[SQUEAKING]

[RUSTLING]

[CLICKING]

PROFESSOR: OK, so let's actually talk about optical fibers and waveguides. And again, we have already mentioned about fiber, why they are so important, why we care about it. What I'm quoting here, this is actually from the citation for the 2009 Nobel Prize in physics awarded to Charles Kao, which basically says, "If we were to unravel all the glass fibers that went around the globe, we would get a single thread over 1 billion kilometers long, which is enough to encircle the globe more than 25,000 times, and it's increasing by thousands of kilometers every hour."

This is 2009. We get a lot more optical fibers, obviously, because driven by the increasing internet traffic and, of course, recently by AI, by the emergence of AI. So needless to say, this is very, very important.

So how does the light propagate in fibers? You are probably aware that essentially light gets trapped in a fiber through a total internal reflection. You have two materials. One is the high index that we call the core. Surrounding it is the low index material that we call the cladding. So then when the light essentially stays in the core and they get reflected at the interface between the core and the cladding, if the total internal reflection condition is satisfied, means that the angle theta greater than some critical angle, then 100% of light will get reflected at every bounce. So you get a very low loss propagation through this mechanism here.

I can actually do a really quick, simple demo here to show you how optical fiber works. I have my little laser pointer. So light goes in straight lines. And what I have here, this is just a little plastic pipe, tube, whatever, just raw, actually, plastic raw. So if I just insert it in here and then I light it up, we will see is-- I don't know if you can see the laser spot coming up.

AUDIENCE: [INAUDIBLE]

PROFESSOR: You can see in the beginning here, the light is kind of getting in there. But then do you see the spot? All good? OK, good. So you can clearly see the laser spot coming out here. And you can clearly see how the light actually propagates and attenuates as it goes along this little pipeline here. So this is just a simple rule of total internal reflection at the plastic and air interface. You can consider this as a very large core kind of optical fiber or light guide.

All right. So next, I'm going to talk a little bit about the terminology we're going to use here, how to describe waveguides in general. Fibers can be considered as a waveguide. Waveguide is just a device that can essentially trap light and allow light propagate through a total internal reflection. So if you have a cylindrical cross-section, these are the fibers we see. There are two common kinds of fibers people use. One is called step-index fiber. Really very simple, you just have core and cladding made of two materials with different indices, and you have a well-defined interface in between them.

You also have so-called graded-index fiber, where you have a gradual change of refractive index from the core to the cladding. You have a diffused interface. So there's no well-defined separation between the two materials. You can similarly trap light inside here with a similar mechanism. They are useful for various applications, such as, for example, engineering, the dispersion behavior of light propagating in the fibers.

Now, turning into what we call the planar waveguides, these are essentially basically photonic wires that can trap photons, but not in along the fiber, but usually on a chip, small silicon chip. And they are fabricated essentially using a standard semiconductor microfabrication techniques, much like how you actually make computer chips. So it usually involves deposition of multilayer thin films, and then you do photolithography to then define those waveguide structures.

So there are three different geometries for these waveguides here. The first one, this is called a slab waveguide. It's basically nothing more than a layer of high-index film sandwiched between two low-index cladding layers. In this configuration in, this slab waveguide configuration, light is essentially only confined in this out-of-plane direction. In the in-plane direction, you have perfect translational symmetry, so light is actually going to spread laterally as a propagating plane. So that makes slab waveguide actually not very useful. Most of the time people don't use them because you don't have any control over where light propagates in plane.

So to enable this kind of two-dimensional confinement also in plane as well, you can either try to pattern this high-index film, so you get essentially this kind of rectangular cross-section waveguides. This is what's called a, depending on who you talk to, strip waveguide, channel waveguide, photonic wire waveguide, whatever. But essentially, you can trap light inside this [INAUDIBLE] core here via total internal reflection. Alternatively, you can also, instead of doing a full etch, you do a partial etch of the film.

You create a height difference here. Similarly, you can also trap light, essentially in the middle here, because effectively what's on the left side here and what's on the right side here, you can think of it as you have less high-index material. So effectively, you have lower average refractive index. So light tend to get trapped right in the middle here. So this is called rib or ridge waveguide.

So those are actually the waveguide people we use, channel or ridge. These are the waveguide people use to actually draw light, for example, on a silicon chip, which we're going to talk about in the next lecture. For this lecture, we're going to be focusing on this cylindrical waveguide or optical fibers. So in general, there are two kinds of optical fibers here, called multimode and single mode. So the concept of mode, it refers to a specific way that light propagates inside a fiber or inside waveguide. The easiest way to understand the mode is you can think of it as it's a horizontal specific angle where the light is propagating in a waveguide or fiber.

So for example, consider this is a core for fiber. And we look at this angle, this angle theta. Each mode corresponds to one particular angle where the light actually propagates inside this fiber here. What we argue is that this angle is actually discretized, if you have a waveguide with a finite thickness or finite diameter. There are a few ways to understand it. If you take my class 346, I actually give a quantum mechanical analogy.

Turns out, mathematically, the Maxwell equation that governs light propagation in this kind of media is exactly similar to a Schrodinger equation. And you can essentially see this kind of waveguide as a particle in a potential well. So you have particle in a potential well. The energy levels actually becomes quantized. You have a few discrete energy levels. Energy cannot access arbitrary values. Similarly, this angle cannot access arbitrary values in that regard. So that's from wave optics perspective. Now,

More simply, you can also think of there's also a simple explanation. You can think of light propagation in this kind of a fiber as the superposition of two plane waves in a waveguide. So you have essentially one plane wave that's going in this direction. You have another plane wave that's going in this direction. So now, essentially, if you look at these two light rays here, they both belong essentially to the same plane wave that propagate along the same direction.

