

Experiment 12: Microwaves

OBJECTIVES

To observe the polarization and angular dependence of radiation from a microwave generator and to measure the wavelength of the microwave radiation by analyzing an interference pattern similar to a standing wave.

INTRODUCTION

Heinrich Hertz first generated electromagnetic waves in 1888, and we replicate Hertz's original experiment here. The method he used was to charge and discharge a capacitor connected to a spark gap and an antenna. When the spark "jumps" across the gap (once per 0.15 millisecond in our experiment), the antenna is excited by this discharge current, and charges oscillate back and forth in the antenna at the antenna's natural resonance frequency. For our experiment, this natural resonance frequency of the antenna is very high, about $2.4 \times 10^9 \text{ Hz} = 2.4 \text{ GHz}$. For a brief period around the breakdown ("spark"), the antenna radiates electromagnetic waves at this high frequency. We will detect and measure the wavelength λ of these bursts of radiation. Using the relation $f\lambda = c = 3 \times 10^{10} \text{ cm/s}$, we will then deduce the natural resonance frequency of the antenna, and show that this frequency is what we expect on the basis of the very simple considerations given below.

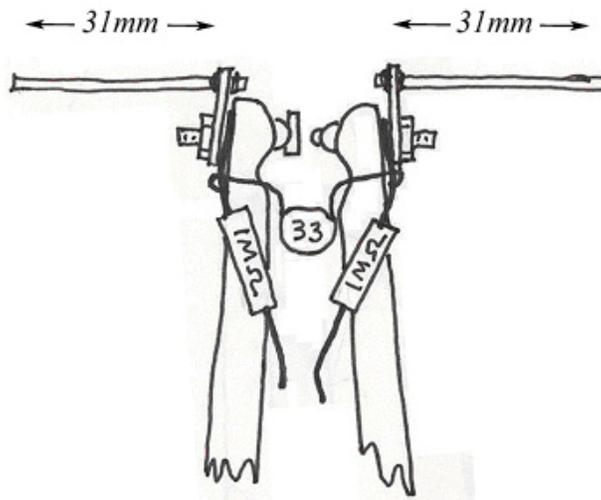


Figure 1 Spark-gap transmitter

The 33-pF capacitor shown in Figure 1 is charged by a high-voltage power supply on the circuit board provided. This HVPS voltage is typically 800 V, but this is a very safe level

because the current is limited to a very small value across the capacitor. When the voltage is high enough and the distance between the tungsten rods in your “spark gap” is small enough, the capacitor discharges across the gap (Figure 2). In Figure 1, the tungsten rods are small cylinders, one with its axis vertical and the other horizontal, allowing a clear path for the arc of the spark. The discharge occurs when the electric field in the gap exceeds the breakdown field of air (about 1000 V/mm).

The radiation we are seeking is generated in this discharge (see explanation below). After discharging, the capacitor charges up again through a total resistance of 4.5MΩ. The time constant is

$$\tau = RC = (4.5 \times 10^6 \Omega)(33 \times 10^{-12} \text{F}) = 1.5 \times 10^{-4} \text{s}, \quad (12.1)$$

so the charging and breakdown will generate a spark discharge about every 0.15ms. This corresponds to a frequency of discharge

$$f_{\text{discharge}} = \frac{1}{\tau} = 6.7 \text{ kHz} \quad (12.2)$$

and will result in bursts of radiation. (This is an example of a “relaxation oscillator.”)

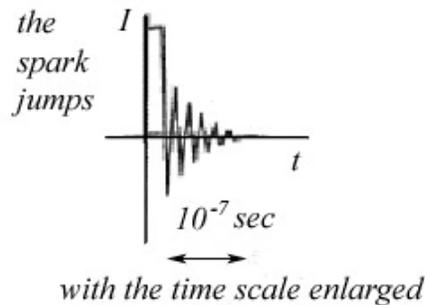


Figure 2 Spark jumps

Then the 33-pF capacitor starts charging up again, ultimately headed toward breakdown in another 0.15ms (see Figure 3).

