Experiment MW—Microwaves

Introduction

Finding ways to generate ever-higher frequencies in an efficient and controllable way has been central in the evolution of radio and related technology. The military need for radar that could "see" airplanes in darkness and fog stimulated the development of efficient power sources at frequencies between 1 and $1 GHz$. Wavelengths between $1 cm$ and $30 cm$ called microwaves (because the size of the wavelengths was considered to be very small compared to, say, AM radio wavelengths that are hundreds of meters). Microwave radar and particularly its spin-off, the microwave oven, have made the expression -- "zap it in the microwave" part of ordinary speech.

The simplest way of generating electromagnetic waves (and the earliest -- used by Hertz 120 years ago) is simply to charge and discharge a capacitor connected to a spark gap and antenna. The antenna is excited at its resonant frequency by high frequency Fourier components in the discharge current and radiates electromagnetic waves. Spark transmitters were extensively used in the early days of radio before the invention of electronic amplifiers.

In this experiment you'll generate microwaves with a simple spark transmitter powered by your HVPS. Two pieces of wire will serve as a transmitting dipole antenna. You'll use another piece of wire as a receiving dipole antenna connected to your amplifier through a diode to detect the microwaves and to investigate their properties.
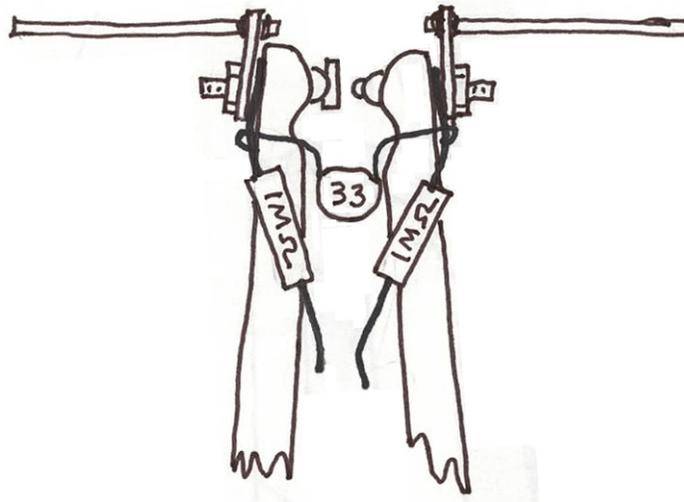

Figure 1: Spark-gap transmitter

Spark gap and Antenna

Your transmitter is based on the adjustable spark gap of Experiment EB (Electrical Breakdown) which you recently worked on. You need only add a $33\,pF$ capacitor across the tungsten rods and two lengths of #12 wire that you will solder to the solder lugs (mounted on the brass screws) which make up the two halves of a dipole antenna (see Figure 1). Each length is $31\,mm$ long.

The capacitor is charged by your HVPS and discharges when its voltage reaches a value such that the electric field in the gap exceeds the breakdown field of air. After discharging, the capacitor charges up again through the $4\,M\Omega$ of resistance outside the HVPS plus its $0.5\,M\Omega$ internal resistance. The time constant

$$\tau = RC = (4.5 \times 10^6\,\Omega)(33 \times 10^{-12}\,F) = 1.5 \times 10^{-4}\,s\,.$$

So the charging and breakdown cycle will recur at a frequency

$$f_{osc} = \frac{1}{\tau} = 6.7kHz\,.$$

This will generate bursts of radiation.

The frequency of the radiation is determined by the time it takes charge to flow on the antenna. Just before breakdown the two halves of the antenna are charged + and - forming an electric dipole. There is an electric field around this dipole. During the short time that the capacitor discharges, the electric field decays and large currents flow producing magnetic fields. These currents flow through the gap and charge the antenna with the opposite polarity. The oscillations damp out as energy is dissipated and some of the energy is radiated with the period $T = 4l/c$ where l is the length of $1/2$ of the dipole and c is the speed of light. The charge travels a distance $4l$ going from + to - and back from - to +. In this experiment we'll make $l = 31\,mm$ so the frequency radiated,

$$f_{rad} = \frac{1}{T} = \frac{c}{4l} = 2.4 \times 10^9\,Hz = 2.4\,GHz$$

Therefore the antenna will emit bursts of damped radiation (every $1.5 \times 10^{-4}\,s$) at frequencies around $2.4GHz$. The range of frequencies depends on the quality, Q, of the antenna. (The quality factor of a resonant system, or the antenna is:

$$Q = (2\pi f)(average\ energy\ stored / average\ power\ dissipated),$$

for each cycle. The quality factor also measures the width of the resonance, $Q = f/\Delta f$. So a high quality factor antenna gives a narrow range of generated frequencies.)

