[SQUEAKING]

[RUSTLING]

[CLICKING]

JUEJUN HU: So in this lecture, we are going to actually turn it over to optical properties of amorphous materials. And in fact, optical properties is probably one of the most important reasons why people use glasses. So I'm actually posing this question here.

What's so special about glass specifically in terms of their optical properties? You can think about it. You don't have to answer me.

To me, there are three striking properties of glass materials that really make them so useful for all sorts of optical applications, the first one being refraction. You can pass light through a glass material because it has an index different from air and it's also transparent. It means that you can use it as a way to essentially change the light propagation direction, and therefore manipulate the light propagation behavior. This will be very, very important for essentially all types of optical devices.

Just to give you an example, showing that we humans already have a very long history of using refraction for useful applications, in the image on the right-hand side, I'm showing you an optical device that uses refraction. Now, I want you to make a guess. What is that optical device for?

AUDIENCE: [INAUDIBLE]

[LAUGHTER]

JUEJUN HU: Where's the glass? Make a wild guess.

AUDIENCE: Sailing device, so it hits the sunlight.

AUDIENCE: I mean, I going to say sundial, but--

JUEJUN HU: OK, great. Well, we have some guesses here. It's a microscope. It's in fact one of the very first microscopes that was developed by the Dutch scientist Leeuwenhoek. So the way it works, if you look at it here, right at this point, there's actually a little glass sphere.

So essentially they use a glass sphere as a ball lens to magnify objects. So when it's actually operating, what you have to do is put a sample on this little tip here. And you see these mechanical screws and things. This is used to adjust the position to adjust focus and adjust where you're looking at. And then you have to position it very closely to your eye and try to peek through a tiny little aperture behind the glass sphere.

AUDIENCE: It's so much easier to be a scientist today.

JUEJUN HU: Right. Well, first thing, this instrument is actually not easy to make. Back at the time, they didn't have the technique to very precisely polish glass to make high-quality lenses. So the way they actually make those little, tiny little spheres, is they have a molten glass.

They just quickly pour it into sand or something, and then you essentially have little droplets jumping around. They then see through all those droplets and pick the ones that actually have a nice spherical shape. Put it there. And then using this, obviously you can imagine, this can be very, very difficult and challenging. But despite that, Leeuwenhoek. Published several big volumes of books just essentially documenting everything he has actually looked at under the microscope.

This is actually one example. This is all hand-drawn. There's no Photoshop, obviously. There's no camera or whatever. So this is actually a flesh fiber, essentially fiber from meat.

And you can look at all the details that's actually revealed here. This is all hand-drawn details. He was looking at it and then put it down on paper, which is quite remarkable. But anyway, now you see, this is essentially the ancestor for all the optical microscopes today. All right, so that's refraction.

Now, the second very remarkable property of glass material I see is transparency. And in fact, glass materials are so transparent, they have such a low loss, that light can propagate within glass for hundreds of kilometers without having to essentially get re-amplified. And this very important property is what underlies today's internet of age. What I'm showing over here, this plot, this is essentially a map showing all the main undersea optical fiber networks.

Without these optical fiber networks, you will not be able to quickly communicate with people around the globe. You will not be able to access essentially data from data centers in Europe, in UK, in China, everywhere. So this is really what enables the whole connected world nowadays. So we are going to discuss about mechanisms, why glass materials can be so transparent, what are the optical loss mechanisms, and how to actually engineer glass compositions so that you can achieve this remarkable transparency.

Now, the last optical property we are going to discuss here is color. I'm showing you a photo here. This is actually from Barcelona in Spain. This is actually a dome window, a colored glass window for one of those buildings there.

Again, even from ancient Roman times, people knew that actually by putting different kinds of elements, additives into glass materials, you can change the color of glasses. And this is a very useful characteristic to artists back in Medieval times when they tried to decorate the big cathedrals to modern artists, to all kinds of glassware, like what you see in an MIT glass lab. It's the same technique that people are still using today. So we'll be going over the chemistry and the physics of how to actually introduce color in glass materials.

So now let's start taking a look at refraction. So speaking of optical properties we need to talk about Maxwell equations. There are four Maxwell equations. You don't have to memorize it, obviously.

In fact, even though I've been working on optics and photonics for more than 20 years, every time I use Maxwell's equations, I just go to Wikipedia and look for it. Well, to be honest, I rarely use Maxwell's equations directly. Most of the time, we're using some kind of experiments.

But if you look at these basic equations, the key takeaway message here, the way I'm quoting it, this is called a macroscopic differential form. You may have seen these spectral equations being cast in many different variants. For this particular macroscopic differential form, we are looking at the field itself-- for example, E electric field and B magnetic induction. These are the fields you will see in media and also in vacuums-- same.

The material properties that we actually care about are hidden in these two variables here-- H and D. D is essentially dielectric displacement and H will be the magnetic field. They are linked to E and B through so-called constitutive relations. All the optical properties of materials basically are described in those constitutive relations

Now, the other thing I also want to mention here is that when you are using this kind of macroscopic differential form. You have these terms here where I put a little subscript f for rho f and Jf. So rho is basically the charge density, J is the current density. With a subscript f, it means that when I'm writing Maxwell equations in this particular form, we should only consider the charge and current induced by the free charges.

So free charges would be, for example, the free electrons in a metal wire that can easily move around across the entire conductive material. Those are the free charges. In dielectric material, what we have is basically the so-called bound charges. And as just a little quick review for general physics here, if you think about a piece of dielectric material that's electrically insulating, like glass, we have some polar molecules or chemical bonds.

So when you actually apply electric field, what's going to happen? If you apply electric field in the material, say E, what's going to happen is that the source center of mass for the positive charge and negative charge is going to get spatially separated. So this is the positive charge. And then this is negative charge.

When there is no electric field, then the center of mass for both charges will be completely aligned. So there is no net charge. But as soon as you apply electric fields, the positive charges move this way. Negative charges move in the opposite direction. So this then creates essentially little electric dipoles.

So if you look at the net charge density, inside homogeneous material, you don't see any net charge density, because any positive charge on this side is essentially compensated by negative charge only on this right side. But on the surface, then you can actually get accumulation of these charges here because there is nothing to compensate against the surface charges. And then these surface charges should not be included in the Maxwell equation if you are writing it in this form here.

Essentially, the surface charges are accounted for. When you are writing D here, the dielectric displacement, they are considered as part of the material response or the material polarization. So Rho f you should only consider charges coming from the free-roaming electrons.

But more specifically, now if you look at the constitutive relations, which is what I mentioned, where all the material properties are essentially embedded in there. The general form for a general non-bianisotropic media-- again, we're not going to talk about what specifically the definition is for non-bianisotropic media. But for amorphous materials, they are typically anisotropic.

So they satisfy this criteria here. And then you can essentially write D as epsilon E plus P. And same thing-- B you can relate it to a H and M.

Now, P is the polarization. P is defined as the total dipole moment induced by external electric fields within a unit volume of the material. So basically, you add up all the dipole moments within a unit volume. That will give you actually the P.

So what we are seeing here is if you have a material that's more polarizable. So typically if you have material consisting of heavier elements or consisting of essentially more polarizable chemical bonds, then you have a larger dipole moment that's induced by external electric fields. And you're going to get a larger P there. Yes,

AUDIENCE: What is chi?

JUEJUN HU: Chi is susceptibility. So basically, if the electric field is not too large, you can then basically do a Taylor expansion of P with respect to electric field E. As I said, if E is not too large, you only take the first order. Then you end up getting this equation here.

And chi basically gives you essentially the proportionality constant. It's a material constant that allows you to characterize how polarizable the material is in response to external electric fields. The larger the susceptibility, the larger the induced dipole moment. And therefore, you have a more polarizable material. So materials consisting of heavy atoms tend to have a larger P.

But mathematically, people typically don't use chi. What they will do is try to absorb chi into this relation between D and E here. And you end up having a very simple proportionality relation. So D becomes directly proportional to the applied electric field.

The proportionality constant here, there are two ways of writing it. Sometimes people essentially put a epsilon null here. This is actually a vacuum permittivity.

In this case, epsilon r becomes a number without unit. This is known as the dielectric constant or just permittivity, depending on who you ask. It's just a single number.

Sometimes, some other people essentially combine epsilon 0 and epsilon r here. They also call it permittivity, which is confusing. But just keep in mind, permittivity sometimes actually has a unit or doesn't have a unit, depending on how you actually define it. But basically, this permittivity or dielectric constant is a measure of how polarizable material is when you apply external electric fields.

What's relevant to optics is that you can derive from Maxwell equation this very simple relation there where refractive index directly scales with the square root of dielectric constant. This works in the case of non-magnetic media, which is usually the case for most of the material we're actually looking at here for most glass materials. So in this case, essentially, if you know the permittivity you can immediately derive the refractive index. So in essence, it says that refractive index is also a measure of the polarizability of the material. If the electric field can induce a larger dipole moment, the material also tends to have a higher refractive index.

OK, one little caveat about this equation. Here, n equals to square root of epsilon r. So epsilon r and n, they are both frequency or wavelength-dependent.

In order for this equation to be satisfied, you need to make sure you measure the n and the epsilon r at the same frequency or the same wavelength. This can sometimes be confusing, because when you're talking about dielectric constant permittivity, sometimes people assume that you are talking about either the DC value of the perpetuity, or you're talking about maybe in the I frequency domain, which is actually very different from the optical frequency permittivity [? there. ?] So that's why you just make sure when you're using that equation, you use it in the same frequency range.

All right. so that's basically the very basics. Now let's take a look and come back to our actual amorphous materials. Let's consider the refractive index of glass materials. So we mentioned the refractive index is a measure of the dielectric polarizability inside the material.

So we expect that something with a large electron density with a more polarizable electron cloud will tend to have a higher refractive index. So that's basically a trick people play in order to increase the refractive index of glass materials. What they do is they will try to add some kind of heavy elements into the glass matrix to boost the refractive index.

One common example is to add lead. So that is basically the heaviest element or the element has the largest Z number that's still stable, meaning not radioactive Lead oxide also usually has very good solubility in many, many kinds of oxide glasses. So it's a very commonly used additive in order to create a higher refractive index glasses.

If you don't want to use lead, especially because a lot of the essentially regular treatments now prohibit using of using of lead metal, you can use other kinds of heavy metals, heavy elements. In addition to composition, I want to mention that the structure itself of the glass also has an impact to the refractive index. You can think about the chemical bonding configuration.

So for example, if you think about silica glass SiO2, because you have very strong chemical bonds, the electrons actually form the chemical bonds, gets very tightly localized into atoms. They actually form the chemical bond. So in this case, the polarizability is limited.

You can therefore increase the polarizability by essentially introducing a non-bridging oxygen. If you put in some alkali-oxides into the glass matrix, for example, you can have non-bridging oxygen. And the electrons around this non-bridging oxygen are actually less localized and hence more polarizable compared to the case of SiO2 network.

And that's why if you think about SiO2 glass, they typically has a refractive index of about 1.45, 1.46 in the wavelength range. If you go to a, say, soda-lime glass, it has an index of about 1.52, 1.53. So it's higher compared to just silica, basically because of the additional polarizability induced by these MBOs.

I also want to mention that the refractive index also depends on the fictive temperature. So this is actually what I'm showing you in this plot here. If you look at the refractive index, it's a function of the cooling rate through which you actually make the glass.

Typically, higher cooling rate leads to glass materials with lower refractive index. So in this case, the chemical composition of glass material is exactly the same. So the main factor that impacts the refractive index in this case is mostly just density.

If you go to a faster cooling rate, then the materials tend to have a bit more free volume. As a result, per unit volume, the number of molecules in that same volume is actually less. And that's why you will have less p, less polarizability by definition, and therefore less smaller refractive index. So these are the basic ways how you can actually engineer the refractive index.

The next topic I want to discuss here is actually the wavelength dependence of refractive index, which is the dispersion. Now, to understand dispersion, it's important to introduce this so-called Kramers-Kronig chronic relation here or K-K relation. Have you learned about K-K relation in any other classes?

AUDIENCE: It's definitely come up.

JUEJUN HU: Sounds familiar? Anyway, K-K relation basically says refractive index and optical absorption of a material, which seems like two separate quantities, they are actually interdependent. You cannot change the refractive index of material without modifying its optical absorption characteristics. That's what it says.

You may wonder why. It actually has to do with causality. I'm not going to go through it.

If you're really interested, I mean, in my other class where I talk about photonic materials, I actually give a discussion about why absorption and refractive index must be related. Otherwise, you're going to violate causality.

Causality essentially means that the consequence or the results of something has to occur before that cause-- sorry, has to occur after the cause. But bottom line, what I will show you here is that this is a typical diagram that shows the relation between refractive index and absorption coefficient. In the refractive index, [INAUDIBLE] is the absorption coefficient.

Now, definition of absorption coefficient-- just to remind you here, if you have a slab of material, let's say with thickness d. You have some light coming in initially with intensity-- let's say I0. And after passing through a material due to absorption its intensity must decrease to I. So I should be related to the incident intensity according to so-called Beer-Lambert law with e alpha d.

Assuming you ignore any kind of surface reflection, then the light intensity inside the material basically would decay exponentially. And the so decay constant is given by alpha. This is the absorption coefficient. So the thickness has a unit of length, so centimeters basically. So then alpha is usually given in terms of inverse centimeter.

All right, we're going to revisit the definition a bit later. But what I'm plotting here, alpha has the form of basically a peak at some particular center frequency. This is a pretty common form of optical absorption here. We essentially characterize this, there's some kind of a transition in the material with a transition energy centered at essentially h bar omega-- omega 0. So this could be, for example, you have an atomic level where the transition energy coincides with essentially M bar omega 0.

It could be you have some kind of atomic vibration where the vibrational characteristic frequency is given by omega 0. In that case, if the incident photon has a frequency coinciding with the vibrational frequency, you are then going to excite that vibration, essentially converting a photon energy into vibrational energy, or essentially into a promoting electron from one energy level to another. It's essentially leading to absorption of photon.

Now, the absorption show up essentially as a peak there with some essentially finite width. That's because this kind of transition usually has some kind of broadening mechanism, so that it doesn't occur strictly only at one particular energy. The broadening mechanism, there are many mechanisms that can do this kind of broadening there. We're not going to go through it. But phenomenologically, you can now capture the absorption coefficient of this kind of transition by essentially a function, like a peak function centers right at one particular frequency.

With K-K relation, it specifies that if you have a absorption coefficient that peaks, the refractive index must show a dependence, like the blue curve on [INAUDIBLE]. A quick way to understand it mathematically is that you can see that this blue curve is almost like a derivative of the red curve.

In fact, you can prove it. If you look at it mathematically, you look at the K-K relation, you can prove that it's like taking the derivative of the absorption coefficient. But if you look, what's the implication here. So a couple of things.

One is that if you have absorption then the refractive index must be wavelength-dependent. If you have a wavelength-dependent refractive index, this is called dispersion. And if you look at how the refraction changes with wavelength, if you look at the regime that's far away from this absorption line, then the refractive index, whether it's on the left side or right side right, it will increase with frequency. Or in other words, the refractive index decreases as you go to longer wavelengths.

This is called a normal dispersion. If you have normal dispersion, you also get anomalous dispersion, obviously. Anomalous dispersion happens around the resonance right here.

Around the resonance, you get this line here where the refractive index actually decreases with increasing frequency, or it decreases as you go to shorter wavelength. That's called anomalous dispersion. The reason why it's called anomalous versus normal is because most of the time when people are using optical materials, they want to use it in a regime where it's transparent. If it's transparent, you must be far away from this absorption line layer. And therefore, you usually see this refractive index will actually decrease as you go to longer wavelengths.

That's why people call it normal dispersion. And anomalous dispersion essentially only takes place where you have a strong absorption. So that's the first thing here. We are going to go back and take a look at that in real materials later.

The second thing is if you look at the refractive index, the limiting values at the high frequency and low frequency, they are not the same. What I'm plotting here is refractive index minus 1. So you see that for this side, as you go to the lower frequency, the refractive index is actually higher than on the higher frequency end. There's a little step as you cross this [? resonant ?] line here.

This essentially corresponds to the polarizability contribution coming from the resonance. So for example, suppose this resonance is caused by vibration of, say, some kind of atoms. Now, you can imagine that this atom, essentially this vibration, will get to the maximum amplitude when you coincide with this resonant frequency.

If you go to an extremely high frequency, much higher than the characteristic vibrational frequency, then this fast oscillating electric field, the atom itself will not be able to keep up with this rapid oscillation of the electric field. So then essentially, it will stop vibrating and therefore, it will stop contributing to polarization. So it means that at the high-frequency end, this atomic vibration will no longer contribute to polarizability, and therefore no longer contribute to refractive index.

So essentially, this index step you are seeing here is, as I said, is the polarizability contribution coming from this particular resonance or this particular vibration. Does that make sense? We can take a look at one real example here, or more specific example here, about why this is actually relevant.

So now what I'm showing you here-- well, let's take a look at actual refractive index of glass materials. In glass materials, let's start by looking at the absorption coefficient. There are typically two classes of absorption mechanism there coming from vibrations.

One is electronic absorption. This can come from, again, discrete energy levels or electron levels, like you have dopants in glass materials. Or you can have essentially conduction band and valence band. If your photon energy is larger than the bandgap, you can essentially promote electrons from valence band to conduction band.

So that's essentially electron absorption. You can think of it as essentially photons inducing electron resonance or electron vibration if you want. You can also have atomic absorption or ionic absorption. This has to do with the atomic vibration I was talking about.

The light can essentially also drive the oscillation of electrons-- sorry, of atoms. And then if the light frequency coincides with the characteristic resonant frequency of the atoms, then you are essentially converting the energy from the optical domain into essentially atomic vibration, which is heat. So that's why this kind of atomic absorption is usually also called a phonon absorption, because essentially atomic vibration is basically phonon OK.

Now, as you can imagine, because atoms are a lot heavier compared to electrons, the characteristic vibrational frequency for atoms will be a lot lower compared to that of electrons. So typically, this kind of atomic absorption that will take place at much longer wavelength. So for glass materials, that's transparent in the visible regime.

The electronic absorption would typically happen in the UV range. The atomic absorption on the other hand, this is usually in the mid-infrared. So we're talking about wavelengths from a few microns-- say 5 microns all the way up to 20, 30 microns

All right, so that's the absorption coefficient. Now what about the corresponding refractive index? We can apply our calculation here. And along every absorption peak, you see a little function, like this zigzag function,

So this is what a typical refractive index is going to look like, starting from this low frequency, so long wavelengths. At very long wavelengths, the oscillation of the electric field is actually slow. So both atoms and electrons can keep up. And therefore, both atomic polarization and electronic polarization will be able to contribute to refractive index at low frequencies.

So for low frequencies, we are talking about essentially from 0 frequency to microwave all the way to [INAUDIBLE] infrared, so tens of microns, hundreds of microns, terahertz. That's the range where both atoms and electrons contribute to refractive index.

Now, if you goes to the more visible or near infrared wavelength range, you move past the vibrational frequency of atoms. Then in this case, you only get electrons contributing to polarization because atoms can no longer keep up. So for typical materials, when you are talking about optical frequency regime polarizability, which is usually visible on near-infrared. The refractive index pretty much solely comes from only electronic contributions. OK, so that's the refractive index in the most common sense.

Now finally, if you move past UV you go to the X-ray or gamma ray regime, then even electrons cannot follow the oscillation of the electric field. And the refractive index now will be close to unity because there is no polarization. Now, if you look closely into this curve here, at the high-frequency end, the curve actually approaches unity from below. So it means that refractive index is actually less than 1.

That's actually the typically the case for X-rays or gamma rays. If you look for the different refractive materials X-ray, they are all 0.99 something They are slightly below 1. It's exactly because of the K-K relation and the fact that no electrons can respond to X-ray frequency oscillation.

And that's also exactly why X-ray optics is so difficult because people always want X-ray optics to essentially manipulate x-rays for X-ray imaging or those type of applications. Invisible frequency range, you can easily make lenses because you have materials with large index differences like glass and air. You can efficiently use refraction to control light propagation direction.

The problem with X-rays is that all the materials have indexes very close to 1. And that's why it's become very, very difficult to actually create refractive optics in the X-ray range. In fact, people usually use diffractive elements to change the light propagation direction, X-ray frequencies, which brings a whole lot of complications there.

All right, so let's see what the spectrum looks like. Now, in terms of dispersion, you again have normal dispersion. You have anomalous dispersion.

Now, for most transparent glasses, if you want it to be transparent, you want the electron absorption to locate in UV. You want the phonon absorption to locate in IR. So in between, in the visible regime, you have no absorption mechanism there. And that's why it becomes transparent.

What that also means is that you must be looking at the normal dispersion regime when you're looking at the transparency range. So refractive index tends to monotonically decrease as you go to longer wavelengths. So to quantitatively characterize this dispersion behavior-- this is called chromatic dispersion, people typically use this number here.

This is called Abbe number or V number. It's defined-- you can look at the equation here, nD, nF, nC. These are the refractive indices of the material at three specific wavelengths. They are chosen because these are specific absorption lines in the solar spectrum. That's why people choose those numbers.

Now, if you look at this V number here, the numerator is basically refractive index, referring to the minus 1. Denominator nF is at a shorter wavelength, so it's a higher refractive index. So you have a normal dispersion media. nF f should be greater than nC. So V number will be a positive number.

And also, if the material is more dispersive, you have a more drastic dependence of refractive index as a function of wavelength. Then the difference between nF and nC will be larger. And therefore you should have a smaller V number. So smaller V number essentially corresponds to material that's more dispersive. Its wavelength more strongly depends-- sorry, its refractive index more strongly depends on wavelength.

All right, now let's take a look at glass materials. If you go to a glass vendor website, the most famous one in particular for this plot is actually from Schott glasses. On this plot, horizontal axis would be the Abbe number, V number. Vertical axis would be the refractive index at one particular wavelength. This is nd.

Now notice here little caveat. This nd is lowercase D. This is different from this uppercase D here. So the wavelength point is actually slightly different. It doesn't really matter.

Bottom line-- if you look at this plot here, this red point corresponds to one particular combination that you can find in the product catalog from Schott. You can directly order it off the shelf, basically. If you look at this plot here, most of the data points go along this diagonal direction.

So what it means is that a glass material with high refractive index also tends to have a small V number, and therefore tends to have higher dispersion. This is a general rule of thumb. High-index materials tend to have a higher dispersion in this case.

Now, intuitively, you can also understand what's actually going on here. If you want to get high refractive index, what you need to do, you need to add heavy elements. Heavy elements tend to reduce the bandgap. So when you reduce the bandgap, it means that you are essentially shifting this absorption line towards the longer wavelength end.

And if you push this feature towards the longer wavelength end, you can see the slope actually increases here. And that's why the material becomes more dispersive. You are pushing this feature essentially to the right side.

So if you push it to the right side for the visible range, you're sampling this part of the curve, rather than this part of the curve. So then it has a higher slope. That's why it becomes more dispersive. So general rule of thumb, high index, usually the material also is more dispersive.

So now if you look at the material it actually has a high index. These glasses are typically labeled with the last letter F. These are called flint glasses. They are the glass materials typically doped with heavy elements like lead And they are characterized high index and also high dispersion.

On the other end these are the glasses ending with the letter K. These are usually called a crown glass So soda-lime glass that we use every day is a kind of crown glass So crown glasses tend to have a low index and low dispersion.

The extreme here is if you go to this one, FK. FK are actually crown glasses doped with fluorine, F. So fluorine is a very, very small atom. It has very few outer shell electrons.

It also has a very small atomic radius. So essentially, all the electrons are tightly bound to the atomic nucleus. And what that means is that the polarizability of fluorine atoms is very low. The electrons just don't want to move around too much So any kind of fluorine-doped glasses tend to have much lower refractive index compared to other kinds of glass materials

The extreme is if you go to a fluorite. A fluorite is basically like calcium fluoride-- for example, CaF_2. So CaF_2, its index is actually 1.4, and it has a V Number of about 95. So it's actually somewhere here out of the chart. So by essentially tuning the chemical composition, you can essentially change the dispersion and refractive index over a pretty wide range

Now you may wonder why people care about that. In fact, before I go to that, I mentioned that in addition to glasses, another commonly used amorphous material for optics is optical polymers. And optical polymers tend to more populate this corner here, which means that for the same refractive index, they tend to have higher dispersion compared to the inorganic glass counterpart

And this capability is actually useful because people can actually use this kind of a chromatic dispersion of materials to engineer the wavelength-dependent response of optical devices. So what I'm showing you here on the photo, this top left corner here, this is basically a dispersion spectrometer-- prism dispersive spectrometer. Its mechanism of operation is fairly straightforward.

This is the same as what Sir Isaac Newton used, his prism to separate sunlight. You can essentially split a polychromatic light into its individual wavelength components, and therefore measure the intensity as a function of wavelength to give you actually a spectrum. So in this case, having a material that's heavily dispersive is actually advantageous.

Now, the flip case is when you are trying to essentially make some kind of imaging instruments-- for example, a lens. In a lens, we know that the light at different wavelengths essentially has different refractive indices. The light at shorter wavelengths, like blue light, blue color light. if it's normal dispersive material, they should have high refractive index.

So it means that if you try to focus light onto one point here, the focal length for the blue light is going to be shorter compared to the focal length of the red light. So now if you have a fixed image plane-- this is, for example, your photographic film or your CMOS image sensor [? it's ?] actually lying there. Then instead of having a single very sharp image, what you get is a blurred image, because essentially, the different parts of the spectrum get focused at different vertical depths there.

So this is known as chromatic aberration. And you can look at this photo here. This is actually a photo of the moon. You can clearly see that if you zoom in, essentially all these images here, they are not sharp. You see this kind of color fringes essentially due to this kind of color aberration.

So how do you correct for this kind of chromatic dispersion? The answer is that you go to not just a single lens. You try to make a lens out of multiple materials.

You can, for example, make a doublet. You have essentially one piece of lens here. You might offer one material.

You put another piece of lens made out of a different kind of material. I'm not very good at drawing this. And by using two materials with different dispersion characteristics, you will then be able to compensate for this kind of chromatic aberration.

I want to show you this little plot here. So if you look at the simple length consisting of only one single material, then this is typically what the focal length is going to look like as a function of wavelength. This black line essentially indicates the wavelength you actually design the lens to actually operate at.

If it's only one single material, its wavelength is going to monotonically increase as you go to longer wavelengths. And therefore, you only hit this desired wavelength at one single point. If you use two materials to make a doublet, then you can create a so-called an achromat. That essentially gives rise to, at two different wavelength points. you can satisfy your design specification in terms of focal length.

If you introduce more materials you can get apochromat, meaning that you have three points that actually hit the same wavelength. You can also get super achromat, which essentially have four different points. They all align with the design-specified focal length.

OK, now I'm going to show you one design of this kind of super achromat. Let's look at the next slide here. It's of course pretty complicated.

This is actually one of the classical designs that was actually done. This one was done quite a while ago. OK you have a total of six pieces of lenses In order to achieve this kind of super achromat behavior.

Now, what's even more important is that if you look at this length L2 piece, this piece is made of a fluorite. In this case, it's calcium fluoride. Now, calcium fluoride is actually not a glass.

It's a crystalline material. It's actually not easy to process. It's actually single crystal

You have to do essentially grinding and polishing to actually get it. And also it's actually a somewhat hygroscopic. If you're leaving air for a long period of time in an environment with high moisture, you are going to cause fogging of the lens.

So this kind of super-accurate math can be very expensive. And that's why if you look at high-end cameras, essentially the lens heads, they cost quite a fortune. It's actually because of this kind of behavior that people are trying to compensate for the chromatic aberration of lenses.

So this is one example where people are trying to suppress chromatic aberration. What I'm going to give you here. this is actually an example where people are in this case trying to use chromatic aberration as a feature rather than as a bug. So the context here is that people want to essentially split sunlight into different spectral components for more efficient solar energy collection.

So in the last lecture, we actually talked about this concept of tandem cells. A tandem cell, essentially you have this kind of vertical stack of solar cells, the top one having the largest bandgap. And you decrease bandgap as you move down the stack.

The whole idea is that you want to have each solar cell to absorb the sunlight only near its bandgap. So if you have-- for example, this is say the bandgap. Suppose you have a photon with energy that's much larger than the bandgap. Then what's going to happen is that it's going to promote, for example, this electron to an energy level that's way above the conduction band edge.

Then what happens is that afterwards, this electron is then going to relax towards the conduction band edge due to a process called thermalization. Then all the energy, this energy difference between this level and the conduction band edge, is essentially wasted in the form of heat. So that's undesirable.

That's why it's best the solar cell becomes most efficient if you try to use it to only absorb light that has energy slightly above the bandgap. So that's why people use these kinds of tandem cells, where each cell essentially only absorbs sunlight above bandgap. And then you stack them together.

But the problem with the tandem cell is that, as I mentioned in last class, these cells essentially are in series connections, So the current has to pass through all the cells in a common path. It means that the photocurrent for all the cells must be exactly equal to each other. Otherwise, the overall current input becomes limited by the cell that has the lowest photocurrent.

OK, so this is usually done by very carefully designing the thickness and the absorption of each cell. So split the solar spectrum into different segments, such that each segment produces the same amount of photocurrent. That's theoretically possible, but in practice, in actual operation conditions, the problem is that you get clouds, for example.

You can get dust accumulating on your panels. You may get a bird flying by, some shadowing effect. All of those can actually change the spectrum. And therefore, it means that most of the time, this tandem cell will not be able to operate at its designed optimal condition.

So that's why tandem cells actually are mostly used for space applications. There's no atmosphere. There's no dusk. So you always are pointing at the sun, get the right condition.

But people still want high-efficiency cells. So one proposal, is instead of trying to stack solar cells vertically, you try to put them in a lateral array. You have strips of solar cells And you try to split sunlight laterally so that each cell essentially only collects a specific spectral component.

Now it comes back to the problem. How do you efficiently split different wavelength components of sunlight. So one way of doing it is try to do exactly the opposite of what you do in a achromatic lens. You just try to mitigate dispersion. You try to maximize dispersion.

You can design this kind of double prism structures. These two prisms have essentially a similar refractive index at one particular wavelength point. But they have opposite dispersion characteristics. So when the light passes through the interface between these two prisms here, because they have basically the same refract index, there's basically no reflection, very little loss. But as I pass through, due to the different dispersion behavior, they are going to split the different spectral components and let them go in two different directions.

It's basically the exact opposite of why you're trying to design an achromatic doublet. You try to increase the separation of the different spectral components. So yeah, this is actually one example of this kind of a solar spectrum splitter here. You can clearly see that you see the color fringes. It's actually coming from the fact that you're splitting sunlight.

You can then combine it with essentially a lens. You can put it in the essentially in the same optical design with two kind of glass materials' optical dispersion. And then you will be able to actually split sunlight into different components. All right. so this is basically about optical refraction. Any questions about refraction before you go to a transparency or loss? OK.

So now coming to the second characteristic of a glass [INAUDIBLE] about essentially transparency. So what I'm plotting on this plot here, this is the optical loss spectrum in silica glass materials-- silica glass fiber. The horizontal axis is wavelength. Vertical axis is a loss. But this loss is measured in dB per kilometer

So the definition of dB this is basically intensity in a logarithmic scale right. So dB is basically given as 10 times logarithm 10 of the starting intensity over the intensity after you pass through a material there So in fact, what you can do, because we know we have a number [INAUDIBLE], you can directly plug [INAUDIBLE] into this equation.

Let's see what we get. It becomes 10. I know divided by I is e alpha d. So it becomes logarithm 10e alpha D. And this essentially gives us 10 alpha d logarithm 10e.

If you move d to the other side, d is basically length right. So then what you get will be dB per length, dB per centimeter, dB per kilometer. So now what you see here is that there is a very simple quantitative relation between these two unit systems here.

Alpha can be the unit of centimeter inverse. It can also be the unit of dB per centimeter or dB per kilometer. And these two are trivially connected by this equation here-- dB per length is just 10 times alpha logarithm 10e, which equals to. 0.23.

So 10 times logarithm 10e is just 0.23. That's why I'm including it on my slide this last equation here. dB per centimeter can be trivially connected to inverse centimeter with that relation.

There it's wavelength independent. In this derivation, there is no wavelength whatsoever So it's a universal relation for all wavelengths.

Now, another some useful relation to also remember here is that because dB is in a 10 base logarithm. So if the light intensity decreases to 10%, you have 10 dB. It decreases 1% you have 20 dB. It decreases to 50%, 10 logarithm 10 of 0.5 is very close to 3.

That's why in optics, and in electronics as well, when people are talking about 3 dB, it essentially means half. If you talk about three dB splitter, it means that essentially you have a splitter, a split light, to 50% 3 dB attenuator means that essentially cuts off half of the light. So 3 dB basically means half.

I will leave it to you as a little homework exercise to figure out the 6 DB p size. What's the 6 dB p size? It's a quarter pizza.

It's in logarithmic scale. 6 dB decibels is 2 3 decibels, so it's a square of 1/2, so it's a quarter pizza. And then 9 dB is one [INAUDIBLE] pizza. Now, [INAUDIBLE].

OK, anyway, what's remarkable about glass materials, if you look at this particular wavelength here, 1,550 nanometers, or 1.55 microns, its loss is actually as low as 0.2db/km. 0.2 dB is about 4% So it means you can send light through this silica glass material, propagates for 1 kilometer. You lose only 4% of the light.

This is really quite remarkable. I mean, you talk about transparent material, like, window pane glasses, it may appear transparent. But if you look from the side, you immediately see this kind of green tint, indicating that some of the light is actually getting absorbed because of impurities. But in a high purity silica, you can propagate for kilometers with minimal attenuation.

So this is really what enables the whole, essentially, fiber optic network and fiber optic communications. That's the backbone of internet. And that's why the inventor of this low-loss glass fiber, Charles Kao, was awarded the Nobel Prize of physics in 2009 for his groundbreaking contributions to enable low loss light transmission fibers.

Now, the reason he can win this Nobel Prize there is because this is really essentially a triumph of the materials science. He looked a lot into how to actually purify glass materials, how to understand the different loss mechanisms. Therefore, you can achieve essentially low-loss light propagation.

So in the next slide here, I'm just going to summarize what are the loss mechanisms in glass materials or more generally in any kind of materials. All right, starting from the first one this is actually straightforward-- electronic absorption. This is the main absorption mechanism in any kind of semiconductor optoelectronic device.

If you have a photon energy greater than the bandgap, you promote electron from valence band to conduction band, And you convert essentially electron energy to photon energy into the electronic domain. So that's electronic absorption.

It can also come from-- for example, you have some dopant atoms where the energy level separation between two discrete energy levels happens to align with some optical frequency. Then you can promote essentially or excite the atoms from the ground state to excited state. Same thing. Like hydrogen atoms, you see absorption lines also due to electron absorption. Straightforward

Now, next one-- phonon absorption. I've also already mentioned about it. Phonon absorption has to do with essentially the vibration of the atoms or the chemical bonds, basically. You can picture these chemical bonds as you have masses or atoms attached to the end of the spring.

And so if the vibrational frequency of the chemical bonds coincides with the oscillation frequency of electromagnetic field, then you can convert photon energy into essentially phonon or vibrational energy.

So just to show you one example of phonon absorption, I'm showing you this picture here. You want to guess who that guy is?

AUDIENCE: Is it [INAUDIBLE]?

JUEJUN HU: Very good.

[CHUCKLES]

I think last time, last year when I was teaching this class, I was asking the same question. And they would be like, this is Morpheus from the movie *Matrix.* No, I don't look like Morpheus. Not at all.

My main point for showing that is that-- look at my glasses, which is metal oxide glasses. It's completely opaque. You don't see my eyes through it.

So the glasses is transparent in the visible regime. But if you go to infrared, this is actually thermal infrared image. Because the wavelength is longer, vibrational frequency lower, the vibrational frequency actually coincides with the, essentially, oscillation of silicon oxygen bond in oxide glasses.

And that's why they absorb very heavily as you go to longer wavelengths. That's why it's opaque. All right, next one, direct scattering. What's this picture?

AUDIENCE: [INAUDIBLE] *Jurassic Park.*

JUEJUN HU: *Jurassic World* to be exact. And what's that thing?

AUDIENCE: It's like the--

JUEJUN HU: Gyrosphere. It's OK. When you actually watch the movie-- OK. When you watch the movie-- I know it's an airplane movie. But when you are on an airplane watching that movie, did you recall what material they used to make the gyrosphere out of?

AUDIENCE: Transparent ceramic?

JUEJUN HU: Yeah, I know. I saw the revealed answer there. Give me the chemical composition.

AUDIENCE: Oh.

JUEJUN HU: It's material science. You should be proficient. OK, there are many, many, many, many scientific flaws in that movie. But there's one thing they got right. They said that the gyrosphere is made of a transparent aluminum oxynitride, which is indeed a transparent ceramic.

And it's actually a transparent ceramic known for very high mechanical strength. You can understand. Its aluminum, oxygen, and nitrogen, small atoms, very strong chemical bonds. It's basically sapphire. So that's why. It makes sense.

AUDIENCE: [INAUDIBLE] if you were to make that [INAUDIBLE] would use

JUEJUN HU: Sorry?

AUDIENCE: That if you were to make that, that would be the material you would use.

JUEJUN HU: I'm not going to write that thing to see dinosaurs. I don't think it's safe, basically. But yeah, as I'm saying, it's a less transparent. I'm not talking about safety. I'm talking about it being transparent.

Now, why are most ceramics opaque. If you look at normal materials, ceramics are opaque, because ceramics are a polycrystalline material. In a polycarbonate material, you all the different grains. If it's an anisotropic material, it means that different grains at different orientations have different refractive indexes. So as light propagates through it, you actually get lots of scattering, essentially, from that refractive index homogeneity.

In addition to that, you also get essentially grain boundaries, integranular phase. Those intergranular phase also has different refractive index compared to the grain matrix itself. So all of this reflecting the fluctuation is what leads to light scattering. And that's why normal ceramics tend to be opaque.

So the trick to make transparent ceramics like aluminum oxynitride, usually what people do is to find a material system that's isotropic, like cubic crystal systems. So a cubic crystal system, they are isotropic, so that regardless of orientation of the grain. You always have the same refractive index-- first step.

Second step is that you have to optimize your process to essentially eliminate the formation of any kind of intergranular phase. So the light will just zip through essentially a uniform media. It's easier said than done. People spent a long time just to develop those transparency materials, but that's the key. Bottom line is that if you have any kind of a structural inhomogeneity, whether it's due to crystalline grain, grain boundaries or maybe micro-voids, microcracks all of those are going to lead to essentially scattering of light.

Now, the scattering is a bit different from actual absorption. For these two mechanisms here, this absorption, you're converting photon energy into something else-- into heat, basically. But for scattering, you're not really absorbing the light. You're just diverting the propagation direction of light. But effectively, this is also light wasted.

Now, last one this is for glass. So for defects, this only exists in crappy glass materials. In glass with micro-voids like air bubbles or glasses with microcracks, that's when the defects comes in.

But for the last one, Rayleigh scattering, this is universal to all amorphous materials. The reason we have Rayleigh scattering is because, if you think about amorphous networks, if you zoom in to look at atomic scale, every location of the network is going to be slightly different because of the [? incoherence ?] of the physical nature of glass structure. So what that also means is that the local polarizability or the local refractive index is different for all the different locations. So now when the light propagates through, it effectively sees this kind of fluctuation of refractive indices, which then leads to scattering. That's called Rayleigh scattering.

Rayleigh scattering is actually universal to any kind of a non-uniform materials or known non-crystalline material-- any kind non-crystalline material, even like air. Air molecules are running around randomly. So there's also really scattering because of air molecules, the random motion of air molecules. And that's actually why the sky is blue. It is because this Rayleigh scattering scatters more strongly the blue light than other shorter, longer wavelengths of the spectrum.

But Rayleigh scattering is a lot weaker compared to defect scattering, basically because of length scale we are talking about here. The microscopic defects, we are talking about hundreds of nanometer microns, so comparable to light wavelengths. So light gets very strongly scattered.

But for Rayleigh scattering this atomic inhomogeneity takes place at atomic scale, much smaller than wavelengths. For Rayleigh scattering, the scattered light intensity scales with wavelength to the negative fourth power. This is for Rayleigh scattering.

So if you go to longer wavelength-- or I should say lambda divided by a, where a is a characteristic length scale of the inhomogeneity. So if your nonuniformity becomes a lot smaller compared to wavelength, then this Rayleigh scattering becomes a lot more insignificant. And that's why glass materials can be very, very transparent despite the presence of Rayleigh scattering.

So if you now look at this plot here, at the short wavelength n, this is bound by essentially Rayleigh scattering there. Long wavelengths n, this is actually due to a chemical bond vibration. In the middle, you have the lowest loss window, which gives rise to this remarkable 0.2 dB per kilometer. This is usually between-- you are seeking a trade-off between Rayleigh scattering and the phonon absorption in glass that's free of defects.

So I will go into more details about these different kinds of loss mechanisms in glass materials in the next lecture. For the remaining 10, 15 minutes, what I will do, I will actually show you a little demo that shows that indeed, you can get a glass material that's transparent at different wavelength regimes. So what I have here, I have actually brought along with me a little infrared camera, a thermal camera.

What I will do, let me try to project it to a screen here. Let me go to Zoom. And let me try to join Zoom from here, so I can share screen. So now let me start the app.

I have brought along with me a little-- this is actually a little infrared camera. So this is actually what the camera looks like. Right here, this is actually camera lens. It's a lens made of chalcogenide glass. We have mentioned that chalcogenide glasses tend to be transparent at infrared wavelength range. So that's actually what happens. And let me plug it in.

If you want, you can come around and take a look. It may be a bit easier. But I will also try to project it to the screen as well. OK camera. And study the app. OK, now I want to share my screen.

OK, now you see the screen share. Now let me turn on the camera. Actually, let me see. Let me [INAUDIBLE] this way.

Then let's see. Let me turn on the camera. All right, already working.

AUDIENCE: Am I hot?

AUDIENCE: Yeah.

JUEJUN HU: You are, yes. It's actually measuring the temperature. It's actually [INAUDIBLE]

AUDIENCE: [INAUDIBLE]

JUEJUN HU: I think it's better to look at glasses.

[LAUGHTER]

OK, now what do I want to do, we can actually change the color scales if we want. [INAUDIBLE] need to make better apps. I bring along with me glasses-- two kinds of glasses. So this is just a regular soda-lime glass light.

Now try to hold it like this. You can put your finger behind it. You can first look at the finger, and then you could cover it up. So the two of you, however you want to do it. Let me first try to get it to work [INAUDIBLE] if you're looking at finger.

AUDIENCE: [INAUDIBLE]

AUDIENCE: Oh yeah. That's true.

JUEJUN HU: All right. Now I can see it.

AUDIENCE: [INAUDIBLE]

JUEJUN HU: So where's the finger? Let me see. Maybe try to put [INAUDIBLE]. It's actually here.

AUDIENCE: Oh.

JUEJUN HU: I see. OK, all right, good. All right, now try to put the glass in front of the finger. I have to try to [INAUDIBLE]. OK, now block it. What do you see?

AUDIENCE: My fingers [INAUDIBLE].

JUEJUN HU: The glass [INAUDIBLE]. See? You can no longer see your finger. So this shows that for thermal infrared, we are talking about wavelengths of the order of, like, 8 to 10, 8 to 12 microns. This normal transparent glass is actually completely opaque at that wavelength. [INAUDIBLE] myself moving or you are moving?

Now let's try this one. This is the chalcogenide glass plate that I have distributed around in the first lecture, which is completely opaque in the visible. So this, you see nothing.

All right, now your finger again. Try to find your finger. Make sure to get a bit closer.

AUDIENCE: OK.

JUEJUN HU: All right.

AUDIENCE: [INAUDIBLE]

JUEJUN HU: Do you see? Maybe [INAUDIBLE] clean background. Yeah, OK, good. That's a bit easier. See? You still see your finger. Move around. Yup. See, it's moving.

AUDIENCE: Yeah, it's still there.

JUEJUN HU: Yup, so this piece is actually completely transparent. I mean, I can [? probably ?] also put my finger. You can clearly see my finger behind the piece of glass.

Well, we are going to explain why this transparent layer, why this piece of material is transparent versus the oxide glass. But the whole idea is that you can tailor essentially the atomic composition, and therefore change the vibrational frequency of the atoms to push the phonon absorption edge to much longer wavelengths to make it transparent.

AUDIENCE: [INAUDIBLE]

JUEJUN HU: Taking a picture of the camera.

[CHUCKLES]

OK, I think we are actually going to stop here. If you want to take a selfie, you can use this [INAUDIBLE] selfie. I have all kinds of color schemes.