Novel CCL Based on New Fluoropolymer Exhibits Extremely Low Loss Characteristics and New Evaluation Method for Separating Dielectric and Conductive Losses

Kazuhiko Niwano[1], Manuel Reyes[1], Mitsufumi Ono[2], Koji Ikawa[1]
[1]Asahi Glass Co., Ltd., Kanagawa, Japan
[2] Asahi Glass Co., Ltd., Chiba, Japan

Abstract
We demonstrate here a novel CCL (Copper Clad Laminate), which exhibits an extremely low transmission loss at mm-wave band. The CCL, which we developed, is based on a new fluoropolymer with adhesive characteristics. In contrast to conventional PTFE, the adhesive fluoropolymer allows us to apply a wholly dry process for CCL fabrication, which contributes to environmental load reduction.

It is well known that the factor of transmission loss mainly consists of conductive loss and dielectric loss. However, in conventional CCL data sheets, only the loss tangent data at specific frequencies are disclosed. Neither the dielectric loss nor the whole transmission loss at the other frequencies is known. In order to minimize the transmission loss at mm-wave band, the quantitative analysis for those factors is essential.

We proposed the evaluation method, which can clarify not only the dielectric loss but also the conductive loss of CCL up to 110GHz. Several transmission lines with different impedance were measured and analyzed; the three different losses were discriminated in straightforward manner. Besides the evaluation method, a highly accurate measurement technique for low loss transmission line was achieved.

Using several kinds of surface roughness of copper foil, we made CCL test samples and evaluated the transmission loss by the above-mentioned method. Since the results indicated that the surface roughness of copper foil remarkably influenced the transmission loss, profile free copper foil was used for developed CCL. Due to the adhesive characteristics of new fluoropolymer, enough peeling strength was obtained without extra surface treatment.

Finally we benchmarked our developed CCL to the Rogers RT/duroid 5880, with the world’s lowest loss characteristics, and the result showed improved loss characteristics compared to RT/duroid 5880.

Introduction
In recent years, more applications in the mm-wave band, such as automotive radars, are being achieved. It is expected That this trend will continue. For PCB (printed circuit boards) to be used in these applications it is very important that they exhibit low loss at high frequencies.

To consider using PCBs in the mm-wave range, fluoropolymer CCL will be a good candidate, due to its extremely low loss characteristics. The PCB with very small loss tangent exhibits a very low dielectric loss. On the other hand, the conductive loss will be relatively large comparing to the dielectric loss, so its influence on the transmission loss will increase. Conductive loss is composed of the loss due to bulk conductivity, and the loss due to the conductor surface roughness. Particularly, the loss due to surface roughness increases in the high frequency range. In this situation, it is very useful to separate the transmission loss into dielectric, conductor and loss of surface roughness, since we can perceive directly the loss factors of a given substrate.

However, only the loss tangent at a specific frequency is disclosed in the conventional data sheet of commercially available PCB data related to the loss. Therefore, we needed to make the transmission lines and measure the transmission loss in order to learn the transmission loss at the frequency we need to use and the frequency response. Moreover, it is impossible to ascertain which substrate will present lower transmission loss using only conventional data sheets.

We measured CBCPW (Conductor Backed Co-Planer Waveguide), which is a much used transmission line in mm-wave band, and in this paper we propose the method to separate the transmission loss into dielectric loss (L_d), conductor loss (L_c) and roughness loss (L_r). One purpose is to use the separated loss factor for our developing new substrates, the other purpose is to propose the separating procedure to be able to judge and compare the loss factors of any substrate and also judge the merits and demerits of different candidates in the same manner.

Analytical calculation of transmission loss

First, we introduce the calculation method of transmission loss of CBCPW. The impedance of CBCPW (Z_{0cp}) is calculated by using quasi-static analysis based on the conformal mapping method [1], [2].

$$Z_{0cp} = \frac{60\pi}{\sqrt{\varepsilon_{re}}} \cdot \frac{1}{K(k_1)/K'(k_1) + K(k_6)/K'(k_6)} \qquad (1)$$

where ε_{re} is the effective dielectric constant and $K(*)$, $K'(*)$ are the elliptic integrals of the first kind and its complement, respectively. The frequency dispersion [3] and the effect of metallization thickness [4] are taken into consideration in equation (1).

Since the effect of conductor surface roughness is not considered in above calculation, we apply the equation, which is based on the ratio of the rms surface roughness (R_q) and the skin depth (δ), to the loss calculation. This equation is as follows [5],

$$L_r = L_c \cdot \frac{2}{\pi} \tan^{-1}\left[1.4 \cdot \left(\frac{R_q}{\delta}\right)^2\right] \qquad (2)$$

This equation was used for the Micro Stripline (MSL) originally, but we confirmed its validation for application to CBCPW, so it was adopted. The other equations of loss factor are referred to [1]. The input parameters, which are necessary to calculate transmission loss, are indicated on Figure 1. Over these parameters, the ways of the consideration of conductivity (σ_c) and surface roughness (R_q) are described in the next.

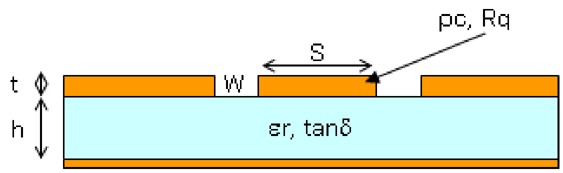
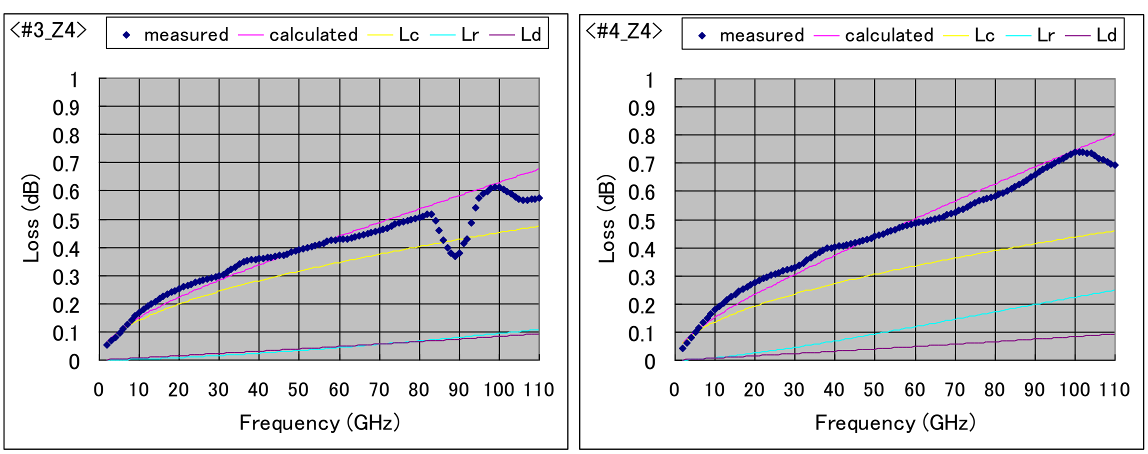


