

Hyperboloid Lens Antenna Design Guide

This paper presents the procedure for the design of dielectric lens antenna. It contains theoretical consideration and foundation, as well as procedure for design in the WIPL-D software suite.

Dielectric lens antenna consists of two parts:

- Feeding cylindrical waveguide (feeder),
- Dielectric lens (lens).

The design procedure is approximately divided into two steps, each corresponding to the design of single part. After a theoretical consideration, the description of the modeling in WIPL-D is provided for each step.

1. Design of Feeder

For Dielectric lens, the feeding antenna is most often chosen to have large beam-width. In our case we will use open-end cylindrical waveguide (CWG).

The feeder design procedure consists of design of CWG, according to the specified central operating frequency, and adding choke to the CWG aperture edge to suppress backward radiation. The details are explained in the following section.

1.1. Design of CWG

CWG is excited by a probe and typical cross-section illustration is shown in Fig. 1.

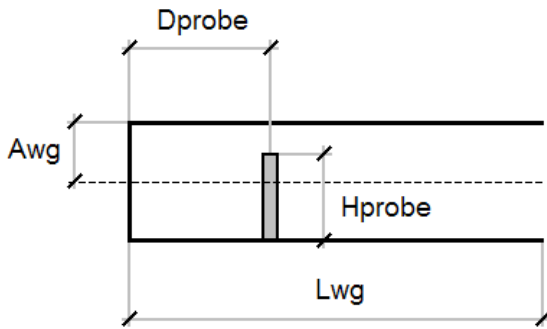


Fig. 1. CWG Cross Section

Design of CWG consists of adopting values for:

A_{wg} – waveguide radius,

L_{wg} – waveguide length (it must be large enough to allow propagation of the dominant mode only, usually half of the wavelength from probe to CWG aperture is sufficient),

H_{probe} – probe height (this should be set according to the wavelength in air or in the waveguide dielectric),

D_{probe} – probe to back wall distance (this should be set to quarter of the wavelength).

The fundamental mode propagating through a cylindrical waveguide is TE₁₁ mode. The next mode is TM₁₀. Cut off frequencies for TE₁₁ and TM₁₀ modes are:

$$F_c(TE_{11}) = 0.293 \frac{c}{A_{wg}} \quad (1)$$

$$F_c(TM_{10}) = 0.383 \frac{c}{A_{wg}} \quad (2)$$

where c is the speed of light and A_{wg} is the radius of the cylindrical waveguide. The optimum operating frequency F_0 is chosen to be geometrical mean value of two cut off frequencies:

$$F_0 = \sqrt{F_c(TE_{11})F_c(TM_{10})} = 0.335 \frac{c}{A_{wg}} \quad (3)$$

Since $c = 10^8 \frac{m}{s}$ from (3) we obtain the radius of the cylindrical waveguide for given operating frequency:

$$A_{wg}[mm] = \frac{100}{F_0[GHz]} \quad (4)$$

At the operating frequency F_0 the wavelength in free space WLO and in the waveguide $WLwg$ are given with:

$$WLO = \frac{c}{F_0} \Rightarrow WLO = \frac{300}{F_0[GHz]} \quad (5)$$

$$WLwg = \frac{WLO}{\sqrt{1 - \left(\frac{F_c(TE_{11})}{F_0}\right)^2}} \quad (6)$$

$$\Rightarrow WLwg = \frac{619}{F_0[GHz]}$$

Waveguide length is chosen in such a manner that higher order modes completely vanish before the aperture. The sufficient length is:

$$L_{wg}[mm] = \frac{3}{4} WLwg[mm] \quad (7)$$

The distance of the probe from the back wall should be:

$$D_{probe}[mm] = \frac{1}{4} WLwg[mm] \quad (8)$$

The probe length should be:

$$H_{probe}[mm] = \frac{1}{4} WLO[mm] \quad (9)$$

The dimensioning of the waveguide is completed with setting the above mentioned variables.

To suppress back radiation a choke is added to the CWG aperture edge. CWG with the choke looks like in Fig. 2.

