Bessel Beam Generation Using Dielectric Planar Lenses at Millimeter Frequencies

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摘要：本文提出了一种由透镜形状的单元构成的单元来调整辐射近场。一种基于二次多项式的方法被提出，以考虑在设计过程中单元的相位偏移响应的角依赖性。为了实现物理实现，提出了两种新型单元，分别为矩形和六边形棱柱，它们的性能进行了比较。这些单元通过空气隔层控制材料的密度来实现介质折射率的变化。在完全特性化单元后，对两种类型的单元进行了设计。对于Bessel光束的要求是深度为650 mm的光束在28 GHz。在全波仿真后，两个原型使用3-D打印技术制造。最后，通过在平面接收范围内测量，对Bessel光束的性能进行了评估。两个透镜在Bessel光束生成方面展示了与仿真结果的良好一致性，获得的性能结果对在Ka-band中使用介电梯度透镜的Bessel光束生成具有前景。

关键词：介电透镜，Bessel光束，近场聚焦。

1. 引言

近场应用近年来的流行性显著增强。这些应用中的多数要求在一定区域对辐射功率进行聚焦，通常位于菲涅耳区域。传统上，近场聚焦天线已经特别有用，特别是在毫米波或微波频段。近年来，一些工作研究了在较低频段生成非衍射光束的新技术，特别是在毫米波和微波频段。一种常见方法是设计其场在天线面内类似Bessel函数的天线。这些解决方案通常使用径向等幅线阵（RLSA）[13]-[15]、近场板[16]或泄漏径向波导[17]、[18]，等等。另一种方法是使用径向等幅线阵（RLSA）[13]-[15]、近场板[16]或泄漏径向波导[17]、[18]，等等。
use of structures that transform an incident wave to a non-diffraction beam, such as axicons [19], [20], holograms [21] or meta-surfaces [22]. A new approach is the use of a phase shifting surface (PSS) [23] or transmitarrays [9] to generate near-fields with a large depth-of-field at Ka and V bands, respectively.

Although these previous works obtain good performances creating non-diffraction beams, they have some drawbacks. The generation of Bessel beam functions at the antenna aperture typically require a complex design or manufacturing process. On the other hand, structures like axicons or holograms involve high costs, complex manufacturing process and bulky solutions. However, planar antenna apertures (transmitarrays, lenses, PSS . . .) minimize these issues, being a suitable alternative in the generation of non-diffraction beams at millimeter band. In this line, graded-index dielectric lenses could be considered as a potential candidate to create these beams too. The working principle of these antennas is similar to a PSS or transmitarrays but the introduced phase-shift of the incoming wave is controlled by the variation of the index dielectric media of the cell. One main advantage regards on the easiness and low-cost fabrication process due to the use of 3-D printing technology [24]–[26]. This process is typically applied to planar lenses, where the index dielectric variation is obtained by adjusting the height of the cells to obtain the desired phase-shift [27]. However, this technique does not provide a planar profile in both surfaces therefore, diffraction problems may appear owing to the edge of the cells on the non-planar surface.

In this paper, a graded-index only dielectric lens is proposed to generate a near-field with a large depth-of-field, particularly a Bessel beam, at Ka-band. Two novel cells, based on square and hexagonal prisms respectively, are proposed to physically implement the lens. Both cells are characterized, and two designs are carried out to evaluate their overall performances. The designed lenses are manufactured using a 3-D printing technique and measured on a planar acquisition range. The measured near field shows a good agreement with simulations.

II. FUNDAMENTALS OF BESSEL BEAMS IN FINITE APERTURES

The main characteristic of Bessel beams is the constant intensity of the field along the propagation distance [28]. Ideal Bessel beams are generated by infinite apertures or apertures whose size is thousands of \( \lambda \). The amplitude of an ideal Bessel beam is given by

\[
E(\rho, z) = E_0 e^{-jkz} J_0(k_\rho \rho)
\]

where \( J_0 \) is the zero-order Bessel function, \( k_\rho \) and \( k_z \) are the radial and longitudinal components of the free space wave vector, such that \( k_\rho^2 = k_z^2 = \sqrt{k_0^2 + k_z^2} \).

However, regarding finite apertures, pseudo Bessel beams are produced. Unlike ideal Bessel beams, the amplitude of the pseudo Bessel beams only remains constant on a certain propagation distance before spreading rapidly. The beam is produced by the generation of a near-field interference pattern that basically keeps constant within an area. The size of this area is given by the size of the antenna aperture \( D \).

