World Applied Sciences Journal 29 (Computer Sciences, Engineering and Its Applications): 285-291, 2014
ISSN 1818-4952

DOI: 10.5829/idosi.wasj.2014.29.csea.2273

Compact Lens Antenna for 60GHz Millimeter-Wave Applications

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Abstract: This project presents a new concept of a steerable beam antenna, where a dielectric lens antenna is tilted and/or rotated in relation to a stationary feed. The dielectric lens is properly shaped and positioned accordingly to two requirements: High gain and Beam tilt capability. In this way, the beam is mechanically steered in elevation and azimuth. The fabricated prototype adopts a circular horn antenna with moderate gain as the feed (13 dBi). The shaped dielectric lens allows performing beam steering while it also increases the entire structure gain to 21dBi. The mechanical steerable beam antenna presents a broadband behavior, including the entire international unlicensed spectrum from f = 57 GHz to f = 66 GHz. The antenna is able to tilt the beam from -45° to 45° for all azimuths with gain scan loss below 1.1 dB and radiation efficiency above 95%. The arrangement is very simple, it requires no rotary joints and it represents a compact and low-cost solution.

Key words: Compact lens antenna · 60GHz wireless communication · Low cost · Mechanical beam steerable

INTRODUCTION

The growth of wireless communications is spurred by the consumer desire for untethered access to information and entertainment. While contemporary unlicensed systems support light and moderate levels of wireless data traffic, as seen in Bluetooth and wireless local area networks (WLANs), current technology is unable to supply data rates comparable to wired standards like gigabit Ethernet and high-definition multimedia interface (HDMI). Fortunately, as illustrated in Fig. 1, an abundance of widely available spectrum surrounding the 60 GHz operating frequency has the ability to support these high-rate, unlicensed wireless Communications. While unlicensed spectrum around 2.5 GHz and 5 GHz is also available internationally, amount of available 60GHz bandwidth is an order of magnitude above that available at 2.5 GHz and 5 Ghz.

Fig. 1 International unlicensed spectrum around 60 Ghz Nowadays the demand for millimeter wave steerable beam antennas is gaining a new interest due to the desire of higher transmission bit rates between fixed and mobile terminals [1, 2]. The growing interest in using the unlicensed spectrum around 60GHz for high data rate applications, such as high speed internet access, has motivated the development of highly integrated compact antennas. At these frequencies the free space attenuation is significantly high even when just considering a few hundred meters communication link [3]. In order to ensure acceptable system performance and range, such antennas must achieve high gain while being capable of directing the electromagnetic energy to the intended target/user [4].

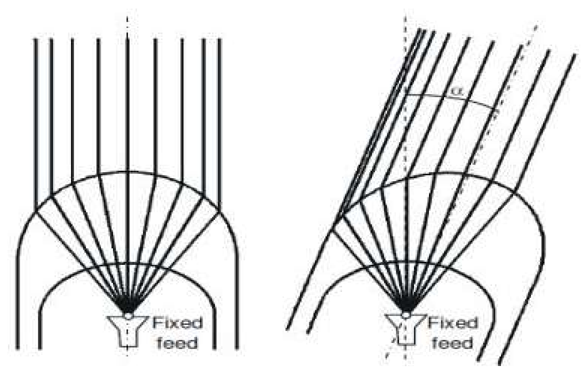

Fig. 1: Ray Tracing in polyethylene elliptical lens

The main objective of this project is to provide a small, inexpensive beam steerable antenna for millimeter wave communication systems. Antenna beam steering can be performed mechanically by moving all parts of the antenna, electrically phased array antennas or switching multiple feed antennas or by combining the two techniques. Electrical steering has the advantage of being