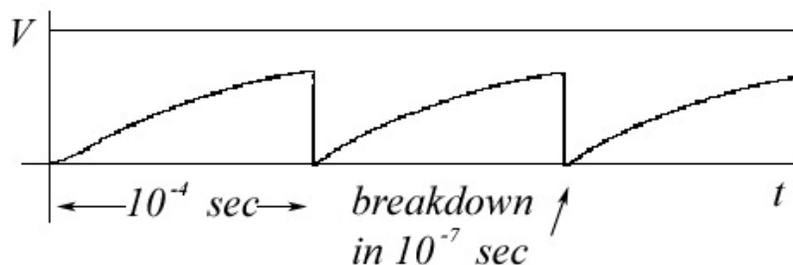


Figure 3 Breakdown Potential

Resonant Frequency of the Antenna

The frequency of the radiation is determined by the time it takes charge to flow along the antenna. Just before breakdown, the two halves of the antenna are charged positive and negative (+, -) forming an electric dipole. There is an electric field in the vicinity of this dipole. During the short time during which the capacitor discharges, the electric field decays and large currents flow, producing magnetic fields. These currents flow through the spark gap and charge the antenna with the opposite polarity. This process continues on and on for many cycles at the resonance frequency of the antenna, $\omega_0 = 1/\sqrt{LC} = 2\pi f_0$. The oscillations damp out as energy is dissipated and some of the energy is radiated away until the antenna is finally discharged. See the 8.02 *Course Notes*, **Section 13.8**, for a further discussion of dipole radiation. Also, see the animations of the electric field lines generated by this back-and-forth “sloshing” of charge between the two halves of the antenna. This is the radiation pattern that we will be studying today.

How fast do these oscillations take place? Equivalently, what is the frequency of the radiated energy? Here is a crude estimate that turns out to be a good prediction. If l is the length of one of the halves of the antenna (about $l = 31$ mm in our case), then the distance that the charge oscillation travels going from the (+, -) polarity to the (-, +) polarity and back again to the original (+, -) polarity is $4l$ (from one tip of the antenna to the other tip and back again). The time T it takes for this to happen, assuming that information is flowing at the speed of light, is $T = 4l/c$, where c is the speed of light. If the charges are oscillating at a frequency of $1/T$, they will radiate electromagnetic radiation at this frequency. For $l = 31$ mm, this estimate of the frequency radiated is given by

$$f_{\text{rad}} = \frac{1}{T} = \frac{c}{4l} = \frac{3 \times 10^{10} \text{ cm/s}}{12.4 \text{ cm}} = 2.4 \times 10^9 \text{ Hz} = 2.4 \text{ GHz}. \quad (12.3)$$

Electromagnetic waves with this frequency will have a wavelength of

$$\lambda = \frac{c}{f_{\text{rad}}} = 4l = 12.4 \text{ cm}. \quad (12.4)$$

An antenna of this sort is known as a “quarter-wave” antenna.

Therefore, the antenna will emit bursts of damped radiation (every 1.5×10^{-4} s) at frequencies around 2.4 GHz. The range of frequencies depends on the quality, Q , of the antenna. The quality of the antenna is defined in a manner similar to the quality of a resonant AC circuit (see the 8.02 *Course Notes*, **Section 12.4.1**) as the ratio of the resonant angular frequency divided by the “line width” Δf :

$$Q = \frac{f_0}{\Delta f}. \quad (12.5)$$

The line width Δf is an indication of the fact that the above estimate of the frequency, based on the time needed for charge oscillations to propagate along the length of the antenna, does not include other frequencies that are present during the capacitor discharge.

Thus, a high quality factor antenna represents a narrow range of generated frequencies. The antenna in the experiment will have a line width of about $\Delta f = 0.5\text{GHz}$, so the quality of the antenna is about $Q \approx 5$.

Thus, our simple picture predicts that we will generate electromagnetic radiation with this antenna with wavelengths of about $\lambda = 12.4\text{cm}$, and this is something that we will confirm experimentally. As mentioned above in the discussion of the quality of the antenna, the spark generates other frequencies as well. To minimize the radiation of these other frequencies, two $1\text{-M}\Omega$ resistors are placed close to the capacitor.