When this concept is applied at millimeter frequencies and, particularly to planar lenses, the working principle is based on the transformation of a spherical incoming wave-front to a plane wave with wave vector lying on a cone, as Fig. 1 depicts. The outgoing wave front must generate a near-field interference pattern that behaves as a pseudo Bessel beam. As Fig. 1 shows, the extent of the shadowed area is defined by \( D \) and \( \gamma \), and it is called depth-of-field (DoF). The DoF can be computed using (2) and it also defines the theoretical 3 dB contour of the field.

\[
\text{DoF} = \frac{D}{2 \tan(\gamma)}
\]

Theoretically, the maximum distance achievable is limited by the Fresnel region of the antenna \((2D^2/\lambda)\). Regarding the angle \( \gamma \), it must satisfy \( \sin(\gamma) \ll 1 \), otherwise the scalar Bessel beam theory, previously explained, cannot be applied [29].

Let us consider a planar lens comprised by a given number of elements regularly distributed on a \( N_x \times N_y \) grid. The lens feed is located at a focal length \( F \) to generate a Bessel beam with angle \( \gamma \). According to Fig. 1, the outgoing wave front must have its wave vector laying on a cone as long as the wave front is radiated through the propagation direction \( \hat{z} \). This condition allows to create the required near-field interference pattern to generate the desired beam.

Then, the phase-shift of the lens elements can be computed using geometrical optics. The phase produced by the elements of the lens are given by

\[
\varphi_{\text{lens}}(\rho) = -\varphi_{\text{inc}}(\rho) - \varphi_{\text{of}} - \frac{2\pi}{\lambda} \rho \tan \gamma
\]

where \( \varphi_{\text{of}} \) is the phase of the outgoing wave front; \( \rho \) is the axial position of an element computed as \( \rho = \sqrt{x_n^2 + y_n^2} \), considering the center of the lens the center of the circumference; and \( \varphi_{\text{inc}}(\rho) \) is the incident phase at an element defined by

\[
\varphi_{\text{inc}}(\rho) = -\frac{2\pi}{\lambda} \sqrt{F^2 + \rho^2}
\]
Fig. 2 shows a comparison of Bessel lenses axial intensities for different aperture sizes while keeping $\gamma$ and $F$ constant. As expected, the use of larger apertures generates beams more similar to ideal Bessel beams with a constant intensity on the propagation direction.

II. DIELECTRIC LENS ELEMENTS

A. WORKING PRINCIPLE OF DIELECTRIC CELLS

A planar lens is required to have the same height in every cell. One approach that satisfies this condition is using total dielectric cells. These cells behave as an effective index media that adds a certain delay to the transmitted ray. The effective index media $n_{\text{eff}}$ is related to the effective dielectric constant as $n_{\text{eff}}^2(\rho) = \epsilon_{\text{eff}}(\rho)$. Thus, the variation of $\epsilon_{\text{eff}}$ allows to physically implement the phase-shift $\phi_{\text{len}}(\rho)$ of the cell.

Let us assume two spatially uniform and isotropic materials with dielectric constants $\epsilon_1$ and $\epsilon_2$, respectively. If the second material is embedded in the other, the effective dielectric constant of the assembled cell does not depend on the geometry but on the dielectric constants and its volume fraction [30]–[32]. The effective dielectric constant of the cell can be computed as

$$
\epsilon_{\text{eff}} = \epsilon_1 \frac{2\epsilon_1 + \epsilon_2 + 2P(\epsilon_2 - \epsilon_1)}{2\epsilon_1 + \epsilon_2 + P(\epsilon_2 - \epsilon_1)}
$$

where $P$ is the volume fraction of the material $\epsilon_2$ over the total volume of the cell. If one of the dielectrics is air, only one dielectric is needed to accomplish (5), being $\epsilon_2 = \epsilon_0$.

In this work, the proposed cells are based on polylactic acid (PLA) ($\epsilon_1 = 2.85$) and $\tan \delta = 0.0121$ @ 40 GHz) [33] as the host material and air ($\epsilon_2 = 1$) to perform the inclusions. Two different cells are analyzed, particularly, square and hexagonal prism cells. In both cases, a variable airgap is embedded in the cell to change the volume fraction and control the $\phi_{\text{len}}(\rho)$ that is introduced.