The spark generates other frequencies as well (as a nearby radio will show) and to minimize the radiation of these we put two $1\,M\Omega$ resistors close to the capacitor.

Building the Transmitter

Solder the $33\,pF$ capacitor to the leads of the $1\,M\Omega$ resistors (see Figure 2). Make the capacitor leads as short and direct as possible without hindering the adjustment of the gap. Cut two $31\,mm$ long straight pieces of bare #12 copper wire (from the piece of plastic insulated wire in the Red Box) and solder them to the solder lugs which protrude above the end of the clothespin. The ends of the wire should extend (at most) a few millimeters from the end of the solder lug. This relatively heavy wire minimizes resistance and maximizes Q. You can strip the insulation from the plastic insulated household wire by stripping a short length and, then holding the bare copper with pliers, pulling off the insulation.

Receiving Antenna

This is made of a single piece of wire made into a one-turn loop with two ends sticking out from the plane of the loop, each a 1/4 wavelength long. The microwave emf developed across the loop is rectified by a diode and the resulting dc is fed to your amplifier through a shielded cable. The loop has two purposes: it provides mechanical stability for the antenna and it acts as a one-turn inductor which prevents low frequency fields from affecting your observations.

The electric fields of the microwaves when parallel to the receiving antenna will cause current to flow. As in the transmitting antenna, the dimension of the receiving dipole makes it broadly resonant at 2 to 3 gigahertz. Voltages developed across the loop are rectified by the diode rectifier that passes only one half-wave of each oscillation to make a train of dc pulses. The capacitance of the wires smooth out the rapid variations and leaves an envelope of the decaying pulses of microwaves. These pulses drive the amplifier, which increases their voltage and smooths out the faster variations. The output of the amplifier then drives the slow-responding multimeter.

Figure 2: Receiving Antenna

Building the Receiving Antenna

Take the insulation off another piece of #12 wire (strip a little and holding the copper with pliers, pull the insulation off) and wrap it around a pen so as to make a loop, about 10-15 mm in diameter, in the middle of the wire. Bend the ends of the wire so that the plane of the loop is perpendicular to the line form by the two ends of the wire (Figure 2). Make the bends as close as possible to the loop. Trim the length of each half of the antenna to $31mm$ as measured from the plane of the loop. The overall length will be about $75mm$, allowing for the wire thickness and bends.

The shielded cable is actually a two conductor shielded wire. Prepare the shielded lead by stripping off about $30\,mm$ of the outer plastic covering. Inside you will find two inner wires (red and white, or red and black) surrounded by a bare metal shield. You may also see a stranded bare wire between the aluminum shield and the plastic covering. (See Figure 3). In order to strip the plastic covering, grab the wire with pliers about 30 mm from one end, use your wire stripper first to cut a groove in the insulation by turning it, and then lever off the insulation. It's important not to damage the inner wires. If you don't succeed at first, practice taking off shorter lengths of insulation (fortunately the exact length of this lead doesn't matter).