The curves shown in Figure 4 represent the current flowing in your receiver as a result of the oscillating electric fields of the microwave radiation. We have a diode in the receiver that allows current to flow in only one direction, and we detect that current using an amplifier and a multimeter to show the voltage from the amplifier. This voltage would be proportional to the current shown in the right-most plot in Figure 4. Since this voltage varies so quickly, the meter will show an “average” voltage, proportional to the amplitude of the intensity of the radiation detected by the receiver.

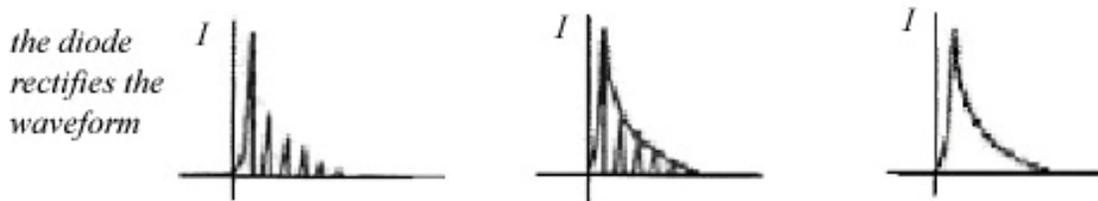


Figure 4 Current in the receiver as a result of microwave radiation

EXPERIMENT

Plug the power supply into your circuit board at the position indicated. Plug in your receiving antenna (which looks like the tube shown Figure 5 below) to the remaining input jack on the board. (Either or both of these steps may have been done for you already.) Figure 5 shows two of the possible orientations of the receiver.

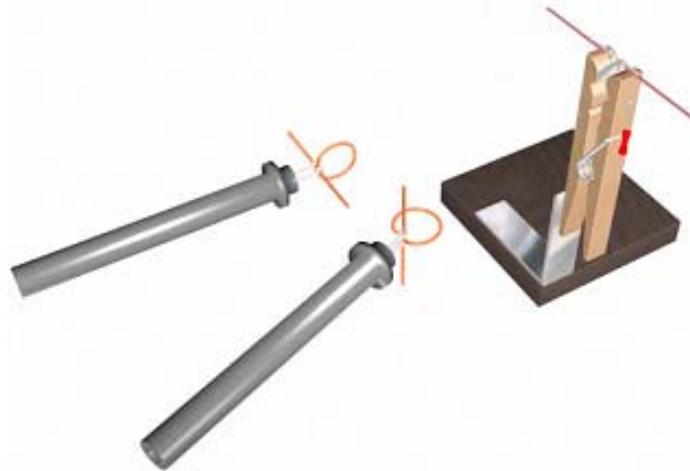


Figure 5 The spark gap transmitting antenna and the receiver

Your transmitting antenna is the clothespin assembly, and the connections shown in Figure 1 have already been made. Once the power supply has been connected, turn on the transmitter (using the off-on switch—the LED will light when it is on). Then, adjust the spark gap using the wing nut on the clothespin antenna until you get a spark discharge. Start with a large gap, and close the gap until a steady spark is observed. Since the relaxation period is so small (10^{-4} s = 0.1 ms), you should observe a small, steady bright blue light. Once you obtain that discharge, and can make it reasonably steady, you can use your receiver to make measurements of the radiation emitted.

Part 1. Polarization of the Emitted Radiation

Arrange the transmitting antenna (Figure 5) on your table as far away from metal as possible. Put your circuit board on the table and somewhat back so that you can explore the radiation field with the receiver. 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 circuit board. Start with the receiver a few centimeters from the transmitter, with the multimeter set on the 5-volt DC scale. When you move the receiver further away, and the strength of the signal decreases, you might want to switch to the 250-mvolt DC scale.

Question 1 (answer on your tear-off sheet at the end): The radiation we are generating is produced by charges oscillating back and forth between the two halves of your antenna (see Figure 1 above). If you hold the receiver in the two orientations shown in Figure 5 above, explain which orientation should produce the larger signal on the voltmeter connected to your receiver. Think about the electric and magnetic fields generated by the radiation and their effect on charges in the receiving antenna. The figure below, part of Figure 13.8.7 from the 8.02 *Course Notes*, shows the electric field configuration near an antenna similar to that used in this experiment.

