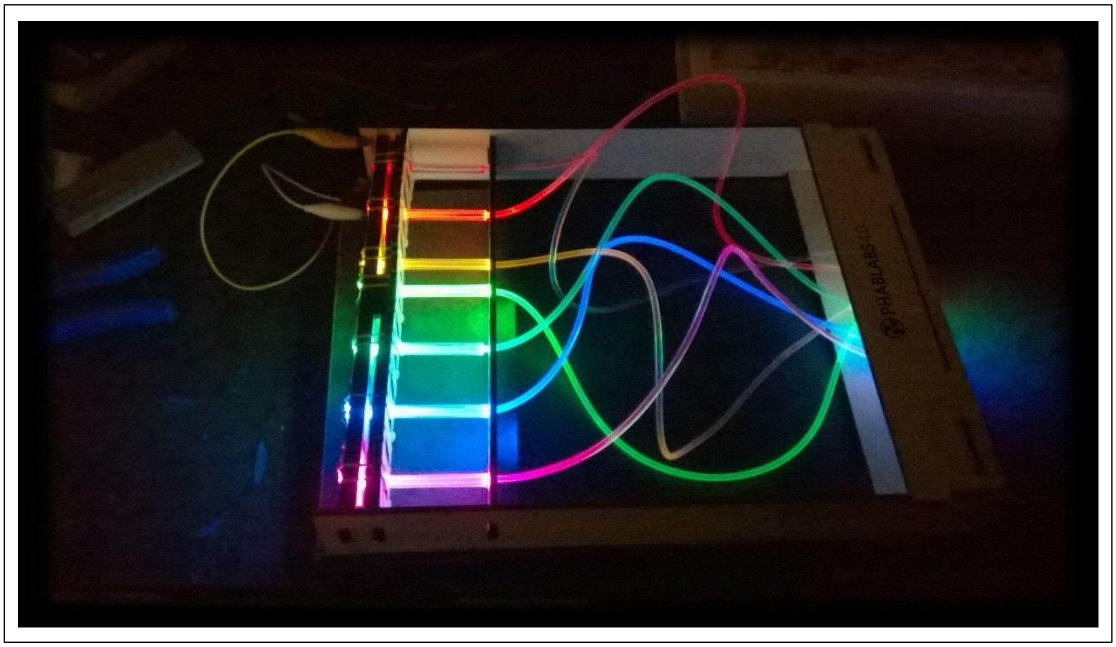
Photonics Piano
- instructor's guide -

Title of the workshop: Optical fibers and music: the photonic piano

Goal of the workshop: Building a "piano"-like device where sound is at first replaced by colored light which is guided and diffused by optical fibers. Conversion of light into sound can be further implemented exploiting commonly available technology.



Target audience: Professionals (>18 years old)

Time planning:

Timing In hours	Activity
0-0.5	Welcome group: Give a short introduction of the topic of the workshop
0.5-1	Familiarizing with optics and photonics, specifically about refraction and optical fibers
1-7	Fabricating the tools
7-7.5	Playing with light
7.5-8	Closing summary and feedback

Part list for each Photonic Piano

Component	Specifications	Quantity
MDF sheet	30cmx35cm, 4mm thickness	1
Optical fibers	Diffusive fibers, 3mm diameter	5m
Plastic/acrylic tubes	internal diameter: 3.5mm; external diameter: 6mm	0.8 m
Rubber bands	Diameter: 2-5 cm	12
LEDs	Colored	12
Resistors	230 Ohm	12
Resistors	390 Ohm	12
Vinylic Glue		1
USB cable	2 m	1

Estimated cost: 30 €

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Introduction to the workshop

Here we briefly introduce the technology of light that will be involved in the construction of the photonic piano.
In the piano, an LED produces an intense light (white or colored). When an optical fiber is placed in front of the LED, some light is captured by the fiber (technically, it is said to be **coupled** into the fiber) and transmitted to its other end, which occurs even when the fiber is bent or very long. On the contrary, when the fiber is not in front of the LED, no light is coupled, and at the other end no light is seen.
In an ordinary piano, when a key is pressed, a sound note is produced. From the simple concepts of transmission through an optical fiber, we can build a very colored and fascinating photonic piano. In the photonic piano the keys are optical fibers: when a key is pressed, we switch the light at its other end.

Orange key is pressed

Green key is pressed

The effect is mainly visual, no sound is produced. However, if the light from the fibers is recorded by a camera or detected by an optical detector and sent to a computer, it is possible to translate the light into sound.

Activity by instructors

I. The instructors should first illustrate to the audience the **main physical processes** at the basics of the "piano" behavior. These concepts are:

- The **refractive index** of transparent materials
- The concepts of **reflection and refraction**
- Total **internal reflection**
- How a **waveguide** works

II. The light is produced by some LEDs: the participants will be very familiar with the LED as a source of light, but maybe they know nothing about how it works, and how to use it in a circuit. For this reason, the instructors should provide a brief **introduction about LEDs** and the design of a working circuit required to power them.

III. Finally, the instructors should stress the **potentiality of light transmission with a fiber**, and of the photonic piano itself:

- A fiber allows to transmit a signal over **<u>long distances</u>**, even when a fiber is bent
- The piano of the workshop produces light at its other side when keys are pressed. Now, if we let this light propagate from the piano to a friend, we are able to transmit our melody to our friend. If she/he is very far, he will never be able to hear you, but he could see the light, and **<u>see your melody</u>**. This transmission occurs simply thanks to light propagation, which is **<u>energy saving</u>** since it occurs without any additional energy expense or electrical transmission line.
- This may also be very important for **<u>hearing-impaired</u>** people: the piano allows to make sound totally visual, and accessible also to them
- The piano can be the first module of a more complex system, which **<u>integrates technologies</u>** from very different fields. For example, by using the camera of a smartphone one could design an app which is able to capture the light from the piano, decode it and translate light back into sound; or by adding some photodiodes at the end of the fibers and an Arduino/Raspberry module. Note that the piano is **<u>powered by a USB cable</u>**: this also is part of the *integration* idea. The LED circuit is designed to work with a 5V power supply, which is now widely spread since it is the standard voltage of any USP device. Hence the piano can be easily powered by the USB port of a pc, by a USB charger, or by a portable USB power bank.

