Millimeter-Wave Automotive Antenna Using Low-Loss Fluoro-resin Substrates

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In order to realize autonomous driving, millimeter-wave radar will become more and more important. Being used in the radar, printed circuit boards (PCBs) are required to have low-loss characteristics, because transmission loss is very high in the millimeter-wave band. We have been developing low-loss PCBs made of fluororesin. We evaluated fluororesin substrates and confirmed their favorable transmission characteristics. We also prototyped an array antenna for automotive millimeter-wave radar using the substrate and successfully downsized the antenna surface area by approximately 40% compared with the conventional ones in the market.

Keywords: antenna, millimeter-wave radar, fluororesin substrate

1. Introduction

In recent years, 76 GHz millimeter-wave automotive radar intended for collision avoidance and following-distance control has rapidly come into wide use against the backdrop of increasingly low-priced millimeter-wave IC devices. Along with the future evolution of autonomous car technology, beyond simply for purposes of collision avoidance and following-distance control, it will become necessary for vehicles to detect other vehicles and pedestrians in all directions. Consequently, an increasing number of millimeter-wave radar devices will be mounted in each vehicle (Fig. 1). The millimeter-wave radar is distinctive in that it detects objects in low visibility such as in adverse weather conditions or at nighttime, compared with other sensor devices such as cameras and LiDAR.*1 Moreover, it has been reported to explore the use of 76 GHz band millimeter-wave radar for infrastructure, as well as for in-vehicle applications.[(1),(2)] Millimeter-wave radar will play an important role for both in-vehicle and infrastructure applications.

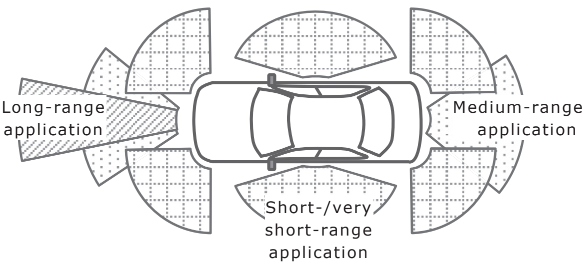


Fig. 1. Millimeter-wave radar arrangements

Sumitomo Electric Industries, Ltd. has developed a low-loss fluororesin printed circuit board (PCB) substrate for millimeter-wave applications. This report describes the evaluation results of the substrate's transmission characteristics in the millimeter-wave band and the results of designing, prototyping, and evaluating antennas intended for millimeter-wave automotive radar.

2. PCB Substrate for Millimeter-Wave Applications

2-1 Antenna for millimeter-wave automotive radar

A radar device emits radio waves, which are reflected by objects. By receiving the reflections, the radar device detects targets. For that purpose, it requires an antenna for transmitting and receiving radio waves. Automotive millimeter-wave radar commonly uses a microstrip antenna (MSA) made from a printed circuit board (PCB) with low cost and flexible design.[(3)-(5)] However, use of an MSA in the millimeter-wave band is subject to a high level of loss incurred over the transmission line such as a microstrip line (MSL) connecting the transmitter/receiver circuits and antenna. Reduced antenna gain due to this loss is a cause of degraded long-range performance of radar. To improve the radar detection range, or to achieve a higher antenna gain, one solution is to enlarge the surface area of the antenna. However, because the number of radar devices installed in each vehicle is expected to increase in the future, as described earlier, there is demand for radar devices with improved mountability. Consequently, it is necessary to make radar devices smaller.

The size of a radar device is proportional to the surface area of the antenna. A reduced surface area of an antenna contributes to reduced device size. By using a low-loss PCB to construct an antenna, it becomes possible to achieve both high antenna gain and reduced antenna size.

2-2 Relationship between transmission loss and surface roughness

A PCB consists of copper foils or other conductors, laminated to both sides of a dielectric body (insulating body), as shown in Fig. 2.

