Primer on Waveguide Gain Horns and Accessories

White Paper



Abstract

The paper describes the basic operation and theory behind various types of waveguide gain horns and highlights the primary gain horn designs used in commercial and military radar and communications applications.

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Primer On Waveguide Gain Horns & Accessories

Introduction

A waveguide gain horn, or gain horn, is a type of aperture antenna that is fed via a waveguide. The aperture of this antenna ends at a gradient transition from the feed port that is designed to be an impedance transition that matches the impedance of free space (~377 Ohm). Without the transition an open-ended waveguide will be poorly matched with the free-space medium and there will be substantial reflections and a standing wave developed. I.e. A waveguide gain horn is in essence a progressive matching transformer with a relatively narrow aperture that ensures high directivity/gain.

The exact dimensions of the gain horn and gradient result in a limited frequency range of operation that can be extended with additional modifications to the gradient and aperture design. Waveguide gain horns can be designed that function with every type of waveguide, rectangular, square, circular, or elliptical. The most common type of waveguide gain horns used in test and measurement, high power, and long-range communications use rectangular waveguide feed ports and are designed to match with the frequency range capability of standard size rectangular waveguides.

Gain horns exhibit high directivity/gain, power handling, and antenna efficiency compared to other antenna types. This is also a benefit that gain horns can be directly fed by waveguides, which results in minimal interface losses. Though precision machining and fabrication techniques are needed to manufacture gain horns, these antennas are relatively simple structures that are extremely compact, reliable, and deliver consistent performance. This is why gain horns are often used in test and measurement for antenna characterization, dielectric free-space characterization of materials, electromagnetic compatibility/electromagnetic interference (EMC/EMI) conformance testing, over-the-air (OTA) testing, satellite communications, and radio telescopes.

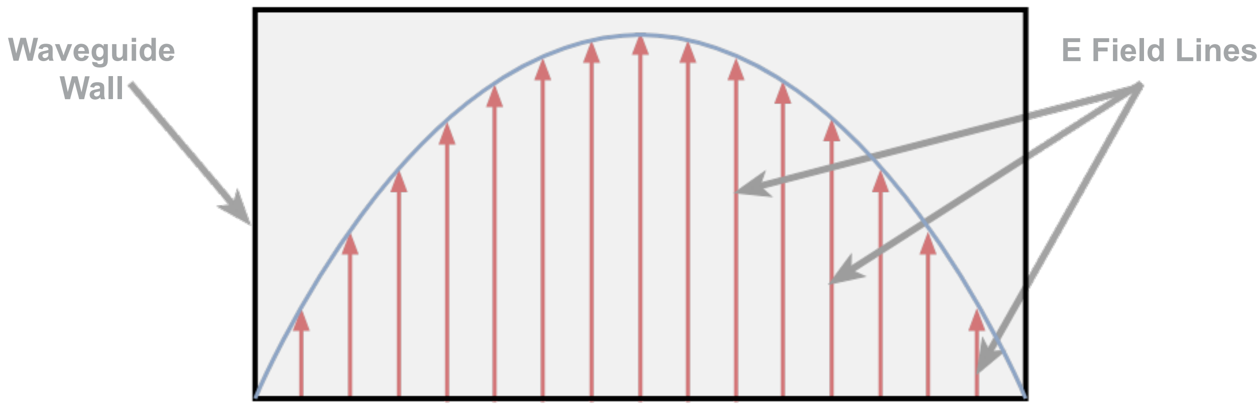
Nuances Of Gain Horn Design

The exact specifications of the horn shape and aperture of a gain horn directly impact the directivity/gain, bandwidth, and antenna pattern performance. This is because the input planar electromagnetic (EM) wave injected at the feed is transitioned to a shape closer to the curved wavefront of a free-space wave propagation. Which means that the interior conductive surfaces within the horn shape and any dielectric material inserted within the horn or at the aperture directly impact the wave shape. The angle and shape of the flare for both the electric plane (E-plane) and magnetic plane (H-plane) of the waveguide all impact the gain horn performance.