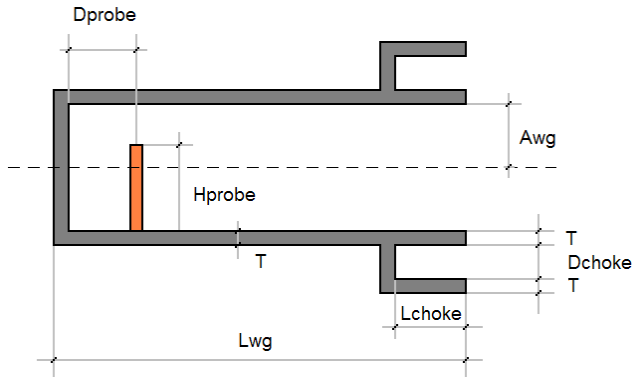


Fig. 2. Cross section of CWG with choke

The choke length should be:

$$L_{choke}[mm] = \frac{WLO[mm]}{4} \quad (10)$$

while the choke width D_{choke} is taken to be equal or greater value of two values: metallic wall thickness T and $WLO/6-2T$. This way the choke will never be too large or too small to lose its function as quarter wave transformer.

1.2. Modeling of Feeder in WIPL-D

The complete CWG feeder can be made of one BoR (body of revolution) object, two Circle objects and single wire. The cross section with the indicated objects can be seen in Fig. 3.

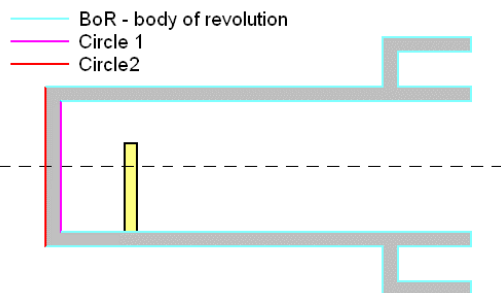



Fig. 3. Objects in WIPL-D mode

Since the feeder has two symmetry planes, both can be used to reduce the analysis time. There are two feeder models:

- Cylindrical waveguide feeder 1 – the model uses one symmetry plane. Only half of the model is built, and it is suitable for calculation of both radiation pattern and input impedance.
- Cylindrical waveguide feeder 2 – the model uses two symmetry planes. Only quarter of the model is built, and it is suitable for calculation of radiation pattern. It is not suitable for calculation of input impedance, because CWG

is excited by a dipole instead by a probe. The de-embedding procedure is required to obtain the proper return loss.

In the Symbols table, we define all the design parameters mentioned in the theoretical consideration and all the relevant coordinates needed to build the model. The Symbols table can be

inspected by clicking  in the WIPL-D Pro.

Symbols numbered 1-5 define the design parameters of the feeder:

$F0$ – Reference frequency (25.5 GHz by default),

BW – 6 dB beam-width (91 deg by default),

T – Metallic wall thickness (1 mm by default),

Z_{feed} – Shift constant (0 by default). By changing Z_{feed} , one moves the feeder along z-axis for the specified length,

N – Number of segments for polygonal approximation of the cylinder (4 by default).

Symbols numbered 6-19 define auxiliary values needed for calculation. The parameter of interest is:



Ceq – Equivalent radius factor. Since the cylinder curvature is approximated by a polygon, design radius A_{wg} should be taken in the model multiplied by Ceq , to compensate for polygonal approximation of the cylinder curvature. Ceq is chosen in such a way that cross section of cylinder (polygon) has the same surface as the circle with Radius A_{wg} .

Symbols numbered 20-43 define p and z coordinates of the BoR object.

Modification of the models is simple. Starting from either Cylindrical waveguide feeder 1 or 2, it is possible to obtain:

- CH without metal thickness – by deleting from (R10,Z10) to (R12,Z12) in the BoR object and by completely deleting Circle #2 object.
- CH without choke – by deleting from (R6,Z6) to (R10,Z10) in the BoR object.

To run simulation, click .

After the simulation is done, to inspect YZS click , and for radiation pattern click .

2. Design and Positioning of Dielectric Lens

2.1. Dielectric Lens

The cross section of the dielectric lens is given in Fig. 4. Top surface of the dielectric is flat, while lower is hyperbolical. The second arm of hyperboloid is drawn using dashed lines, and

serves only as reference. It does not exist in actual antenna design. Dielectric has refraction index N_{ref} equal to square root of the relative permittivity.

