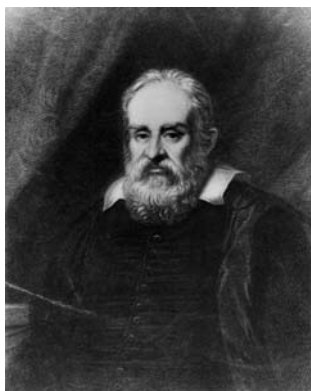


# Synchrotron Investigations

## 10.4 Using a microwave oven to measure the speed of light

### Background



The speed of light is represented by the letter  $c$ . Before the seventeenth century it was generally thought that light is transmitted instantaneously. Nowadays, we know that light is just too fast for the human eye to determine its speed. We do know that our eyes can detect the radiation, which is why we see. Galileo doubted that light speed is infinite, and he described an experiment to measure light's speed by covering and uncovering lanterns observed at a distance of a few kilometres. We don't know if he really attempted the experiment, but  $c$  is too large a number for such a method to work.

#### Portrait of Galileo Galilei (1564-1642)

Image courtesy: AIP Emilio Segrè Visual Archives

Today, science accepts that the speed of light is a fixed value of  $299\,792.458 \text{ km s}^{-1}$  in a vacuum and that nothing that we know of can travel faster than the speed of light. The following table gives the history of some of the best measurements according to Froome and Essen.

Date	Author	Method	Result ( $\text{km s}^{-1}$ )	Error
1676	Olaus Roemer	Jupiter's satellites	214 000	
1726	James Bradley	Stellar aberration	301 000	
1849	Armand Fizeau	Toothed wheel	315 000	
1862	Leon Foucault	Rotating mirror	298 000	$\pm 500$
1879	Albert Michelson	Rotating mirror	299 910	$\pm 50$
1907	Rosa, Dorsay	Electromagnetic constants	299 788	$\pm 30$
1926	Albert Michelson	Rotating mirror	299 796	$\pm 4$
1947	Essen, Gorden-Smith	Cavity resonator	299 792	$\pm 3$
1958	K. D. Froome	Radio interferometer	299 792.5	$\pm 0.1$
1973	Evanson et al	Lasers	299 792.4574	$\pm 0.001$
1983		Adopted value	299 792.458	

Source of information: Froome and Essen (n.d.) *Twentieth Century Physics - Volume 2, The Velocity of Light and Radio Waves*. IOP/AIP Press.

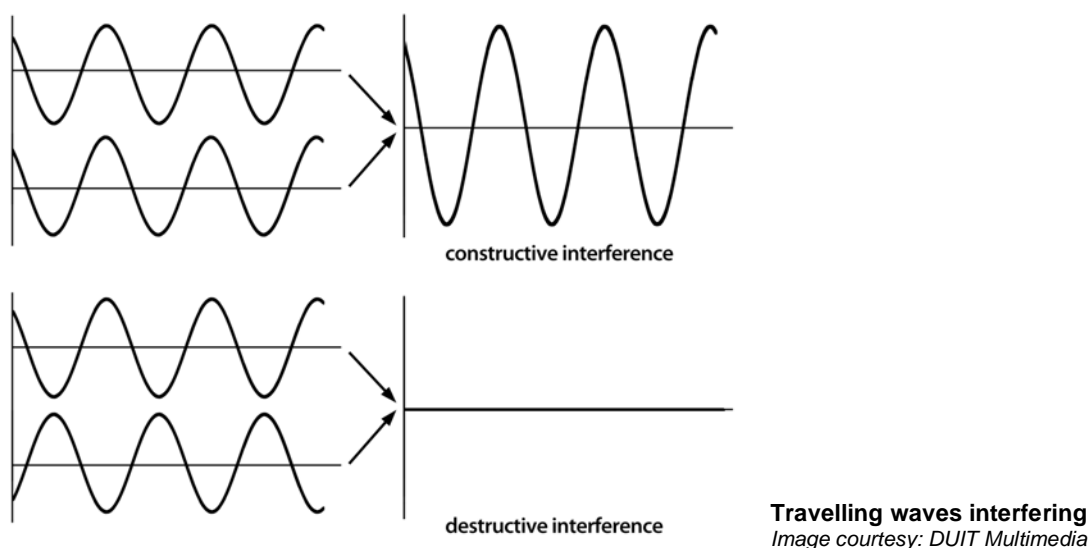
## Aim

The aim of this experiment is to measure the speed of light using food (chocolate, cheese, pappadums or marshmallows), a microwave oven, a ruler (with millimetre measurements) and the relationship between the speed of EMR (in this case microwaves) and their wavelength and frequency. Enjoy the experiment and enjoy eating the food.

