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Design of Cylindrically Bent Antenna Array on LCP Substrate with Large Coverage at 60 GHz

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Abstract—The relative permittivity and homogeneity of LCP material have been characterized within the whole 60 GHz frequency band using the microstrip ring resonator (MRR) method. Using a circuit model, the gap capacitance of the MRR has been taken into account in order to improve the accuracy of the determined relative permittivity. The results show that the relative permittivity of LCP is almost constant (\(\varepsilon_r \approx 3.1\)) within the whole 60 GHz frequency band. The homogeneity of LCP is within 1.5% across the LCP panel. A cylindrically bent antenna based on LCP substrate has been designed, which has 56.3–67.0 GHz bandwidth and 6 dBi gain. With the proposed equilateral triangle grid array topology and sub-array switching, the cylindrically bent antenna array with 16 antenna elements has 13.8 dBi gain up to ±60° scan angles.

I. INTRODUCTION

60-GHz millimeter wave (mmWave) communication systems are getting increasing attention in recent years, especially for low-cost consumer applications [1]. For instance, wireless uncompressed high definition video streaming and ultra-fast wireless LAN are typical indoor environment applications at 60 GHz. These applications require the antenna array to have large scan coverage in order to operate in both line-of-sight (LOS) and non-light-of-sight (NLOS) conditions. In order to achieve the scan coverage requirements, cylindrically bending a planar antenna array can be employed [2]. In practice this means the use of flexible PCB. Currently, Polyimide (PI) materials are one of the dominant flexible substrates in electronics industries. But PI has high loss at mmWave. PTFE-based materials have very good electrical performance, but they are costly. Liquid crystal polymer (LCP) is a promising flexible substrate and packaging material for mmWave applications, especially for a conformal antenna array implemented on flexible PCB, due to its low cost and very attractive properties which include flexibility, ease of fabrication, low relative permittivity, low loss tangent, low moisture absorption, and the coefficient of thermal expansion (CTE) that is matched with copper [3].

The electrical properties of the substrate materials are essential factors for mmWave antenna design. LCP has been characterized at 60 GHz in the literature [4]–[6]. It is found in the literature that the determined loss tangent values are in a good agreement, but the relative permittivities of LCP vary between 2.92 and 3.25. In this work, the microstrip ring resonator (MRR) method will be used to examine the relative permittivity of LCP material in the whole 60 GHz frequency band. One reason for choosing this method is that the MRR method is simple in realization as a planar circuit, and has higher accuracy than the linear resonator method due to its higher quality factor. Furthermore, there is about 9 GHz spectrum allocated at 60 GHz frequency band (57.24–65.88 GHz) according to IEEE 802.15.3c Task Group [7]. However, in the literature the measurement results can not sufficiently cover the whole bandwidth since generally the resonant structure method is very accurate but can only measure the relative permittivity at the resonant frequency. Therefore, MRRs with 5 different resonant peaks, i.e. at 58, 60, 61.5, 63, and 65 GHz, are designed in order to examine the electric properties over the whole 60 GHz frequency band. In addition, the homogeneity of the materials can also cause the variation of the relative permittivity. In this work, the MRRs are distributed in a periodic way on the LCP panel in order to investigate the homogeneity of the LCP panel. The characterization of LCP is addressed in Section II.

In order to enhance the scan coverage of a 60 GHz radio systems, the cylindrically bent antenna array can be employed [2]. The BFACP antenna [8] has been chosen as the candidate of the array elements due to its high radiation efficiency, sufficient bandwidth to cover the whole 60 GHz frequency band, balanced-feed which can ease the integration with RFIC. In Section III, a cylindrically bent BFACP antenna is designed using LCP material as substrates. The antenna is simulated with the determined relative permittivity of LCP. The antenna bandwidth, the radiation efficiency, the antenna gain and the side lobe level (SLL) are optimized to a cylindrically bent configuration. An equilateral triangle grid antenna array topology is proposed in order to reduce the mutual coupling between the antenna elements. With the use of a sub-array switching scheme, the array can provide almost constant gain and low SLL within large scan coverage. Finally, the results are concluded in Section IV.

