Cybersecurity

Electronic and Communication Technologies

Fiber Optic Communications

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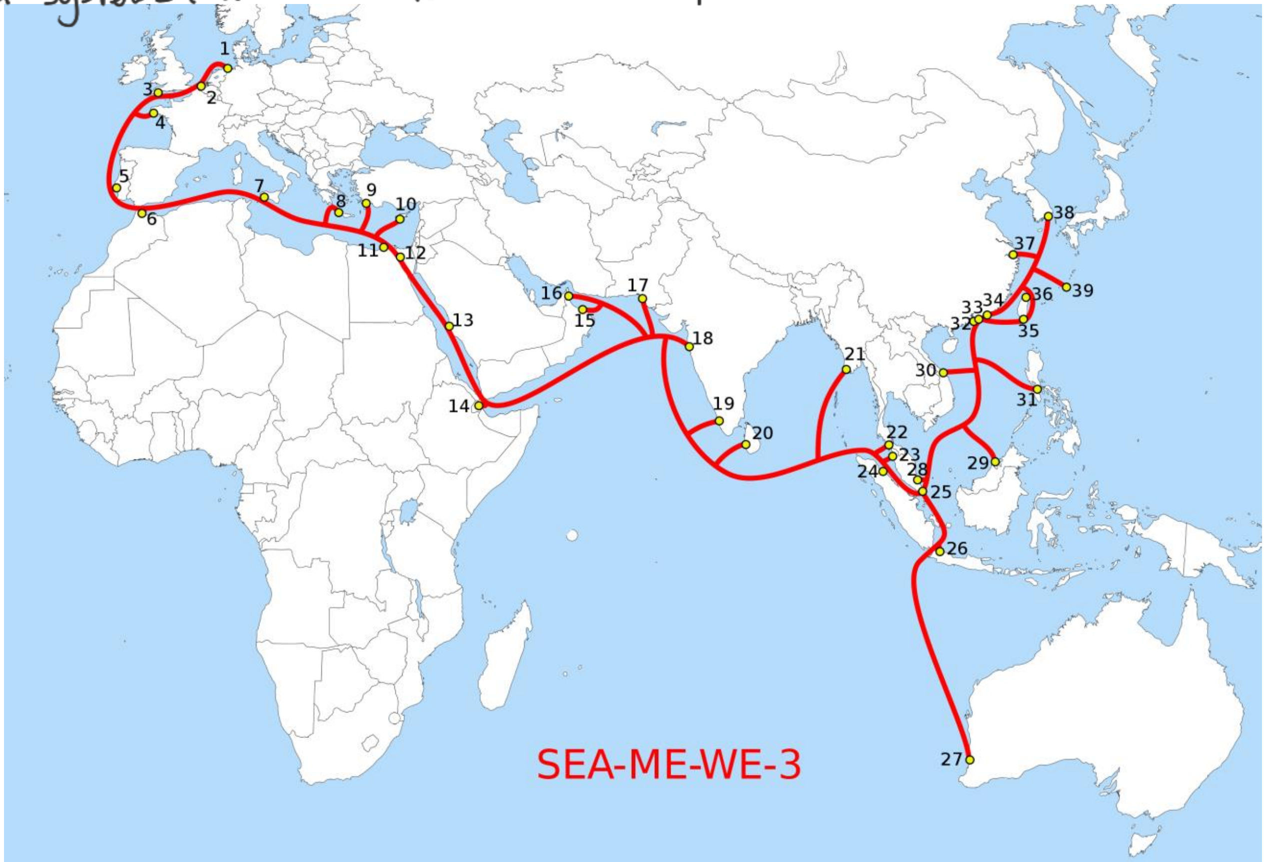
Optical Backbones: Submarine Cable

Back to wired systems (cable). Best tech to have optical fibers

one of the many optical fiber backbone of the net.



Uninterrupted 39,000 km cable

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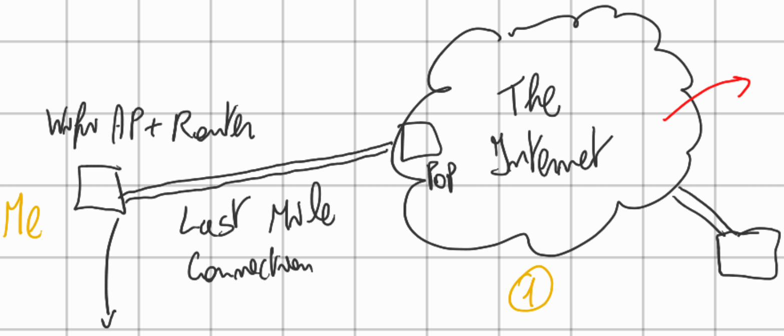
In a network we can find two types of connections



in here, very high speed and long range connection, the backbone.

That goes from your house to the operator's point of presence.
It is the boundary between the cloud and your connection

(1) This is the TRANSPORT NETWORK (uses Opt. Fiber). You are connected to it through the last mile connection and your PoP + Access Point. Collection of all last miles for users is called ACCESS NETWORK. [Leading tech. for wired connection of the last mile is xDSL]. Here you also find cellular networks.

xDSL is being replaced by optical fiber. The tech is very simple, but there's a main problem in providing FTTH: copper is already there for xDSL. Digging and placing cables into the street is extremely difficult.

NOTE: Backbones can reach Tb

First question: why optical and not radio? In the 80s, the backbone was radio relays. Long chain of repeated connection. Across the ocean, satellites. Then optical fiber came, and the bandwidth was so wide, then it was larger than the sum of all satellites in the world. The satellites are now left not for long distance connection, but signal in desert, TV exc.

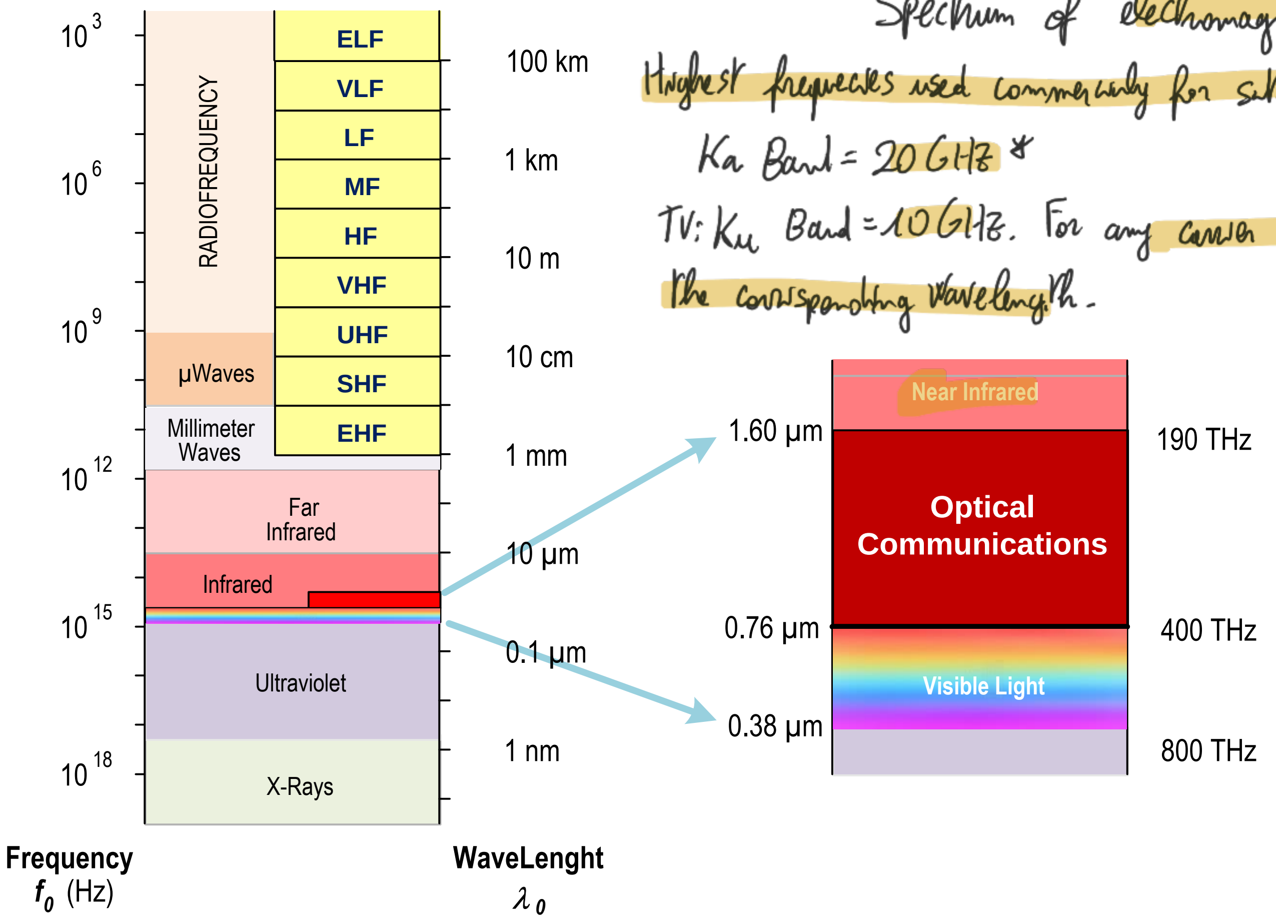
EM Waves Spectrum

Spectrum of electromagnetic waves.

Highest frequencies used commercially for satellites:

Ka Band = 20 GHz *

TV: Ku Band = 10 GHz. For any carrier frequency there's the corresponding wavelength.



$$f_0 = c/\lambda_0$$

* $\lambda_0 = 1.5 \cdot 10^{-2}\, m = 1.5\, cm$ TV: $\lambda_0 = 3\, cm$

VIOLET ← RED

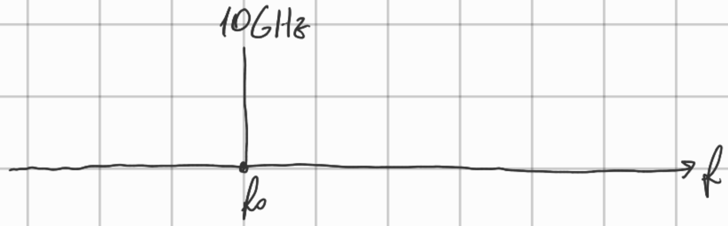
Visible light has wavelengths $\in [0.38, 0.76]\, \mu m$

Waves longer than red: infrared. Waves higher than

We have that light used in optical fiber is in the near infrared region.

The majority of backbones work on $\lambda_0 = 1.55 \mu m$. $f_0 = 194\, THz$.

Why is optical fiber so good?



What is the bandwidth available around a carrier? There's a kind of a 10% rule.

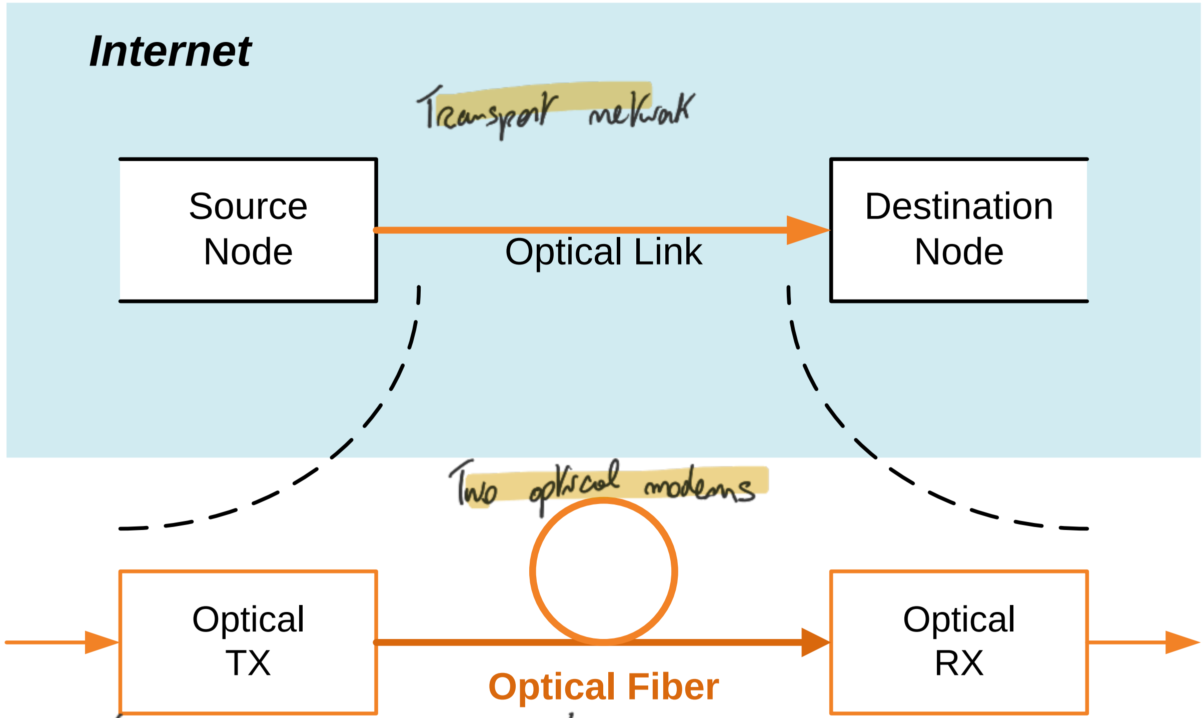
When you have a carrier, your available BW around carrier is 10% of it $\approx 1 GHz$.

What about car radios? $f_0 \approx 100\, MHz$. So, $BW = 10\, MHz$

So higher carrier is better because we have higher BW.

For optical fiber, $f_0 = 194\, THz \Rightarrow BW \approx 20\, THz$

Optical Backbones



Symbol for OF cable. Why? When you test, you have tons of cable rounded up to test the backbone.

This is the backbone

The bit-rate R_b is of the order of hundreds of Gbit/s

here appropriate devices, but architecture is the same

Optical fiber is just a very tiny wire of glass. The diameter is 125 μm, like a human hair. When you lay a cable, you have so many cables (dozens of fibers: so you have a lot of capacity. So much that telecom operators bought cables with so many fibers that they are dark, not used). # of dark fibers for operators can be as high as 95%.

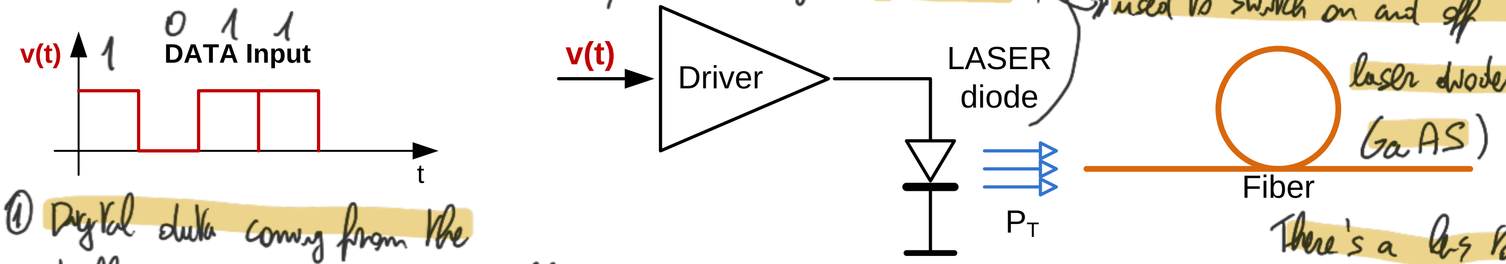
On the backbone but today also in last mile

Optical Link Technology

electrical signal: baseband data

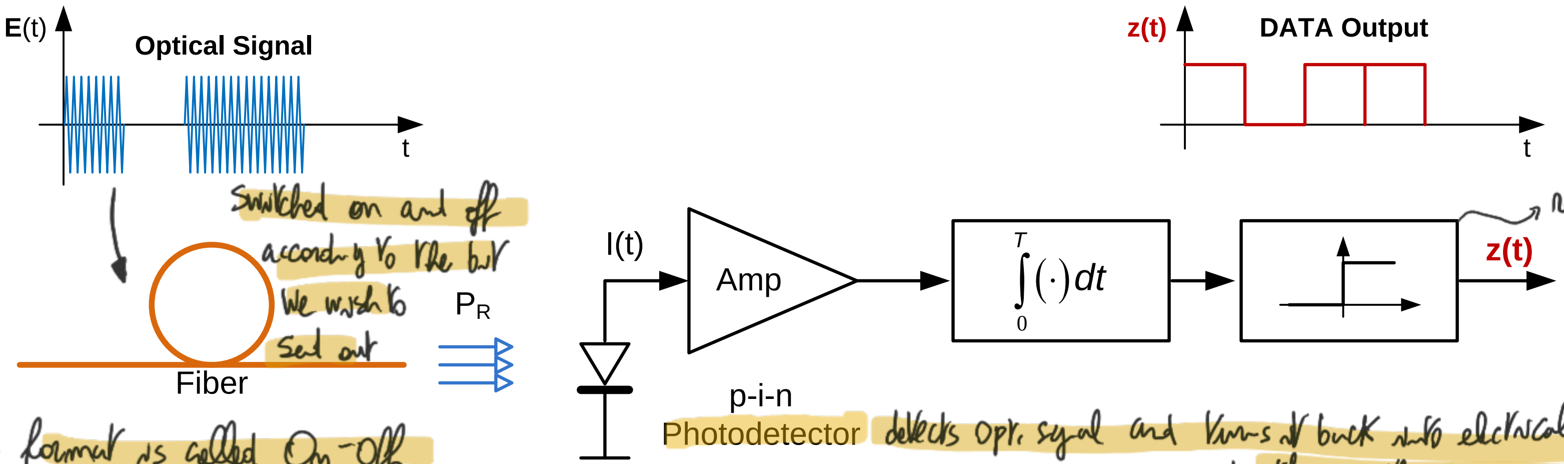
similar to the antenna transmitter.

used to switch on and off a special laser diode (made in GaAS)



(1) Digital data coming from the traffic. Has to be interfaced with fiber

There's a lens to focus the light and that's it.



Switched on and off according to the bit We wish to send out

reclocked

Photodetector detects opt. signal and turns it back into electrical signal in theory with the same shape as previously stated.

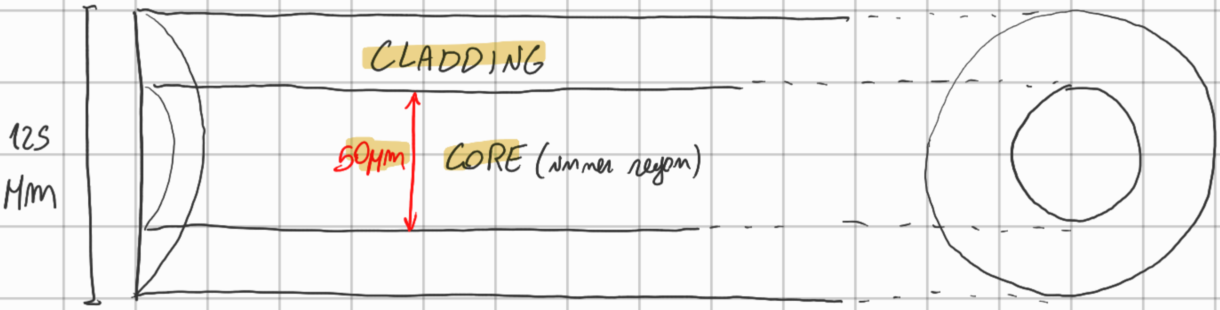
This format is called On-Off keying (encoding) OOK: Very easy! Ofc you will have some attenuation, but shape is same

Key Components: LASER and Photodetector (photodiode)

Back in the days building "fast" lasers and photodetectors was very hard.
With OF connection you have the electrical bottleneck.