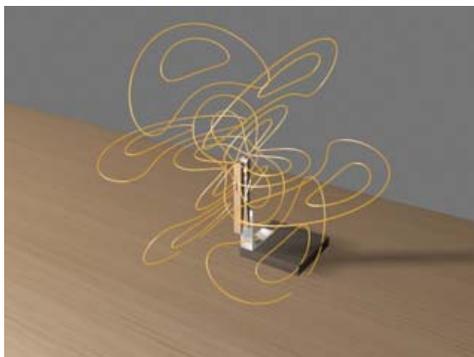


Figure 13.8.7 from the 8.02 *Course Notes*

Question 2 (*answer on your tear-off sheet at the end*): Determine the polarization of the electric field with your receiver. How did your measurement compare to this prediction?

Question 3 (*answer on your tear-off sheet at the end*): Based on your results, what are the directions of the electric and magnetic fields generated by your antenna?

Part 2. Angular Dependence of the Emitted Radiation

The radiation we are generating is produced by charges oscillating back and forth along the length of your antenna. The radiation will have an angular dependence. If you move your receiver along the arc of a circle in a horizontal plane with the spark gap at the center, as shown in Figure 6, the signal will vary. If you also move the receiver along the arc of a circle in a vertical plane with the spark gap at the center, as shown in Figure 7, the variation of the signal will be different.

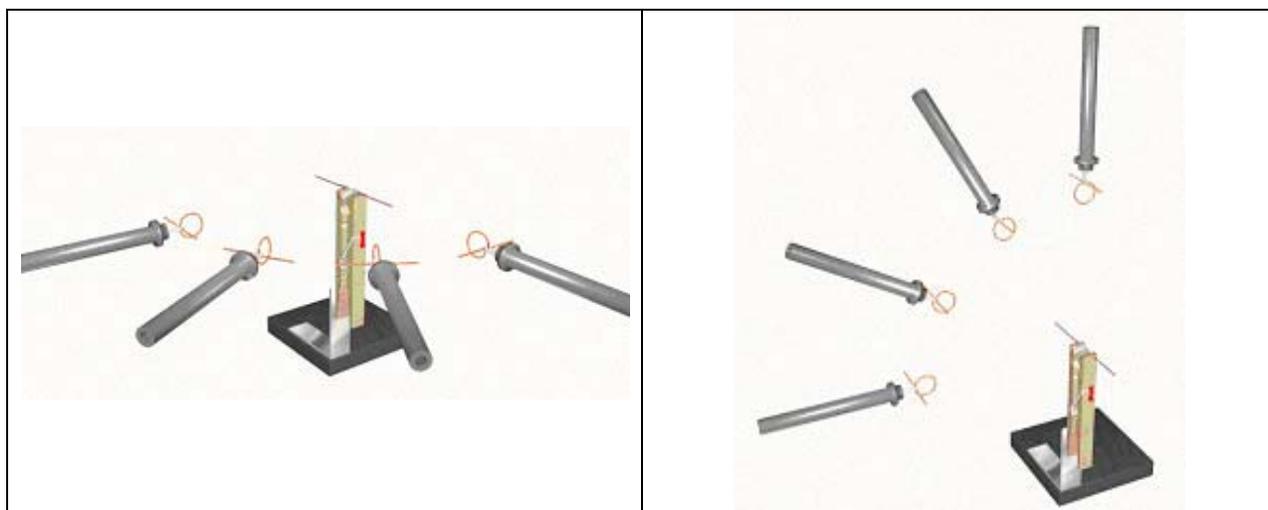


Figure 6: Angular dependence - horizontal **Figure 7:** Angular dependence - vertical

Question 4 (answer on your tear-off sheet at the end): If you move the receiver in the two patterns shown above, should the left pattern (Fig. 6) or the right pattern (Fig. 7) show the larger change in the signal on your voltmeter over the range of motion?

Part 3. Wavelength of the Emitted Radiation

We will measure the wavelength of the radiation from your transmitter by using a reflector to reflect the radiation so that it returns to interfere with itself.

