Microwave Characteristics and Applications of Liquid Crystal Polymer Flex

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Abstract
We present the electrical characterization of our Liquid Crystal Polymer (LCP) at microwave and millimeter frequencies and the applications of LCP to circuit components. We use several methodologies to determine the electrical characteristics of LCP for microwave and millimeter wave frequencies. Cavity resonators [1], micro strip T-resonators [2], and micro strip ring resonators [1, 3] are measured in order to characterize both the dielectric constant and loss tangent up to 40GHz. The measured dielectric constant is shown to be steady near 3.0, and the loss tangent stays below 0.002, which is better than advanced polyimide materials. Furthermore, micro strip lines are designed and fabricated on both LCP substrate and other conventional materials in order to compare loss characteristics. The measured insertion of micro strip lines on a LCP substrate (25μm) and a polyimide substrate (25μm) is 0.11dB/mm and 0.18dB/mm, respectively. These results show that LCP has excellent and stable dielectric properties at high frequencies and the data suggests that this material can be used for applications extending through millimeter wave frequencies. LCP's inherent properties such as multi-layer capabilities, excellent electrical properties, flexibility, and near hermetic nature suit it to a wide range of applications such as passive devices, packages, and RF cables. Finally, we demonstrate the development of a ban pass filter on LCP flex to achieve an insertion loss less than 1 dB at 6 GHz in the pass band. The microwave characteristics of LCP have provided the feasibility of this material for low cost and high performance substrates for microwave and millimeter wave applications.

I. Introduction

Liquid Crystal Polymer (LCP) is an emerging organic dielectric material that has gained attention in recent few years as a potential high performance microwave flexible substrate and packaging material. Unlike traditional dielectric materials such as epoxy based FR-4 and widely used polyimide, LCP offers unique properties and performance. Some of the attractive features offered by LCP include low dielectric constant, low loss tangent, very low moisture absorption (0.04%), high temperature resistance (lead-free solder resistance), flame resistance, chemical resistance, and near hermetic nature. In addition, LCP consists of only aromatic hydrocarbon in chemical composition and adhesive is not necessary for making conductor clad laminates owning to its thermoplastic nature. Thus, this material is environmentally benign, and can be recyclable. In the past few years, a great deal of research efforts has been dedicated to LCP material characterization and application developments including high frequency passive devices and electronic packages [4-5]. Commercial LCP films are currently supplied exclusively by a few manufacturers in thin film with different thickness ranging from 25 to 100 μm. We have developed both single-sided and double-sided copper clad laminates in roll with different copper thickness from 9 to 35μm [6]. Polyimide materials are a currently dominant flexible substrate in electronics industries, but it is obvious that they have high losses and dimensional instabilities at high frequencies. PTFE-based materials are well known as microwave laminates, however, they have two serious concerns in both fabrication and cost [7]. In addition, low temperature co fired ceramic (LTCC) has attractive electrical characteristics, multilayer configurations, and very good package hermeticity, however, the cost is also relatively high. Due to the capability for LCP to adopt roll-to-roll processing, it is expected that production costs will continue to fall with increase in demand.

In this paper, we will present the microwave characterization of our LCP flexible circuits and their applications in the microwave and millimeter wave frequency regime. We have designed and fabricated various planar transmission lines including ring resonators, T-resonators, and micro strip lines on LCP films to demonstrate the electrical performance. By these studies, dielectric properties and transmission line performance of LCP over a range of frequency, temperature, and humidity are demonstrated. Regarding applications of LCP flex, we will summarize the potential applications that exploit the unique properties of LCP. We will also demonstrate a few applications including a compact band pass filter using LCP flex.

II. Description of LCP and its Multi-layer Board Processes

Since LCP is a thermoplastic polymer, both single-sided and double-sided copper clad laminates with LCP can be fabricated by continuous process at more than 200^{o}C and sufficient adhesion strength can be ensured. For the sake of the trend for miniaturization in electronic devices, laminates with thinner copper thickness is necessary for advanced fine line processing of the traces. We have succeeded in production of LCP laminates with thinner 9 and 12 μm thick coppers. Figure 1 shows photographs of traces, which were fabricated with single-sided laminates of 9μm copper and 25μm LCP films by normal photolithographic processes. 40μm pitch traces with excellent linearity and shapes can be obtained, thus, this noble LCP flex can be applicable for more stringent fabrication in line pitch. Although high dimensional stability is required with decrease in trace width, LCP has excellent dimensional stability even in high humidity environment due to its low moisture absorption. This is one of the outstanding features, which cannot be achieved for conventional flexible circuit materials such as polyimide. As for through hole formation, we confirm that CO_2 laser (50μm Through Hole), UV-YAG laser (50μm Blind Via Hole), NC drill (150μm Through Hole) and traditional punching processes can be used for the fabrication of LCP flex. Figure 2 shows two different types of laser ablation processes using LCP flex. Common desmear treatment and plating of these vias can be done using conventional printed circuit technologies. One of the distinctive features of LCP flex is the capability of multi-layer constructions. Multilayer circuits using LCP flex are possible due to two types of LCP material with different heat resistance, although high temperature press at more than 200^{o}C is necessary. High temperature type LCP can be used as core layers, while low temperature type LCP is used as a bond ply, as shown in Figure 3. The combined usage of low and high temperature LCP allows the lamination process from layer to layer without using adhesive materials. Thus, dense and high quality transmission line designs on LCP flex may be realized similar to those in LTCC.