How does it work?

How come that we send an optical pulse and we receive it at the receiver? For 50 km! (Because of attenuation)



Fiber sliced in the diameter. We have super pure, transparent glass to avoid losing energy.

SiO_2 (glass) => You take sand to build glass. Very cheap.

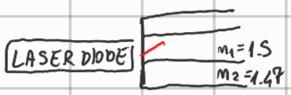
Glass that makes the core is not pure, you add something like Germanium, to make it slightly different. The glass of the core is a bit thicker than the cladding, so speed of light in the core is slower, while in the cladding is faster.

Refractive index $n = \frac{c}{v}$ — c → in the vacuum $3 \cdot 10^8$ m/s; v → speed into the core

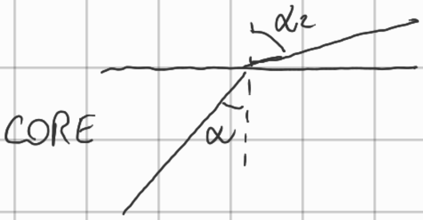
$n > 1$ of course. Typical value for glass is $n = 1.5$. Speed of light is $2 \cdot 10^8$ m/s.

NOTE: Time it takes for transfer: $\Delta S = 40000$ km $\Delta t = \frac{40000}{200000} = 0.2$ s

What happens with 2 regions of fiber? You have a ray of light that goes straight on, until it finds a



discontinuity when we reach the cladding. n_2 is slightly smaller than n_1. Let's zoom:

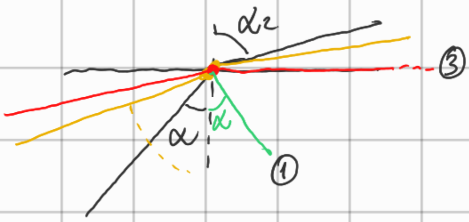


Certain ray with an angle α, while in the other kind of glass (omogeneus), it will have another straight line that will bend α_2. Effect is the bent of ray, following SNELL'S LAW.

LAW: $n_1 \sin\alpha_1 = n_2 \sin\alpha_2$

Depends on angles and difference from materials.
$\alpha_2 > \alpha_1$, because $n_1 > n_2$, so since sine in $[0, \frac{\pi}{2}]$ is an increasing function this has to be like it.

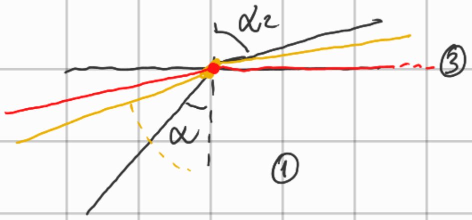
What if ray comes to be a bit more inclined?



③ is parallel to the cable and you have NO REFRACTION.
So Snell's rule is also called REFRACTION RULE.
ns are called refraction ____

But: there's also another phenomenon: when meeting at the difference, you also have REFLECTION: you go away with a same angle of the same angle ①.
REFLECTION IS ALWAYS THERE, INSIDE OF THE CORE, while you can have or not REFRECTION.
If you have a very horizontal signal, you no longer have refraction, so you only have reflection, in what is called TOTAL INTERNAL REFLECTION⑤. And like this, ray will be directed to the end of the fiber.
So all rays that are "more horizontal" will go in the fiber. So we need to find what's the limit case.

What's the condition to have not refraction? When the ray follows the boundary horizontally, so $\alpha_2 = 90°$.



So, $n_1 \sin\alpha_1 = n_2 \sin 90°$

$\sin\alpha_1 = \frac{n_2}{n_1} < 1$. $\alpha_2 = \sin^{-1}\left(\frac{n_2}{n_1}\right)$

↓

CRITICAL ANGLE

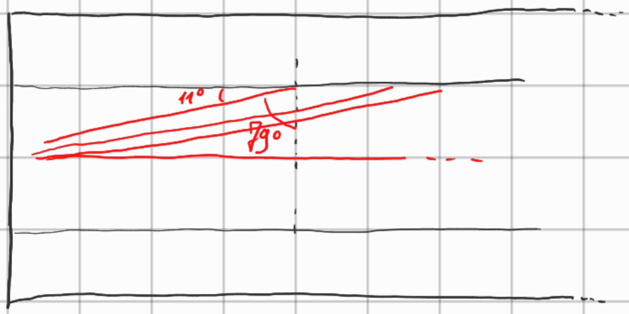
If angle is larger than critical angle we have ⑤, the others for which $\alpha_1 < \alpha_{CRITICAL}$, lost. That's why we have two types of glass. You still have reflection but weaker and lost. With $90° = \alpha$, we have a not generated ray.

This technology is called MM-SI 50/125

size → Multi-mode Step Index

↓ JMP DOWN

Why Multimode?



$\alpha_1 = \sin^{-1}\left(\frac{n_2}{n_1}\right)$

$n_2 = 1,47$ $n_1 = 1,5$

Let's find the critical angle.

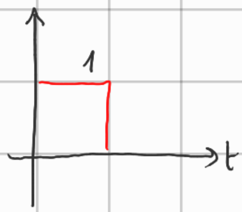
$\frac{n_2}{n_1} = 0,98$, close to 1!

$\alpha_1 = 79°$

Rays in the fiber are very very straight.
In the limit, ray that goes to 90°. Every possible alternative is a way for light to be guided. We have different propagation modes. So MultiMode

$n_1 \sin\alpha_1 = n_2 \sin\alpha_2$ $\alpha_2 = \sin^{-1}\left(\frac{n_1}{n_2}\sin\alpha_1\right)$

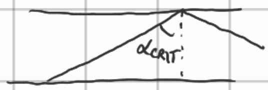
Imagine you send into the fiber 1 pulse for 1 bit. So my fiber will accept all the modes supported. Any ray according to critical angle rule is supported and accepted. BUT:



Let's take the two limit cases: angle that goes straight a and one that go to the critical angles.

What is the diff. of these two rays? The 90° ray will be faster. If I send a pulse at time 0, we have t_1 (time of arrival of the fastest) $= \frac{L}{v} = \frac{L}{c/n_1}$

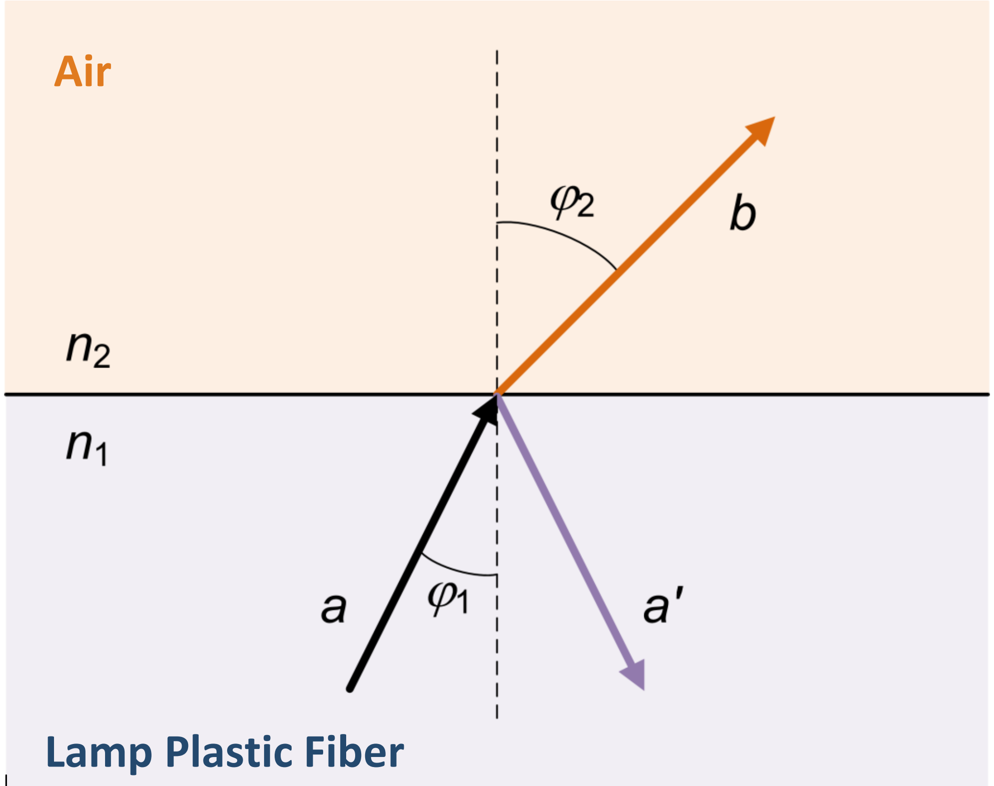
$$t_2 = \frac{L/\sin(\alpha_{critical})}{c/n_1}$$

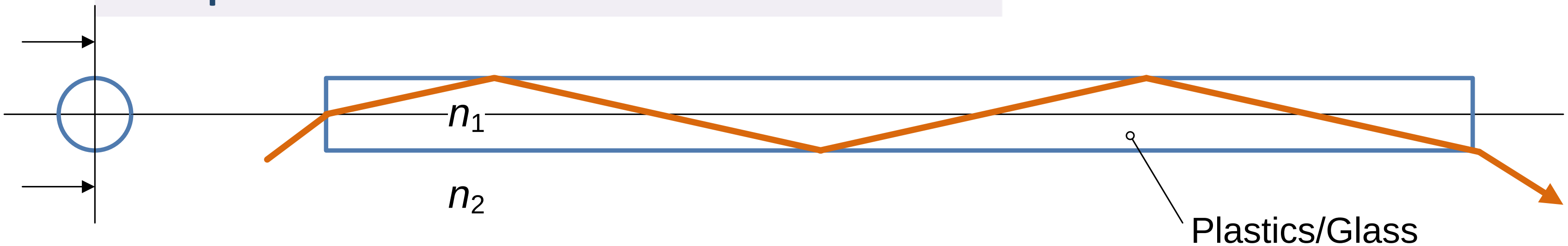


→ during computations the path is longer of a factor of $1/\sin(\alpha_c) > 1$. Longest difference of two modes in terms of propagation time. If a pulse is split, the bits get wider so not good. That's why this tech is not used anymore. Power of laser is spread.

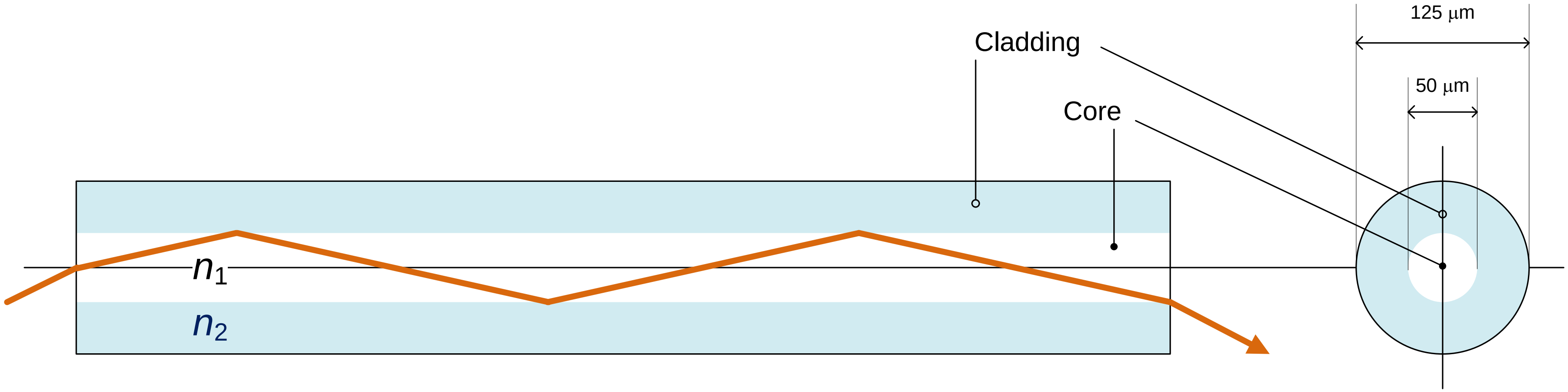
END

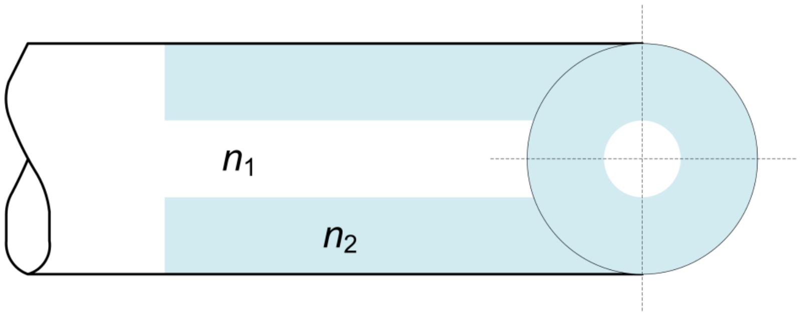
The Fiber Lamp and Snell's Law

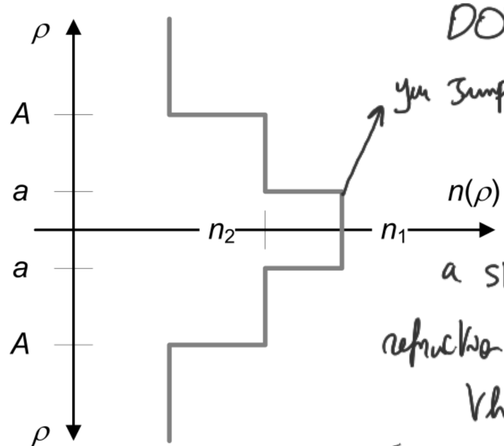




The MultiMode Step-Index (MM-SI) Optical Fiber





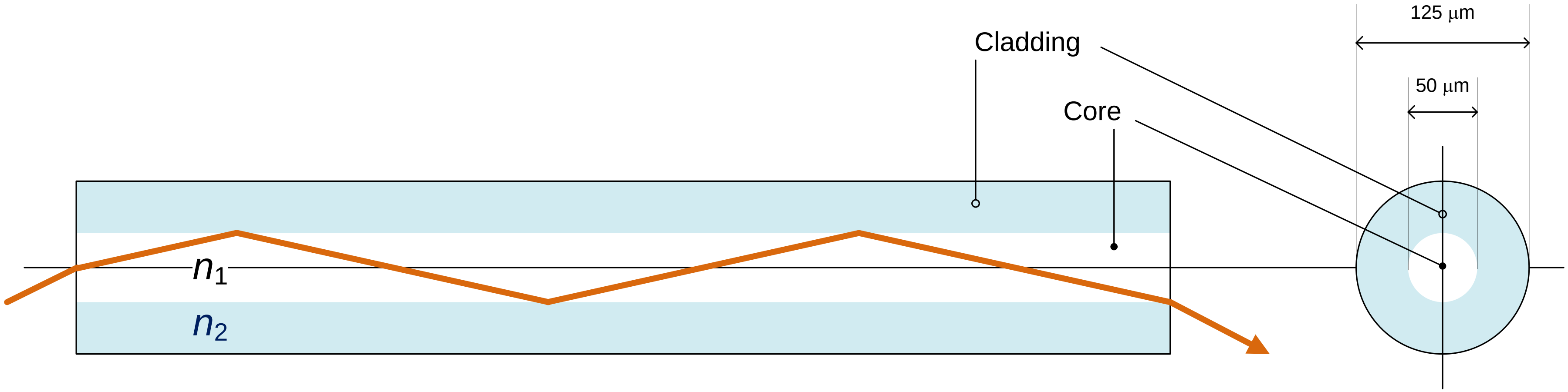


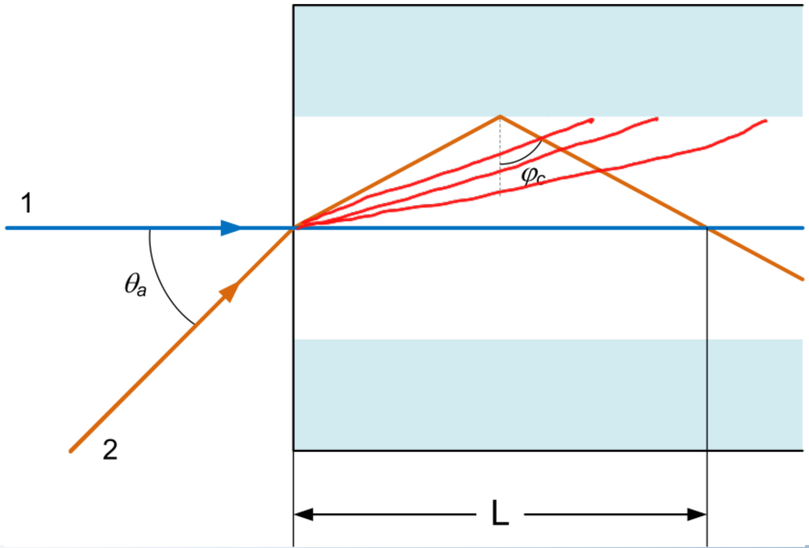
DOWN:
you jump down from 1.5 to 1.47.
So you have a step in terms of refraction index within the fiber.

STEP
RET

You build this with glass vapor by spraying glasses.

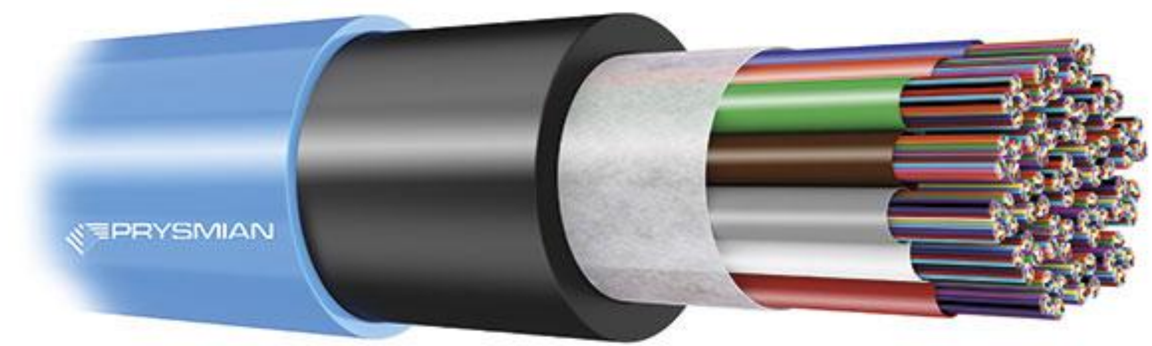
Multi-Mode !