Position the reflector so that it is about 30-40 cm from the spark gap transmitter, oriented so that the plane of the reflector is perpendicular to the direction of propagation of the transmitted wave (that is, so that it reflects). Place the receiver first on one side, then on the other, of the reflector to verify that the wave is not transmitted through the reflector.

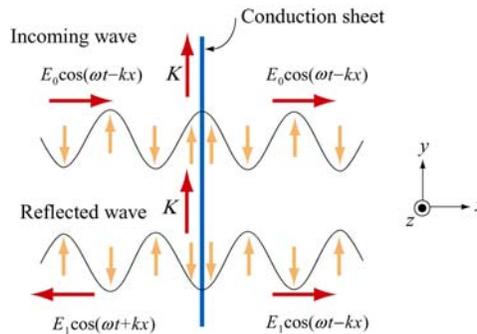


Figure 8 Idealized reflection from a conducting sheet

The reflector will produce an electric field similar to the standing wave as shown in Figure 8 in the region between the transmitter and the receiver. The wave cannot be a standing wave, as the intensity of neither the incident (incoming) or the reflected wave is spatially constant. However, near the reflector the incident wave and the reflected wave will cancel to an extent that should be easily detected by the receiver.

Place the receiver (you should know which orientation is best) near the reflector between the reflector and the transmitter, and move the receiver towards the transmitter. You should find a position of the receiver where the total radiation field (incident plus reflected) is a clear minimum, possibly even close to zero as measured on your meter. Continue moving towards the transmitter to see the variation in the signal, from minimum to maximum and to another minimum (but not as small as that nearest the reflector – you should know why right away).

If you don't see a clear minimum-maximum pattern, try moving the reflector a few centimeters.

When you think you have the reflector positioned so that you obtain a clear pattern, perform the following two measurements:

Imprecise: Move the receiver towards the transmitter, and measure the distance that you need to move the receiver between minima. This measurement is imprecise because your receiver is being held above the table, and it's hard to maintain a constant height and measure the distance in a plane above the table.

Question 5 (answer on your tear-off sheet at the end): What is the distance between interference minima as determined by moving the receiver?

More precise: Place a piece of paper on the table, under the reflector and with enough paper extending away from the transmitter to allow recording of any moving of the reflector (how many wavelengths would this be?). Mark the position of the reflector on the paper.

Have one group member (decide who has the steadiest hand) maintain the receiver at the minimum position nearest the reflector. Another group member should then move the reflector away from the transmitter. A third group member should watch the meter reading as the reflector is moved, and watch for another intensity minimum. Mark the position of the reflector, and measure the distance the reflector has moved.

Make a number of different measurements (at least three or four) to arrive at a reasonable average for the wavelength of your wave using this method. If possible, move the reflector far enough to correspond to one wavelength or three-halves wavelengths.

Question 6 (answer on your tear-off sheet at the end): What is the distance between interference minima as determined by moving the reflector?

DISCUSSION

The phase change in the electric field associated with the wave at the surface of the conductor results in a net electric field which has a minimal intensity at one-half wavelength from the reflector; at this position, the incident and reflected waves will always be out of phase. Similarly, the intensity will have another minimum at a distance of one wavelength from the reflector.

If, then, as described above, the *receiver* remains in the same position (remember the steady hands) while the *reflector* is moved so that the signal at the receiver is observed to change from one minima to another, the reflector must have move a distance of one-half wavelength.

Unlike an idealized standing wave, the minimal signals observed in this experiment will not in general be identically zero intensities. There are many reasons for this, two of which are easily explained and interpreted. First, the intensity from the transmitter is not spatially constant, and decreases with distance from the source; this should be expected, and should have been observed in a preliminary part of this experiment. Therefore, the incident and reflected waves cannot cancel exactly; the idealization represented in **Figure 14.1.1(c)** of the 8.02 *Course Notes*, reproduced below, is exactly that; an idealization.

