Visualizing Microwaves

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I have received several comments suggesting that microwaves are hard to visualize. One ham suggested that Lecher wires did the trick at VHF, but he hadn't found anything similar for microwaves. I vaguely remembered Lecher wires as something for open wire line, which isn't used much for microwaves. A quick search of the ARRL archives found that Lecher wires were described by Eugene Woodruff, 8CMP, in 1925, and last mentioned in QST in 1960.

Heinrich Hertz

What I did remember was an exhibit years ago (1987?) at the MIT Museum which replicated the apparatus that Heinrich Hertz used to demonstrate electromagnetic waves in 1887. He used a spark gap to generate RF, and a small adjustable spark gap to detect it, judging the strength of the wave at each location by adjusting the gap until an arc occurred. Obviously, high power was needed to be detectable with a spark gap. RFI was not a problem since there were no receivers then.

With the apparatus, Hertz was able to demonstrate that the properties of electromagnetic waves are the same as optics: radiation, reflection, refraction, diffraction, polarization, etc. He even made a parabolic reflector. The frequency is estimated to be around 50 MHz, so all the optical objects are quite large and filled a room. For instance, refraction was demonstrated with a wedge of asphalt perhaps five feet high and four feet wide.

Another demonstration apparatus was a coaxial line, consisting of a central wire surrounded by a cage of loosely spaced ground wires. The spacing enabled him to probe the wave along the line, using the spark gap.

Open Coaxial Line

Perhaps I could make a similar demonstration at microwave frequencies. I made an open coaxial line using some hobby tubing and SMA connectors – one end is shown in Figure 1. The length was dictated by the 12-inch lengths of hobby tubing. Twelve inches is about 30 cm, so the line is more than a wavelength (23cm) at 1296 MHz, plenty long enough.

Figure 1 – Open coaxial line made from hobby tubing

With modern electronics, a spark gap is not necessary. Diode detectors are much more sensitive, and RF detector chips even more sensitive. I chose an Analog Devices ADL5513 chip, available already assembled on a small PC board from SV1AFN (SV1AFN.com) at a very reasonable price – see Figure 2. The detector works up to 4 GHz and has an output which is linear in dB. My test showed the output to be 21 millivolts per dB from -50 dBm to +3 dBm, and less accurate down to about -70 dBm.

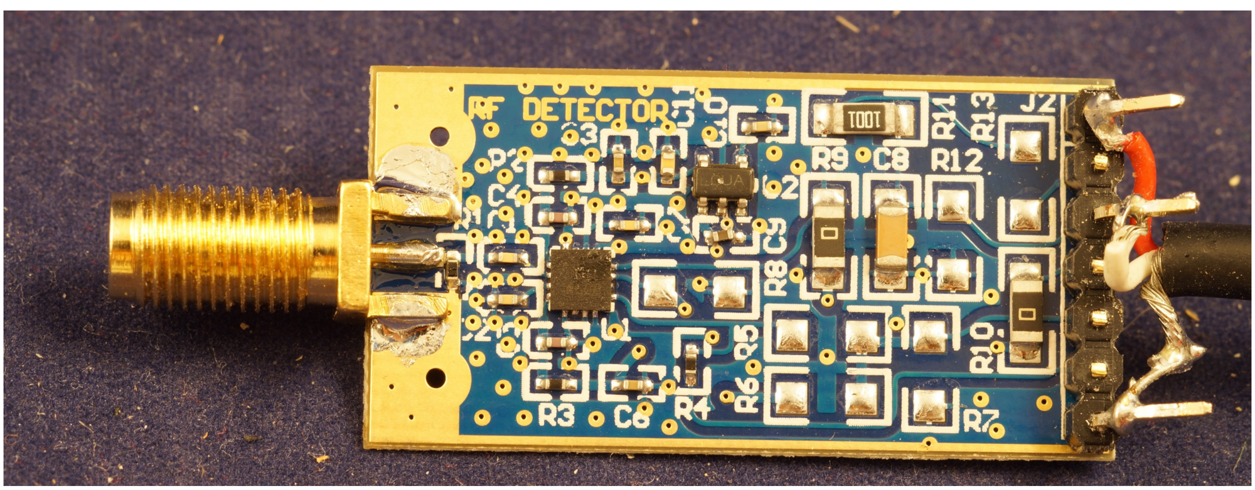

Figure 2 – ADL5513 detector board from SV1AFN

The shortened pin of an SMA connector is used to probe the electric field in the open coaxial line. A couple of standoffs are bolted to the flange to keep the probe centered as it slides along. The probe is shown in Figure 3.