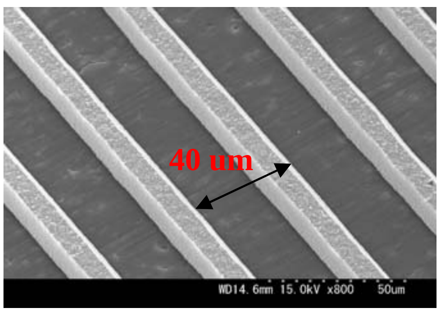


Figure 1 - Fine line process on LCP with 40um pitch traces

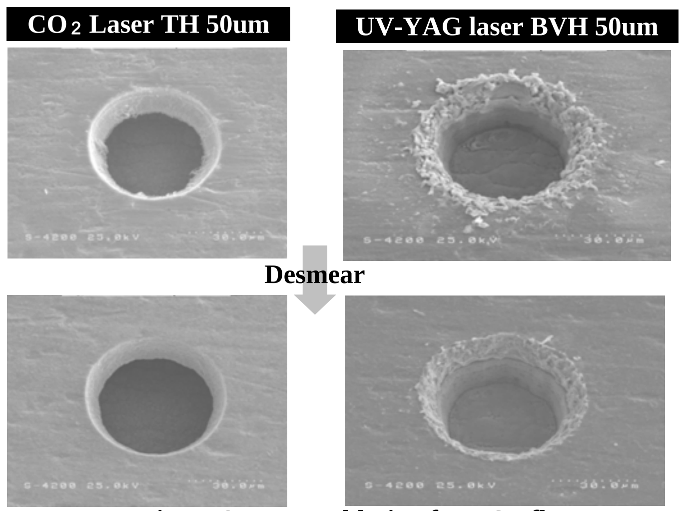


Figure 2 - Laser ablation for LCP flex

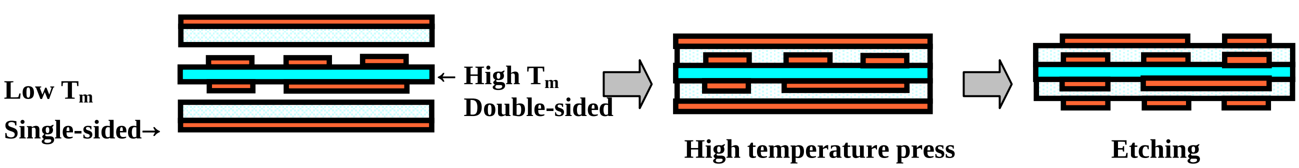
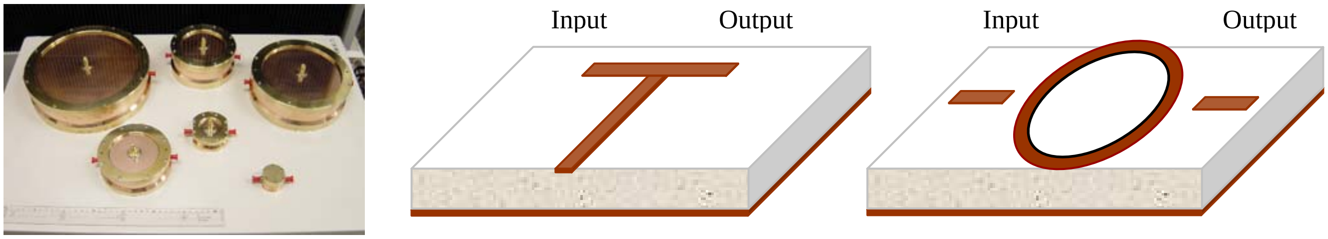


Figure 3 - Multilayer constructions with LCP flex

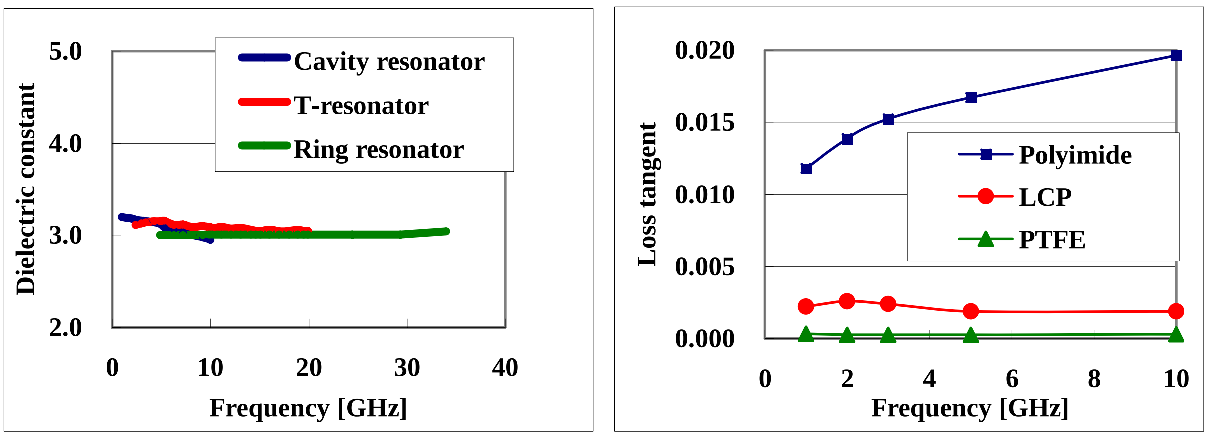
III. Dielectric properties over frequency, temperature, and humidity

Dielectric properties, which include dielectric constant, loss tangent, and stabilities of these two properties, are essential characteristics for microwave designs. In our study, three different types of measurement methods have been considered in order to extract these properties; cavity resonators (up to 10GHz), T-resonators (up to 20GHz), and ring resonators (up to 40GHz). Figure 4 illustrates diagrams and a picture of the resonator. The resonators were measured using an Agilent Performance Network Analyzer, a Cascade Probe Station and microprobes. Extraction of dielectric constant and loss tangent was carried out on the basis of previous literature [1-3]. Figure 5 shows measurement data over frequency for dielectric constant up to 40GHz and loss tangent up to 10GHz. We compared the properties with our advanced adhesiveless polyimide based flex (ESPANEX S series). It turned out that LCP could provide nearly static dielectric properties across a wide frequency range. Loss tangent of LCP flex over frequency is quite different from that of polyimide. The rigid-like aromatic molecules and dense chemical structure are considered to contribute to the stable dielectric properties of LCP.



(a) Cavity resonator (b) T-resonator (c) Ring resonator

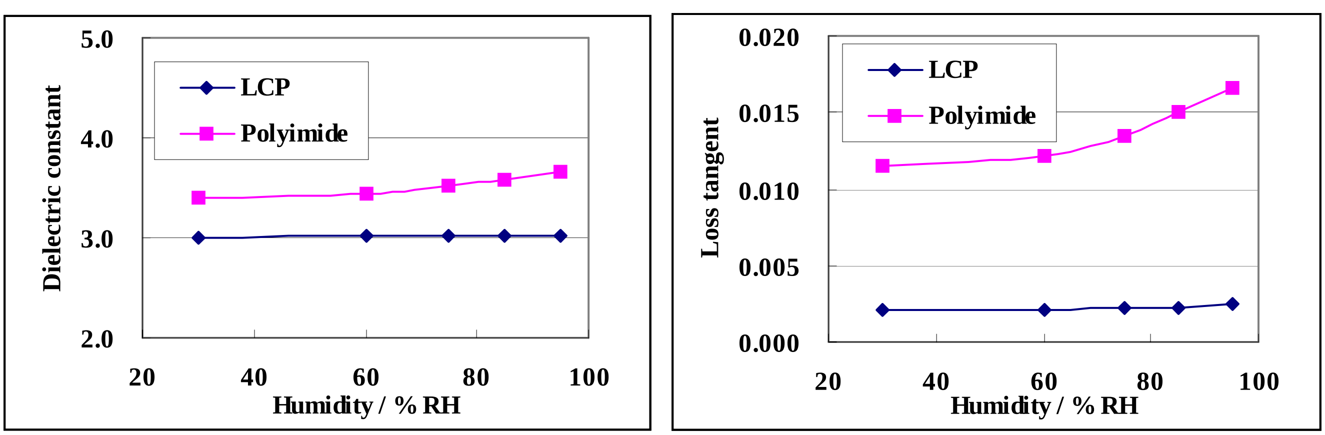
Figure 4 - Three different types of resonators



(a) Dielectric constant (LCP flex) (b) Loss tangent (LCP, Polyimide, PTFE)

Figure 5 - Measured dielectric properties over frequency

Humidity dependent dielectric measurements is also critical for microwave designs because moisture absorption in dielectric films is great concern and it can lead to significant losses in devices such as antennas, filters, and transmission lines [8]. Dielectric properties may vary with increase in humidity, since water has large dielectric constant. Dielectric constant and loss tangent measurements at 1GHz in the environment of humidity have been investigated using a material analyzer and an environmental chamber. Figure 6 indicates the stability of dielectric constant and loss tangent at 1GHz over humidity up to 100% RH. These results show that excellent LCP laminates has stable over humidity, however, polyimide has unstable due to its high moisture absorption (approximately 1%).