Figure 1 - Cross Section of CBCPW and Input Parameters for Transmission Loss Calculation

Plating is sometimes given to a conductor of PCB for antioxidation of Cu. Conductors which are different in the conductivity at that time will be laminated, but it is necessary to obtain the effective conductivity, which considered the skin effect, because a conductor with homogeneous conductivity is assumed in the loss calculation. So we derived the effective conductivity from calculating the distribution of current density in the cross section of CBCPW and the ratio of current density in each conductor using 3D EM simulator. Actually, Ni plating and Au flash plating were done in the measured transmission line, but in the calculation Au flash plating was neglect because it was very thin.

Considering the surface roughness we derived the effective roughness from the ratio of current density on the top and the bottom because the top and the bottom of surface roughness are different and it was considered that both of the roughnesses affect the transmission loss according to the ratio of the current density. Figure 2 shows the examples of measured and calculated results of the fluoropolymer CCL with the roughness of Cu foil (a) R_z=1.8um and (b) R_z =3.6um and overlaying the separating loss factors.



(a) Cu Foil Roughness of R_z=1.8um **(b) Cu Foil Roughness of R_z=3.6um**

Figure 2 - Measured and Calculated Results

(Calculated = Total Loss = $L_c + L_r + L_d$)

The CCL, shown in figure 2 (b), is used as Cu foil categorized in the low-profile class, but the roughness loss in the mm-wave band is relatively large. On the other hand, the CCL, shown figure2 (a), is used in the profile-free class Cu foil, and the roughness loss is the same level to the dielectric loss. Since the results indicated that the surface roughness of Cu foil remarkably influenced the transmission loss, profile free copper foil was used for development of the CCL.

Developing novel CCL

From the above mentioned considerations, we decided to develop the fluoropolymer, which can laminate Cu foil that is profile free (R_z is about 1um). And we developed the new fluoropolymer with adhesive characteristics so it can laminate profile-free Cu foil without special surface treatment. We have confirmed that its peel strength is more than 1kN/m. In contrast to conventional PTFE, the adhesive fluoropolymer allows us to apply a wholly dry process for CCL fabrication, which contributes to environmental load reduction and is expected to reduce the process cost due by eliminating the need for a wet process facility.

Transmission loss measurement

We measured the transmission lines on the network analyzer which was able to sweep continuously up to 110GHz using a probe head. With the measurement system, a highly accurate measurement technique for low loss transmission line was achieved.

The contact pads of transmission lines are CBCPW. MSL was also tried as an evaluation transmission line, but because of the transition of the line the influence of resonance is relatively large compared to the transmission loss in the high frequency range. So we choose CBCPW as the evaluation lines so as to eliminate the transitions. Ni plating and Au flash plating were done in the measured transmission line. Thru-reflect Line (TRL) calibration of the network analyzer was done with the measurement frequency range from 2 to 110 GHz. The length of measured lines is 8mm.

Several transmission lines with 8 different kinds of impedance were measured and analyzed up to 110GHz in order to separate the transmission loss into dielectric loss, conductor loss and roughness loss. Due to the mismatch with 50ohm, transmission loss exhibits the characteristics with ripple. In order to compare with each other, the ripple characteristics are corrected by matching with input and output impedance. After that, the measured data still show a minute ripple due to the discontinuities and time and/or temperature drifting characteristics of the measurement system. But the minute ripple is nonessential characteristics, so it is made smoothened mathematically. This smoothening is without loss of generality. The above-mentioned data processing was performed and the transmission losses of each substrate and impedance were obtained.

Repeatability of the measurement system

Now we confirm the repeatability of the measurement system. A transmission line is measured 4 times and the difference between the raw data of the representative sample S21 is indicated in Figure 3. The repeatability including above-mentioned minute ripple is less than +/- 0.05dB in the whole frequency range.

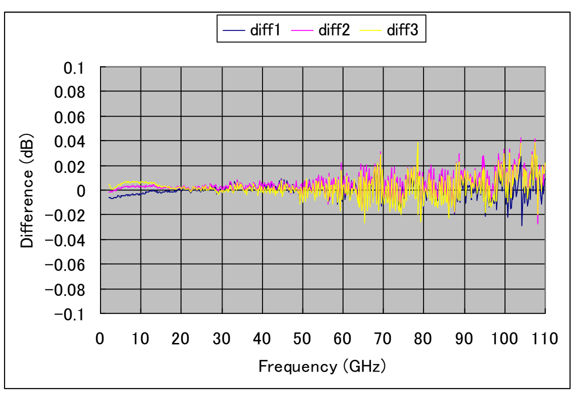


Figure 3 - Repeatability

In this example, the repeatability is about +/- 0.02dB in the 76GHz, which is the frequency of automotive mm-wave radar. By executing the above-mentioned smoothing, it is possible to reduce the error. On the other hand, since the measuring transmission loss at that frequency is about 0.5dB, it would appear that the measurement system possess enough precision for comparing merits and demerits between the substrates without additional consideration.

Measurement results and benchmarking

The benchmarked substrates in this paper and the each parameter are indicated in Table 1.