B. PHASE RESPONSE WITH AIRGAPS

The square prism cells, Fig. 3(a), are based on a square PLA prism of dimensions $a \times a \times t$, and a second embedded airgap prism of variable dimensions $W \times W \times L$ as Fig. 3 shows. The variation of these dimensions changes the volume of air, therefore $P$:

$$
P = \frac{V_{\text{airgap}}}{V_{\text{prism}}} = \frac{W^2 \times L}{a^2 \times t}
$$

The cell is analyzed with CST Microwave Studio [34] using periodic boundary conditions in $x$- and $y$-axis and open in $z$-direction. The cell is illuminated by a normal plane wave propagating in the $z$-direction with the electric field defines in the $y$-direction. The dimensions of the PLA prism are $\lambda_d/2 \times \lambda_d/2 \times 2\lambda_d(a_1 \times a_2 \times t)$, whilst the embedded prism dimensions are swept between $W \in (0, \lambda_d/2)$ and $L \in [0, 2\lambda_d]$. So, either full dielectric cells ($\epsilon_{\text{eff}} = 2.85$) or almost air cells ($\epsilon_{\text{eff}} = 1.28$) are considered. The analysis is performed at central frequency of 28 GHz in a bandwidth of 2 GHz, and $\lambda_d$ is computed as $\lambda_0$ at the highest frequency, 30 GHz.

The amplitude and phase response of the transmission coefficient of the cell as function of the airgap dimensions are shown in Fig. 4, at the central frequency and normal incidence. The different combinations of $L$ and $W$ totally cover the $360^\circ$ required range to implement $\phi_{\text{len}}(\rho)$. More than 85% of the cells present transmission losses lower than 1.5 dB. These values are expected since the $\tan \delta$ of PLA is significantly high. Additionally, Fig. 5 shows the relation between the dimensions of the airgap and the effective dielectric constant of each cell.

On the other hand, the hexagonal cells, Fig. 3 (b), use an embedded cylinder airgap. In accordance with (4), this change in the geometries does not affect the phase-shift so long as $P$ is the same as the square prism cells. Consequently, the volume of the airgaps, both cylinder and square prism, must be the same and the volume of the square and hexagonal prism are also equal. Considering that the lens depth is independent from the type of selected cell, equals to

![Figure 3. Sketch of dielectric cells based on airgaps insertions to control the effective dielectric constant of the total cell. (a) Square prism airgaps (b) Cylindrical airgaps.](image-url)
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FIGURE 4. Square prism cell response in function of the airgap dimensions for normal incident at 28 GHz. (a) Phase (deg) (b) Amplitude (dB).

$\tau = 2\lambda_d$, the condition is only imposed on the cell prism base. Therefore, a hexagon of radius $a_h = 0.31\lambda_d$ is obtained.

In order to compute the cylinder dimensions, the depth of the cylinders remain alike to the depth of square prism airgaps, $L$. Thus, only the radius needs to be calculated using $R^2 = W^2/(\pi)$. In Fig. 6, the amplitude and phase of the transmission coefficient versus frequency for different square and hexagonal prisms are compared, showing that the geometry does not affect the cell response.

C. ANGULAR PERFORMANCES

The phase stability of the cell has been analyzed for different angles of incidence $\theta$ and $\phi$ at 28 GHz. It was considered linear polarization of the incident electric field and angles with variation in $\phi = 0^\circ, 45^\circ$ and $90^\circ$ and $\theta \in [0, 30]^\circ$, being $\theta = 0^\circ$ normal incidence. Fig. 7 shows the phase responses from a set of 6 different cells as a function of

$\theta$ and $\phi$. These results show the independence to $\phi$, whilst $\theta$ notably modifies the phase-shift regarding normal incidence. The dependence of phase-shift versus $\theta$ can be approximated

FIGURE 5. Effective dielectric constant of the square prism cell regarding the volume fraction of air and PLA.

FIGURE 6. Comparison of the (a) transmission phase and (b) transmission amplitude of the different prisms with the same filling factor. Airgap dimensions are in mm.
FIGURE 7. Phase response analyzed for different angles of incidence and the approximation obtained by a polynomial expression for different cells at 28 GHz. (solid) $\phi = 0^\circ$ (Grey square) $\phi = 45^\circ$ (Green circle) $\phi = 90^\circ$.