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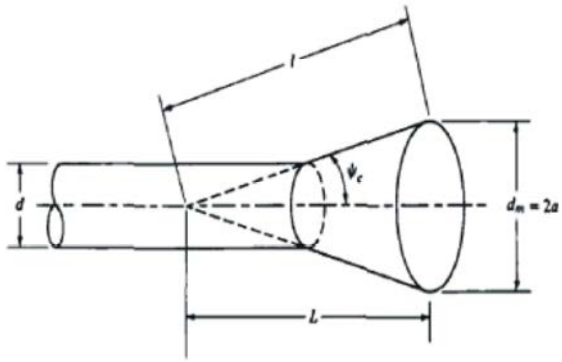

Fig. 2: Conical Horn

faster than mechanical solutions however, at millimeter-waves; efficiency, phase stability and cost are quite critical issues for phased arrays especially when using MMIC technology to reach mass applications [5]. A new antenna concept was developed, which overcomes the limitations of previous solutions. The antenna consists of steerable beam lens antenna which pivots in front of a single stationary moderate gain feed and it does not need RF rotary joints to rotate and it is very compact.

Concept Description: The beam steering is obtained by contactless low loss polyethylene lens above a single fixed circular horn. The lens pivoting about the two main axes enables -45° to +45° elevation scan capability over full 360° azimuth shown in Fig. 2. The radio frquency part is fixed, dispensing rotary joints. This feature favours very low cost mass production and reliable antenna steering. The lens profile was optimized to maximize elevation scanning angle with minimum gain loss. The circular polarization is used to minimize both polarization mismatch and first order reflections in the line-of-sight links with linear polarization portable equipment [6, 7]. The simulation is done using the CST Microwave Studio transient solver, which is efficient software and provide accurate simulation results for Electromagnetic simulations [8].

Circular Horn Feed: The antenna used in this design is a Conical Horn. By flaring the walls of the circular wave guide the conical horn is formed. The feed of a conical horn is often a circular waveguide. The design of the conical horn is shown in Fig. 3.

The diameter of the circular waveguide is referred by d in mm and the horn aperture diameter is d_m in mm (d_m = 2a or 2d). The flared length is given by *l* and L is the length of the horn aperture, all these parameters are used for the design of Conical Horn.

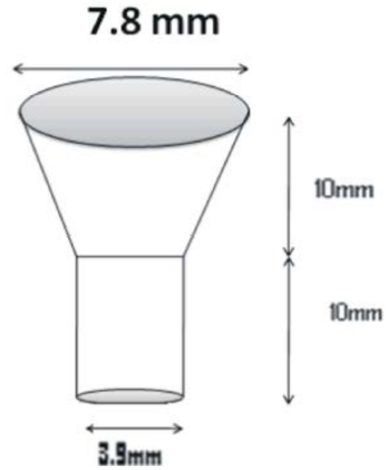

Fig. 3: Horn Dimensions

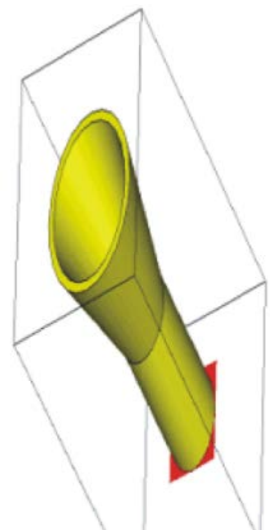

Fig. 4: Simulated horn antenna

Simulated Results of Horn: The horn was designed using the CST Microwave Studio ™ transient solver. The horn was manufactured in aluminum with 7.8 mm inner aperture diameter, 10 mm flared length and 3.9 mm diameter circular waveguide port as shown in Fig. 4. The horn's aperture dimensions were chosen to achieve the desired gain; the flare was adjusted to ensure less than 0.5mm phase center shift in relation to the horn aperture plane, within the whole band. The shift has negligible effect on the antenna performance. The horn is fed with TE_{11} mode with right-hand circular polarization (RHCP). The simulation results are is shown below. The horn antenna was designed to have circular polarization and a full beam width at -10dB of about 70°. The circular polarization was used in order to minimize polarization mismatch that can occur in line-of-sight links with linear polarization portable equipment [9].

