USC University of Southern California

ECE 105: Introduction to Electrical Engineering

Lecture 20

Optical Communications

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How have we done optical communications in the past?

What kind of systems have people used in the past to do optical communications?

Smoke Signals

Signal Lamp

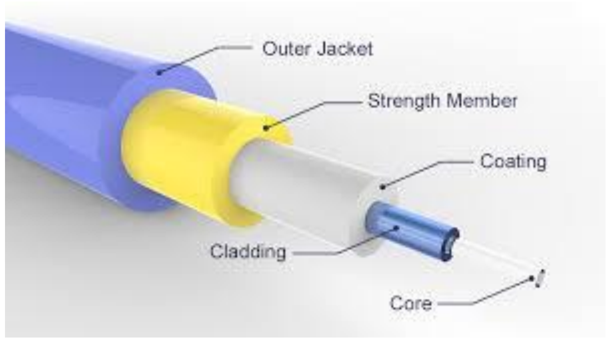
Heliograph

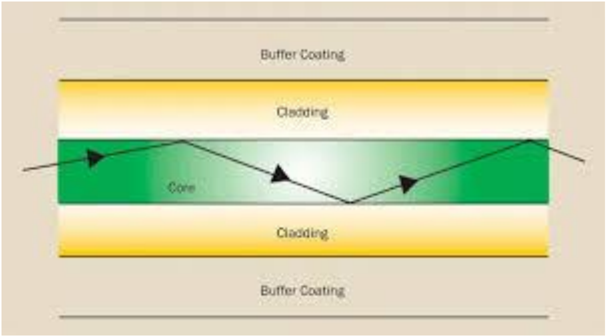
Fiber Optics

How fast could we communicate using smoke signals?

- We could have a short or long pulse to represent a 1 or 0.
- Let's assume 0.5 seconds for short and 1.5 seconds for long pulse
- The gap between the pulses needs to be at least 0.5 seconds for it to be seen
- That means that we would need 0.5+0.5 to send out a short pulse
- We would need 1.5+0.5 to send out a long pulse
- Average time to send a bit = (Short + Long)/2 = 1.5 s
- Our bitrate is 1 bit/1.5s = 0.66 bps

Optical Fiber

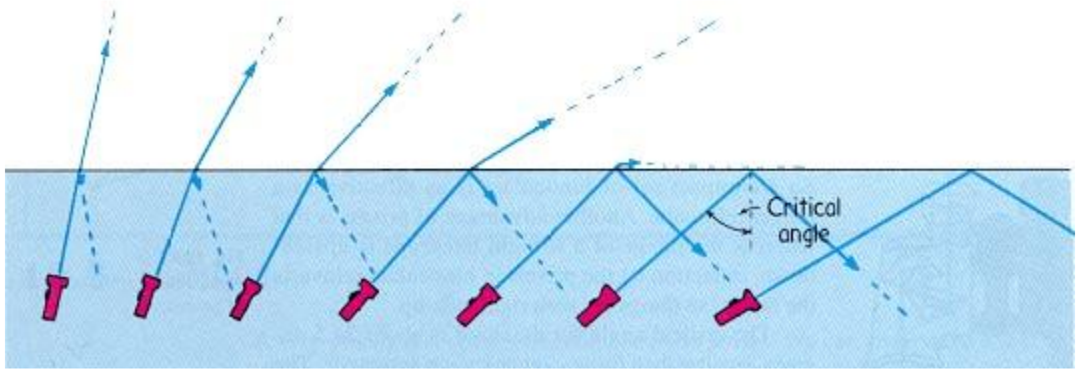




Optical fibers guide light from one point to another confined inside a fiber core.