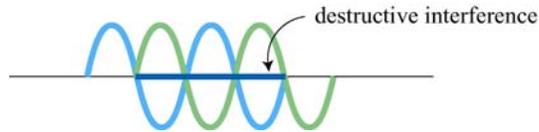


Figure 14.1.1(c) from the 8.02 *Course Notes*

Another consideration is that while the quality $Q \approx 5$ of this antenna is reasonably high for this sort of apparatus, there are other frequencies and wavelengths in the radiation, and radiation of other wavelengths will not exhibit the same destructive interference at the same spatial points. However, if the positions of the reflector for which minima are clearly observed differ by a distance s , the wavelength of the dominant frequency will be given by

$$\lambda = 2s . \quad (12.6)$$

Question 7 (answer on your tear-off sheet at the end): What is the value of your wavelength? Give your answer in centimeters.

Question 8 (answer on your tear-off sheet at the end): From $f\lambda = c = 3 \times 10^{10}$ cm/s, what is the value of the frequency f ? Give your answer in hertz (Hz).

When you find a value for the wavelength and frequency your group is comfortable with, write those values on the whiteboard for your table. At the end of this activity, we will compare values.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Department of Physics

8.02

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Tear off this page and turn it in at the end of class.

Note:

Writing in the name of a student who is not present is a Committee on Discipline offense.

Experiment Summary 12: Microwaves

Group and Section _____ (e.g. 10A, L02: Please Fill Out)

Names _____

Part 1: Polarization of the Emitted Radiation

Question 1: The radiation we are generating is produced by charges oscillating back and forth between the two halves of your antenna. If you hold the receiver in the two orientations shown in Figure 5 above, explain which orientation should produce the biggest signal on the voltmeter connected to your receiver.

Answer:

Question 2: Determine the polarization of the electric field with your receiver. How did your measurement compare to this prediction?

Answer:

Question 3: Based on your results, what are the directions of the electric and magnetic fields generated by your antenna?

Answer:

Part 2. Angular Dependence of the Emitted Radiation

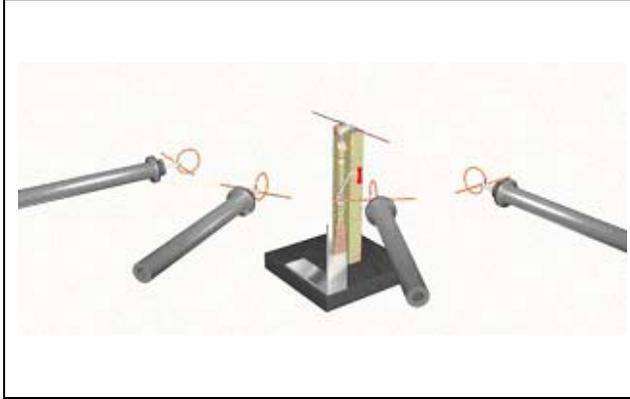


Figure 6: Angular dependence - horizontal

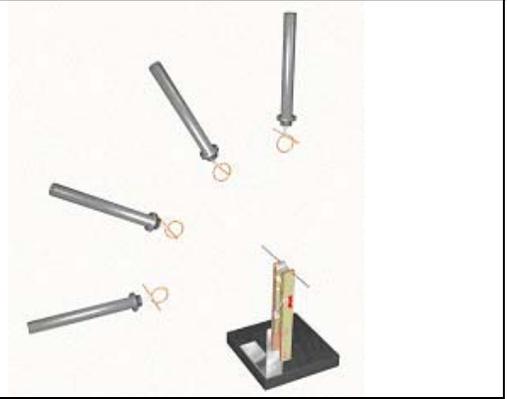


Figure 7: Angular dependence - vertical

Question 4: If you move the receiver in the two patterns shown above, should the left pattern (Figure 6) or the right pattern (Figure 7) show the larger change in signal on your voltmeter over the range of motion?

Answer:

Part 3. Wavelength of the Emitted Radiation

Question 5: What is the distance between interference minima as determined by moving the receiver?

Answer:

Question 6: What is the distance between interference minima as determined by moving the reflector?

Answer:

Question 7: What is the value of your wavelength? Give your answer in centimeters.

Answer:

Question 8: From $f\lambda = c = 3 \times 10^{10} \text{ cm/s}$, what is the value of the frequency f ? Give your answer in hertz (Hz).

Answer: