Measurement aspect of 60-GHz end-to-end antenna system for non-contact gigabit data communication

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ABSTRACT
The need for high-data rate wireless communication inevitably increases. Exploiting the available 60-GHz ISM frequency band is one of the plausible ways to support gigabit data communication. In this work, very-short-range paired antennas are designed, measured, and tested for an end-to-end 60-GHz communication system. The tested system is projected to bridge a small gap while facilitating high-speed data communication. The dual-sense circularly-polarized antenna exhibits the rotational freedom while promoting the spectral efficiency, i.e. a full-duplex antenna. The dielectric rod is incorporated to improve the directivity and reduce the side lobe level (SLL) while still featuring a low radar cross-section (RCS).

Key words: Antennas, rod antenna, millimeter-wave measurement, radiation pattern measurement, end-to-end measurement, radar cross-section.

1. INTRODUCTION
A high-performance dielectric rod antenna with an optimized dielectric shape for high gain is designed by the authors in [1]. This rod antenna will be paired with another identical antenna to facilitate non-contact data communication for very short distance. This high-gain rod antenna has relative small lateral dimensions and a less-complex structure compared to the design in [2] and [3]. These advantages allow more freedom to add more features, such as dual circular polarization. This dual circular polarization can be used for duplex communication and provides rotational freedom while promoting spectral efficiency. Moreover, for smaller dimension, this antenna can obtain better gain and axial ratio bandwidth than what is reported in [4]. The small dimension means that the antenna system can be integrated in small form-factor device or apparatus such as robot arm where the feature of rotational freedom is required.

The detailed design of the rod antenna itself can be found in [1] and [5]. Nonetheless, section 2 of this paper will briefly explain the results that are relevant to the focus of this work.

This work mainly focuses on the study of the paired antenna systems that build an end-to-end communication system. Issues such as degradation of the isolation performance, distance-dependent performance, and so forth may compromise the prototype’s stand-alone performance. Therefore, solution to cope with those is proposed, designed, and measured. Radar cross section (RCS) analysis will also accompany the study. This result will be used as foundation before integrating the antenna system with the 60-GHz Radio Frequency Integrated Circuit (RFIC).

2. ANTENNA DESIGN
The dielectric rod is designed to obtain high radiation performance. The detailed dimensions of the rod are depicted in Fig. 1. This rod will be fed by a patch antenna. The tapered section is to reduce side lobe level (SLL), and the uniform section is to produce maximum gain. The maximum end-fire radiation is obtained by adjusting the length of those sections. The diameter of the rod supports an HE_{11} hybrid mode.
TPX or polymethylpentene is the material for the dielectric rod. The diameter of the rod base is made large to have sufficient surface area for strong adhesion. Note that the thickness of this rod base should not be larger than 0.16λ. Otherwise, the realized gain will deteriorate.

![Copper trac 0/0.25mm, LCP 0/0.5mm, Adhesive 0/0.2mm, Polyimide 0/0.25mm, Adhesive 0/0.13mm, LCP 0/0.1mm, Copper trac 0/0.25mm](image)

**Figure 2.** Manufactured LCP stack-ups and exploded view of the carrier substrate.

A quadrature hybrid coupler excites the patch antenna (dashed line) via electromagnetic coupling to the upper layer. This coupler acts as a 3dB power divider with a phase difference of 90°. This phase difference causes the patch to radiate circular polarization with high port-to-port isolation, i.e. at least 20dB. The two arms should be electrically far from the edge of the patch to maintain the polarization purity of the patch radiator. The square patch antenna is used to ensure identical performances for both resulting polarization senses. Two layers of Liquid Crystal Polymer (LCP) laminate are used in this design as illustrated in Fig. 2.

A balanced-fed input interface to the antenna system is required. The wideband balun is used here to convert the differential to single-ended signal. This is because many millimeter-wave band RFIC and RF packages have differential signal interfaces. The impedance conversion from 100 to 50 Ω (or vice versa) is performed by the λ/4 transformer. The manufactured rod and planar structure is shown in Fig. 3.

The design and simulation in this work are analyzed using a full-wave EM simulator, namely CST Microwave Studio and Design Studio.