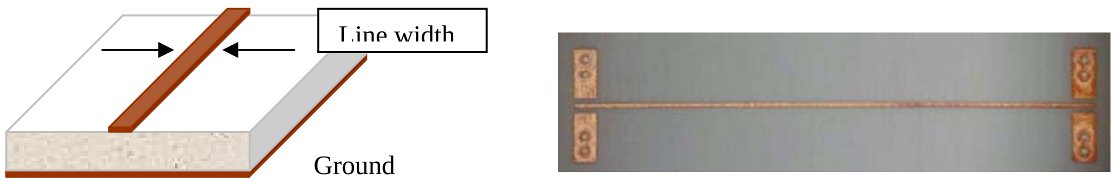


(a) Humidity versus dielectric constant (b) Humidity versus loss tangent

Figure 6 - Measured dielectric properties over humidity at 1GHz

IV. Performance of microstrip transmission lines on LCP

Transmission line loss is critical to the development of microwave and millimeter components and packages. Micro strip lines, which are shown in Figure 7, are dominant structures in microwave designs and very important to investigate the characteristics [9]. First, Agilent Advanced Design System (ADS) was used to determine the width of a micro strip line for a characteristic impedance of 50 ohm with substrate thickness of 25, 50, and 100μm [10]. On-wafer measurements using a Performance Network Analyzer (E8364B) and a Cascade Probe Station have been conducted in order to evaluate the insertion loss (S_{21}) and return loss (S_{11}) of transmission lines. Prior to measurements, a line-reflect-match (LRM) calibration was performed to establish reference planes at probe tips. Table 1 provides the calculated width of 50 ohm micro strip lines and loss per unit length. It turned out that fine line processing is necessary to control the characteristic impedance for thinner flex, since line width is quite narrow. Our LCP flex with thinner copper thickness should be suitable for these designs. The micro strip line on LCP achieves a measured insertion loss of less than 0.1dB/mm up to 30GHz. The line on the thinnest LCP substrate (25μm) had the greatest loss because the line width is the narrowest and conductor loss due to the line resistance is the largest [11].



(a) Microstrip line (b) Top view

Figure 7 - Microstrip line configuration

Table 1 - Designed and measured insertion loss values for 50 mm micro strip line (LCP flex)

Dielectric thickness / μm	Line width / μm*	Insertion loss at 30GHz [dB/mm]
25	54	0.10
50	115	0.06
100	239	0.05

* Designed values by ADS, Copper thickness: 12μm

Next, micro strip line performance with various kinds of laminates, including commercially available FR-4, BT, PTFE, was investigated and compared. In order to exclude the effect of dielectric thickness for transmission line losses, thicker dielectric thickness between 100 to 200μm was chosen in this study. The following Table 2 and Figure 8 summarize the results of micro strip line insertion loss with material parameters. It can be seen that LCP provide low insertion loss, which is almost consistent with that of PTFE materials. Conventional FR-4 and BT materials have much higher insertion loss, indicating that LCP is much suitable as microwave laminates. Although thinner copper clad laminates have been developing for FR-4 and PTFE, these materials need fillers, which cause degradation of flexibility. However, LCP has no fillers in the dielectric film and is more flexible. Thus, LCP flex is an excellent candidate for microwave applications, which needs to be flexible.

Table 2 - Material parameters and design values

Material	Dielectric constant*1	Dielectric thickness [μm]	Line width*2 [μm]
LCP	3.0	100	240
FR-4	4.7	200	350
PTFE	2.6	160	420
BT	3.9	100	195

*1 Representative values at high frequency
*2 Designed values by ADS

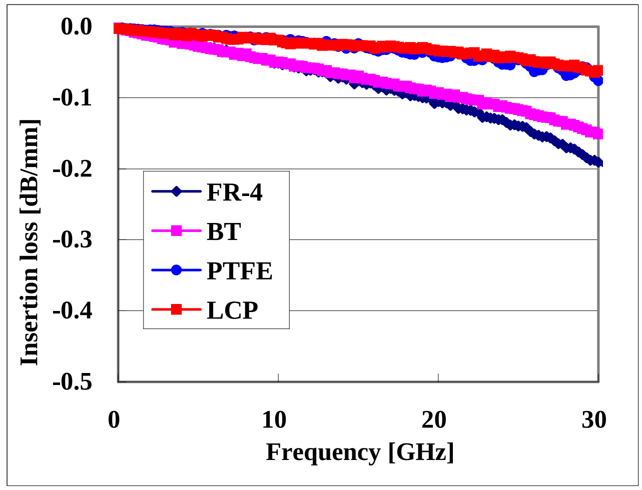


Figure 8 - Micro strip line performance for various types of materials

Finally, the loss characteristics between LCP flex and our advanced polyimide materials (ESPANEX M series) with the same dielectric thickness (25um) and line length (50mm) have been investigated, as shown in Table 3 and Figure 9. Our experimental results demonstrate that a micro strip transmission line on the LCP flex achieves an insertion loss of 0.11 dB/mm at 40GHz, which is almost twice better than that of high functional polyimide materials (0.18dB/mm at 40GHz). These results indicate that LCP flex has stable dielectric properties up to millimeter wave frequencies and the lowest loss among any flexible circuit materials.

Table 3 - Material parameters and design values

Material	Dielectric constant*1	Loss tangent*1	Line width*2 [μm]
LCP	3.0	0.002	58
Polyimide	3.0	0.004	

*1 Representative values at 10GHz, Copper thickness: 12μm
*2 Designed values by ADS
Line length: 50mm

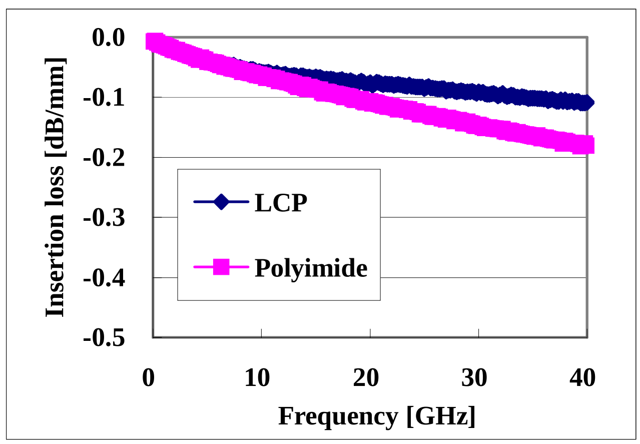


Figure 9 - Measured insertion loss for LCP and polyimide (PI) flex

Application of LCP flex

Currently, universities and many companies are aggressively pursuing research and demonstrating applications using LCP flex, including compact low-cost passive devices and packaging materials as replacement of expensive ceramic substrates. Table 4 summarizes potential applications of LCP flex with distinctive LCP features. These applications were considered on the basis of literature and other information. Although special application such as speaker circuit board can be seen in this summary, most of their applications account for the LCP's excellent microwave characteristics. As one of the demonstrations, a compact band pass filter, which passes only a band of frequencies between two designated values, was designed on the basis of micro strip lines and measured, as illustrated in Figure 10 [12]. Both ADS and Sonnet were used as electromagnetic solvers for the simulation as well as optimization of the filter design [10, 13]. As a result, it turned out that LCP flex could provide low insertion loss (less than 1dB). As discussed earlier in section II, LCP flex can be applicable to conventional photolithographic processes unlike LTCC. Multilayer construction with LCP flex is also possible for more dense structures, thus, LCP flex can provide the solutions for cost reduction and miniaturization in devices.