As various ranges of performance are desirable, there are several common styles and methods of flaring a gain horn. The flare of the gain horn can be a single slope, curved, or nonlinear (soft horn), and may have other features, like ridges or corrugations. A general rule is that the wider the horn flare the greater the resulting bandwidth, but directivity/gain will proportionally be reduced. This results in a trade-off between bandwidth and gain with waveguide horn antennas that can partially be overcome with modifications to the horn structure. Manipulation of the horn structure is also used to reduce undesirable effects of the horn shape. For instance, rectangular/pyramidal gain horns tend to exhibit significant sidelobes as a result of the phase error induced by the horn transition, and modifications of the horn flare can be used to mitigate these sidelobes at the cost of additional manufacturing complexity. Other deleterious phenomena can be overcome by the introduction of a dielectric insert feature, dielectric lens, ridges, slots, or other features. A dielectric lens, for instance, can be used to more precisely transition a planar wavefront to a curved wavefront that better matches a free-space wavefront and result in better directivity/gain than the same gain horn without a dielectric lens.

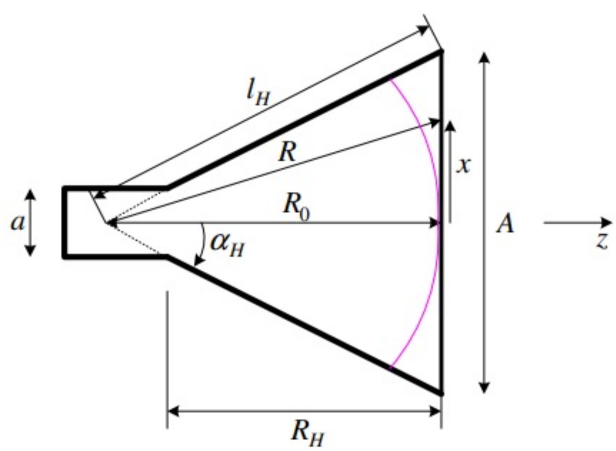
Waveguide Physics

Waveguides provide a conductive guided path for electromagnetic (EM) radiation as a transverse wave. Most waveguides are designed to efficiently pass the transverse electric (TE) mode without an electric field in the direction of propagation as a fundamental mode. This means that the electric field is perpendicular to the sidewalls of the waveguide. Hence, the distance between the sidewalls with the electric field gradient peak can be used to manipulate characteristics of the waveguide. This is a useful phenomenon for ridged waveguides.



TE10 Mode

From the mouth of the waveguide flange into the gain horn, the injected waves begin to propagate within the horn as a spherical wavefront. The apex of the wavefront occurs at the apex of the gain horn, which is referred to as the phase center of the antenna. With spherical waves, there is a phase difference between the apex of the wavefront and the edges of the wavefront, which is a smooth gradient from the apex to the edge. This phase difference results in a phase error, which is a function of the flare angle. A sharper flare angle results in greater phase error, and reduced gain, but a wider beamwidth. Phase error is also a function of the size of the horn, which means larger gain horns experience reduced gain compared to their electric length and wider beam widths. Reducing the angle of flare, i.e. extending the length of the gain horn, results in less phase error. However, building a longer antenna that accurately maintains a fixed flare angle over a longer length and is of adequate structural integrity becomes increasingly difficult, which leads to a practical limitation to gain horn antenna lengths.



The electrical length of a gain horn antenna is a function of frequency. Hence, higher frequency signals experience a larger electrical length for the same size antenna as lower frequency signals. This is why gain and directivity of a gain horn increases as a function of frequency and beamwidth decreases.

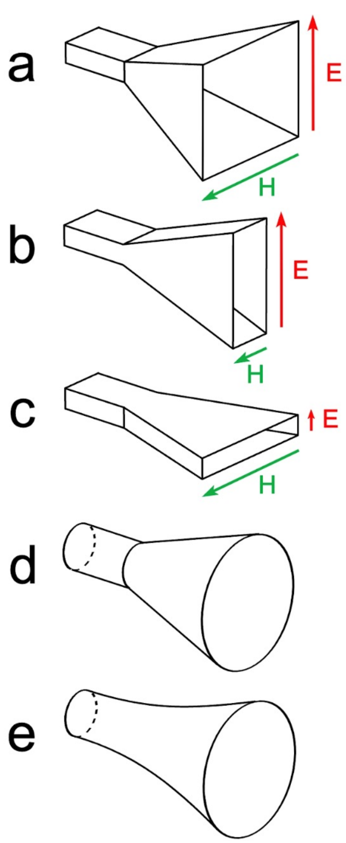
For straight sided gain horns at the interface between the injecting waveguide channel transition to the flare there is a sharp impedance shift as well as at the mouth of the aperture. The amount of reflections at these junctions is a function of the angle of the flare. For narrow flare angles the majority of the reflections occur at the aperture of the horn, where wide flare angles experience higher reflection concentration at the throat of the gain horn. At the two extremes of no flare angle and a 90 degree flare angle, the reflections are extreme and result in low gain. There is an optimum flare angle for a given frequency where the gain is maximum. Most gain horns that are fabricated are optimum gain horns at a given frequency, typically the center frequency or a specified frequency for a desired frequency range.