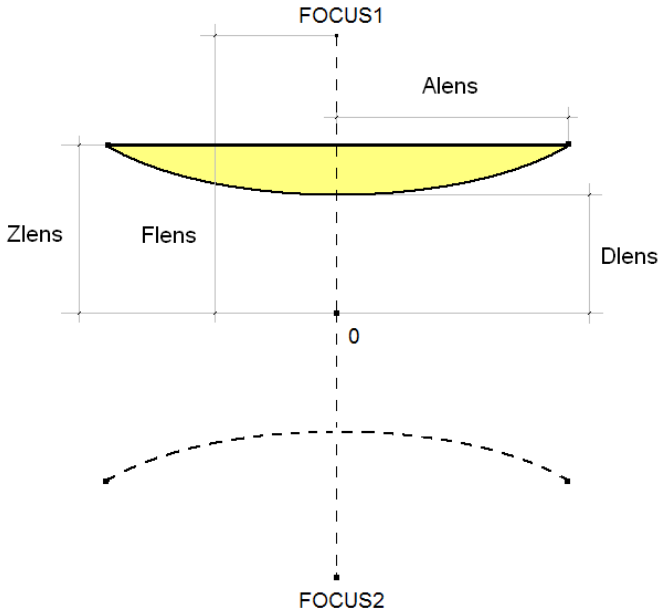


Fig. 4. Cross section of dielectric lens

The hyperboloid is completely determined with the following parameters:

$Flens$ – focal distance of the hyperboloid,

$Alens$ – radius of the hyperboloid,

$Dlens$ – distance from the tip of hyperboloid and coordinate axis, and

$Zlens$ – the height of the hyperboloid edge.

$Zlens$ is related to other parameters as:

$$Zlens = Dlens \sqrt{1 + \frac{Alens^2}{Flens^2 - Dlens^2}} \quad (11)$$

Only the upper hyperboloid is necessary for antenna design. The phase center of the feeder should be placed in the Focus #2 of the hyperboloid.

Theoretical consideration of Fermat's principle (equality of electrical path length) gives relationship between $Flens$ and $Dlens$ as:

$$Flens = N_{ref} * Dlens \quad (12)$$

The only parameter of the lens specified by the designer is $Alens$.

$Dlens$ is obtained from condition that the feeder pattern beam of width BW cover the entire lens. It can be shown that this is given with relation:

$$Dlens = \frac{Alens \sin\left(\frac{BW}{2}\right) \left(N_{ref} \cos\left(\frac{BW}{2}\right) - 1\right)}{N_{ref}^2 - 1} \quad (13)$$

$Flens$ is obtained from $Dlens$ using equation (12).

With $Dlens$ and $Flens$ definitions, all the design parameters are defined.

2.2. Building Model of Dielectric Lens in WIPL-D

The hyperboloidal lens is built using the predefined Rflct. object in WIPL-D Pro, along with one Circle object for the flat surface.

The model of the lens can be found in project "Lens" (two symmetry planes used – quarter model).

Symbols numbered 1-4 are defined by the user and specify referent frequency and geometry of the lens:

$F0$ – Reference frequency (25.5 GHz by default),

BW – 6 dB beam-width (91 deg by default),

$Alens$ – radius of the lens (60 mm by default),

Er – relative permittivity of the dielectric material (4 by default).

Symbols numbered 5-13 stand for:

$Nlens$ – Number of segments per quarter of circumference for hyperbolic surface $Nlens$ should be even integer larger than $NlensMin$ estimated in symbol #6. The estimation of $NlensMin$ is made using the criterion that maximum size of the reflector object patch is no larger than 1.5 wavelength at the referent frequency $F0$.

$Nref$ – refraction index,

BWH – half beamwidth,

$Dlens$ – distance of hyperboloid from origin,

$Flens$ – focal distance of the paraboloid,

AF – ratio of lens radius and focal distance,

DA – ratio of lens distance from origin and radius,

$Zlens$ – height of the upper surface of the lens.

What is left to do is to import the feeder into the project with lens. There are two projects of the complete antenna:

- Hyperboloidal Lens Illuminated by Cylindrical Waveguide 1 (one symmetry plane - half model) – suitable for calculation of both radiation pattern and input impedance.
- Hyperboloidal Lens Illuminated by Cylindrical Waveguide 2 (two symmetry planes – quarter model) – suitable for calculation of radiation pattern only. The de-embedding procedure must be applied to obtain proper return loss.

