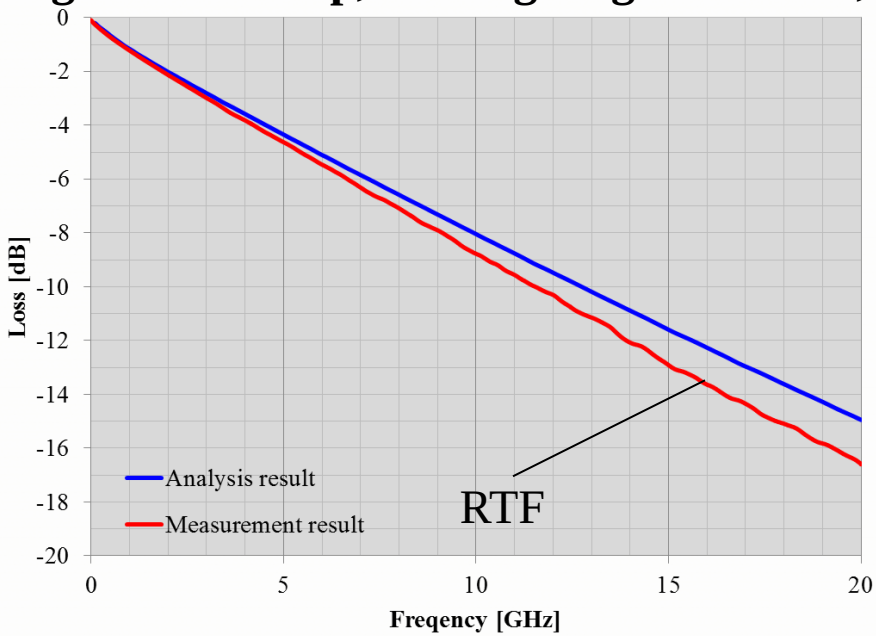
Plane view of wiring trace in HFSS



- This figure shows plane view of wiring trace in HFSS model.
- The distance between the edge of the wiring and the wiring model was 3mm.

Comparison with measured S21 and HFSS result

Structure : Single-ended strip, Wiring length: 200mm, Dielectric : FR-4



- The measured S21 includes the scattering loss caused by surface roughness of the conductor.
- On the other hand, simulated S21 with HFSS does not include the scattering loss due to surface roughness. The simulated model by HFSS was assumed to be completely smooth surface.
- Then, the difference of S21 between measured S21 and HFSS result shows the amount of scattering loss, which was estimated to be approximately 1.5 dB at 20 GHz.

How to decompose the total loss into loss factors?

- The entire loss is represented by following equation.

$$Loss = Loss_D + Loss_C = Af + B\sqrt{f}$$

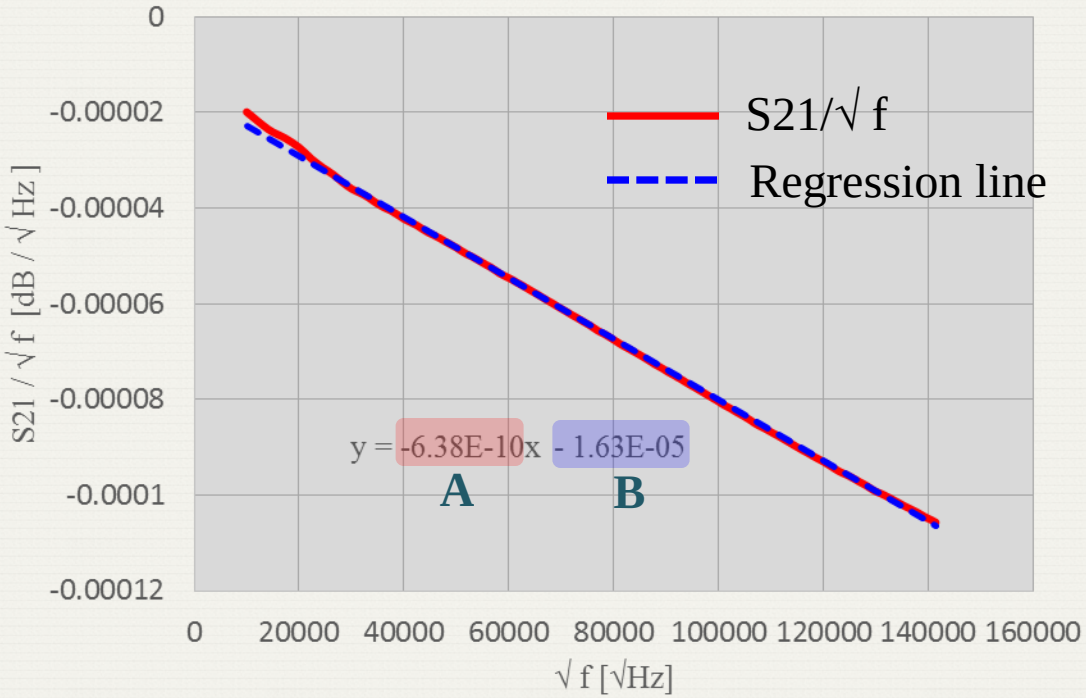
where, **A** and **B** are proportional constant of each loss.

