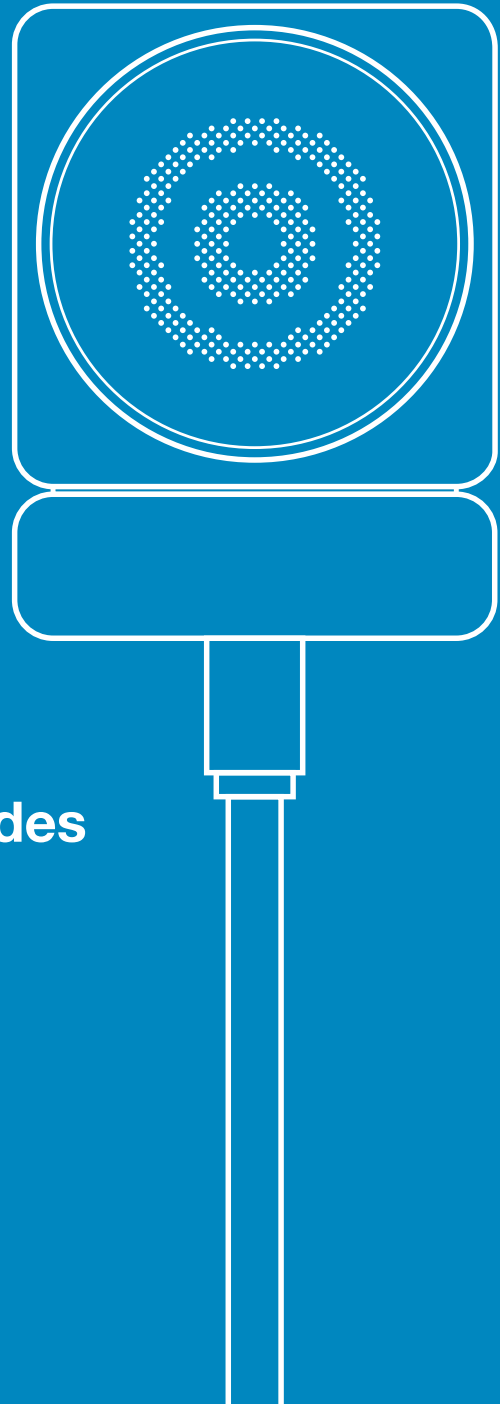


Shift

**An Interactive Device for
Demonstrating Light Guides**

**Sami Kiviharju
2014**



Shift

An Interactive Device for Demonstrating Light Guides

Sami Kiviharju
Master's thesis

Aalto University
School of Arts, Design and Architecture
Department of Design
Industrial and Strategic Design
2014

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Abstract

Light guides are clear optical components used to transfer light with minimal loss by means of total internal reflection. In addition to tunneling light from one place to another, light guides can be used to divide, combine or disperse light. Different types of light guides are used in various application including fiber optics, backlights for liquid crystal displays, automotive lighting and electronics illumination.

The thesis focuses on the development of an interactive demonstration device which purpose is to introduce light guides in an engaging way. The written report is meant to support the physical model in explaining the topic by providing information about light guides to the reader. This is done by first introducing the different application areas for light guides and then explaining the working mechanisms of light guides with illustrations.

The production part of the thesis is completed within a six-month internship in the prototyping team at Microsoft. During the project, prototyping is first used as an empirical research method and later in an iterative design process to develop the physical model. Theoretical research is conducted on the topics of light guides and optics to support learning and to provide a theoretical context for the thesis.

As a result, a demonstration device comprising of two LED-lit light sources, six detachable light guide modules and a light intensity controller, is presented. The physical deliverables also include a storage box designed for the device and a booklet which illustrates the use of light guides in the light guide modules.

Key words: light guide, light pipe, illumination, total internal reflection, optics, prototyping, LED

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1. Introduction

1.1. Topic and Background

Light guide is an optical component designed to propagate light from its original source to another location by means of optical phenomenon called *total internal reflection* (TIR). Light guides can be used for various purposes such as to redirect light from a *light emitting diode* (LED) mounted on a circuit board or to provide an even backlight for *liquid crystal displays* (LCDs). (Avago Technologies, 2006)

Fiber optics is probably the most familiar example of light guiding methods based on TIR. Essentially, light guides are components that capture the light coming from a light source and transfer it to another location by bouncing it inside until the light finally escapes the material. The practical implication of this is that the light source can be situated at a distance from where the light is actually seen. Furthermore, light guides can be used to divide and disperse light which means they can potentially reduce the number of light sources needed. Another advantage of light guides is that they don't generate or transfer heat which might be critical in some cases (Phoenix Proto, 2014).

The topic of light guides was suggested to me by Heikki Hakamäki, the manager of the prototyping team at Microsoft (at the time Nokia). I contacted Hakamäki already in September 2013 and inquired

for a possible topic for master's thesis. Over the next few months we exchanged some emails and had a couple of meetings which finally led to a decision that I would do a six-month internship at Nokia (later Microsoft) starting on 17 March 2014. During the internship, I would work on a given subject and make it a part of my master's thesis.

The prototyping team views itself to be in a supporting role for design. They provide practical solutions and concrete models for concept designers. In addition to their manufacturing role, they produce examples such as material finishes and mechanical solutions that can work as a source of inspiration. According to Hakamäki, there had been a growing interest for illumination and its use for aesthetic as well as functional purposes. Light guides would offer an interesting field for experimentation since they can direct and distribute light optically. In addition to achieving different visual effects, light guides can potentially decrease the number of LEDs needed in a device. Fewer lights reduces the energy consumption and results in a smaller fit, which are both very desirable outcomes when designing a mobile device. A prototyping-based thesis on light guides would fit the company's interest as well as strengthen the prototyping team's proactive role.

1.2. Goals, Methods and Schedule

The original brief was left quite open so I had a lot of freedom to decide how to approach the topic. Furthermore, I was given a chance to work on the project independently and use the methods I liked. It was of course nice to be able to shape the thesis according to my interests but it also meant I had to think about the relevance of the work much more and be very critical of the steps I take.

The thesis focuses on building an interactive device for demonstrating light guides. Prototyping plays a key role in the thesis throughout the process. In the beginning it is used as an empirical research method to understand how light guides work and later in concept development to test and qualify ideas. The main equipments used in the prototyping include 3D printer, CNC machine and laser cutter. Software used to create the 3D models and other geometries include *CATIA*, *Rhinoceros 3D* and *Adobe Illustrator*. In addition, other workshop tools and equipments are used in support of the above mentioned methods.

To learn about light guides and to provide theoretical context for the thesis, research is carried out on different light guide application areas and studies related to topic. The research material consists of product examples, datasheets, light guides studies and literature on optics. Furthermore, feedback and

suggestions from the prototyping team are used for developing and evaluating ideas throughout the project. Other input from the company will come through conversations and interviews with other teams and people related to the subject.

The main objective, as defined earlier in the thesis plan, was to contribute to the knowledge of illumination in Microsoft Design Department through an inspirational tool demonstrating the possibilities of light guides. Furthermore, the thesis could potentially help the collaboration between concept designers and prototyping team by providing a tangible platform for discussion. From these objectives, the following research questions were later formed:

1. How to demonstrate light guides in a tangible way?
2. How to make an engaging tool/device for this purpose?

These questions would help to guide and review my work throughout the project.

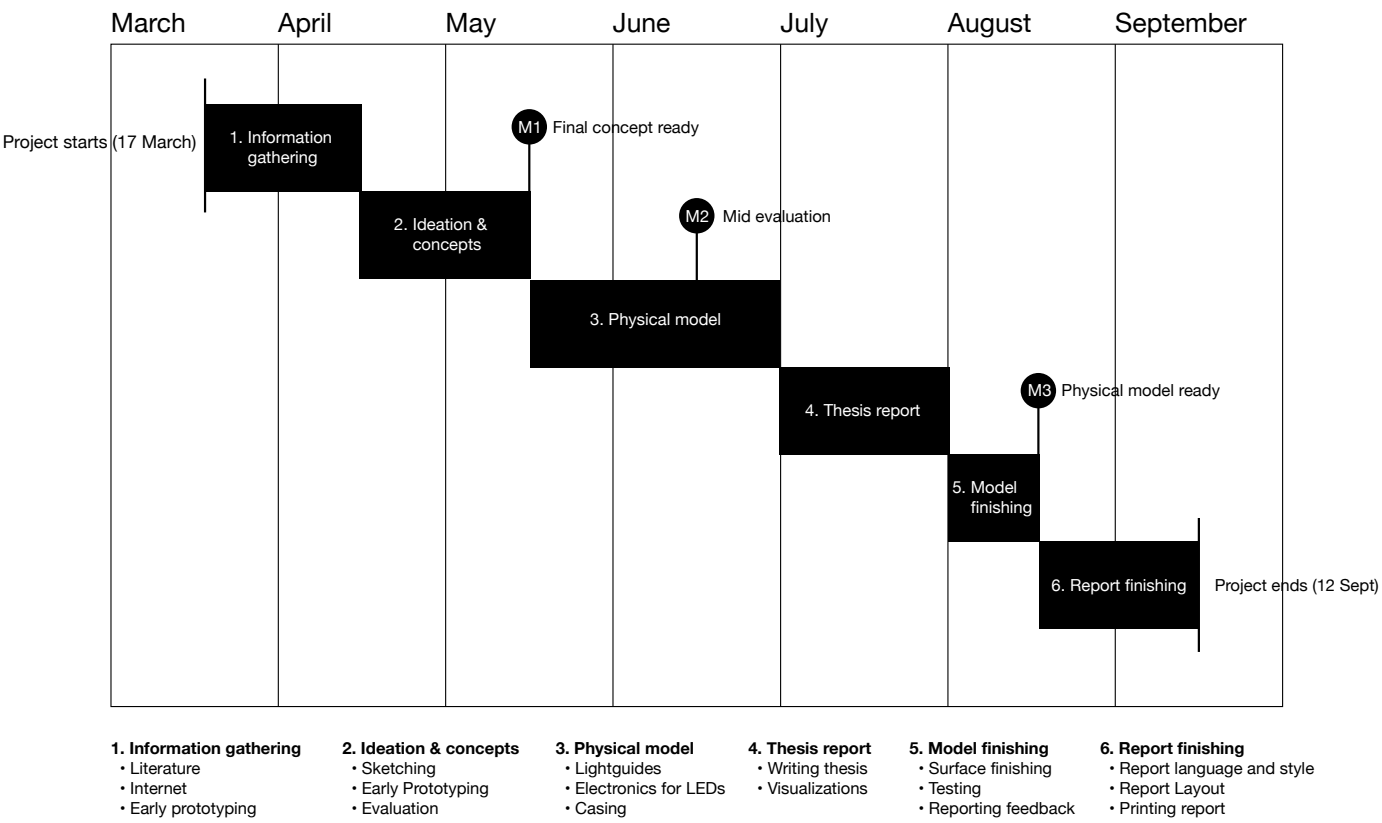


Figure 1: The original schedule. Making the physical models took longer than expected and so the finishing of the report was done after the internship.

1.3. Focus and Sructure of the Thesis

Being a production based thesis, a major part of the report is depicting the process of designing, proto-tying and building the physical model. To provide context for the thesis, the theory part sets out to explain the concept of light guides by introducing their common application areas, how they work and how they are made. The subject of lighting is dis-cussed from the point of view of its optical behavior inside a light guide. Other terms and phenomena re-lated to lighting are not included in the thesis. The light source referred to in the thesis is LED since it is currently the primary source of illumination for light guides (Koshel, 2013). LEDs are discussed to an extend that is necessary to understand how they work together with light guides. The working mecha-nism of LEDs, history or advantages over other light sources are not discussed.

Chapter 2 forms the theory part of the thesis. First, the reader is provided with a brief introduction to the history of light guides and how they are used today (chapter 2.1.). This is done by introducing the main application areas for light guides through examples gathered during the background research. Next, a more detailed look inside the working mechanisms of light guides is done by explaining the main opti-cal phenomena involved (chapter 2.2.) and how light guides differ from other similar optical components (chapter 2.3.). Subsequently, the main light guiding methods are depicted in chapter 2.4. The technical

explanations are supported by easy-to-understand illustrations. Lastly, an overview of the design and manufacturing methods of light guides is provided in chapter 2.5.

Chapters 3-7 depict the process of designing and building the physical model. Chapter 3 describes how research and early prototyping was used to learn about light guides and how the two supported each other in generating ideas. Chapter 4 ex-plains how the early ideas were developed further to functional prototypes and how the idea for the final concept was formed. Chapter 5 describes the process of designing the different parts of the de-vice. Process pictures along with explanations are used to present the various iterations the parts and mechanisms went through before the final model. In addition, the chapter goes trough the process of choosing the electronics and the challenges their implementation set to the design of the casings. Chapter 6 depicts the process of assembling and finishing the final models. In chapter 7, the making of a custom storage box and an instruction booklet for the device is explained. Chapter 8 presents pictures of the finished device.

In chapter 9 I review my work. I discuss the rele-vance of the thesis to the research questions and give a personal overview of the project: how it met my expectations, what were the main challenges and what are my opinions of the final outcome.

2. Light Guides

2.1. History and Application Areas

Physicist Daniel Colladon and Jacques Babinet's light guiding experiment from 1840 can be considered the earliest example of a light guide using TIR. The construction was simple: a stream of water poured out of a hole made on the bottom of a container. The light shone over the surface of the water was transferred into the stream and created an illuminated arc. Later, in 1854, a similar demonstration was presented by an Irish physicist John Tyndall, whom many consider to have discovered the phenomenon. (Woodward and Husson, 2005)

In the following years, light guides of solid material were developed especially in the medical industry for aiding surgeries. In his efforts to make a bendable gastroscope in 1930, a German medical student named Heinrich Lamm used a bundle of fibers to transfer the image – with poor results. In a tight bundle, the fibers leaked the light to the adjacent fibers and distorted the image. A similar construction was later tried in a military context by a Dutch physicist Abraham Van Heel, who was hired to develop new periscopes for submarines. In 1951, Van Heel was able to overcome the light leakage problem with the help of his American colleague Brian O'Brien. Elaborating on the idea he got from O'Brien, Van Heel dipped the fibers into liquid plastic which prevented the fibers from interfering with each other. This was the first adaptation of a method called *cladding* which is still used in fiber optics. (ibid.)

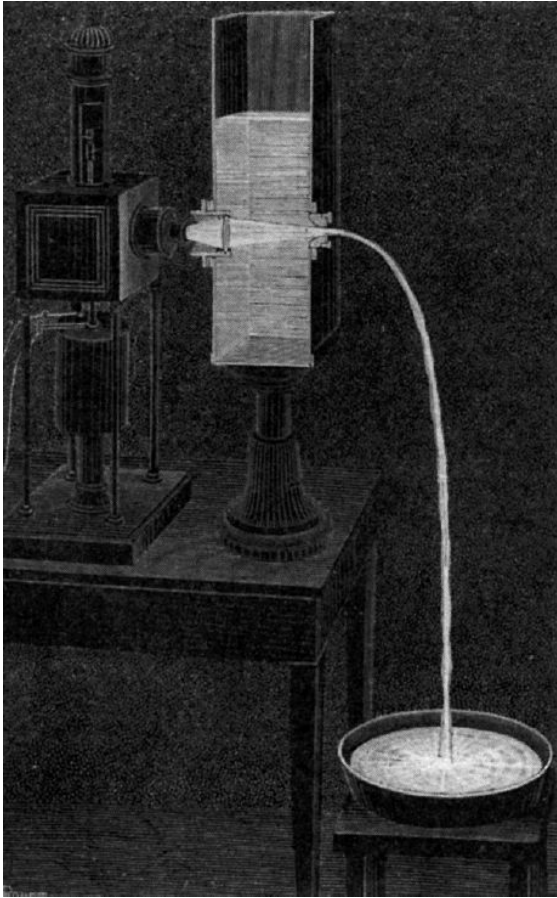


Figure 2: An illustration of the Colladon and Babinet's light guiding apparatus in "La Nature" magazine from 1884



Figure 3: SCHOTT PURAVIS glass optical fibers

It wasn't until the invention of laser in the 60s that fiber optics were seen as a possible medium for data transfer. Driven by the new possibility, manufacturing methods for fiber optics improved and finally, in 1970, a fiber optic with the desired quality and low transmission loss was achieved. Over the next decades fiber optics improved and they were first adopted in telecommunication systems in the 80s and they later spread to information systems and computer networks in the 90s. (ibid.)

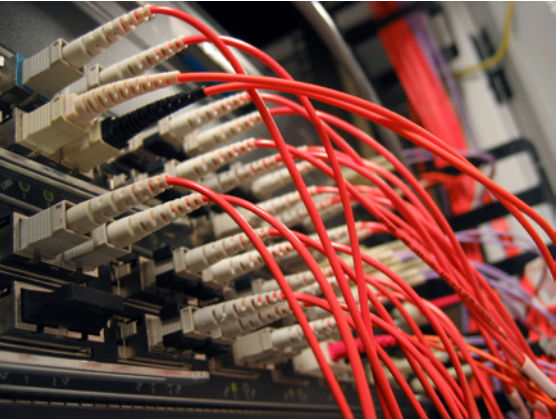


Figure 4: Fiber optic data cables

Having roots in medical imaging, light guiding methods with same optical principles are still used today. In addition to endoscopic purposes, light guides have also been implemented in biomedical applications in the form of *fiber optic sensors* where their inherent qualities, such as immunity to electromagnetic interference, have proved indispensable (Mendez, 2011).



Figure 5: “Piped Light Aids Surgeons and Dentists”, an article in Popular Science magazine from 1939

In dentistry, lighting applications using fiber optics include *fiber-optic transillumination* for detecting caries lesions (Amaechi, 2009) and *dental curing lights* used for dental restorations (Singh et al., 2011).

In addition to fiber optic communication and medical purposes, another major application area for TIR-based light guides is in electronics illumination. Light guides, often called *light pipes*, are especially useful



Figure 6: Olympus CF 100TL Video Colonoscopy device



Figure 7: Illuminated tongue depressor with a removable light guide tip



Figure 8: Light guide tip for dental curing light

in solving practical issues relating to assembly. For example, the light from a single or multiple LEDs mounted on a circuit board can be tunneled to the operating panel with minimal light loss (Lumex, 2012). Furthermore, light pipes can be used to divide the light from a single source to multiple outputs or to combine multiple light sources into a single output (Koshel, 2013). Light pipes called *homogenizers*, *integrator rods* or *waveguides*, can

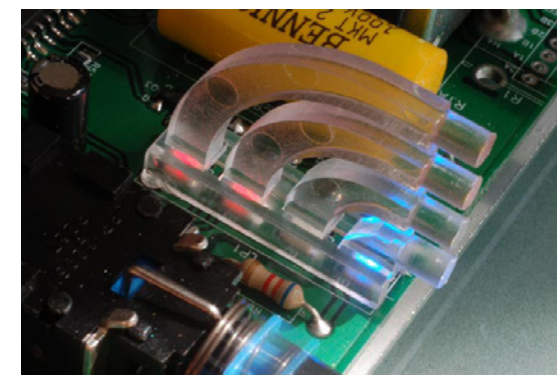


Figure 9: Combined light pipe for four circuit board-mounted LEDs

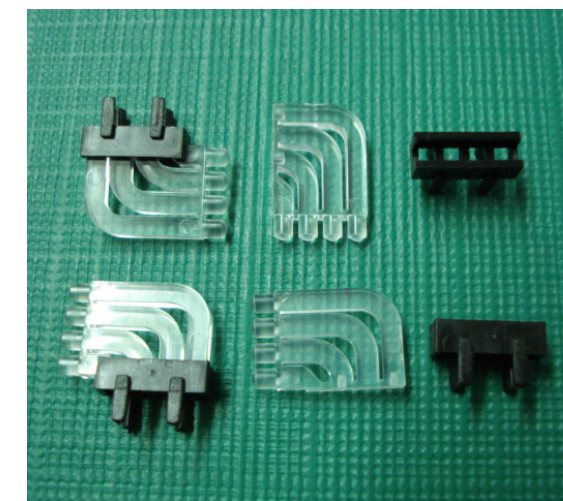


Figure 10: Different types of LED light pipes

◀ Figure 11: Light guide illuminated keyboard

be used to enhance the uniformity of light in different optical systems (Newport, 2014).