Figure 3: Two conductor cable

Solder a short ($\approx 10mm$) piece of bare wire to the antenna immediately next to each side of the loop and as close to it as feasible. Solder one of the wires from the loop to the bare stranded wire or the shield (this is the ground). Solder the wire from the black marked end of the 1N5712 diode to the inner red wire. Solder the other end of the diode to the remaining wire from the loop. (We will not connect anything to the black or white inner wire). Avoid overheating the diode. Use black tape to insulate the diode and its leads from the bare stranded wire. A short here will prevent the antenna from transmitting a signal. Then wrap aluminum foil around the assembly to shield it, making sure that the foil is in contact with the bare stranded wire that acts as ground. (See Figure 4).
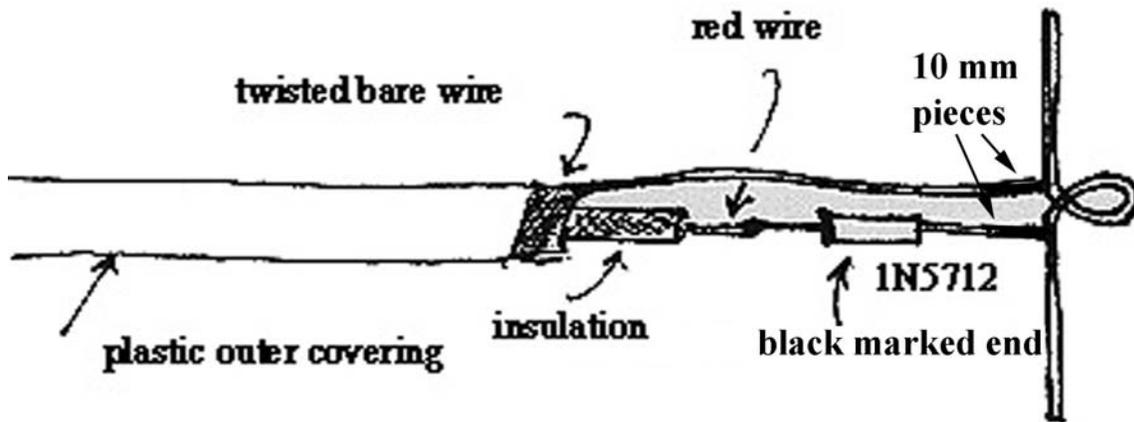
Figure 4: Receiving Antenna

On the other end of the two conductor shielded wire, connect the inner red wire to the input of your amplifier, A. Connect the bare stranded wire to the common, C.

Check to see that your diode is good by measuring the resistance on the R x 1K scale of the MMM. If you connect your clip leads with the positive lead on the red wire and the negative lead on the bare stranded wire, you should measure a resistance of $10\,k\Omega$. If you connect the leads the other way, you should measure a resistance of ∞. The diode can be easily 'popped' if you are not careful. Avoid allowing the receiving antenna to touch the transmitting antenna. If at any time during the experiment, you are not receiving signal, check your diode by measuring its resistance.

Setting up the Apparatus

Stick the transmitter down on your desk with tape about $0.5\,m$ from either side of the desk. Have the adjusting nut of the spark gap facing you. Connect the gap to the HVPS. Place the HVPS out of the way near the edge of the desk. Tape aluminum foil to one of the covers of a textbook and stand it up about $8\,cm$ behind the spark gap transmitter to act as a reflector.

Put your amplifier on the opposite side of the transmitter and somewhat back so that you can explore the radiation field with the receiving antenna. You should be able to move the receiving antenna from a few centimeters from the transmitter to as far as the shielded wire will let you go on the other side -- for larger distances, move the amplifier. You will notice that if the receiving antenna is too close to the transmitter, the signal will saturate the amplifier. You may find that when the receiving antenna is between $15\,cm$ and $30\,cm$ away the transmitter, the signal will not saturate the amplifier. Use one MMM to measure the HVPS output (1000DCV range) and the other MMM to measure the amplifier output (250mV or 5DCV range). Their long leads should be kept out of the way.
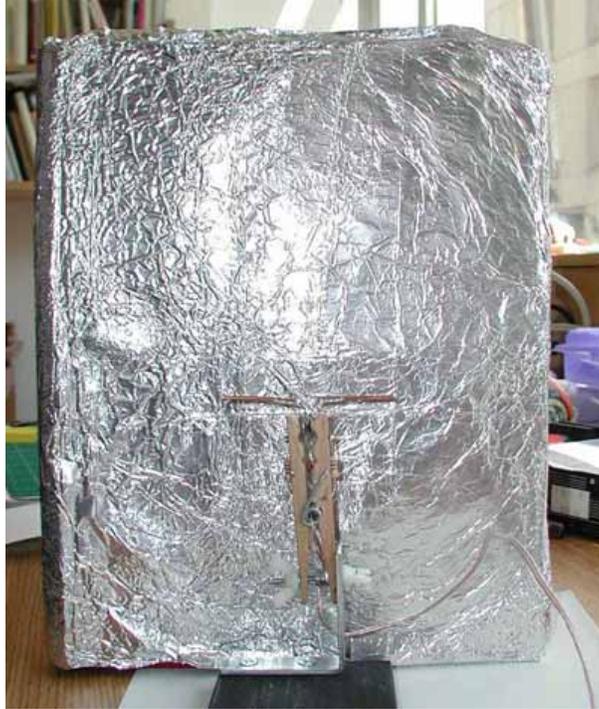
Figure 6: Reflector behind transmitter

Preliminary Observations

Zero your amplifier so that the MMM reads zero on the 250mV range. Set the HVPS to $800V$ with the spark gap open about $0.5mm$. Gradually narrow the gap until you get a steady spark. The meter reading will drop some and you can probably hear the spark as a hissing sound. It can also be heard through an AM radio.