Table 1 - Benchmarked Substrates and their parameters

Substrate #	εr	tanδ	h(mm)	t(um)	Rq(um)	Cu foil
#1	2.2	0.0015	0.25	29	0.37	low profile
#2	2.2	0.0011	0.25	30	0.36	profile free
#3	2.2	0.0011	0.25	27	0.46	low profile
#4	2.2	0.0011	0.25	25	0.77	general
#5	2.2	0.0009	0.25	30.5	0.40	unknown
#6	2.5	0.0018	0.31	29	0.45	unknown

The substrates #1 to #4 are new fluoropolymer CCL, #5 is the Rogers RT/duroid 5880 and #6 is the major fluoropolymer CCL used in Japan at this time. The rms (root mean squared) surface roughness (R_q) is the effective roughness, mentioned before. The top-side surface roughness was directly measured by a stylus profilometer; the bottom-side of roughness was measured on dielectric surface after etching Cu foil.

Each substrate has 8 kinds of characteristic impedance (Z1, Z2, … , Z8) of transmission line in descending order. We benchmarked the transmission loss of average of 8 lines. The average transmission losses in the 40 and 76GHz are indicated in Table 2.

Table 2 - Benchmarking

Substrate #	Transmission Loss (dB/mm)	
	@40GHz	@76GHz
#1	0.0495	0.0690
#2	0.0472	0.0630
#3	0.0467	0.0635
#4	0.0514	0.0728
#5	0.0470	0.0652
#6	0.0569	0.0903

It is found that the transmission loss of our developed CCL #2 is the same level or less than #5 Rogers RT/duroid 5880.

Separating transmission loss into dielectric and conductive loss

From measured transmission losses, we executed the loss separating procedure we proposed in this paper, and compared the loss factors. First, we chose 3 kinds of impedance Z1, Z4, Z8 from 6 kinds of substrate. For the all selected transmission loss, we fitted the conductivity as a parameter, and found the conductivity, which was most suitable ($\square_{opt}$). The reason that this conductivity is adopted as a fitting parameter is because the conductivity of Cu foil or Ni plating are usually worse than ideal bulk conductivity or there exists a conductor loss factor due to imperfection of pattern etching all of which are difficult to consider in calculations. On the other hand, the reason we use a single conductivity in calculation for all substrates compared at this time is because all the substrate see the same condition in plating or etching, so the conductivity must be the same. When there is a difference in the surface roughness of course, the conductivity is different, but we consider in calculations R_q separately (the surface roughness) and so the conductivity, except for roughness, must be the same.

The result of the fitting of the conductivity is shown in Figure 4. "All" in the figure is the conductivity we fit to all substrates described by the above process and the respective substrates are the conductivity we fit to impedance Z4. Further, fitting was executed to data in the 2-80GHz range this time because there is resonance at more than 80 GHz. Using $\square_{opt}$, we separated transmission losses into the loss factors and they are indicated in Figure 5. And the loss factors for each substrate are indicated in Figure 6.

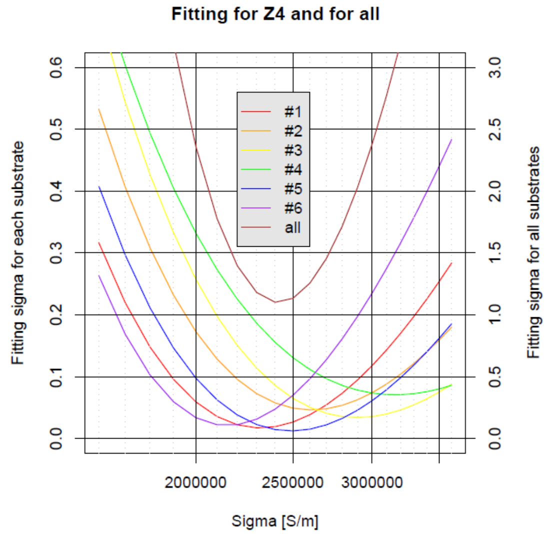
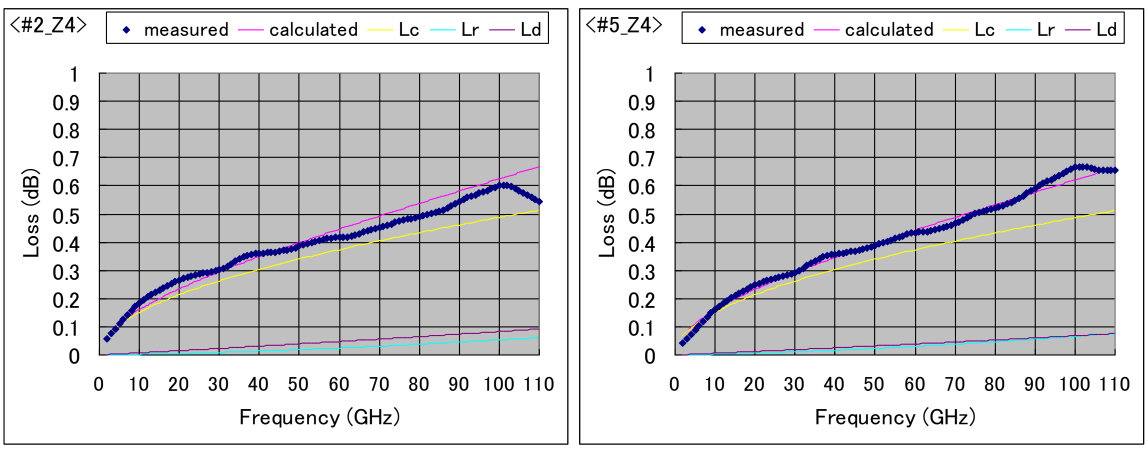