Planar light guides designed to create even light surfaces are called *light guide panels* or *light guide plates* (Vivacity LED, 2008). They are primarily used in LCD-panel backlight units but can also be used for general lighting as such (Langevin and De Berti, 2011). The essential feature of light guide panels is

that they transform a uniform surface of light from a row of LEDs positioned on one or more edges of the panel, reducing the number of LEDs needed. (Chien and Chen, 2008).

Very thin light guides are called *light guide films*. Light guide films can be used for example to illuminate keypads or to create touch sensitive control panels. In the latter case, lit graphic sym-

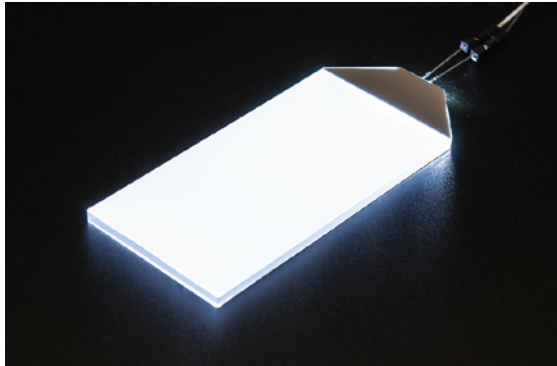


Figure 12: GE Lighting Lumination EL series

◀ Figure 13: White LED backlight module

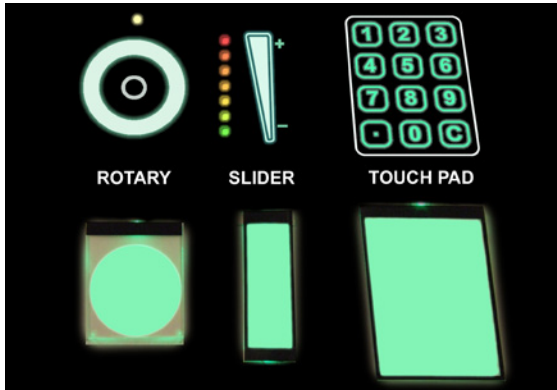


Figure 14: Ultra-thin light guides for backlighting touch-enabled display graphics

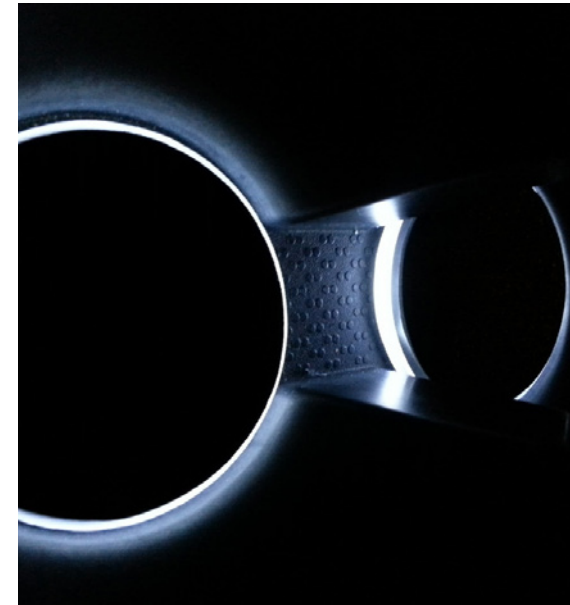
bols integrated into the light guide film are used to indicate the touch sensitive areas. Furthermore, the interface can be changed by selectively illuminating different areas of the film or having multiple overlapping films with different symbols. (Avago Technologies, 2009)

Light guides can also be used to create lighting effects more aesthetic in nature. Such light guide adaptations are especially prominent in automotive



Figure 15: Non-linear curved light extraction technologies from Global Lighting Technologies

industry where light guides can be used to replace multiple LEDs to create more uniform and glare-free tail lights (Yu, Chen and Liu, 2013) or inside the car to achieve intricate dashboard illumination (Lighting Research Center, 2014). Other interesting and creative adaptations of light guides can be found in the field of general lighting and art.



▲ Figure 16: Light guides used in BMW M4 headlights

▲ Figure 17: Light guide illuminated cup holder

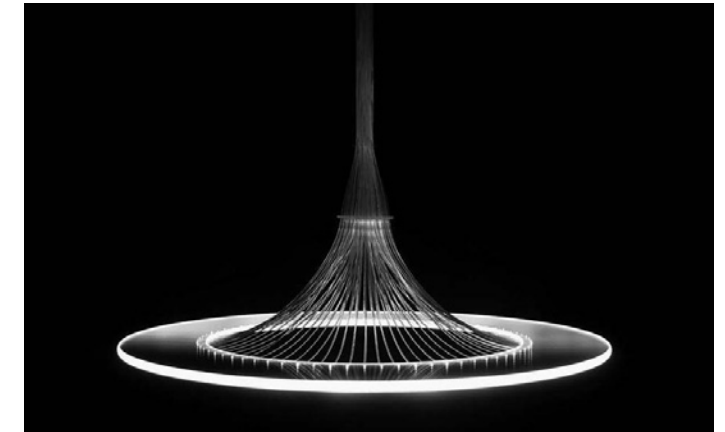


Figure 18: "Ufo light" from neuesLicht with a clever use of optical fibers



Figure 19: "Lambretta" light sculpture made of 28 layers of laser-etched acrylic sheets by Steve Clarkson



Figure 20: "Pole Light" made of curved acrylic by Paul Cocksedge

2.2. Optical Principles

Retrieved and reillustrated from
Basic Geometrical Optics (Pedrotti, 2008)

$$n_i \sin i = n_r \sin r$$

Equation 1: Snell's law of refraction (i = angle of incidence, r = angle of refraction, n = refractive index)

To understand how light guides actually work, it is necessary to understand the optical phenomena that govern the behavior of light in a substance. When light rays hit the boundary of two materials for example air and water, it either goes through the boundary or gets reflected or partially both. What happens, depends on three factors: the angle the light hits the boundary, the refractive indices of the materials and from which side the light is coming.

REFRACTIVE INDEX

Refractive index is a term used to describe the optical density of a material. It is the ratio of the speed of light inside a material and the speed of light in a vacuum. In this case, speed of light in a vacuum is a physical constant to which other instances are compared. Different materials have different refractive indices. For instance, the refractive index for water is approx. 1.33 which means light travels 1.33 times slower inside water than it does in a vacuum.



Figure 21: Diamonds have a high refractive index of 2,24 which causes light to reflect several times inside the material.

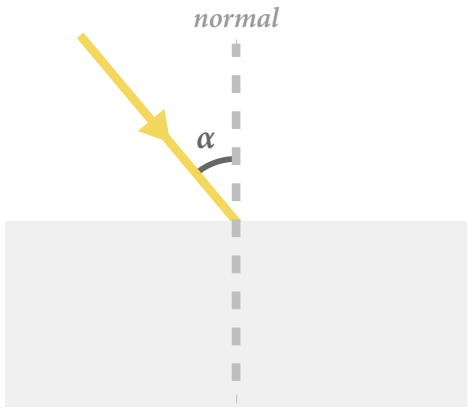


Figure 22.1

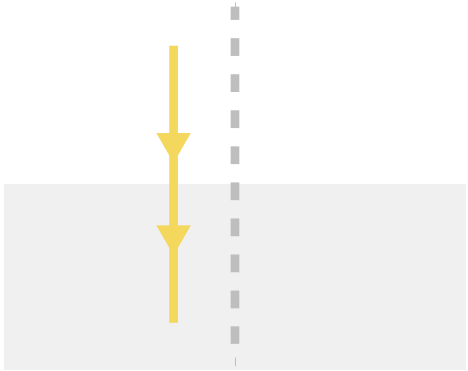


Figure 22.2

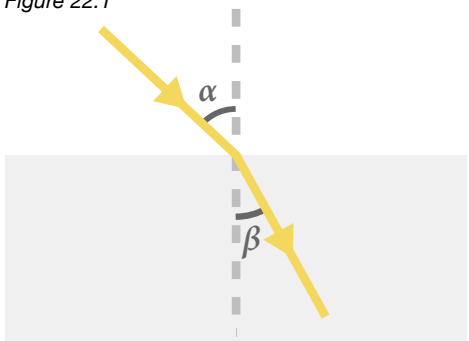


Figure 22.3

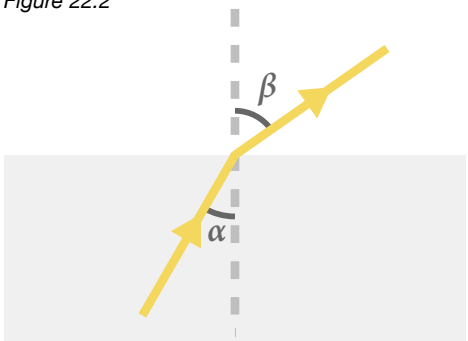


Figure 22.4

REFRACTION

The angle at which light rays hits the boundary in relation to its normal is called the *angle of incidence* (Fig. 22.1). When the angle of incidence is 0, the light rays hit the boundary perpendicularly and the light continues through without changing direction (Fig. 22.2). However, if the light goes through the boundary at an angle, a shift in its direction occurs at the boundary, it refracts. The angle between the normal and the refracted angle is called the *angle of refraction*. The refraction happens because of the different refraction indices of the materials. The

direction to which the refraction happens depends on from which direction the light is coming. If the light travels from a medium with a lower refractive index to a medium with a higher refractive index, the light bends towards the normal (Fig. 22.3). In the opposite case, the light bends away from the normal (Fig. 22.4). The amount of refraction depends on the angle of incidence and the refractive indices. *Snell's law of refraction* is used to predict and calculate refractions (Eq.1).

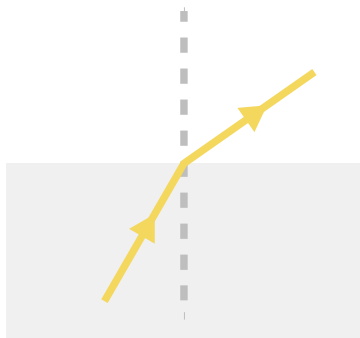


Figure 23.1: Light hits the boundary at a steep angle. The light rays refract and bend away from the normal.

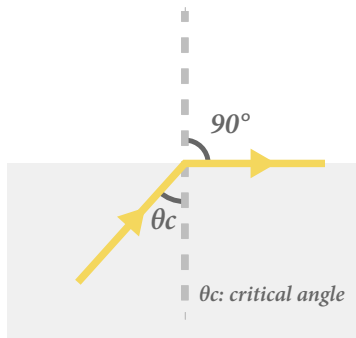


Figure 23.2: As the incident angle increases, the refracted light reaches the level of the boundary. The incident light rays are now at the critical angle.

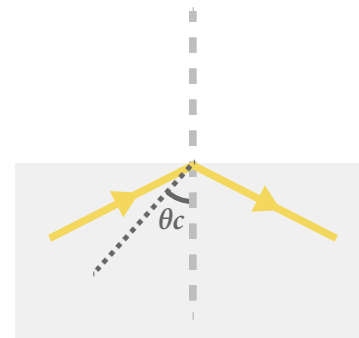


Figure 23.3: When the incident angle is greater than the critical angle, the light rays are reflected at the boundary and total internal reflection occurs.

TOTAL INTERNAL REFLECTION

It is possible for light to get fully reflected at the boundary of two media. This phenomenon is called *total internal reflection* (TIR) and it is the basis of how light guides work. In order for TIR to happen, the material inside which the light travels has to have a higher refractive index than the material it approaches. In other words, light needs to travel from an optically denser material towards a less dense material.

If we imagine a situation where the light is at first hitting the boundary at a steep angle (Fig. 23.1), the light

will go through the boundary and refract. However, as the incident angle increases, at some point the refracted light will reach the boundary of the two media (Fig. 23.2). This point is called the *critical angle* and it marks the change from refraction to reflection. If the incidence angle is greater than the critical angle, total internal reflection occurs (Fig. 23.3). Snell's equation can also be used to calculate the critical angle. It is important to notice that TIR can only happen if the refractive index of the first medium is higher than the refractive index of the second medium.

2.3. Light Guides vs Prisms and Lenses

Lenses and prisms are optical components used in various applications. Lenses are round components with flat, convex or concave back and front surfaces. Depending on the shape, lenses converge or diverge light rays which means they can be used to magnify or focus images or to disperse or focus light. Prisms come in various angular shapes. They use refraction and total internal reflection to alter the direction of the light. They can be used for example to reflect and redirect light or to mirror images. (Pedrotti, 2008)

How do light guides differ from lenses and prisms? To my understanding, the term "light guide" usually refers to a custom made light conveyor that carries light across greater distances through multiple total internal reflections. Lenses and prisms, on the other hand, are more standardized components and affect the passage of light more briefly and predictably. However, they all work on the same optical principles and clear technical separation is hard to make. Furthermore, a complicated light guide structure might include both prisms and lenses.



Figure 24: Prisms of different shapes can be used to redirect or reflect light.



Figure 25: Lenses are used to converge or diverge light depending on their shape. A biconvex lens in the picture

2.4. Basic Light Guiding Methods

Retrieved and reillustrated from *Light guide Techniques Using LED Lamps* (Avago Technologies, 2006). Additional sources are mentioned in the text.

GETTING LIGHT INSIDE A LIGHT GUIDE

Attaching the lightsource to the light guide is called *flux coupling*. Flux coupling is critical in getting the light to transfer into the light guide and achieving good *flux capture* (amount of light entering the light guide). For light to enter the light guide effectively and with minimal loss, the light source should be fixed as close to the light guide as possible. The light loss caused from the reflected light rays at the boundary of two media is called *Fresnel loss* (Fig. 26a).

To minimize Fresnel loss and to capture as much of the light as possible, fixing the light guide to the light source is crucial. The best way to ensure good flux coupling is to fix the LED inside the light guide (Fig. 26b) and to use a LED with narrow *flux radiation* (narrow beam of light). To reduce Fresnel loss even further, the air gap between the LED and the light guide can be glued with epoxy. If fixing the LED inside the light guide isn't possible, fairly effective flux capture can be achieved by making sure the light rays enter the boundary at an angle steep enough to get refracted. In practice, this means using a type of LED that allows the light guide to be placed as close to it as possible (Fig. 26c). Furthermore, a separate lens can be used between the LED and the light guide to converge the light (Fig. 26d).

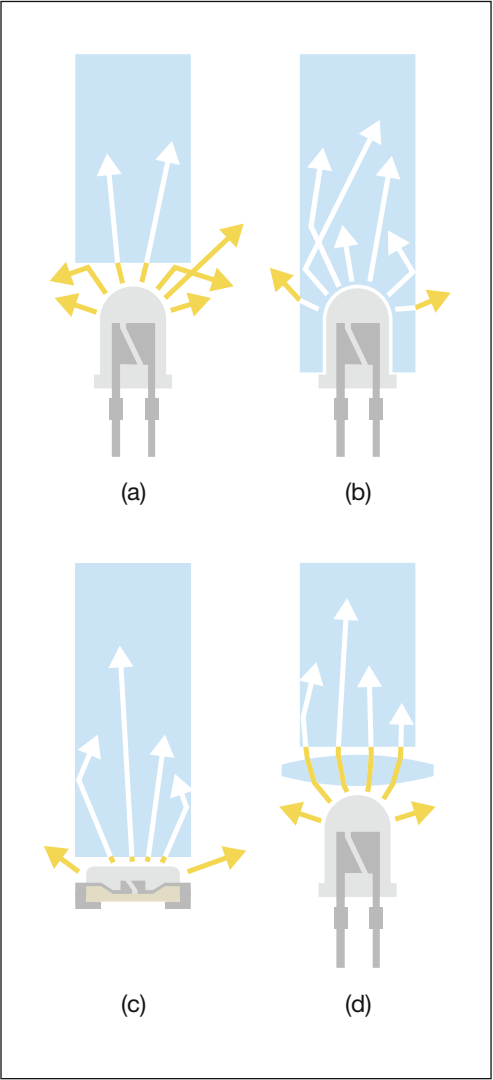


Figure 26: An illustration of how the different coupling methods affect the flux capture

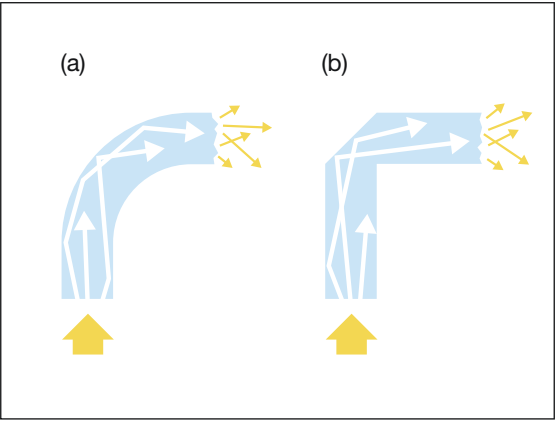
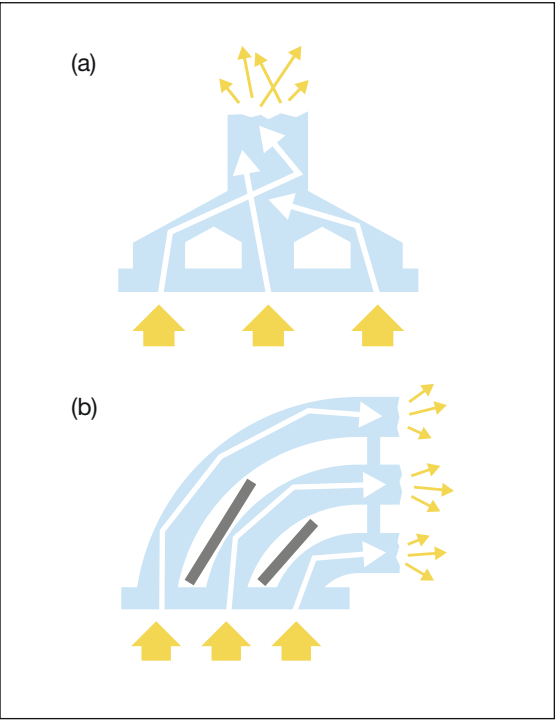


Figure 27: The direction of the light can be altered by bending the light guide or by having a reflective prism in the corner.

Figure 28: Light guides can also be used to combine or divide light from multiple sources. Light shields can be used to prevent the light from interfering with adjacent light guides.



SHAPING THE LIGHT GUIDE

Light guides propagate light to another location by means of TIR. In order to keep the light inside the medium, the light guide should have smooth surfaces. If the light guide needs to change direction, for example to go around obstacles, it should be shaped so that the light doesn't hit the boundaries at an angle below the critical angle or it might refract and "leak out". The radius of the bend should therefore be at least two times the diameter of the light guide (Fig. 27a). If there is a need for a sharp 90° turn, the corner can be cut in 45° angle to work like a prism (Fig. 27b). Furthermore, multiple light guides can be attached together to ease the assembly or to converge the light from multiple LEDs (Fig. 28a).

The ends of the light guide where the light exits, should be diffused. At a microscopic level this means that there are enough refractive surfaces for the light to exit and as little light as possible gets reflected back.

If there is a chance that some of the light rays might leak from the light guide, a *light shield* can be used to prevent the light from entering another light guide (Dialight, n.d.). For example, if adjacent light guides are illuminated separately at different times, light shields can be positioned between them to prevent the light in one of them from partially illuminating the others (Fig. 28b).

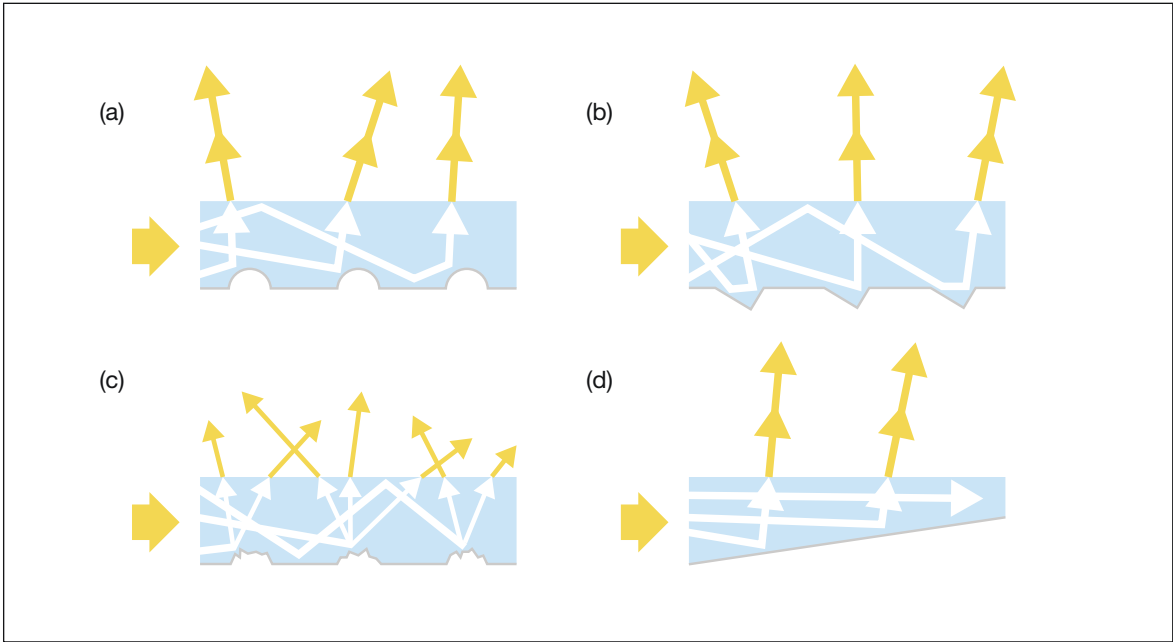


Figure 29: Light guide panels use small light extracting features to distribute light evenly on a surface. Different manufacturing methods result in either diffuse (more random) or specular (more directional) light extraction.

DISPERSING THE LIGHT

It is also possible to distribute light evenly on a surface. In the case of light guide panels, the light coming from a row of LEDs on the side(s) is spread across the panel by creating small, light extracting features on the surfaces. The propagation of light may also be altered by changing the curvature or angle of the bottom surface (Fig. 29d) Depending on the manufacturing method, the extraction of light in

a light guide panel is either diffuse (Fig. 29c) or specular (Fig 29a, 29b) in nature (Shriver, 2012). The light loss towards the end of the panel can be compensated by optimizing the pattern of the light extracting elements, which basically means having fewer of them in the beginning and more towards the end (Kim, Oh and Lee, 2011).

2.5. Design and Manufacturing

RAY TRACING

Designing light guides is quite straightforward when the previously mentioned factors are kept in mind and the optical behavior of light is known. Ultimately, it comes down to ensuring the light to enter the light guide, providing reflective surfaces for the light to propagate through the light guide and finally enable the light to refract where it needs to be seen.

The method of designing optical components by calculating the movement of light rays is called *ray tracing* (Spencer and Murty, 1962). Rudimentary ray tracing can be done on paper by simply by drawing geometrical representations of the passage of individual light rays. However, if the light guide is complicated and high optical quality is required, optical design software such as: *Zemax OpticStudio* or *Qi-optiq WinLens 3D* can be used for accurate simulation of light rays. With the help of such softwares, the design and optical efficiency can be confirmed before moving on to tooling and manufacturing stages (Sievers, 2013). In addition to designing optical components such as lenses and light guides, ray tracing is also the underlying method used to render realistic 3D images for product visualizations and animations (Pacheco, 2008).

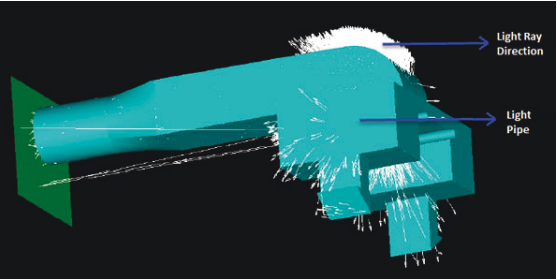


Figure 30: Ray Tracing is used to design and evaluate light guides and other optical components.



Figure 31: Ray tracing can also be used to create realistic product renderings.

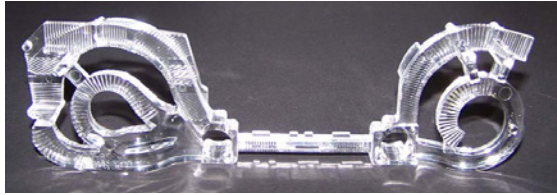


Figure 32: Injection molded intricate light guide structure from Phoenix Proto

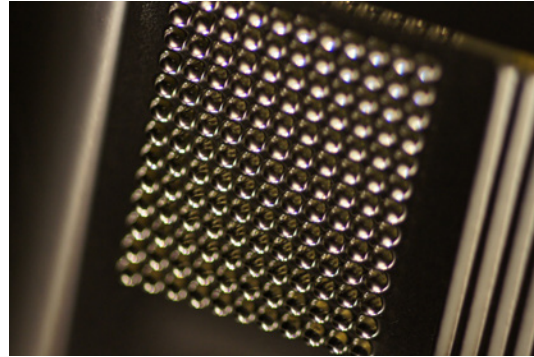


Figure 33: 3D printed optical microstructures from LUXeXcel

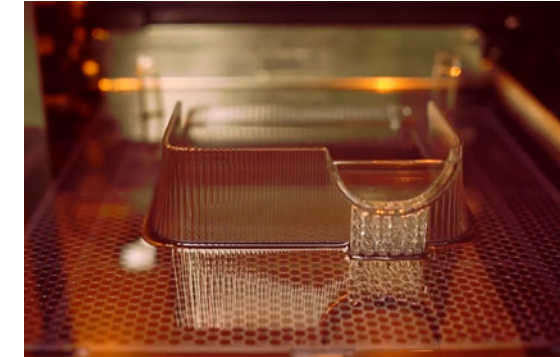


Figure 34: SLA printed clear material

METHODS AND MATERIALS

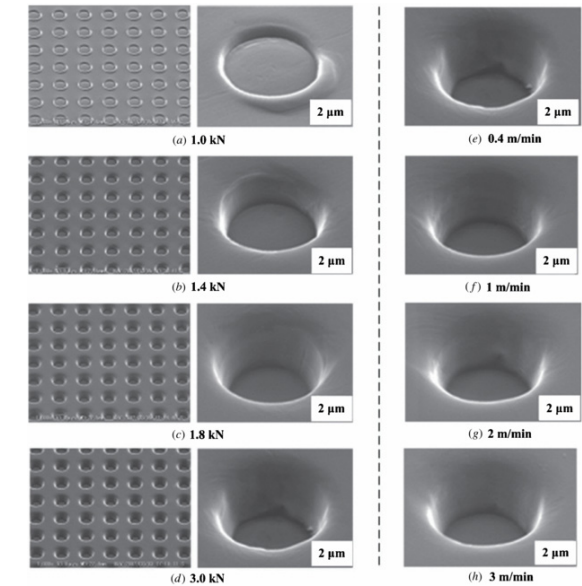
Light pipes and other optical components for illumination purposes are usually injection molded from clear *polymethyl methacrylate* (PMMA, acrylic) or *polycarbonate* (PC) which both have good clarity and optical qualities (Phoenix Proto, 2014). However, other clear materials such as glass, epoxy or silicone can also be used (Avago Technologies, 2006).

Compared to glass, PMMA and polycarbonate, offer better mechanical properties and cost-efficiency through high volume manufacturing methods. Furthermore, as LEDs don't emit heat nearly as much as incandescent light, the high heat resistance of glass is no longer as crucial. Polycarbonate has become an increasingly popular choice for LED attached optical components such as light guides, lenses, diffuser and reflectors. This is mainly due to PC's superior mechanical properties over PMMA. For example, polycarbonate is much stronger of the two and has better heat resistance. The new improved PC materials can now also match the

clarity and UV resistance of PMMA. These factors are crucial in areas requiring durability and high optical quality. Furthermore, considering the fact the LEDs have a remarkably long life span, it makes sense to invest in a material that is able to withstand the test of time. (Bayer MaterialScience team, 2012; Ambravan, 2012)

An interesting new method for creating optical elements is 3D printing. A Dutch company called LUXeXcel specializes in developing high quality *3D printed optics* ranging from custom made lenses to microstructured light diffusers. This technology offers a cost efficient solution especially for smaller quantities as it only requires the 3D file of the model. No expensive preparations such as mold making are needed. In their method, tiny droplets of liquid photopolymer resin are printed on a PMMA or PC substrate and then cured with UV light. Printing can be done on both sides of the substrate to create more complex structures. At the moment the maximum

Figure 35: Hot embossed light extracting microstructures



print height for one side is two millimeters setting some limitations to the design. However, the technology is developing rapidly and higher prints are possible in the future. (L. Klamer, LUXeXcel, pers. comm, Aug 18, 2014)

For prototyping light guides and other optical components, 3D printing method called *stereolithography* can be used. Stereolithography is an additive manufacturing method that uses targeted UV light to form overlapping solid layers in photopolymer resin (THRE3D, 2014). Although SLA parts don't provide the optical clarity and precision often required from the final product, adequate quality for testing simple designs can be achieved by using clear resin and applying a surface after-treatment with transparent spray coating (Parikka, pers.comm, June 25, 2014).

LIGHT GUIDE PANELS

The manufacturing methods for light guide panels along with their optical quality have developed rapidly along the penetration of LEDs in LCD back-lighting industry from 2008. At first the LEDs were placed behind the screen but due to high cost and a demand for a slimmer design, a need for *edge-lit* solution emerged. Using light guide panels made it possible to place the LEDs on the sides of the display. As the technology developed further, the LEDs could finally be reduced to a single row on one edge of the screen. (Kim and Semenza, 2012)

Replicating light extracting microstructure from a master is a cost-effective method for high volumes. The master is usually a *nickel shim* (Ni-shim) which has been electroplated over the original silica

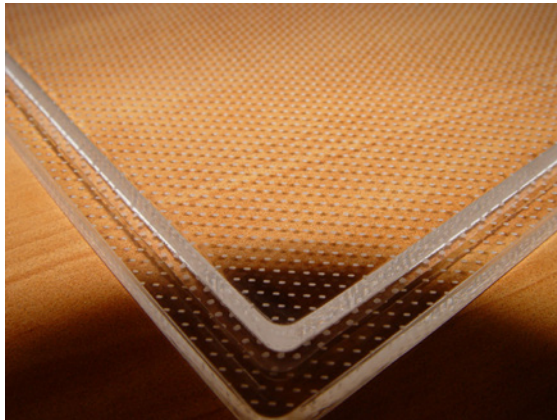


Figure 36: Laser etched dot pattern

substrate containing the pattern. The original pattern is thus transferred on a harder material to withstand the future replications. One method for replicating the pattern is *UV- or thermal casting*, where a thin layer of polymer resin is applied over a substrate and the ni-shim is placed on top. The resin is then cured with UV-light or heat and the Ni-shim is removed. In another method called *hot embossing*, the Ni-shim is pressed directly on to a heated thermoplastic substrate to form the pattern. A faster and a more cost efficient mass production implementation of this is called *roll-to-roll hot embossing*, where substrate is fed under a rolling cylinder containing the pattern. The pattern can also be replicated with an *injection molding* process where the Ni-shim is placed inside the mold into which liquid polymer is injected with high pressure to form the light guide panel. (Tuohioja, 2006)

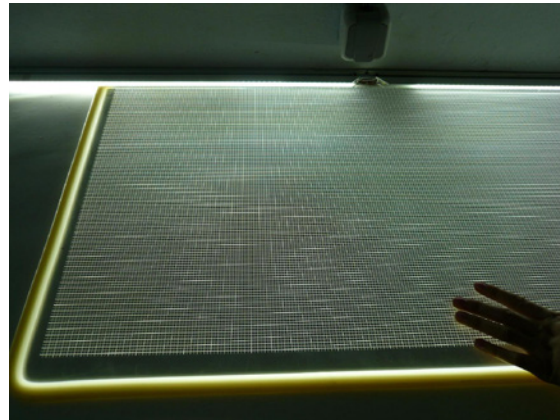


Figure 37: Light guide pattern with V-grooves in both directions

In addition to the above mentioned *pixel based methods*, a good optical quality and ray angle control can be achieved by using *V-grooves*. In this method reflective grooves in one or two directions are mechanically applied to the surface. The downsides of the V-groove technology are slow production time and limitations in optimizing the pattern. In addition to pixel based method and V-groove, light extracting dots can be created by *screen printing* or *chemically etching* the surface of the light guide. The manufacturing speed and cost efficiency of these methods are good but they result in a more diffuse and random light extraction since they cannot be controlled with the same precision as the pixel based and V-groove methods. A somewhat better light extraction can be achieved by *laser etching* the surface, although the etching process is slower. (Langevin and De Berti, 2011; Shriver, 2012)

3. Learning Process

3.1. Research and Inspiration

Since I didn't have any previous experience in light guides, a major part of the project was actually studying the subject. I figured the best way to learn about them was simply to search for examples of light guides used in different applications. I discovered the term *light guide* had slightly different meanings in different contexts so I tried to go through as much material as possible to form an idea of everything the term encompasses.

The literature I found consisted mostly on brochures and datasheets provided by companies manufacturing light guides. Literature with a more general approach to light guides seemed very scarce. Luckily, I found an application brief called *Light Guide Techniques Using LEDs* from Avago Technologies (2006). It was a short and informative paper which explained light guides in a very pragmatic manner. Literature on optics in general was easy to find.

The research papers were mostly very technical and concentrated mainly on evaluating different methods for improving a light guide component. For example, there was a lot of research done on optimizing light guide panels' light extracting features or testing different methods for creating an efficient dot pattern. The multitude of such studies can be explained by the fact that light guide panels are the central element of back light units used in LCD screens (Kim and Semenza, 2012).

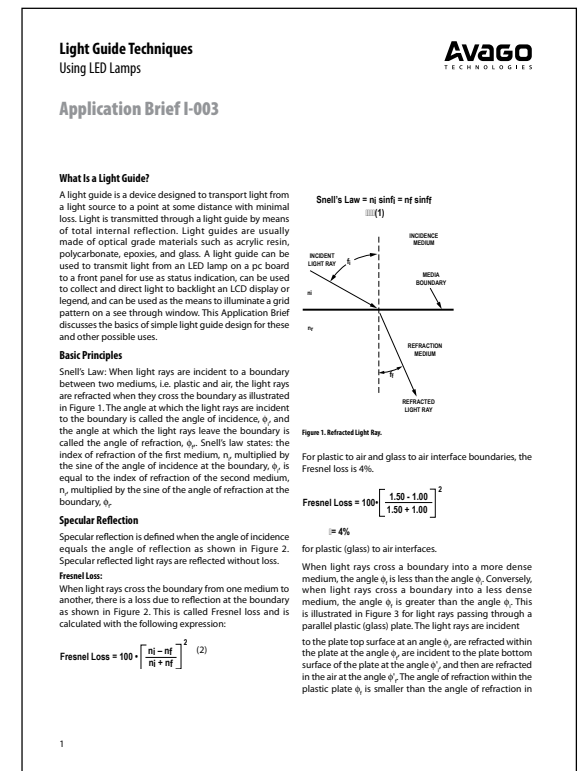


Figure 38: Light Guide Techniques Using LED Lamps (Avago Technologies, 2006)

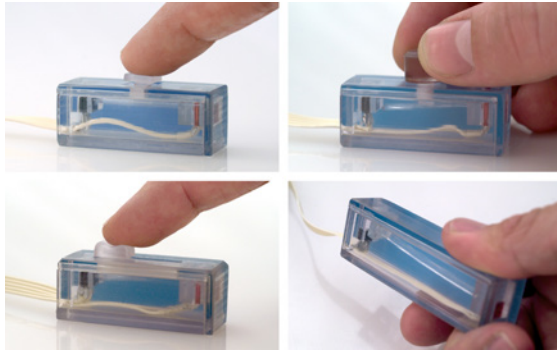


Figure 39: 3D printed mechanical sensors

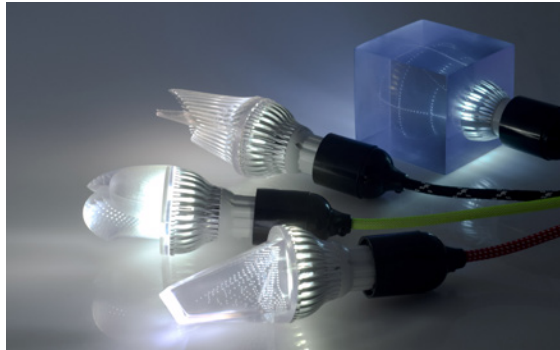


Figure 40: 3D printed light bulbs

Figure 41: 3D printed character with embedded light guides which transfer image projected from the bottom to the character's eyes

An interesting exception was a research paper from Disney Research called *Printed Optics: 3D Printing of Embedded Optical Elements for Interactive Devices* (Willis et al., 2012). It discussed the future possibilities of directly integrating optical elements into products in their 3D printing process. I was intrigued by Disney Research's novel approach to the topic. Most of the examples were small toy-like objects with some sort of simple interaction which made the topic, as well as the implication possibilities, very easy to understand. I believe that it was also the reason why the publications had been quite popular and featured in many design blogs.

In addition to Disney Research's study, there were also some other research with a similar, more experimental, approach to light guides. In most of these studies, light guides were used in objects placed

on a horizontal screen to interact and extend the screen. Probably the most interesting examples were the two studies done for *Microsoft PixelSense* (previously called *Microsoft Surface*), an interactive device which can detect objects placed on the screen based on infrared sensors (Microsoft 2012). The earlier study, done in 2009, was about a drinking glass which could detect the liquid level inside the glass and prompt a refill (Dietz and Eidelson, 2009). This was done using a prism inside the glass that reflected the infra red light back to the screen depending on whether or not there was liquid around it. A relating study done in 2010 featured a toy, remarkably similar to the one seen later in Disney's study. It was a monster toy with a big eye formed from fiber optic bundle that transferred images on screen to the eye (Hoover, Cabrera and Aumiller, 2010).



Figure 42: Monster toy with fiber optic eyes keeping an eye on the liquid level inside the drinking glass

The two experiments were also combined in a charming demonstration where the toy would constantly keep an eye on the drinking glass and announce that he was thirsty when the glass was empty (The Microsoft Pixel Sense Blog, 2009).

In addition to research findings, I was also inspired by a device called *littleBits* which we had in our office. *littleBits* is a device for prototyping and learning basic electronics with modular building blocks (littlebits, 2014). I had some time to play with the device and I really liked the idea of combining different pieces to achieve different effects. The modularity of the device highlighted each module's unique ability to harness and manipulate the electric current. Furthermore, the designers had been able to achieve a toy-like aesthetics without hiding any of the electronics. This made the device appear technical and



Figure 43: littleBits electronics prototyping device with modular parts

still easy to approach. In addition, the attaching mechanism was done with magnets and it was very easy to switch between the modules.

We also had a demonstration device, which was especially ordered for our team's illumination prototyping to test simple illumination effects by attaching different coloured modules to it. The user could test different colored diffusers and adjust the intensity of light with a dimmer switch. One of the team members had also developed a software that could be used to adjust the brightness automatically according to a given pattern. Although this device wasn't directly related to light guides either, it helped me to form a general idea of what my device could be like.

3.2. Early Experiments

I wanted to include prototyping into the project early on to get first hand experience in addition to the knowledge from the research. As soon as I started understanding how light guides worked, I wanted to test if I could make one myself. The first experiment was making a simple light guide panel from 3mm acrylic sheet. The material I happened to use was fluorescent orange acrylic which by its nature has an interesting illumination feature: the edges of the sheet glow from the light that is absorbed by the surface. To the second light guide panel, I added a pattern which would become denser towards the other end to compensate the light loss and distribute the light more evenly. The patterns were designed using Adobe Illustrator and Rhinoceros 3D and milled with CNC machine using a 60° cone shaped drill tip.

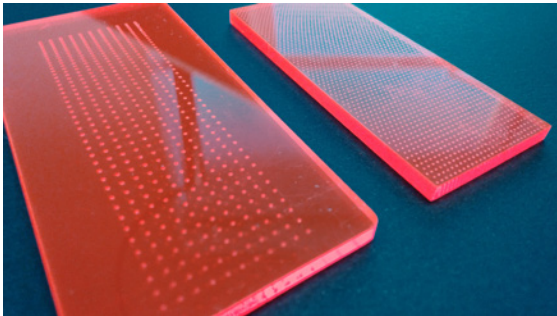


Figure 44: Two different patterns drilled on the surface with cone shaped drill tip.

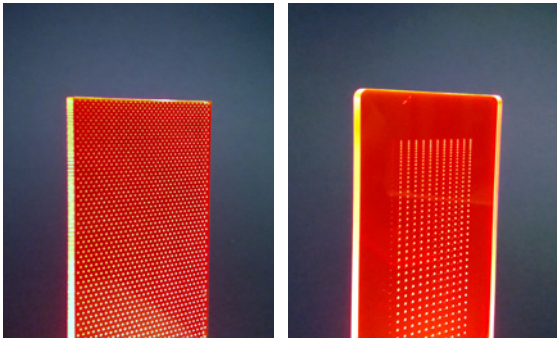


Figure 45: Light guide panels lit from the bottom.

The light guide panels worked relatively well and it was inspiring to see that the effect could be achieved quite easily. As I fiddled with the parts I noticed an interesting effect caused by the different patterns. When the panels were placed together and light was moved from one the layer to the other, it created an nice visual effect. To elaborate on this idea, I decided to try to create a simple animation using five clear acrylic parts that were left over from another project. This time, I first drew the patterns with Illustrator and then cut them out with vinyl cutter to create stencils. I then used micro abrasive blaster to etch the pattern on the surface. The idea seemed to work and the five layers, when lit from the side, created the desired effect. I concluded that I would develop this idea further at some point.

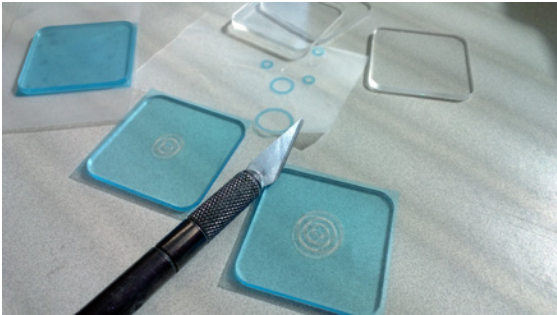


Figure 46: Vinyl cut tapes as stencils



Figure 47: Microabrasive blasting to create the patterns



Figure 48: Patterns formed on the surfaces after blasting

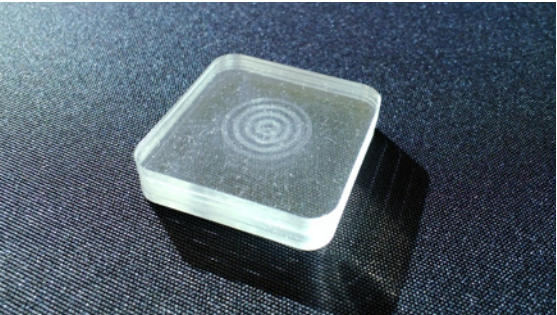


Figure 49: Light guides stacked

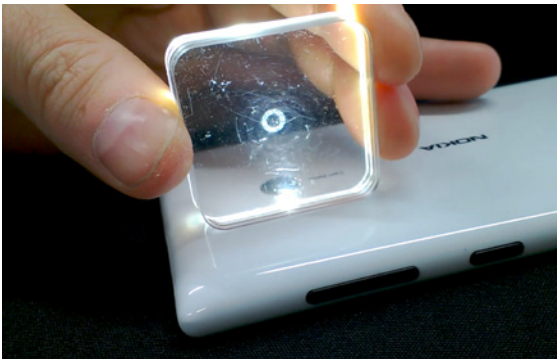


Figure 50: Light shone inside makes the patterns glow.



Figure 51: Illuminated circles appear and disappear when the stack is moved over the light.

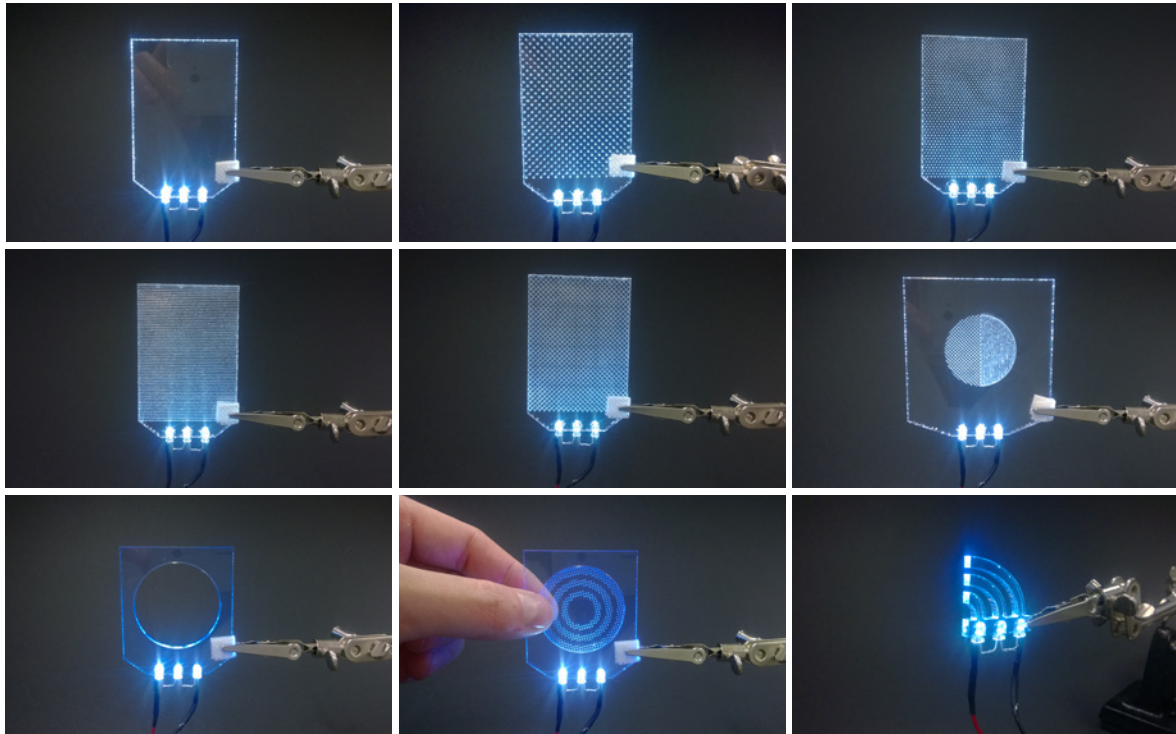


Figure 52: Testing light extraction with different laser cut patterns. On the bottom row, a light guide panel with a separate middle piece and an arc shaped light guide

Since I had now used CNC and sandblasting for the patterns, I thought it might be interesting to try other methods as well. From the research, I had learned that one method for creating light guide panels is by laser etching. The proto team didn't have a laser cutter at the time, so I used the laser cutter at school. The laser cutting proved a very fast method and it was easy to execute the patterns designed with Illustrator. However, I wasn't able to optimize the laser cutter's speed and power to get the quality I wanted. Furthermore the workshop was

going to be closed for the summer, so laser cutting wasn't a feasible option for further prototyping. I also tried 3D printing clear parts with a material called Objet VeroClear. I first tested how the print direction affected the quality and then if it could be improved by sanding. The clarity of the 3D printed optical component was in the end surprisingly good. However, I didn't see a reason to use it later because the quality of the CNC machined acrylic parts was still noticeably better and didn't require so much post processing.

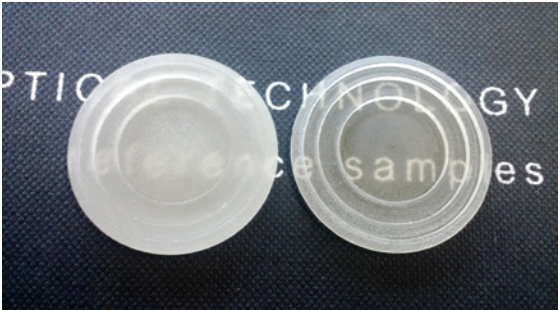


Figure 53: Two 3D printed Fresnel lenses using a clear print material called Objet VeroClear. The clarity of the material is much better when printed flat (the one on the right) than when printed sideways (on the left).

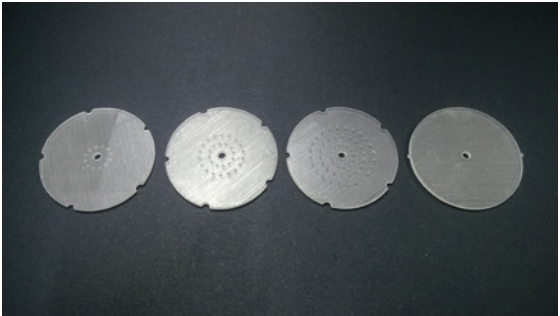


Figure 54: 3D printed parts for testing how sanding and polishing affect the clarity of the material



Figure 55: Sanding the parts starting first with a coarser paper and moving on to a finer grit

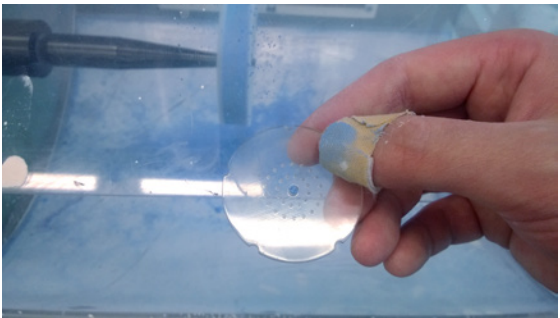


Figure 56: Using a polishing wheel to finish the surface

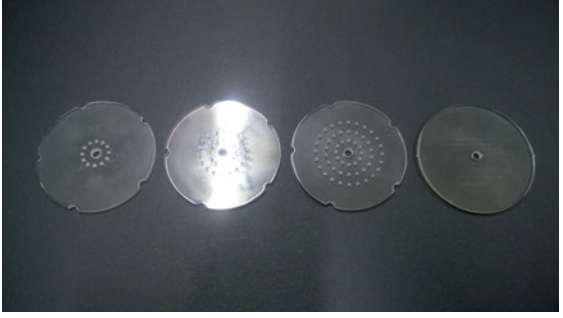


Figure 57: After sanding and polishing the transparency of the 3D printed material was surprisingly good.

4. Concept Development

4.1. First Functional Prototypes

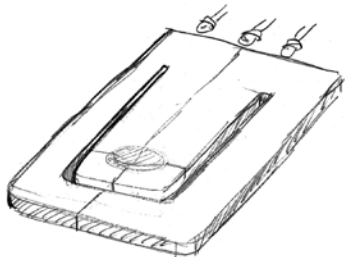


Figure 58: An early sketch of a simple push button

SIMPLE PUSH BUTTON

One of the examples in Disney Research's study was a flexible light guide used as an infrared transmitter (see Fig. 39 on page 30). I wanted to test if the same principle of bending the light guide could be used to create a visual light effect. I 3D modelled a simple sandwich structure with three layers. The top layer had a dot pattern on it to indicate a button. A U-shaped cut around the pattern would enable the button to be pressed inward. The second layer underneath had a hole in it cut in the shape of the button and a dot pattern on top of it. At the bottom was a third layer with no holes or patterns on it. The idea was that light shone into the first layer would

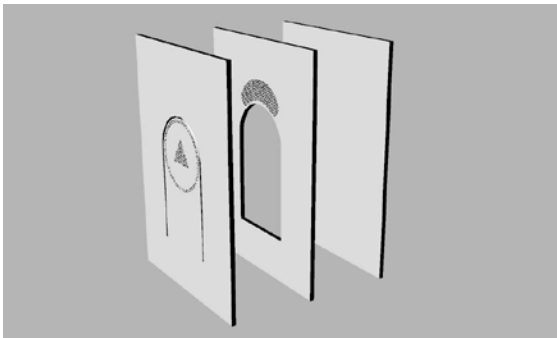


Figure 59: An exploded view of the push button's sandwich structure modelled with Rhinoceros 3D

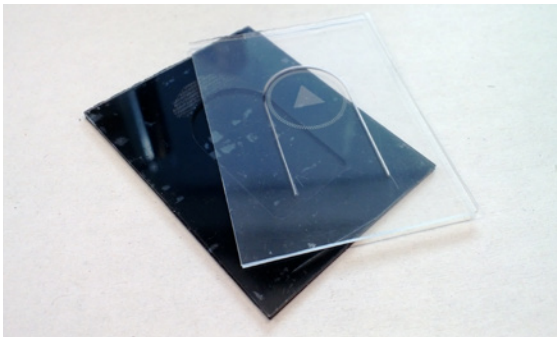


Figure 60: Black tape added behind the bottom layer to make the effect more visible



Figure 61: Light coming from the bottom is extracted by the small holes and the button is illuminated.

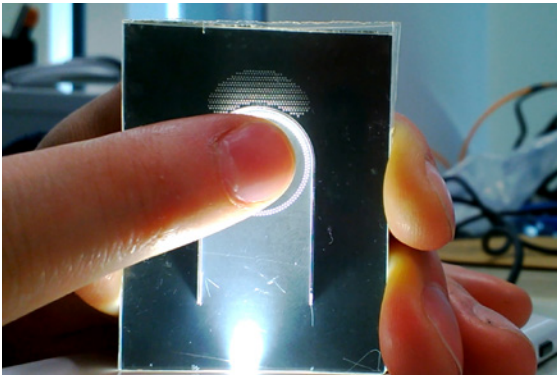


Figure 62: Light enters the second layer and illuminates the area over the button.

first illuminate the dot pattern for the button. When pressed, the button would sink into the hole on the second layer. Some of the light would then transfer into the second layer and illuminate the pattern on top of the hole and give visual feedback from the action. The third layer on the bottom would support the structure and prevent the button from sinking further. The solution worked surprisingly well considering how simple the structure was.

TUNING KNOB

The effect of the five light guide layers made earlier was quite impressive so I definitely wanted to incorporate that in the final concept. I wanted to design a mechanical function with which the animation could be controlled. I started designing a large tuning knob that would elevate the light guide panels when turned. This way the light could be directed into different layers without moving the light source itself.

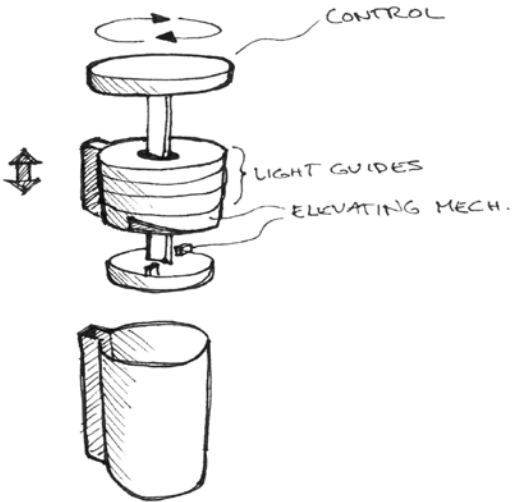


Figure 63: An early sketch depicting the possible construction of a tuning knob

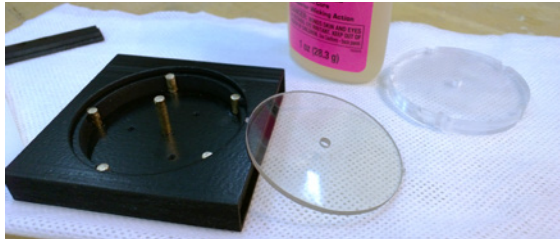


Figure 64: Light guide layers glued together and brass rods inserted in the casing to keep the stack from spinning and tilting

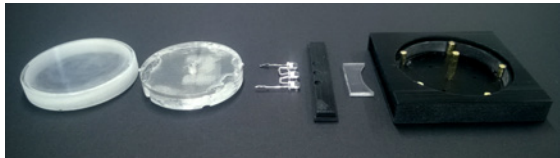


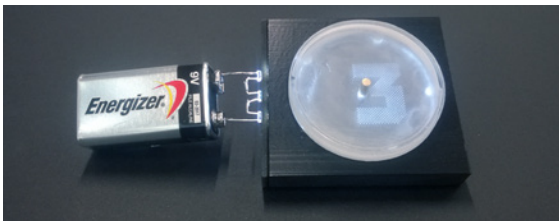
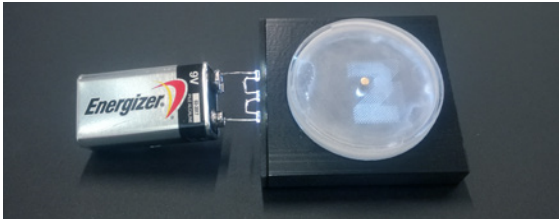
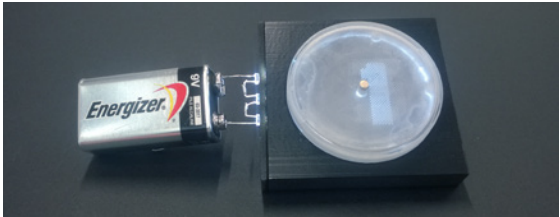
Figure 65: An additional light guide inserted between the LEDs and the layers to transfer the light

Figure 66: By turning the knob, light enters the different layers and illuminates the patterns. ▶

The hardest part in designing the knob turned out to be getting the stack to elevate evenly. I eventually added brass rods on the sides to guide the light guides and reduce the friction. For the light guides I used three 2mm clear acrylic parts which I glued together. The end result wasn't very nice looking but I was very pleased with the mechanical structure and how the whole thing worked. I concluded that I would later try the mechanism with more and thinner layers.

LIGHT GUIDE COASTER

Using a similar principle, I came up with an idea of a light guide coaster utilizing two light guide layers. I had an idea of a surface that would react if the user



pressed it or placed an object on it. I 3D modelled a casing that would cover the light guides and a spring inside which would retract when the top was pressed down. Light entering from the side would first go into the top layer which would shine upward. When pressed the lightguides would sink further inside the casing like a piston and the light would enter the bottom layer. The bottom layer wouldn't shine any light upward but instead direct the light down and create a glowing illumination around the casing. The idea worked relatively well and I personally liked this interaction. Later, however, I decided not to include it in the final concept. I figured that, from the point of view of how light guides were used, it didn't differ enough from the large tuning knob.

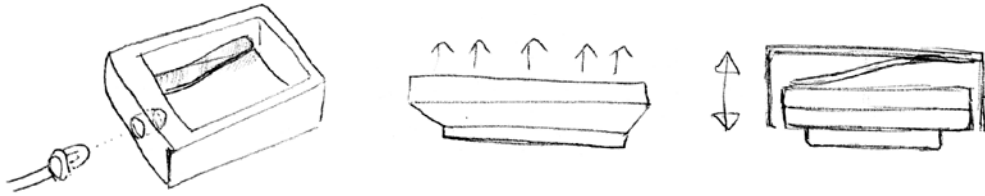


Figure 67: Some quick sketches from the ideation process of the light guide coaster prototype

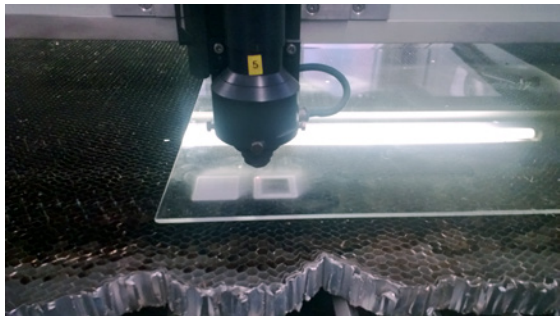


Figure 68: The light guides were cut from 2mm acrylic using the school's laser cutter.

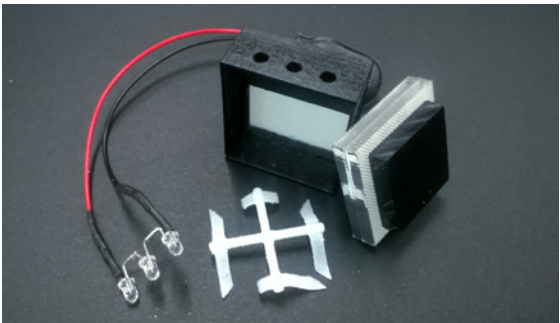


Figure 69: The spring mechanism was quite thin and would break easily. The additional black piece was glued underneath the two light guide layers to elevate the structure.

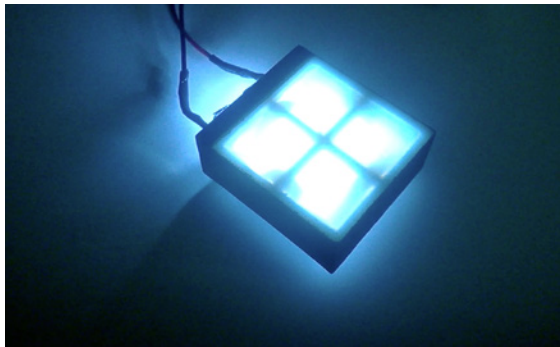


Figure 70: Light enters the first layer and illuminates the top surface.

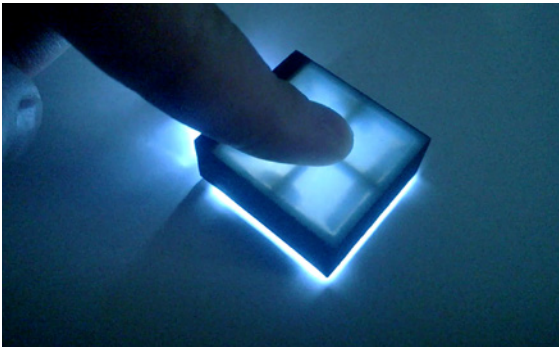


Figure 71: When the surface is pressed, light enters the second layer and illuminates the bottom of the coaster.

4.2. Feedback and Evaluation

Although I was working on the project independently, I reported the progress to my manager frequently and we had conversations on how I would continue. Furthermore, we had a team meeting on Fridays, where we would all share what we had done during the week and what we would focus on next. I presented my ideas and prototypes in the team meetings and received feedback and suggestions from others. The team meetings were also a good chance to look at schedules and agree on certain dates. However, my progress wasn't monitored in any way and I felt that I was trusted to schedule my own work.

At one point me and my manager had a meeting with one member of the *Color and Materials Design* team. I saw some of their illumination related prototypes and received some visual material they had used for ideating. Later I also presented my prototypes to a Beijing based *Color and Materials Design Forward* team. The conference call meeting was arranged by one of our team member Michihito Mizutani, and the idea was to share different project across the teams. At first, I was a bit concerned about how the team would react to my rudimentary prototypes which were meant to serve more as quick proof of concept than to impress a CMD team. Despite my initial con-

cerns, they seemed quite interested in my project and we had an interesting discussion on how the teams could collaborate in the future.

We also had a conference call to Salo to consult an optical engineer Marko Parikka. During our call, I presented the experiments I had done and Parikka some of their earlier projects relating to light guides. He also explained the method of using SLA prints to prototype optical elements (see page 27). After the call, Parikka also sent me some presentations from their earlier light guide projects. The examples in the presentations depicted some very impressive illumination effects that were achieved by intricate light guide designs.

The conversations I had with the CMD Forward team and Parikka were very informative. It was interesting to see how the topic of illumination was dealt with so differently in both teams. Other side focusing on the experiential aspects of light and visual nuances and other on the technical implementations and optical behavior of light. I hoped my work would eventually situate somewhere between the two by demonstrating a technical subject but with the emphasis on the user experience.

4.3. Final Concept Unfolds

In the beginning of the project, I wasn't exactly sure what the final product would be like, other than some sort of a demonstration device for light guides. However, as the prototyping went on, an idea of the final model began to form in my mind. Disney Research's study and the littleBits product were very inspirational and I wanted to include some of the elements that were prominent in their approach into my model. Such features included: simplicity, playfulness and strong emphasis on interaction.

Along the prototyping, I had become aware of the certain limitations to the final model. It was clear that I would not be able to work at a microscopic level or to achieve a very high optical quality due to the machines available. Furthermore, I wasn't an optical engineer so why would I try to accomplish something I had no education for? Instead, I decided I would use my skills as a designer to create a meaningful interactive device for demonstrating light guides with the emphasis on interaction and versatility over optical precision.

Light guides are essentially about manipulating light. To emphasise this ability, I thought it might be interesting if the light source stayed the same and different modules were used to achieve different effects. Similarly to how the littleBits device uses modules to affect the flow of electricity, this device would use light to flow through detachable modules. Further-

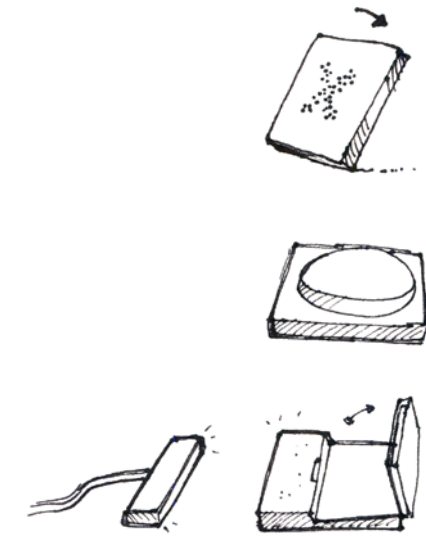


Figure 72: A sketch from the concept development process depicting a light source with multiple detachable light guide modules

more, I imagined it to be a powerful effect to see the otherwise dull parts "come to life" when attached to the light source.

The interactions used in the modules should be simple and universal for people to immediately know how to operate the device. For the user to form a conceptual model of how the device works, I decided to use simple mechanical switches that people know how to use almost intuitively. However, it would be important to keep the interactions and the resulting effects abstract enough so that they wouldn't imply a specific application and therefore take away the attention from the light guides.

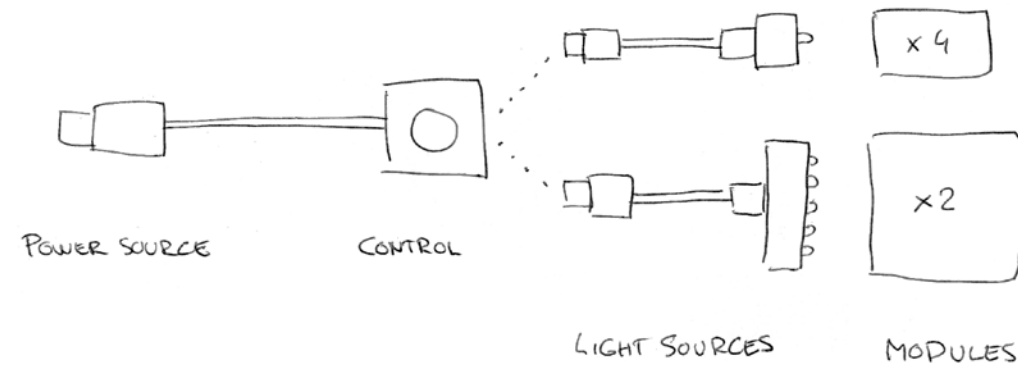


Figure 73: A schematic drawing of the final concept including power cables, light intensity controller, two light sources and light guide modules

I figured that using one or two light sources for multiple modules would emphasize each module's unique ability to manipulate light. I decided to include two light sources to the device: a small one with only one LED and a larger one with multiple LEDs in a row. The larger light source would be suitable for the tuning knob which I had been prototyping earlier. Another module for it could be a *light guide panel module* which would demonstrate light guides' ability to form smooth and uniform surface illumination. The little light source with a single LED would have 3-5 modules. These modules would be smaller and have a simpler construction. Compared to the large modules, they would emphasize light guides' ability to tunnel light more directly. By this time, I had three functional prototypes that I could implement to the final concept: the simple push button, the large tuning knob and the light guide coaster. The last two had fairly complicated structures and they worked on the same principle (light entering different layers), so I decided to focus on the tuning knob and dis-

card the coaster. I decided I would come back to the modules for the larger light source later and focus more on the smaller modules, for which I only had the simple push button as one potential prototype.

After discussing with Michihito, we came up with the overall assembly of the device. We decided it would be clearer to use the same operating switch for both light sources. We ended up choosing a dimmer switch so the user could alter the brightness of the light. This would be useful especially with the light guide panel module where the brightness of the surface could be changed. USB cables would be used to connect the light sources to the dimmer and the dimmer to the power source. Having USB connections between the components meant that it would also be possible to connect the light sources straight to the power source or a computer. The latter option would be beneficial in the case if it was needed to experiment with a programmed sequence of light brightness instead of manual control.

5. Designing the Device

5.1. Shape, Size and Material

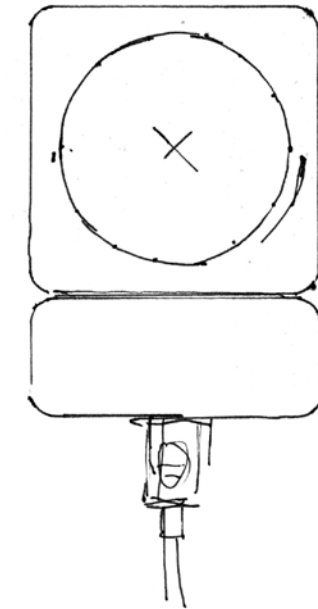


Figure 74: A quick sketch drawn to evaluate the size and proportions of the parts

In addition to prototyping, 3D printing would also be used to make the casings for the final models. Since there were going to be multiple parts in the device, machining them would have simply taken too much time. The actual light guide parts, on the other hand, would be machined from clear acrylic and polycarbonate sheets.

Since the device would consist mostly of different types of switches, I already had an idea of the overall size of the modules. I wanted to keep the parts quite small so they would be easy to play with and they could be stored in compact size. Furthermore, the small size would emphasize light guides' ability to manipulate light effectively as the modules would create interesting effects to the light without bulky and complicated constructions. In other words, the light guide modules should appear quite simple and mundane when not attached to the light source.

It was important that the device would be easy to use and as little instructions as possible was needed. The shape and size of the parts should allow the user to quickly figure out which modules attach to which light source. Hence, the design should indicate the device's *affordances* which "provide strong clues to the operations of things" (Norman, 1988, p.9). Moreover, the shape and size of the parts could be used to create *physical constraints* that work as "physical limitations [to] constrain possible operations" (p.84 - in this case to limit the number of ways to attach the modules).



Figure 75: Mood board inspiration for functionality, form language and packaging, including Google's Project Ara modular smartphone, Muji wall-mounted Bluetooth player and Kano computer and coding kit

The light should play the main part in the device so it would be important to keep the form language anonymous and minimalistic. I tried to avoid any extra styling of the modules and the dimensions and proportions were mainly dictated by the space needed for the light guides and mechanical structures. Furthermore, since the parts would require hand finishing, I figured that simple geometrical forms with flat surfaces would later prove beneficial. The only characteristic visual feature I decided to add to the parts were the noticeably rounded corners. I wanted them to make the otherwise neutral modules appear softer and more playful. The rounded corners would also serve a functional purpose as they would create a clear visual break between the parts and thus emphasize the modularity of the device.

"Affordances suggest the range of possibilities, constraints limit the number of alternatives. The thoughtful use of affordances and constraints together in design lets the user determine readily the proper course of action, even in a novel situation", (Norman, 1988, p. 82)

5.2. Attaching Mechanism

I really liked the way it was possible to change the modules in the littleBit product. Magnets made switching between the modules easy and fast so I decided I would use a similar attaching mechanism. In addition, magnetic fastening wouldn't wear the 3D printed parts as much as a mechanical solution.

Both the larger and smaller light sources would have an overhang which would sink into a pocket on the module's end. Two magnets integrated into the light source would attach to the ones on the module. The LED on the smaller light source would be in the middle making it possible to attach the modules either way. The magnets on the smaller light source would need to be placed in the corners for all of the modules to work (see *slider module* in next chapter).

The LEDs on the larger light source would be placed slightly higher in order for the light guide mechanisms of the large tuning knob to work. This posed a risk that the user might attach the modules the wrong way. To prevent this from happening, the magnetic poles would be positioned so that the light source would reject the modules if the user tried to attach them upside down, and thus compensate for the physical constraints not afforded by the shape and size of the modules. The magnets would provide a subtle solution to the problem and remove the need for any added visual clues that might distract the attention from the illumination.

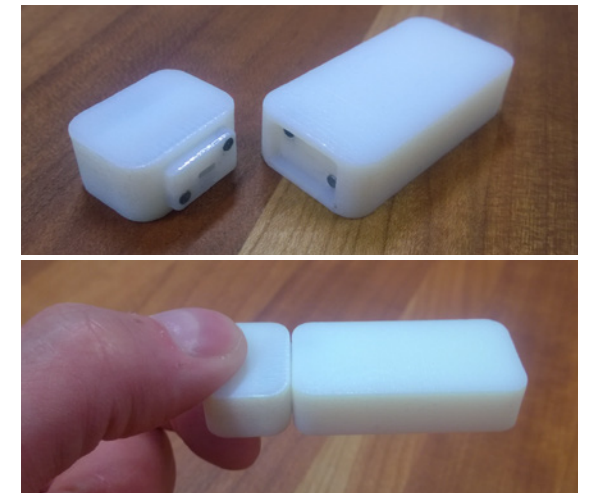


Figure 76: Magnets proved to be an easy and gentle solution to the attaching mechanism. The small light source would need to have the magnets in the corners.

To test the fastening mechanism, I 3D printed parts representing the light source and the module. For the magnets, I chose 2mm x 2mm cylinder shaped, strong *neodymium magnets* that we had in the workshop. The fastening mechanism worked really well and the attachment was firm enough to keep the parts together but light enough to allow the user to easily switch between the modules.

5.3. Light Guide Modules

My criteria in designing the modules for the smaller light source was that they should all have a simple, familiar interaction but each conceal a unique light guide structure. As with choosing the modules for the larger light source, I wanted each small module to represent a different way of implenting light guides, thus adding to the versatility of the device. In this chapter, I will explain the construction and working mechanism of each light guide module and present some of the earlier versions along the way. Pictures of the actual illumination effects are presented later in chapter 8.

ROCKER SWITCH

I started going through different types of switches and thought of interesting ways to integrate light guides into them. One idea came up when I was sketching a rocker switch and thinking of ways light guides could be used to illuminate the different sides of the switch. In this solution, two separate light guides would change their position along with the switch in order to carry the light to either side. First, a short light guide positioned on the end of the switch would direct the light from the light source inside the module. When pressing on either side of the switch, one of the light guides would then align with the entry light guide and allow the light to move forward. Depending on the position of the switch, light would enter either of the two light guides and then be directed up to the surface of the switch.

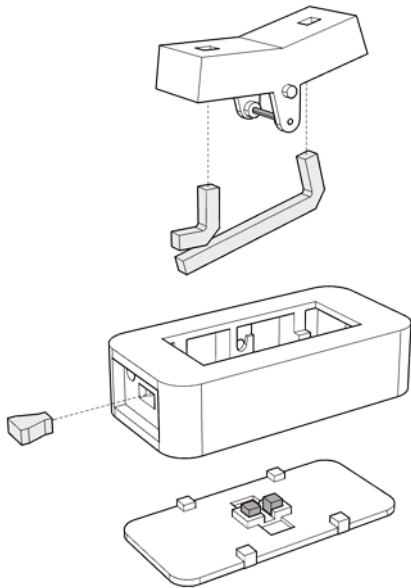


Figure 77: An exploded view of the final 3D model of the rocker switch. The pin on the switch and the two magnets on the bottom plate make the switch snap in either position.

For this model, it was crucial to get the rocking axis and the angles right so that the light guides would align properly in both positions. I was very pleased to find out the idea worked and the effect was very clear. Once I concluded the light guides worked, I started improving the switch's rocking mechanism because I wanted it to clearly snap on either side. I concluded that the spring mechanism used in regular rocker switches would have been difficult to use in this case because of the switch's unique construction. Instead of a spring, I would use two magnets on the bottom of the casing two snap on a pin attached to the switch.

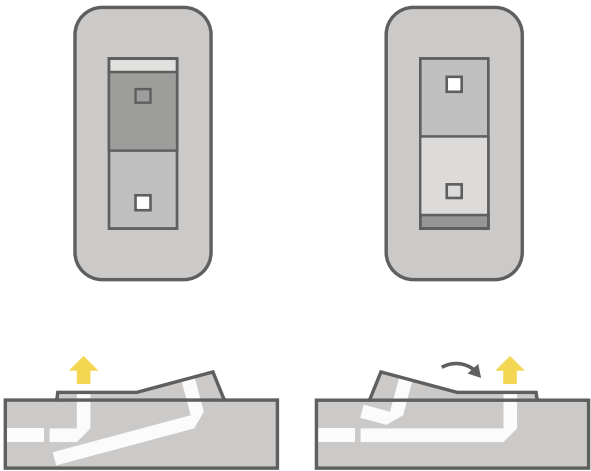


Figure 78: An illustration of the light guide construction inside the rocker switch. Attached to the switch are two L-shaped light guides. In the first position, light enters the shorter light guide and is directed to the surface. In the second position, light enters the longer L-shaped light guide which then carries the light to the farther side of the switch.



Figure 79: Some of the earlier prototypes along the way. In the middle version, the light guides don't come all the way through the surface. The idea was that they would stay invisible until attached to the light source. However, the illumination wasn't so strong and the sockets were difficult to clean from the support material so I discarded the idea.

SMALL TUNING KNOB

Although I already had an idea of the bigger tuning knob, I was interested in the rotating mechanism and thinking ways to make a similar smaller knob that would implement light guides in a simpler way. I decided to make a simple knob that would indicate its position with a small light on the edge of the knob. Light guides inside the module would allow the light to transfer from the side of the module to the surface of the knob.

The final design of the module was very simple: inside the module light would first travel through a horizontal light guide towards the center axis and finally reflect it upward. A second light guide attached to the knob would then capture the light and carry it to the side and finally reflect it upward on the surface of the knob. I first made a smaller prototype of the module to make sure the idea worked. I concluded that the idea was scalable and later made a bigger version of the module where the effect was more noticeable. With this module, I noticed that it was important to have the prisms well polished as some of the light would inevitably escape from the corners. Furthermore, it was crucial to get the light guides as close to each other as possible to enable the light to effectively transfer between them.

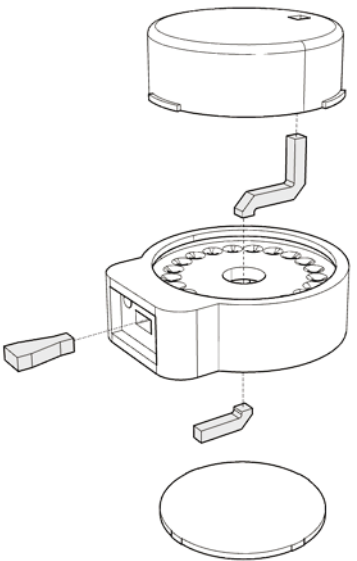


Figure 80: An exploded view of the final 3D model of the small tuning knob. The two light guides connect in the middle to transfer the light to the surface of the knob.

As with the rocker switch, I wanted to include some resistance to the mechanism. I wanted the knob to rotate with noticeable steps instead of spinning loosely. This haptic feature proved to be more difficult to achieve than the actual lighting effect. Eventually however, I was able to come up with a design that produced the desired effect. After being rotated a few times the mechanism also improved as it lost some of its rigidity.

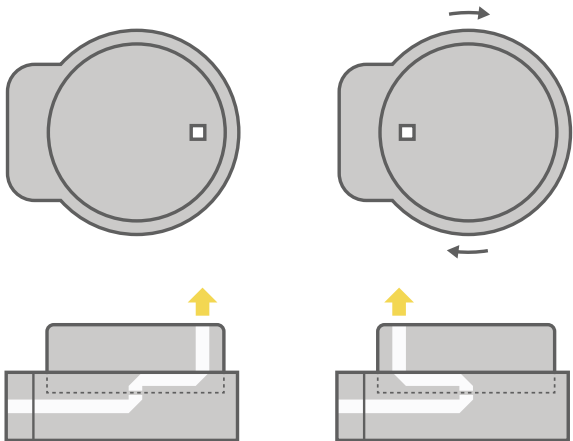


Figure 81: An illustration of the light guide construction inside the small tuning knob. Light travels inside the module to the top surface through two light guides. The corners of the light guides act like prisms and turn the light 90°. When the knob is turned, the upper light guide revolves around the center axis of the knob while staying connected to the lower light guide.

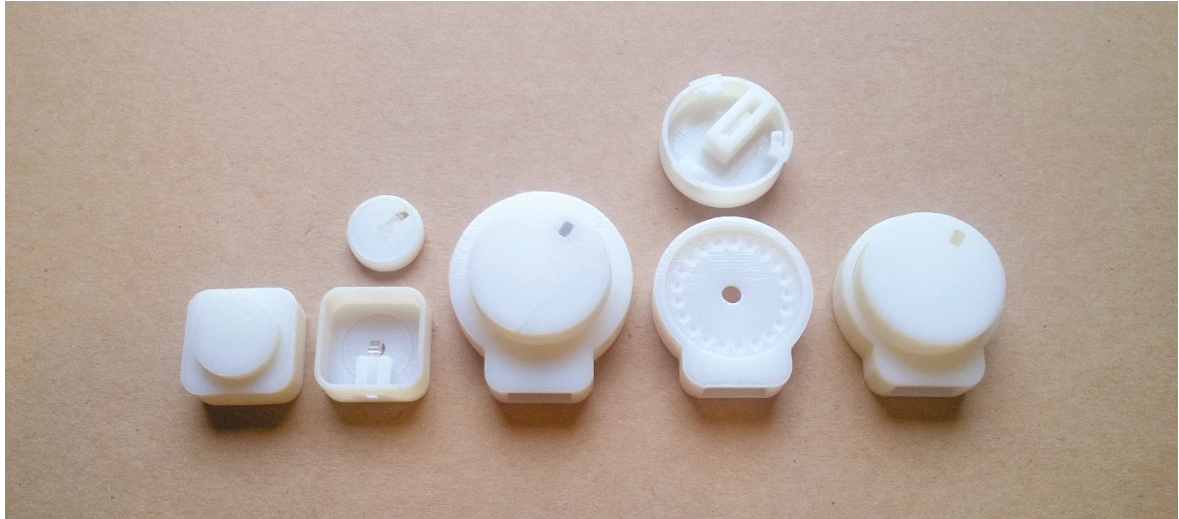


Figure 82: Small tuning knob prototype evolution. The small versions on the left were made first to test if the idea worked. A bigger version with no actual light guides was then made to test the size and proportions. Finally, a mechanism inside the knob was designed to give haptic feedback from the rotation (second proto from the right).

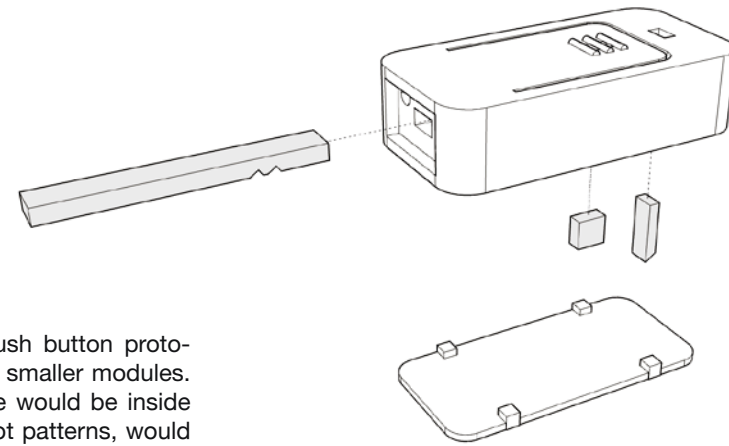


Figure 83: An exploded view of the final 3D model of the push button. A long horizontal light guide tunnels light inside the module as well as provides mechanical response to the push.

PUSH BUTTON

I wanted to develop the early push button prototype further to make it one of the smaller modules. However, this time the light guide would be inside a casing and, instead of drilled dot patterns, would use prisms to illuminate the certain areas. The user would press the top surface of the casing and a U-shaped cut would allow a portion of the surface to sink in. Two illuminated holes on the surface would indicate the button and when pressed, a light would appear over the button to confirm the push.

The light coming from the light source would move along a horizontal light guide inside the module. Two prisms cut on the bottom of the light guide would direct a portion of the light upward and illuminate the button. When pressed the light guide inside the module would bend and redirect the light into a second light guide at the end of the module. This light guide would be vertical and have the bottom cut at an angle that would direct the light coming from the first light guide upward to illuminate the indicator light.

The nice thing about the new version was that because the horizontal light guide was quite thick, it provided a better mechanical response to the push and returned automatically to its original position. The main challenge with this module was to get the reflective angles positioned correctly so that the lights would be bright and the effect clear. To prevent any light from leaking into the vertical light guide before the push, I added opaque tape to some parts to work as light shields.

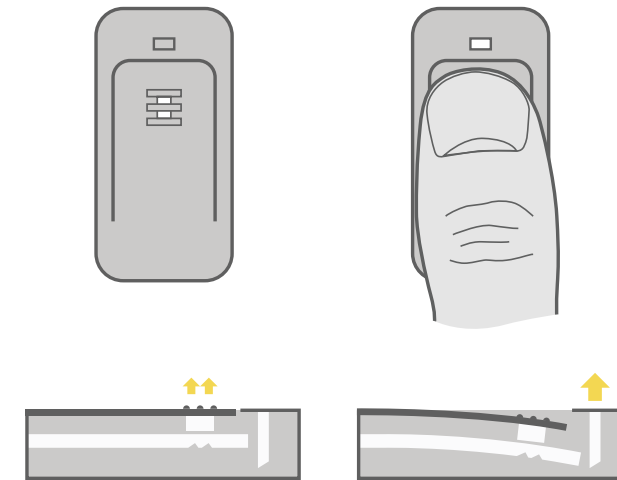


Figure 84: An illustration of the light guide construction inside the push button. Light travels inside the module through a horizontal light guide. Two grooves on the bottom direct a portion of the light upward to illuminate the button. When pressed, light enters the vertical light guide from the bottom. The bottom is cut in an angle so that it directs the light up to the surface.



Figure 85: Push button prototype evolution. The mechanism was tested first with drilled dot patterns. However a much brighter illumination was achieved by using prism cuts. Iterations to the form and size were made before settling with the final design on the right.

SLIDER MODULE

Since I had used prisms in the other modules to alter the direction of light, I thought it might be good to include a module which would demonstrate light guides' ability to tunnel light along curved lines. One of the early laser cut prototypes I had made was a light guide with three adjacent curves tunneling the light from three horizontally placed LEDs to a vertical plane (see Fig. 52 on page 32). It was an adaptation of a standard light pipe used in electronics that were used to direct light from a circuit board mounted LED to a control panel. Furthermore, a similar arc-shaped light guide construction was used in one of the Disney's examples: a 3D printed slab with curved adjacent tunnels formed inside the material guided the light from one side to the other. The movement of light was demonstrated by moving a laser pointer along the other side which caused the light to move along the perpendicular side.

These methods using arc shapes merged into an idea of the fourth module called the *slider module*. The light source would snap to the metal trips inside the groove on the side of the module. The light source could then be slid along the edge and light

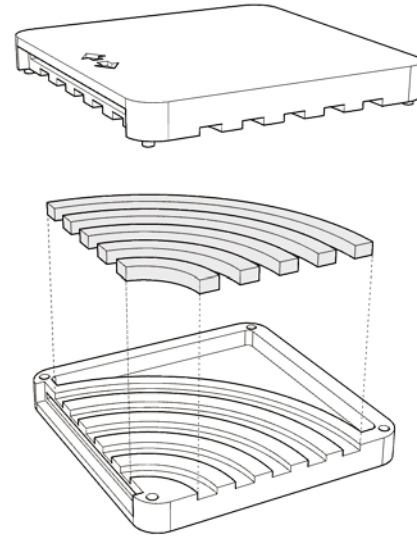


Figure 86: An exploded view of the final 3D model of the slider module. Arc-shaped light guides position inside the similar shaped grooves.

would enter adjacent light guides. The light would then be seen moving along the perpendicular side of the module. For this sliding purpose, the magnets in the smaller light source needed to be placed in the corners and not for example in the middle. The light guides, cut from 2mm acrylic, would be inserted between two 3D printed halves with arc shaped slots. Since the construction of this module is quite simple and straightforward it was one of the easiest to design and build.

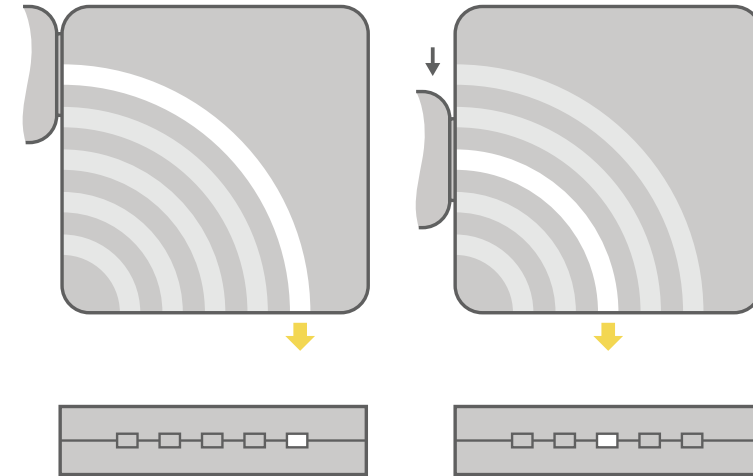


Figure 87: An illustration of the light guide construction inside the push button. Five arc-shaped light guides reach from one side of the module to the perpendicular side. When light source is moved along the module's side, light enters adjacent light guides and the effect is seen on the other side.



Figure 88: Slider module prototype evolution. The shape of the casing was changed to rectangular so that it would be easier to hold. Later the casing was made hollow to reduce the weight of the module.

LARGE TUNING KNOB

After designing the modules for the small light source, I continued developing the larger tuning knob. Earlier I had managed to get the prototype to work rather well but there were things that needed to be improved. First of all, I wanted to add more layers in order to make a longer animation. Secondly, I wanted the layers to be separate and detachable unlike in the early prototype where they were simply glued together. Finally, I wanted to get rid of the central axis so that it wouldn't interfere with the light inside the layers.

In order to have the light guide layers separate, I needed to design a mount that would keep the layers firmly together and enable the knob to lift the mount and the layers when rotated. After multiple iterations on the design, I ended up with a circular mount with three hooks on the side that would keep the light guide layers together. The hooks also prevented the mount from spinning as they fell between the stoppers inside the casing. At first, the stoppers were directly 3D printed to the casing but because of the friction, separate polycarbonate pieces were used the final version.

Removing the center axis proved quite challenging. As the mount was very short, it didn't have room for regular threads. To replace the threads, two pins were first placed on both sides of the mount which had worked well in the previous prototype. However, when the center axis was removed, the mount tilted and got stuck inside the knob. Eventually, this problem was solved by replacing the pins with sections of threads long enough to stabilize the mount. This solution proved functional and in the end the mount elevated evenly.

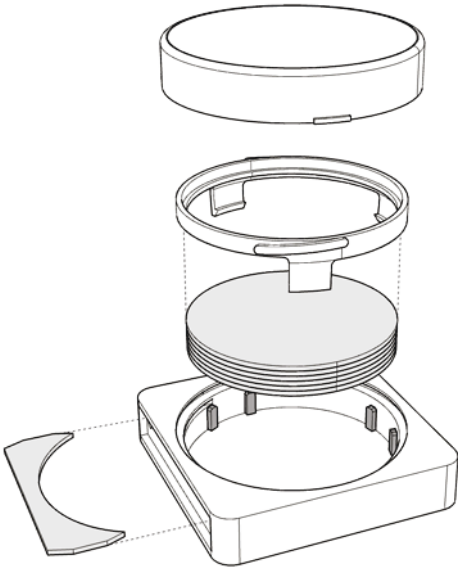


Figure 89: An exploded view of the final 3D model of the large tuning knob. The three hooks on the side of the mount keep the light guide layers stacked.

To include more light guide layers to the module, the material used in the earlier prototype (2mm PMMA) was replaced by 1mm polycarbonate. With a slimmer material it was possible to include five layers to the module. The downside of this was that the light capture from the LEDs would not be as good as with the thicker material.

At some point of the project, our team received samples of three light diffusive materials of different opacities. I needed a part for the lid that would allow the user to see the animation through the lid so I decided to try out the new material. Although the lid was only 1mm thick, the light diffusing properties of the materials were efficient enough to blur the patterns unidentifiable. However, the clarity improved when the material was polished and I finally ended up choosing the clearest of the three options.

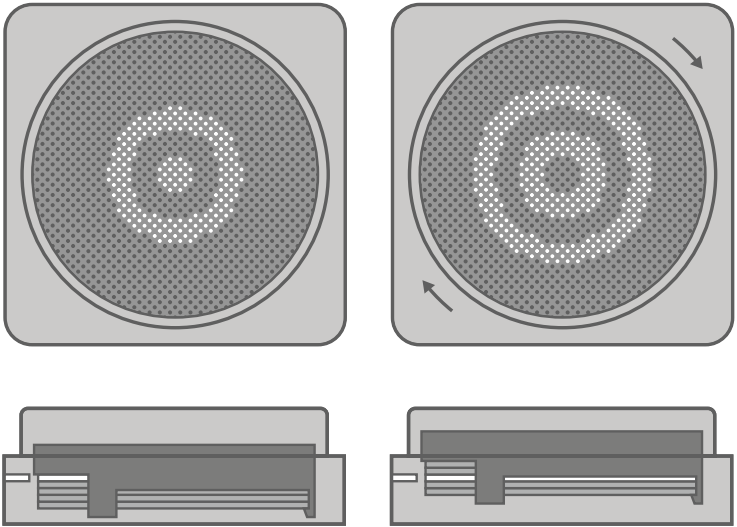


Figure 90: An illustration of the light guide construction inside the large tuning knob. A stack of five light guide panels is mounted inside the knob. Each panel has a different pattern of cone shaped holes drilled on the bottom. When the knob is turned, a mechanism moves the stack up and down. Light coming from the side enters different layers and the pattern changes.

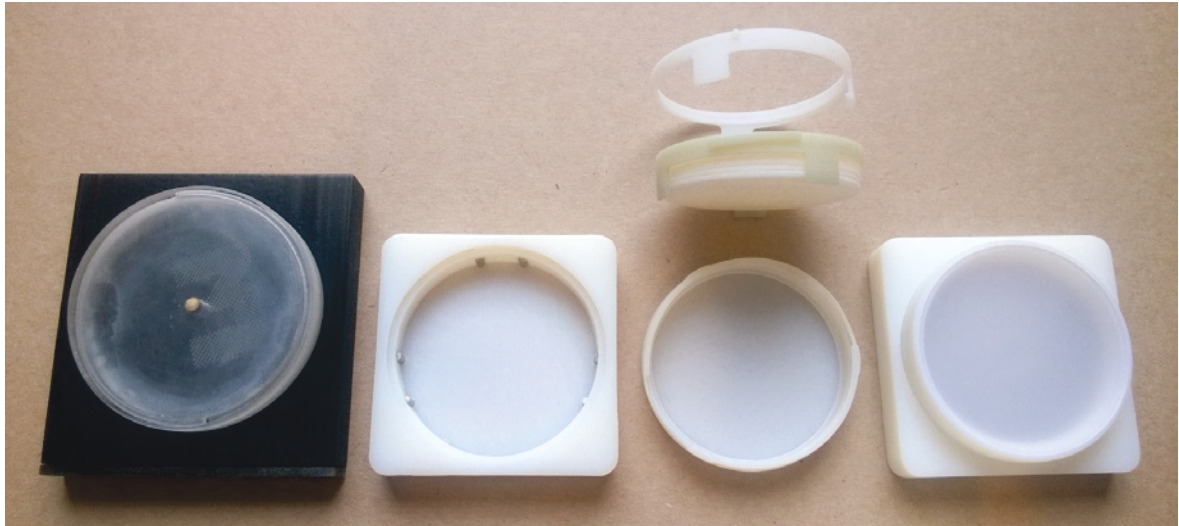


Figure 91: A few of the many prototypes that were made for the large tuning knob module. The metallic stoppers inside the casing were replaced with polycarbonate parts in the final version. The pins on the side of the mount were replaced with a section of a thread to in order to stabilize the elevation of the stack. The top surface of the knob was made from a light diffusing material. It would hide the inside of the knob but allow the illuminated patterns to shine through when attached to the light source.

LIGHT GUIDE PANEL

From the beginning, I had the idea of including a light guide panel of some sort into the final device. The first experiments we made were light guide panels with drilled light extracting patterns on the bottom. Later, laser cutting was also tested for creating similar patterns. An interesting new possibility came about when we contacted a Dutch company LUXeXceL, which is specialized in 3D printed optical components (LUXeXceL, 2014). We thought it would be interesting if some of the parts in my device were ordered from them. I shared my ideas with the company and they were willing to provide consultation on any manufacturing related topics. I made a few 3D models of a light guide panel with extruding elements on the surface and sent them to be reviewed. In the end, however, we decided not to order the models from them. The biggest reason was that I wasn't at all certain whether the design would work because I hadn't yet tested any light guide panel patterns with extruding elements. Furthermore, we already had a proven method for creating relatively effective light extracting features with the CNC machine. Even though we didn't order the model, the collaboration with the company was very enjoyable and we got a lot of good information about the new 3D printing method and how it would develop in the future. Furthermore, we figured there might be some projects in the future with a more developed optical structure suitable for implementing the new technology.

We eventually made the light guide panel using a drill with a 90° tip which appeared to result in a brighter light extraction than the 60° tip used in the early prototypes. In addition, we tested drilling the holes in different depths to find out a good balance

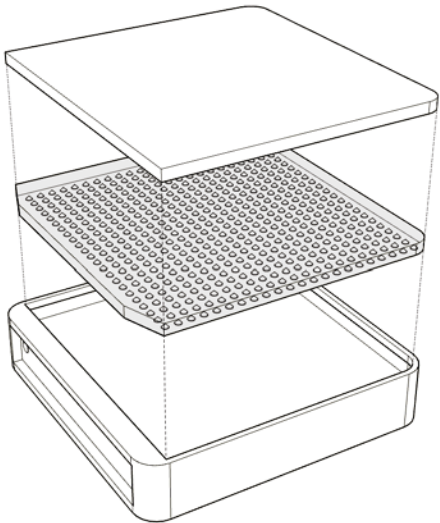


Figure 92: An exploded view of the final 3D model of the light guide panel module

of brightness and uniformity: if the holes were drilled too deep, the extraction points created inside were big and the light was very bright near the LEDs but faded quickly towards the end. If the holes were too shallow, the light was more uniform across the panel but not as bright. To increase the uniformity of the light and make the bright dots disappear, a diffuser made of the same material used in the large tuning knob module was placed on top of the light guide. Furthermore, a reflective tape was placed underneath the light guide panel to reflect back some of the light refracted from the bottom of the panel. This solution seemed to enhance the brightness and uniformity of the light to some extent.

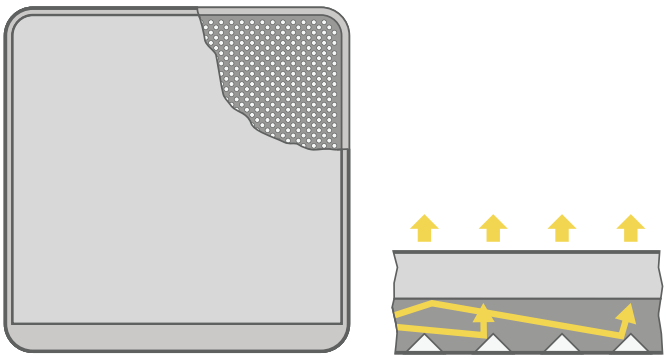


Figure 93: An illustration of the light guide construction inside the light guide panel module. The module consists of two layers: a light guide panel and a diffuser plate on top of it. The light guide panel has small cone shaped holes drilled on the bottom. Light rays propagating inside the panel hit the cones and light gets distributed evenly across the surface. The diffuser plate on top makes the light more uniform.

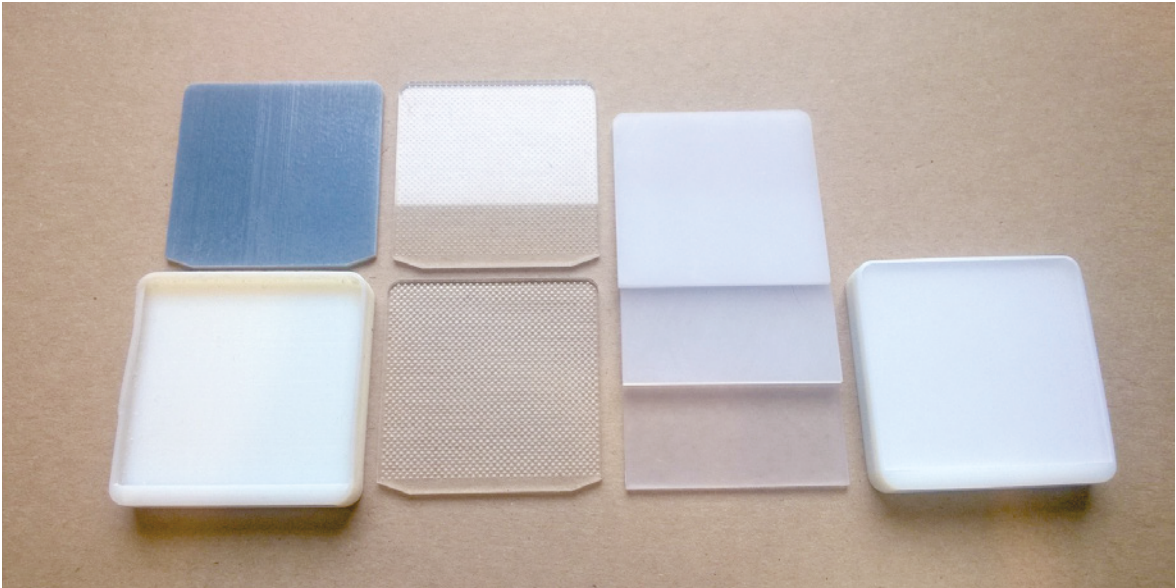


Figure 94: Light guide panel module prototype evolution. 3D printed version was first used to test how the light guide panel would fit inside the casing. Patterns were tested with 60° and 90° cone shaped drill tips. From the three different diffusing materials, the clearest was chosen also for this module.

SLIDER SWITCH (WHICH DIDN'T WORK)

One idea for a small light guide module was a slider switch in which the light entering from the side of the module was supposed to move along the sliding part on top. A small acrylic wedge placed inside a tunnel made of two U-shaped acrylic rods, would slide and reflect the light upward. The slider wouldn't actually touch the reflecting wedge but move it with magnets integrated in both parts.

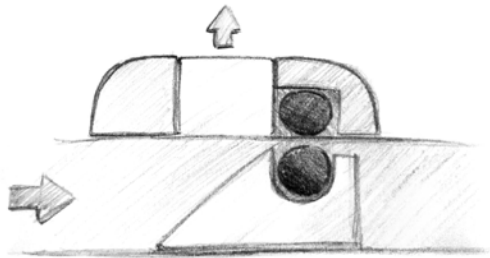


Figure 95: A sketch depicting how the wedge was supposed to reflect the light to the surface

After finishing the prototype, I discovered that the model worked mechanically well but didn't produce the desired illumination. The mirroring part simply didn't reflect the light well enough and the light faded quickly when moved further from the light source. It was then when I realized the remarkable difference between propagating light in an optically denser material with TIR and trying to bounce the light in a space surrounded by reflective surfaces. As a light guide module the prototype was a failure but at least it clearly demonstrated the importance of total internal reflection in a light guide.



Figure 96: the mechanics of the slider switch worked relatively well but the reflected light was bright only when the slider knob was near the light source.



Figure 97: The reflecting wedge was moved inside the slot with a magnet on the slider knob.

5.4. Electronics

For the light guide modules to work properly, it was crucial to ensure effective light capture. Fixing the LEDs inside the light guides were of course out of the question because the parts were modular. Thus, it was important to position the LEDs as near the surface of the casing as possible to make a close connection to the light guide inside the light guide module. Two-millimeter-thick acrylic sheet would be used for the light guides inside the small modules. It was thick enough to capture light inside effectively and it would create suitable sized exit points for the light. Furthermore, the LEDs would need to be smaller than two millimeters to ensure that most of the light would enter the light guide. Eventually, we managed to find suitable LEDs that were small enough but still very bright.

For designing the electronic parts, I got help from my team member Michihito. Since the electronic components were small and they needed to be placed accurately on the printed circuit board (PCB), we agreed that Michihito would do the actual electronic work: PCB connections and soldering of the components. My job was to design how the electronics would fit inside the casings and how the components needed to position on the PCB.



Figure 98: ZSM-S3806-W surface mount white LEDs from JKL Components were used in the light sources.

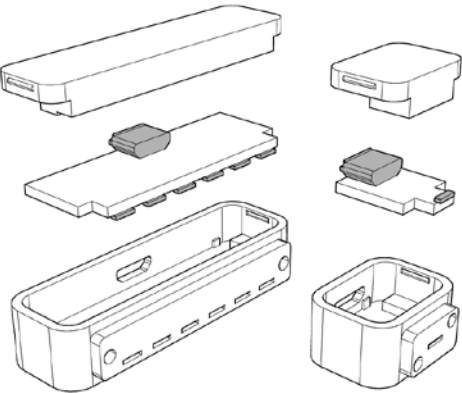


Figure 99: An exploded view of the light sources seen from the bottom. The LEDs on the larger light source needed to be higher so they were placed on the other side of the PCB.

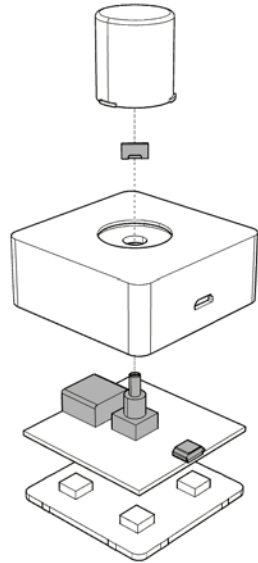


Figure 100: An exploded view of the dimmer switch with a reverse type micro-USB connector

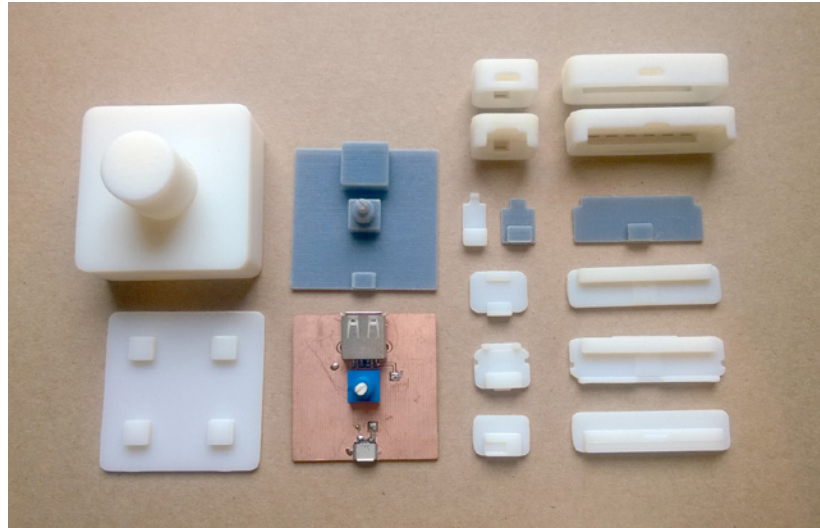


Figure 101: With the 3D printed parts, it was possible to test the fitting of the electronics before they were actually made. Light source casing iterations on the right

A major part of designing the final models was figuring out the integration of electronics. In order to make the casings work, I 3D modelled the electronic parts according to the specifications. It was important that the electronics would fit firmly inside and the LEDs and the USB connectors would align neatly with the holes in the casing. Modelling the individual components proved very beneficial: the first electronics Michihito provided me with fit in the casings nicely and only a few modifications were needed. A casing was also done for the dimmer switch. By Michihito's suggestion, the casing was designed rather big so that it would be stable and easy to control. To connect the knob with the actual dimmer switch inside the casing, I decided to use a separate polycarbonate part which would withstand the mechanical stress much better than the 3D printed material.

One of the tricky things in designing the casings was getting the LEDs and USB connectors at the right height. Because the larger light source would have the LEDs higher, the components needed to be placed on different sides of the PCB. To achieve this, two-sided PCB was used. In the case of the dimmer switch, both USB connectors needed to be on the top side of the PCB or otherwise they would position awkwardly on the side of the casing. Using a standard micro-USB connector would have caused the USB cable to connect to the dimmer upside down. This, of course, would not have affected the functioning of the dimmer in any way. Eventually, however, we decided to order reverse type micro-USB connectors which would accept the USB cable in standard orientation.

6. Finishing the Models

My manager Heikki Hakamäki suggested that I would make five sets of the devices so there would be enough for myself and the company and some extra parts if some of the modules broke. At first it seemed too many and I was worried if I had the time to finish them all. Eventually, however, I figured that I wouldn't get everything right at the first time so instead of aiming for five equally well executed devices, I could think of each set as practice towards the next one. By doing one set at a time, I would know what things needed fine tuning and that way the quality would improve set by set. In addition, we agreed to postpone the thesis report deadline so I could use the remaining internship days finishing the production part as well as I could. Writing the report was something I could continue at home but using the workshop space after the internship might not be so easy.

The final light guide parts were milled from 2mm acrylic and 1mm polycarbonate. Jani Ylinen, who operated the CNC machine, suggested I would use polycarbonate for the thinner parts because it is stronger than acrylic and wouldn't break so easily when removed from the milling block. After the parts were milled, they were cleaned with isopropyl alcohol. The parts with milled dot patterns were cleaned in an ultrasonic cleaner.



Figure 102: The light guide parts were milled from 2mm acrylic and 1mm polycarbonate using the CNC machine.

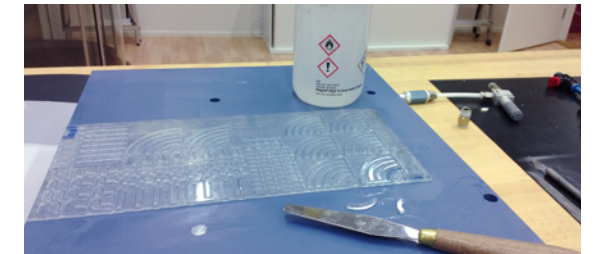


Figure 103: Removing the parts from the milling block

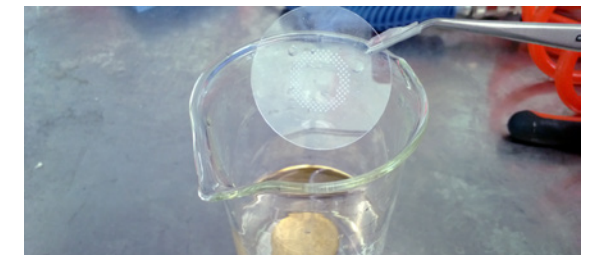


Figure 104: A light guide part for the large tuning knob after being cleaned in the ultrasonic cleaner



Figure 105: Micro abrasive blasting applied to the ends of the light guides. Other surfaces protected with paper

To ensure proper light diffusion, a micro abrasive blaster was used to make the surface of the illuminating ends coarse. Other surfaces were polished with a rotary tool to enhance the total internal reflection and light propagation. Light diffusing plates that were used in the large tuning knob and the light guide panel were milled from the sample material we had received from another company. They were then sanded and polished by hand.

My initial plan was to paint the 3D printed parts white. After testing the painting, however, I was convinced I needed to try something different. The paint highlighted the uneven surface of the 3D print and the result looked quite unfinished. In order to get a nice smooth finish, it would have required multiple rounds of painting and sanding. This was clearly not an option since I would be doing five devices which meant altogether one hundred and five individual parts.

There was nothing especially displeasing about the aesthetics of the 3D printing material. Compared to the test parts painted white, it actually looked more natural and finished. As my manager pointed out, making the parts smooth and white would immediately make them susceptible for more critical



Figure 106: The reflecting surfaces were polished to ensure proper light propagation.



Figure 107: The diffuser plates for the light guide panel and the large tuning knob were sanded and polished to improve the clarity.

evaluation as they would no longer be in the "3D print category". We both agreed that, being a prototyping-driven project, there was no reason to try to hide the fact that they were 3D printed.

The biggest problem with the material as it was, was that it gathered dirt. After fiddling around with the parts a few times, they started to look worn and smudgy. Especially the vertical sides with coarser surface caused by the printing direction, were sensitive to dirt. Sanding the surfaces completely smooth was too rough a solution and would have been extremely hard to do without skewing the geometry of the parts.

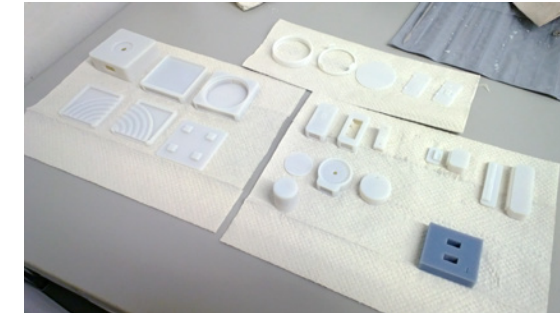


Figure 108: One set of 3D printed parts drying after removing the support material and washing them



Figure 109: Sanding the parts with a sanding pad



Figure 110: Because there were so many parts, it was important to keep everything organized.



Figure 111: Mixing the lacquer which would then be applied using a spray gun



Figure 112: Testing different 3D print materials with lacquer coating. Eventually I made three sets using the white material on the left and two sets using the material next to it.

In Otaniemi, we shared the workshop space with *Nokia Research Center*. One of their employees, Sami Myyriläinen, suggested that I tried coating the parts with lacquer. Before that, I could give the parts a light sanding to remove most of the roughness. With a thin mix of lacquer we were able to achieve the desired result. The lacquer provided a sealed, hard finish that prevented dirt from accumulating on the surface. In addition to the practical benefits, the matt lacquer further smoothed the look of the 3D printing material and gave it a somewhat bone-like feel. Needless to say, I was happy that we had found a solution that looked nice and would make the finishing of the parts a lot easier.

As I had predicted, a range of different problems came up while finishing the 3D printed parts. In order to remove the support material from difficult areas, the prints were soaked in a mild lye solution after most of the support material had been removed manually. It turned out that parts with thin structures tended to bend or shrink after some time in the solution. Therefore, certain parts needed to be cleaned always carefully by hand.

Although, I used a very thin mix of lacquer, it sometimes thickened the parts so that there was not enough clearance. This of course meant extra sanding afterwards. Later I taped some crucial areas that would need to stay in specific dimensions in order for the mechanism to work. These were often areas that would stay hidden so there was no need for lacquer anyway. In some cases though, I had to increase the clearances in the 3D file to compensate for the extra thickness from the lacquer.

The 3D printed material was mechanically very challenging to work with. Many of the parts broke while using too much force trying to assemble them. They couldn't be bended much or they would snap. The material was so brittle that parts often broke even when dropped on the floor. The material's limitations were taken into account in later sets where some of the designs were improved especially to make the assembly less strenuous for the parts. In addition, I 3D printed some custom tools and jigs to make the sanding and cleaning easier.

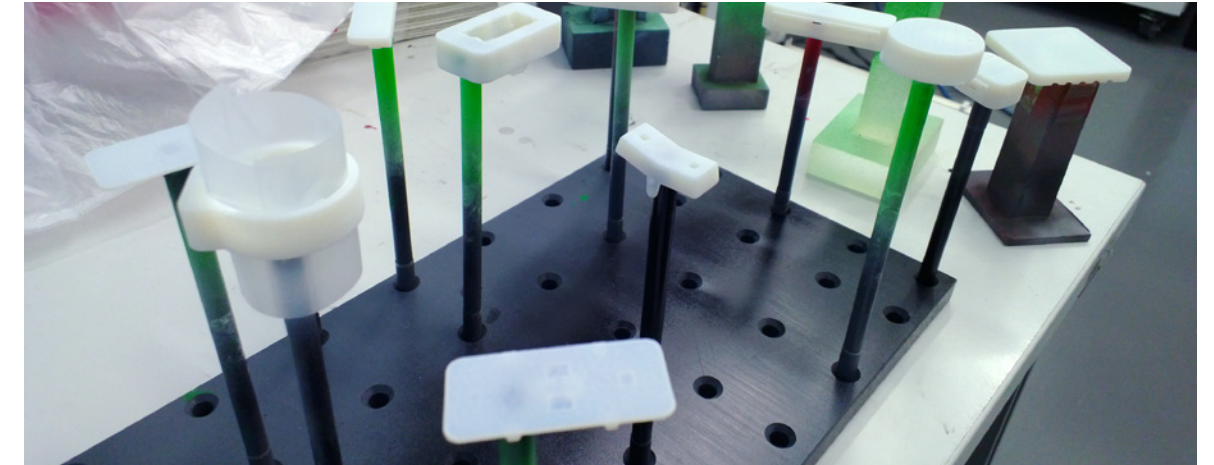


Figure 113: The 3D printed parts ready to be painted

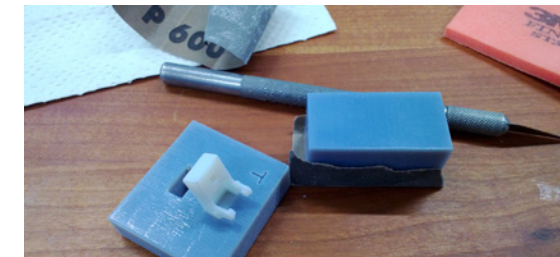


Figure 114: Custom 3D printed sanding jigs



Figure 115: Some tape added to work as light shields



Figure 116: Assembling the electronic parts



Figure 117: Gluing the stoppers and magnets

6. Storage Box and Booklet

In the beginning, I had planned to store the devices in standard black plastic boxes that were frequently used in the design department. Since I was now focusing solely on the devices, I felt I needed to take the design a bit further. While finishing the parts, I started designing a custom storage box that would keep the parts safe and organized. In addition, a custom box would make the device look more appealing and complete. The idea of using a regular cardboard box came by accident. One day, when I was taking the 3D printed parts from Keilalahti to Otaniemi, I packed them in a cardboard mail package that I found in the printing room. I noticed that the parts looked much better inside the cardboard package than in the black plastic case which I normally used. Somehow the cardboard material complemented the 3D printed parts better than the black plastic cases that usually concealed some machined parts with shiny finishes.