- The amount of each loss factor can be obtained by determining the values of A and B. The following equation is the result by dividing the entire loss with the square root of the frequency.

$$\frac{Loss}{\sqrt{f}} = A\sqrt{f} + B$$

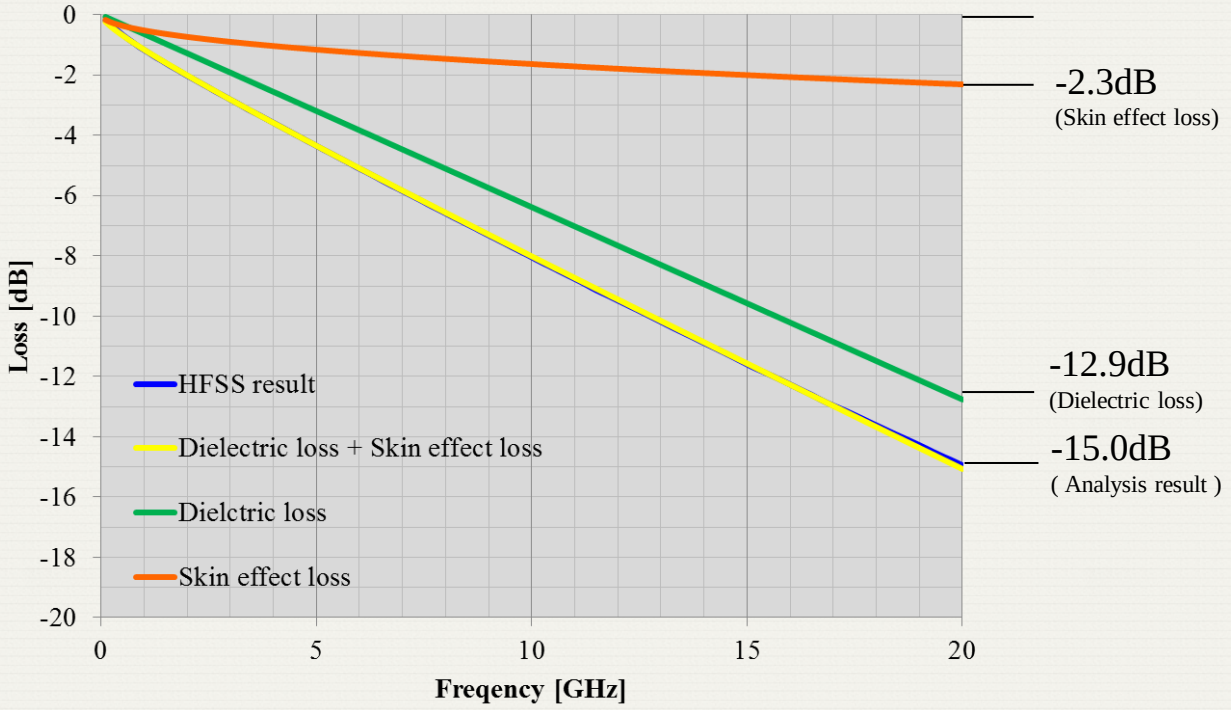
- The values of the constant A and B were obtained from S21 dividing the square root of the frequency. The constant A is the slope and the constant B is the intercept of the graph.

S21/$\sqrt{f}$ and regression line



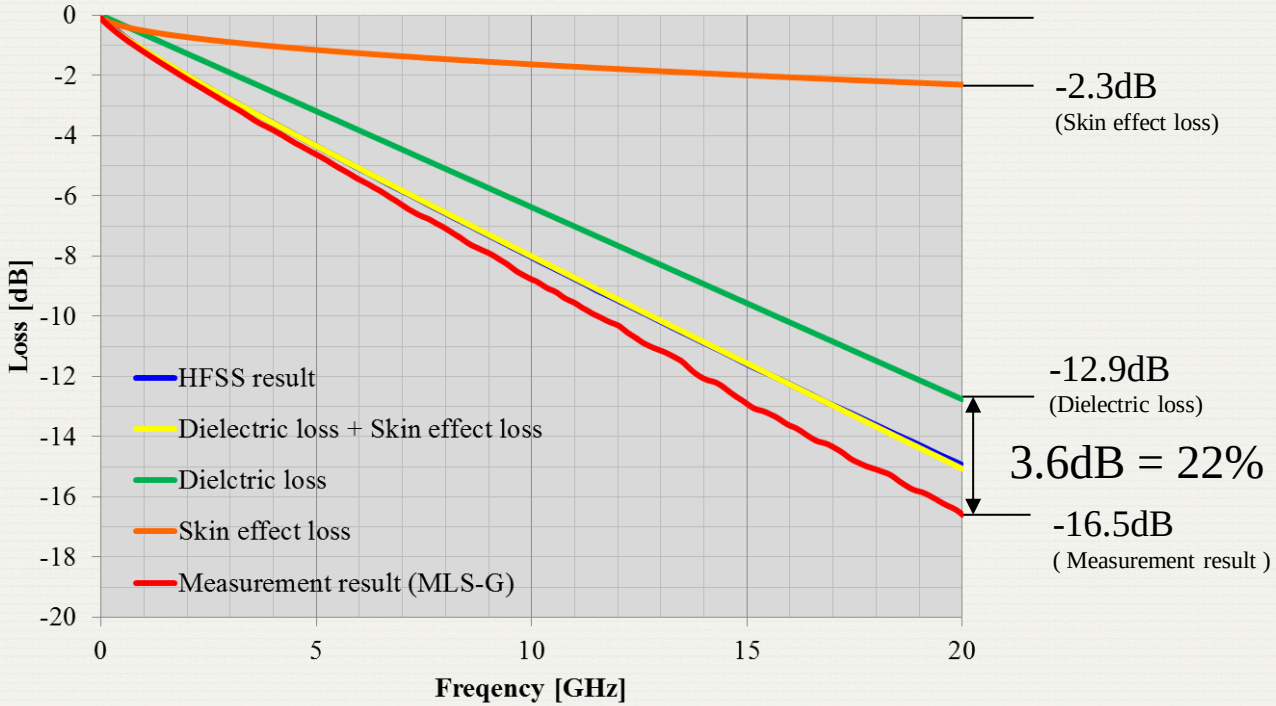
- The blue line shows plots of the S21 divided by the square root of the frequency for FR-4 and red line shows the regression line of that.
- The constant A and B were obtained from the regression line.