Transmission loss attributable to a PCB comprises dielectric and conductor losses (Table 1). Dielectric loss is caused by the electric field generated in the dielectric body. This loss depends on the material constants of the dielectric body, such as dielectric constant (ε_r) and dielectric loss tangent ($\tan\delta$).[(6)] Meanwhile, conductor loss arises from the electric current flow in the conductor. Conductor loss depends on the conductivity and increases in proportion to the square root of the frequency. Also, because high-frequency signal currents concentrate very near the surface of the conductor, known as the skin effect,*2 transmission loss increases with increasing surface roughness (unevenness of conductor surfaces). In this paper, the loss attributable to surface roughness is viewed as part of conductor loss.

Table 1. Causes of transmission loss and affecting parameters

	Dielectric loss	Conductor loss
Cause	Electric field within the line's surface	Current flowing on the line's surface
Affecting parameters	Dielectric constant (ε_r) Dielectric loss tangent (tanδ)	Conductivity **Surface roughness of copper foil**
	↓ Use of fluororesin for its superb dielectric characteristics (low ε_r and low tanδ)	↓ **Substantial effects in millimeter-wave band**

With the millimeter-wave band, a band comprising very short wavelengths, the skin effect is very large such that any loss affected by surface roughness is not negligible. It is a general practice to roughen the bonding surface of copper foils to enhance adhesion between the copper foil and dielectric body. Surface roughening is a cause of increased transmission loss.

2-3 Low-loss fluororesin substrate

Sumitomo Electric is working on development of a low-loss PCB made of low-dielectric loss fluororesin. One feature of this substrate is its extremely low surface roughness due to its copper foil lamination without surface roughening. Current PCBs available on the market have surface roughness of several micrometers at the interface between the copper foil and dielectric body. By contrast, the PCB under development at Sumitomo Electric features unevenness of less than 1 μm, exhibiting favorable smoothness (Fig. 2). This smoothness helps achieve low-loss transmission in the millimeter-wave band. In addition, the newly developed PCB meets the characteristic requirement of peel strength, which indicates the level of copper foil adhesion, required of PCBs.

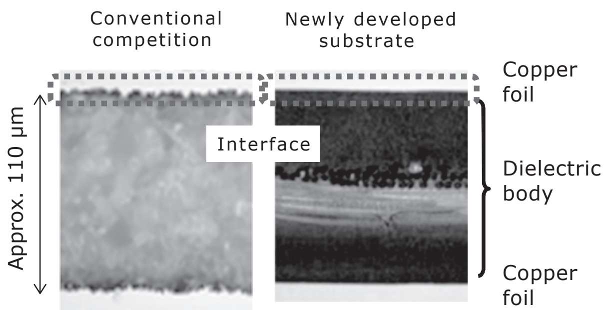


Fig. 2. Photos of cross-sectional views of PCBs

3. Evaluation of Millimeter-Wave Transmission Characteristics

The transmission characteristics of the fluororesin substrate under development were compared with those of conventional commercially available substrates to verify the low-loss performance of the newly developed substrate.

3-1 Substrates used for characteristics evaluation

To evaluate the transmission characteristics of the newly developed substrate, an MSL board was fabricated (Fig. 3 and Table 2) and its transmission characteristics were measured. Additionally, for comparison purposes, MSL boards were fabricated similarly from a liquid crystal polymer (LCP) substrate and a conventional fluororesin substrate, commonly used in millimeter-wave automotive radar devices, and their transmission characteristics were measured. Table 3 shows the substrates used for the evaluation.

Fig. 3. MSL board for transmission characteristics evaluation (Sumitomo Electric's fluoloresin substrate)

Table 2. Evaluation conditions

Parameter	Value
Measurement frequency range [GHz]	75-85
MSL line length [mm]	50, 100

Table 3. Test substrates

	Conventional substrate A	Conventional substrate B	Newly developed substrate
Material	LCP	Fluororesin	Fluororesin
Thickness of dielectric body [μm]	100	127	113
Thickness of copper foil [μm](*)	27	33	27

(*) Thickness includes 15 μm thick through-hole copper plating.

3-2 Evaluation results

Transmission loss per 100 mm was calculated based on the measurement results for two MSL line lengths (Fig. 4). Table 4 presents material constants used when designing antennas. Effective conductivity was used as an indicator to reflect surface roughness on transmission loss during electromagnetic field simulation and as a coefficient of the conductivity of copper foils.