Tables 4 - Potential applications of LCP flex

Applications	Main features
RF cable	Low dielectric, Low water absorption, hermeticity
Passive devices (Filter, balun)	Low dielectric, Low transmission loss, Multilayer constructions
Packaging / RF MEMS packaging board	Hermeticity, Low dielectric, Low transmission loss
Speaker circuit board	Vibration absorption
High frequency antennas	Low transmission loss
Infrared sensor circuit board	Low water absorption, Infrared absorption
Optical pickup board	Bendability, Low dielectric

Top view

Performance

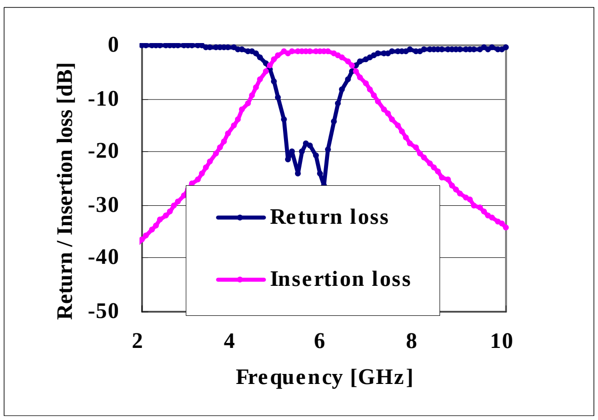


Figure 10 - Planner band pass filter with LCP flex

Conclusions

1. Microwave characteristics for LCP flex such as dielectric properties and transmission line performance have been measured and compared with other conventional substrates. The distinctive features include;
    1) Low dielectric constant and loss tangent up to 40GHz.
    2) Stable dielectric properties over humidity.
    3) Low insertion loss for microstrip line configuration, as compared with FR-4, BT, and polyimide
2. Application of LCP flex for electronic devices have been summarized and demonstrated.
    1) Passive devices such as bandpass filter can be demonstrated and indicated that this application has potential consumer products.
    2) Compact and low cost packaging materials and RF cables are potential applications for LCP flex in industries.

Acknowledgement

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Electronic Materials

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Introduction

Introduction

Liquid Crystal Polymer flexible printed circuit board (LCP flex)

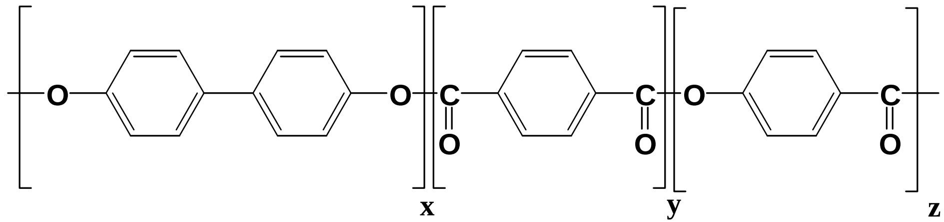
- Low moisture absorption
- Flexibility
- Capability of multi-layer structures
- Recyclability
- Compatibility of lead-free soldering process

Motivation

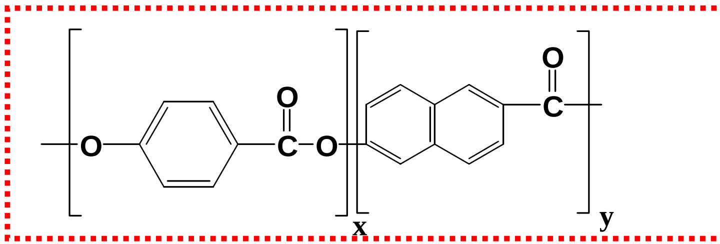
- Microwave and millimeter-wave characteristics of LCP flex
- Applications of LCP flex in electronic devices

Liquid Crystal Polymer

Type 1



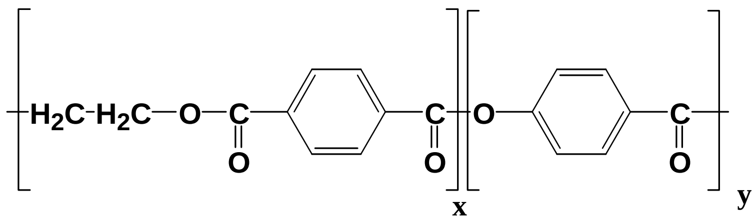
Type 2



HBA : p-Hydroxybenzoic acid
HNA : 6-Hydroxy-2-naphthoic acid

HBA HNA

Type 3



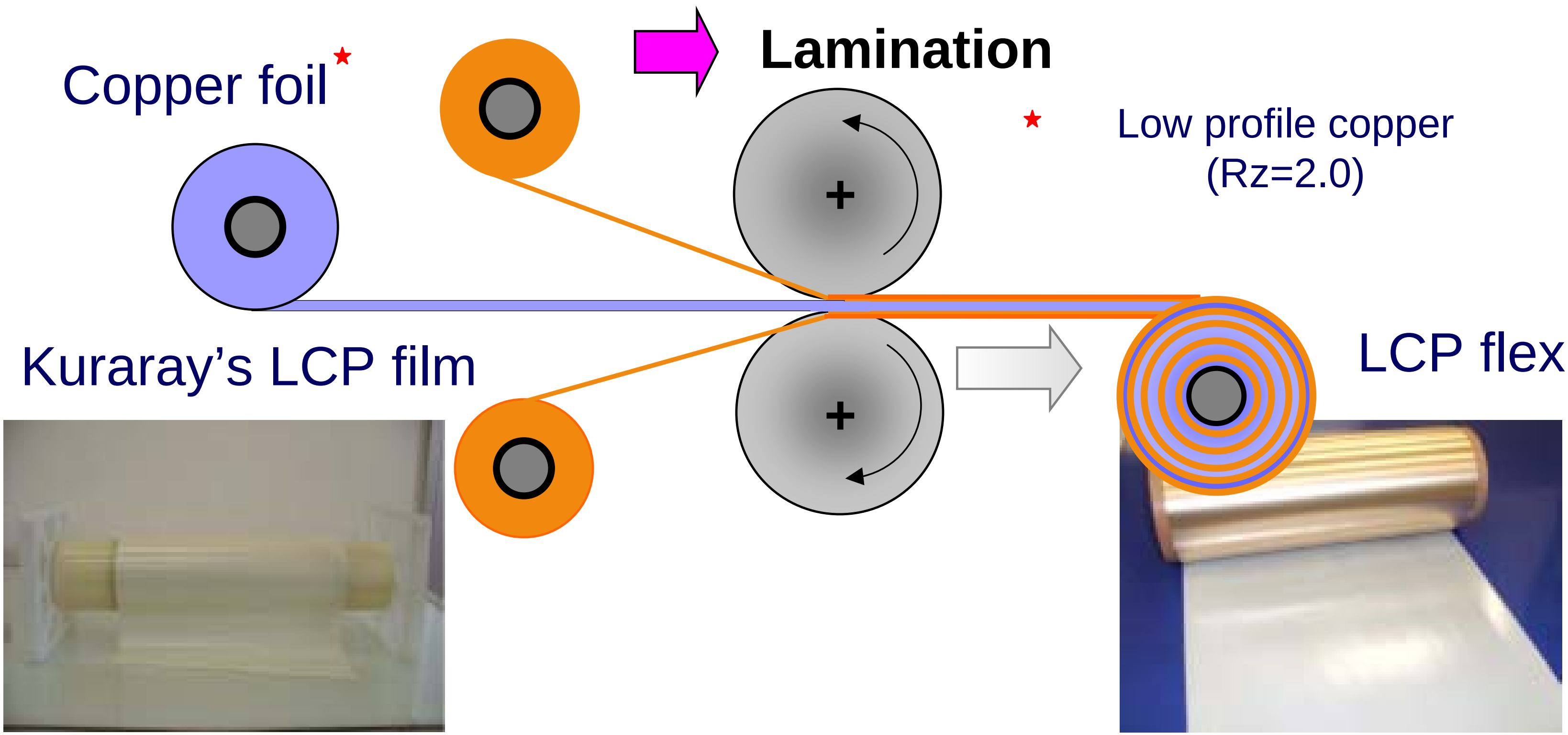
Liquid Crystal Polymer is thermoplastic polymer, which is classified as polyester in chemical composition.