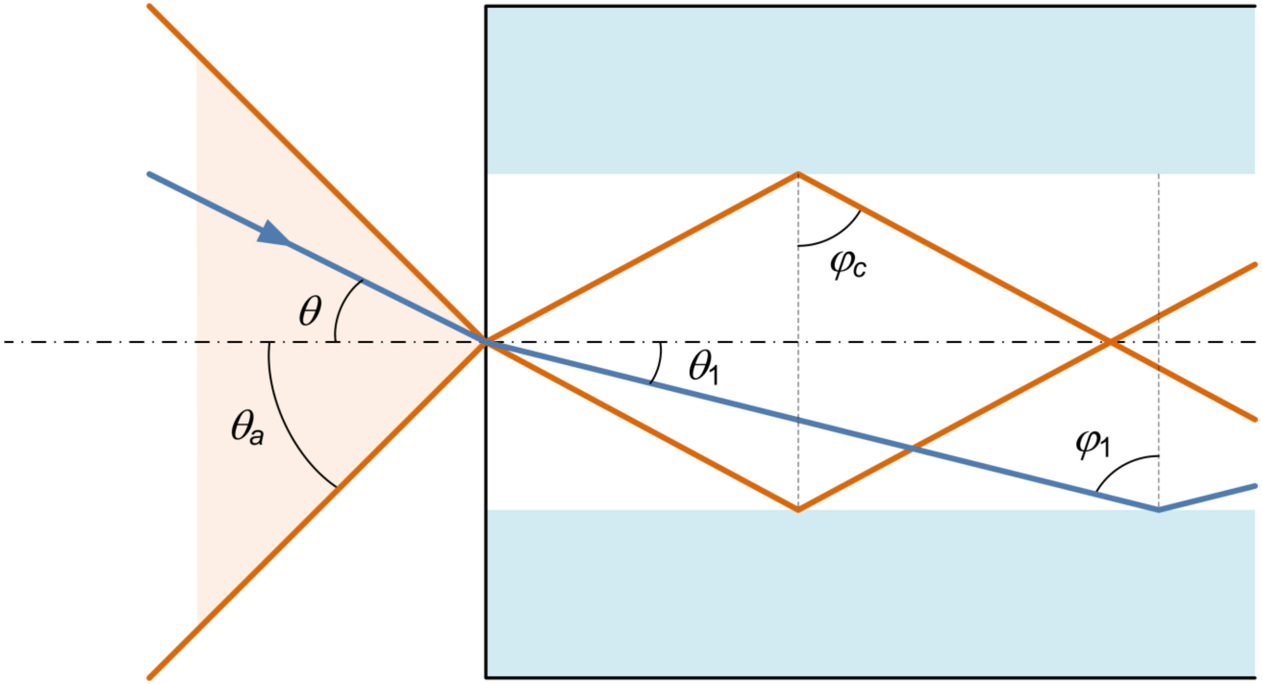


LIMIT CASES: minimum vs maximum angle that give you Total Internal Reflection.
All of the rays between them can contribute to the transm. of info. They are different MODES.

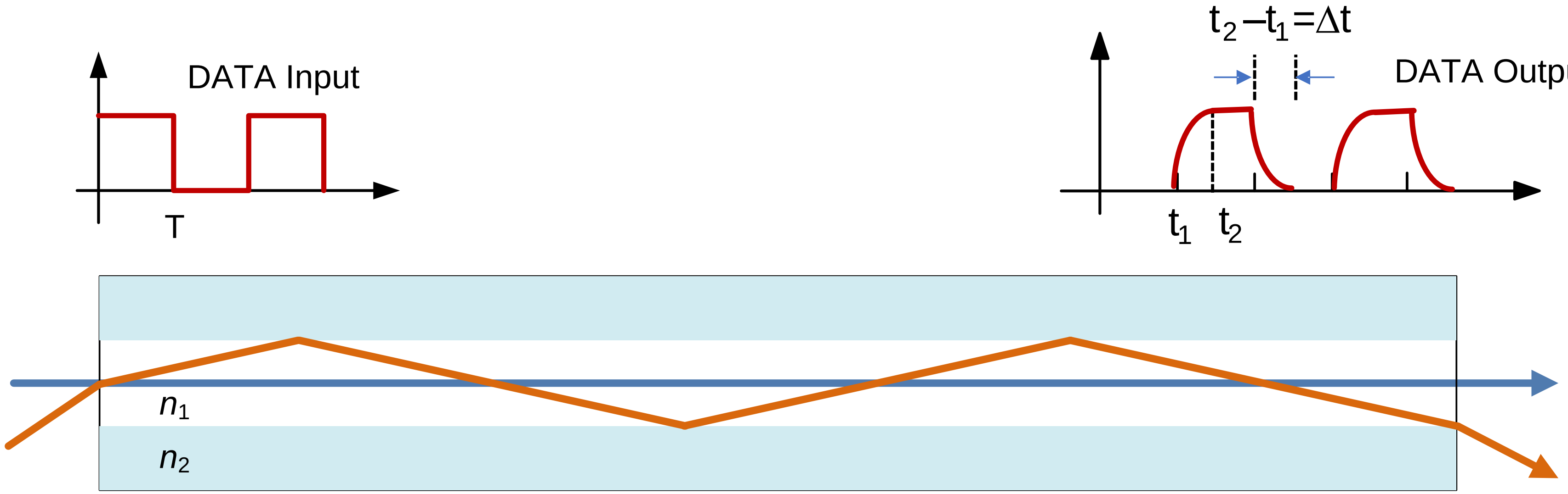
Fiber Cable



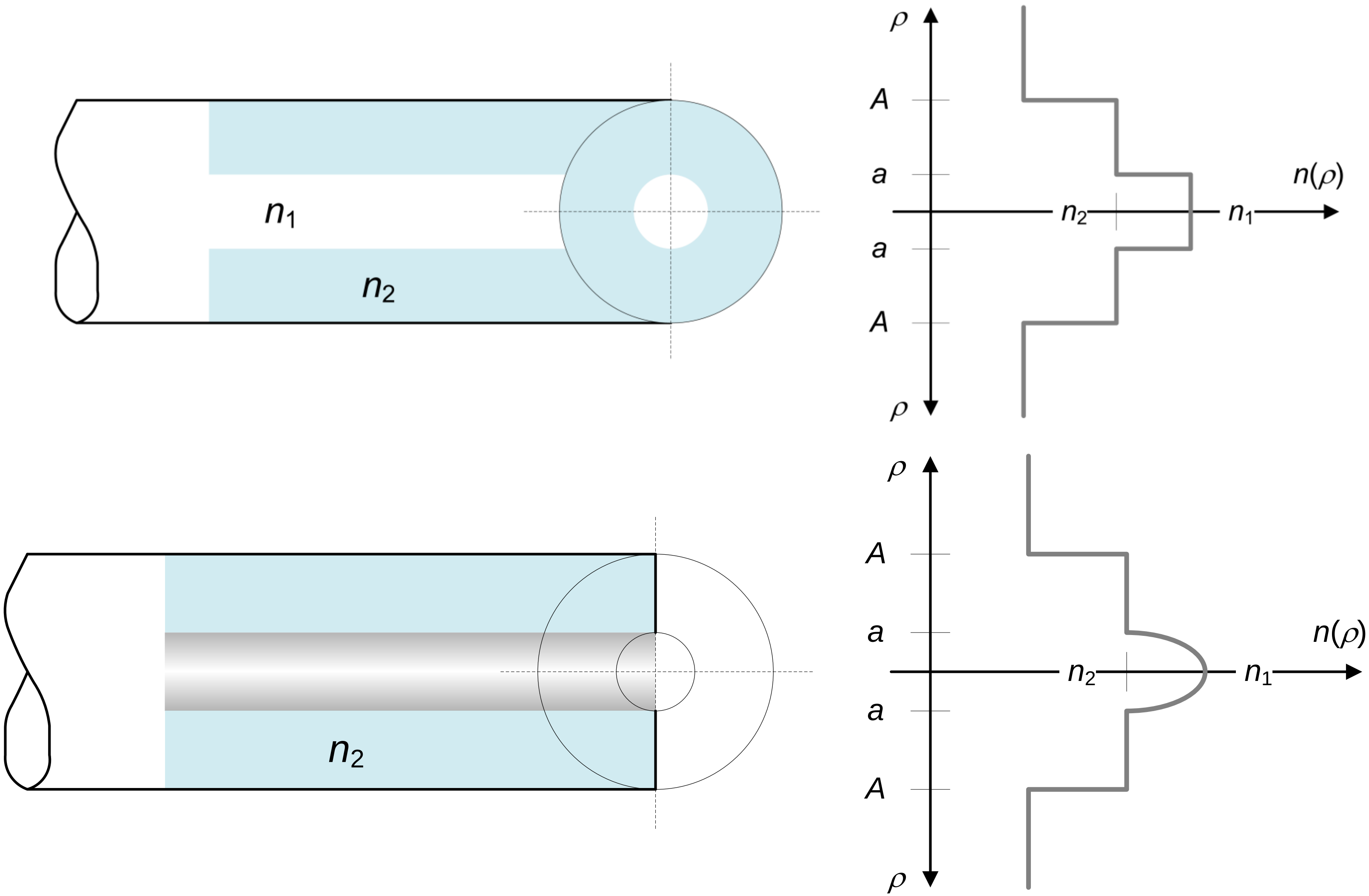
Numerical Aperture



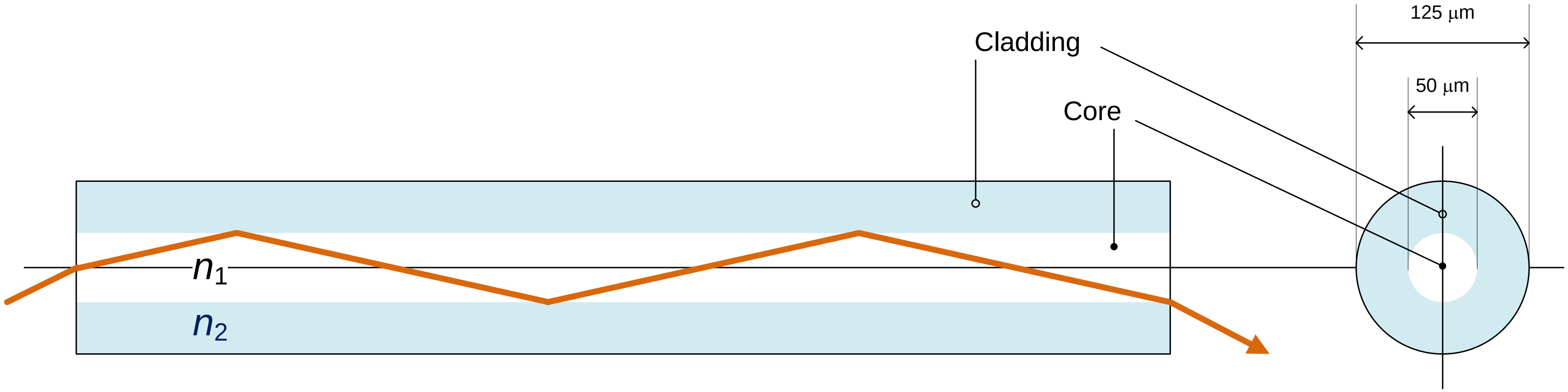
InterModal Dispersion

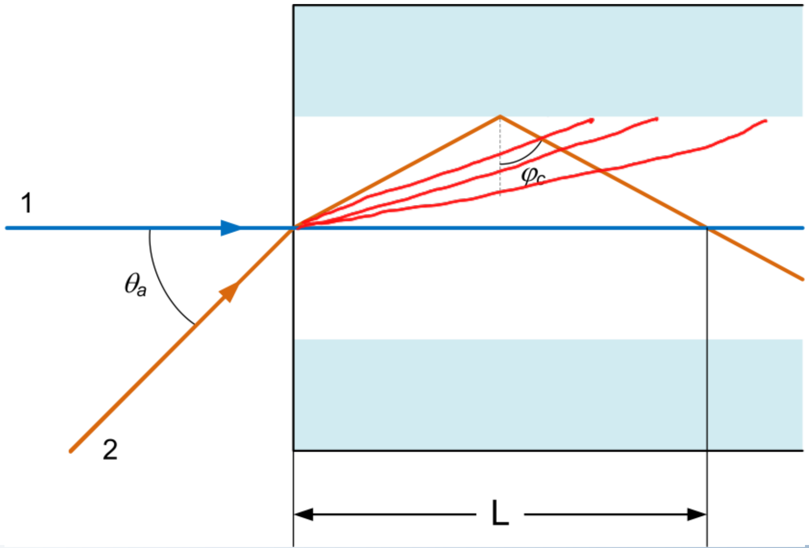


Step-Index vs. Graded-Index Fibers



Multi-Mode !





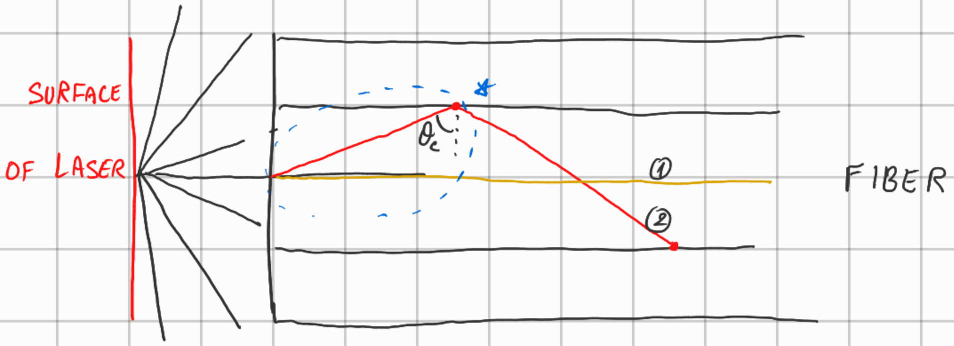
LIMIT CASES: minimum vs maximum angle that give you Total Internal Reflection. All of the rays between them can contribute to the transm. of info. They are different MODES.

Not used in backbone or FTTH, but in short range applications. Big plus: not subject to interference! Standard ethernet cables are subject to interference, even a shielded cable (coaxial) still have interferences. But fiber cables are glass and are not subject to interference. This is also a security aspect.

Plus, anything that's metal generates electromagnetic waves, that might be intercepted by attackers. But optical fibers don't.
↳ when you communicate on it.

Remember: ray stays in the fiber because of TOTAL INTERNAL REFLECTION

What is the consequences of this multimode?



The ray 1 is the fastest, the 2 the slowest. All the other modes are in between.

$$t_1 = \frac{L}{v} = \frac{L}{c/n_1}$$

* If you repeat the reasoning that we did, we come to the conclusion that:

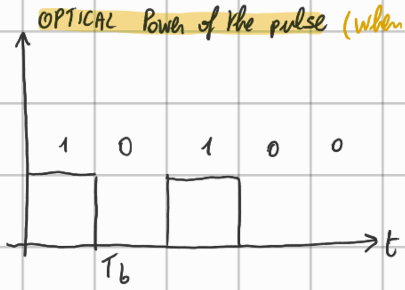
$$t_2 = \frac{L/\sin\theta_c}{c/n_1} > t_1$$

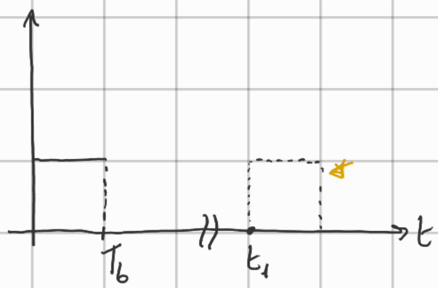
The longer the fiber is, the longer is $t_2 > t_1$. Note: $\Delta t = t_2 - t_1 = \frac{L}{c/n_1} \cdot \left(\frac{1}{\sin\theta_c} - 1\right)$

how slower is 2 with respect to 1

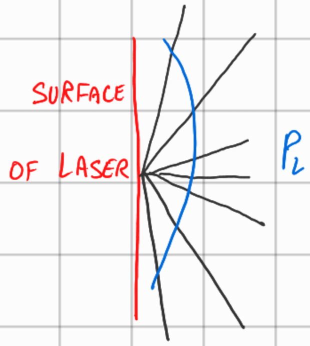
This time distance especially limits the bitrate of this fiber.
Let's see what happens when I send a pulse that represents a bit:

OPTICAL Power of the pulse (when I want to send out a 0, laser is off, otherwise it's high)
↳ in terms of the instantaneous power I'm sending into the power.



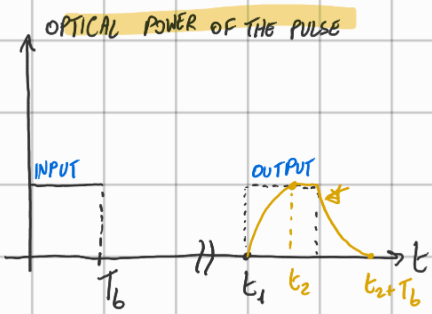


At time $t=0$ I'm switching on the laser, that sends rays with a total power P_L (optical power) (power of the laser).
The total power of the laser are distributed in different rays.



* I would expect to receive my bit at time t_1.
But at t_1 I see just the first ray. They are not coming at the same time. Before fully switching we have a raising time. I see my bit at full power t_2. But at t_1+T_b time, the first ray starts switching off, and I get a fall time that turns things off. There has been some kind of distorsion.

OPTICAL POWER OF THE PULSE



This effect is called PULSE BROADENING. This is bad: we can quantify the broadening with this:

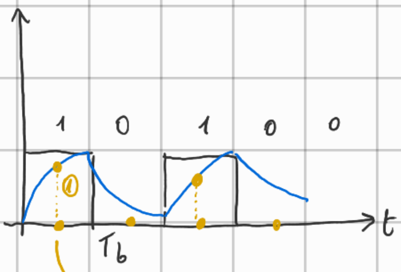
INPUT: pulse is wide $T_b = \frac{1}{R_b}$

OUTPUT: width of the pulse is: $t_2+T_b-t_1=T_b+\Delta t$

So Δt = Pulse broadening. This is no good.

A multimode fiber is the cause of the Pulse broadening effect. This problem is called MULTIMODE DISPERSION; the power is dispersed onto many different rays/modes. The effect of this is PULSE BROADENING

Impact of communication: look at ①. If we have a sequence of bits



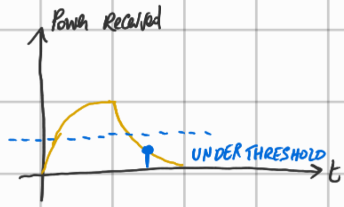
bit clock times at the receiver: I look at the received signal at every clock instant.

This is to regenerate the signal. ①: ok, value $\neq 0$, so I think 1. ③, the same. But because of pulse broadening, in ② and ④ I'm seeing something $\neq 0$. So I interpret them as 1! Here I have a very large value of the BER. Not acceptable at all for optical backbones. A reasonable BER for OPTICAL BACKBONES is 10^{-10} or 10^{12}. Modern backbones go more towards 10^{-12}.

Note: if you are speaking backbone at 1 Tb/s, and require a BER of 10^{-12}, you are seeing 1 error per second on average. With ERROR CORRECTING CODES you have a practical error free backbone.

Snap back: in general, everything that goes on outside of the pulse is a problem (the tail of the pulse). We have to create constraints on Δt.

For instance: $\Delta t \leq T_b$. This because I have a threshold to understand if a bit is 1 or 0:



A real design is much stricter: $\Delta t \leq \frac{1}{10} T_b$.

So $\Delta t \leq T_b$ ← bit time

↳ pulse broadening

$$\Delta t = \frac{L}{c/n_1}\left(\frac{1}{\sin(\varphi_c)} - 1\right)$$

Or: $\frac{1}{\Delta t} \geq \frac{1}{T_b} \Rightarrow R_b \leq \frac{1}{\Delta t}$. Clear limitation in terms of bitrate.

↳ inverse of pulse broadening.

$$\frac{1}{\Delta t} = \frac{c/n_1}{L} \cdot \frac{1}{\left(\frac{1}{\sin\varphi_c} - 1\right)}$$

↳ increasing L gives smaller bitrates.