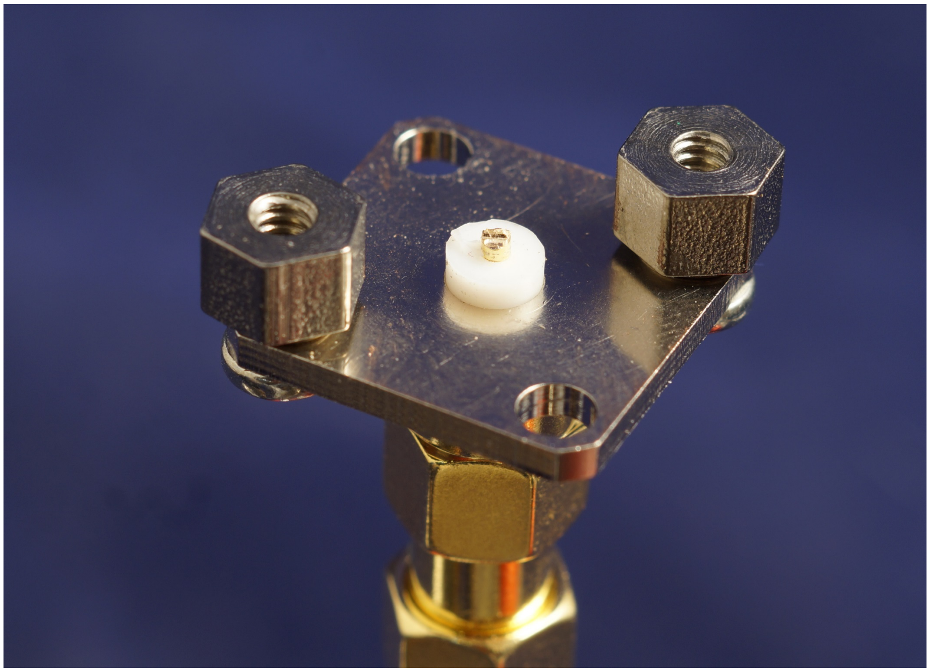

Figure 3 – Probe for open coaxial line

A quick test with a Chinese synthesizer board using an ADL4350 chip showed that a few milliwatts into the open coax is adequate for good readings with the probe and detector – the detected signal is perhaps -30 dBm. Microwaves are much safer at these power levels. Then I added the filter and attenuator shown in Figure 4 to reduce harmonics and isolate the synthesizer from reflections on the line.

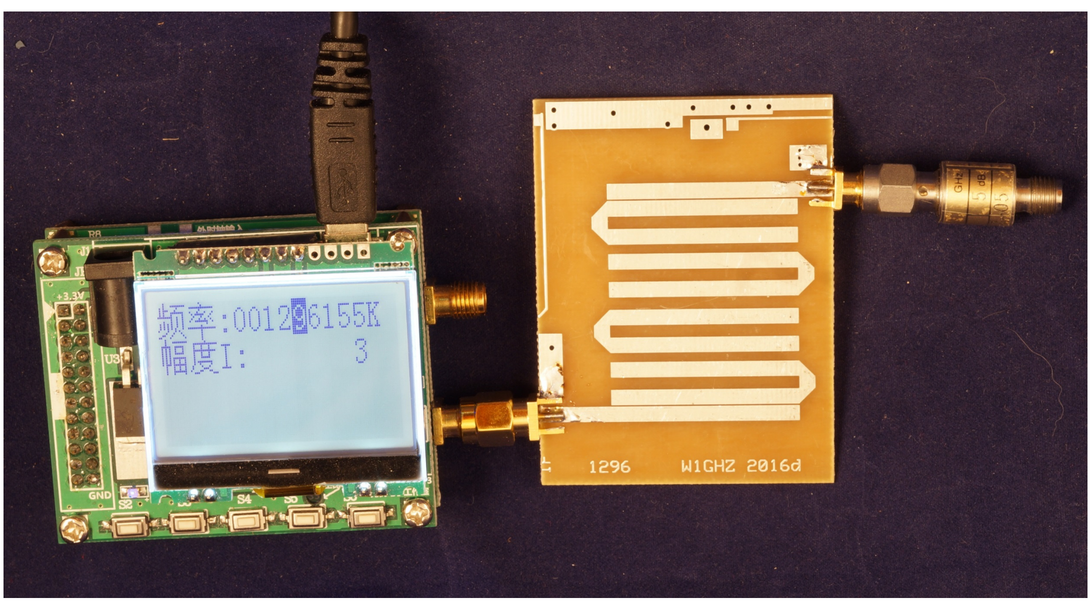

Figure 4 – Signal source: Chinese synthesizer with LP filter and attenuator

Finally, the detector board is mounted in a plastic cover from some dental floss threaders and the probe attached, as shown in Figure 5. The cover keeps my fingers off the board. I quickly found that this detector has many uses as a handy portable power meter with great sensitivity.