Gain Horn Types

The discussion above points out various trade-offs in gain horn design related to the size, flare angle, and length. This is why in test and measurement applications there are usually several sizes of standard gain horns available in order to have an optimal gain horn antenna size for a given application. As discussed earlier, additional features, such as ridges and dielectric inserts/lenses can be used to change the dynamics of these trade-offs and there are many popular gain horn variants that leverage these techniques.

Waveguide Gain Horn Flare Types

The flare type of a gain horn antenna has much to do with the resulting performance. This is why the flare type is an important descriptor of a gain horn when reviewed for selection for a given application.

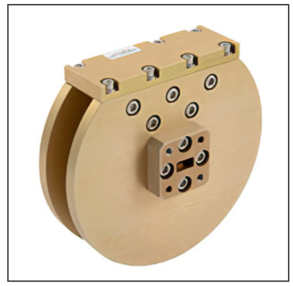


(a) a pyramidal gain horn shaped as a four-sided pyramid with a rectangular cross section aperture and constant flare angle **(b)** a E-plane rectangular horn antenna **(c)** a H-plane rectangular horn antenna **(d)** a conical horn antenna with a circular aperture and a constant flare angle **(e)** a conical horn antenna with an exponential flare angle.

Exponential

An exponential gain horn is designed with a curved flare that has an exponentially increasing angle toward this aperture. This design feature results in a horn with minimal internal reflections and near constant impedance throughout the antenna. Though more difficult to design and manufacture, this design feature results in more optimal performance over the waveguide frequency range and are generally used in high-performance applications.

Sectoral or Sector Waveguide



A sectoral/sector horn antenna, a type of rectangular horn antenna, has one set of sides at a fixed zero flare angle and the other side at either a fixed or exponential flare angle. If the set of sides that are fixed are perpendicular to the long wall of the rectangular waveguide, this is an E-plane sectoral waveguide, and if the fixed set of walls are parallel to the long wall side, this is a H-plane sectoral waveguide. The resulting wavefront expelled from the aperture is “fan” shaped, which means very narrow in the direction of the non-angled flare. Search and scanning radars often used this type of waveguide gain horn as a feed as they make fan-like beams useful for sweeping. Other applications include a wide broadcast where the elevation beam width should be narrow.

The polarization of the wavefront can be controlled by the rotation angle of the waveguide, hence both vertically or horizontally polarized configurations are possible.

Waveguide Gain Horn Design Features

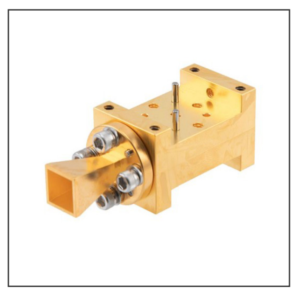
Broadband

A broadband gain horn is simply a gain horn that has at least one of several possible features that extend the bandwidth of the antenna beyond what a typical gain horn can achieve. This could be double-ridge, quad-ridge, varying flare designs, etc.

Open Boundary

The “open boundary” design feature of a gain horn means that one or more sides of the horn antenna walls are replaced with either no material or dielectric structural supports. The open boundary feature provides wider illumination than a typical horn which can be useful in environments where it is desirable to have a wider horn antenna beamwidth, such as in a compact antenna test range.

Dual Polarized Or Dual-Linear Polarized



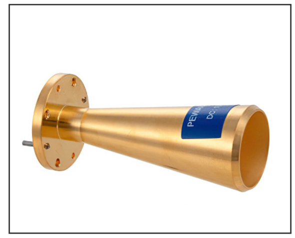
A dual polarized waveguide horn is a horn antenna that is capable of transmitting and receiving both horizontal and vertical linear polarizations simultaneously. One of the benefits of dual polarization is that both polarizations can be measured at the same time without rotating the waveguide, which is necessary with a singular polarized waveguide horn. An example use of this is when performing dielectric free-space measurements a dual polarized gain horn is able to measure both polarizations of the material and provide more detailed dielectric characterization.