So in order for light to propagate over long distances, it's important that all of these light rays that goes in one direction, they have to interfere constructively. So that condition specifies that only at specific angles you can fulfill the constructive interference condition, and therefore this angle has to be discretized. It cannot be arbitrary values.

And similar to quantum mechanics, if you recall, in quantum mechanics, if you have a potential well, if the potential well gets smaller and it gets shallower, then you have a less confined state. Same thing here. For waveguides or for fibers, either way, if you make the core smaller, you also supports less number of modes.

Means there's less number of angles, options that light can propagate inside a small core fiber. Ultimately, if the core size gets really small, once it's below some kind of threshold value, you have the so-called single-mode fiber, where light can only propagate along one specific angle, not in any other angles, versus multimode fiber, light can propagate along multiple different angles there.

So why is that important? Because for fiber, obviously, one big application is for data communications. We want to be able to send data over long distances. If you think about different orders of modes, just by looking at that simple graph on top there, different orders of modes, because they travel at different angles, the path length is different.

So if you're trying to send signal over long distances and you have a multimode fiber, it means that your signal is essentially getting distributed in these different modes. At the other end, the receiver will actually see your signal coming at different times. This will be problematic because the simple way to transmit a signal is you have to essentially modulate the light to encode some digital information.

Simple way, for example, you can turn light on. It's a digital 1. You turn light off, it's digital 0. You do this very, very, very, very quickly, so that you can do high speed data communication. But you can imagine that if the light comes in at a different time, it will completely smear out this kind of on/off tempo for the data stream. So that's why, for long-distance communication, they call long-haul communications, people tend to use a single mode instead of a multimode.

Now, you may wonder, why do people still make multimode waveguides? So this really depends on the application. So even in communications, if you're not trying to send a signal over very long distances, not like kilometers, for example, you only need to send it for a few meters, like between, for example, essentially the modem at your house to maybe high-definition digital TV, that's a pretty short distance. In that case, the velocity difference between the different modes is actually negligible.

And having this kind of multimode fiber will be actually a lot easier in terms of assembly and integration because the core is actually much larger. So in terms of alignment and everything, assembly is all straightforward compared to doing a single mode. So there's one application. It's a lot easier to couple light into a multimode fiber compared to a single mode.

The other application where people like to use multimode if they are doing something for high power, like they are trying to do laser welding, or sometimes they do some laser surgery or infrared countermeasures, whatever. In those cases, multimode fiber offer you much higher power handling capability for obvious reasons, because you get a lot more material. Power density is actually lower, so any kind of nonlinear effect or damage effect is going to be a lot less. So for those reasons, that's why people still use a lot of these multimode fibers, for those kind of applications.

All right. So the main difference between multimode and single mode practically is really just the core size. If you made the core size sufficiently small, you will support only one single mode. You get single-mode fiber. For the standard fiber people use for data communications, this is the standard configuration here. It has a core diameter of about 9 microns, and it has a cladding diameter of 125 microns. These are all international standards. This is the same kind of fiber that people use. And it's all made of-- basically, this is silica glass fiber.

So to make such fibers, you would need to essentially have two glass materials, two silica variants with slightly different refractive indices. So what people will do is then they can essentially dope different kind of elements into the fiber to essentially get the core and cladding in this difference. So for silica, which is the common material that people use for essentially all kind of data communication applications, you can either try to increase the refractive index by adding heavier elements with a higher probability, so they increase index.

You can add germanium oxide, titanium oxide, phosphorus oxide. You can increase index of the core. Or you can also choose to decrease index of cladding. In this case, you essentially add small atoms with small polarizability, like boron, which is much smaller compared to silicon. So there are two different ways to actually create index contrast.

You can also add other kind of functional elements, such as erbium, which we discussed about in last lecture. They are important for erbium-doped optical fiber amplifiers. You can also add other kind of rare earth elements to provide amplification at different wavebands across your communication bandwidth. So silica is the most commonly used material for making fibers, but I want to mention that you can also make fibers out of essentially any kind of glass materials. You can make out of chalcogenides, halides, polymers. People do that all the time.

More recently, in the past couple of decades, people have also developed so-called multi-material fibers. Means that you not only incorporate one single material, you can also incorporate materials that conventionally people think are difficult to make fibers out of, such as the crystalline semiconductors, crystalline oxides, metals. In fact, people, for example, they can even make fibers out of crystalline silicon. They are still a little more tricky to make fibers out of compared to glass materials, but that's a possibility if you get all the thermomechanical conditions correctly.

Now, before I talk about manufacturing process and why glass is preferred, I just want to quickly mention here that this is the standard configuration, if you look at the silica glass fiber. As I've said, you have a core with a diameter of about 9 microns. You have a cladding with a diameter of 125 microns. Both are made of silica glass with some kind of different dopants. Then outside, people usually put a polymer protective layers. That's called a buffer and the jacket.

So the reason they need to put polymer around it essentially is to protect the glass against all kinds of environmental damages. This can come from some kind of optical damage, like UV radiation. So if you have exposed glass core, ultraviolet radiation can actually get absorbed in the glass material, and that can actually create, essentially, damages, like color centers, which increases optical loss in the glass material. So they want to absorb all those UV light in the polymer cladding.

Also, we have learned that glasses, if you have any kind of surface defects, that tend to be a weak point. They eventually lead to a catastrophic failure. So having this polymer protective coatings also prevent the formation of any kind of surface damage that compromise the mechanical robustness of optical fibers. So that's why this is the fiber you will normally get, if you see. If you have fiber, like fiber to the home, this is kind of fiber cable you would normally see.

Now, comes back to the fiber manufacturing process. I have alluded to the fact that it's a lot easier to make fibers out of glass than out of crystalline material, basically because of the glass materials, as we have known, they have this kind of continuous viscosity temperature behavior. By simply changing temperature, you can precisely control the viscosity so that during a fiber formation process, you can essentially get sufficient deformation while also ensure that it doesn't break up easily. So specifically, the way to actually fabricate fiber is so-called using a fiber drawing process. So what you will do, you start from essentially what's called a preform. A preform is basically a glass rod with varying diameter, sometimes as small as millimeters. Big ones can be centimeters.

The key construction for preform is its cross-sectional structure has to exactly map to what you want in the end. So for example, if you're trying to do a simple step-index fiber, you have core and cladding, then what you do, you essentially have a preform with a diameter ratio of core and cladding that's exactly the same as what you want to get in the final fiber. But this is a much bigger version, a scaled version. So during the fiber drawing process, essentially you transform this macroscopic cross-section into something that's a lot smaller, but still maintain exactly the size ratio between this core and cladding part.

And you do this not just for this kind of very simple cross-section here. Later on, we going to talk about so-called microstructured optical fiber, where you can have, for example, you can have not just one core, you can have multiple cores. You can even have some air holes. You can have some additional materials distributed around it.

Whatever you have in the macroscopic preform, when you draw the fiber, it all gets scaled down proportionally into this thin strand of, say, 100 micron thick fiber there. So this is actually quite remarkable. It's one way to essentially allow you to use any kind of ingenious techniques to create a very complicated cross-sectional geometry and then transfer it into the micro domain to actually get the fiber structure there. We're going to show some examples of how people can do that in a very clever manner.

But now, what you do then you have the preform is a glass, you then lower it into the furnace. In the furnace, gets heat up, essentially decrease the viscosity. You want to control the viscosity so they're forced within this window of 10 to the four to 10 to the six parts per second for the reason I mentioned there. Number one, you want the viscosity sufficiently low so you can do the joint process. You also don't want it to be too low, otherwise they break up into droplets. So controlling this viscosity is very important here. You want to make this is how you actually ensure you have a reproducible and scalable process.

So after that, after you exit from the furnace, you then go through essentially a diameter gauge. This is usually essentially measuring the fiber diameter using a laser, using a laser beam. And then after that you go through a coater, where essentially the polymer jackets and the protective coatings, they essentially are coated onto fiber, initially in a liquid monomer form. This liquid monomer then goes through this UV curing lamp, which induces cross-linking of the monomers to form the polymer jacket or the polymer coatings. Finally, the fiber then goes into this winding drum so that you get essentially a large spools of fiber. That's very, very low.

So I want to mention that this manufacturing process is actually very, very efficient. Typical drawing speed of fibers is of the order of several meters per second. So within a day, you can get tens, hundreds of kilometers of optical fiber there. So it's a very, very efficient process. In fact, by the way, there's actually a fiber drawing tower on campus. Do you know that? It's actually in the building starting in the basement from Professor Yoel Fink's group. So if you ever want to see a fiber drawing tower, that's what they have there. So it's a pretty impressive two-story high structure. Lots of fun to look at how they actually make fibers.

All right. So now, come back about the glass lines here. So what glass materials are easier to make fibers? This has to do with fragility, same as any kind of thermal plastic-based kind of glass processing. So a few things that actually impact the ease of fiber processing here. I have quoted two things here, liquid fragility and also glass forming ability. For glass forming ability, it's straightforward to understand.

When you actually are trying to draw glass fibers, the viscosity window is much lower than 10 to the 12 pascal second. 10 to 12 pascal second is basically Tg. So it means that fiber drawing should take place at a temperature much higher than Tg. So if it's much higher than Tg, glass materials will risk crystallization.

The general figure of merit we use to gauge the glass stability or its ability against crystallization is this delta T here, where T is crystallization temperature. Tg is glass transition temperature. So you have a large window large delta T, it means that the glass material is more resistant to crystallization. So you want a glass that does not crystallize, because if you crystallize, you then introducing all this crystalline precipitate. They are going to scatter your light like crazy. You're not going to get a good fiber. It has to be amorphous, normally.

So that's why materials like silica, which never crystallize this, is really a lot more straightforward to join to fibers compared to other glasses, especially things like halite that crystallize a lot easier compared to silica glasses. And that's one of the reasons I mentioned previously. Despite the halides, people predict that they may have lower loss than silica. People still stick to silica glasses, because of the ease of manufacturing.

Second thing is liquid fragility. We talked about this earlier when we talk about viscosity of glass materials. You have this fragility parameter that gives you essentially the slope of the line at the angle plot here. So if you have a steep line, you have a large slope, you have a large fragility. Then it essentially means that if you look at this part here, this is where the fiber drawing takes place, in this viscosity window. So this large slope translates to a much higher temperature sensitivity. Any small variation of temperature leads to a very large change of viscosity there, and that's not preferable. You want a stable process. So that's why glass materials are strong in the glass forming liquid phase with silica, again why it's preferable for drawing optical fibers.

All right. Next, what I want to do is then we can talk a little bit about the fiber drawing process specific parameters. So what I'm showing here on this plot, vertical axis is basically the fiber drawing temperature, this temperature in the furnace. Horizontal axis is the fiber drawing speed. I have two plots here where each of this line on the top panel correspond to one constant fiber radius.

Bottom, each line correspond to constant drawing tension, the tension you apply along the fiber in the axial direction. If you look at these two parts here, this on the top panel, these lines are more or less vertical. So what it says is that if you want to control a fiber radius, it is a lot more effective to actually change the drawing speed. If you change the drawing speed, you can change the fiber radius very effectively. It's a lot less sensitive to the fiber drawing temperature.

So that's why, if you look at this kind of fiber drawing process here, to control the fiber diameter, essentially you change the speed. This winding drum is actually rotating. And usually people do of closed feedback loop control. They have this kind of diameter gauge. They measure the fiber diameter in real time, and then they use it to essentially determine what kind of winding speed they need to have on the winding job. That's how they ensure the fiber, you always have a very uniform diameter.

Now, come back to this plot here. If look at the bottom panel, the draw tension, these lines are pretty much flat. So what that says is that this draw tension will quickly determine by the fiber drawing temperature, which essentially translates to viscosity. But it has a much weaker dependence on the draw speed, so it's pretty much constant draw tension for given fiber drawing temperature.

You can explain that, quantitatively, by looking at this equation here where f is basically the drawing tension, and then on the right-hand side here, eta is viscosity, A is the cross-section at one particular location, and this partial derivative here, vz, is essentially the axial velocity of fiber at that particular location. And z is, of course, the vertical direction.

So what it says, if you have a higher viscosity, you need a higher drawing tension, which makes sense. You have higher viscosity, you need a larger force to essentially introduce in this viscous flow. And that's why you see this dependence here. As you go to higher high temperature, the tension drops pretty rapidly, because of reduced viscosity. You also see that this parameter here the velocity gradient along the z direction.

So what this characterizes, if you have, say, essentially, a cylinder with uniform cross-section, then, due to mass conservation, if you pull it, then all the parts should move at the same velocity, if it's uniform cross-section. You have a velocity gradient, because the diameter during this fiber drawing process actually not constant. On top, you have much wider, of course, the preform. At the bottom, you have a thin strand of fiber.

So because of this diameter non-uniformity, it means that the vertical translational distance for each of the material, each cross-section is different. On top, the deformation is a lot smaller. And then at the bottom, because of the small amount of material at the cross-section, you need to sustain a much higher drawing speed for mass conservation, effectively. So this term, basically, essentially it would reach maximum somewhere right in between here, where you have largest diameter change.

All right. So now, if you now go back come back to this equation here, let's again see F, fiber drawing tension. This is supposed to be constant throughout the entire fiber here, just due to a mechanical balance. So if eta is constant, then what it says is that this term, the velocity gradient, it should be inversely proportional to the cross-sectional area.

This also makes sense because you can imagine that when you have large cross-sectional area here, the extrusion of material is small compared to the cross-sectional area. So the change in the deformation is relatively small, versus, if you move down here, you have a smaller diameter. The shape deformation becomes a lot larger. This also corresponds to a give rise to a much larger velocity gradient.

So if you plot this term here, this velocity gradient, along the z-axis, what you'll see is that initially, when you have a uniform diameter, it's basically 0. It will then increase as you move down here because you start to get shape deformation, and then it will decrease again. It decreases again because as you leave the drawing furnace, the temperature starts to drop. When the temperature drops, viscosity goes up. So viscosity goes up, it means that this term will actually decrease.

At the end, when you are far away from the fiber drawing furnace, you essentially goes back to room temperature, and glass becomes a solid. It doesn't want to flow anymore, and therefore deformation essentially goes to 0. So basically, if you're trying to plot the strain rate of glass materials along the axial direction, it will be essentially 0 here. It goes to some kind of maximum value somewhere in between, and then again drop back to 0. So most of the deformation process essentially takes place along of necking region.

All right. So this is basically about fiber drawing process. So what I want to do-- you can already probably guess what that gadget is for. Oops. Let me just open up the separate slide deck to explain what I'm actually going to do here. I'm going to try to draw fibers using a candy glass. This is exactly the same as actually a real fiber drawing process.

AUDIENCE: [INAUDIBLE]

PROFESSOR: Oh. OK. Sorry. All right. OK I just need to make sure the wire is long enough. Or I can plug in here.

All right. The contact is not very good. And let me put it here. Let me turn around and adjust it a little bit.

So I will leave it to heat up for a little bit. Now, while it's heating up, let me talk a little bit about what we are doing here. So you can probably guess why I'm not using real glass, because glass, of course, would require such a high temperature. You would think EHS would really frown upon it if it I do a real glass fiber drawing here.

But that's not the case if we dial back 70 years, go to 1950s. What I found here, this is actually a toy that was sold by this company, Gilbert, and for kids. So you can actually draw a fiber at home regular time. They actually including a high temperature lamp, and then you can have all the glass and everything. So you can actually do glass blowing at home. You can essentially also draw fibers, obviously.

If you think that's bad, well, I like to open up this. Let's see. Hopefully the internet works. Bottom line, I also found the glass blowing manual. They actually have a digital version for it now. People digitize it. And you would think they would talk about essentially safety precautions. Nothing. Nothing. The only thing they actually mentioned there is, try to not do this in your house. It's going to be a lot of smoke. It's going to make everything very black, and your mom is not going to be happy about it.

Literally, that's actually what it says there. Do it in your backyard, something like that. Well, as a father of three kids, I feel like that doesn't read like a safety precaution. That's more like instruction, how to actually screw up your house and make your parents mad. I'm sure they will just follow that direction, actually do it in the house. So anyway.

Now, if you think that's bad enough, let me show you this. The same company, they also have a kit for-- it's not. Let me see. Oh, [INAUDIBLE]. Come on. I mean, not this one. It's very slow. It's like we bring up. Anyway, you can read the manual there. It says, it's lots of fun actually. OK, see this. You also get a cast kit where you can play around with liquid metal. Liquid metal thing, actually cast figurines and all that stuff. So if you buy both pieces together, you can transform your home into basement of building 10. You get glass lab and metal lab all in your kitchen. You think that's nice? I have something more.

AUDIENCE: Oh, it is the same one [INAUDIBLE].

PROFESSOR: Yeah. You have seen this?

AUDIENCE: Yeah, because I mentioned to Alice, like, the toy uranium.

PROFESSOR: No, I also want-- they actually include a little slip there in the box, if you get the original version. If you use up your radioactive isotope, you can ask for refuel. All right. Good that we have EHS today, right? Is it high enough temperature? Yeah.

So anyway, we're not going to try to do that. We are going to be good citizens. We are on good terms with EHS, so that's why we want to do it with candy. So what I'm showing you on the left-hand side here, this is not a phase diagram, first thing. A lot of books mistakenly call the phase diagram. It's really not. Number one thing, you don't see glass on phase diagram. It's thermodynamically unstable. Also, you don't see this kind of crossings on phase diagram. That should not happen.

This should more correctly called-- this is called a state diagram. The way it works is that in a manufacturing plant, people use this diagram to predict the concentration or composition of sugar [INAUDIBLE] solutions. So if you heat up a solution, it's going to essentially follow this line as it evolves, as you go up to temperature. That's how they actually use it.

But what I want you to focus on is actually this part here. So in this region here, where you have essentially pretty much pure sugar, you can actually form a glassy material. And the way to do it is essentially you heat up a sugar solution, you completely saturate it, and then you quickly cool it down to avoid crystallization, and then you get your glass.

It is a glass, so it behaves exactly in the same way in many, many aspects as oxide glasses. You can see that they are clear. You see some bubbles there. That's because this is a poor manufacturing process. I think I can pass this along. I have a much more clear glass that's bubble free. I did not do it. My student did it, so credit should not come to me. It's gray because we overcook it, so it probably decompose a little bit. But yeah, it's basically sugar.

AUDIENCE: It just really feels like [INAUDIBLE].

PROFESSOR: Yeah. They can crystallize. If you expose them, especially to humidity, then they can crystallize. And you see this kind of foggy kind of precipitation? That's the crystalline materials coming out.

I just want to mention that this is also a really sweet material, as you would expect. Practically all the hard candy is made of amorphous glass. I have to distinguish between another kind of candy, though, called rock candy. So in the food industry, rock candy actually specifically refers to crystalline form of sugar or sucrose. The way they actually make it is they essentially dip this kind of sticks into a solution that's supersaturated with sugar. And then they actually essentially then precipitate onto the stick to get this crystalline. You see the crystalline facets there. So this is crystalline sugar. So hard candy and rock candy are two different things, from a material science perspective. Don't mix the two, even though they may taste similar.

Now, last thing, I also want to acknowledge that I actually get my recipe from a journal. Let's talk about *Cuisine.* I normally don't read that kind of journals, but this is actually where I get my recipe. And it turns out this kind of fibers they actually use in Chinese cuisine. They actually use it for essentially decoration and, of course, for flavoring purposes. So I copy exactly that recipe when we are making this. All right.

And also, because sugar is a glass, essentially means that all the processing methods we talk about for frosted glasses can also be used to essentially structure sugar. So this is a very interesting study where people actually put together a 3D printer in very much the same way as how you actually 3D print glass materials that we talked about earlier. You have basically a little furnace here. Heat up the sugar glass. They come out from this nozzle, and by translating the nozzle in 3D space, you can get all kinds of 3D patterns. So you can actually 3D print sugar in this case.

All right. So before I go to my experiment, I just want to acknowledge, if you want to get a bit more information about this experiment, this is where I got my inspiration from. And then Yifei is one of my former students who had already graduated, but he made those glasses, which I still use after like five years. So now let me turn to this guy here. I hope this is warm enough. Let me see. I can try to put it a bit closer. Sometimes it takes a little bit of time for it to just basically heat up.

I think it's still not flowing yet, so we need a bit of time. So you see what I'm doing here? I'm trying to push this rod close to the surface of lamp, so heat up a bit quickly. Now you also see what happens before I came to class. This sugar basically melt and stick [INAUDIBLE] trying to pull it off. OK, just let it melt. Just be patient.

AUDIENCE: The fiber drawing earlier lecture reminds me of the candy stores where they get really complicated patterns and [INAUDIBLE].

PROFESSOR: You get can essentially pull candy and that kind of thing. It's basically of like a thin fiber. Yeah. Especially when you can solidify, you can pull out, you see long fibers coming out. Yeah, that's basically elasticity, if you remember. So let me see. Maybe one of you can hold this for me for a second. I will try to do-- just hold it like that for a second. All right.

I'm actually interested to see if this candy glass is transparent to this laser beam. I can see [INAUDIBLE] a couple lines to it. Yeah, somewhat, not very transparent. It absorbs a little bit because of the color, but maybe once we draw the fiber, I can see if we can actually send the light through it. I've never tried that. It may not work, but.

OK, where do we stand now? It's still-- oh, it's melting, it's melting. You can see the meniscus, or it or had already deformed, so shifted towards that direction because it's heading a bit lower there. We may still need a few minutes. I think I should have heated up a bit earlier. Oh, actually, it starts there. OK, nice.

Yeah, so then what we'll do, once the viscosity is about right, we're going to try to pull the fiber. And then this is basically the drum, winding drum. So what we have here, the two lamps essentially approximates the fiber drawing furnace. This is our preform, effectively, which contains the sugar glass. And then at the bottom here, we have this a very high-tech version of fiber drum, where we can have long spools of fibers, meters in length. And as you will see, the key parameter here is actually viscosity. If viscosity is too high, then fiber will break, essentially will break up in the middle. If it's too low, you get large chunks of sugar coming out. Then you don't get uniform diameter.

So let's see how-- let's just wait a little bit. You can clearly see it's already flowing. You see a big bubble coming out here [INAUDIBLE] gravity. It's going to-- I'm a bit concerned it's going to flow out a bit. You see it's flowing? It's flowing a bit too fast. I think I need to move it away a little bit away from the. I think it's viscosity gets a bit too low. This is probably going to work. What I'll do is maybe a bit-- I will essentially start to draw a fiber, a thin channel fiber. I will stick it to [INAUDIBLE]. Now I need to maintain the viscosity here.

So now let me try to draw a channel fiber. You can come a little bit closer, if you want to look. And then I stick to a surface, and then I can start to do my fiber drawing. Oh, it breaks. I think the viscosity is a bit too low.

OK, so I don't know if the video can actually see it. It's actually coming. You may have to come close to see it. The fiber is actually coming out. You can draw it at pretty high speed, actually. If it's not flowing even fast enough. Ow! Oops. All right. That's too much. Let's try to do it again.

OK, now you can clearly see the fiber drawing process. You see how it actually deforms as it comes out? And then you get a long spool of wires. Once in a while, there's a big piece comes out, but that's fine. That's why we are not a professional.

AUDIENCE: Is that like the droplet formation, when it's too high viscosity?

PROFESSOR: No, it's probably too low viscosity we are putting out here. I should maybe lift this a little bit higher so that you illuminate the other tip. That's where you want it to have low viscosity. If viscosity gets too low there, then the whole thing just falls off because of gravity. That's just what happens. Yeah, we can see, again, very stably draw long fibers. Oops. This can go on and on almost forever until that big chunk falls off.

Take it off. Any of you want to try it yourself? I have another fiber drum. You can take a look. By the way, this actually comes off. This is the fibers. They actually come up very nicely. These are essentially the chains of fibers. They all stick together now. But yeah. You can see these are basically just sugar fibers. Eat it? No. That's not a good recommendation.

Any of you want to try it? So the idea is that you try to pull a little bit, stick it to the surface, and then you can start rotating. Make sure the stick rotates. Just rotate. It's going to continuously come out. You can also laterally translate it a little bit around it, along it, so that you get essentially that there.

All right. So now, this comes up a little bit. Take a look at how people actually make real silica glass fibers. So one of the critical step in making this kind of fiber here is how to actually make the fiber preform. This is really critical because, as I mentioned, in order to reach this remarkably low loss of 0.2 dB per kilometer at 1,550 nanometer, you really need to get rid of all the impurities to ensure that you can achieve this very low loss.

So the way people actually use to make the preform is to use a so-called Modified Chemical Vapor Deposition process, or MCVD. It is different from conventional CVD because in conventional CVD, if you want to deposit SiO_2, people typically use a silane, SiH_4 gas. Now, the reason people don't use SiH_4 in MCVD is because SiH_4 contains lots of hydrogen. So it's very, very difficult to completely get rid of hydrogen in silica deposited using conventional CVD process. So that's why they have to use, instead of using a silane, they use a silicon chloride as a precursor.

It's also convenient because silicon chloride, turns out, is actually a liquid at room temperature. It has a boiling point of 58 degrees Celsius. So it's really a very easy material that can be subjected to a fractional distillation process to get very high purity of silicon chloride. So this silicon dichloride is then actually oxidized to form essentially this kind of SiO_2. They are deposited in the form of very fine powders. That's called a soot.

The soot eventually condenses with high temperature to form a dense layer of silica glass. Similarly, you can also dope the glass material by essentially adding a little bit of germanium tetrachloride, and then it will decompose to form germanium oxide that forms a dopant in the glass material.

Now, specifically, the way you actually make the preform is start out with essentially a tube, a silica tube that's hollow in the center. You flow the reaction gases through a tube here. You also have a torch that essentially moving in the axial direction of the tube here. So where you have the torch heating up, you have a high enough temperature. You induce the decomposition of the reactants, and that's where the soot is getting deposited. So essentially you're depositing soot as you actually translate this little torch along the axial direction here.

So the process continues until the whole tube becomes completely filled. Then you actually get a high-quality preform. The process is also quite convenient to control here, because you can always change the refractive index distribution as a function of position along the radial position by just simply changing the reactant gas during this process here. Essentially, it's done in a layer by layer manner along the radial direction. So I would like to actually show you just one quick video that actually illustrates this kind of a--

[VIDEO PLAYBACK]

- This three-story [INAUDIBLE] at the Thorlabs headquarters in Newton, New Jersey, houses our fiber draw towers.

[MUSIC PLAYING]

These towers produce many of the optical fibers we offer in our catalog, and also gives us the ability to draw high-quality custom fibers for a variety of applications. The draw process begins by cleaning all surface contaminants from the silica preform. The internal structure of an optical fiber is already present in this 1-meter-long glass cylinder. One quartz handle is welded onto each end of the preform, using an oxygen-hydrogen torch that heats the glass to 2,000 degrees Celsius. Eye protection is required to shield the engineer's eyes from the brightness of the torch.

Once both handles are attached, they are mounted or chucked into a lathe, suspending the preform over the water-cooled half-moon burner. As the lathe rotates the preform, the burner slowly passes along its length, removing all surface contaminants. This process is called fire polishing. The moving burner mills off the outermost layer of glass and removes all organics that may be present on the preform. The more pristine the preform, the higher quality fiber it yields.

Once the fire polishing is complete, one of the two handles is removed, leaving a pointed drop-in. The other handle remains welded to the preform and serves as the support end. The support end is removed from the lathe and chopped into the top feed unit at the top of the draw tower. The unit lowers the preform into the furnace, where it is heated to 2,000 degrees Celsius.

This graphite resistance furnace has an element that surrounds but does not touch the preform. The graphite allows for an even distribution of heat around the glass rod. The fiber is pushed by the top feed unit and pulled, first by hand and then by capstan, down the length of the tower. After exiting the furnace, it travels through a 150-centimeter-long cooling chamber. Chilled water and helium gas keep this chamber at an internal temperature of 12 degrees Celsius. The fiber exiting the cooling chamber has been cooled to room temperature and is ready for coating.

A variety of polymer coatings can be applied to our fiber, depending on the application. A carbide die at the bottom of the conical coating cup ensures that the coating is applied evenly around the fiber. The coated fiber then passes through a set of UV lamps, where the coating is cured. Finally, the fiber receives a blue tassel jacket to protect it from mechanical damage and is then smoothed.

The fiber is closely monitored as it makes the 36-foot journey from the top of the tower to the capstan below. Three meters provide real-time diameter measurements to computers controlling both speed of the top feed and the capstan. These speeds are constantly being adjusted to ensure a consistent diameter throughout the length of the fiber.

Our engineers also monitor the location of the fiber as it travels through the many devices, and make adjustments when necessary. It is important that the fiber is perfectly centered, because any rubbing will negatively affect the quality of the end product. This tower can produce fiber as thin as 50 microns in diameter, which is about the thickness of human hair.

The finished fiber undergoes a four-axis proof test to measure its strength. This thin optical fiber is stronger than stainless steel of the same thickness when pulled along its length. Engineers also measure the attenuation and centration of the fiber. Any fiber that does not meet spec is not sold. The fiber drawn here is sold bare and is also made into connectorized patch cables, or incorporated into many products in our ever-growing line of photonics equipment.

[END PLAYBACK]

PROFESSOR: This is how actually our fiber manufacturing is actually executed in industry setting. Now, comes back here. In the remaining 10 minutes, I will just also quickly talk about some of the more recent developments in constructing fibers with more complex geometry. I have already mentioned that if you can construct essentially a preform with complex structures containing different materials, you can use this fiber drawing process to essentially draw down to create a scale version of optical fibers with different cross sections.

So one such example is so-called Microstructured Optical Fiber. Some people call it MOF. Some people call it photonic crystal fiber. They refer to basically the same thing. You can see in this diagram here, this is actually cross-section of some of the fibers that's shown in this geometry here. You see this kind of hexagonal arrangement of periodic holes, air holes. And you see that in this optical micrograph image here they have different colors due to the different purity of the holes. They essentially refract light differently. That's why they have different colors there. But they are basically colorless. This is silica glass in this case.

So this kind of a fiber can be quite useful here. If you look at the cross-section, this is the way it looks like. They can be used, for example, for sensing applications. You can essentially use this hollow core as a conduit for liquid or air. So when air flow through it, you can also pass light through it so that you can actually create a very strong interaction between light and the material or the gas or species you want to detect to make it more sensitive.

This is also useful for high-power handling applications. So even though we mentioned that glass is basically very low loss, but still there's always a little bit of residual optical loss. This residual optical loss means that if you're passing laser with very high energy through it, it's going to actually heat up the material, which eventually damage it, versus if you have such a hollow core, then the attenuation or the absorption can actually be even lower, such that there is no such photothermal effect, handle much higher power. So these are some applications where you can actually use this kind of fiber for different kind of various implementations.

Now, a couple of questions here. One is that how this fiber is made. You can see this actually manufacturing process. So what you do, you start out by essentially stacking a lot of silica tubes, little tubes, in a hexagonal arrangement. And then you essentially do a little pre-draw to draw this kind of a-- to essentially fuse together all the individual silica rods and then pull them into essentially a little preform that in this case is a few millimeters in diameter. So this is what it looks like once all the tubes are fused together. And then you can then subject it to a fiber drawing process to get the final microstructured optical fiber. So that's how it's made.

Now, the second question is that how you actually guide light in the kind of structure here. So this is not through total internal reflection, because air has a low index. So the way this works is basically through a so-called photonic bandgap effect. So you can see this kind of periodic arrangement of glass and air is essentially correspond to periodic modulation of the refractive index.

So this is basically what people call the photonic crystal. You can create basically photonic bandgaps where certain frequency of light doesn't propagate. This is similar to electronic bandgap. Electronic bandgap, what it means is that electronic wave functions of certain energy cannot exist within that bandgap region. Same idea, so light of certain frequency cannot propagate in this kind of synthetic photonic crystal media. So if you send light in the core because it cannot propagate in the region, they have to be trapped in air through this photonic crystal bandgap effect.

So that's one example about how this kind of fiber could be constructed and used. The figure I'm showing on the right-hand side here, this is actually from Professor Yoel Fink's group. His group is really one of the pioneers of the so-called multi-material fibers. So in this particular example here, it's a hollow core fiber. The cladding consists of alternating layers of a polymer, PES, as well as arsenic selenide, which is the chalcogenide glass.

So the way it operates is that if you have alternating layers of a high- and low-index material, in this case low-index is polymer, high-index is glass, you can also create effectively-- this is a one-dimensional photonic crystal that act as a perfect mirror that reflect 100% of light. So then light will essentially also be trapped just inside this hollow core.

Besides these two materials, they were also able to incorporate, in this case, they have a thin layer of gassed. This is [INAUDIBLE] chalcogenide glass. It's actually amorphous semiconductor. They also put metal in there, in this case metal tin. So metal tin, turns out it has a melting point that's actually comparable to the essentially fiber drawing temperature window of this chalcogenide glass and the polymer there. So they were able to essentially draw all four materials simultaneously together to form this fiber here.

So now you may wonder, why do you actually need to put this metal lines in there? So turns out they can be used essentially as metal electrodes to actually measure the electrical conductance of this amorphous semiconductor embedded in the fiber. So why is it useful? Actually, let me jump ahead and talk a little bit about that first, before coming back to how you actually make the fiber.

So they essentially leverage the fact that the electrical conductivity of this amorphous semiconductor is a very sensitive function of temperature. And the mechanism for electrical conduction in this case is basically through extended states. So if you go to high temperature, you can excite more electrons and hole pairs to the extended states. And as a result, you have a higher electrical conductivity.

So with this kind of embedded thin electrodes, you can then essentially measure the local temperature in the fiber, and this is a way to actually create essentially fiber-based temperature sensing. So in this demo, we have shown here they essentially generate this kind of crisscross pattern of optical fibers. And if you put your finger at one of the cross points here, you can immediately pinpoint this is where you actually have elevated temperature. Similarly, if you put a piece of ice, this is where you actually have depressed temperature. So it's a way to essentially monitor temperature in this case.

Some other examples of applications with this kind of fiber here, this is from Professor Polina Anikeeva's group. What they have demonstrated is a multifunctional platform for essentially neural excitation and recording. So conventionally people can use essentially a light to actually modulate neural activities. They can then use metal electrodes to actually record some of the neural functions, neural activities.

But the conventional way of doing it is that you have separate probes. You have essentially a probe that has electrical functions. You have a fiber or something else to actually implement the light. So what they have demonstrated is that this is really a multifunctional platform here, where you can use a fiber to actually transmit light. You have the electrodes, the metal [INAUDIBLE] electrodes will record neuron activities. You also have a hollow core which allows you to actually inject drugs so that you can also use that to provide additional functions there, so essentially as a microfluidic channel.

So now comes back here. So with all this kind of multi-material, multi-functional fibers, this slide just shows you some of the examples how people can actually fabricate them. It all boils down to how you actually create a preform that has a geometry that's exactly the scaled version of what you want to get in the final fiber.

So on the left-hand side here, these are some of the simple examples, how you create this kind of multi-material platform. You can do rod-in-tube, sliding one material inside the other. You can also use the extrusion method. You start out making this kind of a little pellet here. By extrusion, you can then generate a preform containing multiple different materials. We have already shown you one example about stack-and-draw in the case of a silica microstructured optical fiber here. You can again, by stacking different materials, different tubes together, you can draw them together to form optical fiber.

Now, for the kind of optical fiber from Professor Yoel Fink's group, this is the process they have developed, which I think is quite ingenious. So they will start out by having essentially-- this is like a rod. You then embed this kind of metal strips in there. Those are the metal electrodes. What you do next is that you essentially wrap it around a thin sheet, polymer sheet.

So this polymer sheet, they actually deposit a layer of chalcogenide glass on top of the polymer sheet. So when you are actually loading it, it then creates this kind of alternating layers of chalcogenide glass and polymer here to form this kind of a one-dimensional photonic crystal. So in the end, this is actually what a preform looks like. When you draw it, you get a microstructured fiber that I mentioned in the previous slides.

So this is a very intensively investigated area right now. People have all kinds of very creative pathways to actually generate diverse geometries of microstructured fibers for different applications. All right. So I'm actually going to stop here for this lecture. And then in the next lecture, we're going to switch gears a little bit, talk about optical waveguides, the on-chip version of essentially light conducting media.