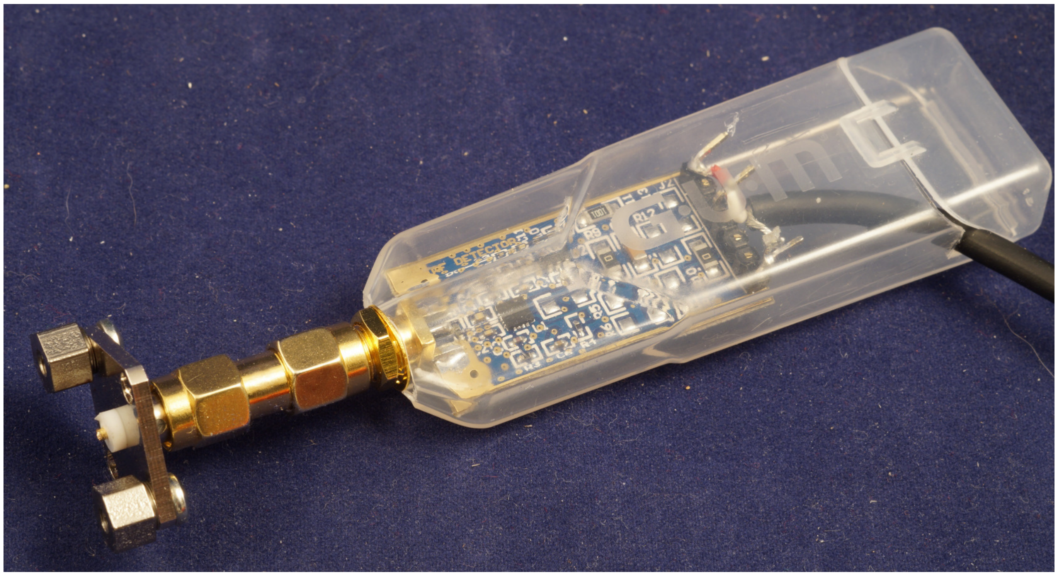

Figure 5 – Detector and probe with plastic cover and flexible cable

The output from the detector is connected by a small flexible cable to a bargraph indicator and to a tonemeter[1] which generates an audio tone whose frequency is proportional to the input voltage. A digital voltmeter measures the true output voltage for conversion to dB. The complete setup is shown in Figure 6.