The concepts of points I. and II. will be given in the following sections.

Introduction to Optics: Refraction, Reflection, LEDs

1.1 The refractive index

The refractive index of a transparent medium is the ratio between the speed of light in vacuum and in the medium. This number indicates how much the light is slower in that medium with respect to the vacuum. For example, the refractive index in water is $n_{water} = c/v_{water} \approx 1.33$, in glass $n_{glass} = c/v_{glass} \approx 1.52$, in plexiglass $n_{plexy} = c/v_{plexy} \approx 1.49$.

1.2 Reflection and refraction

When light hits the boundary between two materials with different refractive indices, two things happen:

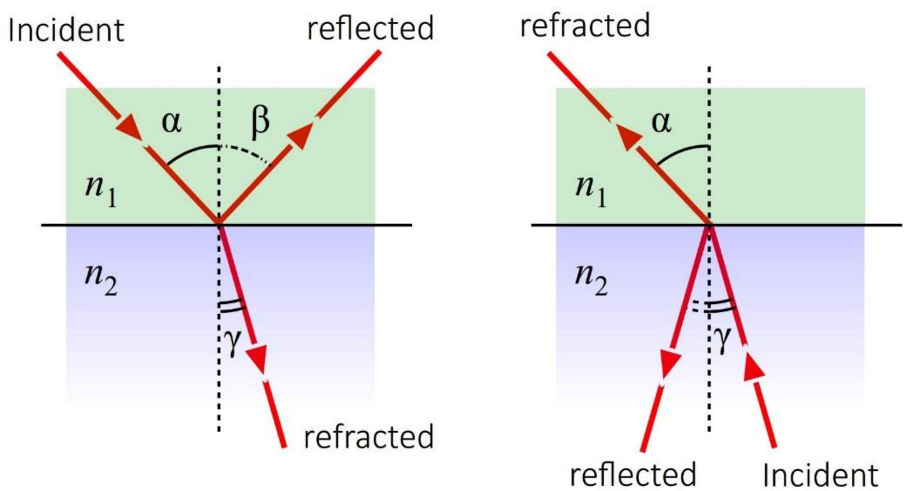
(a) Reflection: part of the light is reflected back with a reflection angle identical to the angle of incidence. Typically, all propagation directions are measured from the direction normal to the surface. In this case, referring to the next figure:

$$\alpha = \beta$$

(b) Refraction: the rest of the light crosses the boundary and is transmitted in the second medium. The transmitted beam changes its propagation direction, and this change is what we call refraction. The new propagation direction, the refraction angle γ is related to the incident angle α by the "Snell's law":

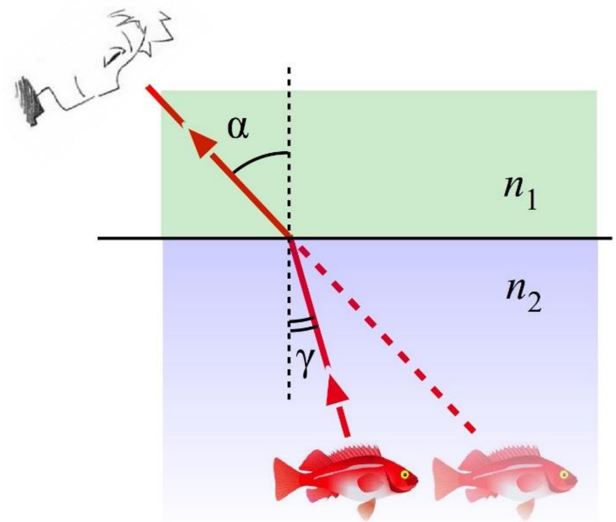
$$n_1 sin\alpha = n_2 sin\gamma$$

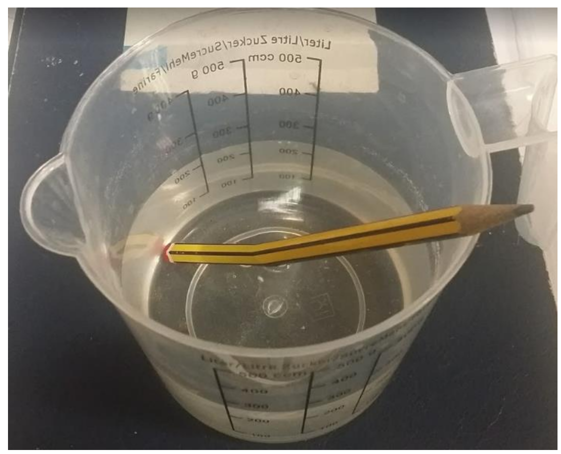
The beams and the angles α, β and γ are shown in the following figures, for the case in which $n_2 > n_1$.



Note that if we reverse the beam propagation (see the right figure), incident and refracted beams follow the same path, but in the opposite direction. In addition, angles α and γ obey the same Snell's law. In the figure at the left, the beam propagates *from lower to higher refractive index*, and the transmitted beam is refracted towards the normal line; in the figure at the right, the beam propagates *from higher to lower refractive index*, and the transmitted beam increases its angle from the normal line.

Refraction is also responsible for the fact that when we observe an object in water, the object seems in a different position: this is because the light from the object gets deflected by refraction, while our brain tends to locate the objects by prolonging the rays propagating towards our eyes. This is sketched in the following picture, where refraction creates the illusion that the fish is along the dashed direction.