One of the major drawbacks of microwave ovens is the hotspots they produce, but it is the distance between these hotspots that is going to be used to calculate the speed of light.

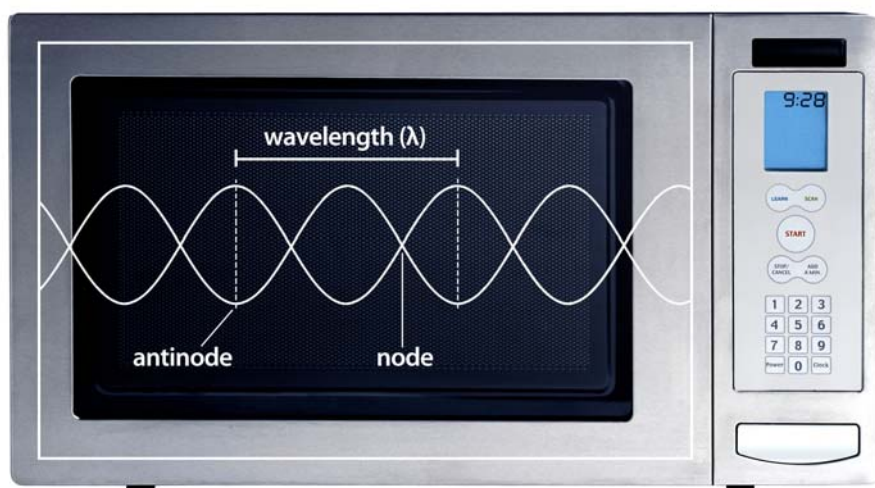
## The science behind the experiment

Microwave radiation, reflects off the internal metal surfaces of the microwave oven and interacts with other reflected radiation in such way that hot and cold spots are formed inside the microwave. The phenomenon responsible for this is the interference of waves, shown below. Waves overlapping in such way that crests that match one another interfere constructively, forming a hot spot. Waves which interfere destructively result in a cold spot. The uneven heating caused by these effects can be significantly reduced by using a rotary platform (or turntable) to put your food on.



If two waves are travelling in opposite directions, then they interfere in a way which creates a standing wave.

Many of the waves in a microwave oven are standing waves. These waves are stationary in space with amplitude changing over time. The nodes arise from destructive interference and are cold spots. The antinodes arise from constructive interference and are hotspots. You can see from the diagram below that hotspots are half a wavelength apart.



**Microwave showing waves travelling in opposite directions at one instant in time**  
 Image courtesy: DUIT Multimedia

The speed of any wave can be calculated using the following relationship

$$c = \lambda f$$

where  $c$  is the speed of light ( $\text{m s}^{-1}$ )

$\lambda$  is the wavelength (m)

$f$  is the frequency ( $\text{s}^{-1}$ )

This experiment is divided into two parts investigating standing waves and measuring the speed of light.

## Part 1a) Investigating standing waves with a slinky spring

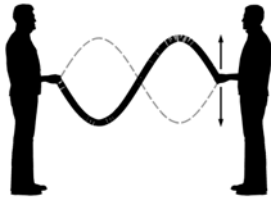
### Materials

- Slinky spring

### Method

1. Two people each hold an end of the spring (as shown in the diagram) stretching it a little.
2. One person holds their end still while the other person oscillates it up and down until a standing wave is formed like that in the diagram.
3. The person moving the spring is putting in the energy and forming a wave of set frequency and wavelength.
4. This wave travels to the other person's hand and is reflected back  $180^\circ$  out of phase.
5. The reflected wave and the incoming wave interact forming a standing wave.
6. This is what occurs in a microwave oven.

Hint: sometimes putting a spring on a floor or a bench will work better. By moving the spring sideways you may get a better result as gravity has less effect.



**Diagram of the creation of a standing wave**  
*Image courtesy: DUIT Multimedia*

### Concept understanding - standing waves

1. Draw a standing wave, as shown in the diagram, and label the following:
  - the nodes,
  - the antinodes and
  - the wavelength.
  
2. Which part of the standing wave can you hold without energy being transferred to your hand?
  
  
  
  
  
  
  
  
  
  
3. What happens if you try to grab the antinodes? Explain in terms of energy transfer.

5. In terms of wavelength, what is the distance between the antinodes?

## Part 1b) Investigating standing waves with 10.1 Standing waves explorer

The electromagnetic radiation produced in a synchrotron is propagated as a wave and interacts in the same way that any two mechanical waves interact with each other.