Material properties

Test item	Unit	LCP	Polyimide
Film tensile strength	MPa	**200**	270
Film tensile modulus	MPa	**2900**	4600
Peel strength	kN/m	**1.1**	1.1
Solder Limits	°C	**280**	>300
Moisture absorption	%	**<0.04**	1.5
Coefficient of hygroscopic expansion	ppm/%RH	**1**	28
Dielectric constant @ 1GHz	-	**3.2**	3.5
Loss tangent @ 1GHz	-	**0.002**	0.011

LCP's advantages :
Low moisture absorption, Low dielectric properties.

Manufacturing process for LCP flex



LCP copper clad laminates can be fabricated by continuous processes at high temperature without any adhesive.

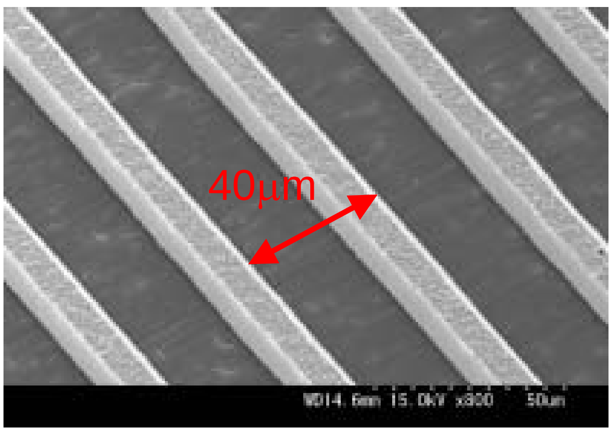
Developed Product lines

Item	Content
Construction type	Single-sided, Double-sided
Standard size	250mm or 305mm x 100m
Heat resistance type	Standard type (Solder limit: 280°C) P type (Solder limit: 270°C)
ED copper thickness	1/4, 1/3, 1/2 oz (9, 12, 18 μm)
LCP thickness	1, 2, 4 mil (25, 50, 100 μm)

We have developed LCP copper clad laminates with different constructions in roll by our proprietary processes.

Circuit fabrication

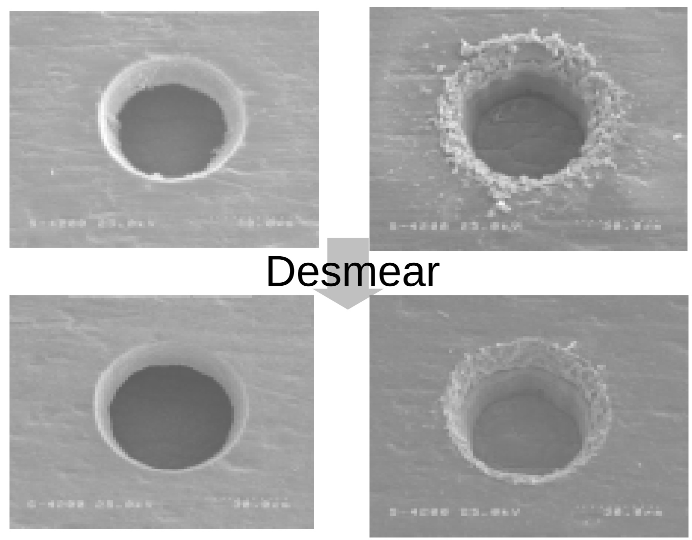
Fine line processing



Laser ablation

CO_2 Laser TH

UV-YAG laser BVH



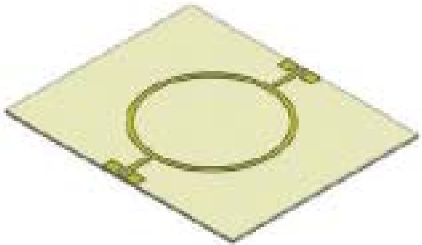
Conventional printed circuit technologies can be applicable in the fabrication.

Characterization 1 ：Dielectric properties over frequency

Network analyzer

Resonators

(a) Cavity resonator

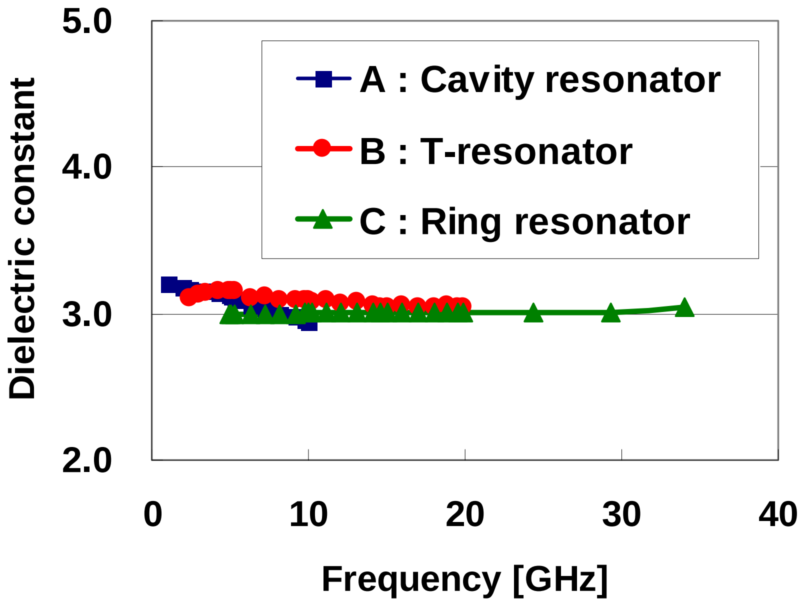


(b) Ring resonator

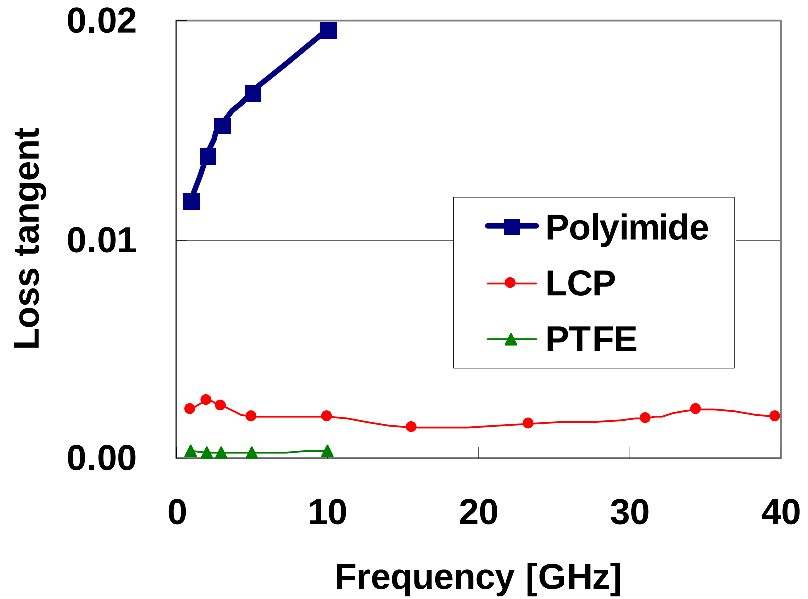
- Changes in resonance curve are measured.
- Both dielectric constant and loss tangent up to 40GHz can be estimated by cavity and ring resonator method.

