Wiring board material technology for millimeter wave application

Contents

1. Introduction

With the expansion of social media services and video distribution services, Internet traffic is rapidly increasing day by day and thus faster and larger capacity services are required. To respond to the demand, 5G communication (5th generation mobile communication) services finally started in 2020 and high-speed communication services over 1 Gbps can be available in mobile communication networks. To realize such high speed, large capacity communications, it is essential to use mmWave, the radio wave whose frequency is approximately 30 GHz or higher because mmWave can provide wider frequency bandwidths than conventional frequency bands.

For the utilization of mmWave in 5G communication networks, it is necessary to reduce the transmission loss of mmWave in electronic wiring boards used in communication equipment. In such wiring boards, various electronic components, such as ICs, capacitors and resistors, are mounted and mmWave signals propagate through the circuit. The wiring circuits are formed on an insulating material and thus affected by the properties of the material. In general electronic equipment, a glass-epoxy rigid board or a polyimide (PI) flex board is widely used. However, in mmWave equipment, those materials suffer a large transmission loss in mmWave signals so that they cannot be employed for 5G applications. Therefore, it is important to choose appropriate materials for wiring boards to reduce the transmission loss of mmWave signals. In addition, since the transmission loss is proportional to the length of the wiring, it is necessary to reduce the wiring length. From this point of view, the structure of antenna in package (AiP), in which ICs and the mmWave antennas are integrated in one substrate, is applied in practical applications.[1]

In this paper, requirements to the circuit board necessary for developing mmWave AiP modules are shown, and the material technology for the development is outlined.

2. Requirements for mmWave wiring board materials

2.1 Multilayer wiring

Figure 1 shows a schematic diagram of a basic structure of AiP. It is a multilayer wiring board consisting of insulating substrate layers and wiring layers. On one side of the wiring board, one or more RF-ICs (radio-frequency integrated circuits) are mounted, and on the other side, patch antennas for transmitting and receiving mmWave are installed. Since space propagation loss becomes large in mmWave bands, it is necessary to increase antenna gain by employing an array antenna structure, in which multiple antennas are arranged at fixed intervals. Therefore, there are multiple wiring routes connecting between RF-ICs and patch antennas in an AiP structure and it is necessary to design wiring routes to minimize connection loss. In other words, line lengths of the circuit should be reduced as small as possible. To meet this requirement, it is essential to connect the traces in the z direction (thickness direction of the AiP board) as well as the x-y direction utilizing a multilayer structure. In some practical cases, multilayer wiring boards use over 10 wiring layers.

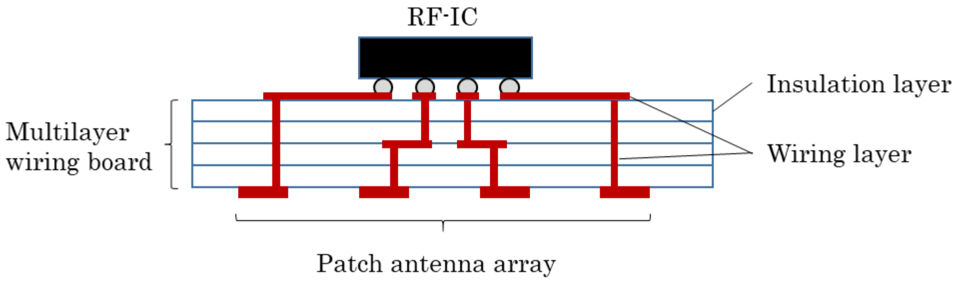


Fig. 1 Basic structure of Antenna in Package (cross-sectional view).

From the viewpoint of material properties of a wiring board, its thermal expansion coefficient (coefficient of thermal expansion, CTE) is an important parameter. In a multilayer wiring board, the warpage of the board is often generated by the difference in CTE of multiple insulating materials and/or the wiring material. Therefore, it is necessary to suppress the CTE difference of the constituent material of the wiring board as small as possible. Copper is a standard wiring material and its CTE is 16 ppm/°C. Consequently, insulating materials are developed to match the CTE value of copper. This also ensures high reliability of the AiP module because the thermally induced stress at joints between the board and the electric components is suppressed.