Another use case is in communications, as dual polarization effectively doubles the throughput of a communication system as it allows for two separate signal streams, one with each polarization. Dual polarized antennas can either be square pyramidal or quad-ridged horns.

Pyramidal/Standard Gain Horn

A pyramidal gain horn or standard gain horn is a rectangular aperture horn with a smooth sidewall. These are broadband horn devices that are often used in test and measurement as calibration devices for the gain of other antennas. These horns are linearly polarized with reasonable gain, low VSWR, and a consistent antenna factor. The performance of a standard gain horn is precise and predictable based on the design, with both measured and computed antenna factors/gain to be shown to agree within a small margin of error.

Conical Gain Horn



A conical horn antenna has a circular aperture (cross section) that outputs a circularly polarized wavefront. Some conical horn antennas are fed via a coaxial probe, but typically a conical horn antenna is designed to accommodate cylindrical or circular waveguides with the appropriate waveguide flange compatible with the horn frequency range.

Scalar or Corrugated Horn

A conical or sectoral horn antenna with precisely designed grooves perpendicular to the wall of the horn is known as a scalar or corrugated gain horn. These horns are designed with groove lengths that are small compared to the wavelength with groove depths a quarter of a wavelength with exception to the grooves near the apex of the cone. The result is a gain horn with an extremely flat output wavefront and a well-defined phase center. Moreover, the radiation pattern of a conical scalar horn is rotationally symmetric between the E-field and H-field. The result is a highly efficient antenna (reduced side-lobes and diffraction from the edges for both sectoral and conical) that can be used to precisely deliver an output wavefront. This is critical for applications like parabolic dishes and point-to-point communications which benefit from antennas that can be manufactured with precise pointing.

Wide Angle Scalar Feed Horn or Choke Horn

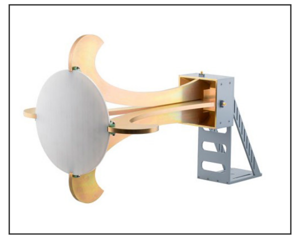
Wide angle scalar feed horns, or choke horns, are designed with grooved features in the horn aperture and with a wider electrical aperture than a typical conical gain horn. These features result in a much wider beamwidth, often above 50 degrees, than a typical gain horn. These horns are used in applications that require a wide beamwidth and compact horns, such as with offset feed and low F/D ratio parabolic reflections applications.

Double-Ridge

One method of extending the frequency range of a rectangular waveguide is to add a double ridge, which extends the lower cutoff frequency significantly. This can enable multi-octave bandwidths with a single waveguide horn. Moreover, a double ridge waveguide horn demonstrates lower impedance than a smooth wall waveguide. As the precise dimensions of the ridges impact the higher order waveguide modes, a double ridge waveguide can also be extended by pushing out the spurious pass-bands that exist at higher order modes. This is done by using the ridge dimensions to push out the higher order mode pass-bands high enough out from the desired frequency bands of operation to limit the impact in the desired bands. A double-ridged waveguide designed in this way can eliminate the need for a low-pass filter that would typically be used to attenuate the high order spurious pass-bands.

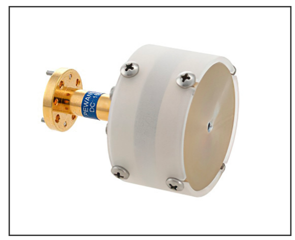
Creating a precision double ridge within the waveguide can be difficult to machine, especially accounting for the gradient of the horn shape. In this case the double ridges are conductive extensions of the short wall of the rectangular waveguide that are parallel to each other and have a specified size and gap distance in between the two ridges. Adding ridges within the waveguide structure does result in higher ohmic losses and due to the narrow gap region between the ridges, the power handling of ridged waveguide is also reduced compared to non-ridged waveguide. Lastly, double-ridged waveguides also tend to be heavier and more rigid than smooth wall waveguides, which could pose limitations for some applications.

Quad-Ridge or Quadratic Ridge Profile



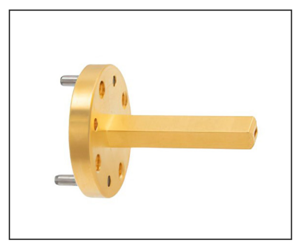
A quad-ridge horn functions similarly to a dual ridge horn, but also allows for automatic dual-linear polarization capability. This type of antenna has been observed to demonstrate the widest antenna bandwidth and lowest sidelobe level (SSL) of various horn antenna types. It is possible to further enhance the performance of a quad-ridge antenna by using open-boundary design techniques. This is a very common horn antenna type used in advanced measurement applications.