Figure 4 - Fitting Sigma



(a) #2, Z4 **(b)#5, Z4**

Figure 5 - Separating Transmission Loss

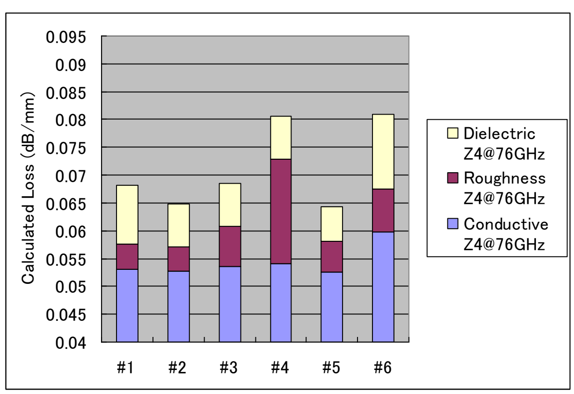


Figure 6 - Calculated Loss Components of Each Substrate of Z4

In Figure 6, in comparison with competitor #5, #2 is small in the roughness loss, but is large in the dielectric loss so the total loss is almost same level. This component plot clarifies the merits and demerits of substrates. Moreover, to compare between #2, #3 and #4, the roughness shows the influence which gives it to the whole transmission loss clearly. Therefore it is very useful to separate loss factors and this separating procedure is expected to allow us to judge and compare the loss factors of any substrate and also judge the merits and demerits of different candidates in the same manner.

Finally, about the fitting, we would like to confirm the matching. The frequency response of difference between measured and calculated result for all substrates and 3 kinds of impedance are indicated in Figure 7.

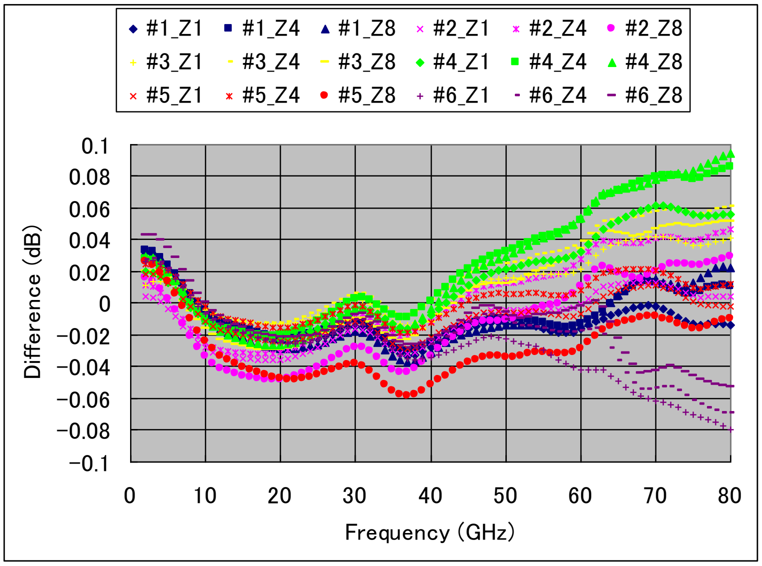


Figure 7 - Difference between Measured and Calculated Loss

It is found that the difference at 80GHz is about +/- 0.08dB/8mm. Therefore, since the total loss at 80GHz is about 0.5dB/8mm, there is an error of about 15%. But, the trend of the difference is the same in each substrate. The reason is believed to be because in the calculation the frequency dispersion of the permittivity is not applied. So to apply dispersion to the permittivity is to be part of future work.

Conclusion

We have proposed an evaluation method which can clarify not only the dielectric loss but also the conductor loss and roughness loss of CCL up to 110GHz.

The impedance of CBCPW (Z_{0cp}) is calculated by using quasi-static analysis based on the conformal mapping method. Moreover we synthesized the effect of dispersion of transmission line, metallization thickness and roughness for CBCPW and then separated the transmission loss into the dielectric, conductor and roughness losses.

We have found that it is very useful to separate loss factors and this separating procedure has allowed us to judge and compare the loss factors of any substrate and also judge the merits and demerits of different candidates in the same manner.

With this procedure we benchmarked our developed CCL and found that our new system (CCL #2), when laminated profile-free Cu foil, exhibits the a transmission loss level equal to or less than the CCL presently judged to exhibit the world lowest loss characteristic.

Reference

[1] K. C. Gupta, Ramesh Garg, Inder Bahl and Prakash Bhartia, *Microstrip Lines and Slotlines*, Artech House, Inc., 1996.

[2] Ghione, G. and C. Naldi, “Parameters of Coplanar Waveguides with Lower Ground Plane,” *Electron. Lett.*, Vol. 19, 1983, pp. 734-735.

[3] Hasnain G., et al., “Dispersion of Picosecond Pulses in Coplanar Transmission Lines,” *IEEE Trans.*, Vol. MTT-34, 1986, pp.738-741.

[4] Kitazawa T., et al., “A Coplanar Waveguide with Thick Metal-Coating,” *IEEE Trans.*, Vol. MTT-24, 1976, pp.604-608.

[5] Goldfarb, Marc E., “Losses in GaAs Microstrip,” *1990 IEEE MTT-S International Microwave Symposium Digest*, pp. 563-565.

Novel CCL Based on New Fluoropolymer Exhibits Extremely Low Loss Characteristics and New Evaluation Method for Separating Dielectric and Conductive Losses

Kazuhiko Niwano[1], Manuel Reyes[1],
Mitsufumi Ono[2], Koji Ikawa[1]

[1]Asahi Glass Co., Ltd., Kanagawa, Japan

[2] Asahi Glass Co., Ltd., Chiba, Japan

AGC

Overview

- Motivations
- Analytical calculation
- Loss separating approach
- Validity of the calculation
- Benchmarking
- Summary

Motivations

- Circuit designers
  - don't know how much the transmission loss in a desired frequency is from the conventional CCL data sheets.
- PCB designers
  - don't know which factor is affected how much in the transmission loss in an assumed frequency.

Motivations

- It's very useful to understand a frequency response of each loss factor of some substrates.

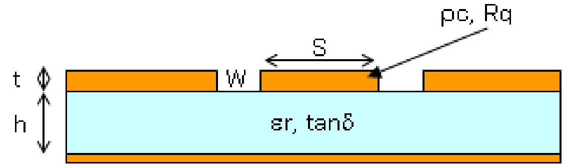
➔We propose an evaluation method, which can clarify the three kinds of loss factors and its frequency response.