2.2 Low dielectric properties

The transmission loss of a high frequency signal propagating through a wiring board depends on the dielectric properties of the insulating material, the characteristics of the wiring conductor, and the wiring thickness and width. The transmission loss α is expressed by the sum of the dielectric loss α_d due to the dielectric property of the insulating material and the conductor loss α_c due to the wiring conductor, and has the following relation with parameters of the insulating material. [2][3]

$$\alpha = \alpha_d + \alpha_c$$

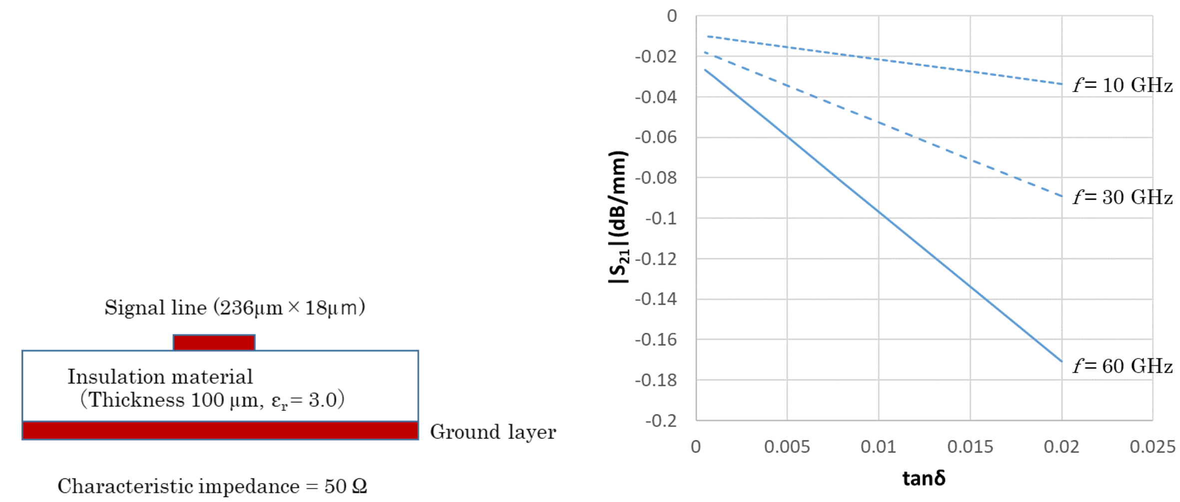
$$\alpha_d \propto \sqrt{\varepsilon_r} \cdot \frac{f}{c} \cdot \tan\delta \qquad (1)$$

$$\alpha_c \propto \sqrt{\varepsilon_r} \cdot \sqrt{f} \cdot \sqrt{\rho} \qquad (2)$$

where f is the frequency of the signal, c is the speed of light in vacuum, ρ is the resistivity of the wiring conductor, and ε_r, $\tan\delta$ are the relative permittivity and dielectric loss tangent of the insulating material, respectively. Equations (1) and (2) indicate the following relationship:

1. α_d is proportional to the frequency f, while α_c is proportional to the square root of the frequency. Therefore, α_d becomes dominant when the frequency becomes higher.
2. It is necessary to choose a material having smaller ε_r, $\tan\delta$ material in order to make α_d smaller.

For resin materials widely used in the insulating layer of wiring boards, $\tan\delta$ is an important index, because the values largely differ by the type of resin while the difference of ε_r is relatively small. Figure 2 shows the calculated results of the relationship between $\tan\delta$ and the transmission characteristics. The calculations are performed on the micro strip transmission line as shown in Fig. 2 (a), and the calculated transmittance, $|S_{21}|$ are shown in Fig.2 (b) as a function of $\tan\delta$. It is clear that the higher the transmission frequency, the smaller the transmittance (i.e. the greater the transmission loss). In the case of conventional insulating materials such as glass epoxy and PI, the value of $\tan\delta$ is around 0.02 and this is not enough for mmWave application. It should be less than 0.005 for the application.