![Figure 3. Manufactured dielectric rod antenna on top of the microstrip structure on LCP carrier.](image)

**3. ANTENNA MEASUREMENTS**

**3.1. S-parameter measurement**

The preparation for the stand-alone antenna measurement is first explained. To feed the antenna system, 60-GHz RPC-1.85 connectors are utilized. The Thru-Reflect-Line (TRL) calibration has been performed before the measurement. For that purpose, it is necessary that RPC connectors with uniform impedance profiles are used. This can be checked using the Time Domain Reflectometry (TDR) measurement technique. The calibration board is shown in Fig. 4. With the TRL calibration, the influences of the microvia, RPC connector and transmission line are de-embedded. The contribution of those components to the insertion loss is depicted in Fig. 5.

![Figure 4. Calibration board for performing 60 GHz TRL calibration.](image)

In Fig. 6, the measured S-parameters are summarized. It can be observed that the measured and simulated results are in a good agreement. From the S11 curves, it can be seen that the (-10dB) impedance bandwidth of the antenna system is quite broad and spans from 53 GHz up to beyond 67 GHz. On the contrary, the (-20dB) port-to-port isolation bandwidth (S21) is relatively narrow, which is around 1.1 GHz. The scattering
parameters are thus interchanged as illustrated in Fig. 6 and are attributed to the existence of the coupler.

![Figure 6. Measured S-parameters of the single antenna.](image)

The mismatch at the input of the antenna is reflected back at both arms. Knowing that the waves in each arm have 90° phase difference, the reflected waves that are going to the other port are constructively added whereas the other waves that are going to the exciting port are destructively added. On that account, for a proper hybrid coupler design, $S_{21}$ is associated with the resonance of the antenna whereas $S_{11}$ is basically the mutual coupling of the two arms. The antenna resonance occurs approximately at 61 GHz, and the antenna’s (-20dB) isolation bandwidth is 1.1 GHz.

The shallow peak around 64 GHz, that is unobserved in the simulation, results from the larger size of the ground plane in the manufactured sample compared to the size of it in the simulation. As soon as the size of the ground plane is minimized, the discrepancy between simulation and measurement disappears.

The measured $S_{21}$ is associated with the port-to-port isolation. This isolation is required to reduce the transmitted/coupled signal from the Tx chip flowing to the close-end Rx chip.

### 3.2. Radiation pattern measurement

The 60-GHz measurement facility is shown in Fig. 7. The holder can be adjusted to position the rotational axis of the standard gain horn (SGH) in the AUT’s phase center. The radiation measurement is performed by rotating SGH 0°, 90°, and 45°. From post-processing of the measured data, the realized gain and axial ratio (AR) of the antenna can be obtained [6].

![Figure 7. 60-GHz anechoic chamber and the dielectric rod antenna being measured.](image)

The measured radiation patterns for both 0° and 90° planes are depicted in Fig. 10 and Fig. 11, respectively. The measurement results in both 0° and 90° planes are also in good agreement with the simulation results. From the observation for $0 < 0°$, the waves are influenced by the RPC connectors and termination.

The measured S-parameters of the two arms are illustrated in Fig. 6. From the observation for $0 < 0°$, the waves are influenced by the RPC connectors and termination.

In Fig. 9, the (-20dB) isolation bandwidth from $S_{21}$ measurement. Note that -20dB isolation means -20dB coupled to port 2.

![Figure 8. Axial ratios in the 0°-plane at 61 GHz.](image)

The measured axial ratio is illustrated in Fig. 8. The axial ratio pattern agrees with the simulated ones. Nevertheless, the measured AR is slightly better than the simulated one.

![Figure 9. Definition of (-20dB) isolation bandwidth from $S_{21}$ measurement. Note that -20dB isolation means -20dB coupled to port 2.](image)
load (obstacles) which slightly shift the mainlobe’s maximum.

Figure 10. Radiation pattern at several frequencies of interest, 90°-plane.

Figure 11. Radiation pattern at several frequencies of interest, 0°-plane.