$\varphi_c \mid \sin(\varphi_c) = n_2/n_1$

NOTE: $\frac{1}{\sin\varphi_c} = \frac{n_1}{n_2} > 1$, so $\frac{1}{\sin\varphi_c} - 1 = \frac{n_1 - n_2}{n_2}$, So:

$n_1 \approx n_2$ (1.5 vs 1.47)

$$R_b \leq \frac{c}{n_1 \cdot L} \cdot \frac{n_2}{n_1 - n_2} \approx \frac{c}{L(n_1 - n_2)} \text{ bit/s}$$

EXAMPLE: Backbone between Pisa to Florence ≈ 100Km

What's the bitrate I get because of MULTIMODE DISPERSION (INTER-MODAL DISPERSION)

across modes

$$R_b \leq \frac{3 \cdot 10^8}{100.000 \cdot (1.5 - 1.47)} = \frac{\cancel{3}^{\,1} \cdot 10^{\cancel{8}\,3}}{\cancel{10^5} \cdot (0.0\cancel{3})} = 10^5 \text{ bit/s} = 100 \text{kbit/s}$$ 💀

Unacceptable for backbones.

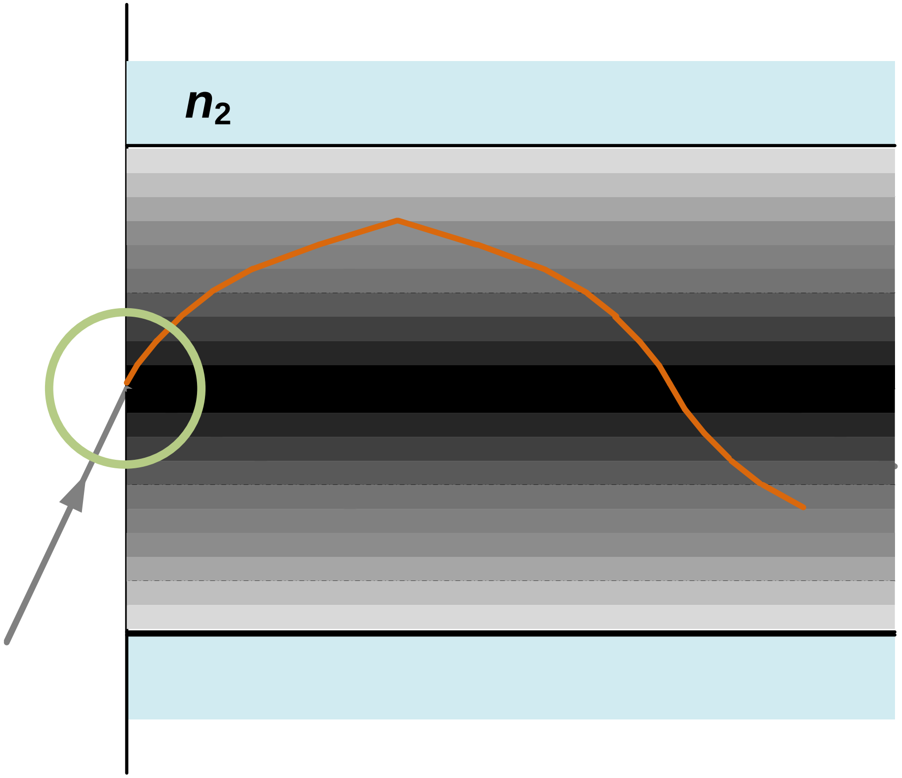
Even with 20Km, I have 20.000 instead of 100.000 => 500 kbit/s

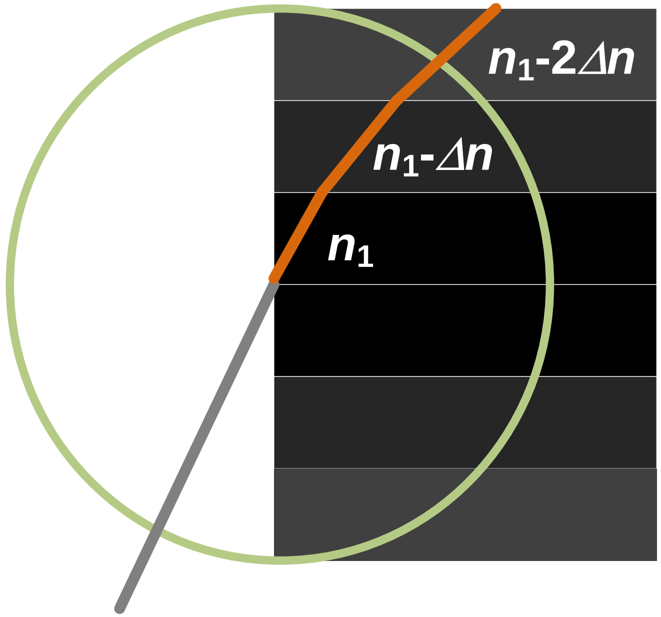
The INTER-MODAL DISPERSION IS THE KILLER OF A BACKBONE

Even with FTTH, with 1Km I would get to 2000 Kbit/s = 20 Mbit/s. Worse than xDSL.

So something was needed to improve this:

Curved Rays in MM-GI Fibers





Manufacturing the fiber is spraying different layers a few hundreds of times.
So, instead of changing the refractive index just once, you do it multiple times.
Since the core is created layer by layer, what we do is create a gradual change of the refractive index. You add layer by layer with a glass slightly different than before.
Start from n_1 (1.5) at the center of the fiber: then you move: $n_1 - \Delta n$, $n_1 - 2\Delta n$ ...
You have a gentle variation of the index. ↓ CALL FIG

Core is not homogeneus. The size of CORE/CLADDING is the same as before.
So what happens to our ray of light in the core? Light doesn't go in a straight line, kinda. When we see a change in the property of the glass, we have reflection and possibly refraction, depending on the value of the incidence angle φ.

In any of the regions, the ray goes in a straight line, but then we have a local step variation and you see a discontinuity. The discontinuity is so small that you don't have reflection. You only have a bend.
This happens until we have an angle so close to 90° that in one discontinuity we only have reflection.

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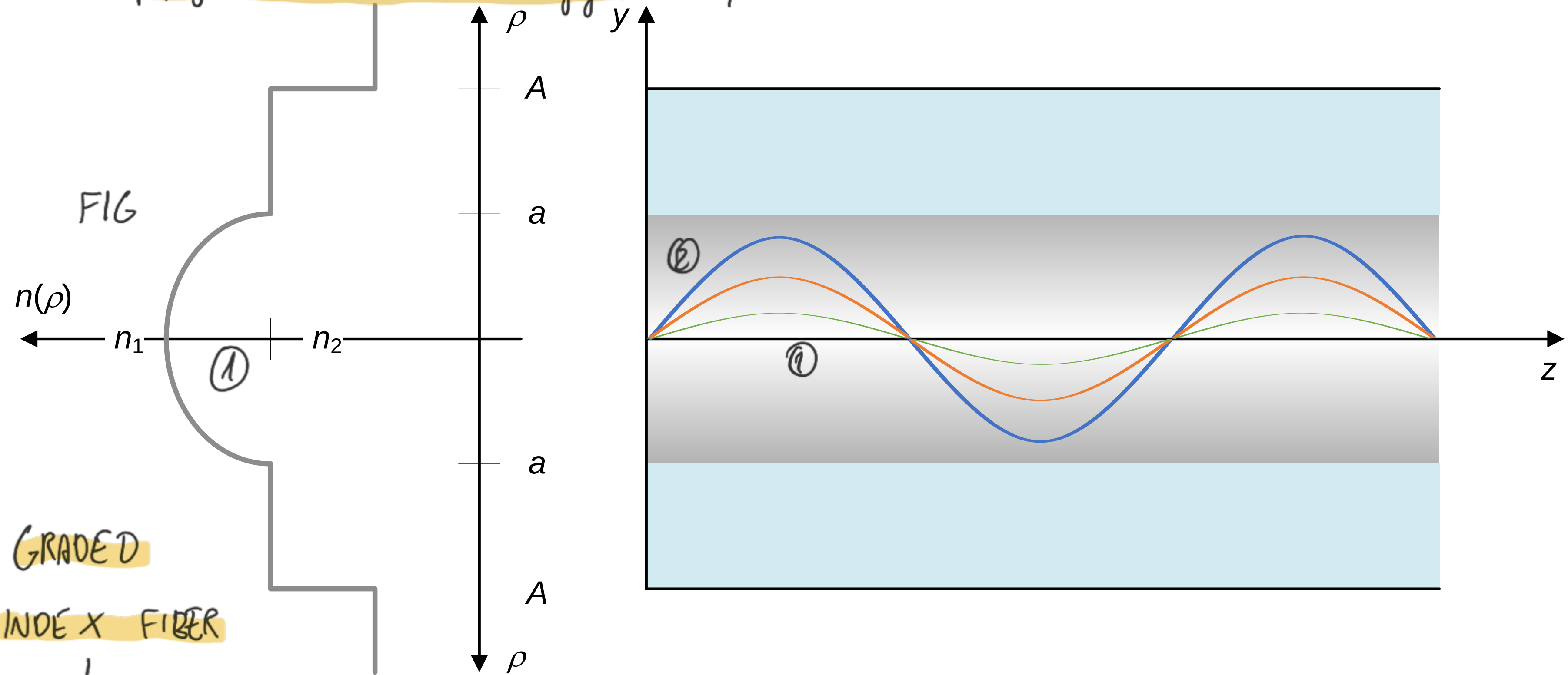
Stil Intermodal Dispersion, but…

Fermat's Principle: ray of light in all the physical means always takes the path that gives the smallest propagation time. With n varying like this, what's the result.



↓ change slowly the property of the glass.

RETURN

If the shape(1) looks like a parabolic shape (best shape), the ray follows a sinusoidal path. Including ray that goes straight on.
Ok! So what? There are still paths faster than others. I have still a MULTIMODE FIBER. I will still have pulse broadening. But, once we understand this, we know the FUNDAMENTAL PATH (1, horizontal), and also (2), the longer ray. BUT.
When we are closer to the core, the refraction index is n_1. When we go further, close to the cladding, i will see something closer to n_2.

$v = \frac{c}{n}$. Ray 1 sees a shorter geometric path, but has the minimum speed possible (n_1 is the max). Close to the cladding, you see a $n \approx n_2$ which is closer to the minimum, so v is close to the max. Your speed is not constant.

So all of the arrival times are almost equal. We reduce Δt by a very high factor. That's why we introduce the GRADED INDEX FIBER $(t_2 - t_1)_{GI} << (t_2 - t_1)_{SI}$
How much we are decreasing $t_2 - t_1$ and so PULSE BROADENING?

$$\Delta t_{GRADED\ INDEX} = \Delta t_{SI} \cdot \left[\frac{n_1 - n_2}{8 n_1}\right]$$, note that $\frac{n_1 - n_2}{n_1} = \Delta n$

a factor

$$\frac{1.5 - 1.47}{8 \cdot 1.5} = \frac{0.03}{1.5 \cdot 8} = \frac{0.02}{8} = \frac{1}{400}$$

400 times smaller!

So, $R_{b\,GI} \overset{\sim}{\leq} \frac{c}{L(n_1 - n_2)} \cdot \frac{8 n_1}{n_1 - n_2}$, or $R_{b\,GI} = R_{b\,SI} \cdot \frac{8}{\Delta n} = R_{b\,SI} \cdot \frac{8 n_1}{n_1 - n_2}$

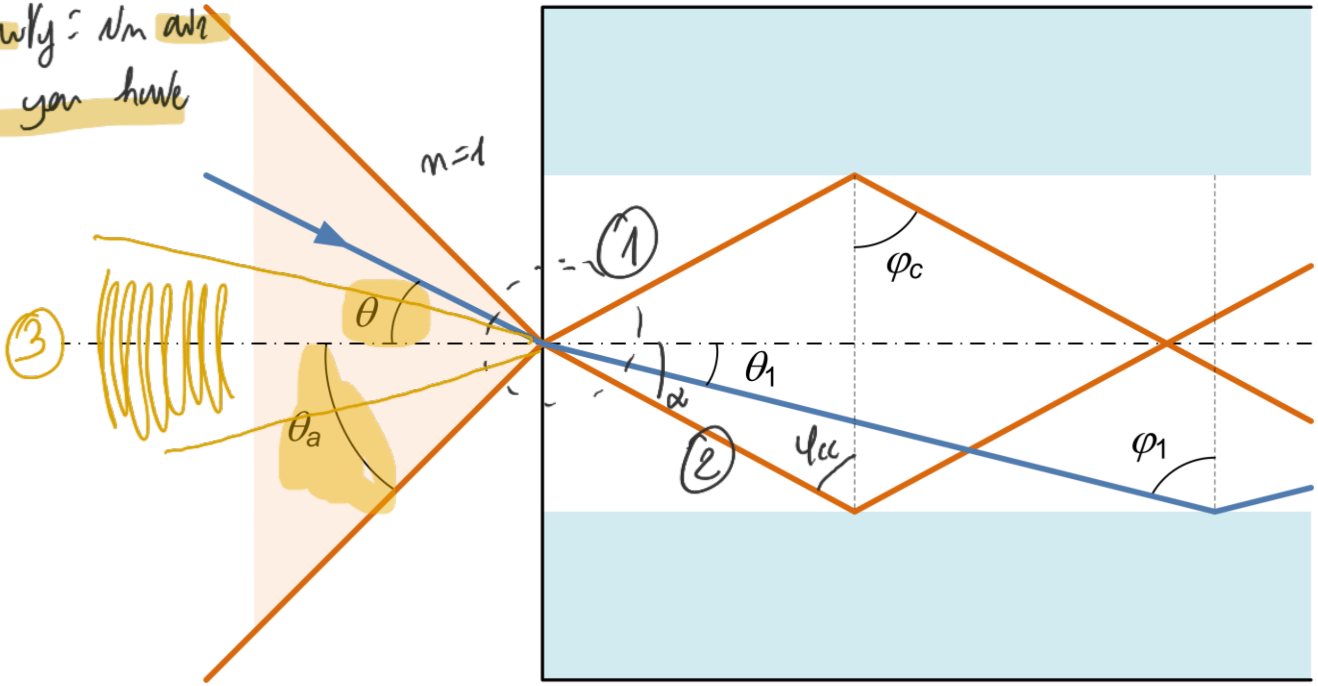
PISA-FIRENZE: $R_{b\,SI} = 100\ Kbit/s$ $R_{b\,GI} = 40\ Mbit/s$ Lot better, but not enough for BACKBONES.
They are very fine for short distances, for FTTH: $L = 1km$
$R_{b\,GI} = 40\ Mbit/s$ on $100km \Rightarrow R_{b\,GI} = 40 \cdot 100 = 4\ Gbit/s$, FINE!
This is GPON applications, we use either GI fibers or the SINGLE MODE FIBERS.
But not enough if I want to update my fibers. Installing GI is risky.

Still, the limit here is intermodal dispersion.
Pitfall of SI/GI fibers is being multimode.

Is there a way to do so?

Numerical Aperture

Look at this pic: I have the $\varphi = 90°$, $\varphi = \varphi_c$ rays and all of the others. These rays come from laser in front of the fibre. So the rays of light is close, but we have a discontinuity: in air $n=1$, then you have glass.



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Let's follow the ray back! We have to write SNELL's LAW to understand what is going on when a ray gets into the fiber. ①

$$n_0 \sin \theta = n_1 \sin \theta_1$$

Let's write this for the ray that becomes critical angle:

SNELL's LAW IN A: look at ② $\alpha = 90° - \varphi_c$

$$n_0 \sin \theta_A = n_1 \sin(90° - \varphi_c) = n_1 \cos(\varphi_c)$$

The good rays into the fiber come from rays that come from the laser with a smaller angle than θ_A (ACCEPTANCE ANGLE). Max angle for a ray outside of the fiber to be accepted in the fiber.

NOTE: $\sin \varphi_c = \frac{n_2}{n_1}$. REM: $\sin\varphi_c^2 + \cos\varphi_c^2 = 1$, so $\cos\varphi_c = \sqrt{1 - \left(\frac{n_2}{n_1}\right)^2}$

$$\text{So, } 1 \cdot \sin \theta_A = n_1 \sqrt{1 - \left(\frac{n_2}{n_1}\right)^2} = \sqrt{n_1^2 - n_2^2}$$

What happens if I'm reducing the difference between $n_1 - n_2$? $\sin \theta_A$ is smaller, so θ_A smaller.

③ The rays in the fiber are almost horizontal. Very few rays are accepted, with an almost horizontal angle.

NOTE: I am reducing diversity for my paths, but out of the rays of my laser, only few are entering the fiber. So I am reducing the actual power that gets into the fiber. So it's a false solution.

$\sin \theta_A$ = NA = NUMERICAL APERTURE → if is wide, fiber is open. If not, it is not so open. It tells me how much fiber is open. Cannot decrease this too much.

↳ because it is not an angle

$\boxed{\text{END}}$

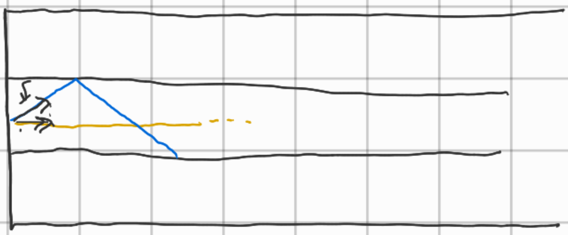
Chromatic (Intra-Modal) Dispersion

We cannot solve the issue by reasoning like this.
Inter modal dispersion and pulse broadening are there because of MULTI MODAL FIBERS!

PITFALL: light into the fiber is split into different rays. This reasoning is not entirely correct. Let's think of light as an actual wave.

Geometric optics means thinking that light propagates as rays and we can apply geometric measures. This works until the size of the object I'm considering is $\gg \lambda_0$ of the fiber. $\lambda_0 = 1.55\mu m$. This is actually satisfied with our fibers! But what if I want to make the core narrower and narrower? Like SI-MM 10/125. Here SIZE OF THE CORE $\not\gg \lambda_0$, then a ratio of 6 now. So what we would find out with the theory of Geom. optics is not true anymore. For this case we talk about ELECTROMAGNETIC OPTICS. [This won't even help you if OBJECT SIZE $\ll \lambda_0$, this won't work, you have to go to QUANTUM OPTICS]

Let's summarise the results of this. With a multimode fiber, we have the longest and shortest path. On those paths the velocity of light is the same. But if I consider the actual speed of the pulse going zigzag can be considered by taking the projection on X axis.



$$v = \frac{c}{n_1} = v_1$$

$$v_2 = v_1 \sin \varphi_c = v_1 \cdot \frac{n_2}{n_1} < v_1$$

With all the modes, we have all possible speeds in $[v_2, v_1]$
We have a distribution of the speeds from v_1 to v_2 by imaging all paths horizontally and get the same results. This is what I get if I solve Maxwell's equation.
The waves propagate along fiber at different speed.

If we shrink the core, we see a situation we could have not predicted with geometric optics. We find that we start seeing a discontinuity in the possible speeds of the wave. There are different possible speeds (associated to the mode) a wave can have. When core is large, they are so many that they appear to be infinite. Here the number is discrete and we can see it.

(Not regularly spaced). It's like you only have 4 different paths.

At one point, with the core very small, you only have one speed, one propagation mode and get SINGLE MODE PROPAGATION FIBER.
There's a rule that tells you when a fiber becomes single mode:

$$V_{PARAMETER} = \frac{2\pi}{\lambda_0} \cdot NA \cdot \frac{d}{2}$$

core diameter

What matters is how small is the core with respect to the diameter.

MAGICAL RULE: if $V < 2{,}405 \Rightarrow$ Fiber is SM.

In general, $d < 4\,\mu m$ when doing computation.

$4\,\mu m$ fully comparable to the wavelength! Cannot use GEOMETRIC OPTICS FOR THIS.