II. LCP CHARACTERIZATION

A. MRR Design

The layout of the designed microstrip ring resonator is shown in Fig. 1. \(R\) is the mean radius of the microstrip ring, \(S\) is the spacing of the coupling gap, and \(W\) is the width of the microstrip line.

The parallel resonant frequency of the unloaded MRR is
The parameters of the microstrip line are given by

\[ f_{0,N} = \frac{cN}{2\pi R \sqrt{\varepsilon_{\text{eff}}}} \]  

(1)

where \( \varepsilon_{\text{eff}} \) is the effective permittivity, \( N \) is the order of resonance, and \( c \) is the speed of light in vacuum [9]. Therefore, with the physical dimensions of the microstrip, the relative permittivity of LCP can be obtained with the relation

\[ \varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \frac{1}{1 + \frac{2t}{\pi h}}, \]  

(2)

with

\[ u_{\text{eff}} = u + \frac{1.25t}{\pi h} \left( 1 + \ln \left( \frac{2h}{t} \right) \right), \quad (\text{for } u > \frac{1}{2\pi}), \]  

(3)

and

\[ u = \frac{W}{h}, \]  

(4)

where \( t \) is the thickness of the microstrip and \( h \) is the height of the dielectric substrate [10]. The use of the effective width of the microstrip \( u_{\text{eff}} \) is because the thickness of the microstrip \( t \) is not negligible in this case.

However, the unloaded MRR has to couple with microstrip transmission lines in order to be measured. Therefore, parasitic capacitances are introduced by the gap between the MRR and the feeding line. This causes the resonant frequency of the loaded MRR to become lower than that of the unloaded MRR. As a result, the relative permittivity will be overestimated if the resonant frequency of the loaded MRR is used. As shown in Fig. 2, a circuit model of the loaded MRR can be used to take this effect into account [9], [11].

\[ Z_r = \frac{Z_0}{2} \coth(\gamma R) \]  

(5)

where \( Z_0 \) is the characteristic impedance of the transmission line and \( \gamma \) is the complex propagation constant. \( C_p \) and \( C_g \) represent the parasitic capacitances, which can be determined by a planar simulation of a T-gap configuration. The resonant peak of the circuit model can be used to compare with that of

the loaded MRR in order to determine the effective permittivity \( \varepsilon_{\text{eff}} \).

The MRRs have been designed on Rogers ULTRALAM 3850 LCP substrate. The LCP panel has the dimension of 457 mm \( \times \) 610 mm with the thickness \( h \) of 101 \( \mu \)m (4 mil). The design layout is shown in Fig. 3. The sub-block is shown in the right side of the figure, it contains the de-embedding structures, a small ring, and a big ring. The small and big rings have the 4th and 8th resonant peaks respectively around the design frequency, which is given by the numeric numbers with the unit of GHz. It is seen that there are 5 different resonant frequencies which are sampled within the whole 60 GHz frequency band in order to determine the electric properties of LCP material. The radii of the designed MRRs for these 5 different resonant frequencies are listed in Table I. The width of the microstrip line \( W \) is 227 \( \mu \)m and the metal thickness \( t \) is 18 \( \mu \)m in order to obtain a characteristic impedance of 50 \( \Omega \). The spacing of the gap \( S \) is 100 \( \mu \)m, which is the minimum achievable spacing of the manufacturer. The probe pitch is designed in order to land the ground-signal-ground (GSG) probes with 250 \( \mu \)m probe tip spacing. Using a through-reflect-line (TRL) calibration, the two-port measurement results are de-embedded to the reference plane as shown in Fig. 1 in order to remove the effects of the transition from the GSG probe to microstrip. Therefore, the measurement results after de-embedding can be used to obtain the resonant frequency of the loaded MRR.

