IMPS ENGINEERING LAB--Device testing

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Now it is time to test the "IMPS chip" you made. You will be provided with a variety of test equipment. This handout is primarily a set of tutorials and condensed manuals for this equipment; it is up to you to decide what your device is to be used for and how to connect and test it for this use. Perhaps you already have ideas; if not, think about it in light of the manuals below and then discuss it with one of the lab assistants. Some of the manuals have some suggested measurements (indicated with a bullet •) to get you going; also as an introduction, we suggest that you all make "measurement 1" (electrical) and/or "measurement 2" (optical) below. Note that while we've tested a couple of potential applications, there are *many* things you could do with your "chip" which we haven't tested out; part of the fun of this lab is just that--this is not a pre-programmed lab where we've worked out all the bugs. What you decide to try may not even work, but that's ok as long as you write about why you thought it might have worked and what went wrong.

We suggest you work in groups of three or four; this will allow you to compare results and ideas with classmates. In addition to testing your results in small groups, we may try a class wide project to determine the resistance of your devices as a function of thickness ("measurement 1" below). We'll attempt to put together one large plot of resistance versus thickness; each data point will be somebody's sample. Think about this right now: theoretically, how *should* resistance scale with thickness? Our results could be non-ideal because of the non uniform and grainy nature of the thinnest films. Attached is also information on the lab write-up. Grading will be based more on creativity and a demonstrated understanding of the principles and engineering behind the devices than on how well your device works.

If you haven't examined the layout file (IMPS01layout.pdf), now would be a good time to do so. You will need to zoom in with the magnify tool to see what is going on.

Good luck. By the way, what is that triangle mystery device, anyhow (it *is* a solid triangle)? And why are its four lower contact pads spaced the way they are?

Initial Experiments suggested for all students (italics refer to manuals below):

Measurement 1 (electrical): Use a *digital multimeter* to measure the resistance (in ohms) of each side of Device B (e.g. between the two square pad terminals closest to the triangle device) and of Small Device B. How do they compare? Are they as you would expect from the geometry (if not, there may be a lithographic defect)? Now have a TA help you measure your film thickness using the step *profilometer* (if there is a wait for this, come back and do it later). Finally, calculate the electrical resistivity of your chrome film.

---**AND/OR** (but please let the optical only folks go first on measurement B)---

Measurement 2 (optical): Shine a *laser* through device "Very Small A". Measure the angular separation between the peaks of the *diffraction* pattern. From that, determine the spacing of the lines that make up this device. Be sure to note the wavelength of light from the laser you use.

Equipment Manuals

Film Thickness Measurement using Alpha-Step Profilometer

(you must ask the alpha-step TA to help you with this)

A surface profilometer measures the thickness of vertical steps on an object. A stylus scans a single line across the surface of the object, moving up and down over the metal lines or other features. As it moves up and down, a voltage is generated by a piezoelectric element. This voltage is proportional to this vertical motion, and is plotted with the attached strip chart recorder. The resulting plot is of the height of the sample versus distance across the sample along the scan line. Our profilometer is sensitive to step heights from a hundred angstroms to several microns, depending on the amplification set by the "full scale" knob. Be sure to write down this full scale value--it tells you the height that you would have if the pen went the full ruled distance of the chart paper. Also write down the horizontal scale factor--if it is 50x, that means that a 1mm line across your sample would take 50mm (or 5cm) of chart recorder paper. •You might want to compare your metal thickness to that of others who pre-etched their sample a different amount [or if you made a glass-only sample, compare the depth of your glass etch to $\lambda/2$ (for some optical light wavelength) and to that of others who etched in HF for a different amount of time]. •Is resistance of a wire correlated to the thickness of a film? •Is there some fundamental property of the metal film (independent of thickness, line width and length) which you can measure? •What about the strength of a wire against burning out; does that depend on thickness?

Microscopy

You will have available at least a stereo zoom microscope or two and a video microscope. Focus and zoom knobs will be marked. With the video microscope you can record images as PICT or TIFF files and email them to yourself. Instructions for doing this and for adding scale markers to your photos will be next to the microscope. •You can make measurements of line widths and spacing and compare them to the L-Edit design file; deviations can be due to processing conditions (in our case they are mostly due to the printer we used to make the film). Such "critical dimensions" are very important to characterize in the semiconductor industry--how well your computer works depends on the ability of engineers to reproducibly get the line widths they want! •You might be able to destroy a device electrically (now, why would that be interesting?) and then look at it under the microscope.