Dielectric properties over frequency

Dielectric constant

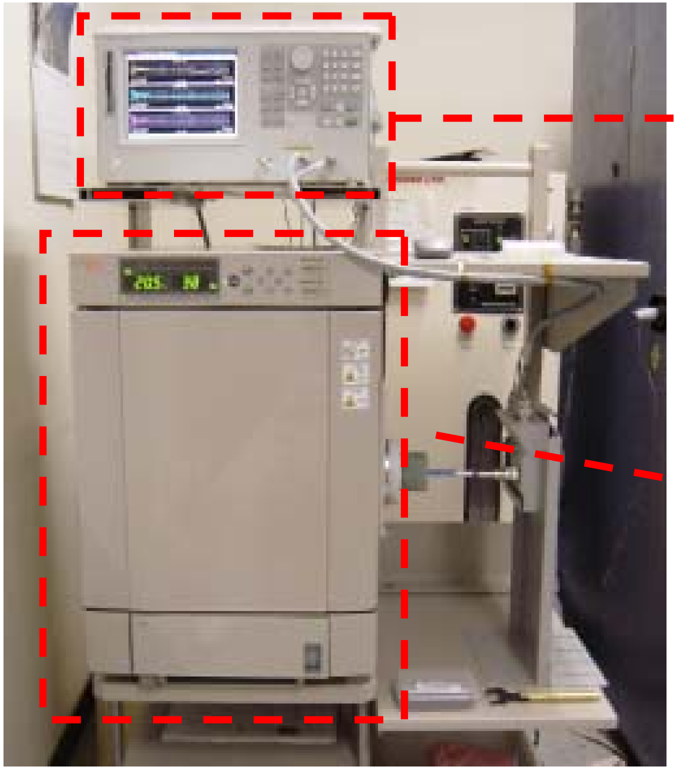


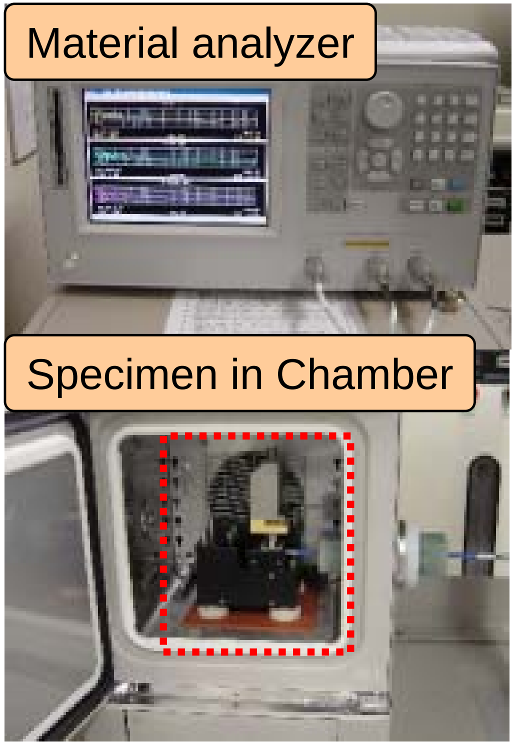
Loss tangent



LCP has stable dielectric properties over frequency up to millimeter-wave frequencies.

Characterization 2 : Dielectric properties over humidity

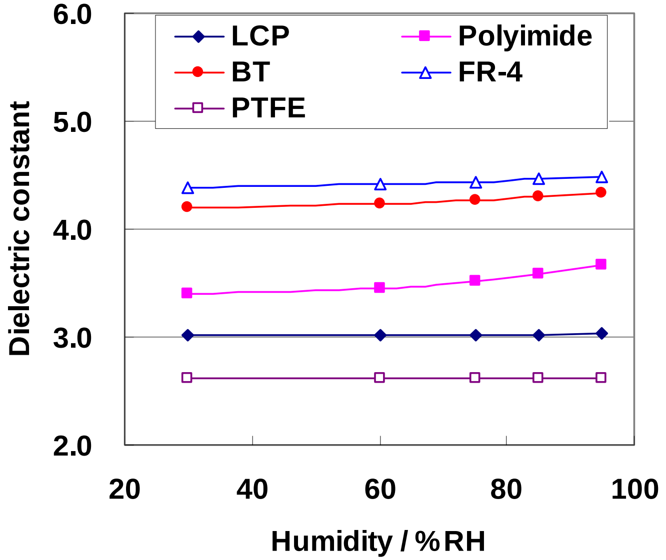




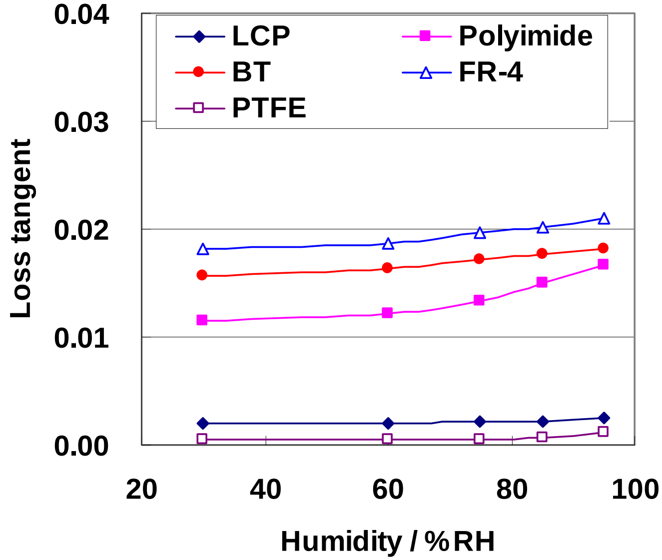
Continuous measurements of dielectric properties in different humidity have been performed.

Dielectric properties over humidity

Dielectric constant



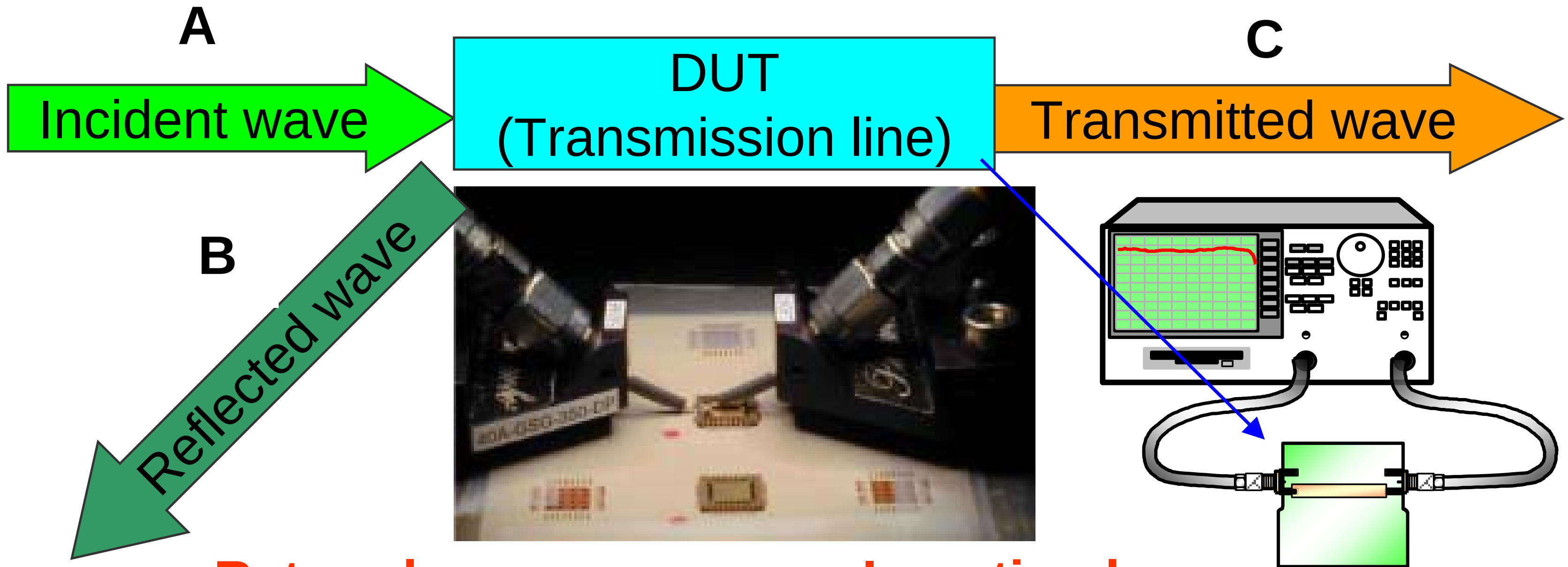
Loss tangent



Measurement frequency : 1GHz

LCP has stable dielectric properties over humidity unlike other conventional laminates.