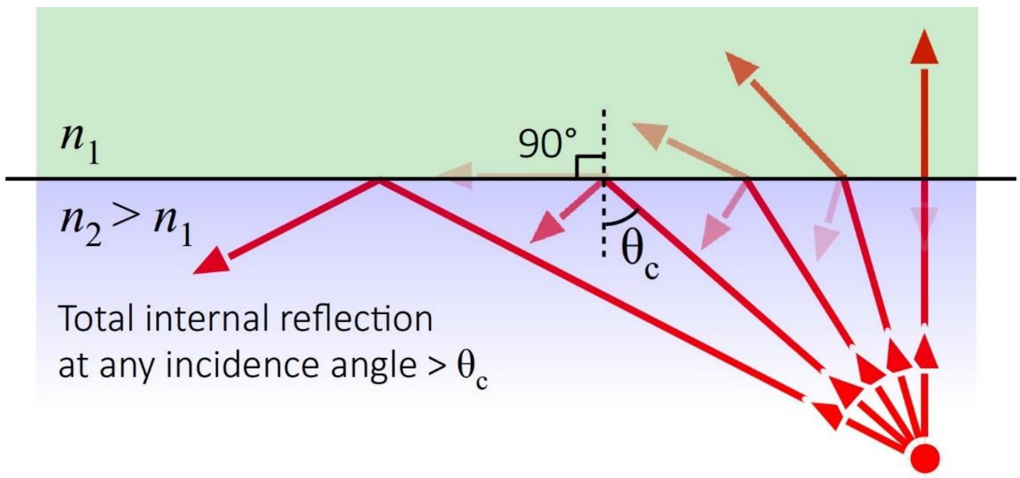




This effect explains why a pencil immersed in water appears to be "broken"

1.3 Total internal reflection

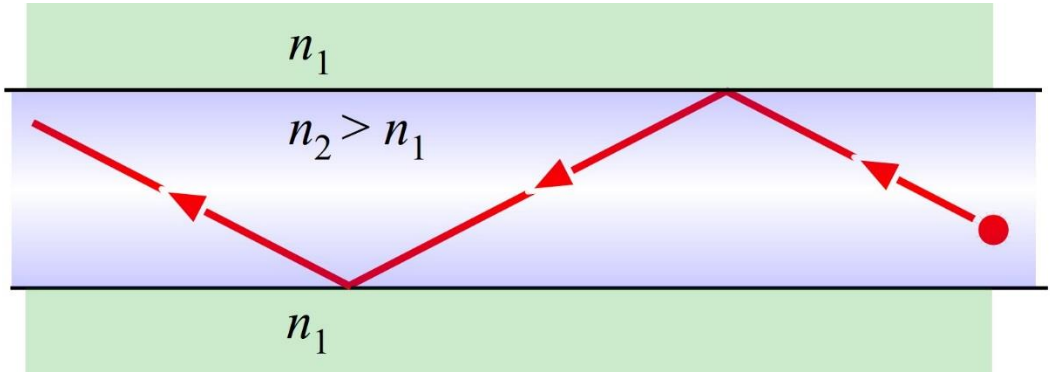
As we have discussed, when light hits the boundary between two materials with different refractive indices, it is split into two rays, the *reflected* and the *refracted* one respectively. The total amount of light is preserved, but which ray is brighter, the reflected or the refracted one?
The splitting ratio between reflected and refracted depends on α and on the refractive indices, n_1 and n_2. Let's estimate this splitting ratio when light travels into a medium with smaller index of refraction. In this case, according to Snell's law, the refracted angle is greater than the incident angle, which means that the ray is bent away from the normal and towards the surface.
Concerning the energy, the closer is the refracted ray from the surface, the smaller is its power. This is schematically sketched in the next figure:



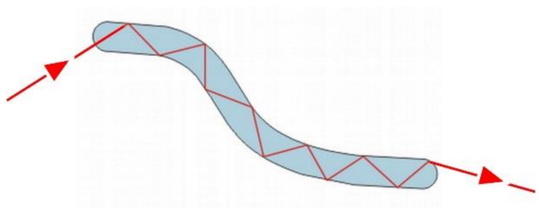
What happens when the refracted angle approaches 90°? And when it is larger than 90°? In this case, the refracted light is negligible, and all the energy of the incident light goes into the reflected ray. This process is called "total internal reflection", and the surface separating the two media acts as a perfect mirror. From this observation, we can also easily calculate the critical incidence angle θ_c at which the refracted beam direction approaches 90°. The critical angle can be calculated from Snell's law by setting the refraction angle equal to 90°:

$$n_1 sin90° = n_2 sin\vartheta_c \quad \rightarrow \quad sin\vartheta_c = \frac{n_1}{n_2}$$

Total internal reflection is the basic process governing light propagation in fiber optics. Their working principle is illustrated in the next figure.



Any time the beam hits the border of the inner medium (with $n_2 > n_1$), if the incidence angle is larger than θ_c then it gets reflected. In principle light can propagate without energy losses along a fiber which could be several kilometers long.

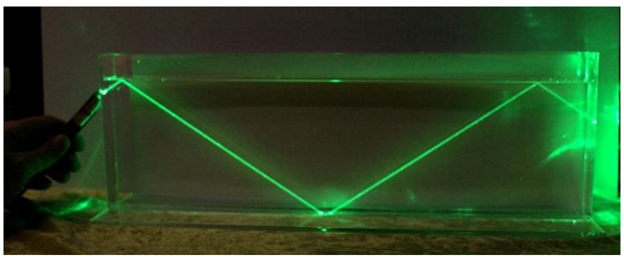


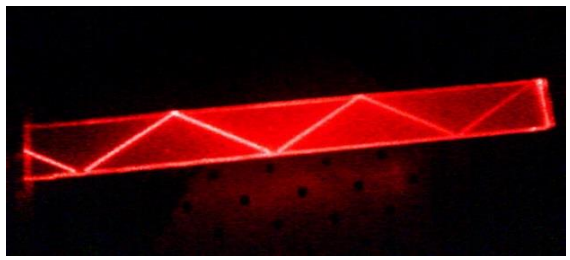
Additional videos and tutorials can be found at these links:

https://www.youtube.com/watch?v=Lic3gCS_bKo

https://www.youtube.com/watch?v=0MwMkBET_5I

The following figures show some examples of multiple reflections of a laser beam in water and in a Plexiglas slab. Such experiments can be easily done by the instructors during the workshop.