• Note that the outer diameter of the fiber is still $125\,\mu m$:

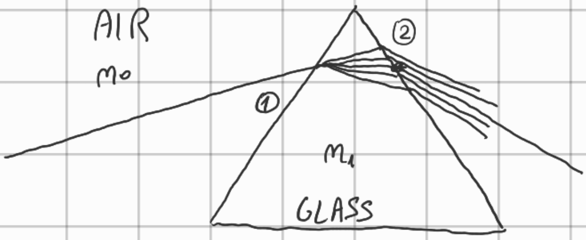
Idea is that the CORE should see the cladding as infinite.
Light is confined in the very small core (at least most of it)

What's the limitation?

(geometric optics is enough)

DSOTM: Ray of light enters this prism. Ray penetrates the glass and is refracted ①

At ② it is bent again.



What dictates this bend? n_0/n_1.

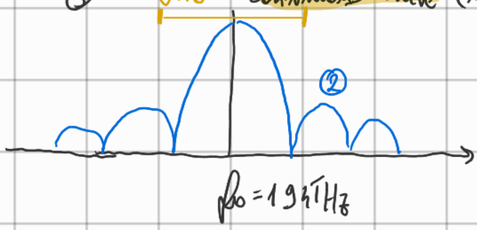
But some wavelengths are bent more than others: $n_1 = n_1(\lambda)$.

So all colors are bent twice differently.

So we see all the colours separated.

We see the same in our single mode fiber. The propagation mode is 1 at one frequency. The $\lambda_0 = 1.55\mu m$ for the laser. But when I do on and off, we do not have a monochromatic light. This is before modulation.

③ $2R_b$ continuous wave (no data: laser always on: pure color).



If you switch on and off, you see a wider spectrum like ②:

We have a carrier frequency, corresponding to the wavelength of the laser.

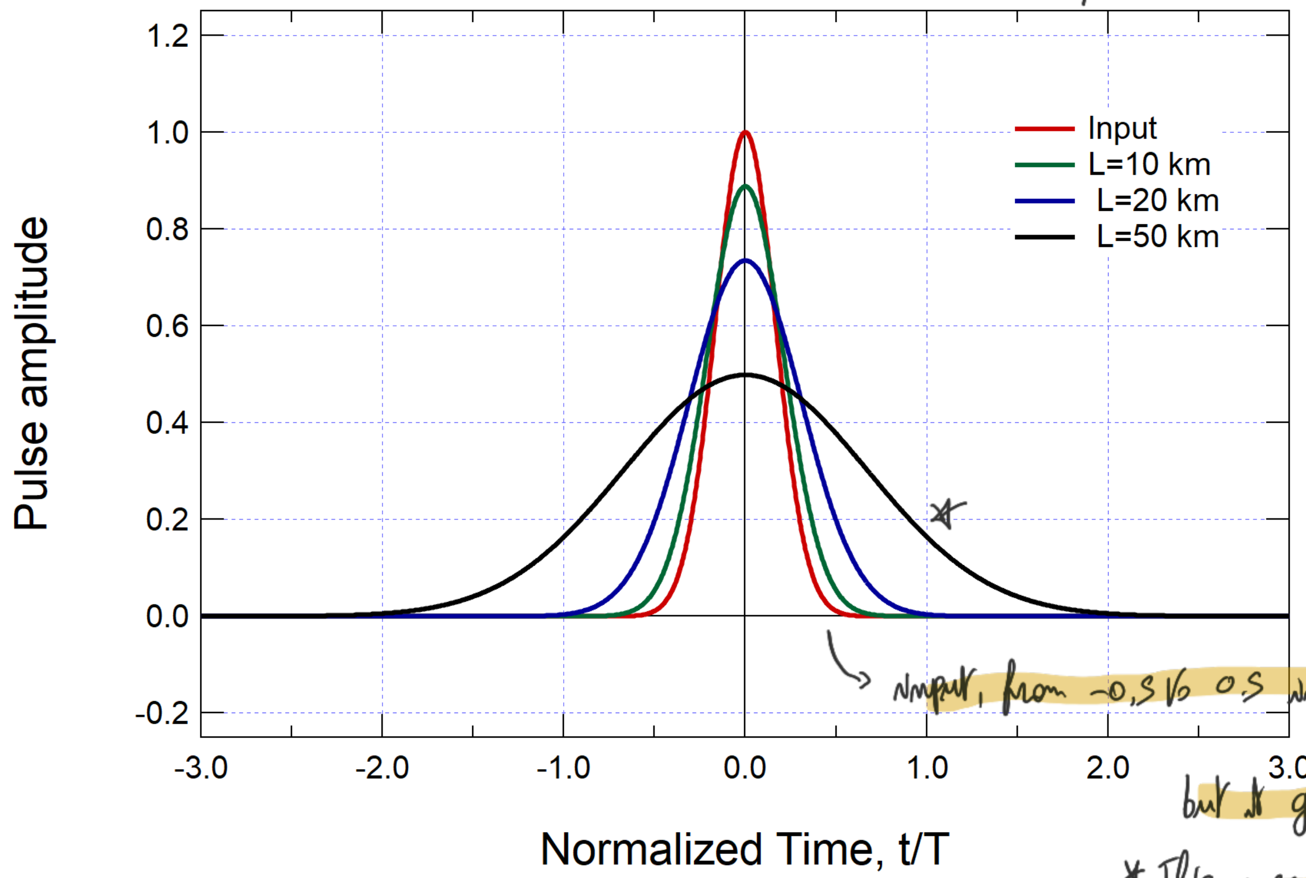
The Bandwidth B depends on how fast I'm switching on and off (R_b). ③

If $R_b = 100$ Gbit/s. $B = 200$ GHz.

We have many colours centered around f_0. So different components of spectrum have different speed. So $v = \frac{c}{n_1} = v(f)$. So for a completely different reason, you still have broadening. Power is dispersed across different frequencies: we call it CHROMATIC DISPERSION.

Pulse Broadening

If you want sharp edges you should have ideally infinite band. So your pulses are smoothed. Electrical components cannot generate pulses so fast.



Input, from -0,5 to 0,5 in normalized time, but it gets wider

* This goes to 4 bit times!

(1)

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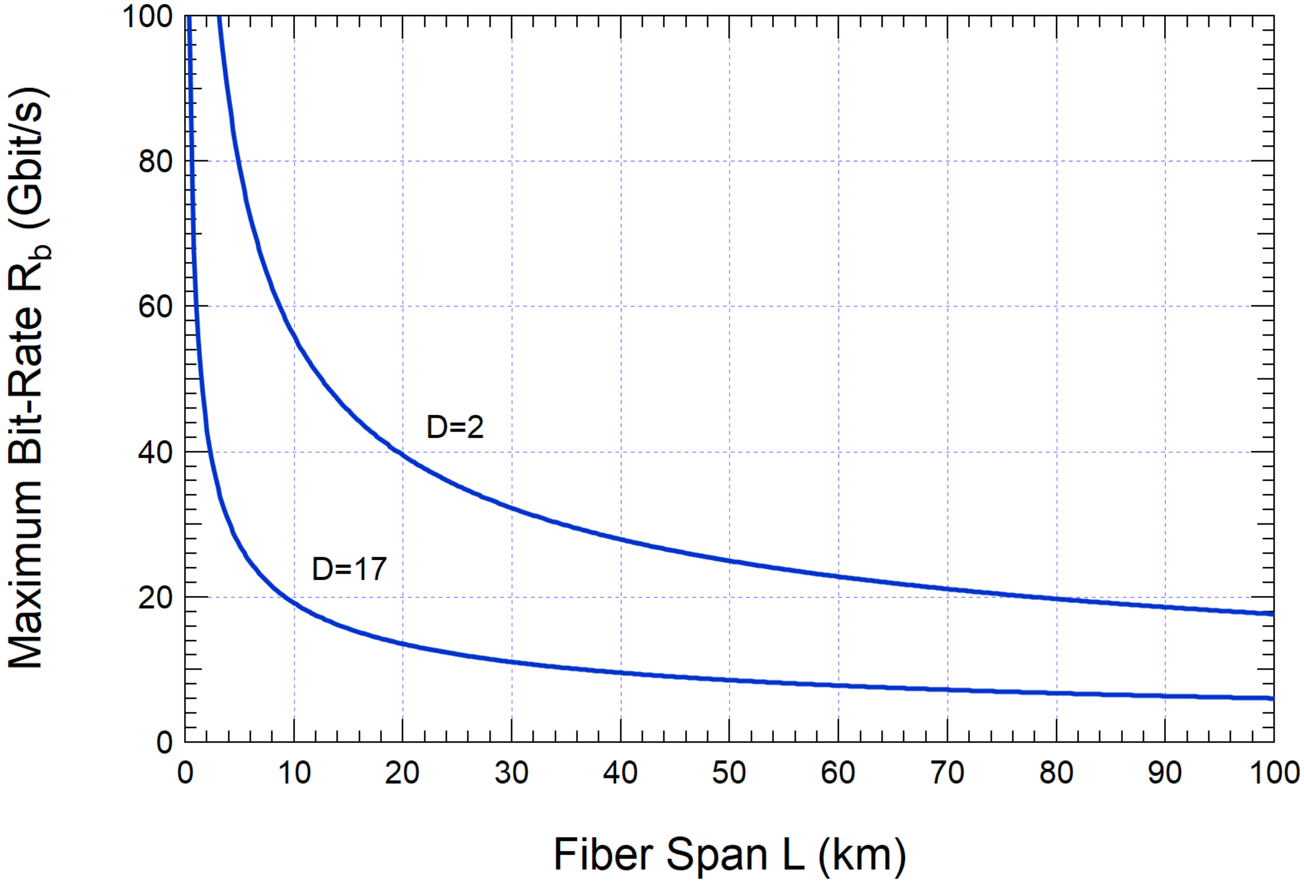
This dispersion is called INTRA-MODAL DISPERSION = CHROMATIC DISPERSION

1

Limitation Due to Intramodal Dispersion

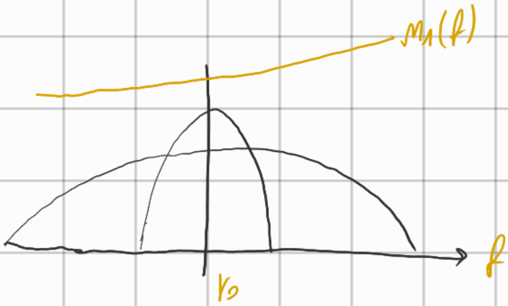


With single mode fibers calculating an upper bound is very complicated.
There's a parameter that tells you how much multi-modal distortion you have (this is there in multi mode too but very negligeable).

↳ chromatic dispersion coefficient (or intramodal disp. coeff.)

Pulse broadening in single mode: $\Delta\tau = L \cdot D \cdot \Delta\lambda$

↳ bandwidth of signal.



If you have a wider bandwidth, you have more dispersion. That's why $\Delta\tau \propto \Delta f$. For historical reasons we use wavelengths.
So you evaluate the spectrum on the wavelength signal (optical spectrum analyzer)

Max. bitrate computed like: $\Delta\tau \leq T_b$. $R_b \leq \frac{1}{\Delta\tau}$ But: $B = 2R_b$, so

Bitrate appears in both sides so you have to solve it.

Variability of D

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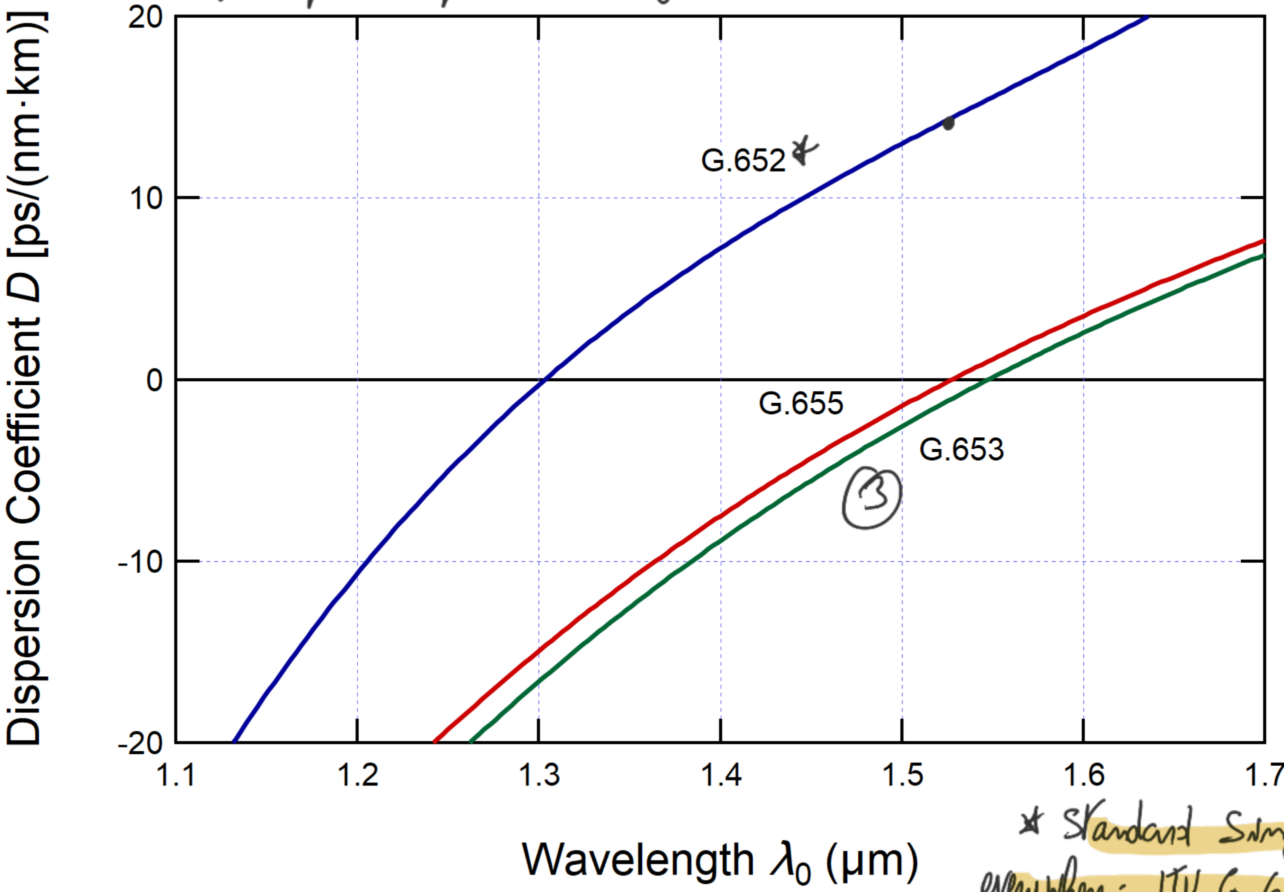
With modern lasers technology, I can move my wavelength to see what happens. So we evaluate the value of D for different wavelengths.



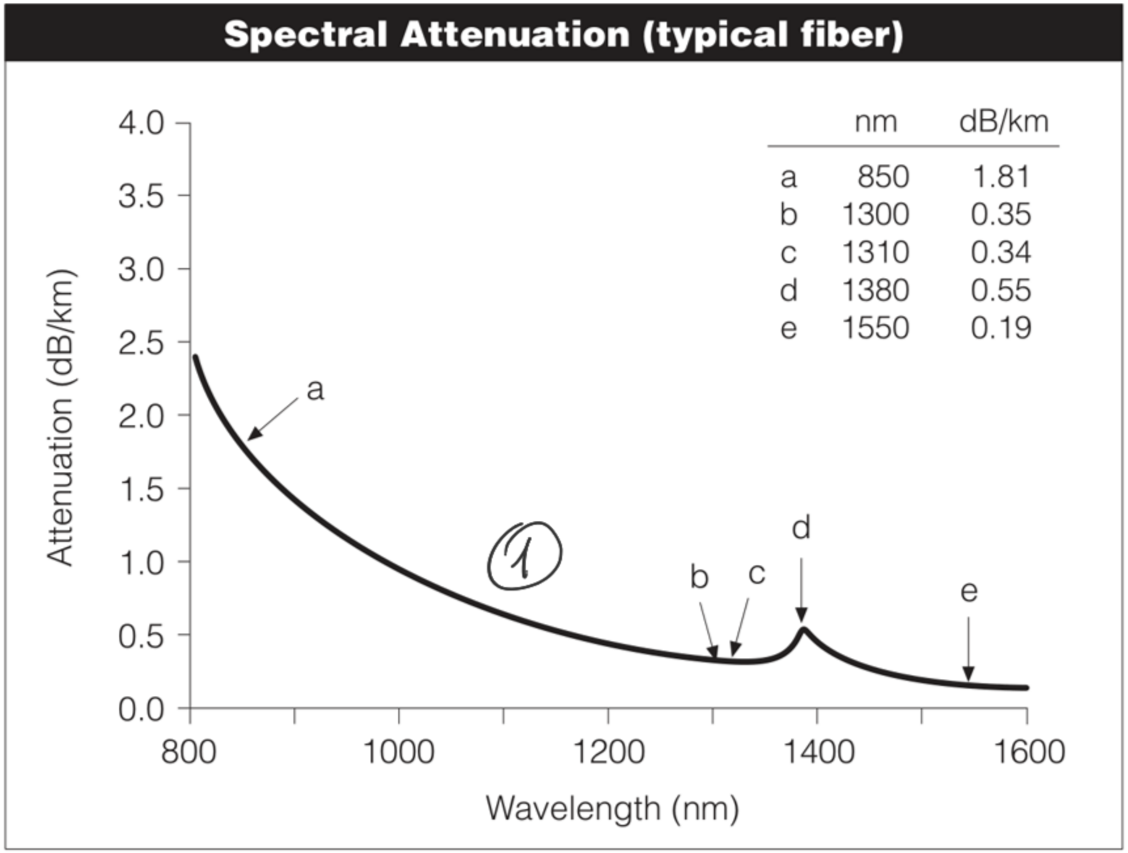
* Standard Single Mode you see everywhere: ITU G.652.

That's why at 1.55 I get 17.

But if I move to wavelengths lower, around 1.3, $\Delta \tau = 0$. But just in one frequency
BTW, but the pulse broadening would be much smaller! So I could have a longer
fiber by 10! But backbones are not operating there. Why? Solution ↓

Why 1.55 ?

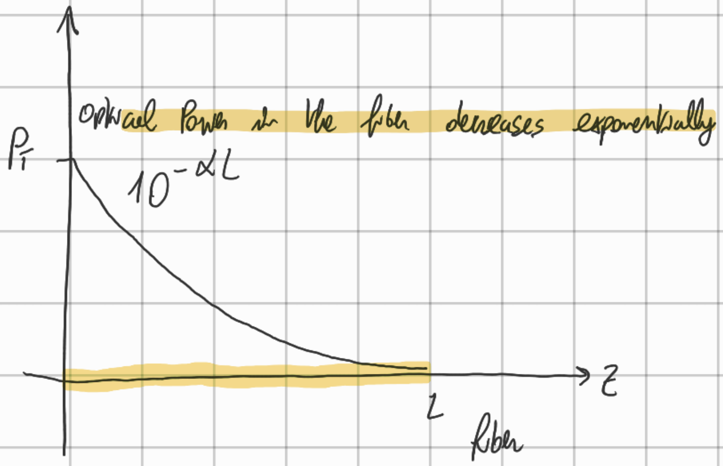
Data sheet of fiber.



We have a phenomenon that is attenuation of the signal of the fiber.

ATTENUATION IS PROPORTIONAL TO THE LENGTH OF THE FIBER.

So there might be a limit for the fiber length.