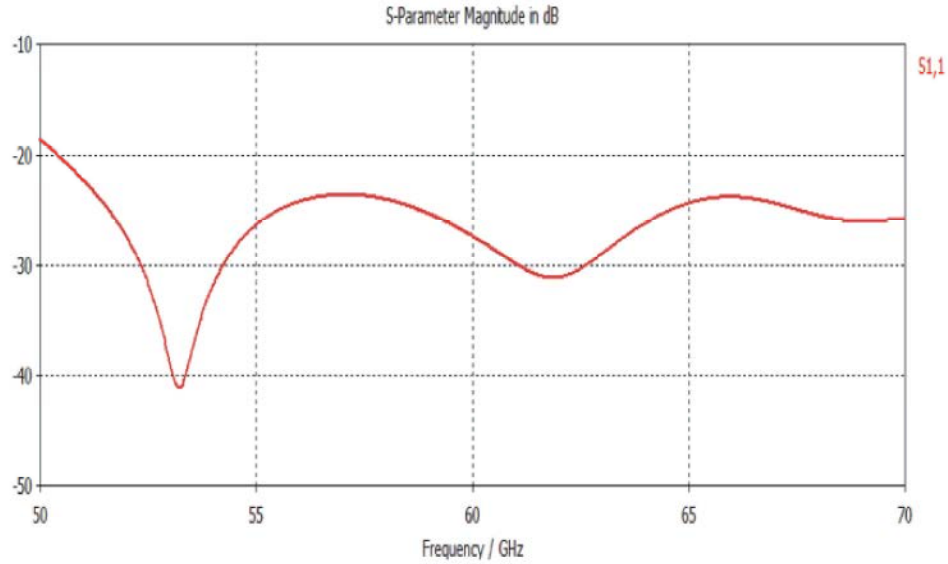

Fig. 5: Amplitude of Input Reflection Coefficient of Horn

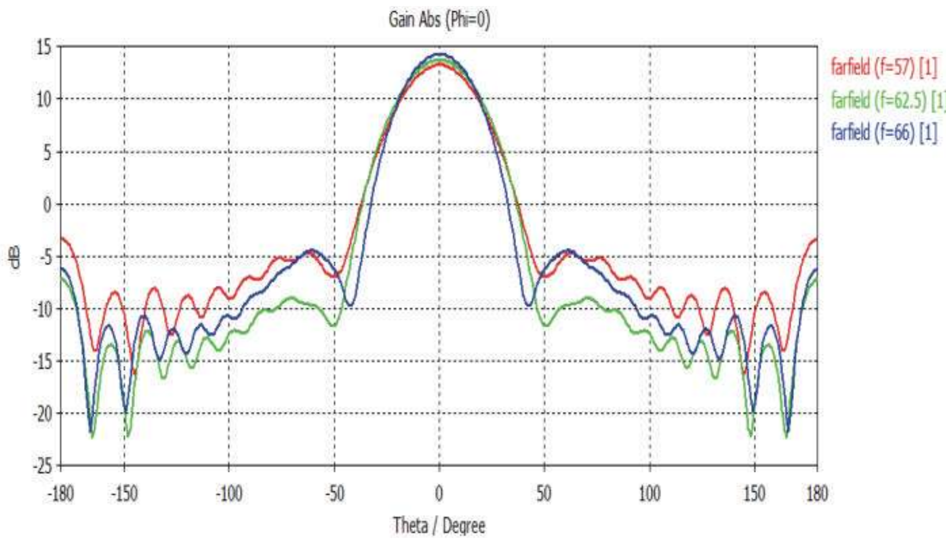

Fig. 6: Radiation Pattern for all Frequencies

The measured gain through CST simulation is 13.7 dBi. For 57 GHz and 60GHz the CST predicts 13.3 dBi and 14.4 dBi gain. Also according to the simulation, the radiation efficiency of the horn is above 98% and the S-parameter value is always below -20dB. The input reflection coefficient of the horn antenna is presented in Fig. 6. It can be seen that the bandwidth of this antenna includes the entire spectrum of the Wireless HD standard, with the |*s11*| parameter always below -20 dB. According to the simulations, radiation efficiency is always above 98% for the entire bandwidth. These results show that the circular horn antenna is appropriate for the whole spectrum of the Wireless HD standard. The circular horn far-field radiation pattern for f=62.5GHz is shown below presenting a gain of 13.7dBi. For f=57GHz and f=66GHz simulations, the gain is 13.3 dBi and 14.4 dBi, respectively [10, 11].

Lens Design and Analysis: The selected material for lens fabrication was polyethylene. The permittivity and loss tangent values were $\varepsilon_r = 2.35$ and $\tan(\delta) = 0.0004$. The low loss tangent value of polyethylene is favorable for high radiation efficiency of the lens [12].

Two lens geometries are presented: a first one based on a single refraction surface (L1Lens), which allows understanding the concept configuration and the second one, a double refraction lens(L2 Lens), optimized in order to improve its performance. The design of the two refraction surface lens that maximizes the portion of the output lens surface that is able to collimate the horn's radiation. The two lens interfaces play a role to broaden the maximum scanning angle θ_{max}.

Lens Formulation: The elliptical lenses are common solutions to obtain collimated beams rays departing from the feed immersed in the dielectric at the ellipse focal point emerge from the lens surface parallel the lens axis. For the low loss dielectric materials the lens antenna gain is mostly determined by its aperture size. In order to be able to tilt the lens without tilting the lens feed, it has to be detached from the lens. Based on Geometrical optics, the collimating region corresponds to:

$$\theta < \theta_{\max} = a\cos\left(\frac{1}{\sqrt{\varepsilon_r}}\right) \quad (1)$$

where ε_r is the lens material permittivity and θ is the angle between a ray path departing from the feed and the lens axis; θ_{max} corresponds to the collimating region of the lens. Outside this region the rays are refracted away from the main beam direction, increasing the side lobe level [13].

L1 Lens: The first design step for the extended elliptical lens is to determine the overall lens dimensions required to obtain 20dBi gain when fed by the designed horn. This can be achieved by using the hybrid Geometric optics and Physical optics lens analysis method. It was found that the main axis of the lens of the lens generating ellipse should be 13.18 mm and 10 mm, which corresponds to a base radius of 10 mm and a height of 21.8 mm. An 8 mm radius spherical air cavity was then added to the lens. The lens wall was extended 5 mm below the horn aperture to provide fixing points for tilting, shown in Fig. 8. With this arrangement the lens can tilt up to α = 40° without hitting the horn.

L1 Lens Experimental Results: The CST full-wave simulation results predicted acceptable performance for the designed lens. The lens spherical cavity reflects back some radiation into the horn.

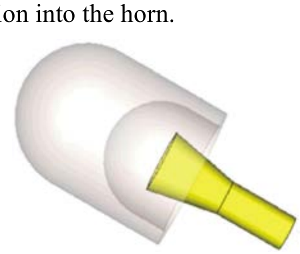

Fig. 7: Simulated Design of Lens L1

Fig. 9 shows $|s11|$ clearly increases with the inclusion of the lens. However it stays below-12dB for all tilt angles, throughout the Wireless HD band. The lens radiation patterns were measured at 62.5 GHz for different tilt angles in the α = 0° to 40° range.

Gain is 21.6 dBi for zero-tilt position and gradually decreases while the beam deforms for increasing lens tilt. It can be noticed though, that the lens preserves the circular polarization of the horn. The cross polarization level in the main beam direction is well below -15dB for all lens tilts. This is an indication that the reflected wave at the inner spherical cavity does not deteriorate much the horn's radiation pattern and polarization. Lens performance indicators computed from measured results are summarized in Table 1 versus tilt angle. Gain is above 20 dB for almost all tilt angles, with excellent radiation efficiency values above 96%.

