Beam-Switching Lens Antenna at 60 GHz for Gigabit Data Rate Wireless Indoor Connections

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Abstract

This paper presents the design and measurements of a beam-switching lens antenna at 60 GHz. The extended hemispherical Teflon lens has a diameter of 20 mm and is fed using a slot-coupled CPW-fed patch antenna on LTCC. The S-parameters measured on a probe station are presented. A V-connector was used to provide the millimetre-wave signal connection to the feed antenna in the radiation pattern measurements. A plastic support made from PVC was fabricated to support the lens. The simulated and measured radiation patterns of the feed and the lens are shown. The maximum gain of 19.5 dBi was measured for the lens antenna. A beam steering range of 56° was demonstrated by manually shifting the lens position by 13.5 mm relative to the feeding antenna. The presented design is a good alternative to a phased array for a beam-steerable moderate-gain antenna for the gigabit data range wireless indoor applications.

Keywords: LTCC, integrated lens antennas, microstrip antennas, millimetre-wave

INTRODUCTION

In recent years, the increasing need for higher data rates in consumer applications has raised a lot of interest in developing low-cost radio solutions for millimetre-wave frequencies. Emerging applications, such as wireless high-definition video transmission require bit rates in the order of 1–4 Gbps and a bandwidth of about 2000 MHz [1] which is not available at microwave frequencies. The wide unlicensed frequency band at 60 GHz is very suitable for gigabit data rate indoor connections and the standardisation work is currently under a strong competition for the winning standard.

To obtain Gbps data rates for link ranges of up to 10 m, directional antennas are needed to fulfil the link-budget requirements. Extra link margin is required for the non-line-of-sight (NLOS) signal path, i.e. when the beam is steered around obstacles and reflected, for example, from a wall or a ceiling to find the best path between a receiver and a transmitter. Beam steering can be done using a phased array in which the phases of the input signals of an antenna array are controlled to focus the array beam toward a desired direction. At 60 GHz, antennas are naturally small and maximum gain of 14–17 dBi is achievable with a planar microstrip antenna array of sixteen elements on LTCC with size of about 20×20 mm^2 [2]. The small and low-cost phase shifters can be fabricated using CMOS [3] or MEMS technologies [4]. The challenge is to obtain low-loss phase shifters at millimetre-wave frequencies with high resolution. Another approach for beam steering is a beam-switching lens antenna in which phase shifters are not needed.

Lens antennas can be used for focusing or collimating the electromagnetic beam. In an integrated lens antenna (ILA), the lens is placed on top of a feed antenna to increase the antenna gain [5]. One of the most popular lens antenna configurations is the extended hemisphere or the synthesised ellipse which is a good approximation of a true elliptical shape, especially with high dielectric constants [6]. The directivity depends mostly on the lens diameter but can be also controlled by varying the extension length of the lens [7]. Beam steering is achieved by placing a feed antenna at different locations with respect to the lens centre. Instead of using only one feed antenna, an array of feed elements can be used in which each feeding element produces a beam toward a specific direction. Feed antennas are not excited simultaneously as in a traditional antenna array but separately one element at a time using, for example, MEMS or other RF switches in the feed network. The number of required feed antennas is determined by the desired scan range and scan resolution. The maximum size of the feed array depends on the fabrication technology. In the LTCC process, the feed array size is restricted by the panel size which is about 50×50 mm^2 or 100×100 mm^2 in current processes. The scan resolution is restricted by the smallest possible feed-element spacing. The radiation pattern and reflection coefficient of the feed antennas can be distorted by mutual coupling between the different feed elements. If a high scan resolution is needed, the mutual coupling should be taken into account in the feed antenna design.

Electrically large lens antennas can be analysed or synthesised using geometrical optics principles (GO). With small lens antennas with sizes of few wavelengths, more accurate analysis methods are required, such as the physical optics (PO) or the FDTD method [8]. Internal reflections inside a lens are relatively small with low dielectric constant materials. With dielectric constants $\varepsilon_r \geq 4$, the aperture efficiency is reduced due to increased power of internal reflections. However, the efficiency can be improved by placing a quarter-wavelength matching layer on top of the lens surface [9].