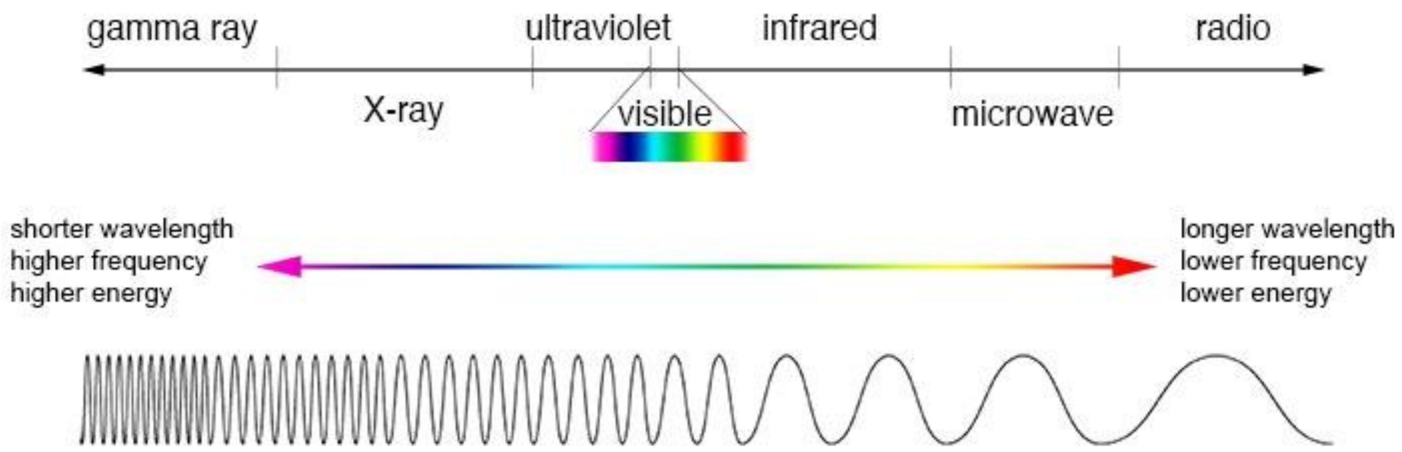
These work based on the principle of total internal reflection. Depending on the angle that light hits the fiber/cladding interface, it can be fully reflected

Total internal reflection



When light moves from a medium of high refractive index to a medium of low refractive index, or vice versa, there is a change in the angle of propagation of light.

General properties of light



The wavelength of light represents the spatial dimension over which it is periodic

Speed of light in different mediums

There is a concept called the refractive index, which is:

$$n = c/v$$

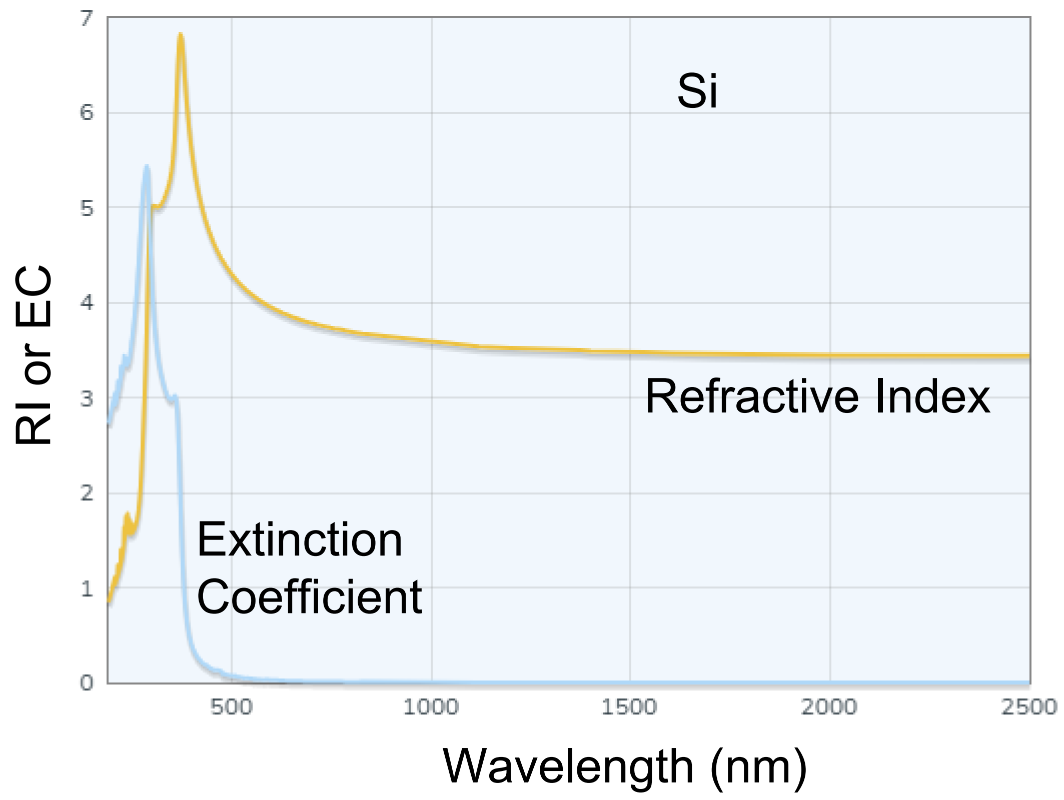
Where
n: refractive index
c: speed of light
v: speed of light in the medium

