

# Inexpensive Microwave Antenna Demonstrations Based on the IEEE Presentation by John Kraus – Jon Wallace

**Abstract:** After seeing a video of John Kraus giving a demonstration on radio antennas to the IEEE many years ago, the author was so inspired that he researched the concepts and sought to reproduce as much of the demonstration as he could. It is hoped that these demonstrations will educate and inspire others to explore as well. They cover topics which include: beam width, inverse square law, polarization, reflection, refraction, interference, absorption, gain, wave guides, diffraction, and more. The equipment used consists of a Gunn diode source with horn antenna and a WR-90 horn antenna with crystal detector, instrumentation amplifier, and voltage controlled oscillator (VCO) so that changes in intensity will be heard as pitch changes.

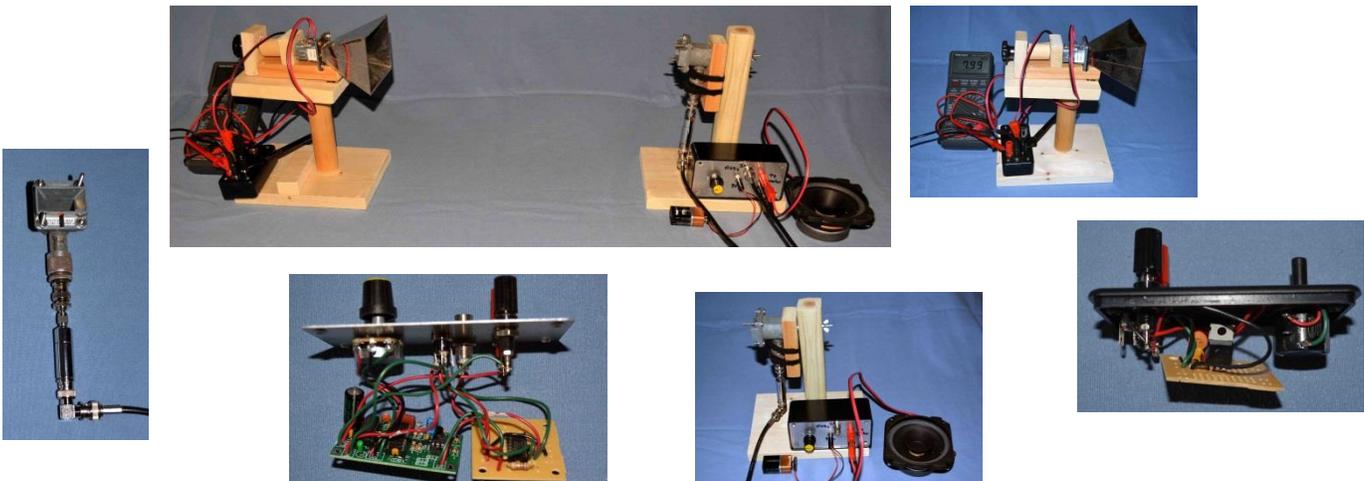
## Safety

Although these microwave frequencies are not the ones used for cooking, they can still cause damage to eyes and sensitive areas of the body. When I started this project I searched for the most stringent safety recommendations I could find for a 10 mW transmitter at about 10 GHz. This recommendation was to keep a minimum distance of 60 cm. (2 ft.). I also designed an aluminum-screened mask that can be worn when presenting the demonstrations. It completely blocks all radiation from the transmitter. Close-up pictures and hints on making one are included at the end of this document. Stay safe!



## The Equipment

The various demonstration devices will be described in each section and building tips are included at the end of the paper. The basic equipment consists of a transmitter (a Gunn diode device) with a larger horn and regulated 8V power supply powered by a 9V battery, a receiver with a small horn antenna, crystal detector, instrumentation amplifier, voltage controlled oscillator, and powerful speaker. The transmitter and receiver are mounted in such a way as to allow them to be rotated 90° to allow polarization to be explored.



Pictures clockwise from top: the transmitter and receiver; the transmitter with power supply and meter; the power supply opened up; the receiver with instrumentation amplifier, VCO, speaker and 9V battery; the receiver electronics opened up; the horn antenna and crystal detector.

## The Demonstrations

Far-Field: For most of these demonstrations we will be at far-field. Far-field is the point where the waves coming from the transmitter are all plane waves, whereas in near-field the electric and magnetic fields interact and create a much more complex zone to try to understand. If the maximum linear dimension of an antenna is  $d$  and you are  $2d^2/\lambda$  or farther from an antenna, you are in the far-field. For us, the maximum dimension is 9.42 cm (transmitter horn) yielding a far field of about 59 cm. We will try to keep all our demonstrations in far-field because it makes them easier to study using simple physics.

Beamwidth: There are many “beamwidths” defined for various reasons. In our case, using the receiver as a power detector, we will use the measure of an angle from the first null on one side of the beam to the first null on the other side of the beam. We will explore the relationship between the small horn on the receiver and a large horn placed over it, demonstrating that the beamwidth for a larger horn is narrower. For a more mathematical expression we can use the approximation for half power beamwidth (HPBW - the beam width at 0.5 peak power or 0.707 peak voltage) also known as the -3dB beam width:

(HPBW) Beamwidth =  $70\lambda / D$  where,  
 $\lambda$  = Wavelength  
 $D$  = Diameter  
 $\lambda = 0.3 / \text{frequency} = 0.03$  (for 10GHz)  
For the small horn (maximum  $d = 3.6$  cm); the  
HPBW =  $58.3^\circ$ .

For the larger horn (maximum  $d = 9.42$  cm); the  
HPBW =  $22.3^\circ$ .



Small horn and large horn

**What is a Decibel?** A decibel (dB) is a way of comparing two things, usually power or intensity. A reference device is compared with a device we're interested in. It is a logarithmic expression meaning that large values can be compared more easily and each value varies by an order of magnitude of 10. Thus a dB value of 5 compared to 6 expresses a 10-fold difference between them.

Examples: the formula is usually written:  $10 \log (P_2/P_1)$  dB where log is base 10 and P is power.