(a) Structure and parameters of calculated micro strip line

(b) Calculated results

Fig. 2 Relationship between transmittance, transmission frequency and $\tan\delta$.

2.3 Surface roughness of wiring conductors

When a high-frequency signal propagates through a conductor, the electric current flow concentrates on the regions from several microns in depth to the conductor surface, which is known as the skin effect. The typical depth is called the skin depth d and determined by[3]

$$d = \sqrt{\frac{\rho}{\pi \cdot \mu_0 \cdot \mu_r \cdot f}} \qquad (3)$$

Here, μ_0, μ_r are the permeability in vacuum and the relative permeability of the conductor, respectively. In the case of copper, which is generally used as a wiring conductor, d = 0.27 μm at a frequency of 60 GHz.

In the standard wiring board process, the surface roughness of wiring metal is set at several microns to improve the adhesion to the insulating material to ensure high reliability. On the other hand, this roughened surface degrades transmittance in high-frequency regions because the electric current path concentrates on the surface region due to the skin effect and thus the effective resistance gets larger. These are trade-offs and the surface roughness of the wiring should be set carefully taking the transmittance at mmWave frequencies into account.

2.4 Low moisture absorption

The last important requirement for wiring board materials for mmWave use is the moisture absorption characteristics of insulating materials. Since a water molecule itself has a high ε_r, $\tan\delta$ in the mmWave range, the dielectric properties of insulating materials degrade once the moisture is absorbed inside the board material even if it originally has good properties. As described in the previous section, this change of dielectric properties results in a degradation of transmittance in mmWave signals. Therefore, it is desirable that the moisture absorption of wiring board materials is kept as low as possible.

3. mmWave wiring board materials and characteristics

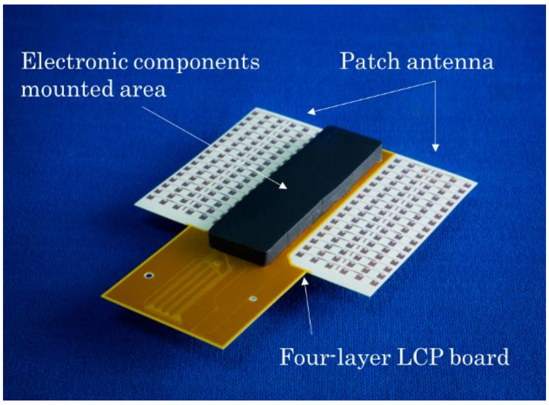
In the previous chapter, requirements for the properties of wiring boards for mmWave use were described. This chapter specifically shows representative materials complying with those requirements and used in mmWave applications. Each material has its own pros and cons and is selected for a most suitable use case. As an example of actual performance comparison among the materials, transmission characteristics at mmWave frequencies will also be shown for typical materials in the last section.

3.1 LCP

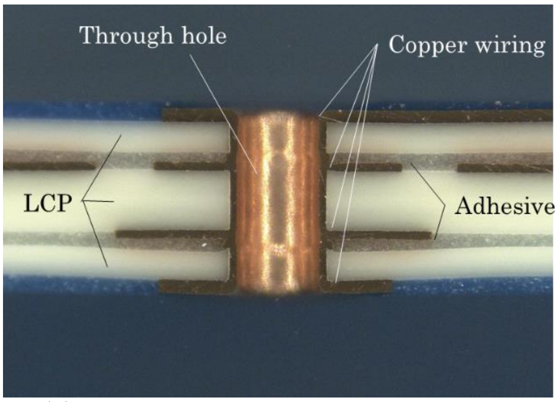
Liquid crystal polymers (LCPs) are reliable thermoplastic resin widely used in electronic components such as a semiconductor package or a connector body. LCPs also have superior dielectric properties and thus are utilized as board materials for mmWave applications. Typical values of ε_r and $\tan\delta$ are 2.8 and 0.003 (@ f = 60 GHz), respectively. In addition, for LCPs, their low humidity absorption of 0.1% yields stable dielectric properties in ambient humidity changes. Therefore, these materials are suitable to be used in practical mmWave electronic equipment.

For a wiring board material, LCP resin is shaped into a thin film with a thickness of 20 to 100 microns and a copper film of 10 to 20-micron thickness is laminated onto the LCP film. This material is called FCCL (flexible copper clad laminate) and a wiring board is fabricated by an FPC (flexible printed circuit) manufacturing process. LCP film tuned for a wiring board has a CTE value of about 16 ppm/°C, which is almost equivalent to that of copper. This is also the superior property of this material.

For a mmWave AiP, it is important to have a multi-layer structure. Although an LCP film is a thermoplastic material, it is difficult to produce a multi-layer structure by unifying separate LCP film circuits because high processing temperatures over 300 °C result in the deformation of the material during the fabrication process. To develop a multi-layer structure, an adhesive film was used to join separately prepared LCP circuit films together at a processing temperature below 200 °C to cause less damage to the LCP circuits and thus a multi-layer board can be produced. Figure 3 (a) shows an example of a 60 GHz AiP module, in which an RF-IC and patch antennas are integrated in a 4-layer LCP board, and figure 3 (b) shows a cross-sectional structure of the LCP board. The LCP films are joined by adhesive layers and copper wiring layers are connected via a through-hole through the LCP board.



(a) Appearance of module



(b) Cross-sectional view of LCP board

Fig. 3 A 60 GHz mmWave communication module using 4-layer LCP board.

3.2 PPE

A material, which is used in mmWave applications and is very common as LCP, is PPE (polyphenylene ether). PPE is widely adopted as a material for rigid circuit boards. In the case of a rigid board, the resin is soaked into woven glass cloth and thermally hardened to form an insulating layer. Therefore, the dielectric properties of a wiring board are affected by those of the glass cloth and, as a result, those of a wiring board are deteriorated compared to those of the original resin. Typical values of its ε_r and $\tan\delta$ are 3.5 and 0.007 (@ f = 56 GHz), respectively. Although these values are inferior to those of LCP, they are sufficient for applications, such as high-speed servers or base stations for mobile networks, because wiring boards are used in the lower mmWave bands (around 30 GHz or below). The handling and processing of rigid PPE materials are almost the same as a conventional rigid material, FR-4, so that a mmWave AiP board can be developed using standard rigid board processes.

3.3. Other materials for mmWave application

・PTFE (polytetrafluoroethylene)

PTFE has the most superior dielectric properties among organic resin materials and provides low transmission loss at mmWave frequencies. Therefore, this material has been used in mmWave radars or satellite communication systems for over 50 years. However, PTFE has weak points of poor adhesion to other materials and a large CTE value of around 100 ppm/°C. This makes it difficult to use PTFE in a multi-layer AiP board.

・MPI (modified polyimide)

MPI is a kind of polyimide resin and its components are modified to improve its dielectric properties. The appearance and the ease of handling of MPI is the same as standard PI film and therefore, it can be processed by an FPC process. The achieved dielectric loss, $\tan\delta$, of MPI at this moment is about 0.005 to 0.01 and it is slightly worse than those of LCP. They are expected to be improved further in the near future.

・LTCC (low temperature co-fired ceramics)

LTCC is made into a multi-layer board composed of inorganic ceramic layers and conductive wiring layers of silver or copper. The multi-layer board is fabricated by consolidating ceramic layers by a single firing process after stacking raw ceramic sheets. It is easy to fabricate multi-layer boards with high layer counts using LTCC and thus LTCC boards are employed as various electronic module boards. The drawback of LTCC is its relatively high ε_r, which results in an increase in transmission loss.

・Fused silica glass

Fused silica glass (SiO_2) has an excellent $\tan\delta$, which is 0.0004 (f = 60 GHz), and devices and waveguides using fused silica exhibit excellent properties at mmWave frequencies. The drawback of fused silica is difficulty in the fabrication process because the material is brittle. It is also difficult to develop a multilayer structure using the material, thus it is not suitable for AiP use. However, in the future, it is expected to be an indispensable material for the development of next generation (Beyond 5G/6G) communication systems, in which mmWave frequencies over 100 GHz are employed.

In closing of this section, a comparison of properties among introduced mmWave board materials are summarized in Table 1.

Table 1 Property comparison among various wiring board materials.

Properties	Organic				Inorganic	
	Flex		Rigid		LTCC	Fused Silica
Principle Component	LCP	MPI	PPE	PTFE	Ceramics (Al,Mg,Si,,,)	SiO_2
Relative dielectric constant, ε_r	2.8	2.7 - 3.0	3.5	2.2 - 3.0	5 - 8	3.8
Loss tangent, $\tan\delta(\times 10^{-3})$	3	7 - 10	7	<1	0.5 - 4	0.4
CTE (ppm/°C)	14 - 18	15 - 50	15	100	3 - 12	0.5
Multilayer Structure	Fair	Fair	Good	Poor	Excellent	Poor
Humidity Absorption	Good	Poor	Good	Good	Excellent	Excellent
Shape and dimension of in-process material	Roll of sheet 500mm width		Square board 600mm sides		Tile <200mm	Wafer <200mm

3.4 Transmission properties for several board materials

For better understanding the impact of material properties on mmWave performance, transmission properties at mmWave frequencies for several board materials are shown below. Micro-strip lines with a characteristic impedance of 50 ohms were prepared for various materials, and transmittance $|S_{21}|$ spectra were measured. Figure 4 shows measured spectra for frequencies ranging from 10 to 67 GHz. As the graph shows, transmittance decreases as frequency increases for all materials. On the other hand, inclinations of the curves are different in each material. Among measured materials, PTFE showed the best transmission performance followed by LCP, MPI, and PPE. This almost coincides with the order of $\tan\delta$ values, and thus the small $\tan\delta$ is confirmed to be desirable for the increase in mmWave performance. In a practical sense, a board material should be chosen by considering not only mmWave performance but also other factors such as availability, quality, delivery and price.

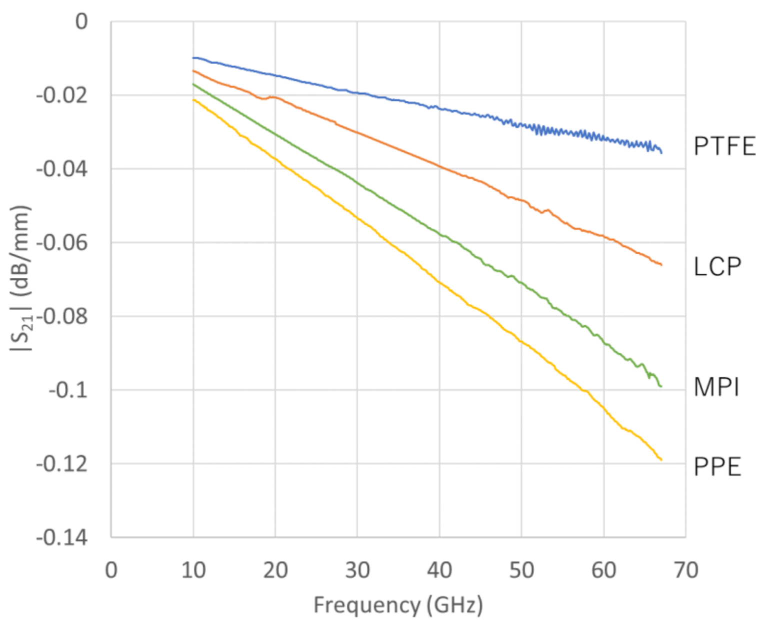


Fig. 4 Measured transmittance spectra of boards made from different materials.

4. Conclusion

This paper outlines wiring board material technology necessary for utilizing mmWave. Because of the inherent properties of mmWave, special material properties and board structures are required to put mmWave to practical use. Various board materials have been researched, and LCP has been confirmed as a promising candidate to fabricate practical mmWave AiP modules. In the field of mobile network technology, discussions about 6th generation communication systems have already started, and mmWave bands of over 100 GHz frequencies will be used to acquire wider bandwidths. Considering these circumstances, continuous and intensive development of board materials is expected to establish future high-speed networks.

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