This paper presents the design and measurements of an integrated Teflon ($\varepsilon_r = 2.1$) lens antenna fed by a slot-coupled coplanar waveguide-fed patch antenna (SCMPA) on LTCC in the 60-GHz frequency band. The feasibility of using a small ILA for beam steering instead of a phased array is demonstrated with gain measurements with different lens positions with respect to the feed antenna. A maximum gain of 19.5 dBi is measured for the lens with a diameter of 20 mm. Beam steering capability of about ±30° is shown. Good agreement is achieved between the simulated and the measured radiation patterns. To the best of our knowledge, no prior work has been published of integrated lens antennas with LTCC feeds in V-band.

ANTENNA DESIGN

Feed Antenna on LTCC

Good candidates for an integrated lens antenna feed are planar antennas, such as a microstrip, a dipole or a slot antenna, on an LTCC substrate. Microstrip patch antenna can be excited through an aperture, a slot, [10] or a probe [11]. The feed line can be, for example, a microstrip line or a coplanar waveguide. Since the output pads of the switches are typically of a coplanar type, the CPW-fed slot-coupled microstrip patch antenna (SCMPA) is a natural selection as a lens feed.

The switch can be a commercial GaAs PIN diode or a MEMS based SP*N*T switch where N=1,2,3, …. (for example SP2T/SPDT Single Pole Double Throw). The higher the number of the switch output ports, the simpler the feed network. The switches can be mounted on LTCC using flip-chip processing. The geometry of an ILA with an 8-element linear feed array of patch antennas with SPDT switches is shown in Fig. 1. Seven switches are needed for this type of feed network. The linear feed array provides beam scanning either in the H-plane or in the E-plane. To scan the beam in both planes, a planar feed array is needed which will make the feed network more complex.

The SCMPA (Fig. 2a) consists of a CPW feed line, a ground plane with a slot, a substrate layer and a radiating element on top. The resonance frequency is determined by the patch size and the input impedance is matched to 50 Ω with a slot and an open-ended CPW stub underneath the radiating element. The feed antenna was optimised at 60 GHz on a 200 μm thick Ferro A6-S LTCC system (ε_r=5.99, tanδ=0.0015) with a commercial three-dimensional electromagnetic software HFSS. The effective conductivity of gold paste σ_{eff}=7.0×10^6 S/m determined using ring resonators [10] was used in the simulations. The half space above the patch was filled with Teflon to simulate the feed antenna radiating to the lens. The feed antenna radiates a broad beam toward the upper hemisphere and the maximum simulated gain was about 4.6 dBi.

A feed array of eight SCMPA elements was also designed on LTCC (see Fig. 2b). The target was to obtain a maximum scan angle of about 30° with the outermost feed antenna. Other feed antennas would provide scan angles of -22.5°, -15°, -7.5°, 0°, 7.5°, 15°, and 22.5°. For the first demonstrator, however, only one patch was used as a feed and signal traces of other patches were terminated with 50 Ω resistors processed on LTCC using resistive paste. For a more advanced demonstrator, the same array configuration can be used just by modifying the transmission lines and adding the SPDT switches into the design. The ground plane of the end part of the CPW was tapered to provide enough space for manually connecting an Anritsu V115FCPW V-connector with conductive epoxy for the gain measurements [2].