Table 4 presents the evaluation results obtained at 77 GHz, which is the upper limit frequency of 76 GHz band radar. Compared with conventional substrates A and B, the newly developed substrate exhibited lower loss by approximately 4 dB/100 mm. This result confirms the low-transmission loss effect of the newly developed substrate due to the smoothness of the copper foil.

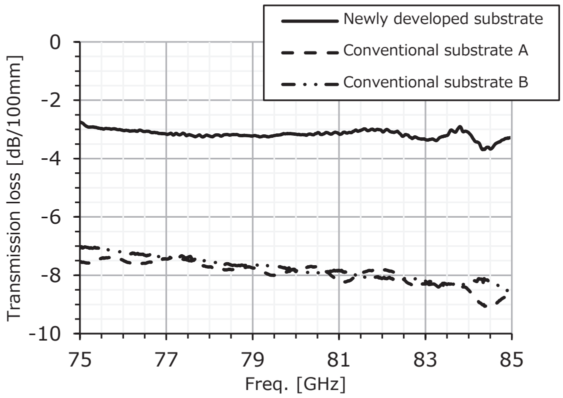


Fig. 4. Loss curves for test MSL boards

Table 4. Material constants

	Conventional substrate A	Conventional substrate B	Newly developed substrate
Material	LCP	Fluororesin	Fluororesin
ε_r	3.04	3.2	2.2
Tanδ at 10 GHz(*)	0.002	0.001	0.0008
Transmission loss [dB/100 mm] at 77 GHz	7.35	7.44	3.16
Effective conductivity (ratio to copper)	0.12	0.05	0.5

(*) Catalog values for conventional substrates A and B; measurements for the newly developed substrate

4. Antenna Design/Prototype Evaluation

Confirmation of the favorable low-loss performance of the fluororesin substrate under development, described in the preceding chapter, was followed by an examination of how much the low-loss performance would contribute to making antennas smaller. For this purpose, we designed an array antenna*3 comprising MSAs for envisioned applications for millimeter-wave automotive radar and checked its characteristics via electromagnetic field simulation. Moreover, a prototype was fabricated based on the antenna design and its characteristics were evaluated using actual equipment. A similar prototype antenna was fabricated using an LCP substrate (conventional substrate A, mentioned in Chapter 3). Using these antennas, a comparative evaluation was conducted.

4-1 Discrete antenna element design

For the type of discrete antenna element used to form the array antenna, a commonly used half-wave patch antenna was adopted (Fig. 5). First, one patch antenna element was designed. The element's characteristics were compared between both substrates via simulation. The required material constants used for this simulation are shown in Table 4.

Table 5 shows the simulation results for the designed discrete patch antenna in Fig. 5. The comparison results showed that the antenna gain of the newly developed substrate was higher than the other by 1 dB. In addition to the substrate's low-loss effect, one factor contributing to the higher gain is a low ε_r compared with the conventional substrate, which contributed to a larger outline of the antenna element and a narrower beamwidth.

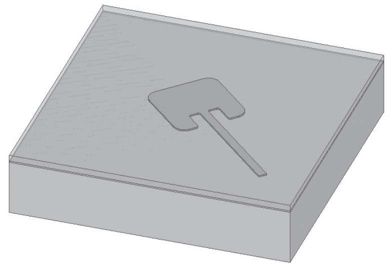


Fig. 5. Simulation model of discrete patch antenna

Table 5. Simulation results for discrete patch antenna

	Conventional substrate A	Newly developed substrate
Element outline [mm]	1.06 × 1.12	1.32 × 1.32
Antenna gain [dBi]	7.3	8.3
Beamwidth [deg] (45° polarized wave, horizontal/vertical)	3 dB width: 54 6 dB width: 106	3 dB width: 56 6 dB width: 98

Values for antenna gain and beamwidth were obtained at 77 GHz.

4-2 Array antenna design

Before designing the array antenna, performance requirements were estimated based on the configuration of conventional millimeter-wave automotive radar to establish target specifications for the transmitting antenna (Table 6). Based on these specifications, array antennas made of two substrates were designed.