1) If you have a device that gives twice the power of a reference device then you get a dB of:  $10 \log(2/1)$ dB = 3dB.

2) If you have a device that gives 10 times the power of a reference device then you get a dB of:  $10 \log(10/1)$ dB = 10dB.

3) If you have a device that gives half the power of a reference device then you get a dB of:  $10 \log(0.5/1)$ dB = -3dB

Gain: Gain is a measure of the antenna's directivity and electrical efficiency. Gain is related directly to antenna area, therefore a larger horn not only has a smaller beam width but a larger gain, which we can hear in the demonstration. Gain can be expressed as:

$$G = [(4\pi A)/\lambda^2]e_A \text{ where,}$$

A is the area of the aperture,

$\lambda$  is the wavelength,

$e_A$  is called the aperture efficiency and ranges from 0 and 1. For a pyramidal horn antenna it is generally around 0.5.

For the small horn (A=6.84) G=4.8.

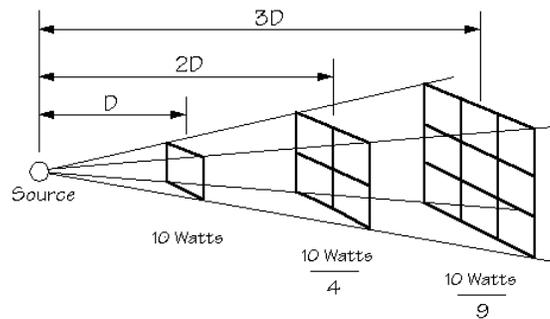
For the large horn (A=64.8) G=45.2.

Antenna gain is usually expressed as  $\text{dB} = 10 \log(G)$ ; so our values become: 6.8dB and 16.6dB respectively.

Table 1 shows dBm, which is the ratio in dB of power in milliwatts (mW) referenced to 1 mW.

dBm	Power (mW)
40	$10^4 = 10,000$
30	$10^3 = 1,000$
20	$10^2 = 100$
10	$10^1 = 10$
7	5.0
6	4.0
5	3.2
3	2
1	1.3
0	1
-1	0.79
-3	0.5
-6	0.25
-10	$10^{-1} = 0.1$
-20	$10^{-2} = 0.01$
-30	$10^{-3} = 0.001$
-40	$10^{-4} = 0.0001$

Inverse Square Law: We are detecting the power transmitted and received by our horn antennas. This is governed by the inverse square law which states that the power received is directly proportional to the inverse of the square of the distance (i.e.:  $1/d^2$ ). This can be heard with our demonstration. It can also be shown that the width and height of the detected signal at twice the distance are each twice as large, yielding an area which is four times larger ( $2W \times 2H = 4A$ ). As a result, the detected signal strength is spread over four times the area and thus four times weaker, demonstrating the inverse square law.



[www.angelfire.com/sc3/sciencevisions/ISL/isldemo.gif](http://www.angelfire.com/sc3/sciencevisions/ISL/isldemo.gif)

Linear polarization: This generally refers to the orientation of the electric field along a single plane – in our case vertical. Rotating the receiver horn shows maximum signal at vertical orientation while no signal at 90 degrees (horizontal) and decreasing signal from 0 to 90 degrees. Placing a grid between the transmitter and receiver shows the effect as well. With the grid vertical no signal can pass through (the electric field is vertical, it comes to the grid, which is parallel, and the electric charge runs along the grid and doesn't pass through). With the grid horizontal you get maximum signal through (the electric field can't move much in the thin grid wires so most of the signal passes through). If you rotate the grid to 45 degrees, then part of the signal passes because it basically rotates the polarization so that the horn can detect some signal at 90 degrees. The grid must have a separation distance less than  $\lambda$  (which in our case is 3 cm) and the metal grid must be a small fraction of the  $\lambda$ . (see cut-off frequency in the waveguide section). I chose a copper clad board and made 4mm gaps with a Moto-tool and grinding blade. You can also use copper wire with gaps between them.

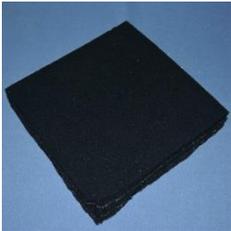


Copper clad grid

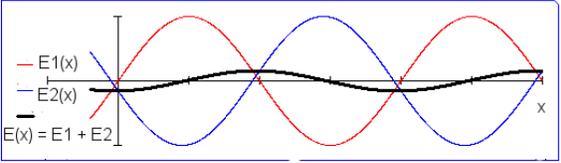
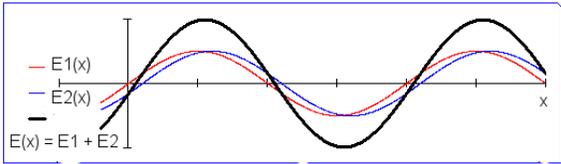
**Reflection:** Remember that the angle of *incidence* equals the angle of *reflection*. Many things will reflect the 10 GHz radiation, including a hand and a metal sheet. By placing three metal plates (available from Home Depot or Lowes) mutually perpendicular to each other, and taping the three sheets together with metal tape (available from Home Depot or Lowes), a three-corner reflector is made. This device has the effect of reflecting any signal that enters it back in the direction it came from. A microwave absorber (Eccosorb – available from SHF Microwave Parts: [www.shfmicro.com/foam.htm](http://www.shfmicro.com/foam.htm)) will also be shown; very little signal is reflected so the effect is quite dramatic.



Three corner reflector and absorber



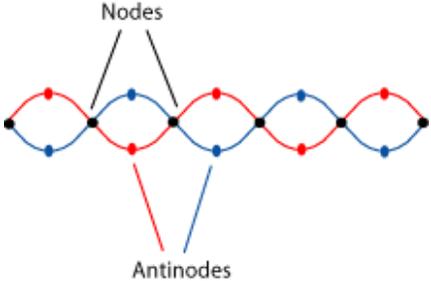
**Interference/Standing Waves:** Placing the receiving horn where it can slightly detect the transmitter signal directly as well as from a reflected source, creates an interference pattern. In this demonstration a flat metal sheet is moved toward the transmitter and aimed toward the receiver. In some instances the signals arrive in phase (for example both at peak – they both add together (constructive interference)) and a maximum signal is heard while when the two signals are out of phase (for example one a peak and one a trough – they both cancel (destructive interference)) and no signal is heard.