Digital Multimeter (Fluke 45 or Keithley 169)

You have seen a digital multimeter already in your DC circuits lab; much of this section will be a review. It can measure electrical potential (VOLTS), current (AMPERES), or resistance (OHMS). Two wires connect the multimeter to metal probes, which in turn can be used to contact your circuit. One probe is black (LO, COM, or negative), the other red (HI or positive).

KEITHLEY: The AC/DC button should be out to measure DC. You need to select a full scale range appropriate to the measurement you expect (e.g. for a 9V battery, press the third dark brown button to select a 20V full scale range).
FLUKE: AC is indicated by ~, DC by --. The meter is auto scaling.

VOLTMETER: Press the V (or V--) button, and connect the leads across your circuit to measure DC volts. • As a review, check the "voltage", i.e. the electrical potential across the transistor radio battery (a nominal 9 volts) and determine which battery terminal is positive. Some batteries have a resistor connected to one terminal. • If you measure the voltage between the free battery terminal and the free end of the resistor, you will also see the full battery voltage, but if you take that free end of the resistor and touch it to the other battery terminal, the voltage you measure will decrease a little. • Why is this? You may use the voltmeter as part of a 4 point resistivity measurement (described below).

OHMMETER: Press the Ω button, and connect the leads across your device to measure DC resistance. The meter will attempt to force a current through the leads and your circuit, measure the resulting voltage drop, and display the resistance as calculated by ohm's law. •You can use an ohmmeter to check which parts of the device you made are connected together (low resistance), and which are isolated from each other. With the smallest devices, is possible that two features that should be isolated are actually shorted together due to a defect in printing the master film. Check for this.

AMMETER: Press the A (or A--) button.   DO NOT place the ammeter across the battery or power supply. To measure DC current in your circuit, you must break a connection in the circuit and insert the ammeter.   Consider the circuit of your battery connected to each end of a resistor. To measure the current, disconnect one end of the battery from the resistor and connect one ammeter lead to the free side of the battery and the other to the free side of the resistor. You may use the ammeter as part of a 4 point resistivity measurement (described below).

Power Supplies

You will have available power supplies that can apply a known DC voltage or current to your devices.

AC Measurements Station

We plan to make available some equipment for measuring AC electrical properties.

Scribe Station

Here you can break your sample into several pieces, or cut through metal lines with a diamond scribe.   You can cut wires on your own, but note that the chrome is so firmly attached that you'll need to scratch through it and into the substrate glass in order to make a good break in the connection.   If you want to break your device into two or more pieces, get help from a TA, and beware of cutting yourself on the sharp glass edges. Also be aware that it is difficult to break off small pieces--there is some risk the sample will not break where you scribe it, but will instead break through the middle of one of your devices. •If you have two pieces with one pattern the same on each, what happens when you put these patterns into contact and shine light through them? What do you expect?

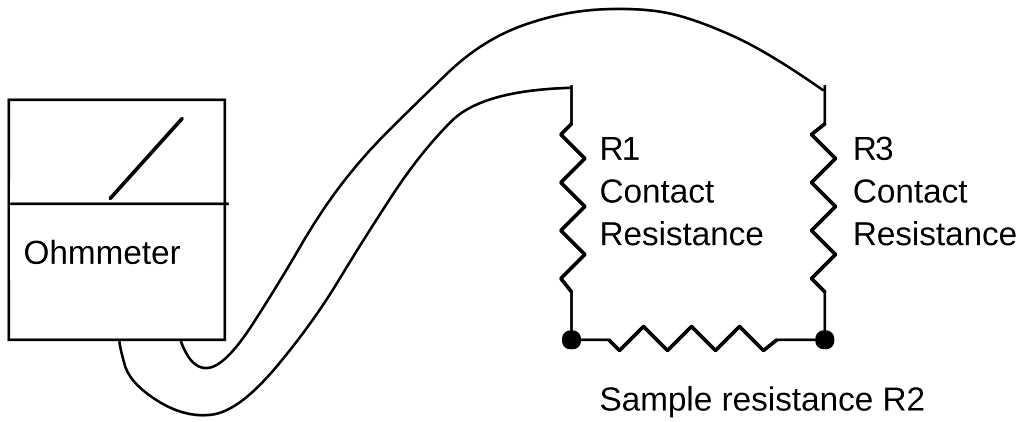
Indium Solder Station (Contacting your device)

In principle, you can just take the probes from the multimeter and push them against the contact pads to make your measurements, but the probes have a tendency to move around. You'll probably get more reliable contacts if you go to the soldering station and attach small blobs of indium to the contact pads. This metal is soft, so you can deform it and make good contact to it with the probes afterwards. Cut a piece of wire about 1-2mm long using the razor blade, then use the soldering iron to attach all or part of it to the contact.

4-point Resistance Technique

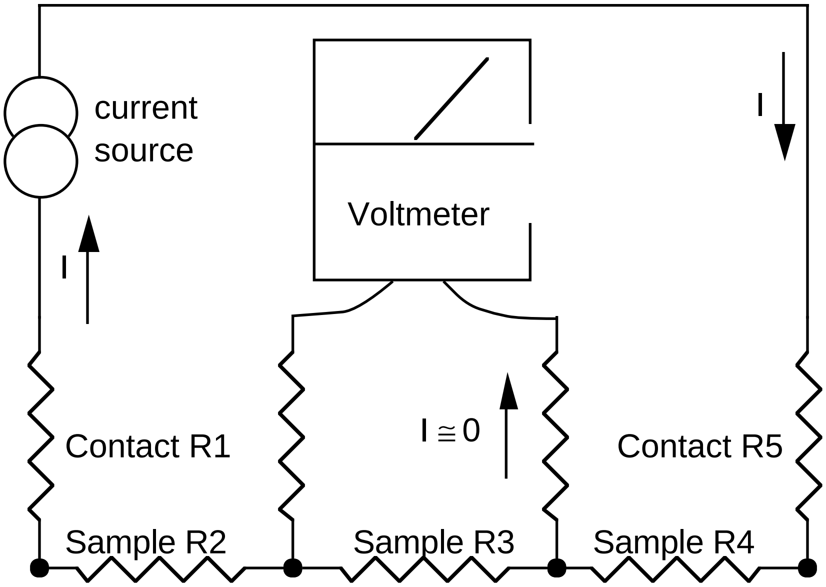
The easiest thing to do to measure the resistance is to hook it up to a multimeter and read off the value. The multimeter puts a voltage across the sample, measures the current, and divides, to give you a value of resistance. This works in some situations, but is not always acceptable. Here's why.

Consider a sample of chrome or silicon, which tend to grow a thin layer of oxide (an insulator, or at least a poor conductor) on the surface. If we take the two probes from the multimeter, we are measuring the sum of three equivalent resistors - the interior of the sample, plus the two contact resistances, as shown below.



Meter measures R1 + R2 + R3 (resulting in large error if R1, R3 >>R2)

What we really want to measure is the sample, not the contacts, and to do this, we use a 4-point measurement, as shown below. How does this get around the problem? In the 2-point measurement, all the current that flows through the sample also must flow through the contact points, and we measure the sum of all the voltage drops. In the 4-point scheme, the current flows through one set of leads, and we measure the voltage across the other set of leads. Since the voltmeter has an internal resistance that is very high, essentially no current flows through this loop. Thus no current flows through the contact resistances that the voltmeter measures across, and the only voltage contribution is from the current flowing through the sample itself.



The voltmeter contact resistances generate no voltage; only sample R3 is measured.

Note that if the contact resistances are very high, unless we use a high voltage power supply, we will get very small currents in the sample, and thus low voltages (hard to measure!) across the sample resistance.

Thermoelectric Peltier Cooler

A thermoelectric cooler is a solid state refrigerator. When current is forced through it in one direction heat is pumped from the top stage to the lower heat sink stage, thereby cooling the top stage. When the current is reversed, the top stage is heated. The physics is just the reverse of that in a thermocouple junction; in both cases a wire is broken and another wire made of a different metal or semiconductor is spliced in, thereby creating two junctions. In the case of the thermocouple, a temperature difference is applied between the two junctions, and a potential difference results. In the case of a Peltier cooler, a potential difference is applied and a temperature difference results. Both make use of the fact that the electrons (or "holes") which are conducting heat are also those that conduct electricity, so one can affect the other. (There is an article on Thermoelectric materials/devices in an issue of Physics Today, a magazine for professional physicists [G. Mahan, B. Sales, and J. Sharp, Physics Today, **50**, 42, March 1997.)

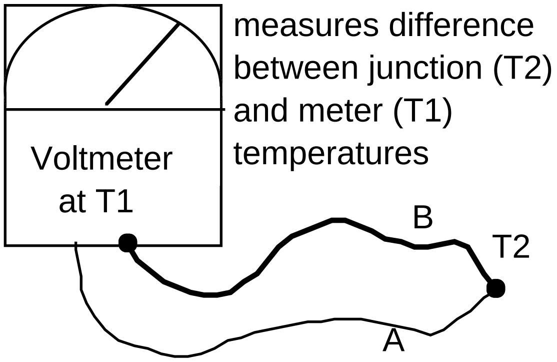
•The Peltier cooler can be used to cool your device. Use some heat sink compound (grease) to stick your device down to the upper plate, centering the part you want to cool. Connect the red lead to the positive power supply and the black to the negative. Do not drive more than 1.5 amps of current through the cooler. It may take several minutes to obtain a temperature change of about 20˚C.

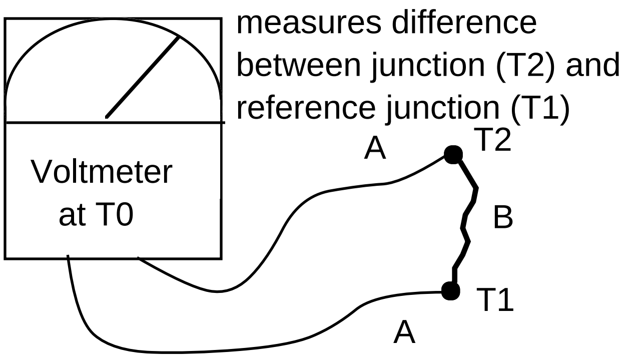
You can monitor the temperature of the stage with a thermocouple junction, however during cool down the stage will be significantly cooler than your device because the thermal conductivity of the glass is poor.

What happens when warm moist air is in contact with a cold object? Some VCR players disable themselves when you bring them in from the cold. They flash a 3 letter word on the display. The sensor that invokes this condition looks much like the sensor you have made.

Thermocouple Junction (Temperature measurements)

There are several ways to measure temperature that are used routinely in laboratory experiments. A simple mercury or alcohol thermometer is one option, or a bimetallic strip in a coil, like a typical dial thermometer. Each of these causes a visible indication of the volume change the materials experience as their temperature changes. While these are reliable sensors, they require an observer. Temperature sensors that give out an electrical signal related to their temperature allow us the luxury of connecting another bit of electronics, a chart recorder, to measure the temperature as a function of time on a continuous basis. Or, one can take the electrical signal and feed it into the computer, and get a plot of temperature vs. time, or measure other signals and correlate the temperature change with some other property. The most common electrical temperature sensors are thermocouples and thermistors. Thermocouples are passive devices that generate a voltage difference when two metal junctions are held at different temperatures, as shown in the figure below:





A crude picture of the origin of this voltage is that the electrons at the hot end of a metal move faster than those in the cold end, and you can get a ‘pileup’ of electrons at the cold end, making that end more negative than the hot end. The amount of electron separation that develops depends on the material. Since both ends of the voltmeter are at the same temperature, we have to rely on a difference in voltage generated by having two different metals in our sensor. So the voltage we measure will be a difference in the voltages that each material tries to set up. The second junction is used to provide a reference temperature, and most tables of thermocouple voltages (vs. T) use 0° C for the reference temperature. If you skip the reference junction, you will measure the voltage difference between the probe and room temperature; you can use a thermometer to determine room temperature, and add the equivalent voltage to your reading to make it compare with the chart. Be sure that your temperatures are in the same kinds of degrees as the chart!

One of the most common combinations of metals used in thermocouple junctions is Chromel and Alumel, a couple of alloys. The voltage values for this combination are listed on the attached chart for a range of temperatures. (Coincidentally, this is the combination we will use in the lab.) Note the units -- millivolts; you’ll need to think about that when you look at feeding that signal into the multimeter.

Photodetector and Light Source

We will also have available a white light source and a photodetector that will give you a millivolt reading as a function of the light that strikes it. The detector is rather sensitive, and will saturate if too much light hits is, but is quite linear over a pretty good range. There will be a cardboard box to put around the setup if you want to get rid of the effect of ambient light. Can you think of a way to use the light transmission through two IMPS chips to measure something useful? •You can first experiment by just looking through them as you put them into contact.

Salt Solution

Some salt solutions will be available in dropper bottles. •How might contact with salt water change the properties of your device? Could you make something useful of this effect?

Lens Manual

You will have some lenses available to you for use with the optics. Lenses are primarily used for concentrating light to small areas and for imaging purposes. For thin lenses (i.e. a lens whose thickness is considered small in comparison with the distances generally associated with its optical properties) it is sufficient to know its diameter and its focal length. The focal length can be defined as the distance behind the lens at which all parallel incoming light rays are focused, see fig.5.

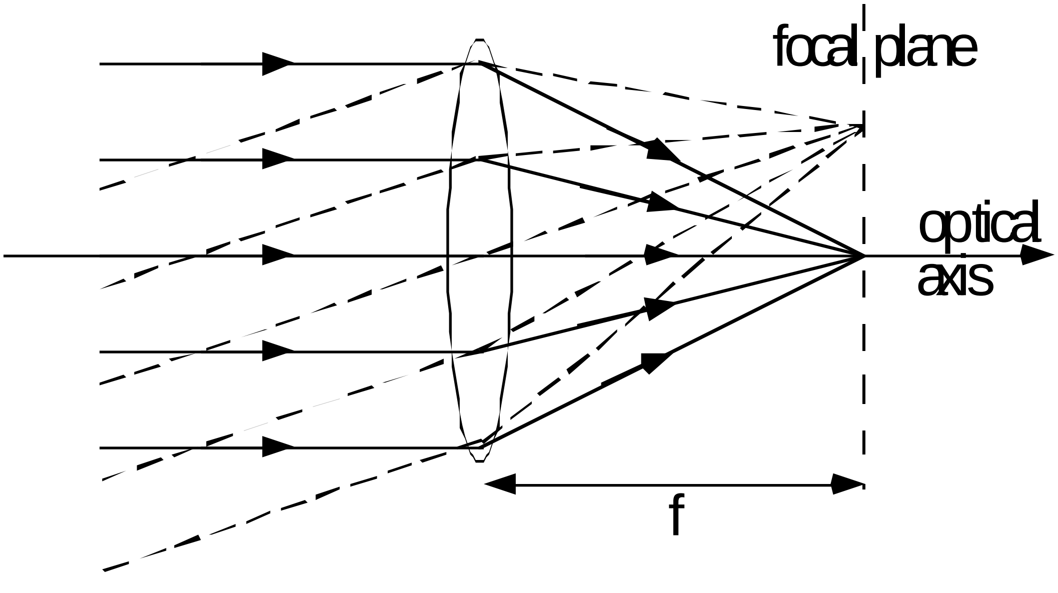


Fig.5

An easy way to determine the focal length of a lens is to illuminate it with a collimated light beam (i.e. the light rays are parallel, just like in the figure above) and observe with a moving paper at what distance the light produces a minimum spot. This lens to paper distance is the approximate focal length. The laser beam we will use is slightly diverging; it can be collimated with a lens.

Laser Manual

Several lasers will be available to you, including both red and green helium-neon lasers and a laser pointer.

DANGER: Laser radiation can damage your eyesight. NEVER look directly into a laser beam or a reflection of a laser beam. Keep the beams in a low plane (benchtop level) and your eyes well above this plane. Beware of reflections off your glass slide or your watch. Ask for clearance from the instructor before you use the lasers, particularly the green helium neon laser.

The laser beams can be used as very small beams (for illuminating single slits and the like), or expanded to about a 1cm collimated beam with lenses (for illumination of larger elements). •Would any of your devices make an interesting addition to a laser pointer? If you were to redesign our "chip", what shapes might you use to make it even more interesting? Is it better to use "shadows" or "diffraction"?