Table 6. Array antenna design specification

Parameter	Performance
Polarization	45°
Design band [GHz]	76 - 77
Gain [dBi] (Antenna + Input block)	Min. 20
Beamwidth [deg]	Horizontal plane: min. 20 Vertical plane: min. 4
F/S ratio [dB]*4	Min. 17

Based on the transmission performance evaluation results presented in Chapter 3 and the discrete antenna element analysis results in the preceding section, element configurations were explored to meet the target performance using the aforementioned substrates. The outcome of this exploration was a 4 × 16 element antenna made of conventional substrate A and a 3 × 16 element antenna made of the newly developed substrate.

Three characteristics were compared between these antennas (Table 7): simulation results for gain attributable to directivity of the array antennas (directive gain); loss occurring at the MSL block determined based on the array antenna MSL lengths and the transmission loss of the substrates (Table 4); and the antenna gain simulation results. The gain of the antenna comprising fewer elements formed on the newly developed substrate was similar to that of the other antenna due to the low loss attributable to the MSL block, although its directive gain is lower.

Table 7. Comparison of array antenna simulation at 77 GHz

	Conventional substrate A	Newly developed substrate
Directive gain [dBi]	24.4	22.8
MSL loss [dB]	3.6	1.3
Antenna gain [dBi]	21.6	21.8

Figure 6 presents photos of the prototype antennas. The array antenna designed for the evaluation is split into two parts at the input block, with its power distributed to each array to meet the target specifications for side-lobe characteristics. Table 8 shows the results of a comparison of areas occupied by the two antennas. The array antenna made of the newly developed substrate is smaller than the array antenna made of conventional substrate A by approximately 40% in total area including the splitter, and by approximately 30% in the area of the element block, which is equivalent to antenna aperture.

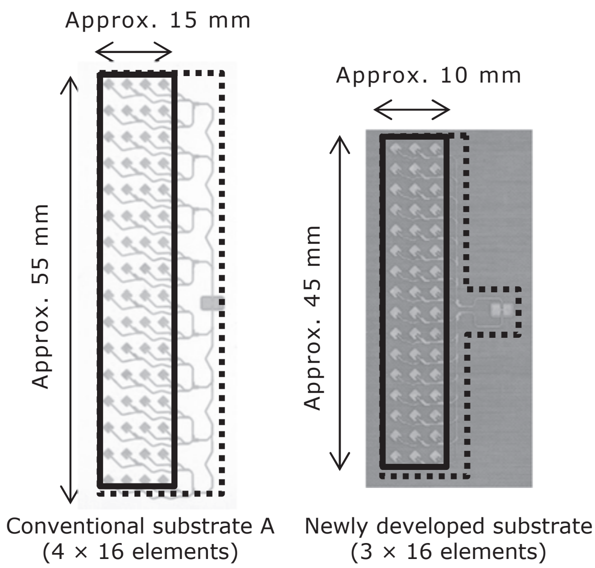


Fig. 6. Photos of prototype array antenna boards

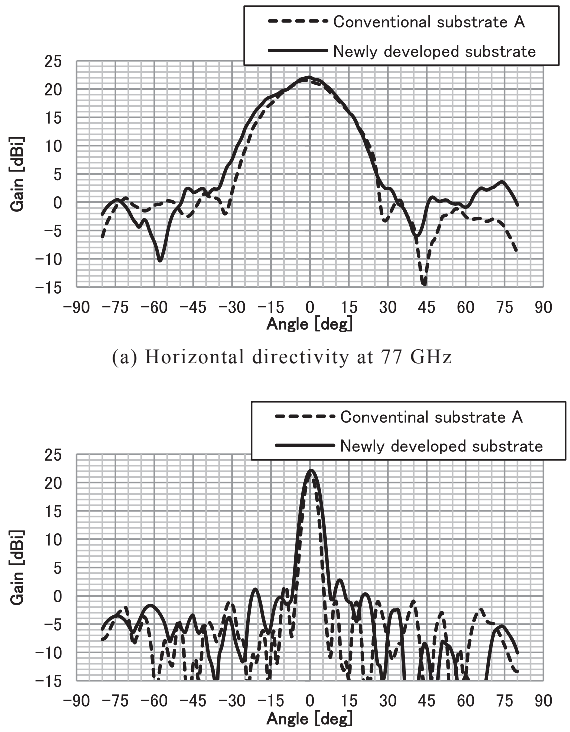
Table 8. Comparison of areas occupied by antennas