Post-processing the measured horizontal and vertical field values for the spatial angle $\phi$ and different elevation angle $\theta$ results in the polarization ellipse and pattern. In Fig. 12, the normalized polarization ellipses are plotted for $\theta$ values which have the 3dB AR and in the main beam direction or 0°. In the main beam direction, the circular pattern is observed, indicating a circularly polarized radiation. The polarization pattern and ellipse for the worst-case AR (for $\theta = 82^\circ$) can be seen in Fig. 12(b) (see also in Fig. 8) whereby the slanted ellipse pattern and the tilt angle of 20.9° are observed.

Figure 12. Normalized polarization ellipse at 61.5 GHz for several elevation angles $\theta$ and (b) normalized pattern and ellipse for $\theta = 82^\circ$. The result is obtained in the 0°-plane of the Poincaré sphere.

In Fig. 13, the performance of the dielectric rod antenna for the antenna's (-20dB) isolation bandwidth is summarized for both 0°-plane and 90°-plane. It can be observed that the obtained gain is around 15 dBi. The AR is below 0.5 dB. The 3dB beamwidth for both principle planes is similar over the frequency band, showing the symmetry property of the rod's radiation pattern. The sidelobe level is measured to be around -9.5 dB.

Figure 13. Measured antenna performance over the frequency band of interest (i.e. (-20dB) isolation bandwidth from 60.45 – 61.55 GHz). (a) Co-polarization gain, (b) Axial ratio, (c) 3dB beamwidth, and (d) SLL.
4. MEASUREMENT OF ANTENNA PAIR

As explained in the previous section, the antenna supports full-duplex communication by means of dual-circular polarization. To evaluate it, the fixture shown in Fig. 14 is created.

![Test fixture of the end-to-end systems.](image)

This fixture is used for end-to-end testing (see Fig. 15), i.e., to measure the reflection coefficient or $S_{11}$, transmittance or $S_{41}$, near-end cross-talk (NEXT) or $S_{21}$, and far-end cross-talk (FEXT) or $S_{31}$. The measurement of misaligned and tilted pair of the antenna system is also made possible by this fixture. This measurement is provided here to investigate when the communication outage occurs if the misalignment or tilt is incrementally applied. Furthermore, the RCS of each antenna has to be considered to minimize the multiple reflections caused by scattered wave as will be discussed in the next paragraphs. The test fixture is covered with absorbing material to reduce the reflection and scattering from the fixture.

![Measurement setup of the end-to-end antenna systems.](image)

Fig. 16 illustrates the transmittance when different distances from tip to tip of the dielectric rod are applied. A good agreement between the simulation and measurement is observed indicating that the test fixture with the absorber can mimic the ideal condition of the simulator, leaving the cause of the ripple on the $S_{41}$-curve (a.o. reflection and scattering) in the antenna’s RCS.

![Measured transmittance for different distances. Otherwise specified, the distance in this paper is the tip-to-tip distance between the rods.](image)

To summarize, Fig. 17 depicts the transmittances from the Friis equation calculation, measurement, and simulation. The measurement and simulation results have a good agreement while the calculation result gives a minor discrepancy.

![Comparison between antenna system’s transmittances based on Friis transmission equation, measurement, and simulation. The distance being used here is between the planar antennas.](image)

Fig. 18 summarizes the measurement results of all S-parameters of the complete system. It can be observed that reflection is small in the whole band of interest as shown in the previous section. The transmittance shows a value around -7 dB between 58 – 62.5 GHz, proving the efficient radiation in that frequency range. FEXT($S_{31}$) is below -20 dB for the whole frequency band.
Interesting isolation result is observed when the pair of antenna system is set, as illustrated in Fig. 18 (also in Fig. 21). Particularly for 0cm distance, the isolation is degraded. Obviously the criterion of -20dB isolation turns to be very limiting now. In other words, when the antennas are paired, multiple reflections influence the channel’s coherence bandwidth.

This effect is more pronounced at port 2. This is due to the switched polarization sense of the wave after reflection and scattering. Note that for very short distance and high-directive antenna, the influence from the environment, a.o. the reflection, is negligible.