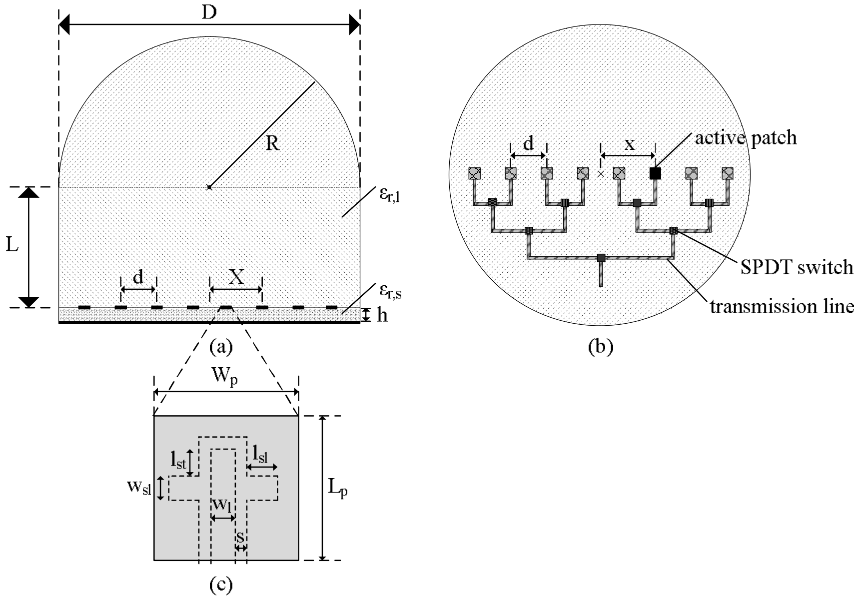

Fig. 1. Principle of the beam switching extended hemispherical lens antenna: (a) side view, (b) top view. The lens is fed with a linear array of patch antennas on LTCC. The feed network consists of SPDT switches and transmission lines. (c) Geometry of a slot-coupled coplanar waveguide-fed patch antenna (SCMPA).

Extended Hemispherical Lens Antenna

The extension length of an elliptical lens antenna can be approximated from [12]

$$L = \frac{R}{\sqrt{\varepsilon_r} - 1}, \tag{1}$$

where R is the lens radius and ε_r is the dielectric constant of the lens material. Equation (1) is suitable for large lenses whose diameter is several wavelengths in free space. With reduced-sized lenses with diameters of a few wavelengths, the asymptotic GO-PO methods are inaccurate and full electromagnetic simulation of the lens is needed [8]. In this work, an in-house FDTD analysis tool was used to simulate the together with the LTCC feed antenna.

An extended hemispherical lens antenna was designed for the 60-GHz frequency band. The target was to obtain a directivity of about 20 dBi, a scan range in between $-30° \leq \theta \leq 30°$, and a -3-dB beamwidth (HPBW) of 15° for beam overlap level of about 1 dB. Teflon was selected as the lens material due to moderately low dielectric constant and suitability for milling. The drawback of Teflon is the high density (2.2 g/cm^3) which makes the lens quite heavy with larger sizes.

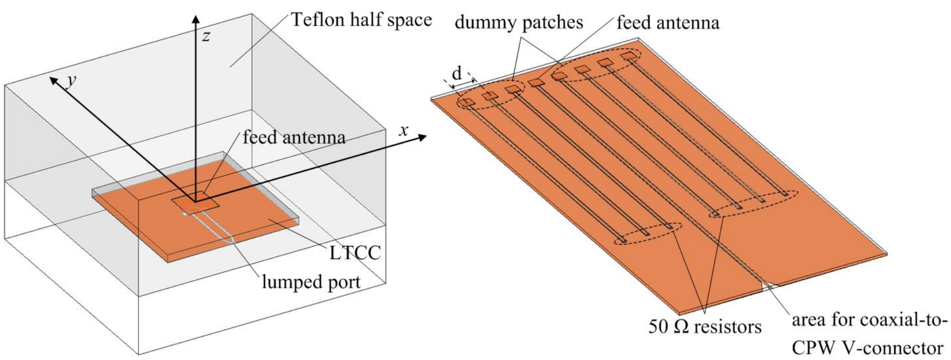

Fig. 2. (a) Simulation model of the optimised SCMPA feed. The dimensions are (in mm): h=0.2, l_p=w_p=0.8, l_{sl}=0.175, l_{st}=0.08, s=0.05, w_l=0.2, and w_{sl}=0.13. The ground plane size is 3.4×3.4 mm^2. (b) The final layout of the feed antenna array with an overall size of 15.3×31.7 mm^2. The inter-element spacing d equals 1.7 mm.

Table 1. Simulation results of the optimised lens antenna at 60 GHz.

X/*R*	DIRECTIVITY (dBi)	SIDE-LOBE LEVEL (dB)	HPBW (deg.)	SCAN ANGLE (deg.)
0	20.3	-12	13.2	0
0.51	18	-10	13.4	24
0.68	16.9	-4.5	13	28

The diameter of the optimised Teflon lens was $D=4\times\lambda_0$, i.e. 20 mm. The extension length was 13.3 mm which corresponds well with the values calculated for $D=\lambda_0$, $D=3\times\lambda_0$, and $D=5\times\lambda_0$ at 50 GHz in [8]. A flange was designed around the lens for measurement purposes and its effect was investigated through FDTD simulations. The effect on the radiation was very small, and in fact, the side-lobe level was slightly smaller with the flange than without one. The summary of the simulation results are given in Table 1.

RF TESTING

S-parameters

Test structures of SCMPAs and transmission lines were measured on a probe station to investigate the transmission line losses, the reflection coefficients of the feed antenna and the mutual coupling between two neighbouring feed antennas. Teflon and Rohacell slabs were placed underneath the SCMPAs to simulate radiation toward the Teflon lens. An RF absorber was used onto bottom to prevent reflections from the vacuum chuck of the probe station. The reflection coefficient from the V-connector of the feed array (Fig. 2b) was also measured using a 1.85 mm coaxial feed. Time gating was used in the HP8510C VNA to investigate the reflection from the V-connector and the SCMPA.

Radiation patterns

A test fixture was designed and fabricated from PVC plastic to support the lens and protect the fragile LTCC substrate in the radiation pattern measurements (Fig. 3). The fixture consists of a base and a connector holder. First, the V-connector is glued into the LTCC substrate and then the V-connector is mounted on the holder. Thereafter, the holder is screwed to the base. Finally, the lens is screwed through the slots to the base. Wide slots in the base enable the shifting of the lens position in the measurements. A groove with thickness slightly smaller than the LTCC slab enables a tight contact between the lens and the feed antenna.

The radiation performance of the lens antenna was measured in an anechoic chamber. The absolute gain was determined with reference measurements using two identical 24 dBi standard-gain-horn (SGH) antennas. The largest dimension of the lens is about 25 mm. The basic far-field criteria $2d^2/\lambda$ gives a value of 250 mm so the 820 mm spacing between the transmitting SGH and the lens was large enough for antennas to operate in the far-field region. The radiation patterns were measured for different values of X/R, i.e. the H-plane offset. The position of the lens was measured using a slide gauge. The E-plane pattern was measured with $X/R=0$.

RESULTS

The reflection coefficients and mutual coupling between two feed antennas are shown in Fig. 4. The measured centre frequency of the SCMPA differs about 1.3 GHz from simulations which is mostly due to fabrication inaccuracies. Some error could be caused by the only few millimetres thick Teflon slab used in the probe-station measurements. The centre frequency is at 60.2 GHz when time gating is used and measured with the Teflon lens placed on top of the feed antenna. The $|S_{11}|$ from the V-connector is about -9.2 dB. The S-parameters of the 3.4 mm long 50-Ω CPW lines are represented in Fig. 5. The measured $|S_{21}|$ indicates about 1.1 dB losses per centimetre. This value was used to extract the feed-line losses for determining the absolute antenna gain.

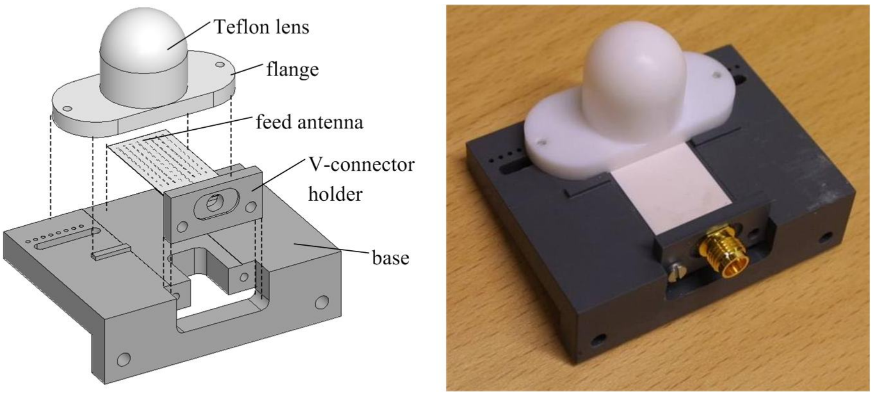

Fig. 3. Plastic test fixture to support the lens for the radiation pattern measurements. (a) 3-D CAD layout. (b) Photograph of the Teflon lens and the LTCC feed antenna with a V-connector.