This emerges due to the oscillations of electrons in a material creating dipoles that interact with electromagnetic waves and slow them down

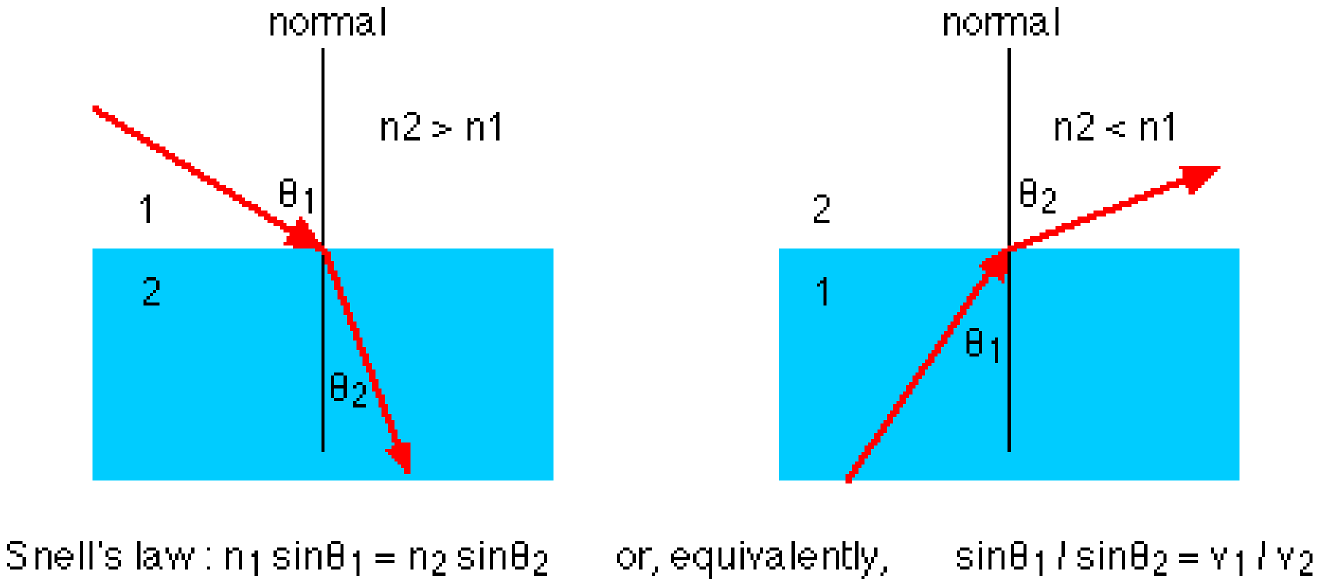
Refractive index of different materials

Material	*n*
Vacuum	1
Gases at 0 °C and 1 atm	
Air	1.000 293
Helium	1.000 036
Hydrogen	1.000 132
Carbon dioxide	1.000 45
Liquids at 20 °C	
Water	1.333
Ethanol	1.36
Olive oil	1.47
Solids	
Ice	1.31
Fused silica (quartz)	1.46[11]
PMMA (acrylic, plexiglas, lucite, perspex)	1.49
Window glass	1.52[12]
Polycarbonate (Lexan™)	1.58[13]
Flint glass (typical)	1.69
Sapphire	1.77[14]
Cubic zirconia	2.15
Diamond	2.417
Moissanite	2.65