The experiment with water can be done with the help of a laser (we recommend a green laser, since it can be better seen) and a fish tank with some water (few-centimeters-deep is more than enough). Put a spoon of salt into the water: this will enhance the visibility of the beam propagating in the liquid. If you shine the beam from outside the tank towards the water surface, you should see the reflected beam and some light should emerge from the surface (remember: never stare directly into the laser beam, therefore to check whether lights emerges from the surface, use a piece of paper and evaluated whether some transmitted light is projected on it). By changing the incidence angle, you will see that the transmitted beam vanishes, and all light goes into the reflected beam. Thanks to the internal reflection, you have just built a mirror…. without a mirror. If the water is not too deep, you should also see that the beam reflected from the surface gets subsequently reflected also by the bottom surface of the tank, and directed back toward the surface. You have just built a liquid prototype of an optical fiber.

1.4 LEDs and resistors

LED/Diode

A **diode** is an *electronic device* which conducts current on **only one direction**, when its positive terminal ("Anode") is connected to the "+" of a voltage supplier or a battery, and its negative terminal ("Cathode") to the "-".

When we connect its terminals the other way round, the diode behaves as an insulator and it does not conduct any current. It conducts electricity like the valve of a tire conducts air: air can be pumped from outside into the tire, but it cannot flow outside.

There are many diodes for all kinds of purposes in electronics; some of them emit light. They are called "**L**ight-**E**mitting **D**iodes", or short "LEDs". In this workshop, you are going to encounter LEDs shining in various colors. They will only **light up** if you connect them the right way (**Anode to "+"**, **Cathode to "-"**), they stay dark (and sometimes they burn) when connected the other way around.

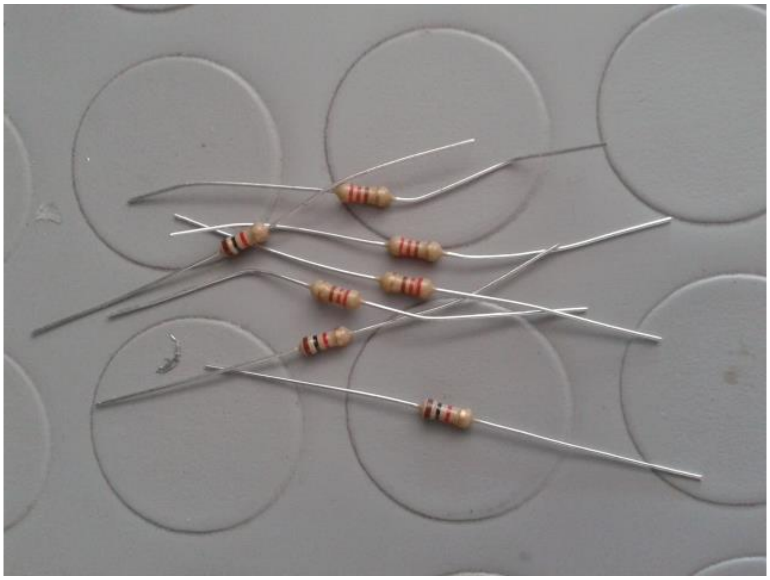
How to recognize the Anode? It is usually the longer terminal wire.

Resistor

A resistor is an electric device which conducts electricity when a voltage is applied to its end connections. The applied voltage V and the transmitted current i are related by "Ohm's law":

$$V = Ri$$

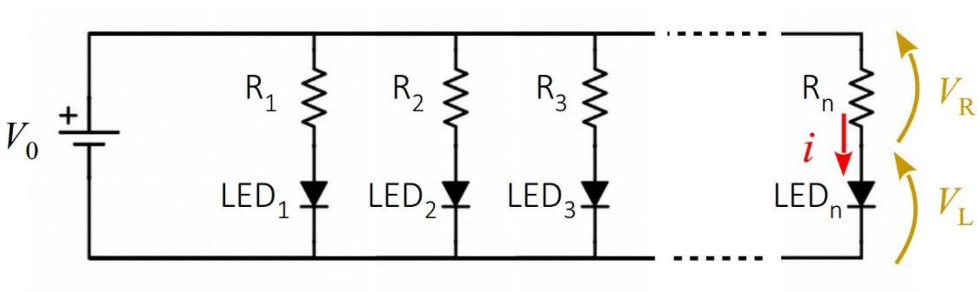
where R is called the "electrical resistance" and its units of measurement is *Ohm* (Ω). The units of the voltage V is the Volt (V), the unit of the current i is the Ampére (A). In contrast with the LED, a resistor conducts current in both directions, which means that it can be connected either way.



In the **workshop**, the **resistor** will be used to limit the current that goes through the LED. Without it, the LED will likely get damaged. Each LED requires its own resistor before you connect it to a power supply.

1.5 Protecting the LEDs

To limit the current flowing through the LED, each LED is connected to a resistor, according to the following scheme:



Each LED works with a specific voltage (V_L) and a preferred current; by choosing the proper resistor for any LED, it is possible to feed the LED with the desired voltage and current. In the workshop we will use a set of 7 LEDs (12 LEDs in the extended version). If they are all different (for example because they are of different colors) the value of each resistor must be chosen according to the properties of the corresponding LED.

Let's now evaluate how to calculate the resistor for a typical LED.

In the workshop, the piano will be powered by a USB charger (or the USB port of a computer). The voltage of such power supply is 5V. Hence we calculate the resistance for the case

$$V_0 = 5V$$

Let's consider a LED with the following characteristics (we took these data from the official technical sheet of the LED):

$$V_L = 3V$$

i = 20 mA = 0.02A (suggested current)

According to the figure with the circuit:

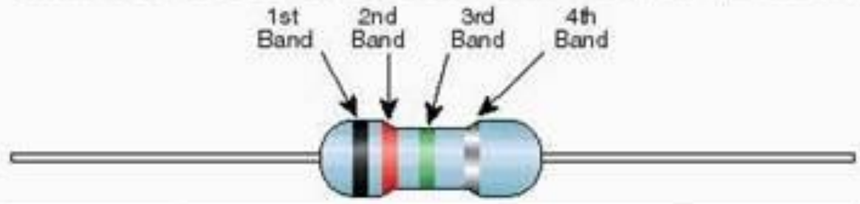
$$V_0 = V_L + V_R \quad \rightarrow \quad V_R = V_0 - V_L = 5V\text{-}3V = 2V$$

The current i flows through both the LED and the resistor. Therefore, from Ohm's law we get the resistance of the resistor:

$$R = \frac{V_R}{i} = \frac{5V}{20mA} = 250\Omega$$

A resistor has a set of colored rings on it which denote its electrical resistance. Here is the encryption key:

Standard EIA Color Code Table **4 Band**: ±2%, ±5%, and ±10%



Color	1st Band (1st figure)	2nd Band (2nd figure)	3rd Band (multiplier)	4th Band (tolerance)
Black	0	0	10^0	
Brown	1	1	10^1	
Red	2	2	10^2	±2%
Orange	3	3	10^3	
Yellow	4	4	10^4	
Green	5	5	10^5	
Blue	6	6	10^6	
Violet	7	7	10^7	
Gray	8	8	10^8	
White	9	9	10^9	
Gold			10^{-1}	±5%
Silver			10^{-2}	±10%

Not all resistance values are available commercially. We suggest to choose, among the available ones, the resistor with the closest lower value of its resistance. In our case this is 220Ω. This corresponds to a current of 22mA, just a little higher than the suggested one, but still enough not to burn the LED.

Part list

To build the photonic piano, the following components are required:

Photonics parts:

- Optical fibers (7 or 12 pieces, 40-50cm each)
- LEDs

Electronic parts:

- Resistors (the value depends on the characteristics [Voltage and Current] of the available LED)
- USB cable

  Note: A USB power supply is required to drive the piano; the power supply is not provided by Phablabs4.0. Any USB charger is suitable as a driver. Any participant should be kindly requested to bring one power supply.

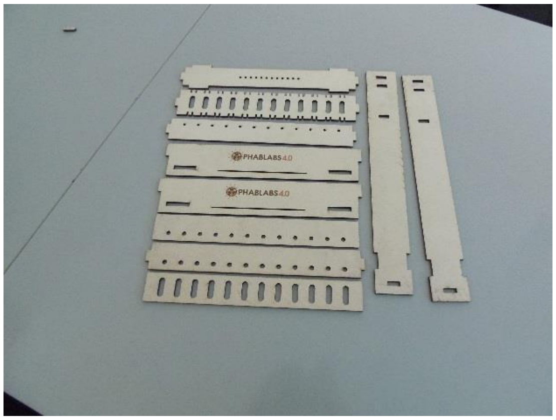
Other parts:

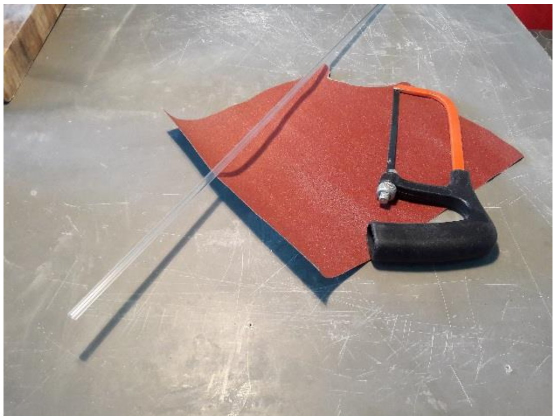
Provided by Phablabs4.0

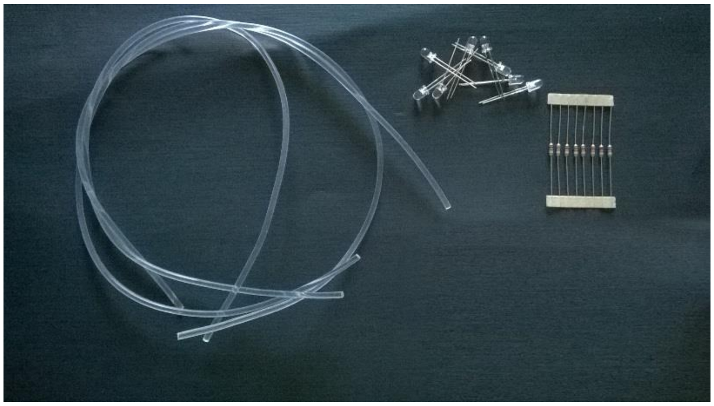
- Plastic/acrylic tube (internal diameter: 3.5mm; external diameter: 6mm; length: 1 m);
- 12 rubber bands, with diameter from 2 to 5 cm;

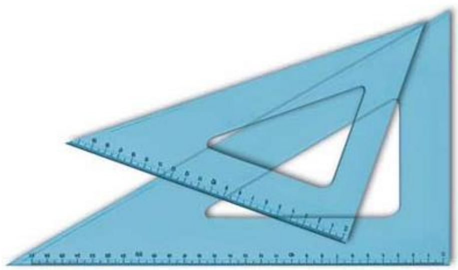
Not provided by Phablabs4.0

- MDF sheet, laser-cut according to file *PhotonicPiano.svg*; We strongly recommend to cut all the pieces before the starting of the workshop.
- vinyl glue;
- solder;
- scissors;
- set square.









The photonics parts can be bought by EYESTvzw.
The electronic parts can be bought by Fablabfactory.

Assembling the device

Now the participants are ready to assemble the piano. The activities required to build each piano are illustrated in steps 3-4 of the participant's instructions, and summarized here:

Step 3 - Assembling the piano

Step 4 - Preparing the LEDs and the circuit

Although very simple, these steps require a lot of time, since step 3 involves **gluing** (and waiting for the glue to dry) while step 4 involves **soldering**. For this reason, to make the workshop more efficient, we suggest to proceed in parallel, as in the following example:

- arrange the participants in **groups of maximum 3 people**: the goal of each group is to produce at least one piano
- the activities of steps 3 and 4 are distributed **in parallel** among the three participants.

Here are the detailed steps:

Step 3 - Assembling the piano

1. Cutting the tubes

   We will cut acrylic tubes, which will serve as rigid piano keys, and will wrap the soft fibers.

2. Preparing the fibers

   The fibers will be cut and glued on one piece of the frame.

3. Mounting the framework I - The keys holders

   We will glue those wooden/MDF pieces of the framework that will hold the piano keys

4. Mounting the framework II - The sides

   We will glue the lateral parts of the framework

5. Mounting the framework III - The tops

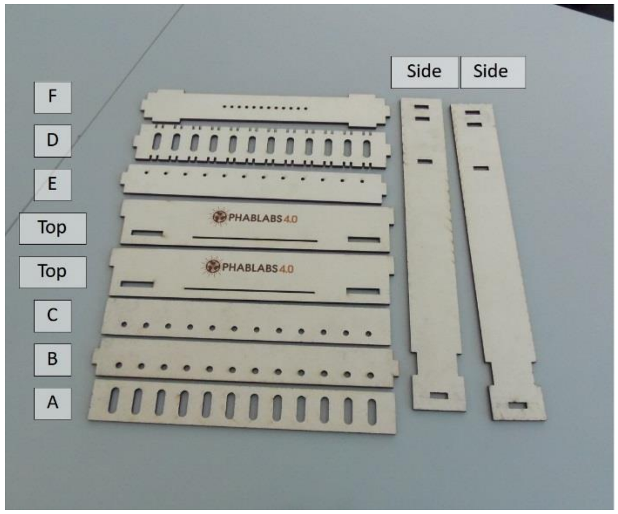
   We will glue the top parts of the framework

The frame is **laser-cut** from a 4-mm thick MDF sheet, according to file

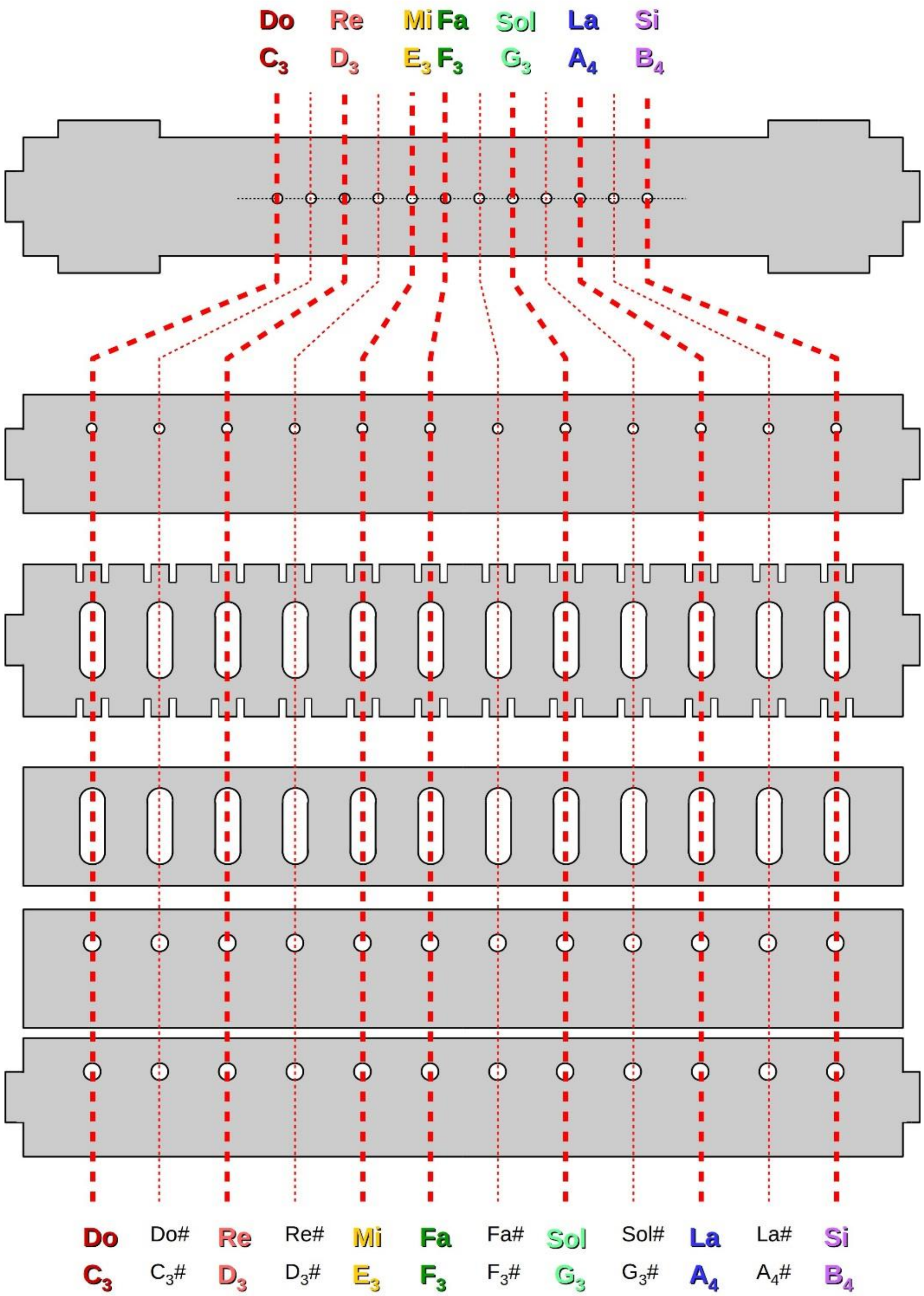
`PhotonicPiano.svg`

Do not throw away the small leftovers after the laser-cutting, they will be necessary to assemble the **framework**. The framework holds the fibers and the LEDs.

Note that cutting all the pieces may take a lot of time. For this reason we suggest to cut the pieces before the start of the workshop.



The laser-cut frame has space for 12 fibers: this is because one octave of a piano has 12 notes (white and black keys). Each participant can choose the number and sequence of “notes” up to 12 fibers. In the instructions we show how to assemble 7 fibers, corresponding to the natural notes (white keys of a piano); we call this configuration as “**basic**”. We label “**extension**” the case where all 12 slots are used. In the following figure, we show how the fibers should be placed in order to mimic a piano.



Suggestion 1:
It is better to start with 7 fibers per piano, because there may be not enough optical fiber if all participants go for 12 fibers.

Suggestion 2:
After receiving their laser-cut parts, the participants should identify all the parts according to the picture. They'd better *label them with a pencil*.

Suggestion 3:

Activities 1, 2 and 3 are independent and could be switched: Since the glue needs some time to dry, we suggest to start from activity 3. and to do activities 1. and 2. while the glue is drying.

Step 4 – Preparing the LEDs and the circuit

1. Preparing the USB cable for the power supply

We will cut the USB cable and identify the (+) and (-) wires

2. Soldering the resistors and the LEDs

We will select the colored LEDs and we will solder them to the resistors

3. Placing the tubes and fibers in position

We will place the fibers and tubes at their proper position in the framework.

Preparing the USB cable for the power supply

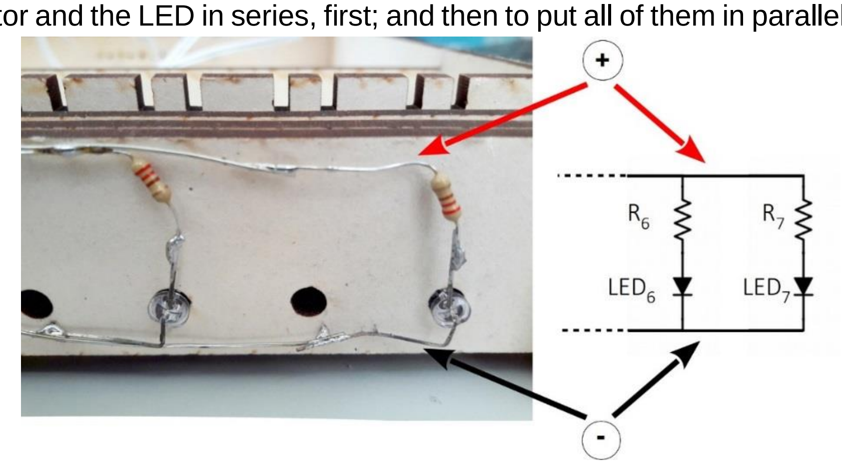
The power of the piano will be supplied by a USB cable connected either to a PC, a power bank or a phone charger (none provided by Phablabs4.0). In all cases, the USB port provides a voltage of 5V.

Typically, the power is supplied by the red and black cables. To check if this is true, and to identify the wire carrying the positive and negative voltage, we will use a multimeter. It is better to help the participant at this stage, to avoid burning the power supply in case of short circuit between the cables. Make sure that the metallic tips of the wires are not touching each other.

When cutting the USB cable, keep the leftover wires: they will be useful to solder the resistor+LED in parallel. Neglect this suggestion if the Fablab can provide additional isolate wire.

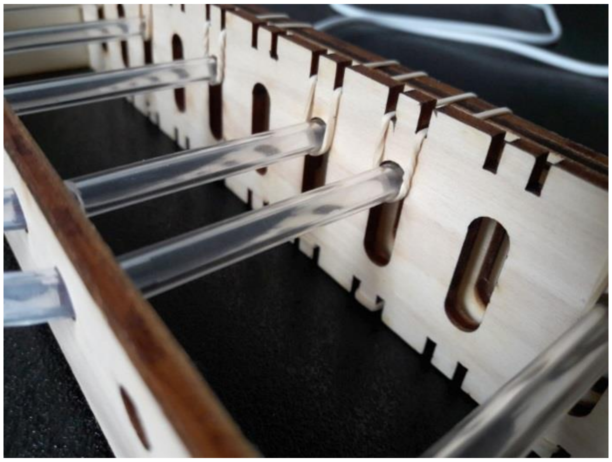
Soldering the resistors and the LEDs

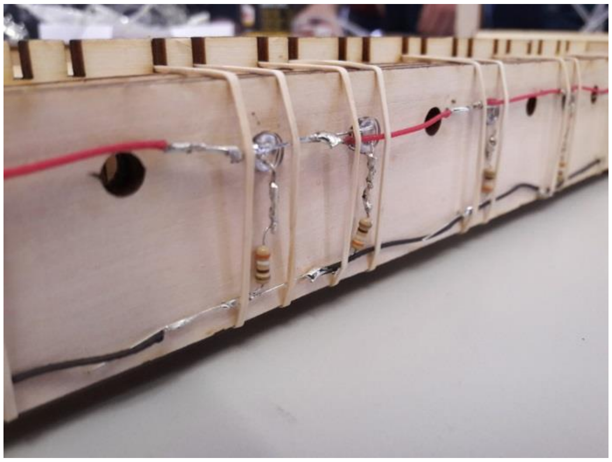
We suggest to solder the resistor and the LED in series, first; and then to put all of them in parallel.



Placing the tubes and fibers in position

Place the tubes, the fibers and the rubber band, as in these figures. The rubber bands will also allow to keep the LEDs in position, without the need to glue them.

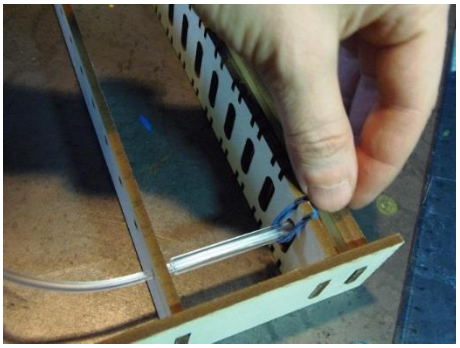


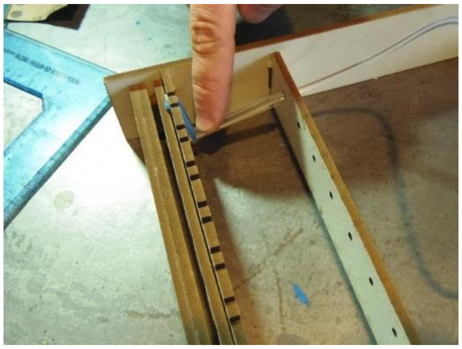


The rubber bands, in particular, will keep the fibers at their rest position after a key has been released.

The assembled piano can be work in **two complementary configurations**: they are determined simply by the arrangement of the elastic rubber bands. The configuration can be easily switched at any time after the final assembly of the piano, by a very simple change in the arrangement of the rubber bands. Such configurations are:

- *Normally on*: in this configurations, the fibers are in front of the LEDs, so that when no key is pressed or a key is released, the light of each LED is transmitted by the corresponding fiber. By pressing a key, the corresponding fiber is moved away from the LED, no more light is transmitted and the corresponding fiber gets dark. The "Normally on" configuration is visually very appealing, since the piano is lighted, and all fibers are all simultaneously glowing.