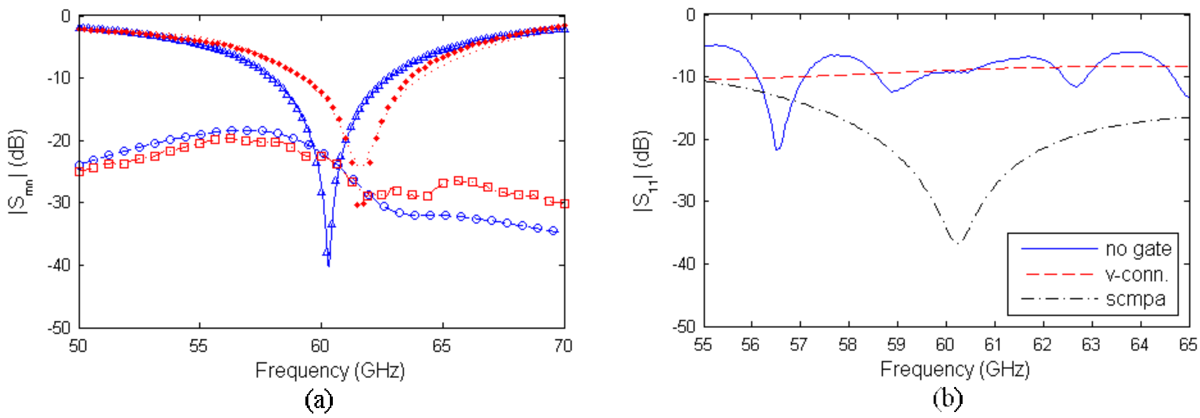

Fig. 4. S-parameter results of the feed antenna. (a) Simulated and measured reflection coefficient and mutual coupling between two SCMPAs in H-plane with separation of 1.7 mm. Solid line: sim. S_{11}, triangle: sim. S_{22}, dashed line: sim. S_{21}, circle: sim. S_{12}, dotted line: meas. S_{11}, dash-dot line: meas. S_{21}, square: meas. S_{12}, and point: meas. S_{22}. (b) Measured $|S_{11}|$ of the feed with the V-connector and the lens antenna. Gating function used in VNA to separate reflections from the V-connector and the SCMPA.

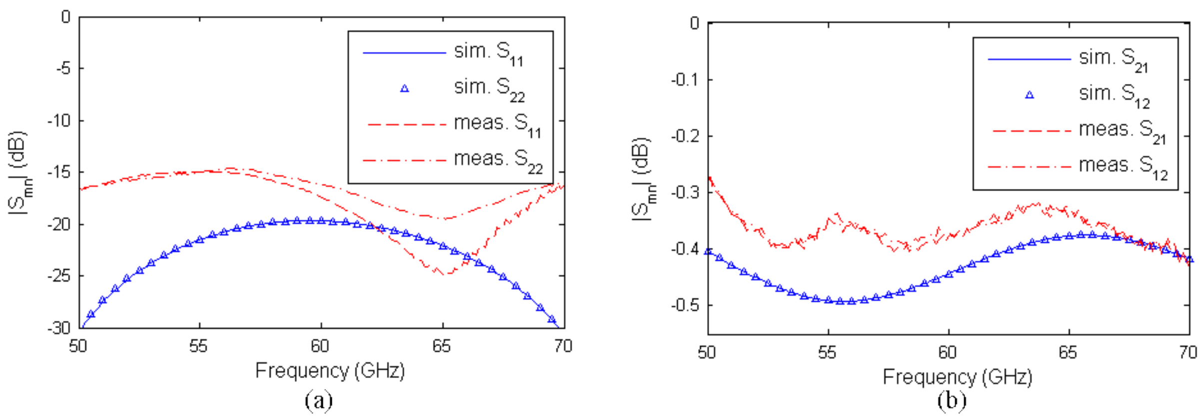

Fig. 5. Simulated and measured S-parameters of the 3.4 mm long CPW. (a) Reflection, and (b) transmission coefficients.