As lens tilts, the feed illumination gradually exceeds the previously defined $\theta < \theta_{max}$ region of the lens.

According to expression (1), we obtain θ_{max} = 49° for a polyethylene lens. On the other hand, the -10dB half-beam width of the horn radiation θ_{-10dB} = 35° Therefore, according to GO, the lens shall be tilted only up to $\alpha = \theta_{max} - \theta_{-10dB}$ = 14° before part of the feed radiation starts to build side lobes and launches a surface wave along the lens outer interface Increasing the material permittivity would increase θ_{max}, but this would also increase the adverse effects of reflected waves over the lenses interfaces. The solution is to use a second refraction surface to try to increase θ_{max}, an approach that is explored in next section [14, 15].

L2 Lens: The objective is to design a two refraction surface lens that maximizes the portion of the output lens surface that is able to collimate the horn's radiation. This is equivalent to increasing the lens θ_{max} value. Consider the lens geometry is presented in Fig. 11 the inner shell is defined by r (θ) while the outer shell is represented by the length l(θ) and the angle $\gamma(\theta)$.

The Snell's law condition at the inner shell interface leads to:

$$\frac{\partial r(\theta)}{\partial(\theta)} = \frac{\sqrt{\varepsilon_r}Sin[\theta-\gamma(\theta)]}{\sqrt{\varepsilon_r}cox[\theta-\gamma(\theta)]-1}r(\theta) \quad (2)$$

When imposing an electrical path length condition we get:

$$F + \sqrt{\varepsilon_r}T = r(\theta) + \sqrt{\varepsilon_r}l(\theta) + s(\theta) \quad (3)$$