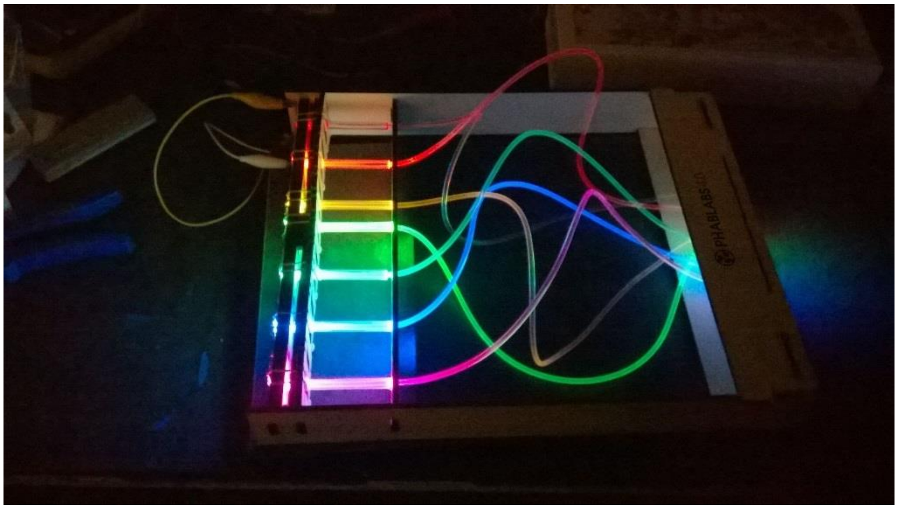




- *Normally off*: in this configuration, the fibers are not in front of the LEDs, so that each fiber is dark. Only by pressing the key the fiber is moved close to the corresponding LED and light glows. In this configuration, when no keys are pressed, the fibers are all dark.

The outcome

After assembling the piano and the LEDs, the participant should now test if all LEDs are working, and if the coupling between LED and fiber is properly optimized. The next figure shows what the piano looks like when the USB cable is connected to the power supply. In this figure, the piano is in the "Normally on" configuration: in steady state, all fibers are in front of the corresponding LED, so that the light goes through each fiber to its other end.



More impressive results are obtained in dim ambient light; in this case, the fiber should glow, as in the picture. The participants should now:

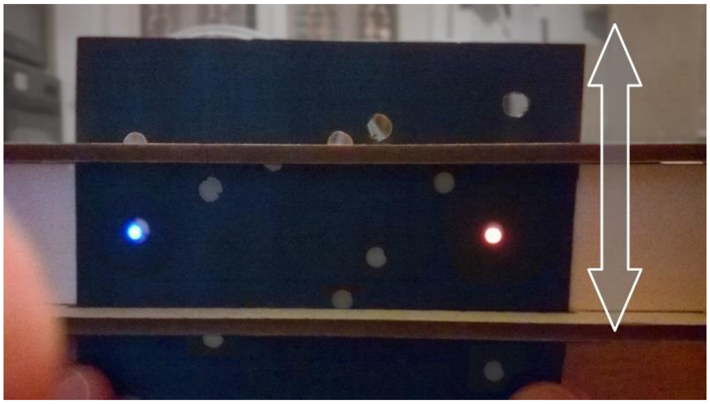
- Check that the light propagates to the other end of the piano;
- Verify that, by pressing any key, the corresponding fiber switches off; and by releasing the key, the fiber recovers its initial position;
- Test also the "Normally off" configuration. This is obtained by changing the arrangement of the rubber bands.
- Try to send a "melody" to friends at the other side of the room
- Download the app "PhotonicPiano" from the Store of the smartphone and convert light into sound.

Extensions

We suggest at least 4 extensions to the basic piano setup.

EXTENSION 1: Change the number of fibers

EXTENSION 2: Use the piano as a carillon:



You can record your favorite melody by drilling holes in a piece of black paper, and sliding it into the thin slit at the Top parts

EXTENSION 3: Coupling light with sound by a smartphone

The goal of this extension is to couple the light-switching process with sound. In particular the photonic piano works if a given note is produced once the corresponding illuminated fiber is switched off.

One way to get this is through the potentialities offered by smartphones, which can read an image and correspondingly generate a sound. A demo app for iOs has been developed to test the potentiality of this technique. It is sufficient to view the light spots with the camera of the smartphone or tablet, press the piano keys, and let the app translate the light pattern into sound. The app is configured to play both in the “Normally on” and “Normally off” configuration. The app “PhotonicPiano” is available in the Apple Store.

__EXTENSION 4:__ Coupling light with sound by Arduino

The goal of this extension is again to couple the light switching process with sound. One possibility is to detect the light by photodiodes and to use the photodiode output signal to activate the playback of a selected sound through an Arduino board. The system is configured to play both in the “Normally off” configuration, even if it could be also modified to work in the “Normally on” configuration, which is less intuitive.

End results and conclusions

What we learned?

- Light propagation and diffusion in optical fibers
- Total internal reflection
- Working principles of LEDs
- Fablabs and their capabilities

Concluding thoughts

In this workshop a technology based on light and photonics is used to practically explore fundamental properties of light such as light propagation, total internal reflection, and diffusion and possible applications. This is done with a hands on approach aimed at the fabrication of a musical tool, the “photonic piano” where light can be switched on and off as one likes. The further coupling to sound through modern technology makes the project more challenging and appealing for the participants. The provided kit (which can be taken home by participants) and the acquired experience can be an inspiration for future original explorations and trials.

PHABLABS 4.0 is a European project where **two major trends** are combined into one powerful and ambitious innovation pathway for digitization of European industry:
On the one hand the growing awareness of **photonics** as an important innovation driver and a **key enabling technology towards a better society**, and on the other hand the **exploding network of vibrant Fab Labs** where next-generation **practical skills-based learning** using KETs is core but where photonics is currently lacking.

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