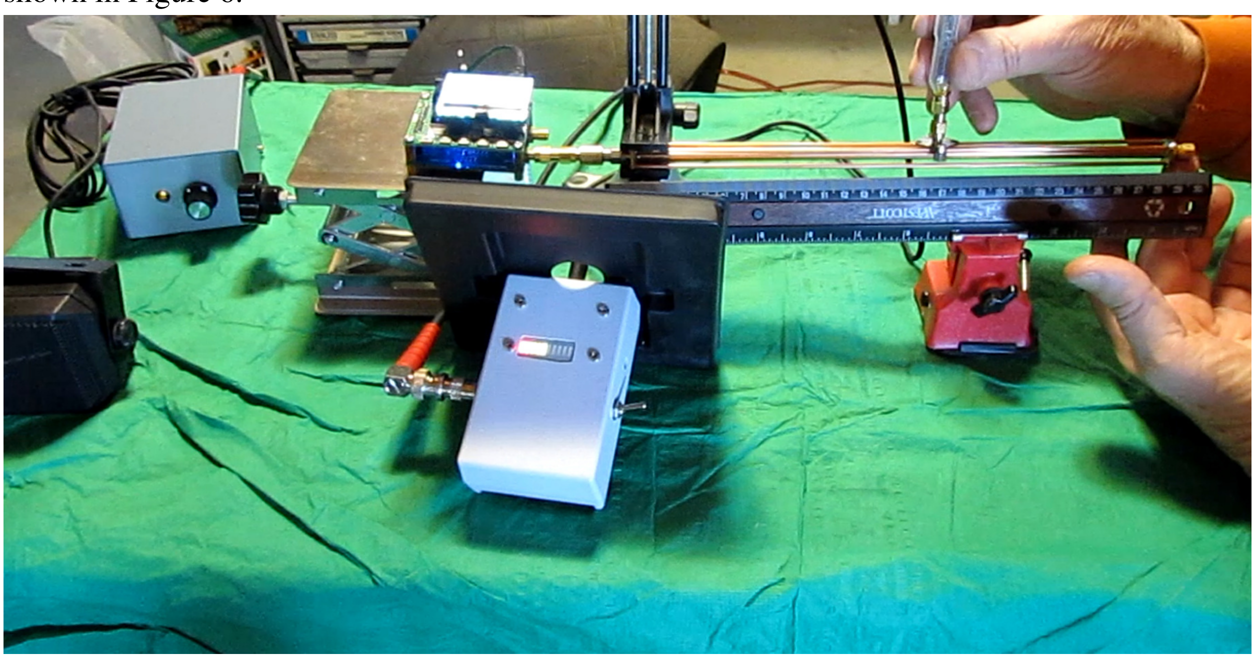

Figure 6 – Complete setup for probing open coaxial line

The object is to detect standing waves on the coaxial line. As microwaves flow along line, the detector can sample the peak voltage at each point along the line. With a short circuit at the end of the line, we know that the voltage at the end must be zero. The waveform is a sine wave, so the voltage must vary sinusoidally along the line, with zero voltage every half-wavelength and maximum voltage halfway between the minimums. This pattern is a standing wave, sketched in Figure 7.

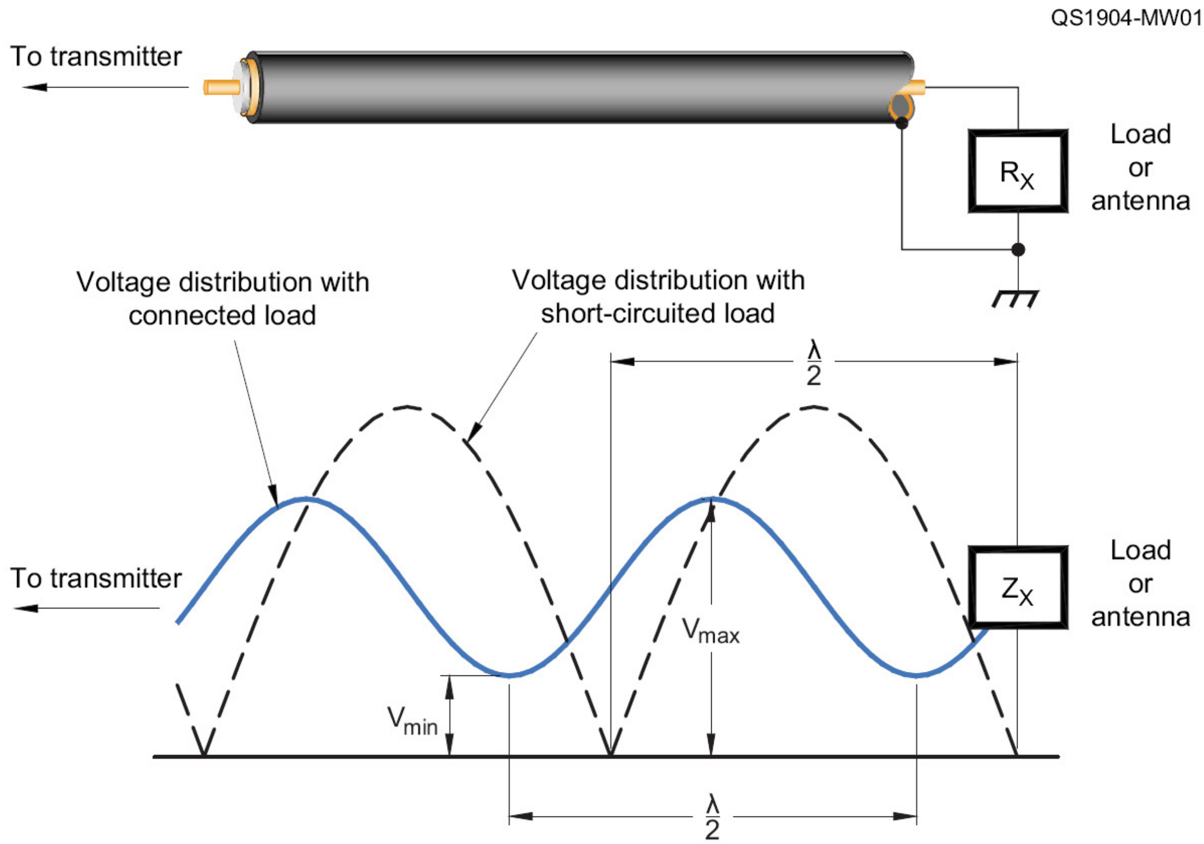

Figure 7 – Standing waves on transmission line

(from QST, April 2019)

Sliding the probe along the line allows us to see the standing wave pattern, and note the locations of the minima. With the short circuit, I found a minimum at 17 cm on the scale and another at 5.5 cm, a difference of 11.5 cm for a half-wavelength. This is the expected wavelength of 23 cm at 1296 MHz. The measured maximum detector output was 1120 mV, and the minimum was 560 mV, a difference of 560 mV. At 21 mV/dB, the difference is 27 dB, or a voltage ratio of about 22. Thus, the Voltage Standing Wave Ratio, or VSWR, is 22. It is not infinite because there is some loss in the line and perhaps some radiation from the open structure.