![Fig. 1. Layout of a two-port microstrip ring resonator.](image1)

![Fig. 2. Circuit model of loaded MRR.](image2)

![Fig. 3. Layout of LCP panel.](image3)

![Table I: Radius of MRRs.](image4)
of this MRR is at 60.42 GHz, which is close to the designed resonant frequency 60 GHz.

![Fig. 4. S21 measurement of a small MRR.](image)

With the use of the circuit model presented in Fig. 2, the relation between the relative permittivity of the LCP materials and the resonant frequencies of the MRRs can be obtained. Fig. 5 shows this relation for the small MRRs which have 4th resonant peaks around 60 GHz. It is found that the corresponding relative permittivity \( \varepsilon_r = 3.099 \) if the 4th resonant frequency is 60.42 GHz. It is seen that the fabricated dimension of MRRs should be used, otherwise the relative permittivity is about 1.3% lower if the design values are used.

![Fig. 5. The relative permittivity of LCP materials determination.](image)

The fabricated dimensions of the MRRs are measured by comparing with reference coplanar lines on the calibration substrate through a microscope, which are listed in Table II. It is seen that both the spacing of the gap S and the width of the microstrip line W have about 30 \( \mu \)m tolerance compared with the design value. The details are documented in [12].

**Table II**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>W (( \mu )m)</th>
<th>S (( \mu )m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>227</td>
<td>100</td>
</tr>
<tr>
<td>Fabrication</td>
<td>196</td>
<td>129</td>
</tr>
</tbody>
</table>

![Fig. 6. The relative permittivity of the LCP panel.](image)

Fig. 6 shows the relative permittivity at 5 different resonant frequencies, as obtained from small MRRs using the circuit model. It is observed that the relative permittivities at 5 different frequencies are almost constant. It is found that the average of the relative permittivities of the measured LCP samples \( \varepsilon_r = 3.093 \), and the sample standard deviation \( \sigma = 0.012 \).

![Fig. 7. The relative permittivity of the LCP panel obtained from big MRRs.](image)

From Fig. 6 and Fig. 7 it is also found that the variation of the relative permittivities at different positions of the LCP panel is within about 1.5% across the whole LCP panel. This
variation can be caused by the fabrication tolerance of the MRR radius, the measurement errors, and the homogeneity of the LCP panel. As a result, the homogeneity of the LCP panel is suitable for mass production of bent antenna arrays operating in the 60 GHz frequency band.

III. ANTENNA ARRAY DESIGN

A. Antenna Design

To cope with the large scan coverage requirements of 60 GHz radio systems, e.g., ±60°, it is feasible to use cylindrically bent antenna array instead of a planar array [2]. It has been demonstrated that a planar array of balanced-fed aperture-coupled patch (BFACP) antennas can provide about ±30° scan range [13]. In order to enhance the scan coverage, the cylindrically bent BFACP antenna has been designed based on the flexible LCP substrate. The layout is shown in Fig. 8. LCP is used in all the substrate layers. The thickness of substrates is 254 µm (10 mil), 101.6 µ (4 mil), and 254 µm (10 mil) from top to down layers respectively. The copper thickness is 18 µm. The antenna will be bent cylindrically with 7.64 mm radius. In that way, an 8 element linear array with λ0/2 spacing becomes about a 150° arc. The slots are excited by a dipole with a coplanar stripline as the balanced input. The patch is excited by the slots due to the coupling effect. The slots and the patch are resonant at slightly different frequencies in order to increase the impedance bandwidth of the antenna. The reflector is used to reduce the back radiation. The important dimensions of the antenna are given in Table III.