Constructive (a) and Destructive (b) Interference – [upload.wikimedia.org/wikipedia/commons/1/14/ConstructiveAndDestructiveInterference](http://upload.wikimedia.org/wikipedia/commons/1/14/ConstructiveAndDestructiveInterference).

As the flat metal plate is moved, a pattern is seen such that every  $\lambda/2$  (~1.5 cm) a peak is heard. This is called a standing wave pattern.

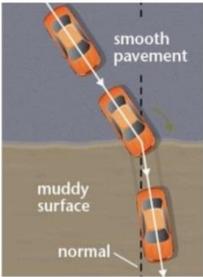
Standing Waves – [cnx.org/contents/07970e19-2e42-4b8e-9a7d-2749bf5d8529@15/Standing\\_Waves\\_and\\_Musical\\_Ins](http://cnx.org/contents/07970e19-2e42-4b8e-9a7d-2749bf5d8529@15/Standing_Waves_and_Musical_Ins)



**Refraction:** Radio waves can bend when they encounter materials with different refractive indexes and lenses can be made to take advantage of this property. The effect is likened to a car traveling from pavement to mud. When the car's front wheel hits the dividing line (see picture at right), it slows down while the rest of the tires keep moving quickly causing the car's trajectory to bend. That is similar to what happens with refraction.

[image.slidesharecdn.com/refraction-111126024630-phppapp02/95/refraction-9-728.jpg?cb=1322299139](http://image.slidesharecdn.com/refraction-111126024630-phppapp02/95/refraction-9-728.jpg?cb=1322299139)

**Cause of Refraction**

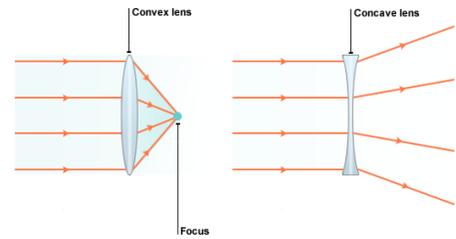


- Car Analogy**
- Car travelling at an angle towards a muddy surface
  - One front wheel hits muddy surface and slows down
  - Other wheels continue to move at a higher speed
  - Causes the path to bend

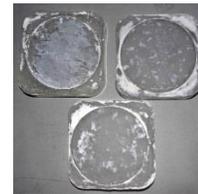
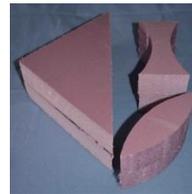
## Convex and Concave lenses

Convex lenses cause the radiation to converge to a focus while the concave lens will cause the radiation to diverge or spread.

Many materials can be used as a lens for microwaves and three will be shown; polystyrene, which is the least effective, paraffin wax, and acrylic, by far superior to both. Polystyrene can be cut with a thin saw blade or “foam knife” (a heated wire that cuts through the foam). Wax lenses can be made by using a disposable loaf tin and wax (from a grocery store – used for canning). To obtain the desired shape, push the bottom of the tin against a lens (I used a satellite dish antenna); cut up and carefully melt the wax in the tin over a pan of very hot water then push the tin against the dish and wait for the wax to harden. The acrylic lenses were made by using a cheap 4” magnifying lens (from a dollar store) to make molds in a plastic container with plaster of paris. Once I got one mold, I put a sheet of plastic wrap over it and filled it with plaster to make the inverse mold. Once all molds were made and hardened I used a mold separator spray (that didn’t work - I read that Vaseline might work – spread it over your mold) and mixed the acrylic material with a hardener (available from art supply stores like Dick Blick) and poured it into the molds to create the lens. This material smells extremely bad and you **need** ventilation!



[www.bbc.co.uk/staticarchive/9a2daecd646597696e9c26e8df970182bf0355dc](http://www.bbc.co.uk/staticarchive/9a2daecd646597696e9c26e8df970182bf0355dc)



Wax prism, convex and concave lenses; wax prism on stand; polystyrene lenses and prism; acrylic lenses (these have remnants of the plaster mold on them)

## The Prism

The prism is a large triangle of wax of  $45^\circ/45^\circ/90^\circ$  (actually, mine is  $43^\circ/47^\circ/90^\circ$ ). The waves hitting it are bent as shown in the picture and as calculated below. The calculations are done as follows:

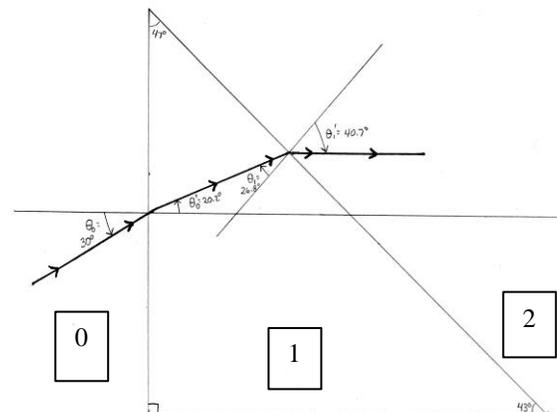
$\theta_0$  = incident angle of the transmitter wave ( $30^\circ$ ).

$\theta_0'$  =  $\arcsin(\text{refractive index of 0 (air)}/\text{refractive index of 1 (wax)} * \sin \theta_0) = \arcsin(1/1.446 * \sin 30^\circ) = 20.2^\circ$ .

$\theta_1$  = top angle ( $47^\circ$ ) -  $\theta_0' = 47^\circ - 20.2^\circ = 26.8^\circ$ .

$\theta_1'$  =  $\arcsin(\text{refractive index of 1 (wax)}/\text{refractive index of 2 (air)} * \sin \theta_1) = \arcsin(1.446/1 * \sin 26.8^\circ) = 40.7^\circ$ .

$\theta_2 = \theta_1' - \text{top angle } (47^\circ) = 40.7^\circ - 47^\circ = -6.3^\circ$ .