The refractive index is a function of material AND wavelength of the electromagnetic radiation

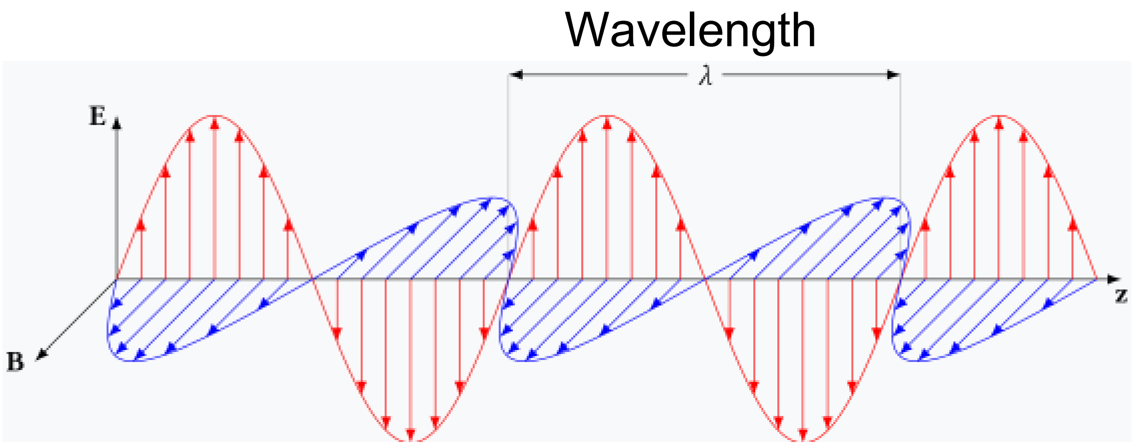


Snell's Law



Snell's law gives us the relationship between the angle of light in one medium with respect to normal and the angle of light in another medium with respect to normal when an interface is crossed at an angle.

Polarization of light



Electromagnetic waves have an electric field and magnetic field that oscillate in orthogonal planes.

The polarization of light indicates the plane in which the electric field is oscillating

s-polarization and p-polarization

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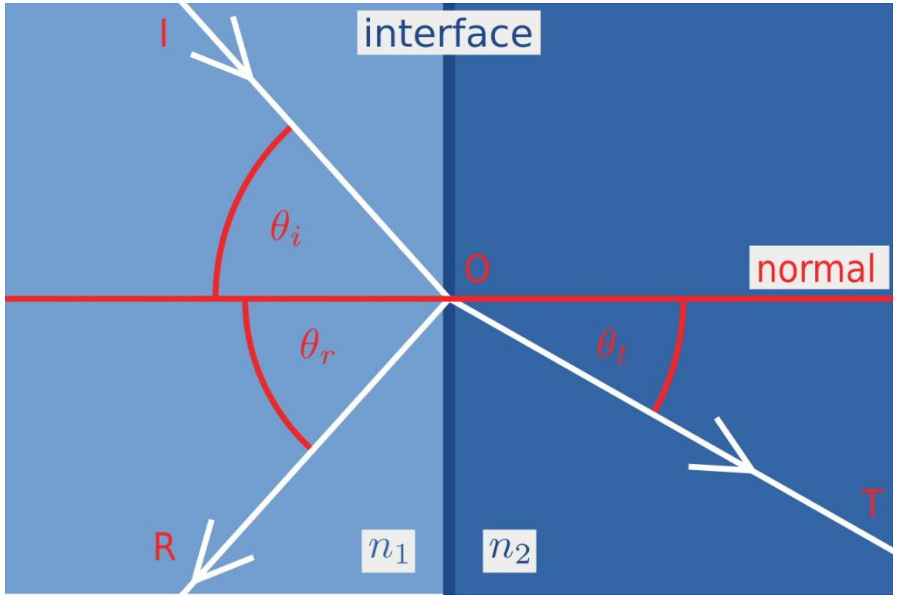
Depending whether the polarization is in plane or orthogonal to the interface

p-polarized light has the electric field in plane or parallel with the interface

s-polarized light has the electric field orthogonal or perpendicular to the interface