Different loads at the end of the produce distinctive standing wave patterns. An open circuit at the end also results in a high VSWR, but with the maximum and minimum positions reversed. A perfect load produces no reflections, so the voltage along the line is constant and the VSWR is 1.

A 50-ohm termination at the end produced a maximum detector output of 1040 mV and a minimum of 970 mV, a difference of 70 mV or 3.3 dB. This is a ratio of 1.5 – the VSWR is greater than 1 because the characteristic impedance, Zo, of the open line is not 50 ohms, but probably somewhat higher, around 65 to 70 ohms.

A 100-ohm load produced a VSWR of about 2.7, while a 68-ohm load produced a VSWR of 1.4, still not perfect. And it is unlikely that any value will produce a perfect termination, since the line has 50-ohm SMA connectors at each end, guaranteeing a mismatch. The 68-ohm load is shown in Figure 8 – a chip resistor right across the connector with no lead length is pretty good up to low microwave frequencies.

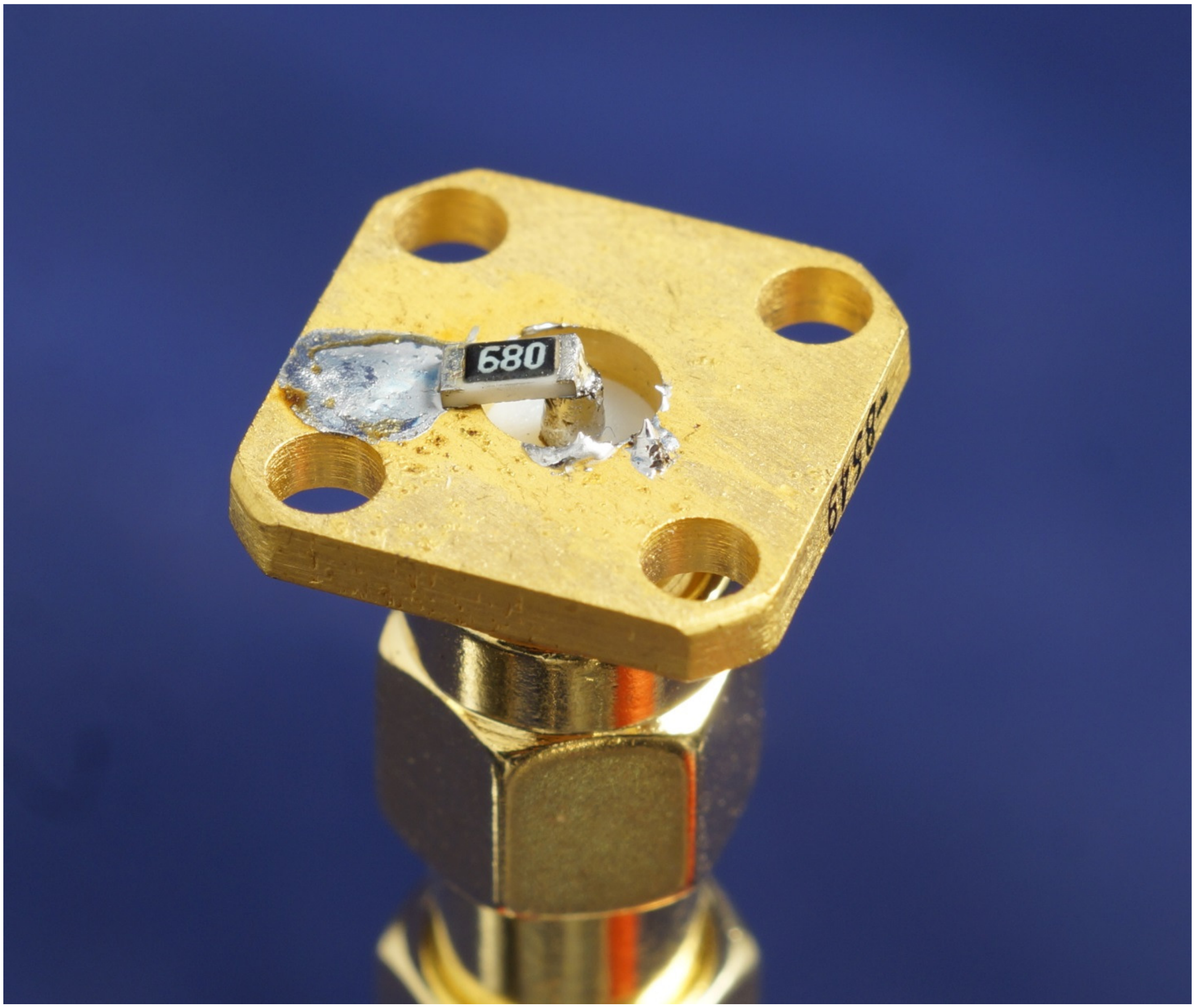

Figure 8 – Simple 68-ohm coaxial termination

Waveguide

Visualizing what happens in a waveguide is more interesting than a simple coax line, but there is a problem making an open waveguide. A symmetrical coaxial line like Figure 1 has the same voltage potential on all ground lines, so no return current flows between them and no connections are required. However, a waveguide has no central conductor, so all currents must flow through walls – continuity is required. Plain wires will not work.

The solution for open conducting walls is to use copper mesh for the waveguide. The mesh, sold at art supply places, is great for microwave experiments. It can be bent, folded, squeezed, stretched, shaped, and soldered to make antennas, shields, and enclosures. I folded a piece to fit inside a WR-229 transition to coax, with the other end held by a short waveguide section. I left a slot in the center of one broad wall of the coax – no current flows here since the electric field should be symmetrical around the center. The open waveguide section is shown in Figure 9.

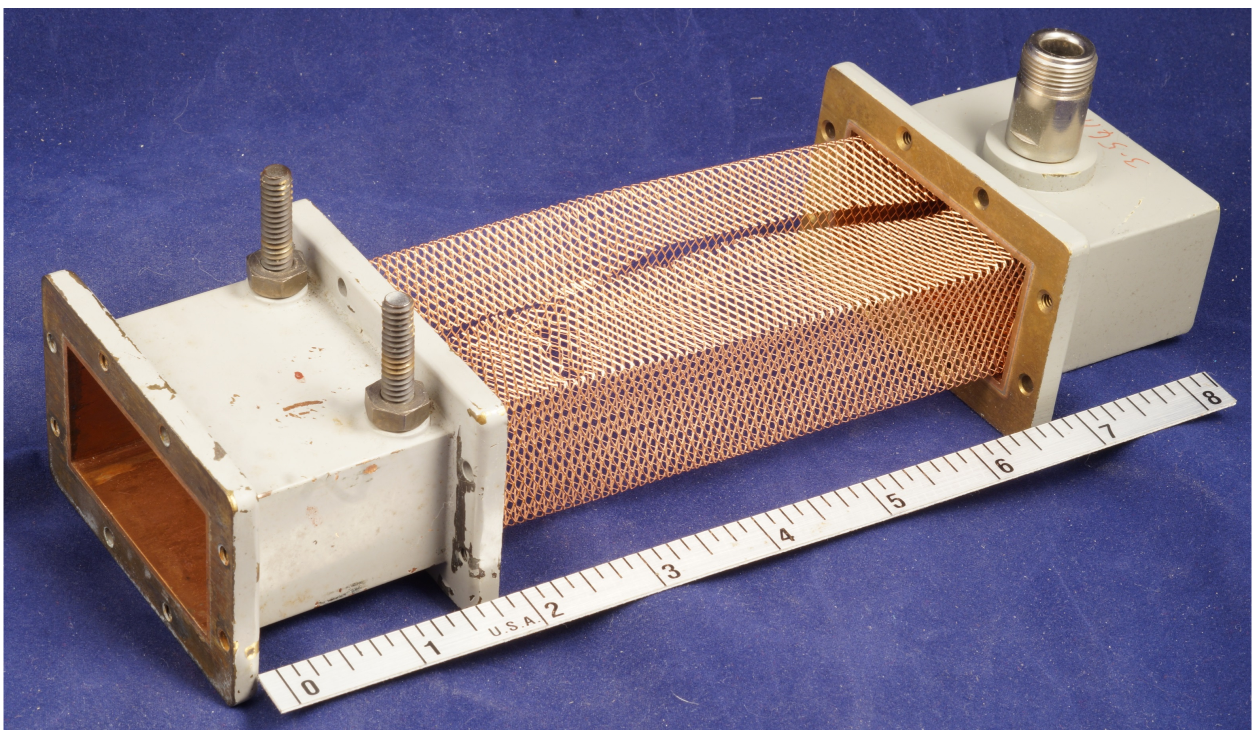

Figure 9 – Copper mesh waveguide suitable for probing

The WR-229 waveguide was the largest size I could find. It works at 3456 MHz, which is also the highest ham band for both the synthesizer and the detector. Another SMA connector with a slightly longer pin was attached to the detector as a probe and spaghetti insulation slipped over the pin so it can probe through the mesh.