![Fig. 8. The side view of the cylindrically bent BFACP antenna based on the LCP substrate.](image)

**TABLE III**  
**DIMENSIONS OF THE CYLINDRICALLY BENT ANTENNA**

<table>
<thead>
<tr>
<th>Element</th>
<th>Parameter</th>
<th>Value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>patch</td>
<td>length</td>
<td>1.08</td>
</tr>
<tr>
<td>slots</td>
<td>length</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>spacing</td>
<td>1.3</td>
</tr>
<tr>
<td>dipole</td>
<td>length</td>
<td>1.66</td>
</tr>
</tbody>
</table>

Fig. 9 shows simulation results of the reflection coefficients and the radiation efficiency of the cylindrically bent BFACP antenna using CST Microwave Studio with the relative permittivity εr = 3.1, which is determined in the previous section. It is observed that the designed antenna has 56.3–67.0 GHz (17.4%) -10 dB impedance bandwidth, which can fully cover the whole 60 GHz frequency band defined in [7]. It is also seen that the radiation efficiency of the antenna is always larger than 80% in the whole interested frequency band in order to provide sufficient transmit power.

![Fig. 9. The reflection coefficients and the radiation efficiency of the cylindrically bent BFACP antenna.](image)

Fig. 10 shows the gain and the SLL of the designed antenna. It is seen that the antenna gain is about 6 dBi over the whole target bandwidth. The SLL is always lower than -10 dB since the backward radiation is reduced by the reflector element.

![Fig. 10. The gain and the SLL of the cylindrically bent BFACP antenna.](image)

Fig. 11 shows the radiation pattern of the designed antenna at 60 GHz. It is found that the half-power beamwidth (HPBW) is 116° in E-plane (the bending plane), and 75° in H-plane.

![Fig. 11. The radiation pattern of the cylindrically bent BFACP antenna at 60 GHz; E-plane (solid), H-plane (dashed).](image)
B. Array Design

As shown in Fig. 12, an equilateral triangle grid array topology is proposed. The spacing between the elements in this topology can be $\lambda_0/\sqrt{3}$ instead of $\lambda_0/2$. As a result, the mutual coupling between the elements is reduced. But the form factor of the array will become bigger. For instance, with the use of the proposed antenna, an 8 element linear array with $\lambda_0/\sqrt{3}$ spacing becomes about a 173° arc instead of a 150° arc. For 60-GHz applications, it is desired to use the maximum EIRP within the whole scan range. Therefore, sub-array switching can be employed to take the advantage of the cylindrical configuration in order to keep the array gain as constant as possible at different scan angles. With a uniform excitation, the sub-arrays can be switched in such a way that at the different scan angles, the one which can provide the highest array gain is used. This can be achieved by controlling the amplifier integrated with each antenna element. In this way, the SLL of the antenna array can also be reduced since the elements that mainly contribute to the side lobe directions are switched off.

![Sub-array](image)

Fig. 12. The topology of the triangle grid array with 2 rows.

Fig. 13 shows the gain and the SLL at different scan angles of a cylindrically bent triangle grid array which consists of 2 rows of 8 antenna elements with $\lambda_0/\sqrt{3}$ spacing. As shown in Fig. 12, 8 elements sub-arrays are employed. It is seen that the array gain keeps about 13.8 dBi up to around 60°, and the SLL is lower than -10 dB in the whole scan range.

![Gain and SLL](image)

Fig. 13. The gain and the SLL of a cylindrically bent equilateral triangle grid array.

IV. CONCLUSIONS

In this paper, the characterization of the relative permittivity and the homogeneity of LCP material has been carried out using the MRR method. It is found that the relative permittivity of LCP is almost constant ($\varepsilon_r \approx 3.1$) within the whole 60 GHz frequency band. The variation of the relative permittivity is found to be within 1.5% across the LCP panel. As a result, the homogeneity of the LCP panel is suitable for mass production of bent antenna arrays operating in the 60 GHz frequency band. With the determined relative permittivity, a cylindrically bent BFACP antenna has been designed based on LCP substrates. The simulation results show that the antenna has 56.3–67.0 GHz (17.4%) -10 dB impedance bandwidth, 6 dBi antenna gain, and higher than 80% radiation efficiency. In order to reduce the mutual coupling between the antenna elements, an equilateral triangle grid antenna array topology is proposed. With 8 elements sub-array excitation, the antenna array has 13.8 dBi gain up to ±60° scan angles, and lower than -10 dB SLL.

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REFERENCES