Transmission and Reflection



S-Polarized Light

$$R_s = \left| \frac{Z_2 \cos\theta_i - Z_1 \cos\theta_t}{Z_2 \cos\theta_i + Z_1 \cos\theta_t} \right|^2$$

P-Polarized Light

$$R_p = \left| \frac{Z_2 \cos\theta_t - Z_1 \cos\theta_i}{Z_2 \cos\theta_t + Z_1 \cos\theta_i} \right|^2$$

$$Z_i = \frac{Z_0}{n_i}$$

Snell's law gives us the relationship between the angle of light in one medium with respect to normal and the angle of light in another medium with respect to normal when an interface is crossed at an angle.

Transmission and Reflection

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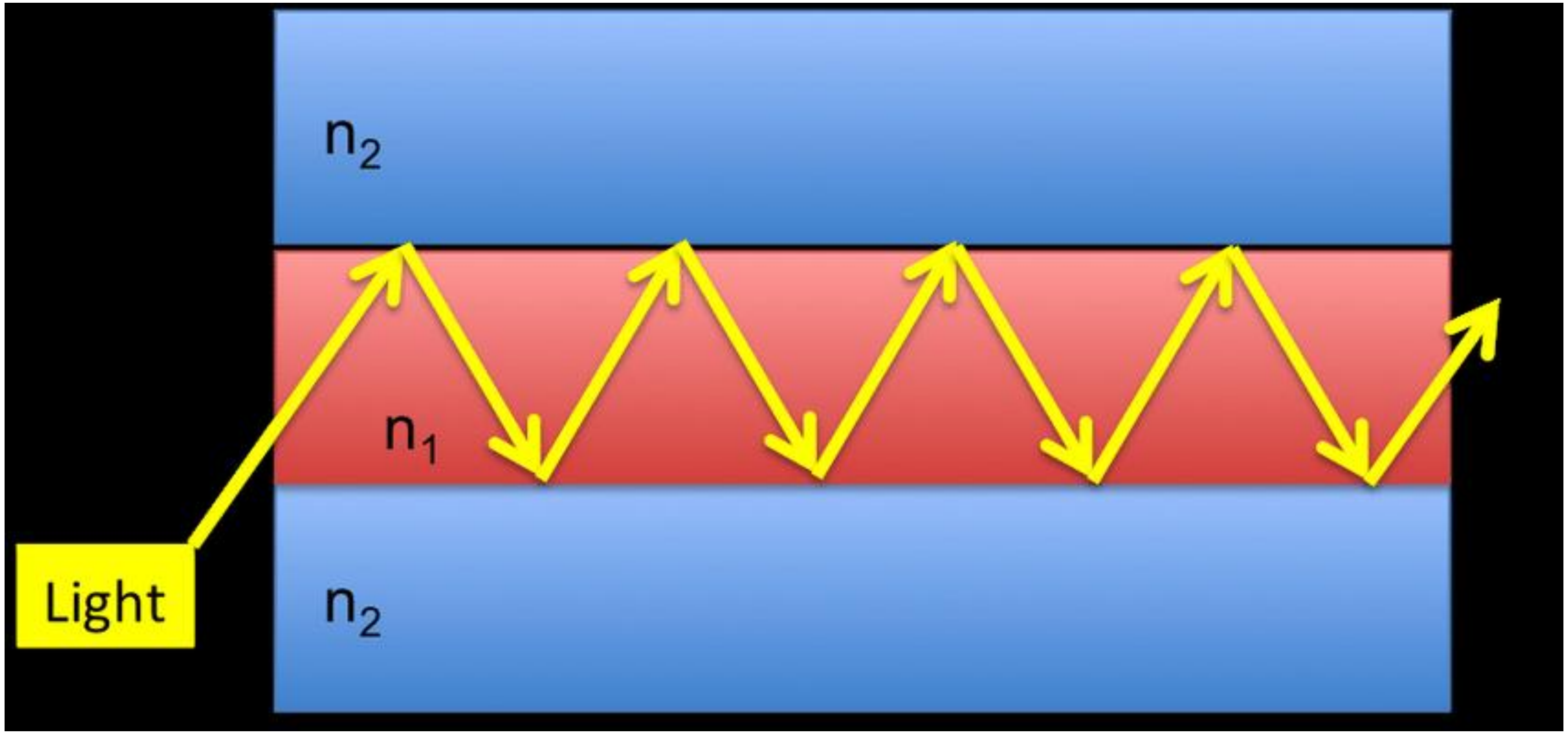
$$Z_i = \frac{Z_0}{n_i}$$

$$R_\mathrm{s} = \left|\frac{n_1 \cos\theta_\mathrm{i} - n_2 \cos\theta_\mathrm{t}}{n_1 \cos\theta_\mathrm{i} + n_2 \cos\theta_\mathrm{t}}\right|^2 = \left|\frac{n_1 \cos\theta_\mathrm{i} - n_2 \sqrt{1 - \left(\frac{n_1}{n_2}\sin\theta_\mathrm{i}\right)^2}}{n_1 \cos\theta_\mathrm{i} + n_2 \sqrt{1 - \left(\frac{n_1}{n_2}\sin\theta_\mathrm{i}\right)^2}}\right|^2$$

$$R_\mathrm{p} = \left|\frac{n_1 \cos\theta_\mathrm{t} - n_2 \cos\theta_\mathrm{i}}{n_1 \cos\theta_\mathrm{t} + n_2 \cos\theta_\mathrm{i}}\right|^2 = \left|\frac{n_1 \sqrt{1 - \left(\frac{n_1}{n_2}\sin\theta_\mathrm{i}\right)^2} - n_2 \cos\theta_\mathrm{i}}{n_1 \sqrt{1 - \left(\frac{n_1}{n_2}\sin\theta_\mathrm{i}\right)^2} + n_2 \cos\theta_\mathrm{i}}\right|^2$$

Snell's law gives us the relationship between the angle of light in one medium with respect to normal and the angle of light in another medium with respect to normal when an interface is crossed at an angle.

Waveguides



If light is incident on an interface at an angle beyond the critical angle, then it is reflected back. It will also be incident on the lower surface at an angle that enables total internal reflection. This allows us to create a waveguide, where light will just propagate in a confined guide as long as possible.

Optical Fiber Transmission Speeds

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Year	Organization	Aggregate speed	Bandwidth	Spectral efficiency, (bit/s)/Hz	WDM channels	Per-channel speed	Distance
2009	Alcatel-Lucent[39]	15.5 Tbit/s			155	100 Gbit/s	7000 km
2010	NTT[40]	69.1 Tbit/s			432	171 Gbit/s	240 km
2011	NEC[41]	101.7 Tbit/s			370	273 Gbit/s	165 km
2011	KIT[42][43]	26 Tbit/s			336[A]	77 Gbit/s	50 km
2016	BT & Huawei[44]	5.6 Tbit/s			28	200 Gbit/s	~140 km?
2016	Nokia Bell Labs, Deutsche Telekom & Technical University of Munich[45][46]	1 Tbit/s		5–6.75	4	250 Gbit/s	419–951 km
2016	Nokia-Alcatel-Lucent[47]	65 Tbit/s					6600 km
2017	BT & Huawei[48]	11.2 Tbit/s		6.25	28	400 Gbit/s	250 km
2020	RMIT, Monash & Swinburne Universities[49][50]	39.0–40.1 Tbit/s	~4 THz	10.4 (10.1–10.4)	160[A]	244 Gbit/s	76.6 km
2020	UCL[51]	178.08 Tbit/s	16.83 THz	10.8	660 (S, C, L bands)	270 Gbit/s	40 km
2023	NICT[52]	301 Tbit/s	27.8 THz	10.8	1097 (E, S, C, L bands)	250–300 Gbit/s	50–150 km
2024	NICT[53]	402 Tbit/s	37.6 THz	10.7	1505 (O, E, S, C, L, U bands)	170–320 Gbit/s	50 km

Optical Modulation Techniques

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Intensity Modulation: Where you modulate the intensity of the light, and have predetermined values for each intensity of light.

On-off keying is where you have two values that represent 1 and 0, allowing you to transmit binary information