Before probing the waveguide, I tested the open coax line at 3456 MHz with a short circuit on the end. The standing wave pattern now had minima much closer together, roughly 4.5 cm apart, as expected for a wavelength of 8.7 cm.

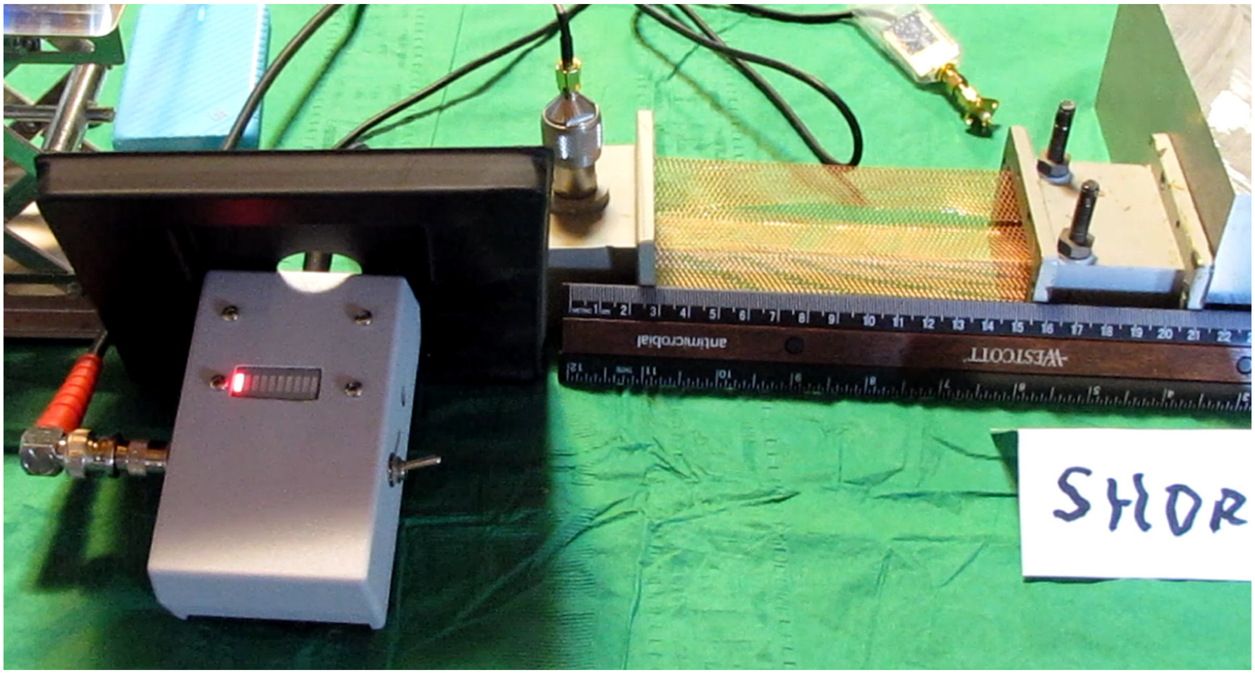

Figure 10 – Setup for probing mesh waveguide

The demonstration setup was changed to the open waveguide section, shown in Figure 10, with a metal plate closing the end to make a short circuit. Then the standing wave pattern on the waveguide was probed, finding minima at 8.5 and 15 cm. The wavelength in this waveguide, λg, is 13 cm. We read in books that the guide wavelength is a function of the waveguide cutoff wavelength, λc , and longer than the free space wavelength λ:

$$\lambda_g = \frac{\lambda}{\sqrt{1 - \left(\frac{\lambda}{\lambda_c}\right)^2}}$$

With the mesh waveguide, we can probe the standing wave and actually see the guide wavelength. The cutoff wavelength of a waveguide is twice the wide dimension. For WR-229, the dimension is 2.29 inches, or 5.816 cm, so the cutoff wavelength is 10.4 cm. The copper mesh inside the WR-229 reduces the wide dimension and the cutoff wavelength somewhat, making cutoff closer to λ which increases the guide wavelength.