To import use option Edit/Structure/Import. After the import, move the feeder phase center to hyperbola focus by specifying Zfeed = - Flens in the Symbols table.

The final model with one symmetry plane (Hyperboloidal Lens Illuminated by Cylindrical Waveguide 1) is shown in Fig. 7.

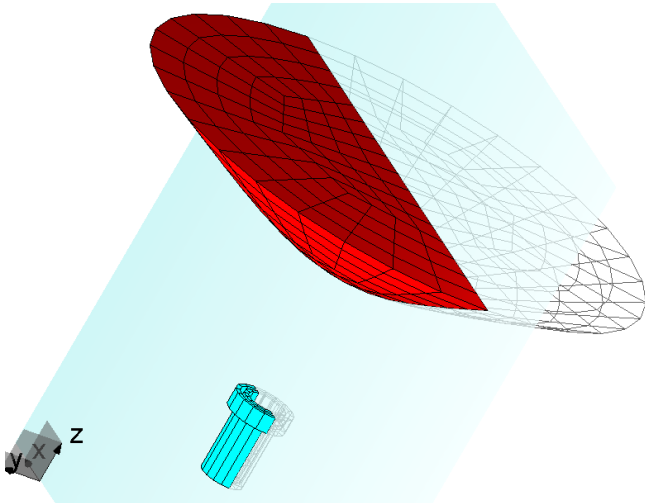


Fig. 5. Model of Hyperboloidal Lens Illuminated by Cylindrical Waveguide in WIPL-D Pro

The Default analysis parameters are:

- Frequency range: 25.5 GHz (set in Edit/Frequency),
- Radiation pattern: $\phi=0, 90$ and $-90^\circ \leq \theta \leq 90^\circ$ at 361 points (can be modified in Edit/Output Results/Radiation)

After the analysis, the radiation patterns in 3D, E and H plane are shown in Fig. 6. The model requires only 3,170 unknowns to be simulated in WIPL-D Pro. Simulation time at the everyday inexpensive work PC (CPU: Intel i7-7700K@3.60 GHz) is under 3 seconds per frequency point.

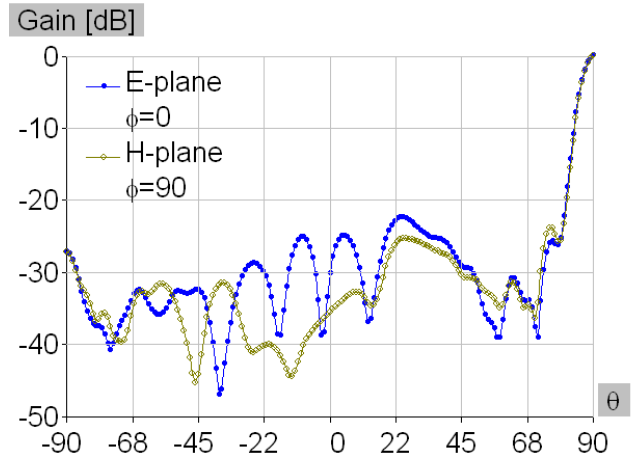
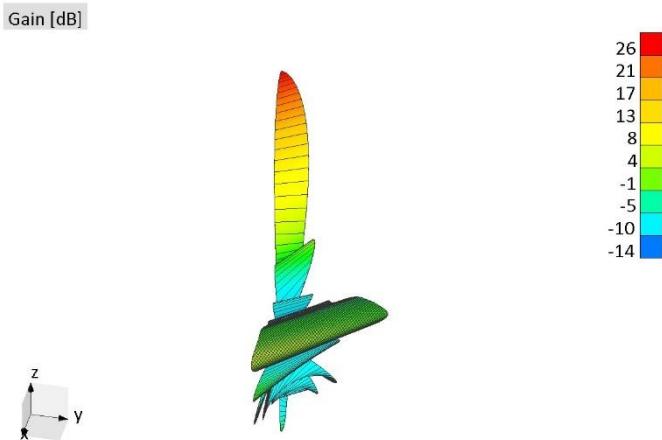


Fig. 6. Radiation pattern

Simple modification of the model is possible. To obtain:

- CWG feeder – remove lens by deleting Rflct. and Circle objects.

For the models described in this application note, please contact WIPL-D support team.