A special kind of interaction occurs when two travelling waves, of the same wavelength, are moving towards each other from opposite directions. This creates what is known as a standing wave where the nodes and antinodes remain in a fixed position in space.

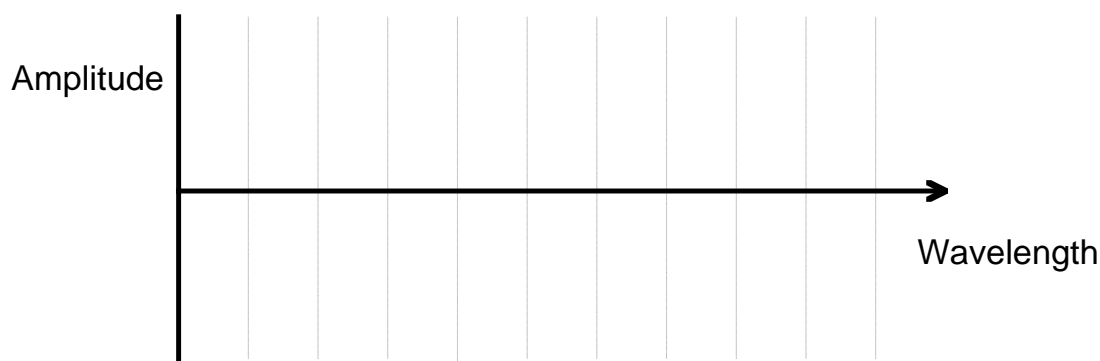
Microwaves produced in the microwave oven are all the same wavelength. They are reflected back and forth off the internal metal surface of the microwave oven. This environment creates the condition needed for the microwaves to interact and form standing waves within the microwave oven. In other words, two travelling waves of the same wavelength are moving in the opposite direction though each other.

Open the learning object *10.1 Standing waves explorer* and select the correct screen by following the instructions below.

1. Open *Standing waves explorer*
2. Set the amplitude of both *A* and *B* to *maximum*.
3. Set the wavelength of both to the same *maximum* value.
4. Select *reverse wave* direction.

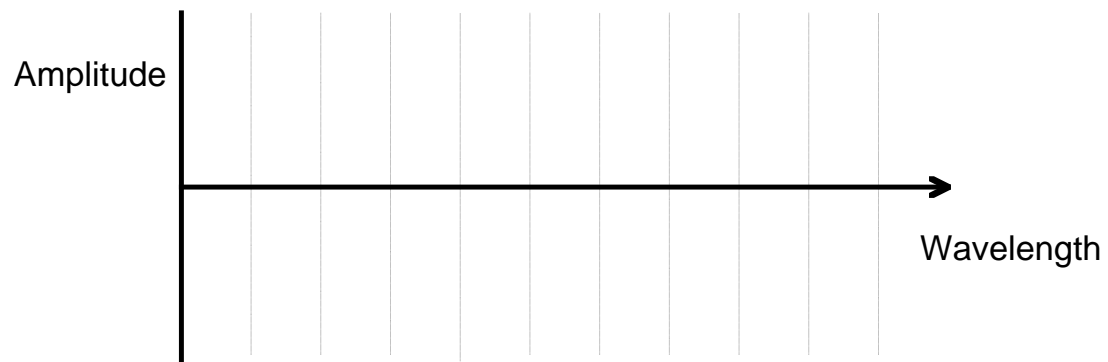
### Investigation

1. The waves are travelling in the same direction, and are in phase with each other. What does the resulting wave look like? Sketch it. (Use the gridlines on the phase explorer to help you plot it.)