Analytical calculation

Impedance of CBCPW*

*Conductor Backed CoPlanar Waveguide

- Cross Section of CBCPW



- Quasi-static analysis based on the conformal mapping method

$$Z_{0cp} = \frac{60\pi}{\sqrt{\varepsilon_{re}}} \cdot \frac{1}{K(k_1)/K'(k_1) + K(k_6)/K'(k_6)} \qquad (1)$$

- Effect of metallization thickness

$$S_e = S + \Delta, W_e = W - \Delta \qquad (2)$$

$$\Delta = (1.25t/\pi) \cdot [1 + \ln(4\pi S/t)] \qquad (3)$$

Impedance of CBCPW

- Frequency dispersion

$$\sqrt{\varepsilon_{re}(f)} = \sqrt{\varepsilon_{re}(0)} + \frac{\sqrt{\varepsilon_r} - \sqrt{\varepsilon_{re}(0)}}{1 + G(f / f_{TE})^{-1.8}} \qquad (4)$$

- Z_{0cp} can be derived from substituting (4) in (1)

Transmission loss of CBCPW

- Effect of surface roughness

$$L_r = L_c \cdot \frac{2}{\pi} \tan^{-1}\left[1.4 \cdot \left(\frac{R_q}{\delta}\right)^2\right] \qquad (5)$$

R_q : the rms conductor surface roughness
δ : the skin depth

- Conductor loss

$$L_c = 4.88 \times 10^{-4} \cdot R_s \varepsilon_{re} Z_{0cp} \frac{P'}{\pi W}\left(1 + \frac{S}{W}\right) \cdot \left\{ \frac{1 + 1.25t/\pi S + (1.25/\pi)\ln(4\pi S/t)}{\left[2 + S/W - (1.25t/\pi W)(1 + \ln(4\pi S/t))\right]^2} \right\} \qquad (6)$$

- Dielectric loss

$$L_d = 2.73 \frac{\varepsilon_r}{\sqrt{\varepsilon_{re}}} \frac{\varepsilon_{re} - 1}{\varepsilon_r - 1} \frac{\tan\delta}{\lambda_0} \qquad (7)$$

Loss separating approach

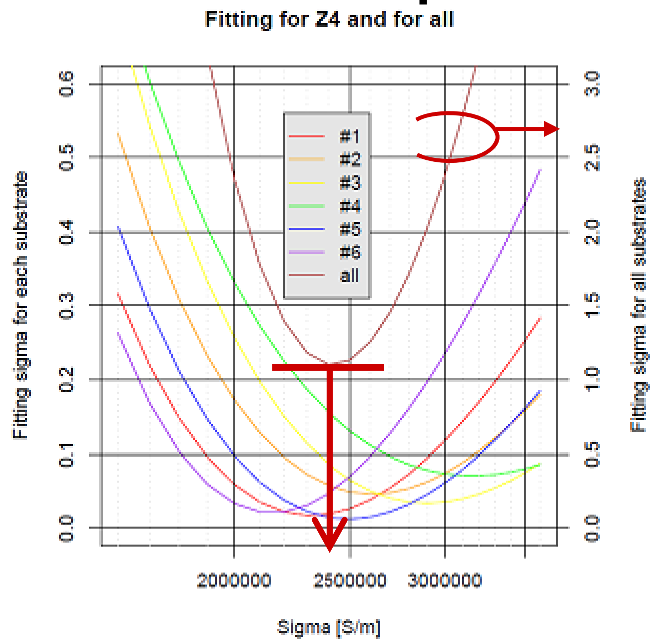
Evaluated substrates

Substrate #	εr	$\tan\delta$	h(mm)	t(um)	Rq(um)	Cu foil
#1	2.2	0.0015	0.25	29	0.37	low profile
#2	2.2	0.0011	0.25	30	0.36	profile free
#3	2.2	0.0011	0.25	27	0.46	low profile
#4	2.2	0.0011	0.25	25	0.77	general
#5	2.2	0.0009	0.25	30.5	0.40	unknown
#6	2.5	0.0018	0.31	29	0.45	unknown

- #1 to #4 are our new developing fluoropolymer CCLs
- #5 is the Rogers RT/duroid 5880
- #6 is the major fluoropolymer CCL in Japan.
- For all, we designed transmission lines with Z_c=45~55ohm (8 kinds of Z_c, named Z1-8 in descending order) , L=8mm

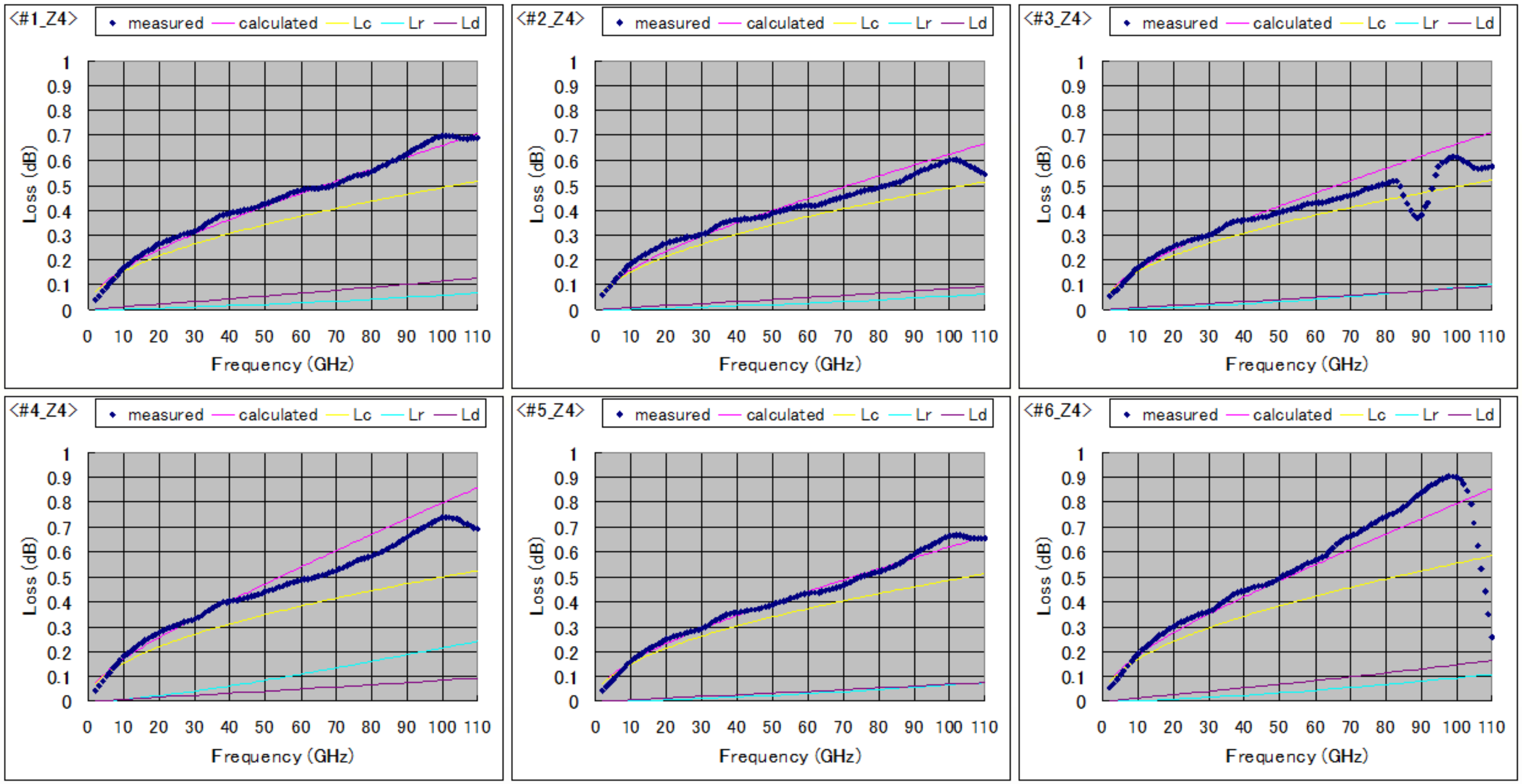
Loss separating approach

- Fitting with σ as a parameter



- Using optimum σ for Z4(≈50ohm) of #1~6, we derived the separated loss factors

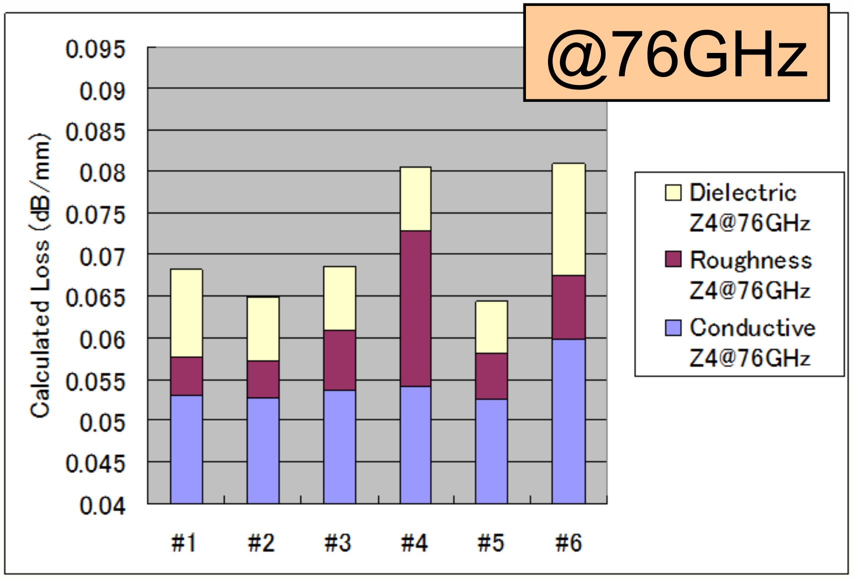
Separated loss factors w/ meas.



- σ_{opt} = 2.43E6 [S/m]
- Fitting in frequency range up to 80GHz

Loss factors of each substrate

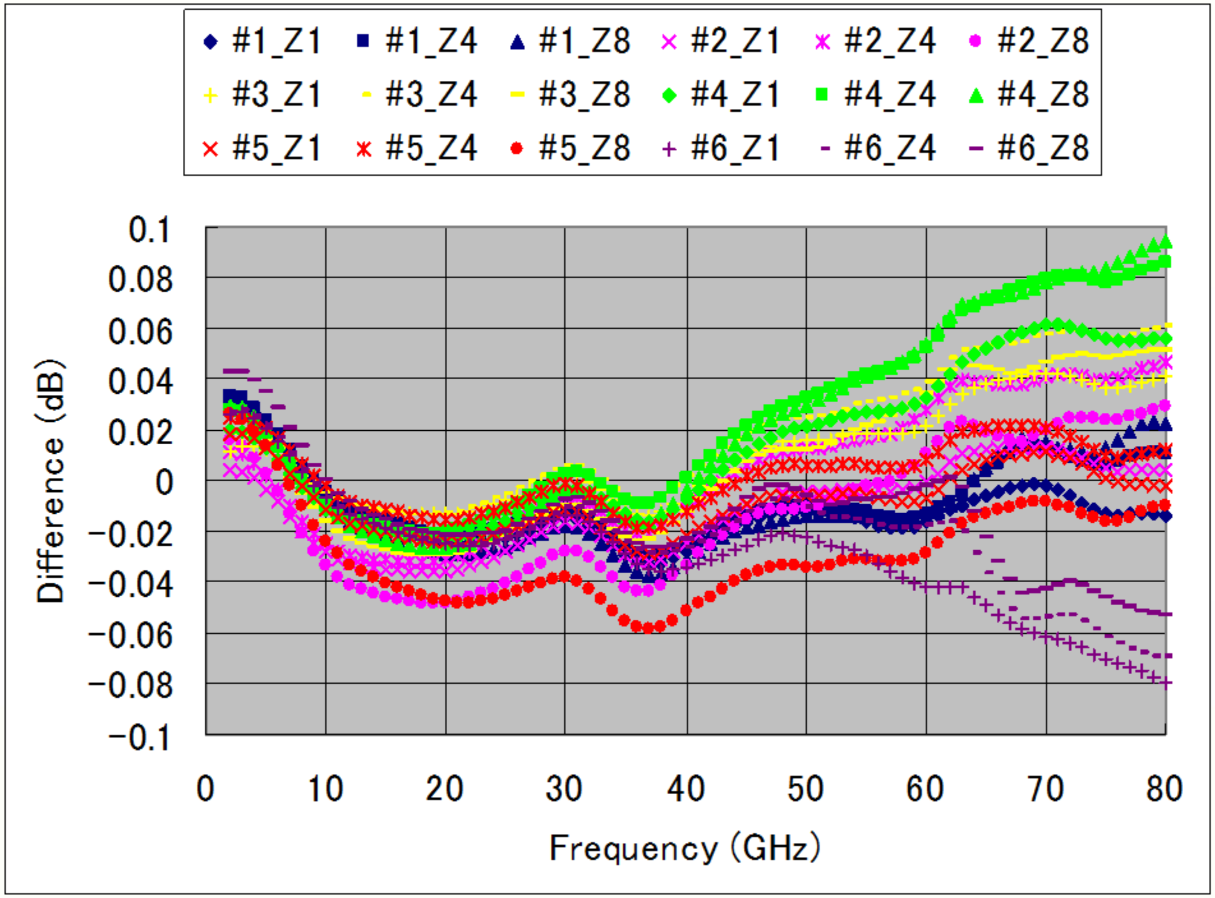
- Comparison of #2 with #5
  - Lr : #2＜#5, Ld : #2＞#5
  - Same level in total loss
- Comparison between #2, #3 and #4
  - Rougher conductor, the Larger Lr
  - Ratio of Lr in total loss
    - #2 : 7%
    - #3 : 11%
    - #4 : 23%



