Development of millimeter-wave devices based on liquid crystal polymer (LCP) substrate

Ryohei Hosono\textsuperscript{a)}, Yusuke Uemichi, Yuta Hasegawa, Yusuke Nakatani, Kiyoshi Kobayashi, and Ning Guan

Fujikura, Ltd.,
1440 Mutsuzaki, Sakura, Chiba 285–8550, Japan
\textsuperscript{a}) ryohei.hosono@jp.fujikura.com

Abstract: Millimeter-wave (mm-Wave) technology is a promising solution to meet ever-increasing demand in wireless data transmission capacity thanks to the availability of large bandwidths at mm-Wave frequencies, where the choice of dielectric materials is one of important issues because the high water absorption at mm-Wave frequencies restricts remarkably the choice. Liquid crystal polymer (LCP) is one of materials available for mm-Wave applications and is able to provide cost-effective solution. In this paper, features of LCP will be introduced for applications at V-band (60 GHz) and E-band (70 GHz, 80 GHz) in terms of dielectric constant, feasible structure, process and reliability. Some LCP-based devices such as transmission line, mode transition between different transmission-lines, antenna and filter will be reviewed. It is demonstrated that LCP-based devices actually have shown good performance and LCP is especially suitable for consumer applications that require high reliability and cost-effectiveness.

Keywords: millimeter wave, dielectric material, liquid crystal polymer (LCP), mode transition, post wall waveguide (PWW), array antenna, filter

Classification: Microwave and millimeter-wave devices, circuits, and modules

References


1 Introduction

Wireless data traffic will probably grow 10,000 fold within the next 20 years for increased usage of smartphones, tablets and the Internet of Things (IoT), along with rich-content services, such as HD video, high-resolution music, video games and augmented reality (AR). Millimeter-wave (mm-Wave) technology is a promising solution to meet this ever-increasing demand in capacity thanks to the availability of large bandwidths at mm-Wave frequencies. Recently, mm-Wave technologies at 60 GHz (V-band), 70GHz and 80 GHz (E-band) are expected to be applied for the high-speed wireless communication and many devices have been developed [1, 2, 3, 4].

Among other technical issues in mm-Wave systems, choice of suitable dielectric materials as substrate is a critical one. As frequencies tend to increase up to mm-Wave, many materials such as FR4-material and polyimide whose losses are small at microwave frequencies are no longer suitable due to the water absorption which leads to unacceptable losses. It makes the choice ever more important that a mm-Wave transmission line has much higher loss than that for microwave transmission due to the small dimensions. Dielectric loss becomes quite significant when dielectric substrates are used for transmission lines and antennas. Fine-process availability with conductive through-holes and multiple layers, and good surface roughness are also required for the substrates. In addition, consumer applications are demanding cost effectiveness and handling easiness [5]. Liquid crystal polymer (LCP) is a potential material for mm-Wave devices [6]. Firstly, it has low dielectric loss even in mm-Wave frequencies due to its near hermetic nature [7]. LCP itself is a flexible-printed-circuit (FPC)-like thin-film and thus can be processed very cost-effectively. It is also easy to have conductive through-holes and be stacked to be multi-layered. Finally, a device made on LCP substrate maintains flexibility and can be easily handled [8].

In this paper, progress on development and evaluation for LCP-based mm-Wave devices is surveyed. As examples, LCP-based mm-Wave devices such as

transmission line, mode-transition between different transmission-lines, antenna and filter are introduced with comparison between simulated and measured results. It will be demonstrated that LCP has reasonably good properties and devices based on LCP-substrate can show good performance at mm-Wave frequencies. LCP can be used as a good substrate for cost-effective mm-Wave applications.

2 LCP as a low-loss dielectric material for mm-Wave applications

Although there are some popular epoxy-based dielectric materials to be used in microwave devices, few of them can support mm-Wave devices because their loss tangent increases rapidly when the operation frequency approaches up to mm-Wave bands. Fig. 1 compares frequency characteristics of loss for microstrip line (MSL) by using Polyamide (PI) and LCP substrates where the MSLs have similar cross-sectional dimensions. Even the PI-based MSL has the same loss with the LCP-based one at microwave frequencies, it shows much higher loss at mm-Wave ones.

![Fig. 1. Comparison of frequency characteristics of loss for PI- and LCP-based MSLs.](image)

For materials applying for mm-Wave applications, low-temperature co-fired ceramics (LTCC), LCP, polytetrafluoroethylene (PTFE) and silica glass are useful in terms of low-loss tangent. Table I lists up main features for these materials at around 60 GHz. LTCC is a well-used substrate in mm-Wave applications [9]. It has relative low-loss tangent at mm-Wave frequencies and is possible to be processed to multilayered structure that is required for many kinds of devices. However, the high dielectric constant and dimension variation during processing make it difficult to maintain high precision. PTFE has a loss tangent as low as $0.5 \times 10^{-3}$ at 60 GHz which exhibits significant impact on total loss in mm-Wave transmission-line but the processing such as metal sputtering deposition and electroplating for PTFE is also known to be difficult [10]. A ceramic-filled PTFE laminate makes the processing easier but also deteriorates slightly the ultra-low-loss property. Pure silica glass also shows ultra-low loss at mm-Wave frequencies and a post-wall waveguide (PWW) fabricated on silica glass has shown very low loss at mm-Wave frequencies [11]. However, a special laser processing technique is necessary for conductive via-holes.

LCP has been measured to have a relative dielectric constant of 2.91 and a loss tangent of $3.55 \times 10^{-3}$ at 60 GHz which is as low as that of LTCC, by using an apparatus based on dielectric resonator [12]. Lower dielectric constant is welcome
at mm-Wave frequencies because it allows larger dimensions in devices which contribute lower metallic loss and better dimensional precision. LCP film has slightly different dielectric constant in z-axis with that in-plane [13] but the impact on design is limited or can be easily controlled by taking the constants into simulation. Coefficient of thermal expansion (CTE) of LCP can be controlled by changing the fabrication condition and it is generally arranged to fit to the CTE of Cu film of 18 ppm/°C for commercially available LCPs so that it can provide high reliability when it is laminated with Cu films. Furthermore, surface roughness of LCP helps contact between Cu and LCP itself. Multi-layered substrate can be realized by using a standard laminate process and conductive via-holes can be easily completed by mechanic machining and electroplating. A roll-to-roll process can make the process very cost-effective. LCP-based substrate remains flexible and is even bendable without variation on performance, when the thickness is limited [8]. Based on these unique features, cost-effective and flexible mm-Wave components can be realized by LCP-based substrate.

### Table I. Comparison of mm-Wave available materials at around 60 GHz

<table>
<thead>
<tr>
<th></th>
<th>LTCC</th>
<th>LCP</th>
<th>Silica glass</th>
<th>PTFE</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\varepsilon_r)</td>
<td>5.9~9.1</td>
<td>2.91</td>
<td>3.8</td>
<td>2.1</td>
</tr>
<tr>
<td>(\tan \delta)</td>
<td>(4.0 \times 10^{-3})</td>
<td>(3.5 \times 10^{-3})</td>
<td>(0.8 \times 10^{-3})</td>
<td>(0.5 \times 10^{-3})</td>
</tr>
<tr>
<td>CTE [ppm/°C]</td>
<td>6</td>
<td>0~40</td>
<td>0.4~0.5</td>
<td>40</td>
</tr>
<tr>
<td>Machinability</td>
<td>normal</td>
<td>easy</td>
<td>difficult</td>
<td>difficult</td>
</tr>
<tr>
<td>Surface roughness</td>
<td>rough</td>
<td>rough</td>
<td>smooth</td>
<td>smooth</td>
</tr>
<tr>
<td>Work size</td>
<td>normal</td>
<td>large</td>
<td>small</td>
<td>normal</td>
</tr>
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</table>

3 Transition between different transmission lines

3.1 Transformer between MSL and PWW with blind-via excitation

To realize flexible RF package with low loss, configuration with PWW devices is important due to its low transmission loss and small influences from outside because of the closed structure. Additionally, due to its lower loss, antenna with higher gain such as slot array antenna is also realized. In general, integrated RF package with RFIC, transmission line and antenna in the same substrate is essential and is called antenna-in-package (AiP). To realize the packaging, consideration of connection to RFIC is needed and a mode conversion from MSL to PWW has to be constructed [14, 15]. Transformer between MSL and PWW on LCP substrate is proposed by using a blind-via as shown in Fig. 2 [8]. The transformer has multi-layered structure and thickness of 150 µm. Impedance matching is done by setting location of the blind-via, open-stubs and short strips of GSG pad. A paste-via to connect the MSL and blind-alias is adopted, which also connects GND pads and the top metal of PWW. Fig. 3 shows simulated and measured S-parameters of the transformer with blind-via where the simulation is carried out by HFSS™. Good agreement between the measured and simulated results is obtained and the bandwidth for a reflectance smaller than \(-15\) dB of 5.6 GHz is realized.
3.2 Transformer between MSL and PWW with through-via and anti-pad

In the previous structure, broadband operation is achieved by using an open-ended excitation where a blind-via is applied. Precise control of the size as well as the depth of the blind-via is required to optimize the bandwidth but it needs special fabrication technique. To overcome this technical difficulty, a new solution to realize broadband compatible with easy-to-fabricate transformer by using printed circuit board (PCB) technology is proposed [16, 17]. Fig. 4 shows the proposed MSL-PWW transformer with a through-via and an anti-pad excitation. The transformer uses the through-via to excite the TE10 mode into PWW and the anti-pad is set around the through-via so that it is electrically separated from the bottom broad wall of the PWW. By adapting this structure, simpler fabrication process can be available and it is easier to optimize transmission characteristics. Fig. 5 shows simulated and measured S-parameters of the transformer. Reasonable agreement
between simulated and measured S-parameters is confirmed and a bandwidth of 8 GHz for a reflectance smaller than −15 dB is obtained which is even broader than that realized by the transformer with blind-via. These mode transformers are promising for low-cost and integrated mm-Wave AiP.

![Simulated and measured S-parameters of the transformer with through-via and anti-pad.](image)

**Fig. 5.** Simulated and measured S-parameters of the transformer with through-via and anti-pad.

### 3.3 Loss evaluation of planar transmission lines

To evaluate intrinsic loss of transmission line based on the LCP substrate, broadband impedance matching is one of important thing and several kinds of transmission line losses should be evaluated for construction of efficient RF system. To achieve this purpose, a mode transition between grounded-coplanar waveguide (GCPW) and PWW is proposed in Fig. 6 [18]. Broadband impedance matching can be achieved by applying rectangular slit and through holes to the GCPW. The proposed structure is fabricated with different length of PWW (4.8 and 9.6 mm) and Fig. 7 shows the measured S-parameters of the mode-transitions. Return loss less than −15 dB from 52.7 GHz to 67 GHz is obtained and a dependency of transmission line length which is appeared in [19] is relatively small. Based on the measured S-parameters in Fig. 7, losses in different parts such as GCPW and tapered MSL in the transition are calculated by applying the de-embedding method [20]. Table II shows the extracted losses of the mode-transition at 60 GHz. Loss of

![Configuration of GCPW-PWW planar mode transition.](image)

**Fig. 6.** Configuration of GCPW-PWW planar mode transition.
GCPW itself can be obtained from the de-embedded data from the straight MSL, and that in the tapered MSL can be obtained by subtraction of losses of GCPW and straight MSL from the GCPW-PWW transition. The loss of tapered MSL of 0.286 dB is estimated so that all the other losses are figured out.

Fig. 7. Measured S-parameters of mode-transition for different length of PWW.

Table II. Extracted losses of the mode-transition at 60 GHz

<table>
<thead>
<tr>
<th>Type of loss</th>
<th>Measured value</th>
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<tbody>
<tr>
<td>Loss of GCPW</td>
<td>0.120 dB</td>
</tr>
<tr>
<td>Loss of straight MSL (length = 1.15 mm)</td>
<td>0.067 dB</td>
</tr>
<tr>
<td>Loss of GCPW-PWW transition</td>
<td>0.473 dB</td>
</tr>
<tr>
<td>Loss of tapered MSL (length = 1 mm)</td>
<td>0.286 dB</td>
</tr>
<tr>
<td>Loss of PWW per mm</td>
<td>0.086 dB/mm</td>
</tr>
</tbody>
</table>

4 Antenna

4.1 Microstrip comb-line antenna

A LCP-based microstrip comb-line antenna with bandwidth enhancement by using parasitic elements is considered [21]. Fig. 8 shows the configuration of the proposed antenna. The antenna is excited by a rectangular waveguide which is used for mm-Wave applications due to its lower loss. Propagation mode of the rectangular waveguide is transformed into MSL mode by the mode transition in the proposed antenna which has an inversely-tapered shape at the longitudinal direction. The transition contributes to reduce a reflectance of the antenna. Each radiation element has slot to reduce the reflectance. Broadband operation is realized by setting three kinds of parasitic elements around each radiation element with small gap for coupling whose dimension is 50 µm. Fig. 9 shows simulated and measured input characteristics and radiation pattern of the antenna at 60 GHz. Good agreement between simulation and measurement is obtained and an impedance bandwidth of 3.2 GHz and a peak gain of 13 dBi are demonstrated.
4.2 Corporate feed microstrip array antenna

In the previous microstrip comb-line antenna, there is dependency of beam direction on frequency because the phase differences on radiation elements depend on operating frequency. As a result, beam tilting is occurred to degrade the performance on data transmission at fixed point wireless application in mm-Wave band [22]. To avoiding the degradation of the wireless communication capacity, use of corporate-feed antenna is one of solutions because zenith angle of beam in an array antenna has no dependency on operating frequency by the same path and power to each element in the feeding circuit [23, 24]. A LCP-based corporate-feed microstrip array antenna for the lower E-band (71–76 GHz) is investigated as shown in Fig. 10. The antenna has MSL-typed feed line with slot at every end for aperture coupling to the patch antennas. The MSL feeder has a tournament shape to provide power from the waveguide with equi-amplitude and phase to the antennas as shown in Fig. 10(a). The aperture coupling is applied to avoid influence from the feeding line. The antenna is fed by a rectangular waveguide WR-12 and an interface for the mode transition is located on the center of the feeding line as shown in Fig. 10(b). By using this configuration, broadband
operation compatible with fixed-beam radiation can be realized based on parametric study of the proposed antenna. In the fabrication of the antenna, the mode transition is constructed on a fully metallic object fabricated by machining process. The substrate part of the antenna has a dimension of $30 \times 30 \times 0.23 \text{ mm}^3$ due to the thickness of substrate of 0.1 mm and adhesive layer of 0.03 mm. Fig. 11 shows input characteristics and radiation pattern at several frequencies. Impedance bandwidth is 71.9–77.9 GHz which is enough to cover a specification of the lower E-band which requires a bandwidth of 5 GHz. Peak gain exists at an angle of 0 degree at each frequency so that a fixed beam radiation is demonstrated in the proposed structure. Peak gain around 10 dBi in each frequency is also observed. The antenna can be used as one with steady beam radiation.

5 Multi-layered bandpass filter

Frequency selective surface (FSS) which is a thin, repetitive surface designed to reflect, transmit electric field for selective frequency can be used for reflect-array antenna, planar filter-lens and polarizer. LCP can be easily laminated to many layers and then is suitable for these applications which generally require broadband
operation at mm-Wave frequencies. Fig. 12 shows a bandpass filter by using multilayered LCP substrate which is configured with FSS as described in [25, 26]. The proposed structure is composed of capacitive layer (C-layer), inductive layer (L-layer) and LCP dielectric material. Bandpass filtering characteristics are achieved by cascading these elements with the parameters determined by filter response with the transmission line theory [27]. In this investigation, 6 C-layers and 4 L-layers are sandwiched by 250 µm-thick LCPs. Fig. 13 shows the simulated and measured frequency responses of the filter with perpendicularly entered electric field excited from a horn antenna. Good agreement is observed between simulation and measurement and a passband of 6.5 GHz is obtained in measured results.

6 Conclusion
In this paper, features of LCP have been introduced for mm-Wave applications and some devices based on the LCP substrate have been reviewed. Among available materials for mm-Wave applications, LCP has relative low-loss tangent and is easy to be laminated for multi-layered structure. LCP substrate can be fabricated by standard printed circuit process and a roll-to-roll technology makes the process further cost-effective. Flexibility maintained in LCP-based substrates makes the devices have good reliability and could be useful for unique applications that require flexibility.

LCP can be used for almost all the devices necessary for mm-Wave applications. LCP-based MSL as well as PWW provide transmission lines with low loss.
Broadband operable mode transitions between different transmission-lines make it possible to guide RF-signal from RFIC chip to low-loss waveguide and vice versa. LCP is suitable for multi-layered structure and is good for planar array antenna. It is easy to separate radiation elements from feeding circuit and couple them by a simple aperture structure by using the multi-layered structure. Good isolation between each radiation element is easily realized so that an array antenna can be systematically designed and the performance can be well controlled. Other functional components are also available by the LCP substrate. A spatial bandpass filter based on LCP-based FSS has been introduced and broadband operation has been demonstrated.

In conclusion, LCP is an appropriate material for mm-Wave applications. It can provide flexible substrate for mm-Wave devices with very low cost. Especially, LCP is suitable for consumer applications which generally require high reliability and cost-effectiveness.

Ryohei Hosono
was born in Chiba, Japan, in 1984. He received the B.E. and M.E. degrees in Faculty of Engineering from Chiba University, Chiba, Japan in 2007 and 2009, respectively. He joined the Optics and Electronics Laboratory, Fujikura Ltd. in 2009 and has engaged in research and development of antennas and millimeter-wave devices for wireless communications.

Yusuke Uemichi
was born in Aomori, Japan, in 1980. He received the B.E. and M.E. degrees in Faculty of Science from Tohoku University, Sendai, Japan in 2003 and 2005 respectively. He joined the Electron Device Laboratory, Fujikura Ltd. in 2005 and he has engaged in research and development of integrated passives and millimeter-wave devices for wireless communications.

Yuta Hasegawa
was born in Ibaraki, Japan, on February 28, 1989. He received the B.E. and M.E. degrees in Electronic Engineering from the University of Tokyo, Japan in 2012 and 2014. In 2014, he joined the Optics and Electronics Lab., Fujikura Ltd., where he has been engaged in research and development of millimeter-wave devices.

Yusuke Nakatani
has engaged in development of fabrication technology for flexible printed circuit board and materials for millimeter-wave frequency.
Kiyoshi Kobayashi received the B.E., M.E. and Ph.D. degrees from Tokyo University of Science, Japan, in 1987, 1989 and 2004, respectively. He joined NTT Radio Communication Systems Laboratories in 1989. Since then, he has been engaged in the research and development of advanced digital signal processing technologies including modulation/demodulation, synchronization control as well as advanced applications of wireless communications. From 2011 to 2014, he had been the director of ATR Wave Engineering Laboratories at Advanced Telecommunications Research Institute International. From 2007 to 2011 and in 2012, he had been a visiting professor at University of Tsukuba and Muroran Institute of Technology, respectively. Since 2016, he has been a deputy general manager of Electromagnetic Field Research Department, Advanced Technology Laboratory at Fujikura Ltd. He is a member of IEEE and a senior member of IEICE.

Ning Guan was born in Hunan, China, in 1962. He received the B.E., M.E. and Ph.D. degrees in electrical and electronics engineering from Chiba University, Chiba, Japan, in 1985, 1987, and 1990, respectively. From 1991 to 2000, he was a Research Associate at the Department of Electronics and Mechanical Engineering, Chiba University, studying on magnetostatic wave devices, theory of propagation of electromagnetic waves and applications of wavelet to boundary value problems in electromagnetic theory. Since 2000, he joined the Optics and Electronics Laboratory, Fujikura Ltd. His current research interests include analysis and design of optical fibers and optical devices for telecommunications, microwave devices and antennas for mobile communications. Dr. Guan is a member of IEEE.