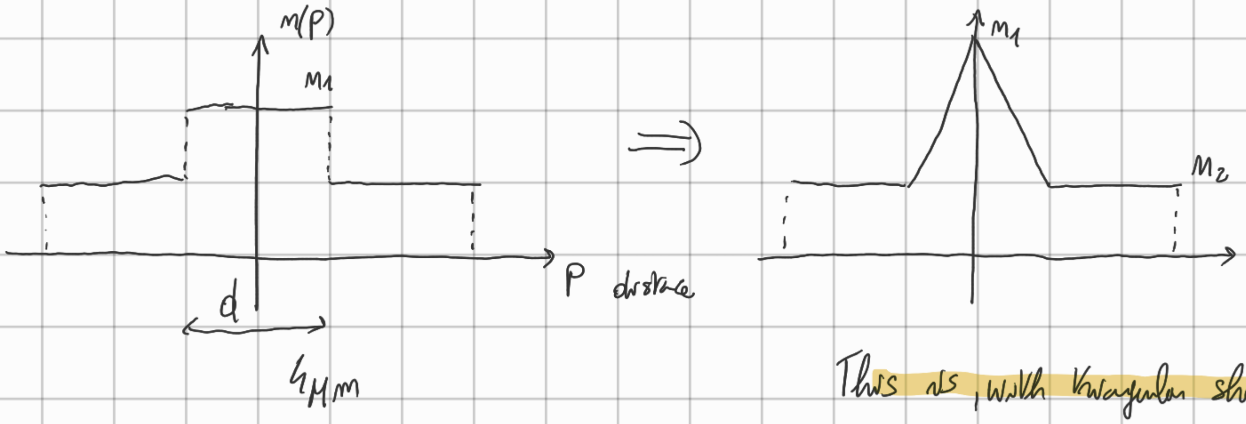
This has nothing to do with dispersion, but justifies why we use 1.55 and not 1.3.

By physical properties of the glass, we discover that the behavior of the fiber is different from the ones we discussed. $\ell = 1{,}55$ nm is the wavelength of minimum attenuation. This is the α parameter: (1)

So you have less dispersion but signal is useless in terms of attenuation.
Priority goes to having a signal.

We use wavelength division multiplexing for uplink and downlink in FTTH. In a backbone we have other solutions because they take a lot more space.

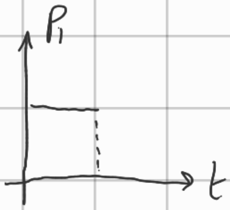
What about curves (3)? They are not SM-SI like G652. Idea: can you do it better? One in which we have minimum distortion and attenuation?
Yes. That is another kind of fiber like this:

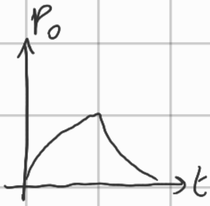


This is, with triangular shape, the fiber we want: SM-DS: Single mode dispersion shifted. You shift the 0 point of dispersion to the wavelength that is correct.

Not used because RN we still have a lot of unused fibers. We do not need better right now. For G.652:

We might say that we still have dispersion anyway. Signal is strong enough, but dispersion is better. Can we improve on dispersion?





No problem of attenuation, but $D=17$, so dispersion is considerable.

We have a photoreceptor and a broadened bit. Solve is the following.

I can interpret it as a distortion generated by a filter with an $H(f)$ equal to fiber.

So at my receiver I can design a filter that does the opposite:

$Y(f) = H(f)X(f)$ So ① $= \frac{1}{H(f)}$

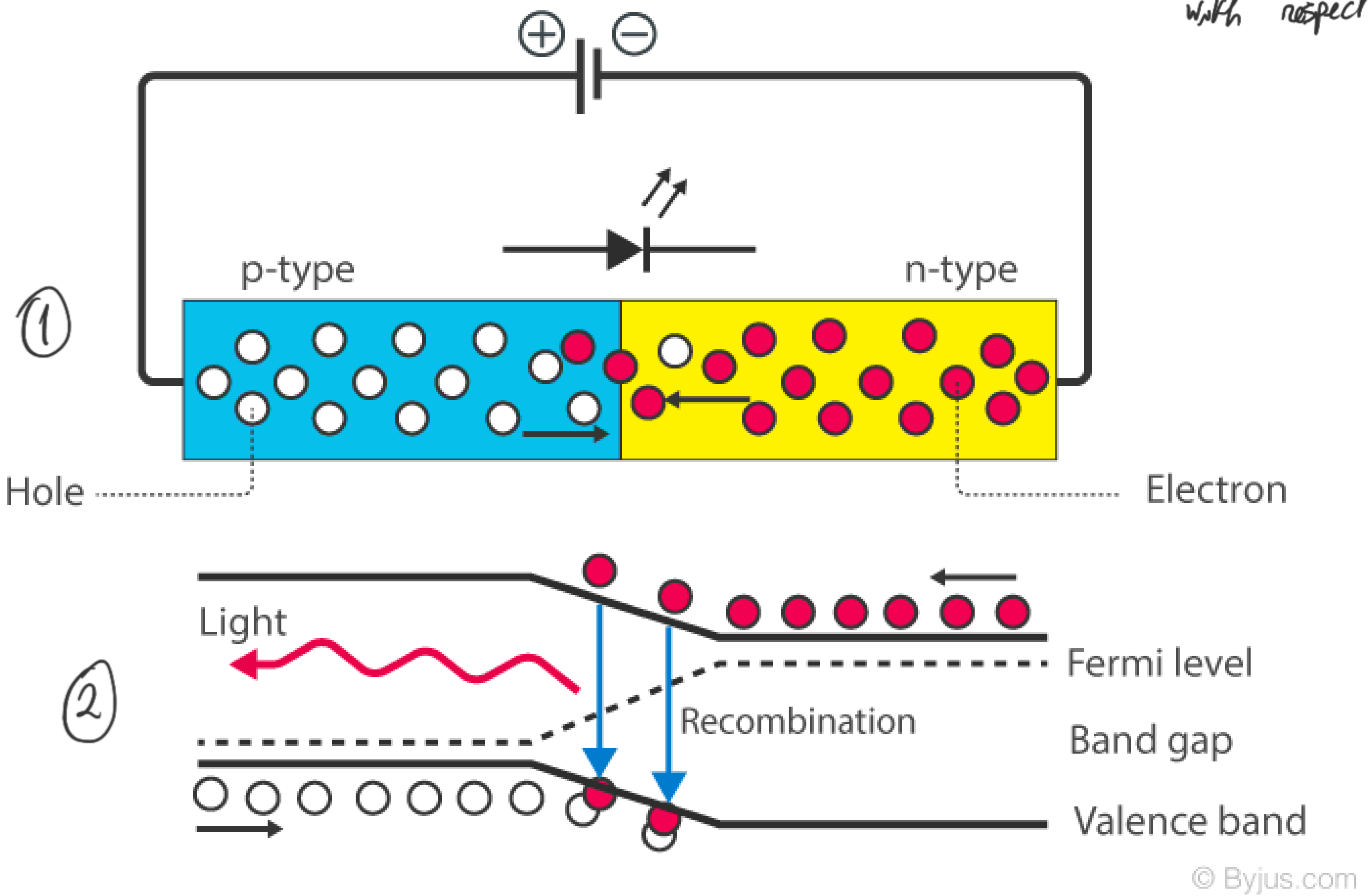
Not simple, you have to estimate $H(f)$, but this compensation is good enough.

This filter is called EQUALIZER

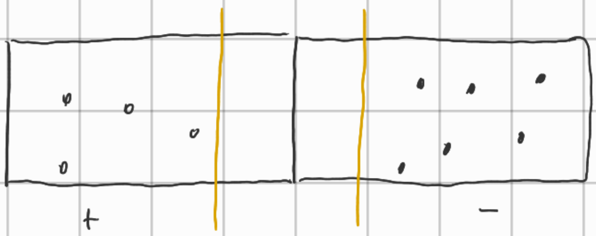
END

The Light-Emitting Diode (LED)

Very efficient in terms of light with respect of electrical power



Semiconductor used is GaAs (arseniuro di gallio). We create a pn junction.
Hole can be thought as a positive charge.



All the charges close to the junction annihilate each other. You don't have charges anymore, so you call it DEPLATION LAYER. So we create an intrinsic

Then you supply energy from outside, by attaching something positively charged to p, negatively charged to n.
What happens is that electrons are pushed towards the n junction.
So electrons start to move towards the DL. Same thing for holes, pushed by battery. When they get to the depletion layer, they disappear.
Battery supplies charges, device makes them disappear.
This is called DIRECT CURRENT that works. Push current the right way.
REVERSE CURRENT should theoretically be 0, but it is in the order of mA.

[FOSFURO DI ARSENIURO DI INDIO E GALLIO] InP (fosfuro di indio)

In GaAs, what is happening is: when the charges disappear, some energy has been spent by battery to push the charges together, so when they disappear, energy is transformed (in silicon in heat), but in GaAs (or InP or a combination of two, InGaAsP, which is an alloy, lega), in RECOMBINATION of charges in the depletion layer, the energy is turned into light. This in a very efficient way: 1/2 of the particles that recombinate turns into light, the other 50% in light.
50% in theory, but 20-30-40. This is called RADIATIVE RECOMBINATION.

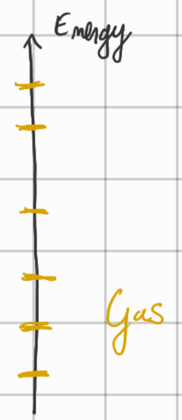
(2) is the quantum description of the phenomenon.

- NOTE: can I predict the wavelength of the light? 1.55 is the MINIMUM ATTENUATION WAVEL.

GaAs generates a wavelength $\lambda_0 \simeq 0.85 \mu m$, infrared, close to red. Wavelength of GaAs devices. In the graph, a is called FIRST WINDOW, b, c, d is the 2nd window, e is 3rd window.

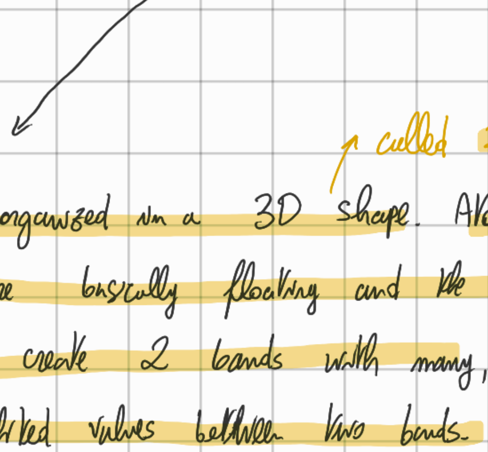
That's why we use an alloy. How can we control the wavelength emitted? Einstein explained it in the photoelectric effect.

It works like this:



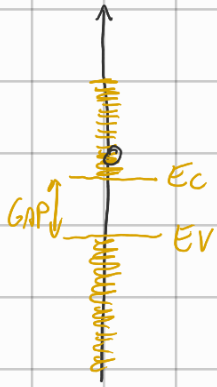
One result of the quantum model, is that you have a number of quantized states corresponding to levels of energy.

For gases the energy levels are very separated. What about semiconductors?



called 3D lattice

Atoms are organized in a 3D shape. Atoms are very close to each other, and the free electrons are basically floating and the levels of energy are so close to each other until you create 2 bands with many, infinitely many levels separated by a gap of prohibited values between two bands. Band of high energy and of low energy.



Why Ec? If an electron is in the high band, the conduction band, it can flow and contribute to the external current. Can conduct. If the energy is lower, it is trapped in the 3d structure, back to the atoms and cannot be carried away. This is the Valence Band.

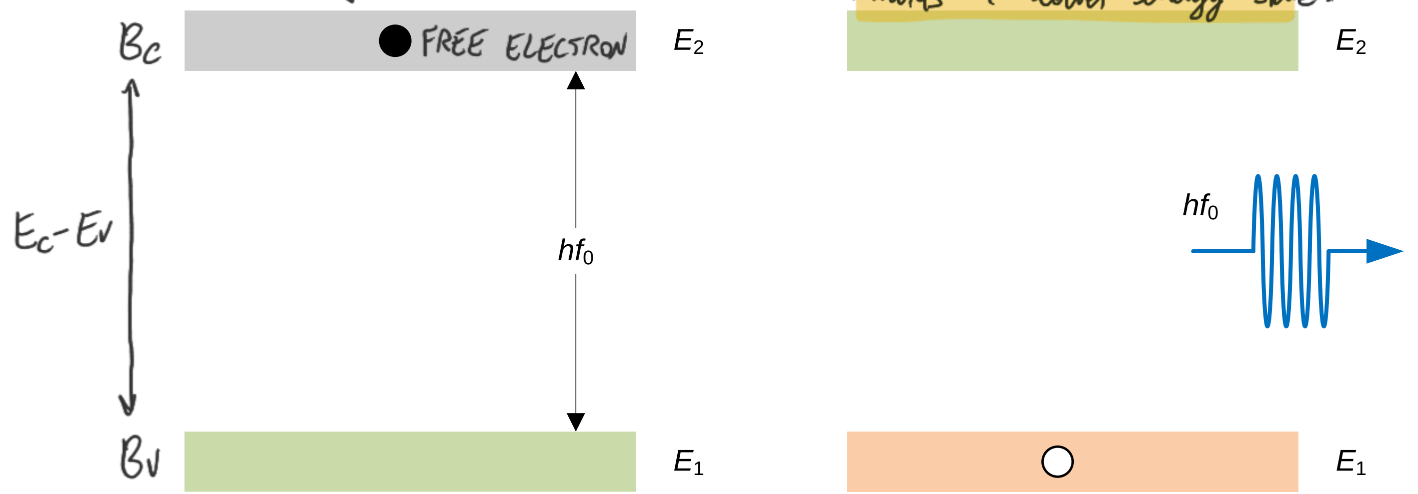
Spontaneous Emission

Another way to interpret recombination: once I know the two bands:

A battery raises the energy of an electron bringing it in conduction band.

Before Interaction | *After* Interaction

Sooner or later, the electron will tend to spontaneously get down to a lower state of energy. So it will do this transition towards a lower energy state.



So electron is losing energy. So this energy has to go somewhere: if there's nothing special in material you have heat. But with radiative recomb, energy will be turned into a QUANTUM of LIGHT, a PHOTON. So electrons don't disappear, but go to a lower energy state. It is trapped into the 3D lattice

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We can think of light as a continuous stream of photons. Light is not a wave anymore, but just a set of small particle. Each photon carries one QUANTUM of energy and $E_{photon} = hf_0$, related to the frequency of the wave it belongs to. Wave has an oscillation frequency, but the macroscopic oscillation frequency is returned to the discrete element in the quantum world.

h = Plank's constant ($\approx 10^{-34}$) $f_0 = 194 \cdot 10^{12}$ Hz. $h = 6.62 \cdot 10^{-34}$

eV = energy of one electron pushed by $1V = 1.602 \cdot 10^{-19}$ J.

- So how much energy am I losing going from E_c to E_v?

$\boxed{E_c - E_v = hf_0}$, the gap energy. I can predict the colour of light emitted from this fundamental relation. $[E_c - E_v]$ = GAP energy, strictly related to properties of material.

ONE OF THE RELATION OF THE PHOTOELECTRIC EFFECT.

Power of the light depends on the number of photons we have emitted.

Receivers count the photons in the fibers. The sensitivity of commercial fibers is so good that a bit is detected with as few as 100 photons.

NOTE: the energy gap of GaAs is such that $\lambda_0 = 0.85\ \mu m$.

So the game is finding the Gap energy to have a certain λ_0.

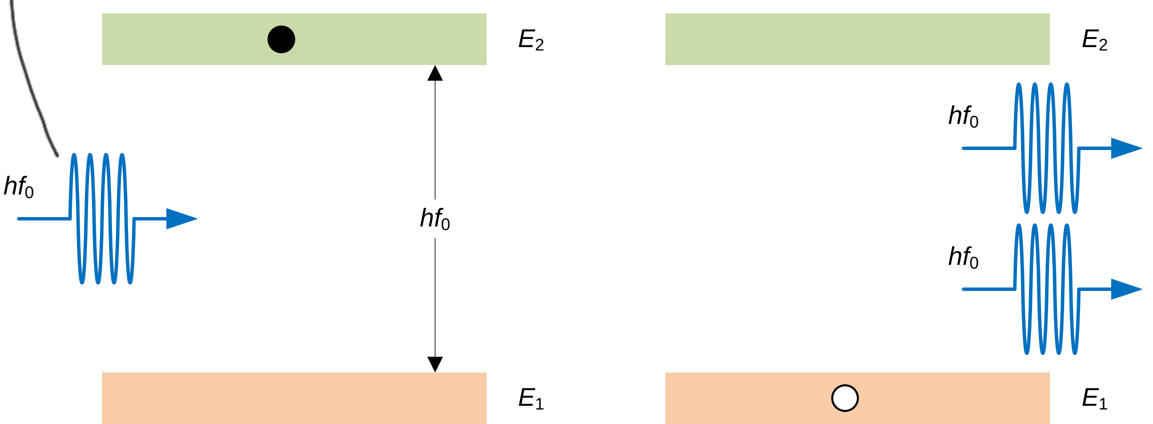
THIS EMISSION IS CALLED SPONTANEOUS EMISSION.

But this for LED. Why do we use laser? There's another better quantum phenomenon...]

Stimulated Emission

before, out of recombination (even spontaneous) we already have a photon.

***Before* Interaction** | ***After* Interaction**



Photon and electrons can interact with each other. What happens is that the photon stimulates a premature transition of the electron before the spontaneous transition. So I may have two photons.

It s the basis of Light Amplification through Stimulated Emission of Radiation: LASER

The two photons are one the copy of the other, with same propagation direction and energy. So this creates a chain reaction. This is a phenomenon of Amplification of light.

To build a laser, you have to make sure that

Before, photons could have different directions, but here you have a directional ray. Because of this. Called COHERENT LIGHT, and it is also MONOCHROMATIC.
Because photons have same energy, wavelength, direction.
At the end of the story you will have pure oscillation: $\cos(2\pi f_0 t)$.

So this is a carrier generator!

Spectrum of the LED is subject to dispersion. Bad!

1st breakthrough 70': fibers. 2nd breakthrough 80': reliable lasers.

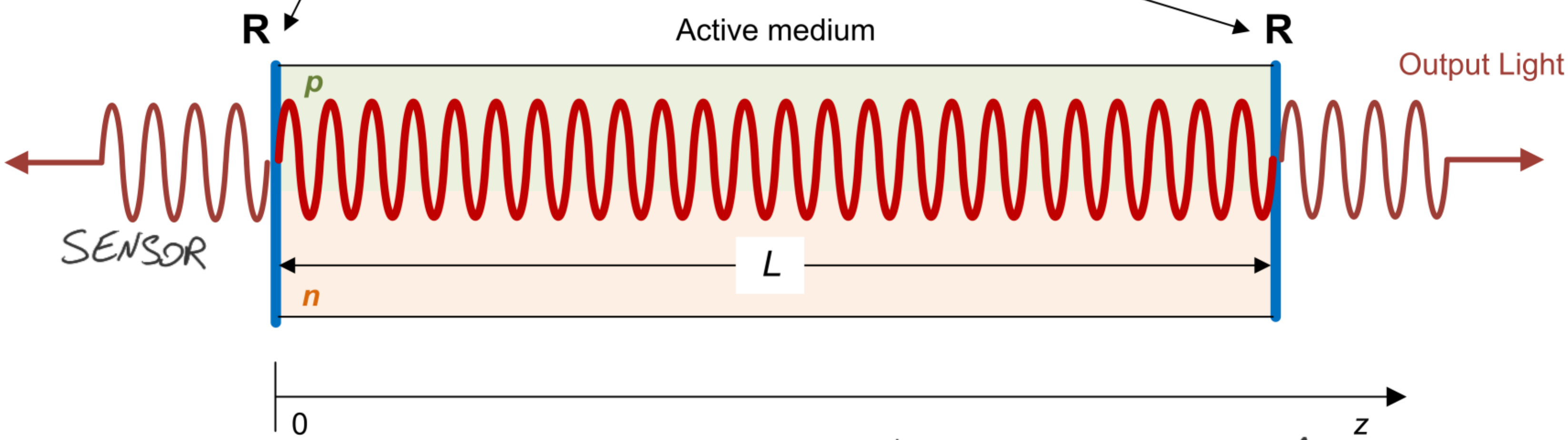
Fabry-Pérot LASER

Difference in manufacturing: to promote Stim. Em: 1. Provide very high supply current (so population of excited carriers is very high, for amplification: so not many electrons in Ev: this is called Population inversion, because normally you have a lot of electrons in the Ev to create an unnatural state)

2. Make sure that the emission is stable. You do this by creating an OPTICAL CAVITY by placing two mirrors

Reflective facets

CAVITY LASER



L= 100 μm, length of a laser.

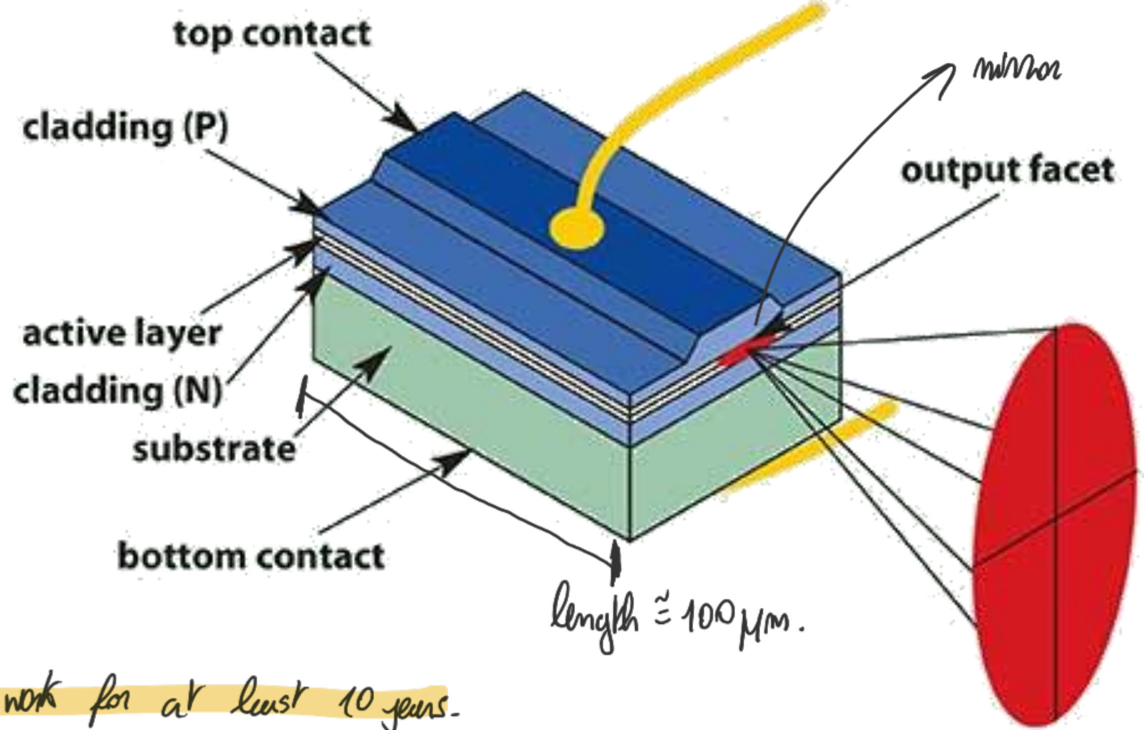
They are semi transparent mirrors: because you have bouncing back and forth to reinforce your wave, but one part goes out. Because of this simmetry, 50% of the power is wasted. You use it for monitoring purposes.

This bouncing back and forth is called OPTICAL FEEDBACK.

Length of the cavity selected properly, so you make sure that the internal wave becomes a STANDING WAVE and never ends.

1. POPULATION INVERSION 2. OPTICAL FEEDBACK. Laser has something more, the two mirrors for ex.

Semiconductor Lasers for Optical Communications



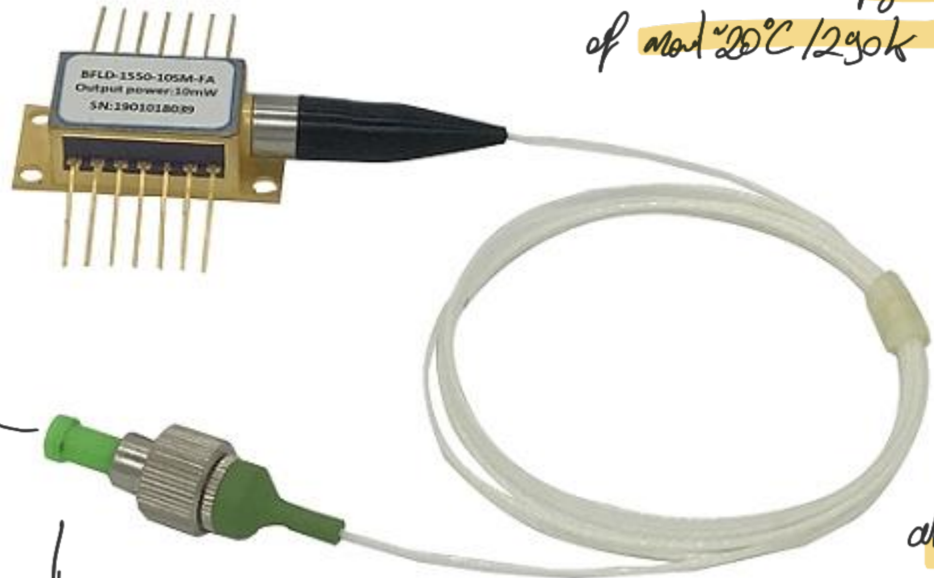
Has to work for at least 10 years.

How much is the power of this laser? Much less than Leds: $P_T = 10\,mW$ (one that gets into fiber)

But this in a diameter of 5μm. So we have a very high density of power in that area. So much that we go through 50 km.

Semiconductor Lasers for Optical Communications

2 of those bits, to cool down the laser. To prevent generating less power for the fiber. Typically you want temperature of about ~20°C / 290K



Pigtail, single mode fiber, attached via a microscope precisely

Connector to the transport fiber.

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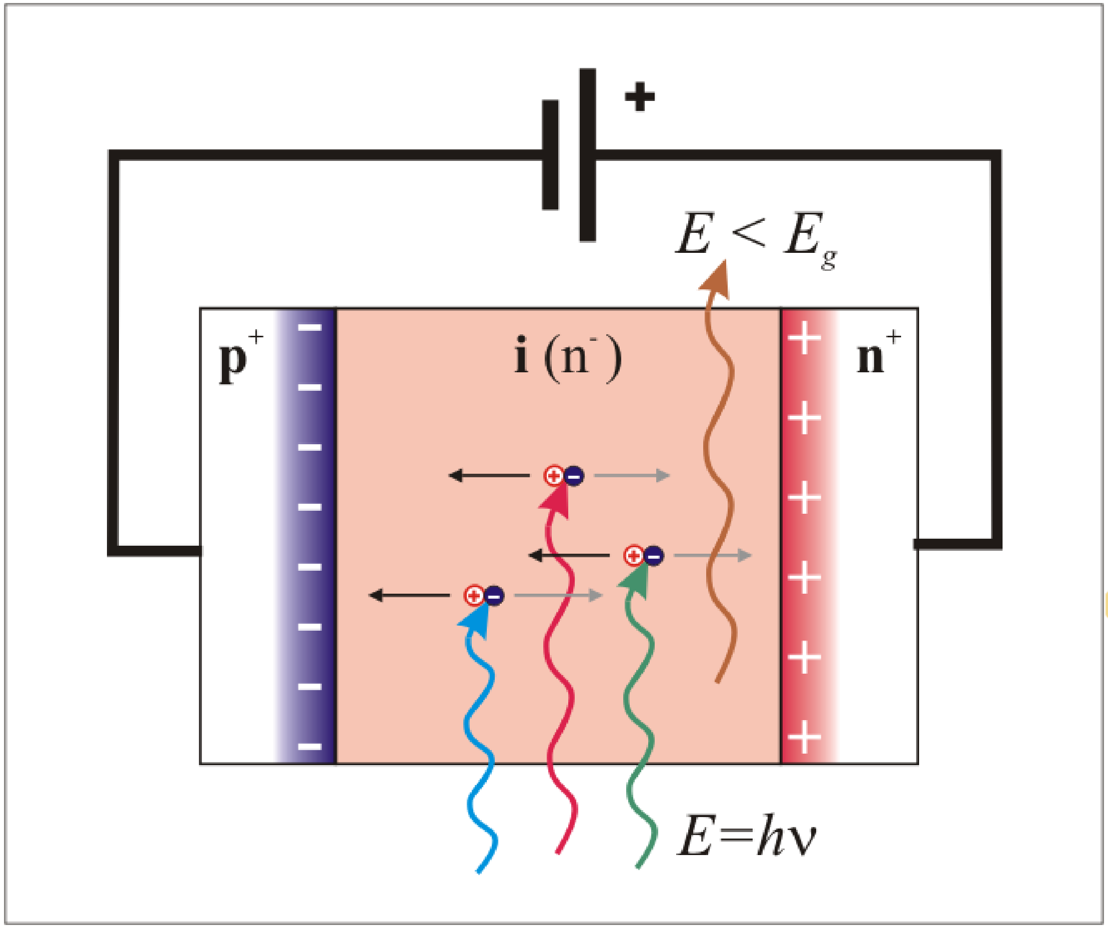
The p-i-n Photodiode



This is a special Junction called PIN, 3 layer diode: you have a very large depletion layer with a slice of intrinsic semiconductor with no doping.

So P-I-N Photodetector.

Large because absorption is carried out in this intrinsic region. So you generate free electron attracted to the positive potential, while the hole to the negative (1)

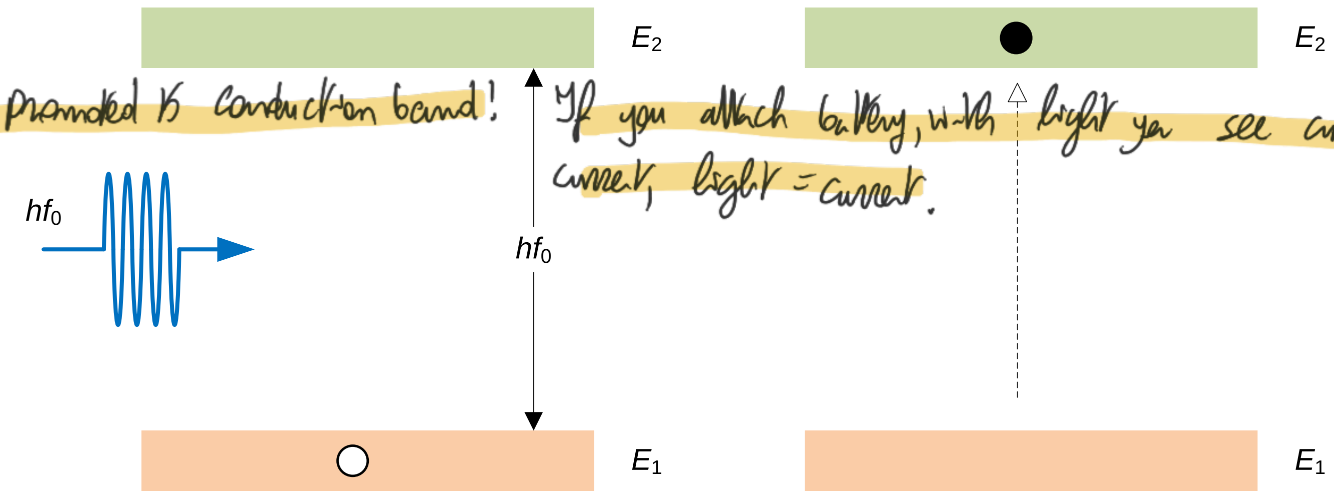
Photodetectors were already there: The photodetector needs to be wideband enough. If we have a $R_b = 100\,Gbit/s$, the photodetector needs to have a speed high enough to represent the bits. $R_b = 100\,Gbit/s \Rightarrow T_b = 10\,ps$. So you need to be able to represent bits on a very tiny time. So issue with both devices is the BANDWIDTH in the sense of switching speed from 0 to 1. Not particularly critical. Uses the 3rd and last photoelectric phenomenon:

① This current goes from low potential to high potential, so REVERSE CURRENT (PHOTODETECTION CURRENT). Here almost no problems in reliability.

Absorption

Absorption: emission, generate light. Absorption receives light and generate current, needed in the receiver.
So photons arriving with a certain color. Now I focus on low state energy electrons.
Electrons take energy from photons (that disappear), and electron is promoted to high state, as long as $E_{GAP} = hf_0$.

Before Interaction **After Interaction**



Electron promoted to conduction band!

If you attach battery, with light you see current. No light, no current, light = current.

JUMP UP:

Batteria connessa a diodo

So we have reverse current. (REVERSE BIAS). So to have current you need light.

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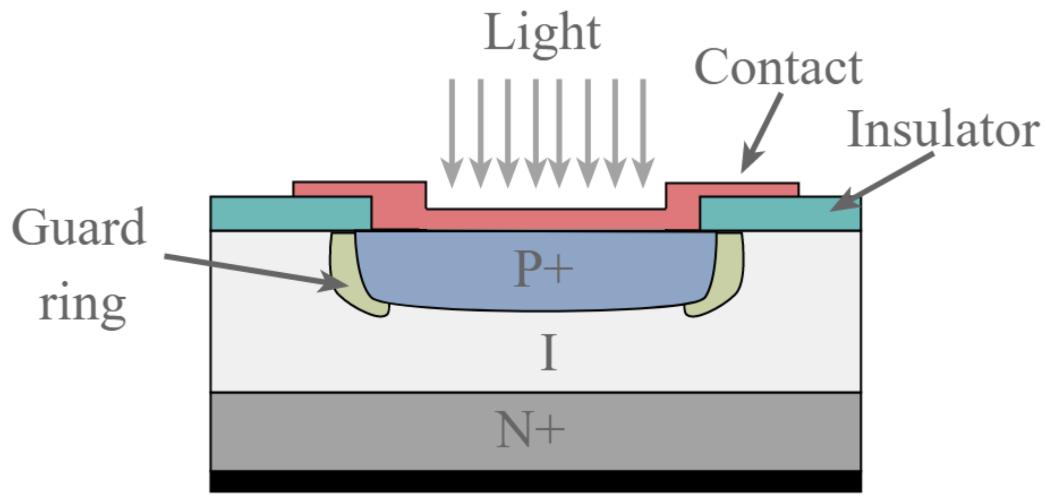
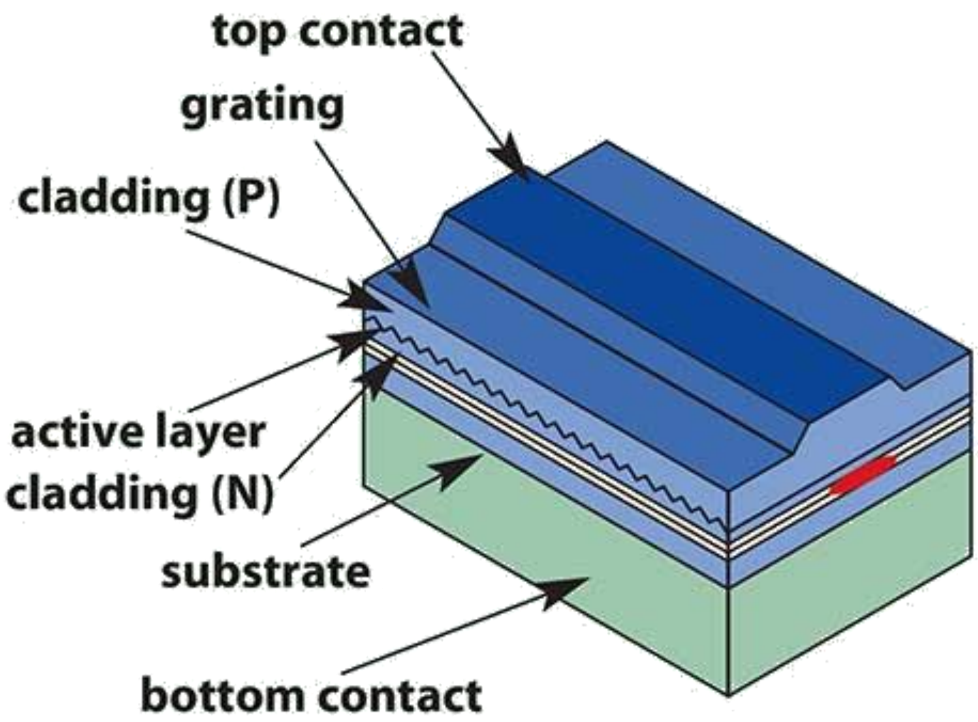
The p-i-n Photodiode - structure

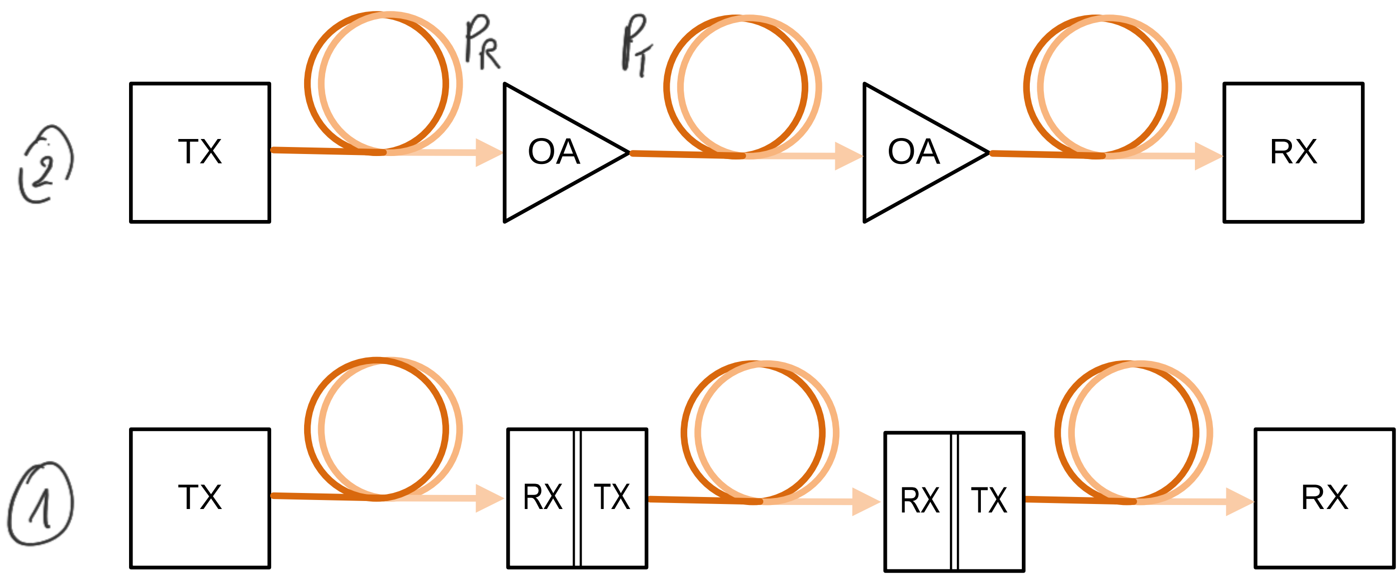


DFB Laser


top contact
grating
cladding (P)
active layer
cladding (N)
substrate
bottom contact

Multi-Hop Backbones

Transparent



Regenerative

Note: backbone is not just a passive OF. We have to be able to cover very long distances. Unrealistic to cover these distances with passive fiber.