## The Polyrod Lens/Antenna

The polyrod antenna (aka: an end fire leaky wave antenna) acts somewhat like a waveguide (waveguide: usually a tube used to guide a microwave signal from one end to the other). There is a loss of energy when the microwaves pass through the rod. This energy loss ‘leaks’ out of the dielectric material (the acrylic) and generates a microwave field at the surface of the rod that runs along the rod to the receiver. The polyrod has a narrow beamwidth and behaves as if the effective aperture (i.e.: the area) is much greater. A polyrod lens/antenna (in this case a  $3/8$ ” acrylic rod) will be demonstrated and the effect is obvious! The

design is so efficient that it is employed in the retina of the human eye, where over 100 million polyrods (millions of times smaller than our 10 GHz version) are used to gather light and form images.



Acrylic poly-rod antenna

**Waveguides:** A waveguide is a device that ‘guides’ the electromagnetic radiation. In this demonstration metal pipes will be used. We start with a large diameter pipe (1 ¼”) and notice that the signal is passed through the pipe; we continue to decrease the size of the pipe opening until we see no signal (1/2” pipe). This is known as the cut-off frequency and is calculated with the following formula:



Waveguides – metal pipes

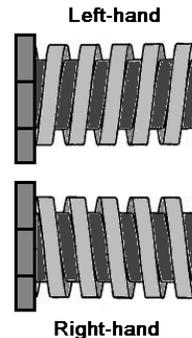
**Cut-off frequency =  $c/2a$**  where,  
 $c$  = speed of light (300,000,000 m/s)  
 $a$  = largest side length (2.2cm = 0.022m)

For our receiver waveguide, the cut-off frequency is about 6.8 GHz. The rule of thumb for rectangular waveguides is that they operate at between 125% and 189% of the cutoff frequency. Thus for our WR-90 receiving antenna, the cut-off is about 6.8 GHz, and the band of operation is about 8.2 to 12.4 GHz. For the pipes used, the smallest has an inside diameter of 1/2 inch which is equal to about 1.25 cm = 0.0125m. Therefore our cutoff frequency for this pipe is about 12GHz, so our 10GHz signal will not be passed through. Inserting a poly-rod antenna will allow the signal through because the poly-rod increases the effective aperture as mentioned above. The pipes are available at Home Depot or Lowes.

**Circular Polarization:** In this case the orientation of the electric field is rotated in a circular motion by a helical (spiral) antenna. With the poly-rod antenna in place, a helix is pulled over the rod causing the receiving horn to be circularly polarized so that the signal can be detected in all orientations as the horn is rotated.

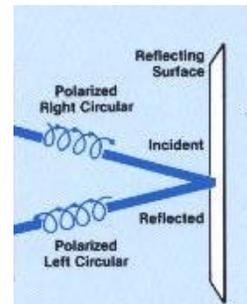
There are left-handed and right-handed helices but which one you use will have no bearing on the performance of the demonstrations. My demonstration uses left-handed helices since they were easier to make. The helices were made from copper wire wound around a 3/8” rod (the poly-rod would work!) with a spacing of 0.7cm between spirals. Be sure you wind all helices in the same direction; a right circular helix is not able to detect a signal from a left circular helix!

The slip-on loop was made from small gauge wire and consisted of only about 5-6 loops. It is stored on a short piece of rod so it wouldn’t get squashed.



[forum.flitetest.com/showthread.php?2169-How-to-build-a-5-8GHz-Helical-Antenna/page2](http://forum.flitetest.com/showthread.php?2169-How-to-build-a-5-8GHz-Helical-Antenna/page2)

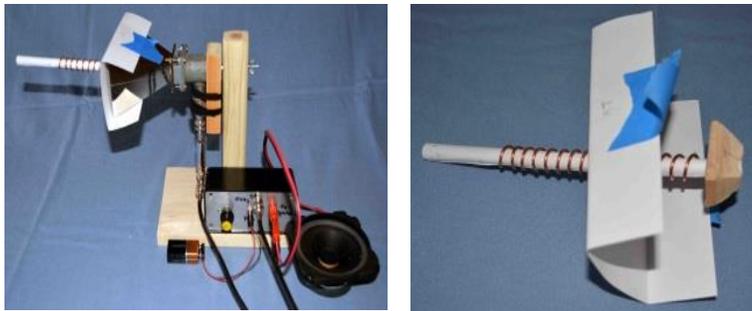
**Aluminum Ground Plane:** By placing a long sheet of aluminum foil over the table we create a ground plane which can reflect radiation, acting like the metal sheet seen in the interference demonstration done earlier. This simulates the real-world antenna situation where a transmitter tower is a long way off and the radiation not only comes directly to your receiver but the signal is reflected off the ground and interferes with the incoming direct signal creating the standing wave pattern. As the receiving horn, is raised the standing wave pattern can be heard. By placing a helical antenna on both the transmitter and receiver, a circularly polarized signal is created and the standing wave pattern is theoretically eliminated. This is due to the fact that the reflected circularly polarized signal is oppositely polarized from the incoming signal and can’t be detected by the left-handed helix being



[nns-technology.com/?page\\_id=96](http://nns-technology.com/?page_id=96)  
(cropped image)

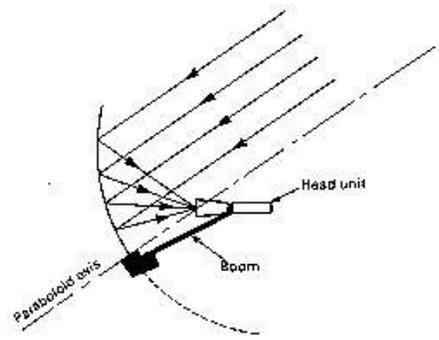
used for this demonstration. Only the direct signal is detected. This, of course, is theoretical. In our case there is some mismatch of the impedances; placing the loops in the horn is not a very good method for coupling, and the helices aren't made very accurately. With this in mind, the demonstration shows the ideas mentioned here reasonably well. The larger loops used in this demonstration were made from 14 gauge household electrical wire (solid not stranded!) and are about 15 loops long. Be sure you wind all loops in the same direction! A wooden base was fashioned to make it fit better in the horns as shown in the picture.