	Conventional substrate A	Newly developed substrate	Area ratio
Entire array (dashed line)	Approx. 865 mm^2	Approx. 485 mm^2	Δ44%
Element block (solid line)	Approx. 500 mm^2	Approx. 340 mm^2	Δ32%

Regarding the evaluation results for the two antennas, gain, beamwidth, and front-to-side (F/S) ratio are shown in Table 9. Directivity is presented in Fig. 7. The surface area of the antenna made of the newly developed substrate is substantially smaller. Nonetheless, both antennas have the same level of antenna gain and beamwidth. This is due to the low-loss performance of the newly developed substrate.

Table 9. Evaluation results of prototype array antenna

	Target value	Conventional substrate A	Newly developed substrate
Gain [dBi]	Min. 20	22.0	22.3
Beamwidth [deg]	Horizontal: min. 20 Vertical: min. 4	21.8 4.0	22.3 5.5
F/S ratio [dB]	Min. 17	20	17.5



(a) Horizontal directivity at 77 GHz

(b) Vertical directivity at 77 GHz

Fig. 7. Prototype array antenna evaluation results

5. Conclusion

The transmission characteristics of a low-loss fluoro-resin substrate under development at Sumitomo Electric for millimeter-wave applications were evaluated. Compared with a conventional substrate, the newly developed substrate contributed to reduced loss by approximately 4 dB/100 mm at 77 GHz. The loss reduction is due to the distinctive smoothness of the copper foil of Sumitomo Electric's board.

An example of an array antenna designed for millimeter-wave automotive radar applications was presented. Evaluated were two prototype antennas, one made of a conventional substrate and one of Sumitomo Electric's newly developed substrate. The evaluation results revealed that the newly developed substrate enables an antenna surface area reduction of approximately 40% due to the substrate's low-loss effect, while delivering similar performance as the conventional substrate.

Future challenges to resolve before commercializing the new substrate are evaluations of its temperature characteristics and linear thermal expansion coefficient. We will continue working on the development.

Technical Terms

∗1 Light detection and ranging (LiDAR): an infrared radar-based device used to measure the distance between a device and an object

∗2 Skin effect: The phenomenon of the largest current density occurring near the surface of a conductor when high-frequency signals are transmitted through the conductor

∗3 Array antenna: An antenna comprising two or more antenna elements so as to control directivity and to achieve higher antenna gain

∗4 F/S ratio: The ratio of the main-lobe level to side-lobe level in the context of antenna directivity. With radar antennas, miss-detection decreases with increasing F/S ratio.

References

(1) I. Jimbo, T. Inaba, and S. Ogawa, "A study on 2 Frequency Interrupted CW Radar for Driving Safety Support Systems," The 2013 IEICE general conference, B-2-23 (March 2013)

(2) T. Fukunaga, T. Takano, and S. Yamagishi, "A Study of 76GHz Band Patch Antenna for Vehicle Detection Radar," The 2017 IEICE general Conference, B-1-110 (March 2017)

(3) Y. Uezato, H. Yoshitake, M. Shono, M. Fujimoto, and T. Yamawaki, "Compact and High-performance Millimeter-wave Antennas," Fujitsu Ten Technical Report, Vol.28 Mo.2, pp. 19-25 (2010)

(4) Y. Kashino, H. Uno, and J. Sato, "Design Of Millimeter-Wave High Gain Array Antenna with Loop Elements," IEICE Technical Report, vol. 114, no. 450, AP2014-199, pp. 71-74 (February 2015)

(5) K. Sakakibara, D. Nakazawa, and N. Kikuma, "Multibeam-switching Millimeter-wave Electronic Beam-scanning Antenna using Multiple Microstrip Comb-line Antennas with Beam-tilting Design in Perpendicular Plane to Feeding-line," IEICE Technical Report, vol. 115, no. 40, AP2015-30, pp. 63-67 (May 2015)

(6) H. Shimizu, "Electrical Property Evaluation Technology and Latest Low Transmission Loss Materials for High Speed Application," PWB EXPO 2018, PWB-5, pp.77-103 (Tokyo, January 2018)

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