Airgap dimensions are in mm.

by a second-order polynomial as:

$$\Delta \varphi(\theta) = p_1 \cdot \theta + p_2 \cdot \theta^2$$  \hspace{1cm} \text{(7)}

As shown in Fig. 7, the curve shape is very similar to the analyzed cells and the polynomial model of $\Delta \varphi$ in the previous equation is common for all of them ($p_1 = 0.7453$ and $p_2 = 0.0425$). Then, the phase of the transmission coefficient for each cell of the lens can, therefore, be determined using the following equation.

$$\varphi_{\text{lens}}(\theta) = \varphi_{\text{norm}} + \Delta \varphi(\theta)$$  \hspace{1cm} \text{(8)}

being $\Delta \varphi$ obtained with the polynomial (6) and $\varphi_{\text{norm}}$ the phase of the transmission coefficient obtained for normal incidence analysis. This function nearly predicts the real phase-shift of a cell under oblique incidence, without considering the angle on the preliminary cell study. The maximum error produced in most cases is lower than $5^\circ$.

IV. DIELECTRIC BESSEL LENS BASED ON AIRGAP CELLS

In order to validate both square and hexagonal prism cells, this section addresses the lens design and simulation for both type of cells.

A. ANTENNA OPTICS

The proposed antenna to generate a Bessel beam is a square planar dielectric lens of equivalent aperture $D$ of $120 \times 120 \text{ mm}^2$ at 28 GHz. The distribution of the elements depends on the cell geometry. For square cells, a regular grid is used with periodicity $5 \times 5 \text{ mm}^2$ and made up of $24 \times 24$ elements. In the case of the hexagonal prism cells, they are arranged as a honeycomb, so the cells are located on an axial distribution as shown in Fig. 8.

The lenses are defined using a centered optics (see Fig. 1), and the phase center of the feed is placed at $(x_f, y_f, z_f) = (0, 0, F = -100) \text{ mm}$, taking the center of the lens as the origin of the system of coordinates.

The proposed antenna should generate the Bessel beam close to the lens, therefore a maximum DoF of 650 mm is established. According to (2), the beam theoretically behaves as a Bessel beam within this area if $\gamma = 5^\circ$.

B. DESIGN PROCEDURE

The lens design is based on geometrical optics theory according to (3) and (4). These equations provide the required phase-shift that should introduce the lens elements to radiate the beam previously defined. In this case, the phase distribution of the elements along the lens surface is shown in Fig. 9, reminding the physical distribution shown in Fig. 8.

Once the phase distribution along the lens surface is computed, the elements must be designed. In the designing process, the dimensions of the airgaps ($R$, $W$ and $L$) are adjusted to produce the required phase-shift according to $\phi_{\text{lens}}(\rho)$ in equation (3). Note that for, each cell, the incidence angle ($\theta$), the focal distance ($F$) of the lens and the radius of the center
of the cell in the lens (ρ) are related through

\[ \theta = \text{atan} \left( \frac{\rho}{F} \right) \]  

(9)

Therefore, the equation (6) can be rewritten in the following form:

\[ \Delta \varphi(\rho) = p_1 \cdot \text{atan} \left( \frac{\rho}{F} \right) + p_2 \left( \text{atan} \left( \frac{\rho}{F} \right) \right)^2 \]  

(10)

And then substituting (10) in (8)

\[ \varphi_{\text{lens}}(\rho) = \varphi_{\text{norm}} + \Delta \varphi(\rho) = \varphi_{\text{norm}} + p_1 \cdot \text{atan} \left( \frac{\rho}{F} \right) + p_2 \left( \text{atan} \left( \frac{\rho}{F} \right) \right)^2 \]  

(11)

Finally, the adjustment is done element by element, considering the real angle of incidence \( \varphi_{\text{norm}} \) shown in Fig. 4(b) with the desired one \( \varphi_{\text{lens}}(\rho) \) of Fig. 9. In order to improve the design, an angular correction \( \Delta \varphi(\rho) \) is introduced throughout the process; thus, the real phase-shift of each cell is considered. The resulting lens layout is made by the cells that minimize their phase-shift to the theoretical response. The amplitude of the cell response is used to discard cells with high losses.