The simulated and measured radiation patterns with zero feed offset (X/R=0) are presented in Fig. 6. The beam points toward θ=0° and the -3-dB beamwidth is about 11°. The simulated and measured H-plane patterns agree well with each other. Some differences are observed in the E-plane patterns. Bigger side lobes in measured E-plane results are probably due to the test fixture and the V-connector that may cause additional reflections. Simulated and measured patterns with two H-plane offset values are shown in Fig. 7. The beam is tilted toward 21° and 30° with X/R=0.51 and X/R=0.68, respectively. Small differences between simulated and measured beam directions are caused by the inaccuracy of the lens positioning due to quite small shifts (for example X/R=0.05 is only 0.5 mm). The measured gain patterns with feed offset values X/R=0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, and 0.7 in x-direction are shown in Fig. 8. The maximum gain ranges from 19.5 dBi to 17.7 dBi with tilt angles from 0° to 30°. Similarly, the beam is steered toward $\theta \leq 0°$ with feed offset in +x-direction.

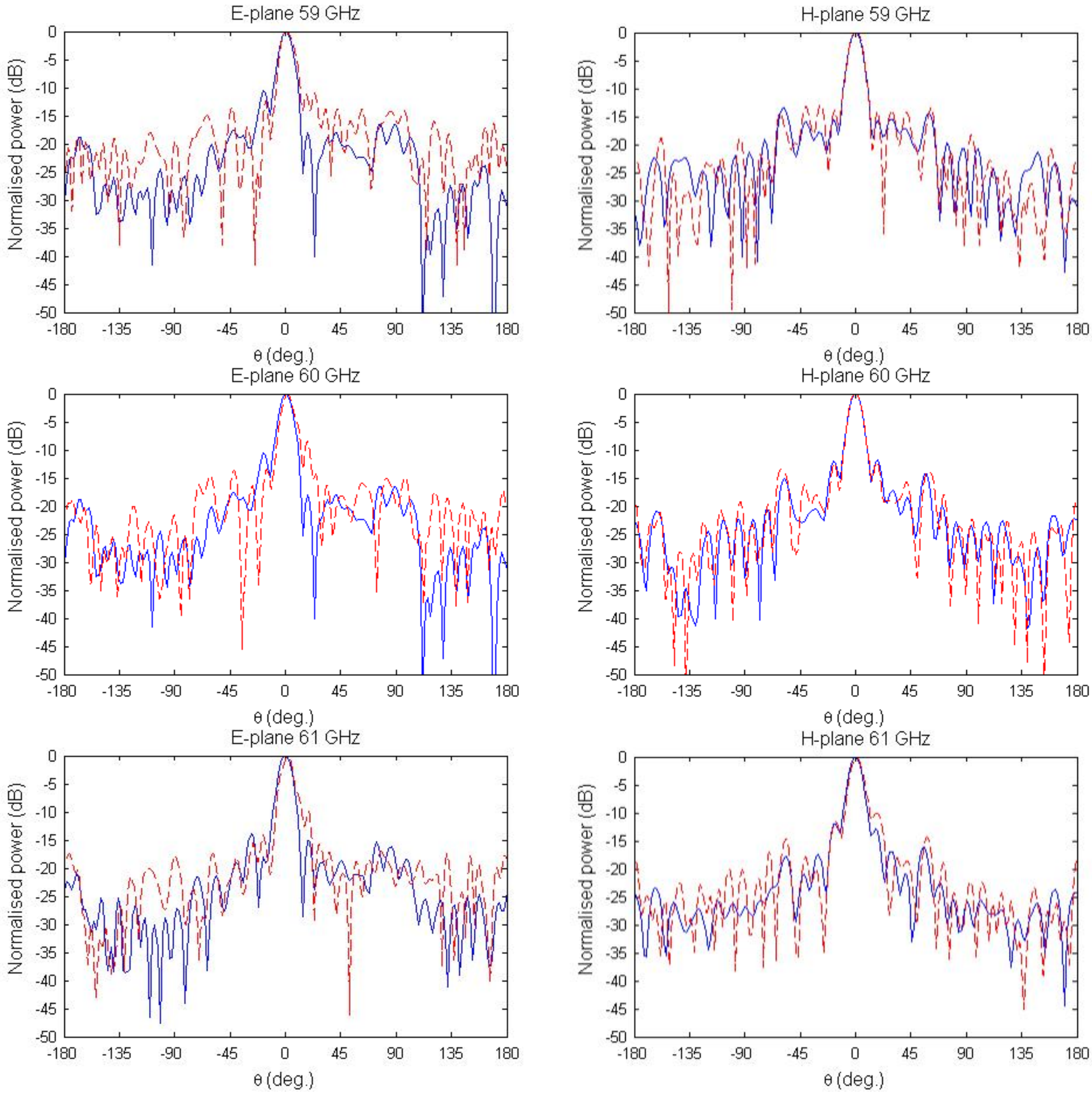

Fig. 6. Radiation patterns of the integrated lens antenna in E- and H-planes at different frequencies. The solid and dashed lines are the simulated and measured patterns, respectively.