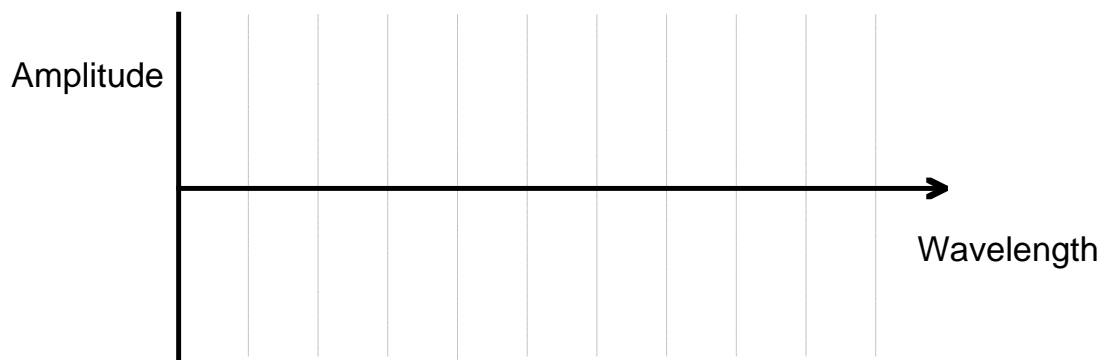
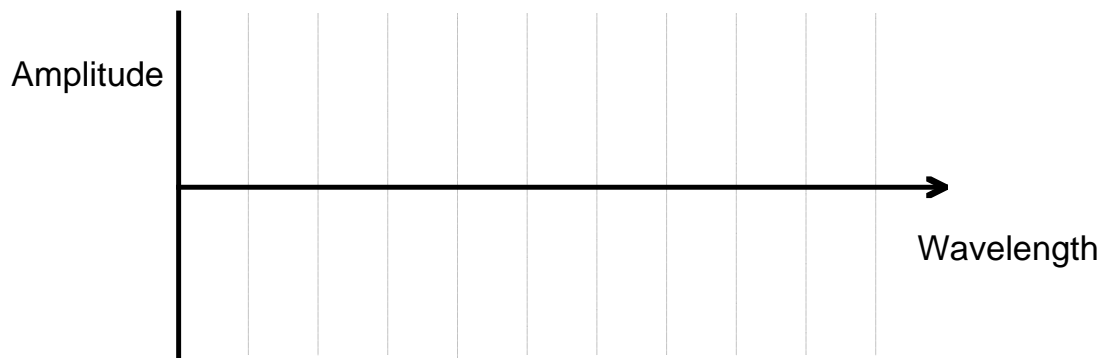
This is **constructive interference**.

2. Change the phase to half way (out of phase). What happens to the resulting wave? Sketch it.



This is **destructive interference**.

3. In a microwave oven the wave is reflected back off the walls of the microwave. Select **reverse wave direction** to see what happens. Using the pause button, sketch **A+B** at three different times so that your diagram shows the range of movement of the combined waves: when the combined wave is flat, when it has maximum amplitude, and when it has maximum amplitude in the opposite direction.



These **standing waves** are set up in fixed positions in the microwave oven when it is running.

4. On all of your sketches label the nodes and antinode positions.
5. Then label where you think the cool and the hot spots would be in a microwave oven.



6. In terms of wavelength, what is the distance between hot spots?
7. What problems could this phenomena cause when food is being cooked in a microwave oven?
8. Explain two ways of overcoming these problems.
9. Use the *Standing waves explorer* to find out what effect changing the phase has on a standing wave?  
(You will need to unclick *Reverse Wave Direction* to change the phase.)

## Part 2 - Measuring the speed of light

### Materials

- a microwave oven
- a microwave safe dish at least 30 cm in diameter (bigger is better)
- one of the following: mini-marshmallows, chocolate chips, pappadums, grated cheese or any food that melts (choc chips work the best)
- ruler
- calculator

### Method

1. Cover the bottom of your oven proof dish with a thin layer of the food.
2. Remove the entire turntable from the microwave.
3. Put the oven proof dish in the microwave.
4. Cook on low heat for 30 seconds. The microwave will not heat evenly after the removal of the turntable and the food will begin to melt or cook at the hottest spots in the microwave.
5. Open the door and without removing the dish check that melted spots have appeared. If they have not, close the door and heat again for short bursts until they do appear.
6. Carefully remove the dish and measure the distance between the melted spots.
7. You should find that one distance appears over and over. This distance will correspond to half the wavelength of the microwaves used in your oven.
8. Record this information in your data table.
9. Now, turn the microwave around and look for a small plate or sign. This will inform you of the microwave's frequency. Most commercial microwaves operate at 2458 MHz.
10. Check this value and record it in your data chart.
11. Use your data to calculate the speed of light.
12. Calculate the percentage error in your result using the value of  $c$  as  $299792.458 \text{ km s}^{-1}$  (you may need to convert so the units are correct).
13. Now eat your experiment. Don't burn yourself!

### Data Table

Group	Wavelength (m)	Frequency ( $\text{s}^{-1}$ )	Speed ( $\text{m s}^{-1}$ )	Percentage error