Total loss and loss factors for FR-4



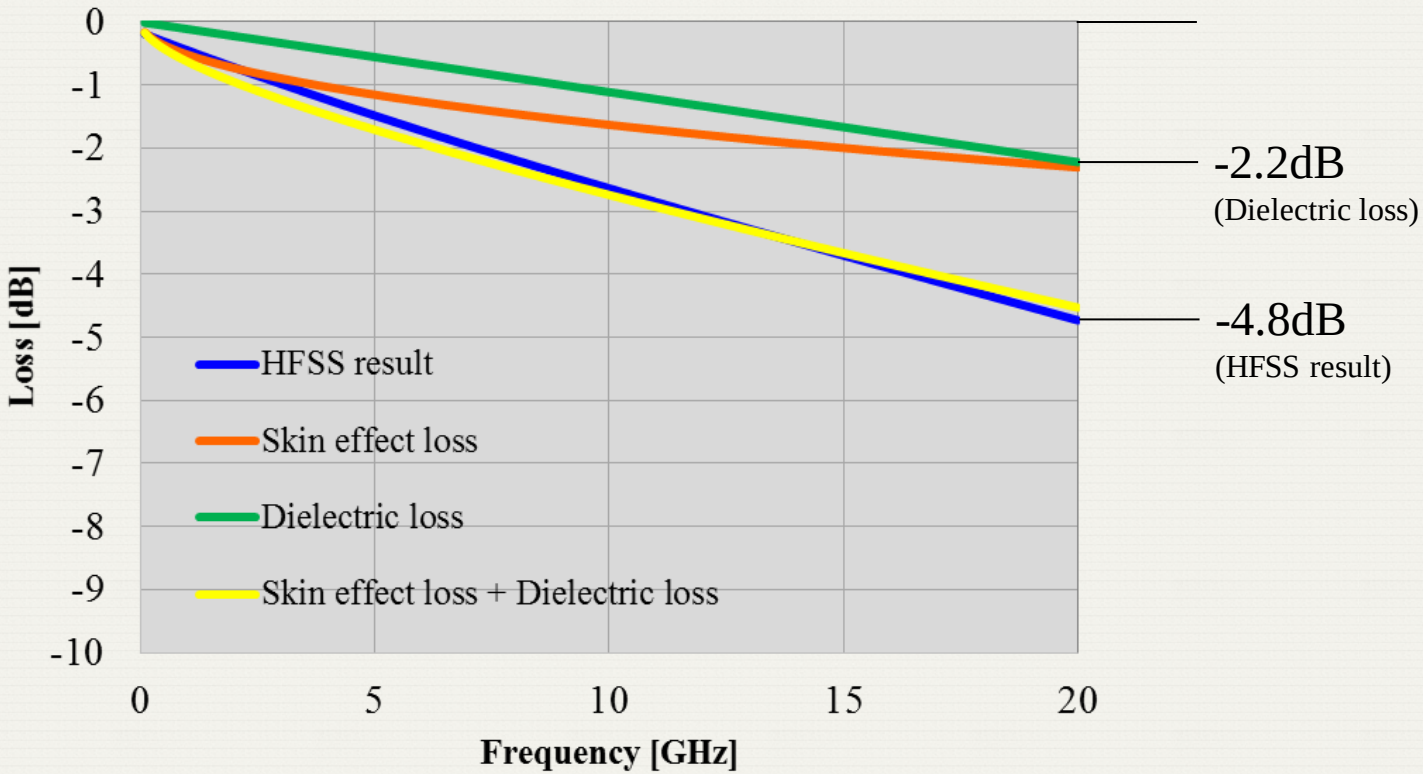
- This figure shows the decomposed each loss factors of simulated result with HFSS.
- The orange line indicates the conductor loss due to only skin effect.
- On the other hand, the green line shows the dielectric loss.

Total loss and decomposed loss factors for FR-4



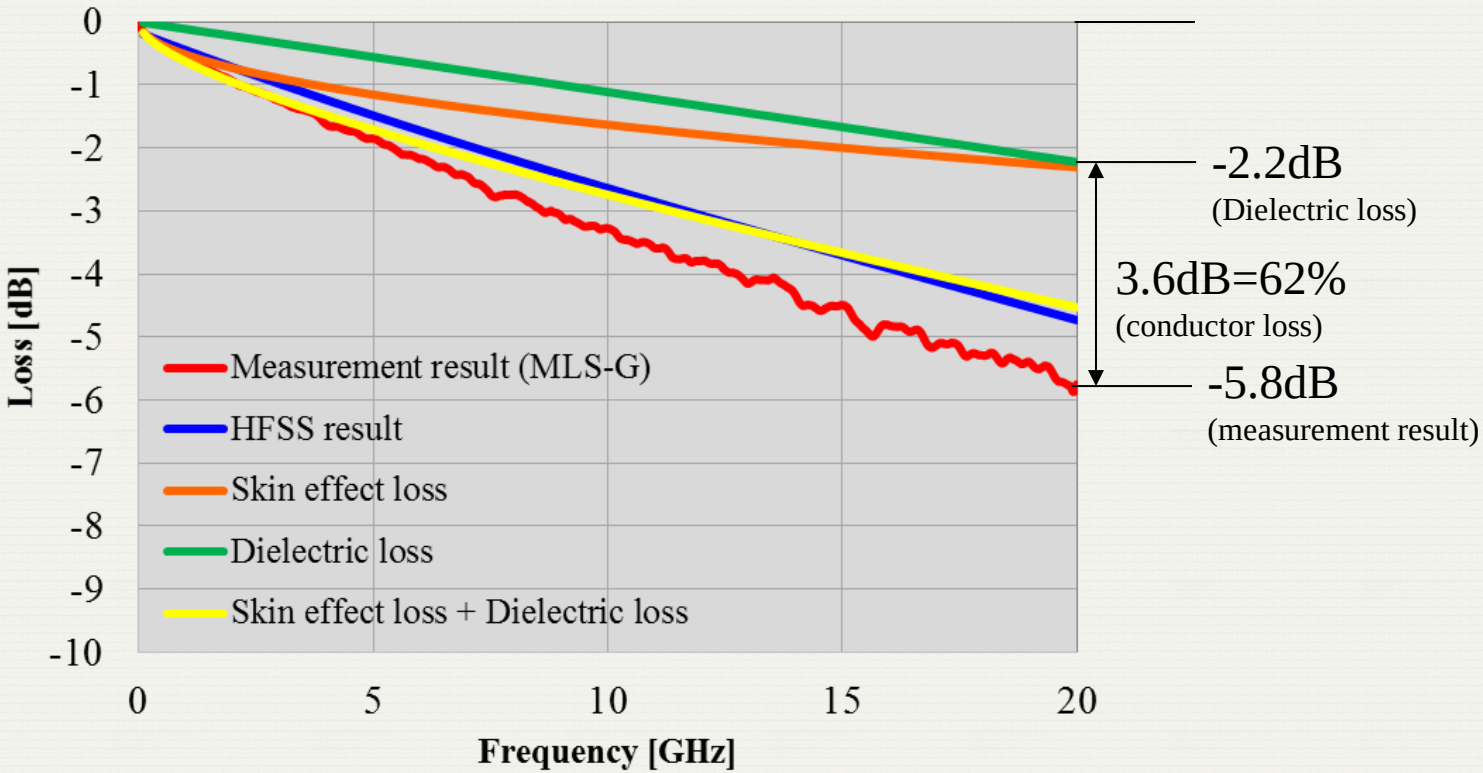
- The red trace shows the measured result for foil MLS-G(RTF).
- The sum of two loss factors decomposed from measured result was well coincident with the simulated result by HFSS.
- The estimated value of conductor loss was about 3.6 dB at 20 GHz. It corresponds to about 22% for total loss at 20 GHz.

Total loss and decomposed loss factors for dielectric G1



- This figure shows the decomposed each loss factors in case of dielectric G1.
- Each loss factor was decomposed from total loss which agreed well with simulated result.
- In comparison with FR-4, the dielectric loss was reduced considerably, then the percentage of the skin effect loss was relatively increased.

Comparison with measurement S21 and each loss factors

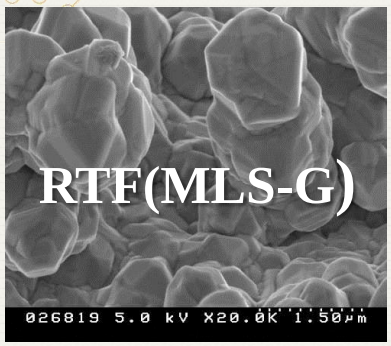


- The measurement result of the foil MLS-G was compared with the simulated result of HFSS.
- The difference between measured S21 and HFSS result was the scattering loss.
- The percentage of conductor loss for total loss was about 62%.
- From this, it is confirmed that reducing the conductor loss becomes more important when low dielectric constant materials were used.

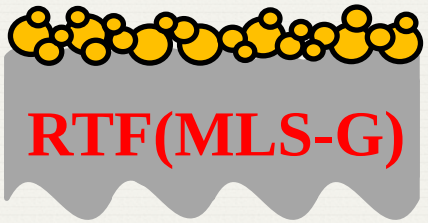
Agenda

1. Introduction and research purpose
2. Signal transmission loss
3. Configuration of the evaluation board
4. Measurement and simulated results
5. Loss and surface roughness of copper foil
6. Summary

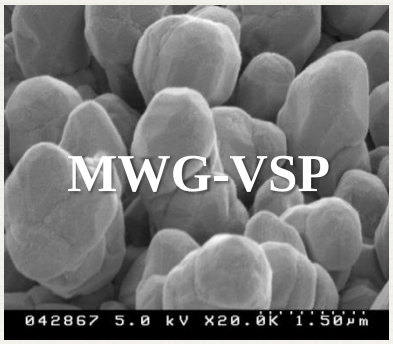
Surface roughnesses of copper foils



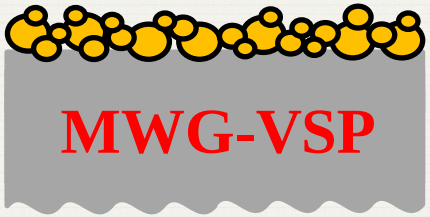
Large tangled Cu



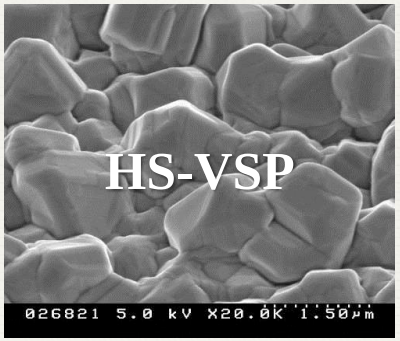
Resist side : Large waving



Large tangled Cu

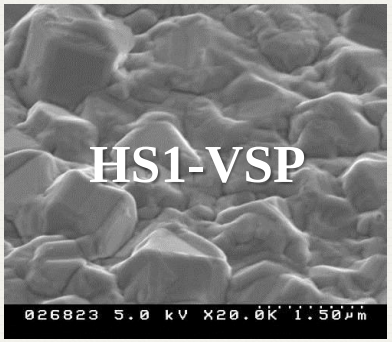


Resist side : Little waving

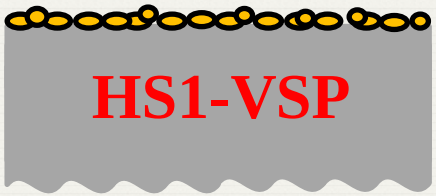


Small tangled Cu

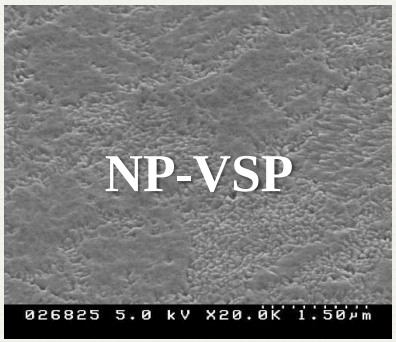
Resist side : small waving



Very small tangled Cu:



Resist side : small waving



No tangled Cu
(Primer was used instead of tangles.)

Resist side : small waving

- These figures show SEM image and schematic image of each copper foil.

Surface roughnesses on the mat face

Rz : average of ten points on the surface

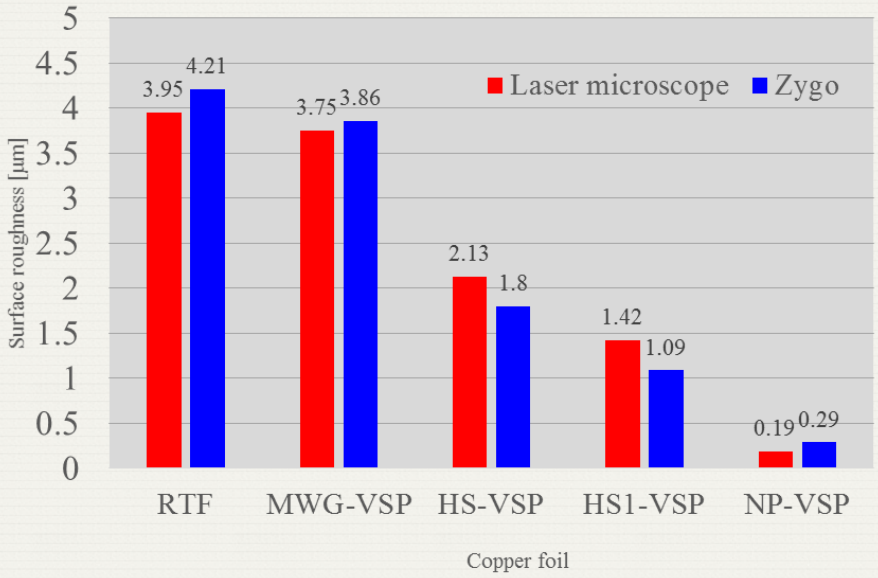
[μ m]

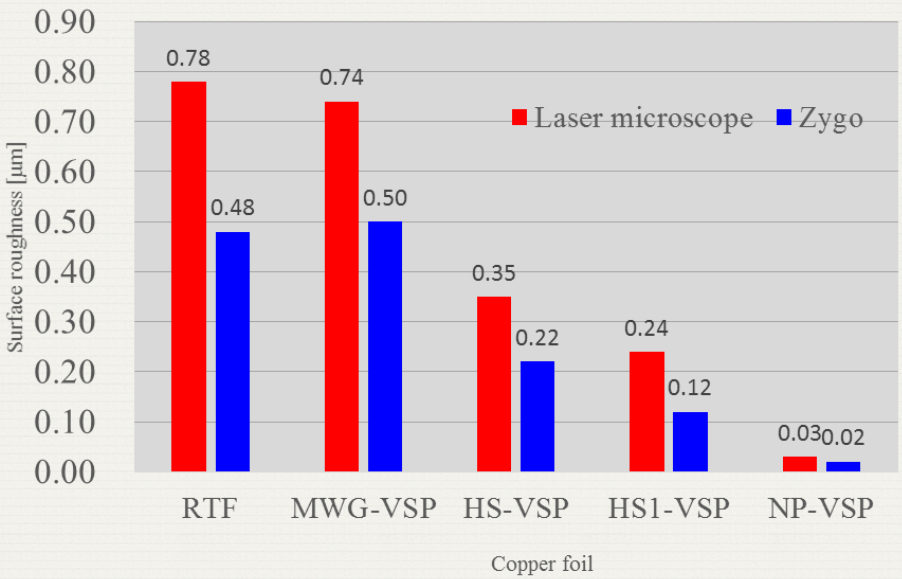
copper foil	Laser microscope	Zygo
RTF	3.95	4.21
MWG-VSP	3.75	3.86
HS-VSP	2.13	1.80
HS1-VSP	1.42	1.09
NP-VSP	0.19	0.29

Rq : root-mean-square of roughnesses

[μ m]

copper foil	Laser microscope	Zygo
RTF	2.49	3.13
MWG-VSP	0.99	1.21
HS-VSP	0.97	1.23
HS1-VSP	1.06	0.99
NP-VSP	1.25	1.15





◆ Surface roughness of each copper foils were RTF > MWG-VSP > HS-VSP > NP-VSP.

Surface roughnesses on the shiny face

Rz : average of ten points on the surface

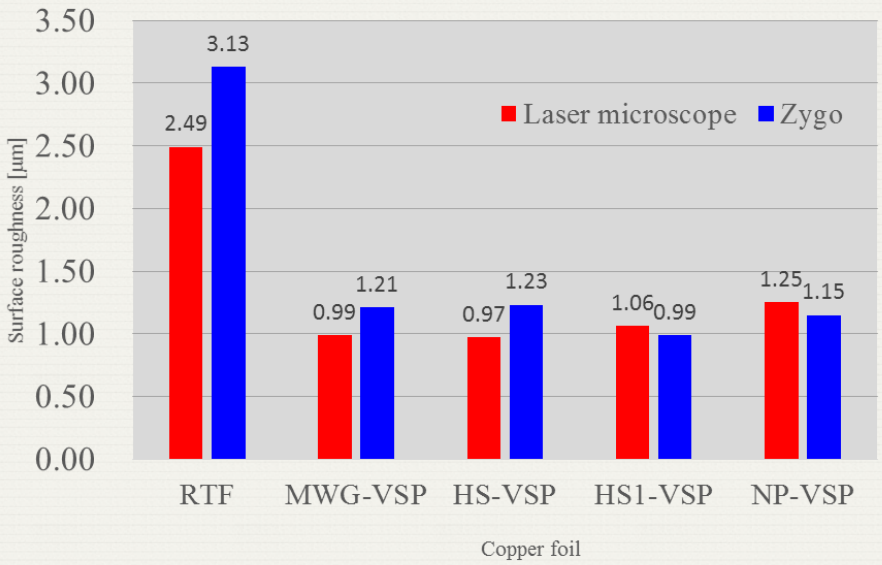
[μ m]

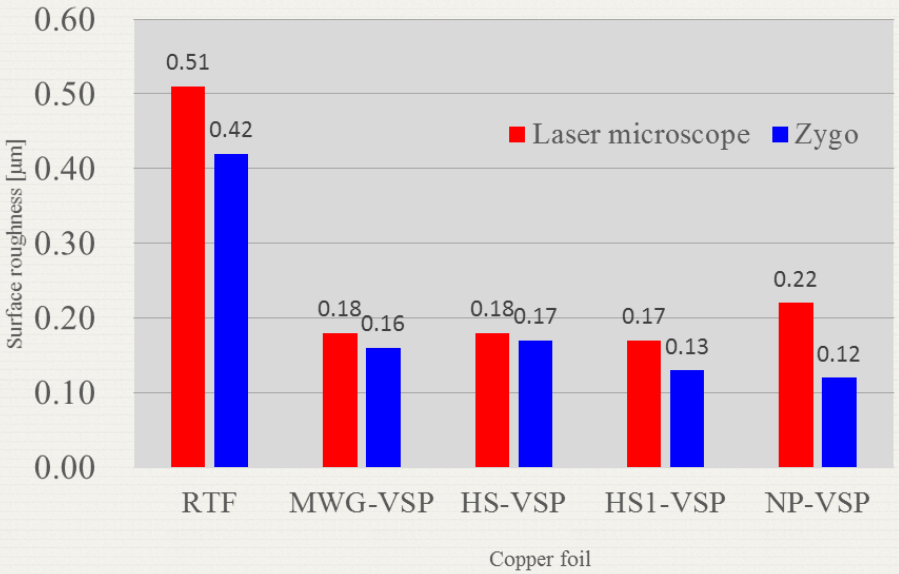
copper foil	Laser microscope	Zygo
RTF	2.49	3.13
MWG-VSP	0.99	1.21
HS-VSP	0.97	1.23
HS1-VSP	1.06	0.99
NP-VSP	1.25	1.15

Rq : root-mean-square of roughnesses

[μ m]

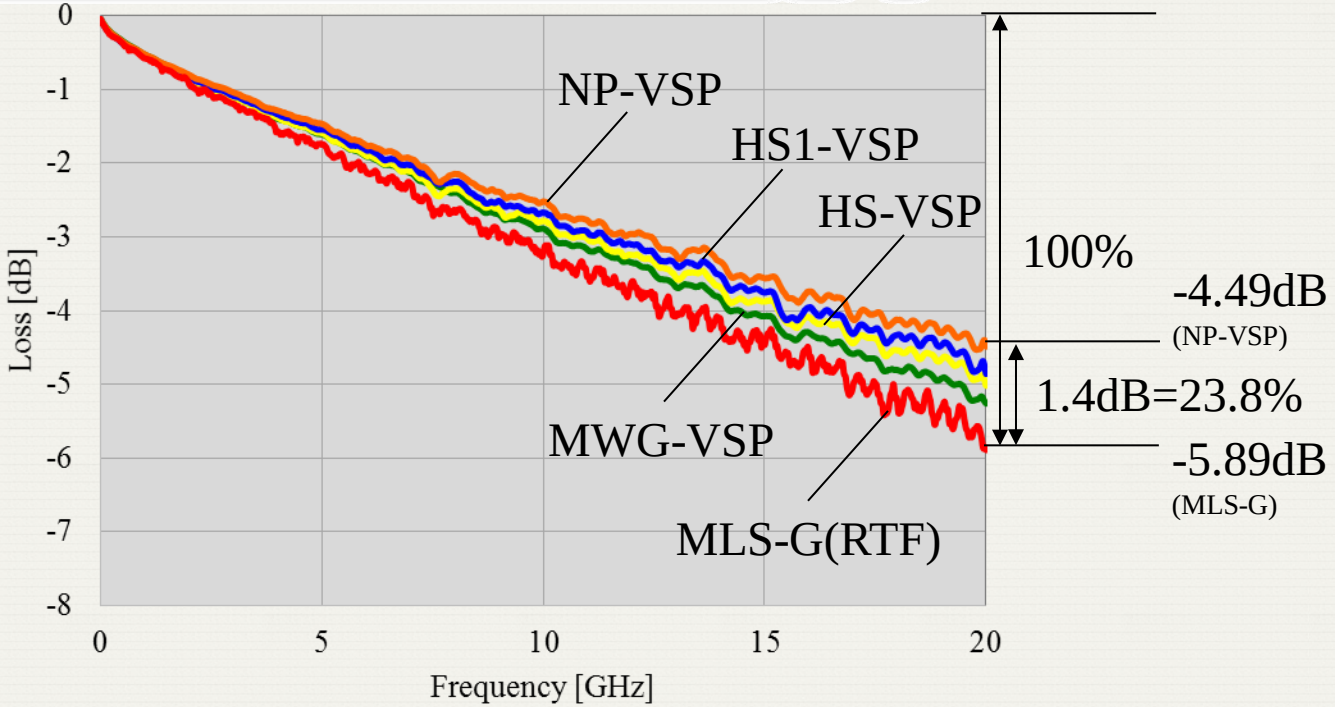
copper foil	Laser microscope	Zygo
RTF	0.51	0.42
MWG-VSP	0.18	0.16
HS-VSP	0.18	0.17
HS1-VSP	0.17	0.13
NP-VSP	0.22	0.12





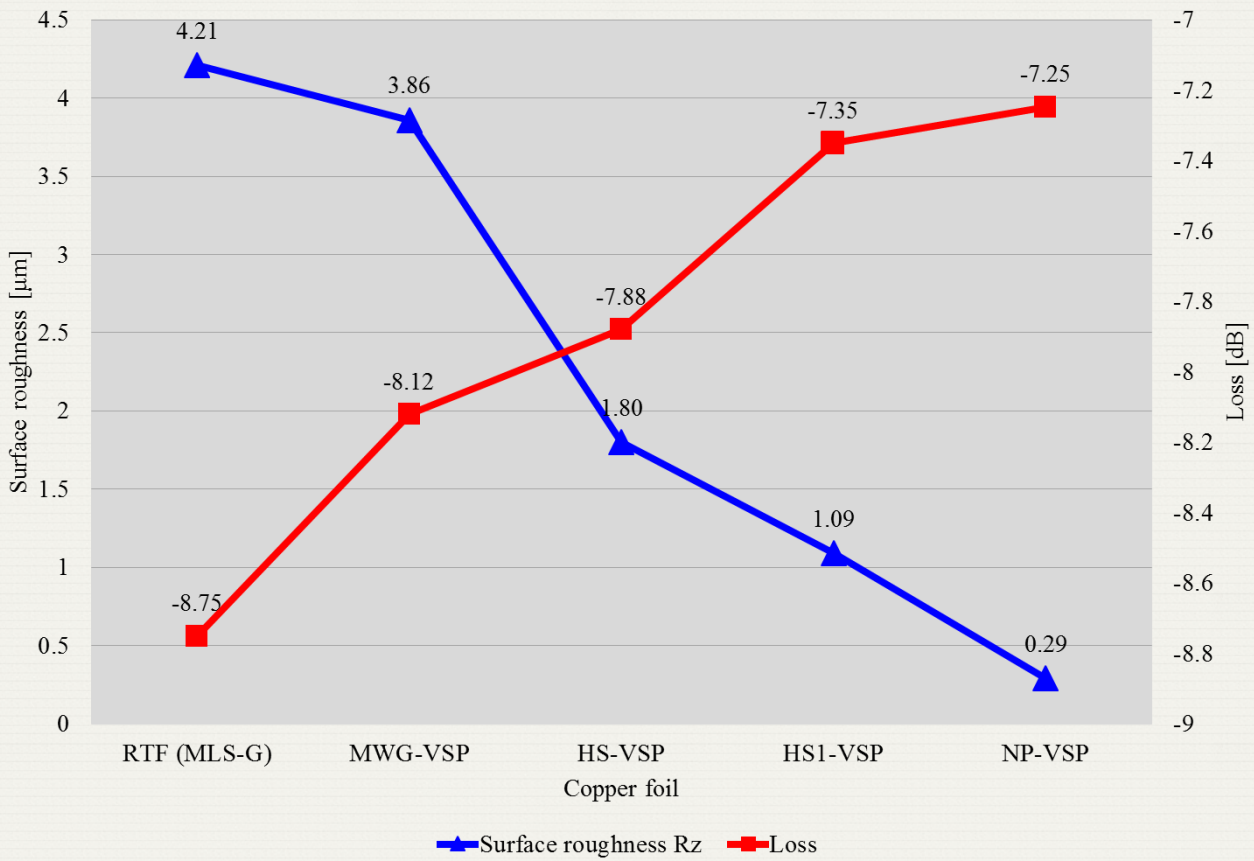
◆ The surface roughnesses on the shiny face of each copper foils were RTF>MWG-VSP≒HS-VSP≒HS1-VSP≒NP-VSP.

The loss difference due to surface roughness of copper foils



- When the foil MLS-G(RTF) was compared with the foil NP-VSP, the signal loss of the foil NP-VSP was reduced by approximately 23.8% of the signal loss of the foil MLS-G.
- This shows that the usage of copper foil with low surface roughness is effective to reduce the scattering loss of the conductor.

Relationships between signal loss and surface roughness



- This figure shows the relationship between loss and surface roughness of each copper foils.
- It was confirmed that as the roughness became smaller, the loss was decreased.

Summary

1) In this research, S parameters of various types of transmission lines structures on an evaluation board were measured and simulated in detail. Furthermore, several types of surface roughnesses of copper conductors have been examined.

2) First, purely total signal loss for the stripline structure has been obtained by deducting the loss due to via structure. Next, the pure total loss has been decomposed into the conductor loss due to skin effect and the dielectric loss along with HFSS model. Finally, the amount of scattering loss due to surface roughness has been extracted.

3)Signal loss has been greatly reduced by adopting low dielectric constant material. It has been confirmed that the signal loss of dielectric G1 was reduced by about 68% compared with the signal loss of FR-4.

4) Low roughness copper foil has been found to be effective in reducing the overall loss when low dielectric material is used as dielectric. When the foil A was compared with the foil D, signal loss was reduced by about 1.4 dB, at 20 GHz. This corresponds to approximately 23.8% reduction in the conductor loss.

Thank you for listening.