To study this behavior, the time signal at port 2 is recorded (see Fig. 19). The signal contribution at port 2 from the delayed incoming wave is recorded to occur 0.5 ns later. This wave component has been travelling through the dielectric rods and reflected back. As expected the initial $S_{21}$ is spoiled by the reflected wave component. The notch width is due to the delay spreads; its relative depth is due to the difference in path gain (or loss). The delay spread can be interpreted as the difference between the arrival time of the earliest wave component and the arrival time of the latest wave component. Therefore, the delay spread becomes larger when the size of the environment is larger. In addition to that, obviously, the delay spread also depends on amplitude difference.

Therefore, by performing windowing the signal from 0 to 0.45 ns, the expected isolation can be restored as seen in Fig. 20. Now the back-scattered wave at 0.5 ns is excluded from the observation.

Although it is not mentioned here for brevity, the transmitted wave is recorded at port 4 after 0.29 ns. Further, another component of the transmitted wave is recorded again at port 4 after 0.6 ns. That second incident wave is in fact the multiple-reflected wave version of the transmitted wave. Therefore, its power has been strongly reduced during propagation. Hence, no significant influence in the antenna’s transmission is observed though weak ripples can still be observed (see Fig. 16).

To tackle the issue caused by the back-scattered wave, minimizing the ground plane or applying the absorber in the outer part of the planar structure is proposed.
Reducing the ground plane dimension will not decrease the antenna gain in the direction of the main beam. This fact is due to the use of directive dielectric rod. Therefore, the antenna’s radiation performance is still maintained.

To study the multiple reflection behavior, investigation on the antenna’s RCS is performed. RCS is the measure of a target’s ability to reflect an incident wave in the direction of the sender’s receiver (see Eq. 1) [7]. The sender is the sending rod antenna, and the target in this case is the opposite rod antenna.

\[ RCS = \frac{4\pi R^2 |E_t|^2}{|E_0|^2} \]  

(1)

where \( E_0 \) is the electric-field strength of the incident wave impinging on the target, and \( E_t \) is the electric-field strength of the scattered wave at the sender. Mono-static RCS is employed in this investigation because in the practical application, the sender’s transmitter and receiver are collocated.

From Fig. 22 it can be observed that by reducing the size of the ground plane can reduce 3 dBsm (dBm^2) RCS in \( \theta=0^\circ \). This reduction even becomes more significant up to \( \theta=20^\circ \). Tilted pair of antenna systems can therefore benefit more from this small ground plane. At \( \theta=40^\circ \), the increasing ripples in Fig. 22 suggest the presence of a wave due to edge diffraction as seen at the edges of a large ground plane in Fig. 23.

RCS values for both ground plane’s dimension can be verified through backscattering formula from a flat plate as in Eq. 2:

\[ RCS_{\text{max}} = \frac{4\pi l^2w^2}{\lambda^2} \]  

(2)

where \( l \) (dimension in \( 0^\circ \)-plane) and \( w \) (dimension in \( 90^\circ \)-plane) are the length and width of the ground plane, respectively. For large ground plane, \( l \) and \( w \) are 6.91 and 8 mm, respectively. For small ground plane, these are 3.36 and 5.2 mm, respectively. Calculated RCS_{\text{max}} for large and small ground plane is -28.13 and -38.14 dBsm, respectively. The discrepancy between the value in Fig. 22 and the calculated value is mainly due to the presence of the dielectric rod and dielectric laminates in the simulated value. This influence becomes more prominent for small ground plane since large portion of the back-scattered wave will be redirected by the dielectric rod to the sender.
solder bumps for interconnection with the 60-GHz RFIC is animated. The high isolation is responsible to obtain good received signal in this full-duplex communication system.

Figure 25. Surface current of bent antenna structure with small ground plane connected to baluns and 60GHz RFIC. The dielectric rod is hidden for clarity.

5. CONCLUSIONS

The dielectric rod antenna with dual circular polarization has been designed, manufactured, and measured. The obtained 15dBi circularly-polarized gain occurs around 61 GHz. The port-to-port (-20dB) isolation bandwidth is 1.1 GHz. It is demonstrated through simulation and measurement that reducing the size of the antenna’s ground plane and bending the flexible laminate will reduce the multiple reflections while maintaining its performance. This result is verified by the mono-static RCS analysis. The high port-to-port isolation is thus maintained in the paired system. The antenna is suitable for the application of bidirectional non-contact gigabit data communication.

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7. REFERENCES