I eventually found suitable sized cardboard boxes from *Sinelli* craft store. Since cardboard is an easy material to prototype with, I decided I would also use it for the fastening system. I tested different sized holes and eventually found dimensions that would keep the parts secure but loose enough to be removed. The boxes were quite tall and the parts were difficult to reach if they were on the bottom. To elevate the parts, I needed to create a support structure underneath the fastening layer. For the support structure, I used thick black cardboard we had in Otaniemi. Since the area in which the parts

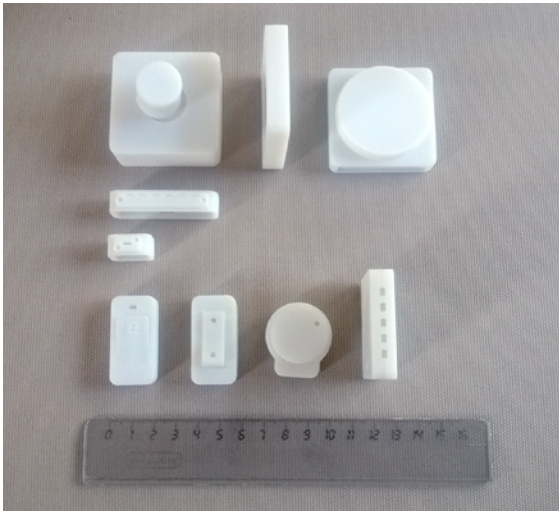


Figure 118: Measuring the space required for the modules

needed to fit was quite small and some space was also needed for the cables, the light sources, slider module and light guide panel module were placed sideways. The support structure was then designed to allow some parts to sink in deeper and compensate for the height differences.

When designing the storage box, I came up with an idea to make a small instruction manual for the device. I figured that a small booklet inside the box would be a lot more convenient than having to find the pictures from the report. The idea was that the user could simultaneously test the device and flip through the booklet to see how light guides were used in each module. Finally I added instructions under the lid of the box to help the user organize the parts.



Figure 119: Planning the order of the modules

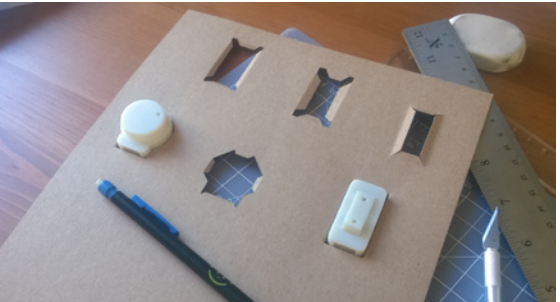


Figure 120: Testing different ways to fasten the modules

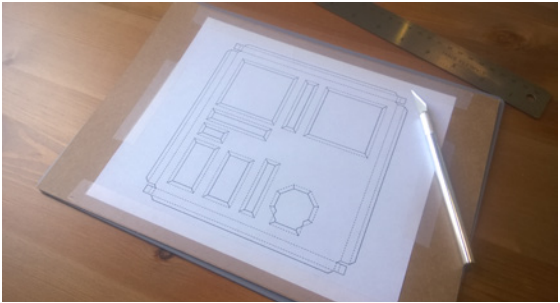


Figure 121: A cutting template made with Illustrator



Figure 122: Making the support structure for the modules



Figure 123: Instructions printed on a cardboard paper were glued under the lid.

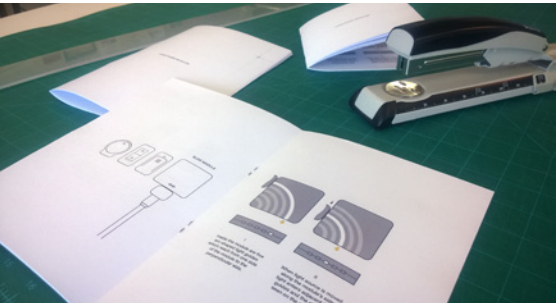


Figure 124: Binding the booklet

8. Finished Device



Figure 125: “Shift Light Guide Demo Device”



Figure 126: The modules, booklet and white flat USB cables

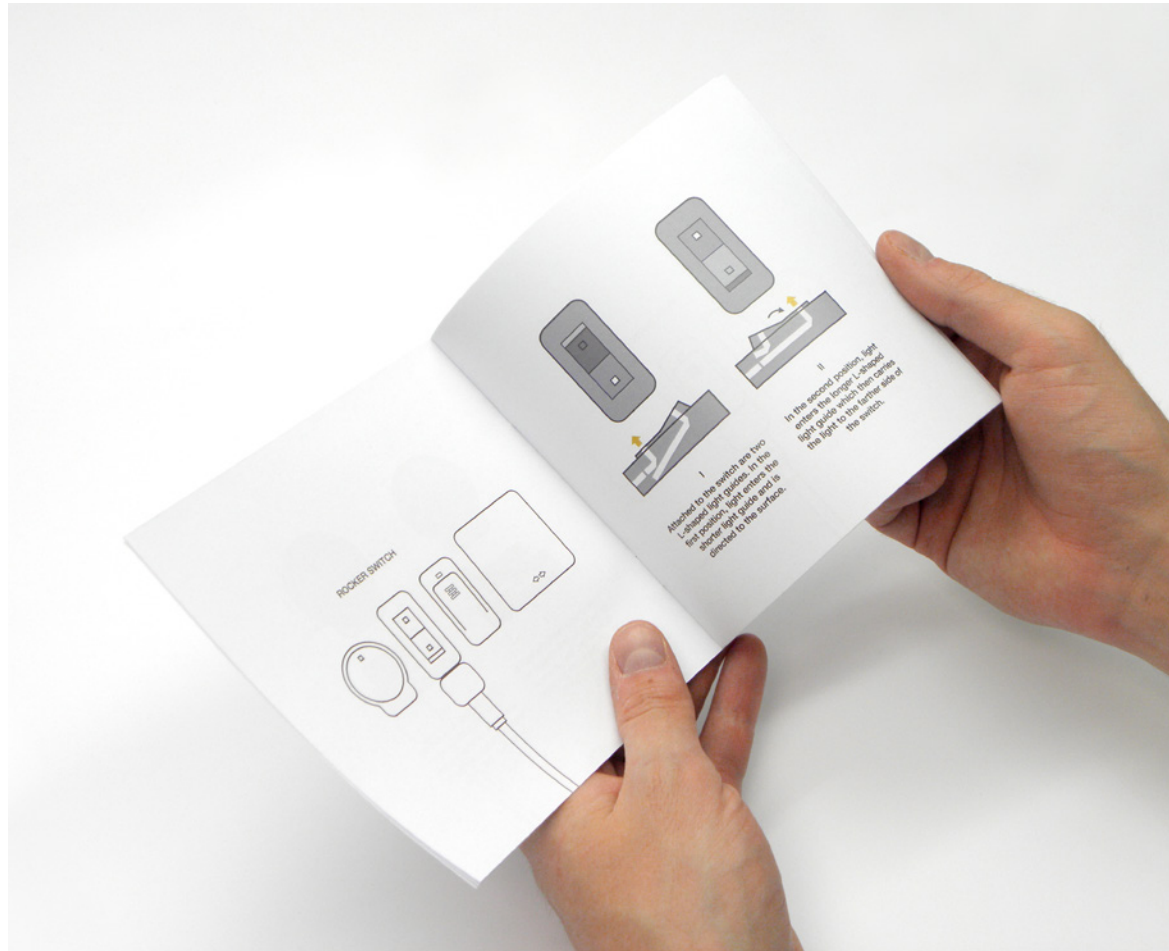


Figure 127: The booklet illustrating the use of light guides

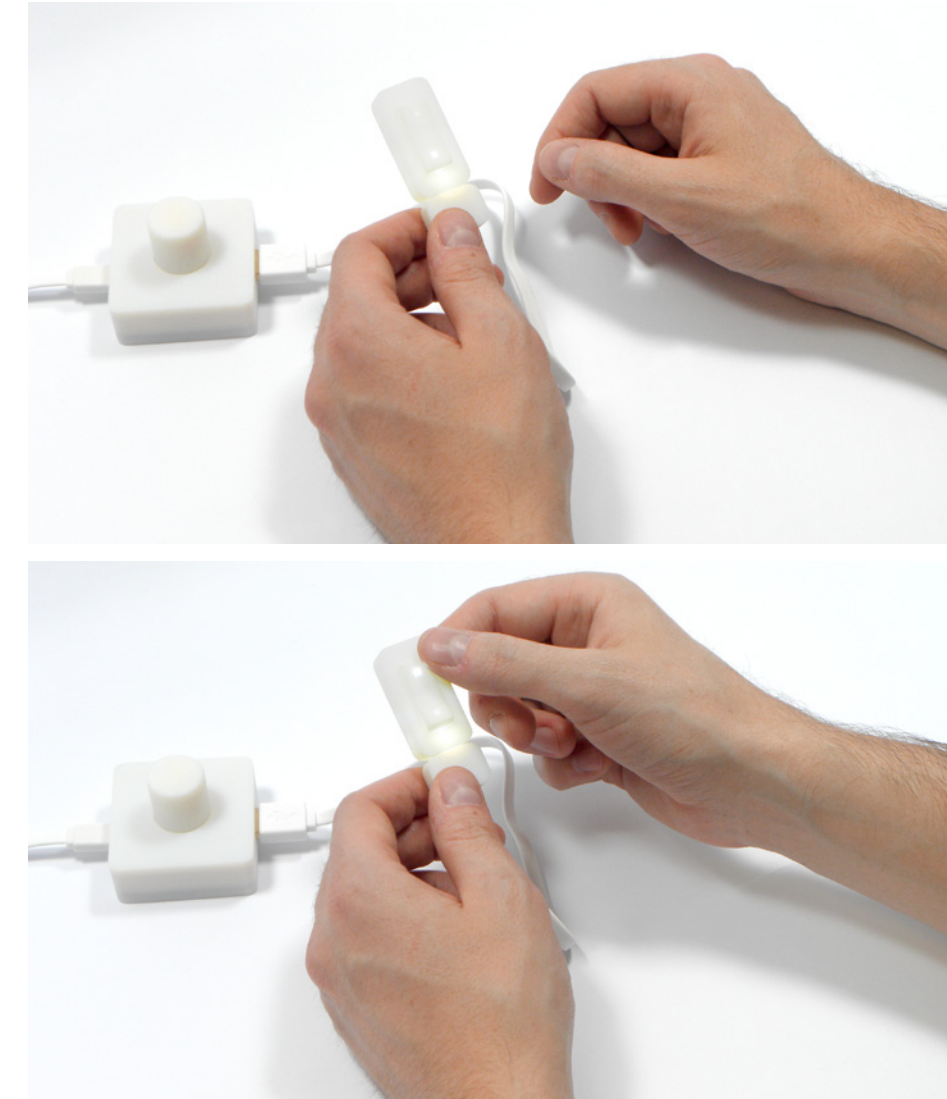


Figure 128: Rocker switch



Figure 129: Push button



Figure 130: Small tuning knob



Figure 131: Slider module



Figure 132: Light guide panel module

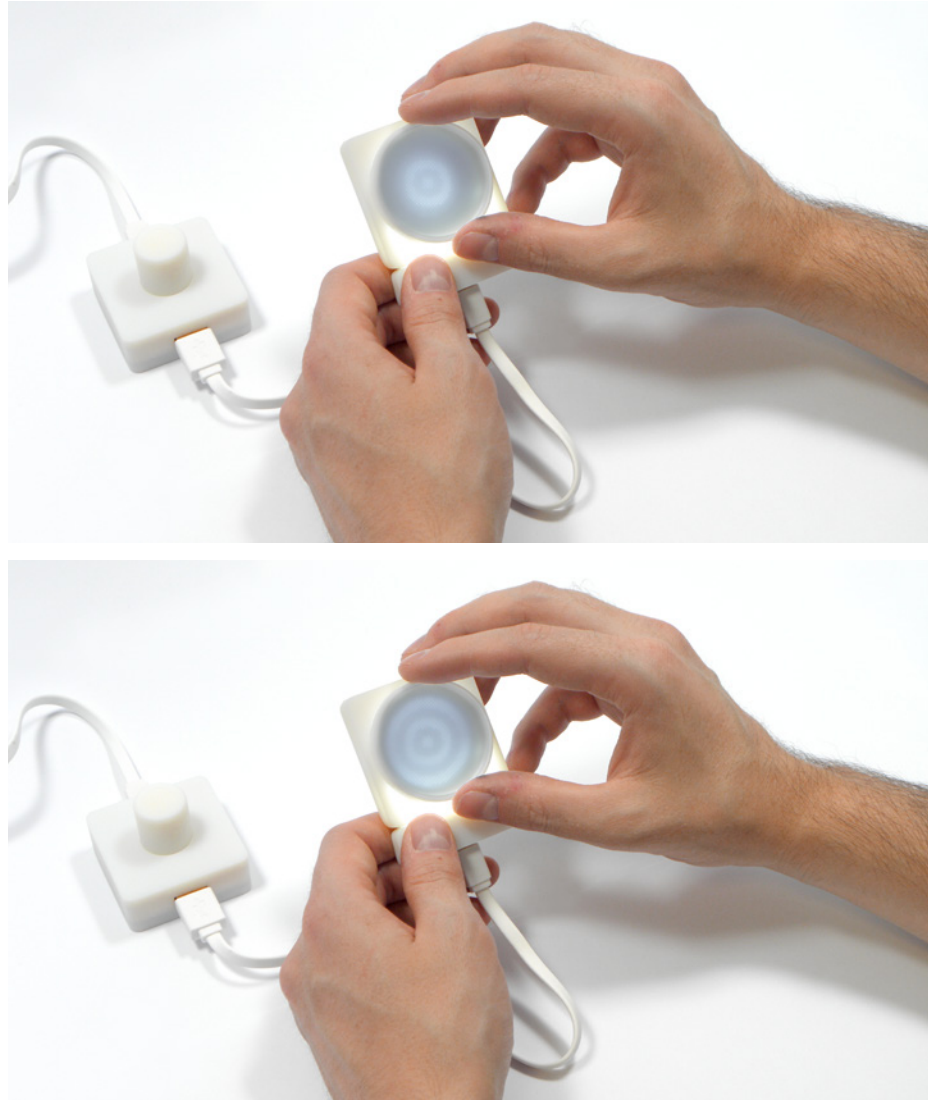


Figure 133: Large tuning knob

9. Discussion and Conclusion

The starting point for the thesis was the topic of light guides which I received from my manager in the beginning of my six-month internship at Microsoft. Behind the topic was the company's broader interest in the field of illumination and the prototyping team's possibility to support it through experimental prototyping. The main goal of the project was to contribute to the knowledge of illumination in the company by creating a device for demonstrating light guides. This device was hoped to present the topic of light guides in an interesting and inspiring way and to spark creative discussion around the subject.

From the basis of these goals, two research questions were formed. Instead of trying to answer these questions specifically, I would use them as a guidance to develop my ideas in the right direction. The purpose of the first question, "How to demonstrate light guides in a tangible way?", was to generate ideas in the beginning and to help discover the defining attributes for the possible solution. The second question: "How to make an engaging tool/device for this purpose?" was then, in the later stages, meant to assess how well the physical model implemented these ideas.

Empirical research for the thesis was carried out through experimenting and prototyping with light guides. Furthermore, to learn about the subject and to provide background for the thesis, theoretical research was conducted on the topic of light guides as well as on the optical principles that form the technical basis for light guides. Following the research, prototyping was used to assess and develop the ideas further. Findings and ideas were reported to the manager as well as reviewed and commented by the team. Furthermore, other teams and people related to the topic were consulted on the subject. Their input for the thesis ranged from technical assistance to aspirational views. Following the concept development, eventually five sets of light guide devices were built mainly using 3D printing and CNC milling.

Still missing some electronic components, the device hasn't yet been presented and tested with people outside the team. Aside from the positive feedback so far, the wider reception and future utilization of the device remain to be seen. Therefore, it is not possible to assess how well the actual device answered the research questions either. However, to answer the research questions on some level, I will now give a personal review of the project.

In retrospect, the freedom that I had in this project had both positive and negative aspects. On the otherhand, it allowed me to shape the project according to my own interests and strengths. However, without a clear directions, the freedom added to the pressure of qualifying my own efforts and choices making it sometimes extremely difficult to take the next step. Another issue that made the project somewhat challenging but all the more interesting, was that there wasn't any specific problem to which I was trying to find a solution. Rather, I was given a topic and encouraged to experiment with it until I would come up with a meaningful way to present it. This was, especially in the beginning, hard for me because I am used to having a clear plan before I actually try to build anything. It was new to me to start prototyping at such an early stage with no idea what to expect. However, it didn't take long for me to notice the benefits of the method as half of the ideas came "accidentally" along the prototyping. I now consider prototyping also an effective ideation method especially if the subject is not familiar.

Because the topic was completely new to me, a large part of the project was spent on learning about light guides. Information on optics, LEDs and lighting in general was more than enough but comprehensive literature on light guides specifically was hard to find. A lot of information existed but it seemed to be scattered in different industries where development was done in some specific light guide application area. Furthermore, the inconsistency of the use of the term and its different meanings in different contexts indicated that the general con-

cept of light guides was not well established or at least not so well defined. In my efforts to compile a comprehensive data package to help my own work, the information would also serve as the theoretical background for the thesis. In addition, the gathered information could be of value to the company if such information was needed at some point. As stated in the original thesis plan, the idea was that the thesis report would support the physical model by providing the reader with visualized information about the working mechanisms of light guides. Looking back at the research process, I'm am pleased with how I managed to combine and summarize the fragmented information.

As mentioned, the device has not yet been introduced to many people so it is difficult to assess how well it succeeds in its role as an inspirational demonstration tool. Because it is an interactive device, it would no doubt have been beneficial to include some sort of usability testing to the project. However, designing and building the actual models was very time consuming and I simply ran out of time for any tests. Of course, I could have conducted some sort of usability test with look-like prototypes earlier in the project, but I'm not sure if that would have given me any more valuable insights than just presenting the idea and asking for comments. Now of course, with the prototypes ready, testing the device and evaluating the illumination would be easy.

One potential future use for the device is in a workshop, where it could be used as an inspirational tool to introduce the topic. The attendees could then

ideate products implementing light guides. I am not sure of the possibilities of implementing these particular types of light guide mechanisms to mobile devices since there are less mechanical functions in them nowadays. However, I could imagine similar constructions implemented in larger accessory devices which might still have some moving parts.

Personally, I am very happy with the overall functioning of the device. There are of course many small things I would like to develop and improve. However, acknowledging that they are just prototypes and that the time was limited, I am mostly happy with the results. I am also happy that I managed to find my own angle to the topic. At the moment, the development of light guides is driven by huge industries striving for high optical precision and improved manufacturing methods. Although the technical aspects are developing rapidly, I didn't encounter so many novel ways of using light guides. Realizing the technical limitations made me shift my focus to a simpler direction and I consider to have made the right decision. I think that the simple mechanical switches with integrated light guides convey the idea of light guides in a very tangible way and with the help of the booklet, the user is able to see what actually happens inside each module. In addition, the written report provides more information about light guides and how they work in an easy-to-understand visualized form.

Overall, I consider this project a great learning experience for me. Aside from the subject itself, I learned a lot about prototyping and especially 3D printing,

its possibilities and limitations. It was nice to be able to use the 3D printing in an iterative design process whereas, until now, I have only used it in school projects for making a single appearance model at the end of a project.

Although I had no previous knowledge on light guides, I know the topic now quite well. Experimenting with a completely new subject also forced me to rethink my own conventions and adopt new methods of ideating. It was challenging and fun to work on a subject from which I had no previous experience. Although this particular project didn't necessarily result in any new innovation, I think many technical fields would benefit from having more similar projects with a fresh approach to the topic. In addition to testing different materials and building prototypes, I think it is the possibility to facilitate these types of experimental projects where in lies another great potential for prototyping team to contribute to design.

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