Characterization 3 : Microstrip line characteristics



Return loss

S_{11}= B / A

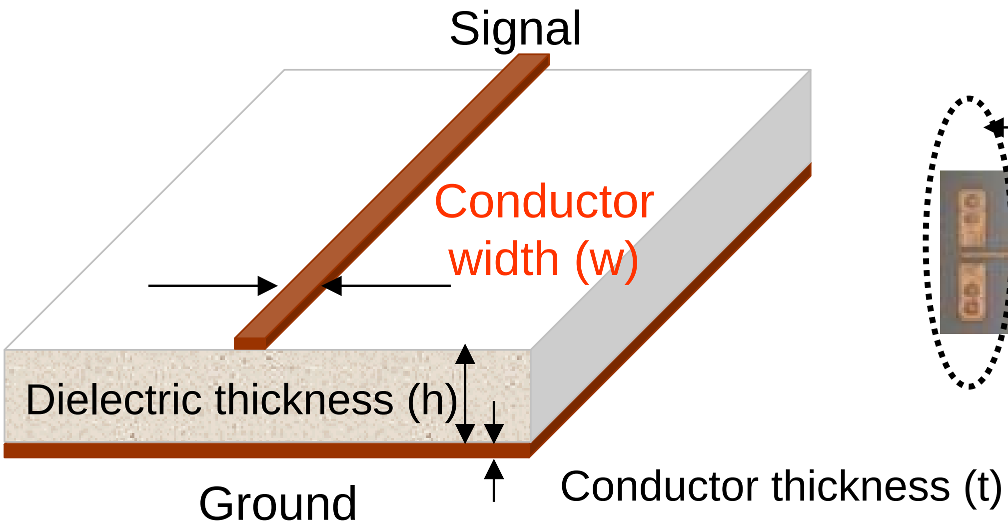
Insertion loss

S_{21} = C / A

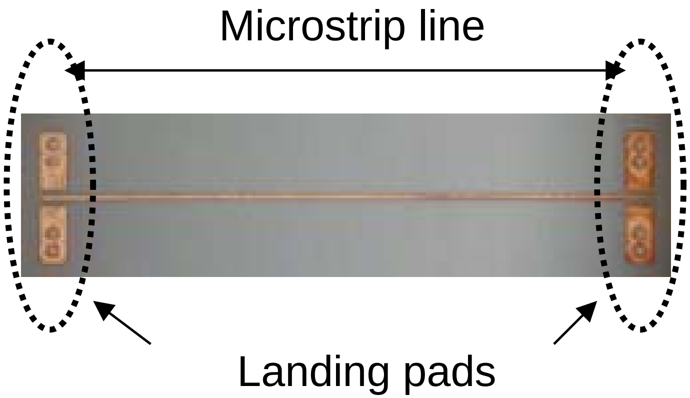
Microstrip line characteristics have been investigated by S-parameter method.

Microstrip line design

Schematic



Top view



- Characteristic impedance (Z_0) should be 50Ω.
- Impedance mismatch may cause undesirable high return loss.
- Z_0 is a function of dielectric constant and physical dimensions.
- Electromagnetic simulation was performed for the design.

Microstrip line design using LCP flex

Designed line width

		LCP thickness		
Copper thickness	[μm]	25	50	100
	9	56	117	241
	12	54	115	239
	18	52	112	234
Insertion loss at 30GHz [dB/mm]		0.10	0.06	0.05

※ Designed by Agilent Advanced Design System (ADS)

The thinner dielectric thickness,
The thinner designed line width & The more insertion loss

Microstrip line performance with thick film

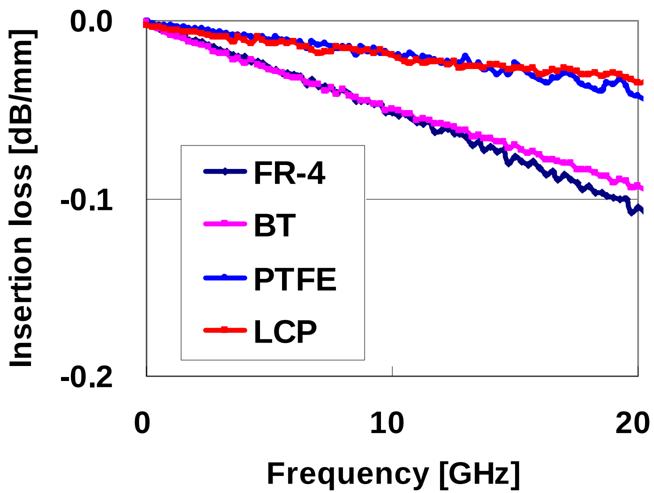
Material parameters

Material	Dielectric constant※1	Dielectric thickness [μm]	Line width※2 [μm]
LCP	3.0	100	240
FR-4	4.7	200	350
PTFE	2.6	160	420
BT	3.9	100	195

※ 1 Representative values at high frequency

※ 2 Designed values by ADS, Line length : 50mm

Measurement results



LCP provides low insertion loss, thus it is good candidate for microwave laminates. (Order : FR-4 = BT > **LCP** = PTFE)

Microstrip line performance with thin film

Material parameters

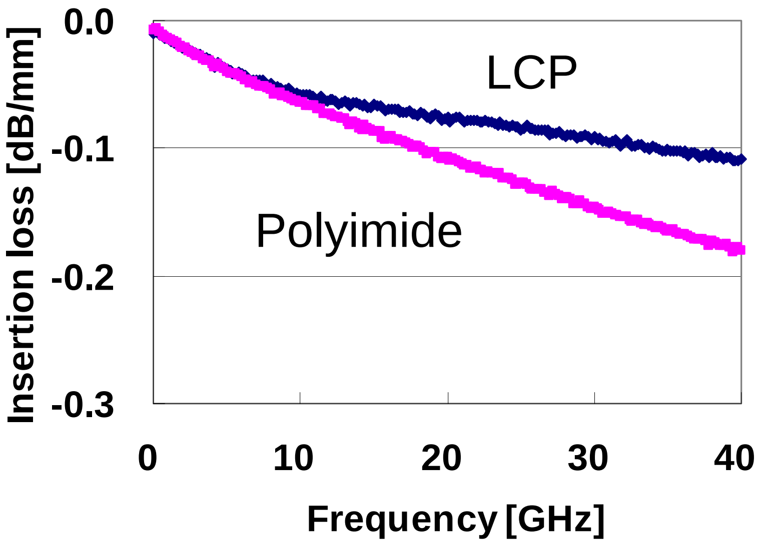
Material	Dielectric constant※1	Los tangent ※1	Line width※2 [µm]
LCP	3.0	100	58
Polyimide	3.0	200	

※ 1 Representative values at 10GHz.