With

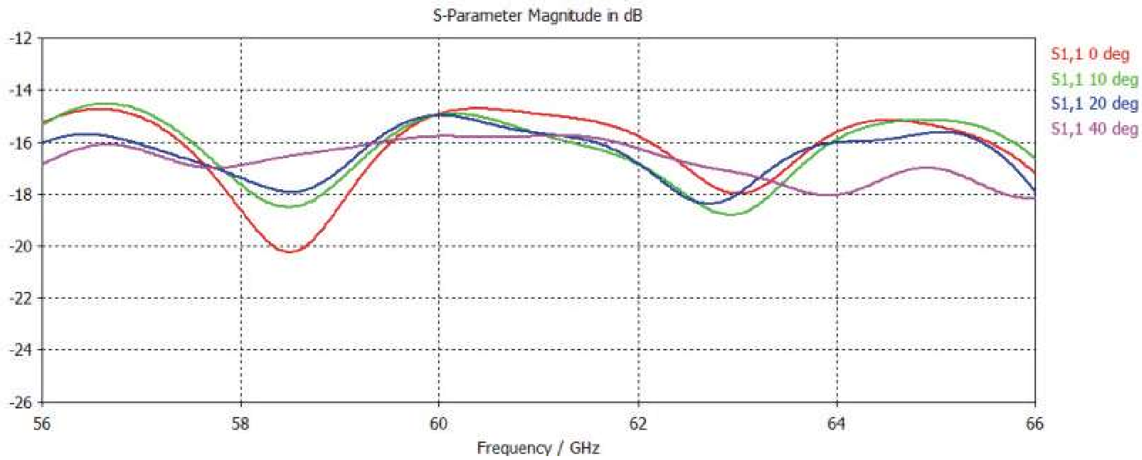

Fig. 8: Magnitude of the input reflection coefficient of L1

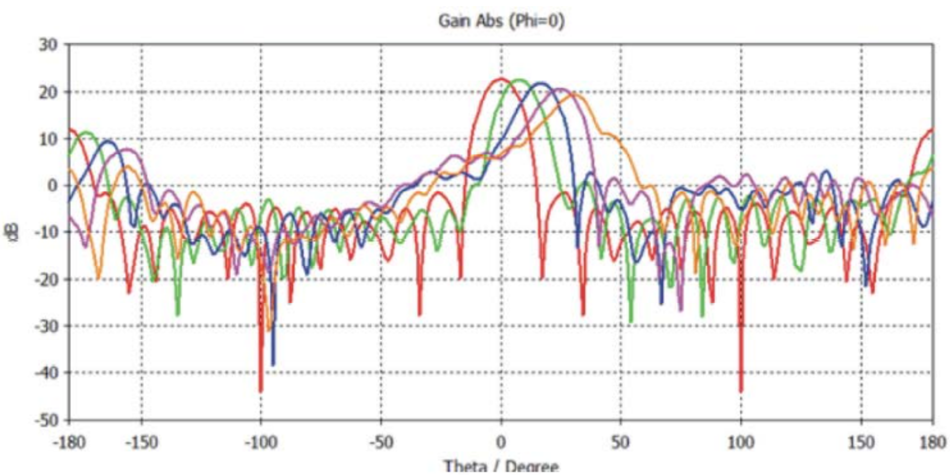

Fig. 9: Radiation Pattern of L1

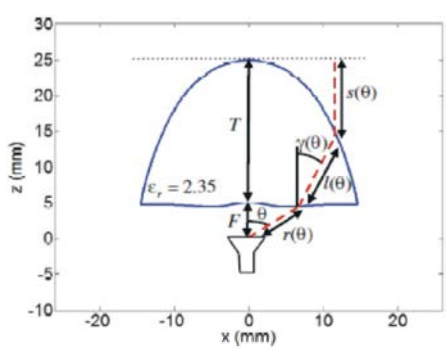

Fig. 10: Lens Geometry

$$s(\theta) = F + T - r(\theta)\ \mathrm{cox}(\theta) - l9-)\ \cos[\gamma(\theta)] \quad (4)$$

and *F* and *T* are input constants. However, a third equation is required to obtain a lens profile. Therefore, we have imposed the condition that $r(\theta)$ can be analytically defined by a finite Taylor series in θ.

$$r(\theta) = \sum_{n-0}^{8} c_n \theta^n \quad (5)$$

Using (4), the derivative in the left side of equation (1) can be written analytically. The coefficients C_2 to C_8 are generated by the GA algorithm in the each lens iteration. Coefficients C_0 and C_1 are equal to F and 0, in order to impose $\partial r / \partial\theta = 0$ at $\theta = 0°$ Once $r(\theta)$ is defined, equation (1) can be used to determine and subsequently $\gamma(\theta)$ from equations (2) and (3), $l(\theta)$ is obtained. For each lens generated, the corresponding $\theta_{\max}$ is calculated. The GA procedure tries to maximize the θ_{max} subject to following constraints.

- $r(\theta) > 4.5mm$, to ensure that the lens is tilted, the edge of the feed never touch bottom of the lens surface;
- The bottom of the lens surface cannot cross the upper surface except at the edge of the lens;