Helical coils placed in horns



Impedance – the opposition in a circuit to current flow when voltage is applied. It consists of two different parts: an inductive part due mainly to the magnetic field in coils and the capacitive part due mainly to the electric field charging separated conductors. A mismatch occurs when the input impedance does not match the output impedance as in our case where the linear input from the transmitter does not match the circularly polarized output from the helix and reflection occurs and interferes with our signal.

Parabolic Reflectors: Using a parabolic shape to focus the signal more tightly greatly increases the gain and narrows the beamwidth. The effect is so great that the demonstration has to be done at some distance from the transmitter. I used a standard satellite dish antenna. I made a mount from small pieces of 2x4 to hold it on a tripod and used a 4 prong, 1/4-20 thread connector (from a hardware store) to attach it to the screw on the tripod.

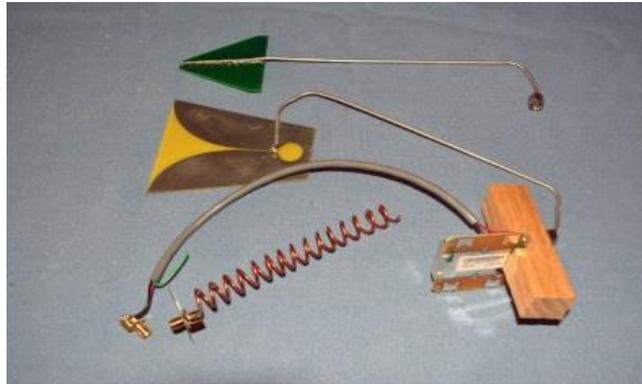


[n8ppq.net/Physics/geo2.html](http://n8ppq.net/Physics/geo2.html)

Parabolic antenna – back view; side view; bottom view; complete dish with tripod



Other Antennas Demonstrated: A true helical antenna, log-periodic, and Vivaldi antenna are shown and compared to the horn used in this demonstration. The helical was wound by me so doesn't quite live up to its 11dB calculation; the other antennas were built by Kent Britain. The log-periodic has a gain of about 6 dB and the Vivaldi which has a gain of about 8-10 dB. The patch antenna is of poor quality and I have removed it from the demonstration. The helical was made exactly as in the circular polarization section, but I attached a small (3.5cm) brass circular base, a SMA connector which was soldered to the base, and the center pin attached to the helix. A small triangle of brass, 3x7mm in size, can be soldered to the end of the helix attached to a SMA ground connector to better match the impedance, but it is quite tricky to solder without getting burned.



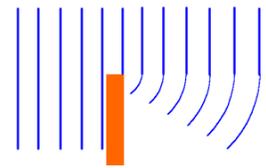
Antennas from top: log-periodic; Vivaldi; patch; helical

More Antennas: After attending a talk on 'traditional' antennas, I decided to try them at x-band microwave frequencies. The picture below shows the various antennas I built and attached directly to SMA connectors. Most of these antennas use quarter wavelengths of wire (in this case about 7.1 mm). The ground plane antenna uses 4 lengths for a ground plane and one for the antenna (central pin). The dipole antenna uses a wire bent so that the horizontal end is 7.1 mm and the other end is long enough to allow it to be attached to the connector easily. The reflector is about 5-10% longer and the director is 5-10% shorter (tough to be exact at these short lengths). The square loop antenna is 7.1 mm on a side with the bottom bent to allow attachment to the connector. The circular loop is a full wave long, which is about 3 cm with extra length to make the ends to attach to your connector. The J-pole antenna has a long side of 21.5 mm and a short side of 7.1 mm. The feed point is slightly up from the bottom of the short side, about 0.7 mm, and the spacing between the short and long side is 0.7 mm as well.



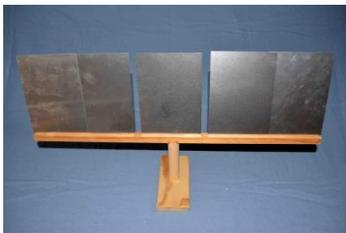
Antennas: (from the top): ground plane antenna; reflector, dipole, and director; square loop; circular loop; J pole antenna

Diffraction: Diffraction is the bending of waves around an obstacle or slit. It is another form of interference. Four diffraction demonstrations can be done by tilting the transmitter and receiver so that the electrical field is oriented horizontally and can pass through vertical slits and edges. In order to do these demonstrations you will need metal sheets and a stand to hold them in various arrangements. The stand was made from a 24 inch long piece of  $\frac{3}{4}$  x  $\frac{3}{4}$ " pine slotted by grinding a slot with a Moto-tool and cutting blade. This was glued into a  $\frac{3}{4}$ " slot made in a 1" dowel attached to a wooden base with a screw as shown in the picture below.

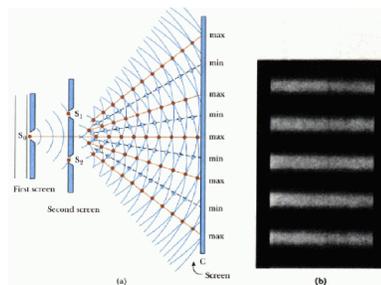


[www.school-for-champions.com/science/waves\\_obstacles.htm#.VV-Zk6jD85s](http://www.school-for-champions.com/science/waves_obstacles.htm#.VV-Zk6jD85s)

Although this demonstration was not shown in the final video, I started with the single slit experiment, where the signal is diffracted through a single slit and produces an interference pattern. The slit should be on the order of the wavelength of radiation; in our case a 1.5 cm wide slit is used and the interference pattern will be detected. Then move on to the double slit experiment. Begin by placing a metal sheet about 13cm wide in the center of the stand; leave a 1.5 cm gap on both sides, followed by metal sheets on the ends. The stand and sheets are placed about half way between the two units and the receiver is moved side to side in front of the sheets. A diffraction pattern with a large peak in the center and lower intensity peaks every 10-15 degrees on either side of the central peak is generated. This satisfies the equation for diffraction:  $\theta = \sin^{-1}(n\lambda/d)$ , where  $\theta$  is the angle,  $n$  is an integer,  $\lambda$  is the wavelength (about 3cm), and  $d$  is the width between openings (in our case above about 14.5 cm). If we calculate for the first peak we get about 12 degrees; the second at about 24 degrees; and so on.