Validity of the calculation

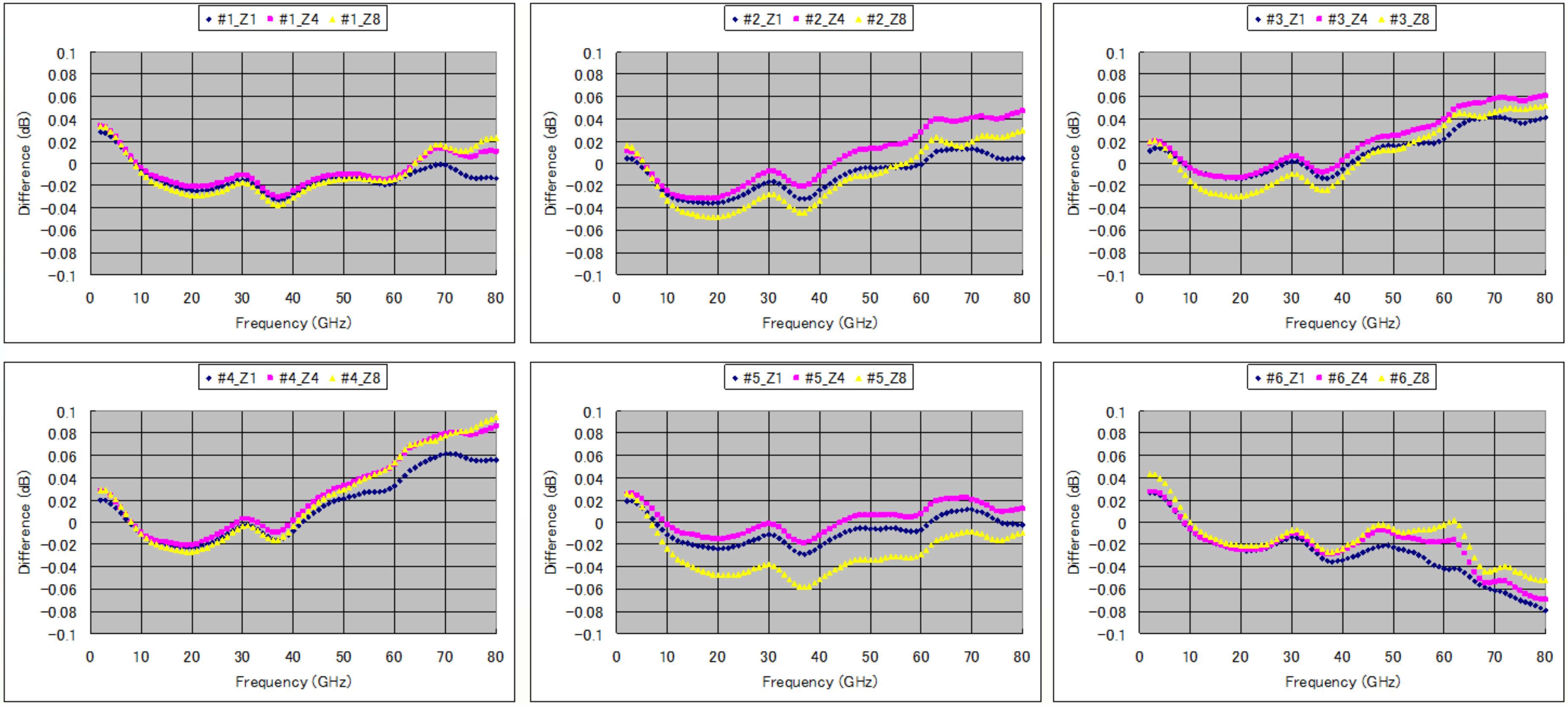
Difference bet. meas. & calc.

- Diff = Calc. – Meas.