Fig. 11: Simulated Design of Lens L2

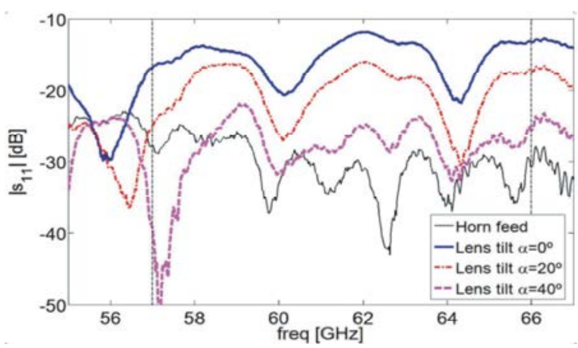

Fig. 12: Magnitude of the input reflection coefficient of L2

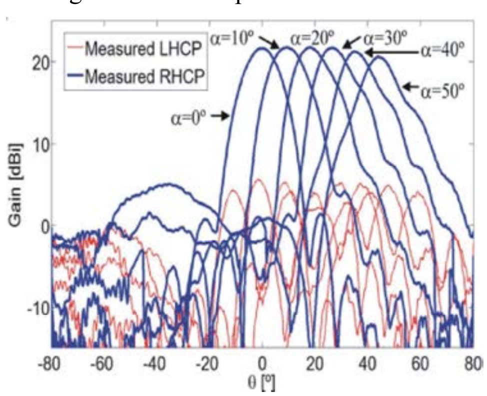

Fig. 13: Radiation Pattern of Lens L2

- Ray incidence angle at the upper lens interface must be below 95% of the critical angle i_c.

The latter constrain minimizes the excitation of a lateral wave along the lens upper surface. This can happen when ray's incidence angles *i* approach the total reflection condition.

$$i \geq i_c = a\sin\left(\frac{1}{\sqrt{\varepsilon_r}}\right) = 40.7^\circ \tag{6}$$

As previously referred, the surface wave tends to deflect part of the lens radiation away from the main beam direction reducing the directivity. The optimization process was executed considering F= 5 mm and T= 20 mm and the best lens solution was found for:

$$r(\theta) = 0.0274\theta^6 + 0.7683\theta^7 + 0.4522\theta^8$$
$$+ 0.2553\theta^5\ 0.3774\theta^4 + 0.7369\theta^3 + 0.7353\theta^2 + 5 \tag{7}$$

This lens presents a θ_{max} value of 72°, much wider than the 49° of the elliptical lens. The bottom lens surface no longer surrounds the feed and therefore it is mechanically possible to tilt the lens for much wider angles. The base radius of the lens L2 is 29.4mm.

Simulated Results for Lens L2: After the GO design, the actual lens performance was evaluated using CST Microwave Studio and the simulated results are analysed.

Measurements: The measured return loss at the horn input port is presented in Fig. 11 Now $|S_{11}|$ decreases with lens tilt since the slight reflected wave at the bottom of the lens is deflected way from the horn aperture, unlike the previous lens with spherical inner cavity. The measured co-polarization radiation patterns of the L2 lens are presented in Fig. 12 for 62.5 GHz. The presented curves correspond to 10 steps of the lens tilt angle in the α = 0° to 50° range. L2 presents considerable lower scanning loss than the L1 lens and also presents a much better defined main beam up to a maximum scan angle of 45°. The observed beam deformation with tilt angle is not critical for the WirelessHD application since the gain scan loss is negligible.

The measured gain, in the order of 21.7 dBi, is remarkably stable with lens tilt and this behaviour is extended up to 50 tilt shown in Fig.13; corresponding beam direction is near 45°, almost doubling the maximum scan angle of the L1 lens, considering the same 2 dB scan loss.

CONCLUSION

This paper introduced a simple, compact and low-cost antenna solution to perform total mechanical beam steering in the 60-GHz WirelessHD band, intended preferably for a fixed terminal like the flat TV screen. The beam steering is obtained by pivoting an appropriately shaped dielectric lens in front of a single fixed feed. The fabricated lens assembly demonstrated -45° to +45° elevation scan capability over full azimuth, with better than 1.1 dB gain scan loss and radiation efficiency always above 95% for the entire spectrum of the referred standard (from f=57GHz to f=66 GHz). Circular polarization is used to minimize polarization mismatch that can occur in line-of-sight links with linear polarization portable equipments, but the same concept was also tested with similar performance using linear polarization. The beam steering is obtained by pivoting an appropriately shaped dielectric lens in front of a single fixed feed. The different gain can be achieved by changing the lens overall size. The complete antenna analysis was performed with CST Microwave Studio, which is a full-featured software package for electromagnetic analysis and design in the high frequency range.

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