Omnidirectional Waveguide Antenna Or Omnidirectional Horn



An omnidirectional waveguide antenna is essentially a horn antenna with an aperture that extends in a complete circle perpendicular to the waveguide input with a transition optimized for the waveguide frequency range. This allows for relatively high gains and an omni-directional antenna pattern. This means that these waveguide antennas radiated equally in all azimuth (horizontal) directions, with little radiation energy emitted along the elevation. These antennas are used in applications where it is desirable to monitor or send signals out in all horizontal directions simultaneously, such as spectrum monitoring.

Waveguide Probes



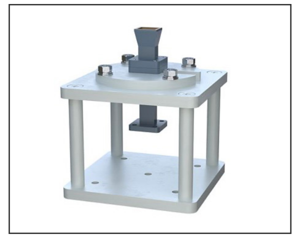
A waveguide probes are used for near-field measurements as they provide minimal perturbations of the incident field during sampling. These waveguide antennas are not designed for optimal gain or beamwidth, but instead the near-field reception directly in front of the waveguide probe. These are typically used for measuring materials and surfaces where the probe is placed in very close proximity to the sample surface.

Gain Horn Accessories

Radomes/Cover Flange

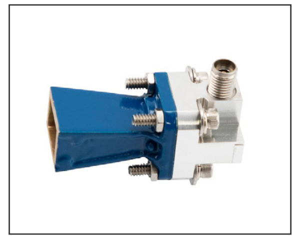
Waveguide antenna cover flanges, sometimes called radomes, are a thin dielectric material that is placed on the aperture of the waveguide antenna to provide additional environmental protection. Cover flanges help to prevent environmental ingress into the waveguide horn body, which could degrade performance of the antenna, especially in high humidity, corrosive, or heavy particular environments. Waveguide antenna cover flanges provide a seal with the aperture of the antenna while also only minimally impacting the performance of the antenna. As any material placed in the path of the wavefront emitted from the antenna will interact with the wavefront it is important that waveguide flanges are made of very low dielectric constant material that is also very low loss and ideally closely matches the external atmosphere.

Gain Horn Mounts



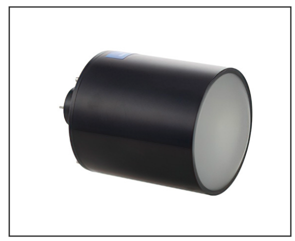
Horn antenna mounts help to ensure precision alignment and placement of a gain horn without impacting the gain horn performance. If a horn antenna mount is properly designed it will match with the mounting flange of the antenna allowing the horn to be installed along with the connecting waveguide or coaxial-to-waveguide adapter. This connection at the flange provides good mechanical stability, compact fixturing, and allows for the cage-mount, L-style, or round mounts to be placed on a tripod or other positioner for better precision in alignment/placement. These types of cages/mounts can be invaluable in test and measurement applications where alignment is crucial to achieving repeatable and reliable results.

Waveguide-to-coaxial Transition/Adapter or Coaxial-to-Waveguide Transition/Adapter



A waveguide-to-coaxial transition/adapter is a passive device that has a coaxial port that feeds a waveguide designed to pair with a similarly sized waveguide and flange. The coaxial connector size and design is typically selected to cover the maximum frequency capability of the waveguide, however the waveguide transition will limit the lower frequency capability of the coaxial connector.

Dielectric Lenses or Lens Horn Antennas



A dielectric lens can be added to the aperture or even internal structure of a horn antenna to change the behavior of the wavefront as it travels through the horn antenna, at the aperture of the horn antenna, or after the aperture of the horn antenna. The possible design goals of a dielectric lens for a horn antenna are to correct for phase-error within the horn antenna to minimize side-lobs, to enhance directivity/gain, to minimize the beamwidth, extend the beamwidth, to realize a shorter/more compact gain horn, or provide a better impedance match with the external environment. Waveguide horns that are specifically designed to accommodate a dielectric lens insert may feature different flare angles, extended apertures, and other physical features that are only possible with a dielectric lens. Such waveguide horns are often referred to as lens horns.

Conclusion

Gain horn antennas are widely used throughout communications, Satcom, radar/sensing, and measurement applications for the high performance and high power exhibited by gain horns. There are a variety of different gain horns designed with advanced features and accessories that enhance performance and ease of use during alignment and positioning.