In Fig. 10 the cut \( y = 0 \) mm of the theoretical phase-shift distribution is compared with the chosen cell of the final design, showing a good agreement between both. Additionally, a comparison with the design, based only on normal incidence, is done to highlight the importance of the angular correction through the design process. Notice that the difference between selected cells occurs more at the edge of the lens where the incidence angle is farther from the normal incidence. Two different layouts are obtained, one for each type of cell.

In the evaluation of the Bessel beam performances, both layouts have been analyzed with CST Microwave Studio [32] in a full-wave simulation (see Fig. 11). The selected feed is a pyramidal horn antenna with 15 dBi gain placed at a distance \( F = 100 \) mm from the surface of the lens.

This configuration illuminates the lens surface with an amplitude taper of \(-17\) dB at the edge of the lens.

The simulation results are shown in Fig. 12 for the \( X_oZ \) plane and in Fig. 14 the electric field along the \( z \)-axis is compared with the measurements. Because the horn antenna is non-symmetric regarding its main cuts, \( E \)- and \( H \)- plane, the outgoing wave-front is not perfectly formed. Hence, the near-field interference pattern is not properly created in the closest area of the antenna, having strong fluctuations on this area. This effect is minimized when hexagonal prism cells are used in the design. The cells achieve a more stable beam and concentrate it through a larger range than square prism cells, as Fig. 12 shows. However, when a horn antenna feeds a Bessel beam generator with small aperture, it is expected to obtain a shorter DoF range than the one computed with (2).

V. EXPERIMENTAL RESULTS

Both planar dielectric lenses, made up of either square or hexagonal cells, have been manufactured and evaluated in the planar acquisition range at University of Oviedo. The lenses have been manufactured using a Fused Deposition Modeling (FDM), a 3-D printing technique based on the melting
and extrusion of a thermoplastic polymer, such PLA, through a nozzle tip to deposit the material layer-by-layer onto a platform. This technique is widely used in additive manufacturing processes to fabricate prototypes since it is easily controlled and reduces the costs significantly. However, when dealing with accurate designs like these lenses, it is important to set a proper configuration to obtain a high precision. Especially, the thickness wall and layer height since both control the resolution of the pieces. In this case, the thickness wall is set to 0.4 mm and the layer height to 0.1 mm, providing a high-resolution printing. Low resolution configuration could modify or eliminate the internal wall of low infill cell ($P$ factor close to 1), therefore change the effective dielectric constant and the cell response. On the other hand, high-resolution configurations inherently increase the printing time to 40 hours for the lens made of square prism cells and 48 hours for the lens made of hexagon prisms cells. Throughout the whole process is highly relevant to keep the environmental conditions, for instance variation on temperature could produce air flows and lead to structural deformations on the pieces such as curvatures on the corners.

Both prototypes are shown in Fig. 13(a) and Fig. 13(b) depicts the setup used to measure both lenses. In this setup a vector network analyzer (PNA-X of Keysight) is connected to the feeding horn, a pyramidal standard gain horn of 15 dBi gain, whilst the second port is connected to the probe, an open-ended Ka-band waveguide. The lens is placed on a PLA structure aligned to the aperture of the probe. The measurements are performed from 26 to 30 GHz evaluating the electric field at the horizontal plane $X_0Z$ and at different transversal planes $XY$.

The normalized electric field along the propagation direction $\hat{z}$ is compared with simulations in Fig. 14 at 28 GHz. Measurements highly agreed with simulations, highlighting the range of the DoF or the decay of the Bessel beam. Additionally, the transversal $X_0Z(y = 0)$ plane is shown in Fig. 15 at different frequencies for both lenses. The 3 dB level indicates the maximum attenuation allowed in the DoF, whose theoretical range is 650 mm according to (2). Both lenses obtain their best results at the highest frequencies, from 28 to 30 GHz, where the DoF reaches.
a 475 (47.50\(\lambda_0\)) mm range. It is worth noting the hexagonal prism lens behavior, showing an improvement in the results regarding the square prism cell. The in-band response, particularly at the upper frequencies, barely change, whilst square prism lens increases its variation due to frequency shifts. Furthermore, the non-diffraction area is larger in all cases, but it also starts closer to the antenna aperture, creating a more stable Bessel beam through the propagation direction.