Next, the short circuit is removed, leaving the end of the waveguide open. Now the VSWR is fairly low, since the open end radiates – if the end were flared, it would be called a horn antenna. Moving the probe near the open end, Figure 11, allows the sensitive detector to show a broad radiation pattern. Rotating it 90 degrees finds no radiation, demonstrating polarization. Finally, moving a metal plate behind the probe demonstrates reflection and interference – as the plate is moved away, the detected signal increases and decreases for every quarter wavelength.

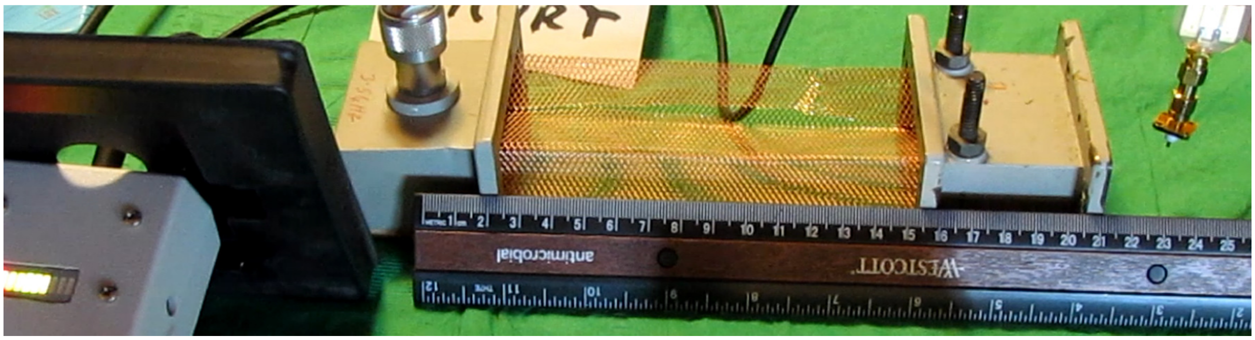

Figure 11 – Probing radiation from open waveguide

Adding another coax to waveguide transition at the end of the guide and terminating it with a 50 ohm load produces a very low VSWR.

Finally, the field inside the waveguide can be probed. From the books, we expect an E-field voltage pattern inside the waveguide like Figure 12.

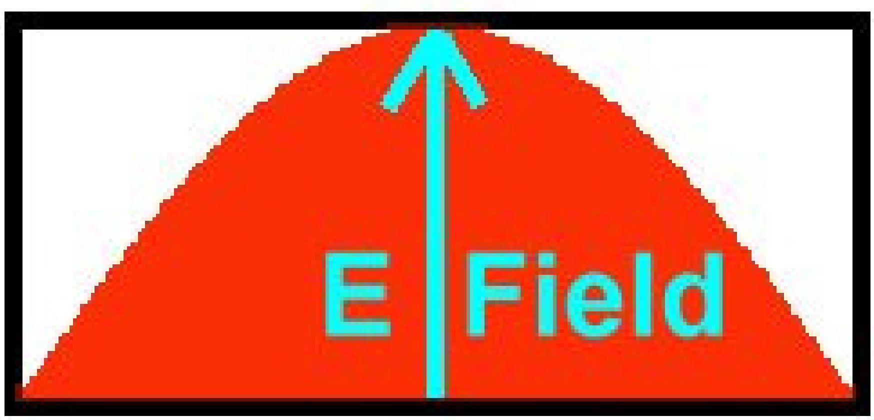

Figure 12 – Textbook E-field inside waveguide

Probing through the mesh at locations moving away from the center shows decreasing voltage toward the side walls – we can see the E-field. Probing thru the side wall produces very little signal, since it is cross-polarized.

I made a second mesh waveguide using smaller WR-187 waveguide. With the copper mesh inside the guide, this one is very close to cutoff, and the first minimum spacing appeared to be beyond the end of the mesh section – the guide wavelength is very long.

Optics

The optical properties: radiation, reflection, refraction, diffraction, and polarization can be explored with a pair of small antennas and the sensitive detector. For instance, a simple dipole for 1296 MHz can be made by soldering a couple of wires to an SMA connector. The dipole could even be tuned using the standing waves on the open coax line. A second dipole on the detector can be used to probe the radiation from the first dipole, just as the simple probe was used to demonstrate these properties with radiation from the open waveguide.

Summary

With simple gear and a bit of homebrewing, we have made a microwave lab that allows easy and save experimentation. Using it, we are able to visualize microwaves and see for ourselves phenomena that were just equations and sketches in textbooks. You probably won't duplicate it, but you might find inspiration for another experiment or project.