Observing Polarization

Observe the waves by holding the receiving antenna parallel to the transmitting antenna and moving it back and forth. Adjust the spark gap for an optimum signal. Rotate the receiving antenna until it is perpendicular to the transmitter antenna. Observe what happens to the signal. Interpose a metal plate such as an aluminum foil wrapped envelope between the transmitting antenna and the receiving antenna. Observe what happens to the signal. This should provide convincing evidence that transverse EM waves are present. Remember that your amplifier "overloads" at about $4V$ and is no longer linear in its response. If you have too much signal, move the antennas apart.

Measuring the wavelength

When everything is optimized in your microwave set-up and with a steady spark, search for minima and maxima by moving the receiving antenna slowly toward or away from the transmitting antenna between $20cm$ and $40cm$ from the transmitter. Place the receiving antenna in a position that gives a maxima in this range.

You can improve your measurement by adjusting the reflector that you placed on the other side of the transmitter from the receiving antenna. As you move the reflector closer to the transmitter, the receiving antenna will show maxima and minima.

If the transmitting antenna is a distance d away from the reflector, the effect of the reflector is to create a virtual transmitter a distance d behind the reflector. The reflected wave undergoes a 180^0 phase change at the surface of the reflector. The reason for this is that the reflector is a conductor and the component of the electric field parallel to the surface of a conductor is zero. Therefore the reflected wave and the transmitted waves must exactly cancel on the surface of the reflector. A 180^0 phase change corresponds to a shift in wavelength of $\lambda/2$. So in order for the virtual transmitter and the real transmitter to constructively interfere, they must be a distance $\lambda/2$ apart. So the correct choice for the distance between the reflector and the transmitter is $2d = \lambda/2$ or $d = \lambda/4$, one quarter of a wavelength. The next maximun will occur when the reflector is a distance $2d = 3\lambda/2$ or $d = 3\lambda/4$.
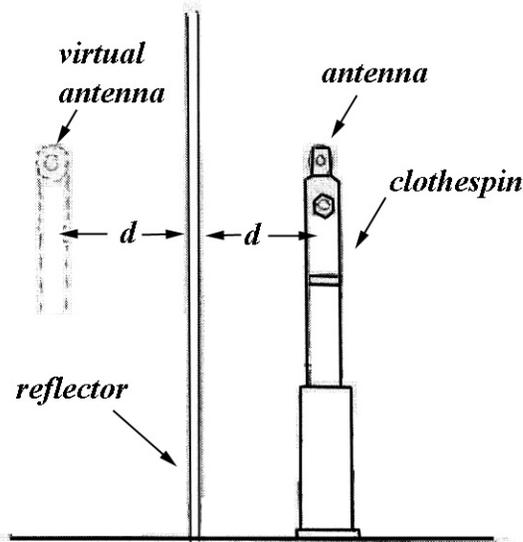
Figure 7: Reflector and transmitter geometry

Mark the location of the reflector on a paper taped to the table underneath the reflector, when the signal is a maxima. Measure your distance, *s*, between two adjacent maxima. Calculate the wavelength according to

$$\lambda = 2s.$$

Standing Waves

To get standing waves, put one reflector (textbook covered with foil) close behind the transmitter, and another reflecting screen some distance (about a foot) behind the receiver. Adjust the receiver's reflecting screen until your signal is a maximum. Remember you can improve your measurement by putting the transmitter's reflector a quarter wavelength behind the transmitter.

Standing waves are produced by the interference pattern of two waves traveling in opposite directions. These two waves come from the transmitter and the reflector. Mark the position of the antenna for the minima and maxima intensities (for later measurement) on a piece of paper taped to your desk. The peaks should be a half-wavelength apart. Measure and record the average wavelength that you observed. If you feel that your hand is disturbing the measurements, try holding the receiving antenna with a piece of wood or some other insulator (for example a toothbrush) taped to the receiving antenna.