Double slit diffraction set-up

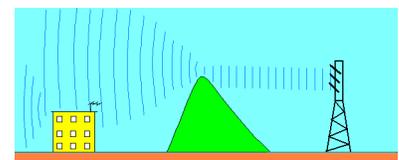


[psi.phys.wits.ac.za/teaching/Connell/phys284/2005/lecture-02/lecture\\_02/node3.html](http://psi.phys.wits.ac.za/teaching/Connell/phys284/2005/lecture-02/lecture_02/node3.html)

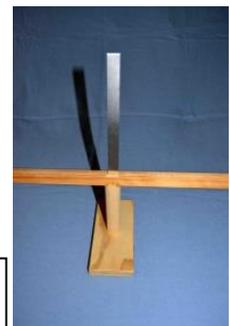
Next is the knife edge effect, where the microwaves are diffracted around an obstruction and the receiver detects the signal in an interference pattern. This is observed when radio waves encounter a building or mountain.

Although you will not see this in the final video, the double knife edge demonstrations can be done by placing a small (1.5cm wide - see picture) piece of metal in the path of the signal (about half way between the transmitter and receiver) so that an interference pattern is heard. This is like the old demonstration to measure a hair with a laser beam.

A second knife edge experiment can be set-up using a long row of metal sheets and blocks half the beam. A signal that is fairly strong is detected in the blocked zone showing diffraction around the edge (you can also detect the diffraction off the top of the sheets if you wish). Larger sheets of metal would block radiation better and provide for clearer interference patterns but the metal sheets I used were inexpensive and easy to find at Home Depot.

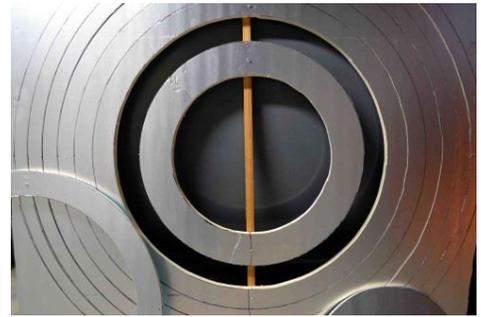


[www.peoplephysics.com/physics-laws10.html](http://www.peoplephysics.com/physics-laws10.html)



Double knife-edge diffraction set-up

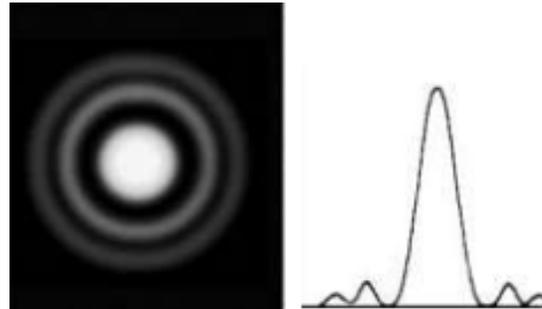
Fresnel Zone Lens / Antenna: Fresnel Zone Lenses / Antennas are devices that focus radiation (microwaves in this case) using diffraction instead of refraction or reflection. The device consists of a set of alternating transparent and opaque, symmetric rings. At the edges of the opaque rings the microwaves diffract and constructively interfere, creating a lens. In the title above I list two different devices (lens and antenna) that I'd like to try to explain a little better.



Fresnel zone lens / antenna

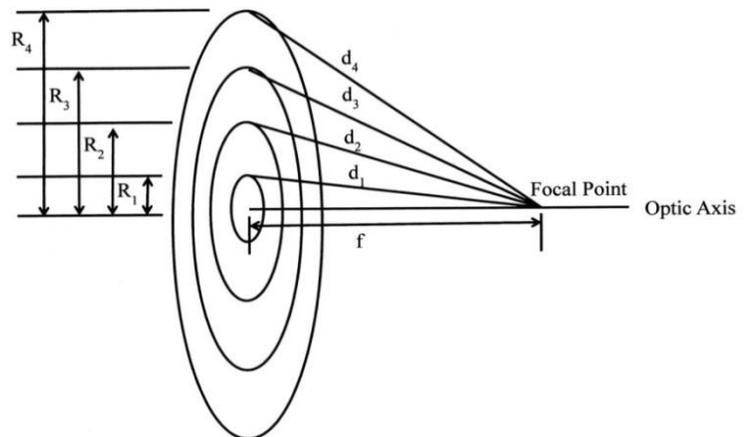
Lens: The lens was calculated for a focal point distance of 1 meter (the calculations follow this discussion). The transmitter is placed at far field so that the waves hitting the Fresnel lens are plane waves, all in phase (peaks and troughs all line up). The waves pass through the openings and set up spherical wavelets due to diffraction at the ring edges. These spherical waves move toward the receiving horn and, due to the placement and spacing of the rings, the waves add up in phase (peaks corresponding to peaks and troughs to troughs) and amplitude (signal strengths) at a distance of 1 meter so that an increase in signal is detected there. When the opposite rings are exposed, the opposite effect occurs and the phases and amplitudes add to a minimum signal detection.

Antenna: By moving the transmitter from far field to about 1 meter, or the lens' focal point, you will cause spherical waves to hit the Fresnel antenna. As a result, our receiving horn, also located at a distance of 1 meter (?), will no longer be at the focal point. The diffraction pattern that is generated will resemble an "Airy disk" with a sharp central cone pattern surrounded by radial side lobes, looking something like our Fresnel zone antenna in three dimensions. A friend calculated that the pattern would become better defined at about 220 feet or so. Not having the room for this demonstration, the calculations and the performance of this device was not demonstrated. I hope to have the room to try this at a later date and will add it to the video at that time.



Airy Disk: [electron6.phys.utk.edu/optics421/modules/m5/diffraction\\_summary.htm](http://electron6.phys.utk.edu/optics421/modules/m5/diffraction_summary.htm)

The Lens Calculations: Rather than derive the equations, I'll just list them and show how they work. The formula is based on the diagram to the right and is:  $\lambda/2 = (d_i - d_{i-1})$ ; where  $\lambda$  = wavelength (about 0.0286 m in our case), and the d's refer to the distances in the diagram and are calculated using the Pythagorean Theorem ( $a^2 + b^2 = c^2$  thus:  $d_i = \sqrt{f^2 + R_n^2}$ ).



Here are some example calculations:

Ring #1:  $\lambda/2 = (d_1 - f)$ ,  $d_1 = \sqrt{f^2 + R_1^2}$ . So,  $\lambda/2 = \sqrt{f^2 + R_1^2} - f$   
 $(\lambda/2 + f)^2 = (\sqrt{f^2 + R_1^2})^2$   
 $\lambda^2/4 + \lambda f + f^2 = f^2 + R_1^2$   
 $R_1^2 = \lambda^2/4 + \lambda f$

$R_1^2 = 0.00020449 + 0.0286$ ; take the square root;

$R_1 = 0.1697\text{m} = 16.97\text{cm}$

Ring #2:  $\lambda/2 = (d_2 - d_1)$ ,  $d_1 = \sqrt{f^2 + R_1^2}$  and  $d_2 = \sqrt{f^2 + R_2^2}$ . So,  $\lambda/2 = \sqrt{f^2 + R_2^2} - \sqrt{f^2 + R_1^2}$

$\lambda/2 = \sqrt{f^2 + R_2^2} - \sqrt{f^2 + R_1^2}$

$0.0143 = \sqrt{1 + R_2^2} - \sqrt{1 + (0.1697)^2}$

$(0.0143 + 1.0143)^2 = (\sqrt{1 + R_2^2})^2$

$1.058 = 1 + R_2^2$

$R_2^2 = 1.058 - 1$ ; take the square root;

$R_1 = 0.2409\text{m} = 24.09\text{cm}$

The rest I leave for you. The final calculations are listed below.

Ring Number	Ring Edge ( $R_N$ )
1	16.97 cm
2	24.09 cm
3	29.61 cm
4	34.30 cm
5	38.49 cm
6	42.30 cm
7	45.85 cm
8	49.18 cm

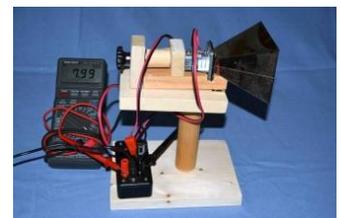
Acknowledgements: The following people provided invaluable help in making this project happen: Paul Wade and Dale Clement (ARRL); Alan Rutz (SHF Microwave Supply); Kent Britain (PCB Antennas); Richard Bitzer and Carl Lyster (SARA); Peter Kandefer and Shef Robotham (Litchfield Hills Amateur Astronomy Club), Vacek Miglus and Dr. Meredith Hughes (Wesleyan University), Dr. Joe Taylor (Princeton University), Dr. Wolfgang Rueckner (Harvard University), Dr. Matti Herben (Eindhoven University), and of course Dr. John Kraus (Ohio State University). I'd also like to thank Dr. Wolfgang Rueckner (Harvard University) and SARA members Richard Bitzer, Lee Scheppmann, and Bruce Randall for helping edit the video. Lastly, I'd like to thank my wife for helping create and capture the film, editing the support materials and supporting me during the process.

## Building Instructions

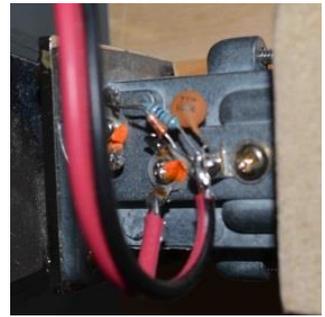
I am not skilled in electrical circuit designer and so I found most of my circuits and equipment online. Remember that all equipment must be made for our frequency – X-band ~ 10GHz - and must be included in any description of the equipment. Starting from the front end (the transmitter) the parts include:

### Transmitter:

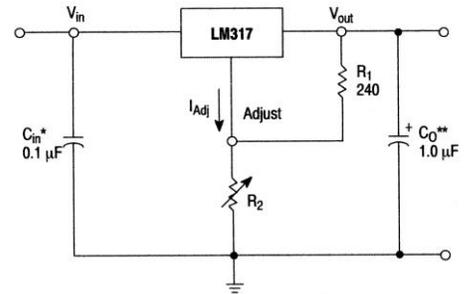
Large Horn Antenna: (2 needed – one for the transmitter and one for the receiver): I bought mine from SHF Microwave Parts Company for \$28 each but they are also available from e-bay.



**Gunn Diode Source:** This will be the most difficult item to find since they are not sold anymore (replaced by cheap DROs (Dielectric-resonant Oscillators) like those used in garage door openers). Be sure to find this item first! I purchased this one on e-bay from a person in Portugal (the title was “GunnPlexer 10 GHz radio amateur X-band”) for about \$20. Note from the picture that I soldered wire with banana plug ends on the transmitter: +V (red wire) to the V bias post on the Gunn diode and the ground (red with black stripe wire) to the ground pin. The other components were soldered there to begin with and are not used (they are for receiving signals and we are not using this device for that purpose.).



**Regulated Eight Volt Power Supply:** This circuit I got off the internet at [www.onsemi.com/pub\\_link/Collateral/LM317-D.PDF](http://www.onsemi.com/pub_link/Collateral/LM317-D.PDF). The circuit diagram is pretty simple and copied here from the website above. The values are in the diagram except R2. I used a 5K potentiometer for R2 so that I could adjust the voltage if it drifted slightly. I also used banana plugs so I could plug in the transmitter easily. This allows for quick disconnect while I attach horn antennas, helices, etc. A 12V wall supply is the input voltage through an ‘M’ connector. A volt meter was used to check the 8V output for the Gunn device.



**The Stand:** The wood stand was constructed to allow the transmitter to rotate and be held in place. I attached a square piece of pine to the back of the Gunn diode source with screws (the side has screw taps that I used – most units I’ve seen have these). To this I nailed a large (about 1” in diameter) dowel at one end, and drilled a hole and screwed in a ¼-20, wood screw / machine screw combination with a ¼ - 20 knob at the other end. I made a pine base and back plate for the Gunn device; the plate was slotted for the knob / screw, and the base was slotted to better fit the device. This base was attached to a hinged base (to allow the whole thing to tilt) and then attached to a large dowel on a base of pine for stability. The height of this and the receiver stand should be the same for maximum signal strength (see transmitter picture above).



**Receiver:**

**WR-90 Horn Antenna:** I bought this one on E-bay for about \$20. This device is also more difficult to find since items on E-bay are not always available when you want them. Be sure to look for this when you look for the Gunn device. I purchased my crystal detector separately, but it often comes attached to the horn. For some experiments it is easier to have separate parts so I recommend buying them separately. I attached the horn with two long screws to allow the large horn to be placed accurately over the WR-90 antenna.



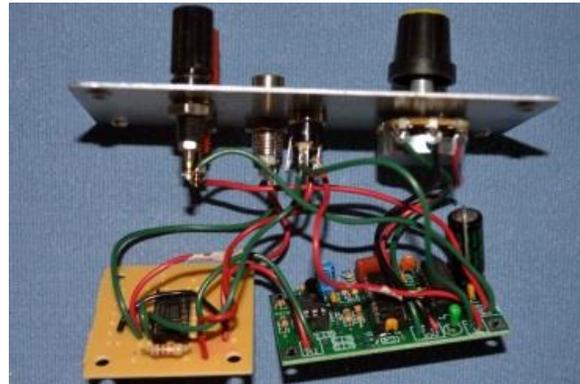
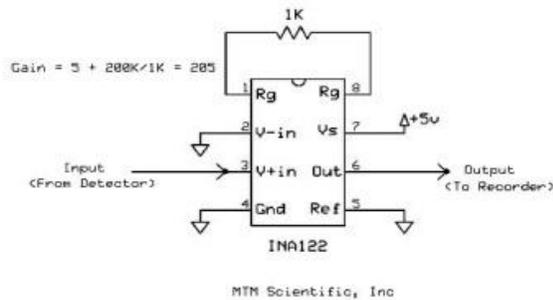
Crystal Detector: This was also purchased from e-bay for about \$20. Once again, this is more difficult to find since items on E-bay are not always available when you want them. Be sure to look for this when you look for the Gunn device. Be sure it covers the X-band (about 10 GHz for our Gunn source). Three different examples are shown – all work fine with the device used here.



BNC Cable: To connect between the crystal detector and the instrumentation amplifier. This needs to be 50 ohm. I bought a RG-58 cable for this and you need at least 6 feet (I bought 10 feet).

Instrumentation Amplifier: This is another internet find and is very simple to build. The link to the webpage is: [www.mtmscientific.com/dcamp.html](http://www.mtmscientific.com/dcamp.html). The schematic from the webpage is copied here and is also found on the website.

Single Supply Instrumentation Amplifier with Adjustable Gain



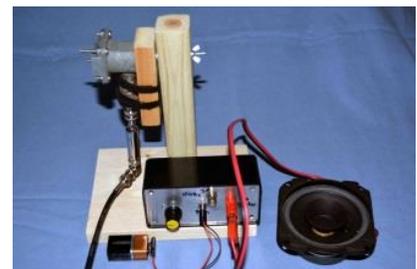
Tonemeter - Voltage Controlled Oscillator: A circuit board for this device - called the “Tonemeter” - is available from Paul Wade (website: [www.w1ghz.org/small\\_proj/small\\_proj.htm](http://www.w1ghz.org/small_proj/small_proj.htm)). It is a wonderful device, useful for ‘hearing’ any voltage changes, not just those in these demonstrations. If the voltage is too high for proper tone production, it can be adjusted by changing some components. For mine, the R4 resistor was disconnected and the C2 capacitor was increased by soldering a 0.1 uF capacitor (marked 104) to the base of C2 (see picture on right). This change moves the range down in frequency so the signal is easier to hear. I have the output go to banana sockets so that I can quickly hook up the speaker (which has banana plug wires).



9 Volt Battery: This is the power source for the instrumentation amplifier, the tonemeter, and the speaker. I used a 9V connector attached to an ‘M’ power connector from an electronics supply company to connect to the box holding the instrumentation amplifier and the tonemeter. This allows fast connection and take-down.

Speaker: I bought a 20 watt full range speaker many years ago from Radio Shack but any full range speaker would do.

The Stand: The wood stand was constructed to allow the receiver to rotate and be held in place. I attached a 2x2” square piece of wood to a base. The piece of 3/4” x 2” pine holding the WR-90 horn antenna was



ground out with a Moto-tool and cutting bit to fit the back end of the WR-90 as a press fit. Velcro ties were used to hold the receiver to the stand. Through the back of the ground out area, I drilled a hole, placed a thick washer between the 2x2 and the pine piece holding the WR-90, and screwed the parts together with a long 8-32 screw and wing nut. This allows for rotating the whole device. The height, as mentioned previously, is critical and should be identical to the height of the transmitter horn so that both openings are identical in height. The end of the crystal detector is fitted with a right angle BNC connector to allow it to fit comfortably in the stand and not be too tall.



Safety Equipment: As I mentioned in the beginning of this document, my teaching experiences have made safety an issue that is constantly on my mind. I decided to add the ‘screen hat’ to the safety protocol in order to make these demonstrations as safe as possible. The ‘screen hat’ blocks all radiation hitting it with the aluminum screen over the eyes and most of the face. It was easy to make. I took an old hat, cut some aluminum window screen to fit around the edge and put aluminum tape along all edges to keep them from fraying and provide a smooth finish. I then made a small bend in the screen and stapled the screening to the hat making sure the staples were bent over completely. In just a few minutes the hat was ready to use.



Any questions or comments are welcome. Contact me at [wallacefj@comcast.net](mailto:wallacefj@comcast.net).