Every cable is multi hop, with each passive cables composing it 50-100Km long. Because of attenuation we can't go far.

① Architecture of the very first backbone. You put intermediate stations: you regenerate signals by receiving it and then you remodulate it again with another laser. P-I-N at Rx, laser at Tx.
This station is called intermediate repeating station (or REPEATER).

True that on the link you can have errors, but BER is so small you can practically say that you have the same signal.
1 DISADVANTAGE: there's an optical-electrical then electrical-optical, which happens frequently. This is a bottleneck. Let's say you design sys to work at 100 Gbit/s. You can't decide to increase sys at 400Gbit/s, the repeaters cannot be updated. This sys is not upgradable.

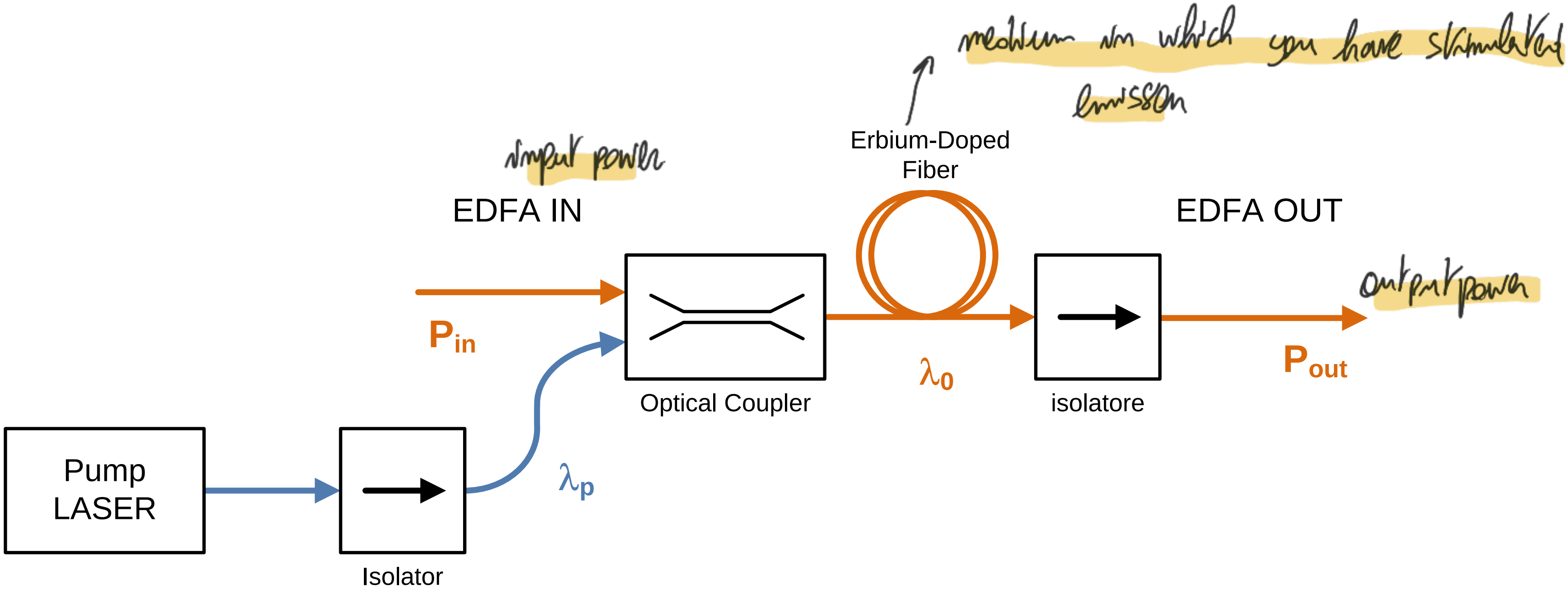
② Works with a fundamental component, you have an OPTICAL AMPLIFIER.
↳ you got the optical signal at the end of the hop is very weak, so you need something to repeat the signal. Idea: I stay in the optical domain, but amplify it.

In a sense, ② is digital processing. ① is analog processing
You don't care about the type of signal you are transforming.
So this operation doesn't care about content of signal.

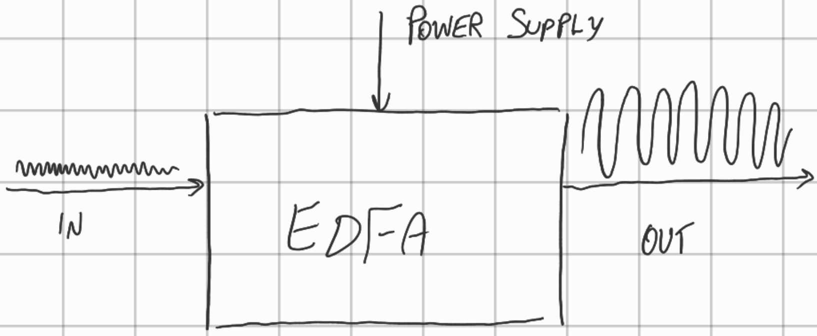
② Theoretically is better (because you cancel noise instead of amplifying) but it does not scale.

So one big next step was creating useful OA. From late 90s every backbone has OA. This not needed for FTTH. Called PON: Passive (just fiber)

Optical Amplifiers



OA



Key: We stay in the optical domain. Out has same shape but larger.
Of course you need some power supply.

This type of ampl. is called EDFA tech.: Erbium-Doped Fiber Amplifier.

You are doping a fiber: we are not talking about semiconductors.
It is a short section of fiber: that's why it's called fiber amplifier.
Single mode similar to the main fiber.

Lo length is 10-20 m. In these 10m signal is amplified by 1000, 30dB = $10^{\frac{30}{10}}$
Where does the power supply come from?
Do you remember laser used as generator of light? LASER = Light Amplification.
That used stimulated emission. But laser is not an amplifier.
NOTE: it is the mirrors that create optical feedback.

In OA you don't have semiconductor. That stimulated emission happens within the fiber. It is a laser effect.
Feedback is a generator; if you give optical feedback to an amplifier, you get a generator. But here, we are using laser effect, not to generate, but to amplify.

- ↑, What is turning a fiber into a laser? How do you achieve spontaneous emission? The dopant that you put into the fiber. Which is ERBIUM.
We add to the glass of the fiber to provide amplifications (stimulated emission).

To make this emission, you need population inversion: to achieve this, you need additional steps: pump LASER is pumping photons from the bottom to the top. Amplifier operates at usual 1.55 μm. The pump LASER on another wavelength, and to promote electrons you provide it with photons at another frequency. $\lambda_p = \lambda$ pump.

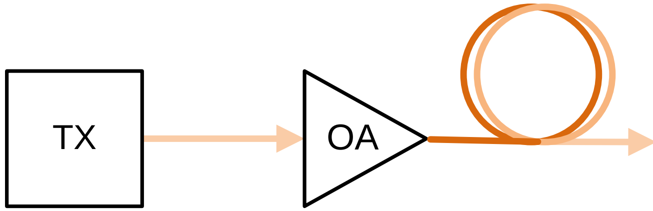
So, if I need 1 Tb/s right now lasers are not already here.

EDFA

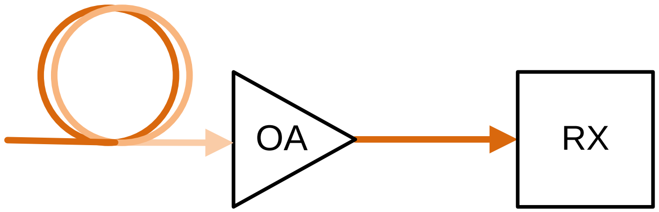
here you amplify.

Usage of Optcal Amplifiers

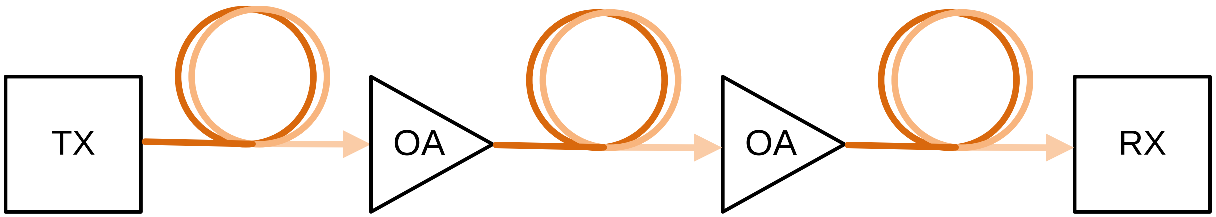
- Booster



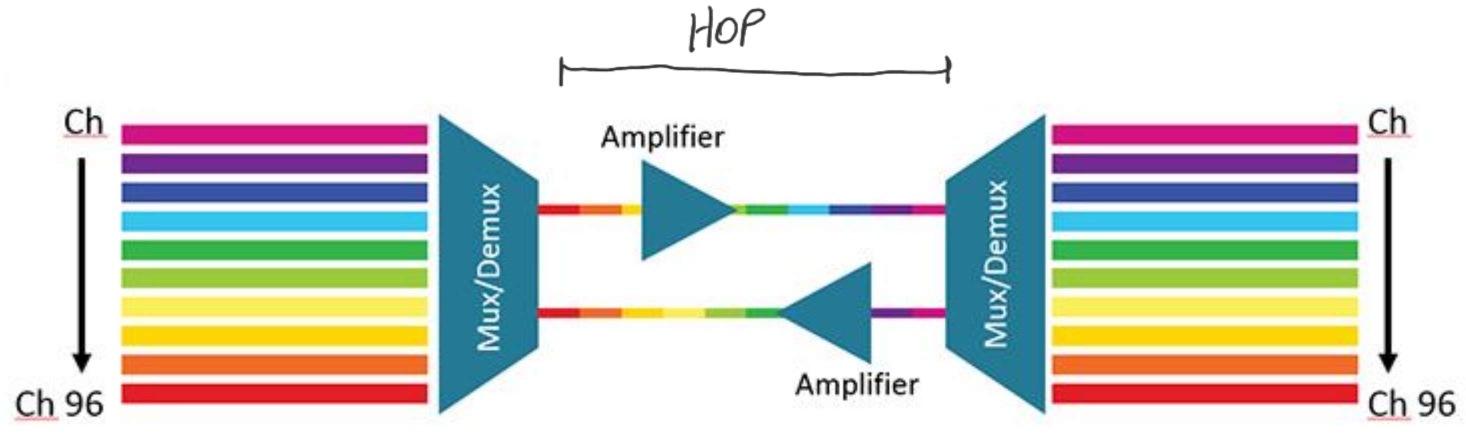
- Pre-Amplifier



- (Transparent) Repeater

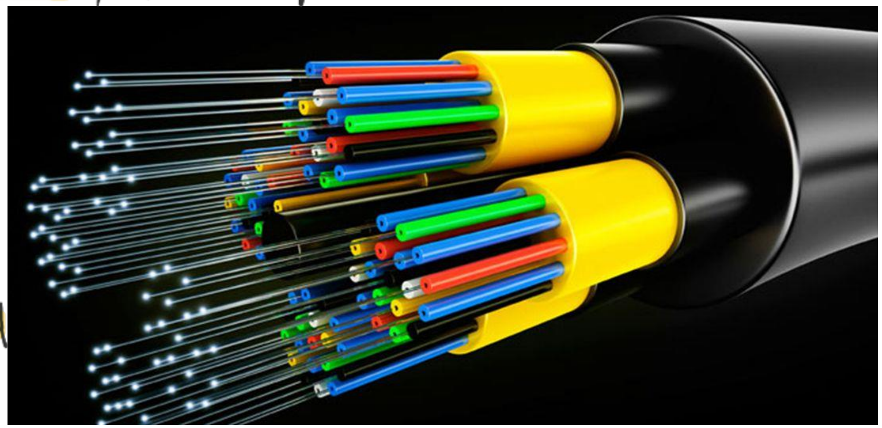


WIRED Systems for the Transport Network



On the backbone, 2 fibers, one with 1 dir., the other for the other.

At the two ends of the hop you have many channels that communicate on different wavelengths: W.Division multiplexing. You have multiple channels on the same fiber on different wavelengths. Each one is narrowband that work together on a broadband signal.



Optical (D)WDM

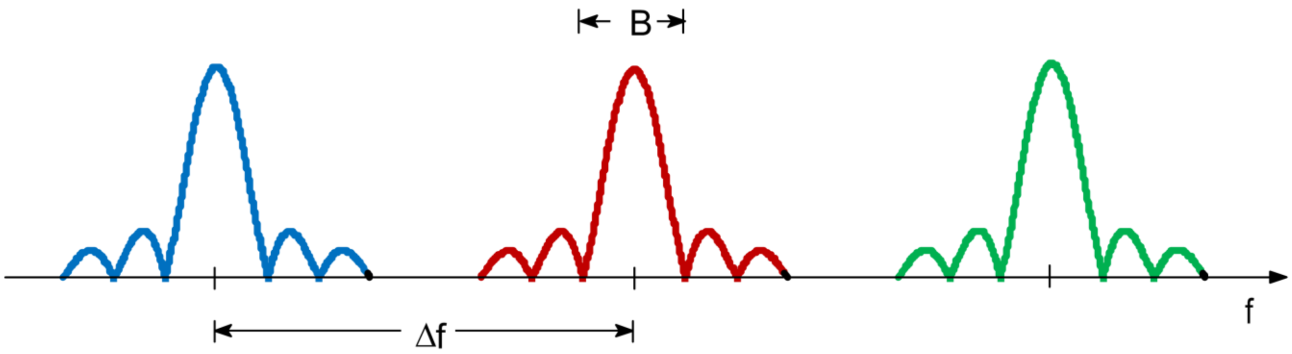
=> 40Gbit/s for each channel, 100 channels, so 4 Tbit/s.

So many channels that implement lasers at 40Gbit/s. Double. Only problem is actually doing the multiplexing

If I want to go to WDM, OA are transparent. They don't care if we have 1 or many channels.

Why Transparent? WDM !

WDM: second key tech of backbones



FIRST

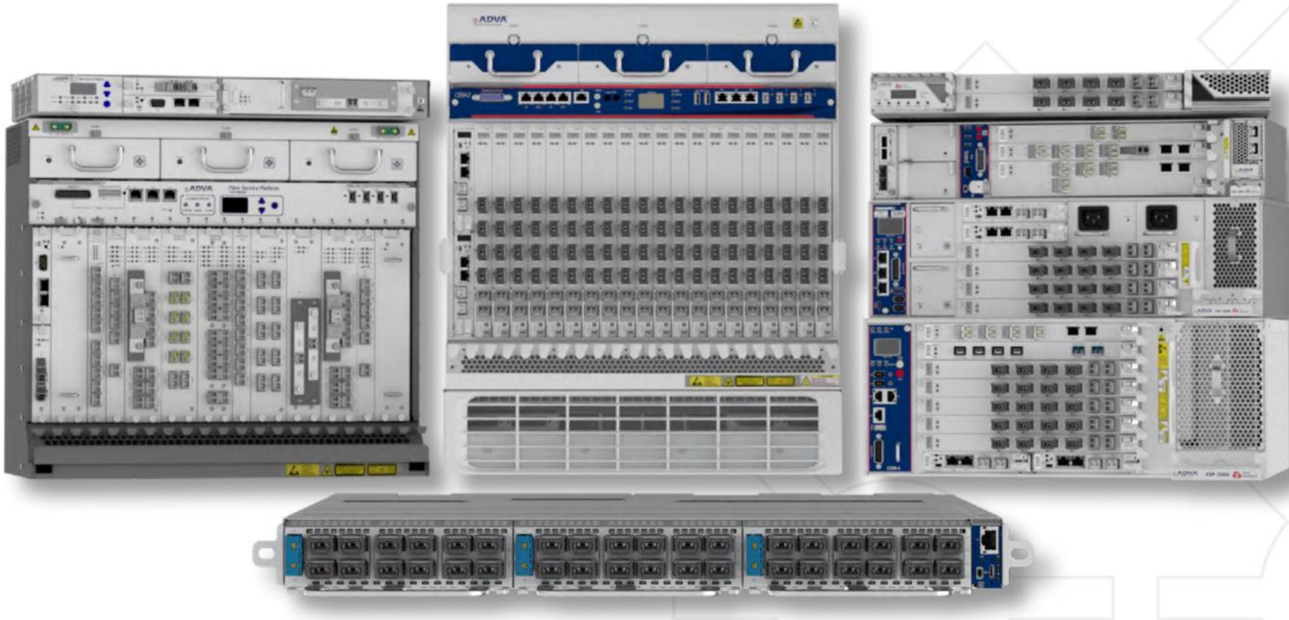
Very few, well separated in wavelength. Before, building lasers and make sure that they stay on the right frequency not feasible

- **COARSE WDM (CDWM): Few channels, high Δf**
- **DENSe WDM (DWDM): Many channels, low Δf**

100GHz of spacing which is the standard spacing, So you can have 100 GHz of bandwidth

(ITU 100 GHz)

ITU channel	Frequency (THz)	Center Wavelength (nm)
61	196.1	1528.77
60	196.0	1529.55
59	195.9	1530.33
58	195.8	1531.12
57	195.7	1531.90
56	195.6	1532.68
55	195.5	1533.47
54	195.4	1534.25
53	195.3	1535.04
52	195.2	1535.82
51	195.1	1536.61
50	195.0	1537.40
49	194.9	1538.19
48	194.8	1538.98
47	194.7	1539.77
46	194.6	1540.56
45	194.5	1541.35
44	194.4	1542.14
43	194.3	1542.94
42	194.2	1543.73
41	194.1	1544.53
40	194.0	1545.32
39	193.9	1546.12
38	193.8	1546.92
37	193.7	1547.72
36	193.6	1548.51
35	193.5	1549.32
34	193.4	1550.12
33	193.3	1550.92
32	193.2	1551.72
31	193.1	1552.52
30	193.0	1553.33
29	192.9	1554.13
28	192.8	1554.94
27	192.7	1555.75
26	192.6	1556.55
25	192.5	1557.36
24	192.4	1558.17
23	192.3	1558.98
22	192.2	1559.79
21	192.1	1560.61
20	192.0	1561.42
19	191.9	1562.23
18	191.8	1563.05
17	191.7	1563.86



Your benefits

2 dir

1 channel

- **Scalability**
  Up to 600Gbit/s per wavelength and 38.4Tbit/s duplex capacity per fiber pair with best-in-class metrics; up to 3.6Tbit/s per 1RU chassis
- **Flexibility**
  From complete turnkey systems including all equipment necessary for end-to-end transport applications to disaggregated solutions
- **Pay-as-you-grow design**
  Modular and scalable architecture that ensures both low initial cost and flexibility into the future
- **Fully open and programmable**
  Open line system (OLS) architecture and YANG-based APIs (OpenConfig) for network disaggregation and easy integration into SDN-based environments
- **Dynamic and scalable optical layer**
  Multitude of ROADM options from metro-optimized 2-degree ROADM to multi-degree ROADM for flexgrid optical layer
- **ConnectGuard™ encryption technology**
  Certified data encryption with 100% throughput for any service on the transport layer