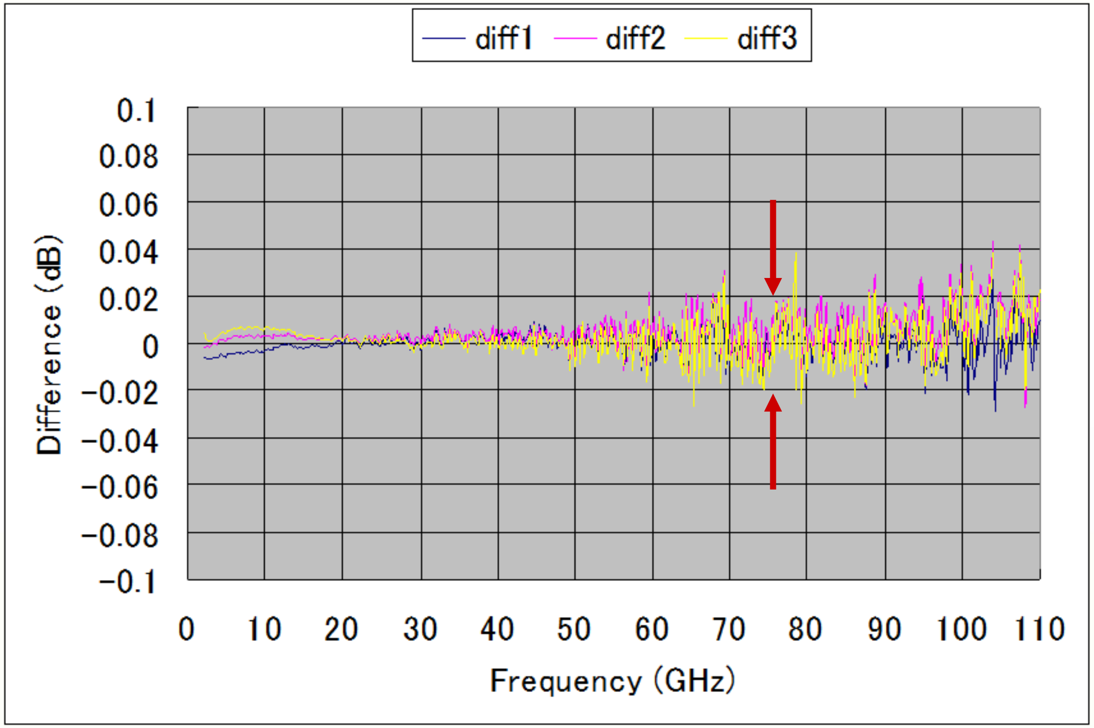
Individual difference

- There are trends depending on substrates



Measurement accuracy

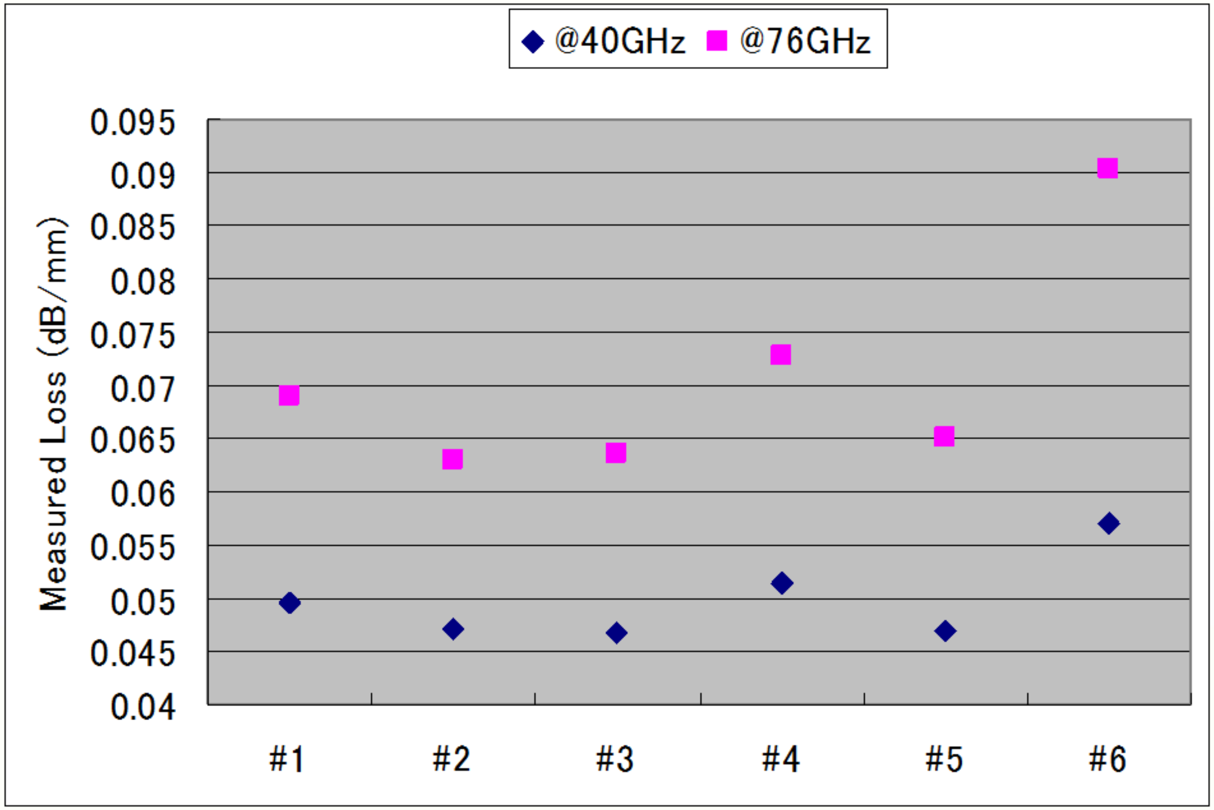
- Repeatability
  - Difference of raw S21 data per 8mm length
  - +/- 0.0025dB/mm (@76GHz)



Benchmarking

Loss of CBCPW

- #2 with profile-free Cu foil is same as or less than the world lowest loss level.



Summary

- We proposed the evaluation method, which can clarify not only the dielectric loss but also the conductor loss and roughness loss of CCL, up to 110GHz.
- To calculation of Imp of CBCPW by using quasi-static analysis based on the conformal mapping method, we synthesized the effect of dispersion of CPCBW, conductor thickness and roughness.
- Then we separated the transmission loss into the dielectric, conductor and roughness loss.

Summary

- It is very useful to understand the separated loss factors, which is expected to be able to judge and compare the loss characteristics of any CCL and also judge the pros and cons of different candidates in the same manner.
- We benchmarked our developed CCL; it is found our developed CCL #2, which laminated profile-free Cu foil, exhibits the same level as or less than the loss of the world lowest CCL.

Thank you for your attention.