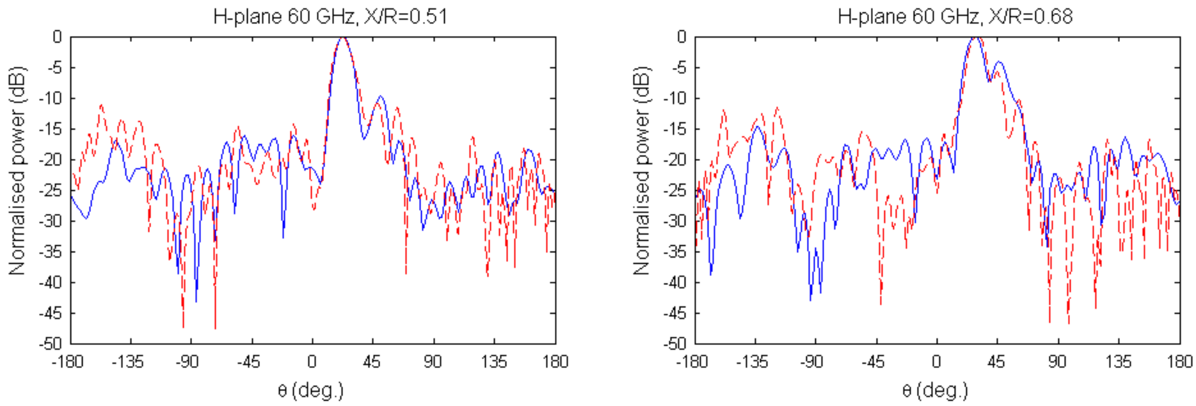

Fig. 7. H-plane patterns of the integrated lens antenna with two different feed offset values. The solid and dashed lines are the simulated and measured patterns, respectively.

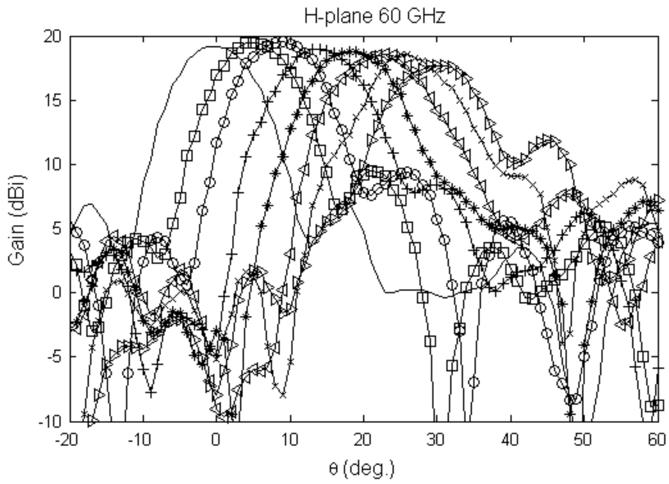

Fig. 8. Measured H-plane gain patterns with feed offset values *X*/*R* ranging from 0 (θ =0°) to 0.7 (θ=30°) with 0.1 steps.

CONCLUSIONS

We have designed, fabricated and tested a beam switching integrated lens antenna with the primary feed on LTCC at 60 GHz. Good agreements between simulated and measured characteristics have been obtained. A maximum gain of 19.5 dBi was measured for the lens antenna. A beam-steering range of 56° was measured by manually shifting the lens position by 13.5 mm relative to the feeding antenna. For future development, an electronically beam steerable lens antenna will be designed for the gigabit data range wireless indoor applications. The design is also extended to other frequency bands to develop novel high-gain (~25-30 dBi) antenna technology for directive applications.

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