The transverse profile is also evaluated in a plane \(XY\) at \(z = 250\) mm at 26.5, 28 and 29.5 GHz. The plane is parallel to the antenna aperture and shown in Fig. 16. Measurements show good axial symmetry with a field distribution similar to the Bessel main lobe, whilst the side lobes are hidden due to the antenna size.

The cut \(y = 0\) of three different transversal \(XY\) planes, \(z = 150, 200\) and 250 mm, is measured at the whole band and
Figure 16. Measured transversal XY profiles at \( z = 250 \) mm parallel to the antenna aperture at 26.5, 28 and 29.5 GHz.

Table 1. Comparison of the antenna and Bessel beam performances with published works.

| Ref. | Frequency [GHz] | Size \([\lambda_0(@GHz)]\) | Thickness \([\lambda_0(@GHz)]\) | Phase-shift implementation | Depth-of-field \([\lambda_0(@GHz)]\) | Manufacturing technique |
|------|----------------|--------------------------|-------------------|---------------------------|---------------------------|-----------------------|
| [24] | 35             | (14 \times 14) (35)     | 1.51(35)          | Height of the cell         | 23.33(35)                 | NA                    |
| [25]  | 60             | 13.12(60)                | 1.16(60)          | Height of the cell         | 30.00(60)                 | Simulation results    |
| [26]  | 26 – 32        | 20(30)                   | 2.00(30)          | Height of the cell         | 11.13(26)/14.90(29)       | NA                    |
| [36]  | 300            | 15(300)                  | 1.90(300)         | Height of the cell         | 18.13(32)                 | In-home developed technique using laser and high-temperature resin |
| [35]  | 300            | (12 \times 12)(30)      | 2.02(300)         | Airgaps insertions         | 11.20(300)                | Stereo Lithography (SLA) |
| This work | 26 – 30       | (12 \times 12)(30)      | 2.00(30)          | Airgaps insertions         | 21.40(26) (square prism)  | Fused Deposition Modeling (FDM) |

*This work presents a 3-D printed axicon lens based on dielectric cells instead of a planar lens.

shown in Fig. 17. These measurements evaluate the beam-waist of the beams through the non-diffraction range. Neither the hexagonal prism lens nor the square prism lens is able to properly form the beam at the closest plane, \( z = 150 \) mm. However, at \( z = 200 \) mm the beam of the hexagonal prism lens is similar to a Bessel distribution and the beam is confined in a spot smaller than \( 4\lambda \). The main lobe of the square prism lens is flattened at this plane, especially at 28 GHz and higher frequencies. At the further plane, \( z = 250 \) mm, the square prism lens shows a beam similar to a Bessel function. As expected, the hexagonal prism lens keeps its Bessel behaviour. It must be noted that the hexagonal beam-waist nearly unchanges when the frequency varies.

Different published works of 3-D printed Bessel lens are compared in Table 1. Regardless the geometry and frequency, these works use cells based on a height variation to control the phase-shift introduced by each cell. In this work, the cell keeps its height constant and the phase-shift is obtained by the insertions of airgaps, obtaining a double planar surface lens that minimizes possible diffractions caused by the height difference of the cells and offers an easier integration of the lens. Considering the size, the depth-of-field and, especially
working in Ka-band, the results of this work make the proposed cells as an attractive solution in the generation of Bessel beams using 3-D printing technology in millimeter band.

VI. CONCLUSION

Dielectric planar lenses are demonstrated to generate near-field Bessel beams in Ka-band. The proposed lenses are made up of dielectric cells based on either square or hexagonal prisms. Both cells ensure the variation of their index dielectric media using airgaps to control the overall density of the material. A design is carried out to generate a Bessel beam with a depth-of-field of 650 mm, and it has been implemented for both type of cells, each one based on a proposed cell. The dependence of the phase response of the cell and the angle of incidence is considered with a second order polynomial. Both prototypes were manufactured using a 3-D printing technique and measured in a planar acquisition range, obtaining a good agreement between simulations and measurements. Although measurements show good performances in both cases, the hexagonal prism cell exhibits a superior behavior regarding the non-diffraction range and the in-band response. In light of these results, graded-index dielectric lenses have demonstrated to be a potential candidate to generate Bessel beams at Ka-band frequencies, taking the advantage of reducing the manufacturing cost process and reaching a simple structure.

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et al. Bessel Beam Generation Using Dielectric Planar Lenses at Millimeter Frequencies

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