Parts List:

MW   PLASTIC BAG

1   diode, Schottky 1N5711
1   capacitor, 33 pF ceramic disc
4.5 in wire, household 14x2 w/ground(NM)
4 ft wire, 2 conductor shielded
3 ft wire, #22 speaker (from EB)

Red Box

1   piece of aluminum foil in white envelope

Experiment MW: Observations

1) Observe the waves by holding the receiving antenna parallel to the transmitting antenna and moving it back and forth. In the "near" or "induction" field, less than a few wavelengths, the strength of the field falls off as $1/r^2$ and hence the power falls as $1/r^4$. But in the "far" or "wave" zone, greater than a few wavelengths, the field falls off as $1/r$, and the power as $1/r^2$ as is appropriate for EM radiation. Remember that your amplifier "overloads" at about $4V$ and is no longer linear in its response. If you have too much signal, move the antennas apart. Briefly describe your observations.

2) Turn the receiving antenna 360° about the line between it and the transmitter; What happens? Explain.

3) Interpose a metal plate such as an aluminum-wrapped envelope with its plane perpendicular to the line joining the antennas. What happens? Is the effect different according to whether the envelope is placed between the antennas with its long dimension horizontal or vertical?

4) With the receiver at a fixed location, say $0.5m$ from the transmitter, adjust the reflector (use a textbook covered with foil) for maximum signal. What is the optimum distance between reflector and transmitting antenna?

5) Explore briefly how the received signal varies with the position of the receiving antenna:

   a) as you move the antenna in a horizontal circle about the transmitting antenna as center; keep the receiving antenna horizontal and always at right angles to the line from it to the transmitter.

   b) as you move it around a vertical circle; keep the receiving antenna horizontal (parallel to the transmitter dipole).

6) Make a polarizer by wrapping #26 wire from your 38 turn coil (no longer needed) around an envelope. Tape the wire. Interpose this between the antennas and see what happens as you turn it, so the wires are parallel and perpendicular to the antennas.

Experiment MW: Measuring the Wavelength

When everything is optimized in your microwave set-up and with a steady spark, search for minima and maxima by moving the receiving antenna slowly toward or away from the transmitting antenna. Standing waves are produced by the interference pattern of two waves traveling in opposite directions. These two waves come from the transmitter and the reflector.

You can improve your measurement by putting the transmitter's reflector behind the transmitter. Fix your receiving antenna about $20\,cm$ to $30\,cm$ away from the transmitter. As you move the reflector closer to the transmitter, the receiving antenna will show maxima and minima.

a) What distance is your receiving antenna from your transmitter?

b) What were the nearest and second nearest distances you put your transmitter's reflector behind the transmitter so that the receiving antenna showed a maxima?

c) What were the nearest and second nearest distances you put your transmitter's reflector behind the transmitter so that the receiving antenna showed a minima?

d) From the data in parts b) and c), what is the wavelength of the radiation? Explain how you obtained your answer.

Problem 1: *Microwave Experiment*

Suppose the transmitting antenna located at the position $x = d$ in the microwave experiment is parallel to the y-axis and generates a plane sinusoidal wave of frequency $f = 2.4 \times 10^9 \, Hz$. The amplitude of the wave is E_0.

a) What is the wavelength of the wave?

b) Approximate the electromagnetic wave generated by the transmitter field by a plane wave that is traveling in the negative x-direction. The y-component of the electric field is given by

$$E_y = E_{y,0} \cos(kx + \omega t).$$

Write down an expression for the magnetic field of the plane wave that is traveling in the negative x-direction. Indicate the direction and amplitude of the magnetic field.

c) A conducting plate is placed at the position $x = 0$, a distance d behind the transmitting antenna. At time $\omega t = \pi$, and at the position of the conductor $x = 0$, what are the directions of the electric and magnetic fields of the plane wave that is reflected from the conductor.

d) Find the closest distance d behind the transmitter that the conductor must be placed in order for the reflected wave and the transmitted wave to add up to produce a maximum constructive interference pattern. These two waves are each travelling in the positive x-direction. Briefly explain your reasoning.

e) Now suppose a second conducting plate is placed at a position $x = L$ in order to maximize the signal from the receiving antenna when it is placed between the plates. The receiving antenna is moved along the x-axis. Briefly explain what signal pattern the antenna receives. Briefly explain what type of wave now exists between the plates.

f) With the two conducting plates in place, the receiving antenna is moved along the x-axis. Briefly explain what signal pattern the antenna receives.