Following ref.2 we note the following specifics about laser light versus other light.

- <u>Monochromaticity</u> – Lasers produce very pure colors. For light to be completely monochromatic is, in principle, impossible however a laser beam comes very close to being monochromatic. For the He-Ne laser we will be using in the lab the spectral purity will be approximately $5 \cdot 10^{-6}$. The spectral purity is estimated by taking the ratio of the range of frequencies $\Delta\nu$ (bandwidth) the laser is emitting to its carrier frequency ν_0. For our laser, $\Delta\upsilon \approx 10^9$Hz and $\upsilon_0 \approx 5 \cdot 10^{14}$Hz.
- <u>Coherence Length</u> – Due to the laser's small bandwidth it takes a long time for these frequencies to get out of phase. The distance over which these frequencies have to travel before they are out of phase is the coherence length $l_c \approx \frac{c}{\Delta\upsilon}$ which for the laser in the lab is approximately 20cm. Lasers with coherence lengths of tens of kms can be bought commercially.
- <u>Spectral Brightness</u> – Has to do with how much light intensity can be obtained per area, bandwidth, and solid angle from a particular source, units are [W/cm^2·sr·Hz]. For sunlight the spectral brightness is approx. $1.5 \cdot 10^{-15}$ W/cm^2·sr·Hz for the low power lab laser it is 25 W/cm^2·sr·Hz.
- <u>Directionality</u> - Lasers can deliver nearly ideal plane wavefronts, only diffraction imposes a lower limit on the angular spread of a laser beam. $\Delta\theta$ for our lab laser is about 5 mrad.

Diffraction

A tutorial is below. The main results you need to remember are that

* Small features diffract light. The smaller they are, the larger the angles of diffraction. The amount of diffraction also depends on the wavelength of light used.

* The more lines in a diffraction grating, the sharper the diffraction peaks

* The line spacing (or, better, the spatial frequency in lines per millimeter) determines the diffraction angle--higher spatial frequency (smaller spacing between lines) results in a larger angle.

* The width of the individual slits determines the envelope function which controls the relative brightness of various diffraction orders.

Diffraction Tutorial

Light can often be described as propagating in straight lines (ray optics). This approximation works fine as long as the dimensions of the optical elements are quite large compared to the wavelength of light ($0.4\mu m < \lambda < 0.8\mu m$). For obstructions that are smaller than approx. 100μm the light starts to deviate from its rectilinear propagation and its true wave character manifests itself as diffraction. To analyze diffraction we need the wave equation

$$\nabla^2 U - \frac{1}{c^2}\frac{\partial^2 U}{\partial t^2} = 0$$

where U is the amplitude of the light wave and c is the speed of light in vacuum. This partial differential equation is *linear in U* which means that if U_1, U_2, U_3, and so on are solutions to the wave equation, so is the *linear superposition* $U = U_1 + U_2 + U_3 + \ldots$. The fact that several waves can add together in a point to produce a new wave gives rise to interference. We can think of interference as occurring when a finite number of waves (typically 2-3) are being added together. Diffraction is an interference phenomena involving the superposition of "thousands" of infinitesimally small waves. What we usually observe is not the amplitude of the light, but its intensity $I = |\psi|^2$, measured in [Watts/cm^2]. We can use the linear superposition approach to derive formulas for how this intensity varies on the other side of an obstruction. For the purposes of this lab, we choose to calculate the diffraction pattern that arises when monochromatic[1] plane parallel light is incident on a narrow slit, a double slit and N slits. Imagine the slit divided into very many narrow sections parallel to its length and each section becomes a narrow line source of secondary waves (wavelets), see fig.1. This idea is originally from Huygens.

For light of wavelength λ propagating along the x-axis, the electric field oscillation is given by $\exp[i(2\pi x/\lambda - \omega t)]$. For light propagating in an arbitrary direction, we define a vector k which points in the direction of propagation and has a magnitude of (2π/λ), and neglecting the time dependence we have for the input light

$$E = E_0 \exp[i(\bar{k} \cdot \bar{r})]$$

We have used the dot product between k and the position vector r to force propagation of the wave along k. Note how this reduces to the familiar case above when k has only an x component. Consider a narrow segment of the slit Δs located a distance s from the axis of the slit, it acts as a source of spherical waves of the form

$$\Delta E = \frac{E_0 \Delta s}{r} \exp[i(\bar{k} \cdot \bar{r})]$$

where $\left|\bar{k}\right| = \left|\bar{k}\right| = \frac{2\pi}{\lambda}$. In a specific direction θ the phase of a ray emitted from a segment Δs at s differs from that of a ray through 0 by an amount

$$\frac{2\pi}{\lambda} \cdot s(\sin i + \sin\theta)$$

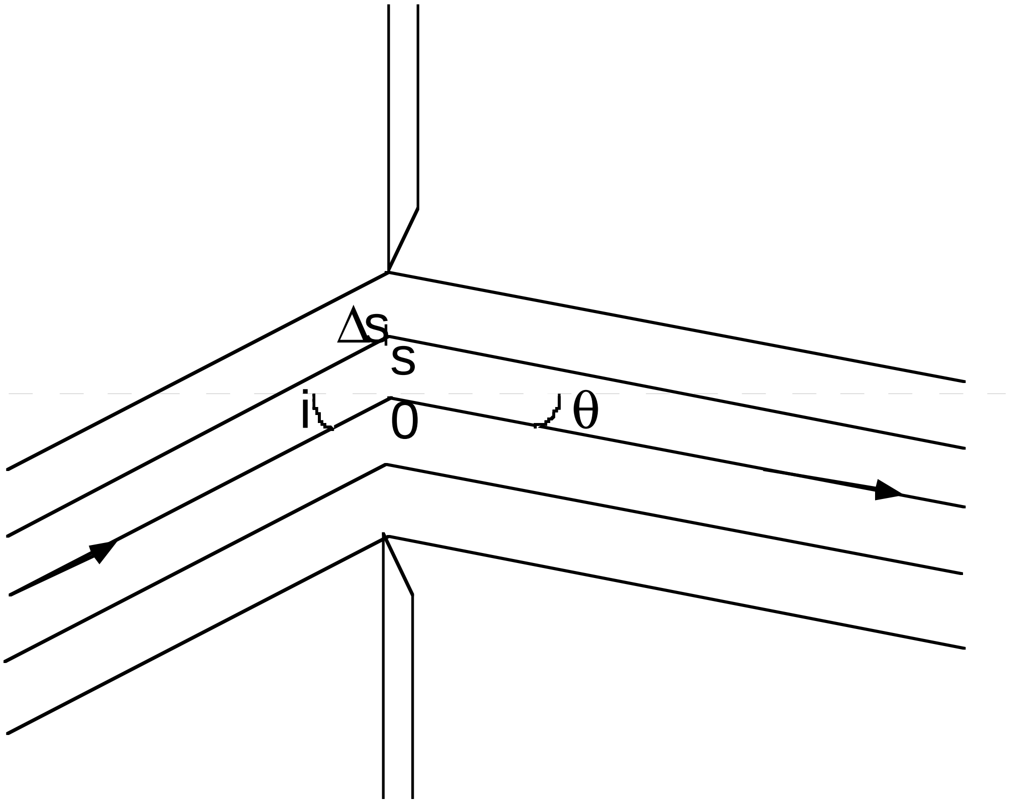


Fig.1

This assumes that the incoming plane wave is incident onto the slit at an angle i; for perpendicularly incoming light we would have i = 0. Relative to the central ray through 0 we can write the amplitude arising from an arbitrary segment located at s as

$$\Delta E = \frac{E_0 \Delta s}{r} \exp[i(\bar{k} \cdot \bar{r})] \exp[i \frac{2\pi s}{\lambda}(\sin i + \sin\theta)]$$

and the total signal amplitude leaving the slit is the sum over all the segments Δs. In the limit $\Delta s \cap 0$ we find at an arbitrary distance from 0 in the θ direction that the field amplitude can be expressed as

$$E = E_0 \cdot d \cdot \frac{\sin \frac{Kd}{2}}{\frac{Kd}{2}}$$

where *d* is the full width of the slit and $K = \frac{2\pi}{\lambda}(\sin i + \sin \theta)$. The diffracted rays leave the slit as parallel beams and if we place a lens immediately after the slit the diffraction pattern is formed in the focal plane and can be observed on a screen as indicated by the Fraunhofer pattern in fig.2.