Copper thickness: 12µm, dielectric thickness: 25µm

※ 2 Designed values by ADS, Line length : 50mm

Measurement results



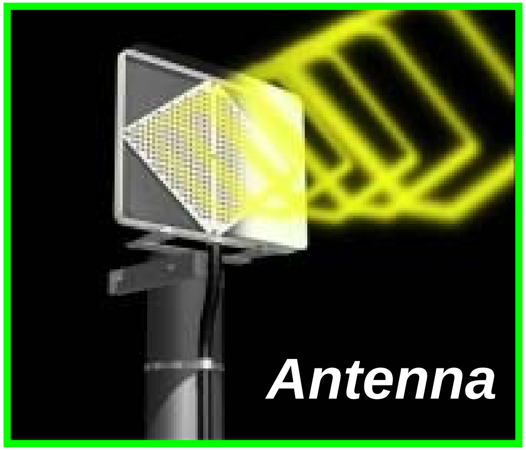
LCP provides much lower insertion loss above 10GHz, thus it is good candidate for flexible microwave laminates. (Order : **LCP** > Polyimide)

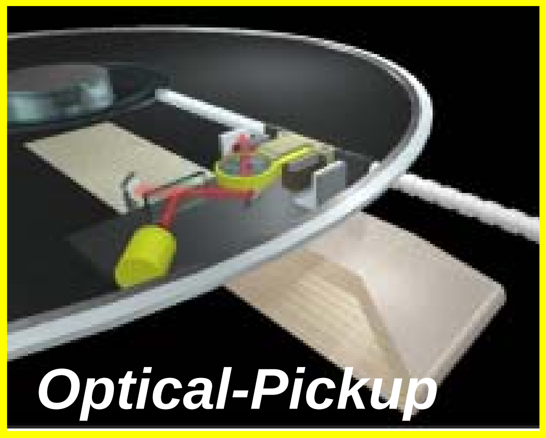
Multiple applications of LCP flex

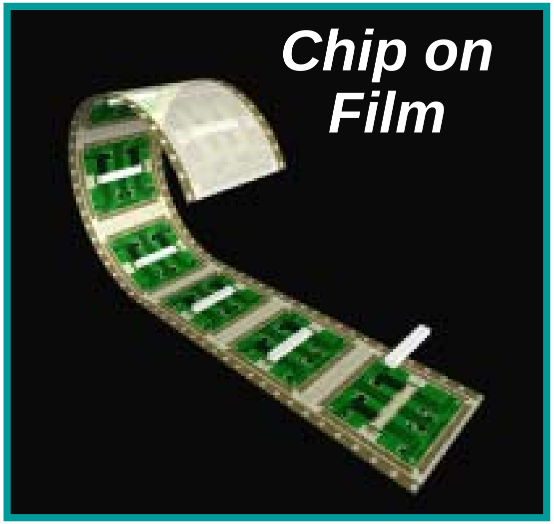
Applications	Main features
RF cable	Low dielectric, Low water absorption, hermeticity
Passive devices (Filter, Balun)	Low dielectric, Low transmission loss, Multilayer constructions
Packaging / RF MEMS packaging board	Hermeticity, Low dielectric, Low transmission loss
Speaker circuit board	Vibration absorption
Antennas	Low transmission loss
IR sensor circuit board	Low water absorption, IR absorption
Optical pickup board	Bendability, Low dielectric

Alternative to polyimide, LTCC, and PTFE as these devices are considered as applications of LCP flex.

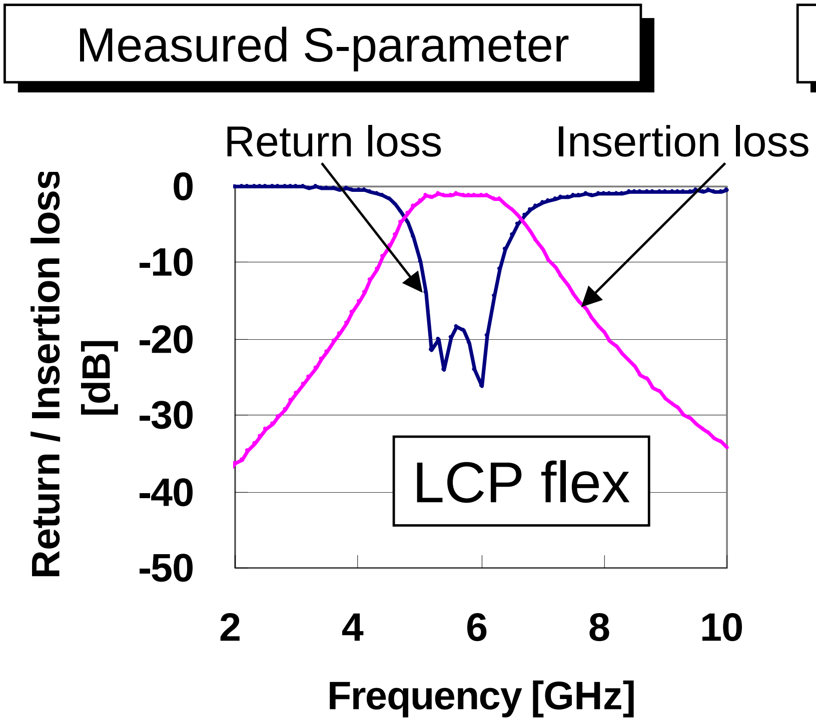
Applications

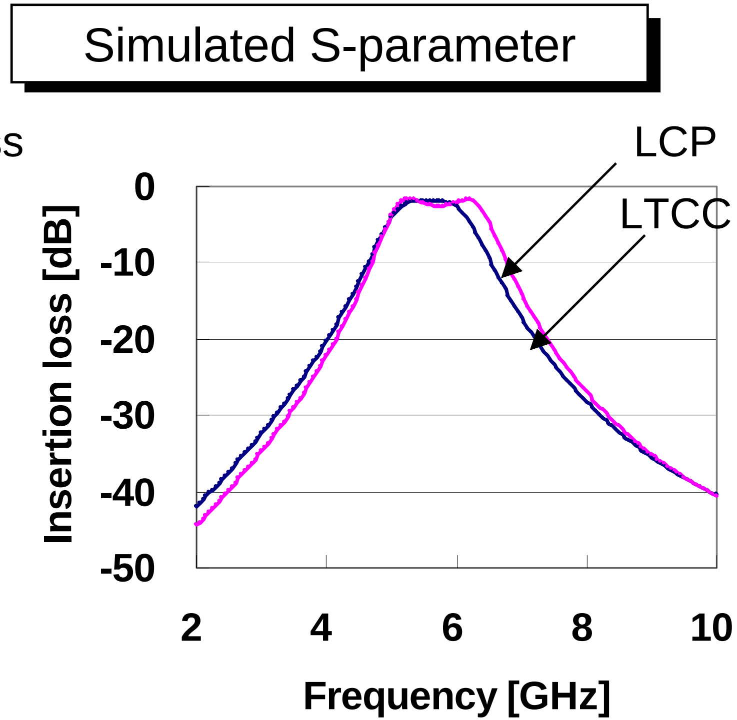






Planar bandpass filter with LCP flex





Bandpass filter with LCP flex shows low insertion loss, which is comparable to that of LTCC.

Summary

1. Microwave characteristics for LCP flex have been measured and compared with other conventional substrates.

- Stable low dielectric constant and loss tangent up to 40GHz
- Stable dielectric properties over humidity
- Low insertion loss for microstrip line configuration

2. Application of LCP flex for electronics devices have been summarized and demonstrated.

- Passive devices such as bandpass filter can be demonstrated and indicated the properties are comparable to those of LTCC.
- Compact and low cost packaging and RF cables are potential applications for LCP flex.