Long distance daylight transport over optical fiber

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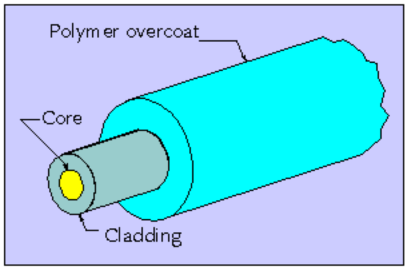
1. Intro

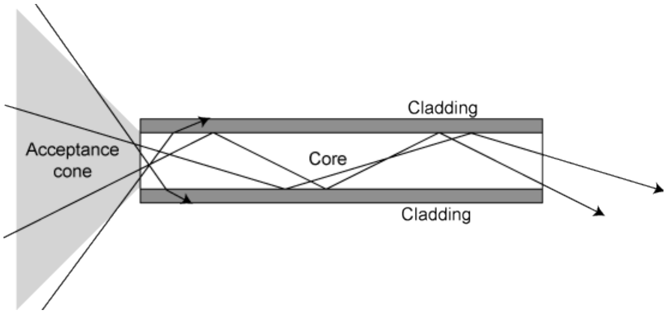
In this short report I explore the feasibility of conducting daylight over long distances using optical fibers. I will present current technologies and materials used in fiber optic and their limiting factors in achieving such a goal.

2. Background

a. Fiber geometry and terms



optical fiber



The core is where light is confined and it has a higher refractive index than the cladding. The profile of the refractive index inside the core can vary. I will focus in this study on the case where the refractive index is constant over the core ("step index" fiber). The core size ranges from few microns to millimeters.
Cone of acceptance defines the rays that are permitted to propagate in the fiber. Rays with higher angles will not experience total internal reflection and will not be able to propagate.

b. Types of fibers

Optical fibers can be categorized by the size of their core. We have Multimode (MM) fibers and Single mode (SM) fibers

i. Multimode (MM) fibers: those are fibers with cores dimensions much bigger than the wavelength (more than 10 microns in diameter) of the light they convey. Such fibers are called multimode fibers because they support propagation for different modes simultaneously. As we will see this the kind fiber that we are interested in when we think of conducting daylight over fibers. Light propagation in such fibers is described using geometrical optics. The geometrical optics description stipulates that the light propagating in a fiber propagating by bouncing back and forth off the boundary between the core and cladding due to the total internal reflection occurring for angles higher than some critical angle. This picture describes well MM fibers.

ii. Single mode (SM) Fibers: these fibers support for a given wavelength only one mode (spatial distribution of the intensity). In other words the core size is chosen in such a way that only one mode can exist in the fiber for a specific color. This kind of fiber is extensively used in telecommunication but is less of interest when it comes to transport of broadband (multicolor) visible light. Such fibers have typically cores dimensions of less 10 microns and the description of the propagation inside cannot be done using the geometrical approach. One has to use the wave description of light to study the propagation inside such fibers.

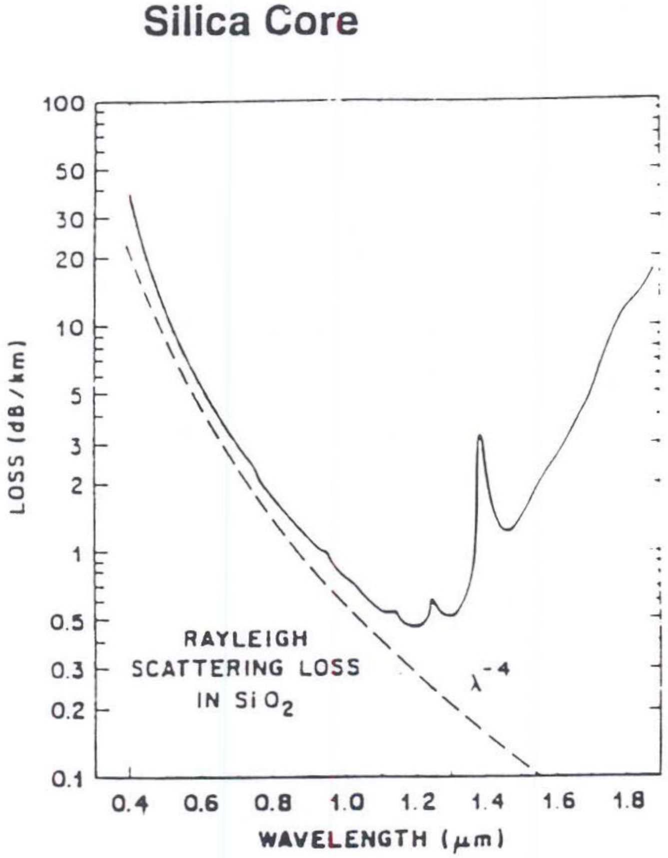
Conclusion pertinent to our application: Daylight is comprised of a wide range of wavelengths (colors): from 390 nm to 750nm. Based on what has been described above the primary choice for a fiber to transport daylight will be a MM fiber with proper core dimensions. The proper core dimension will be dictated by one of the loss mechanisms: input coupling. As we can see from simple geometrical consideration the larger the core, the larger the cone of acceptance and the higher the coupling efficiency.

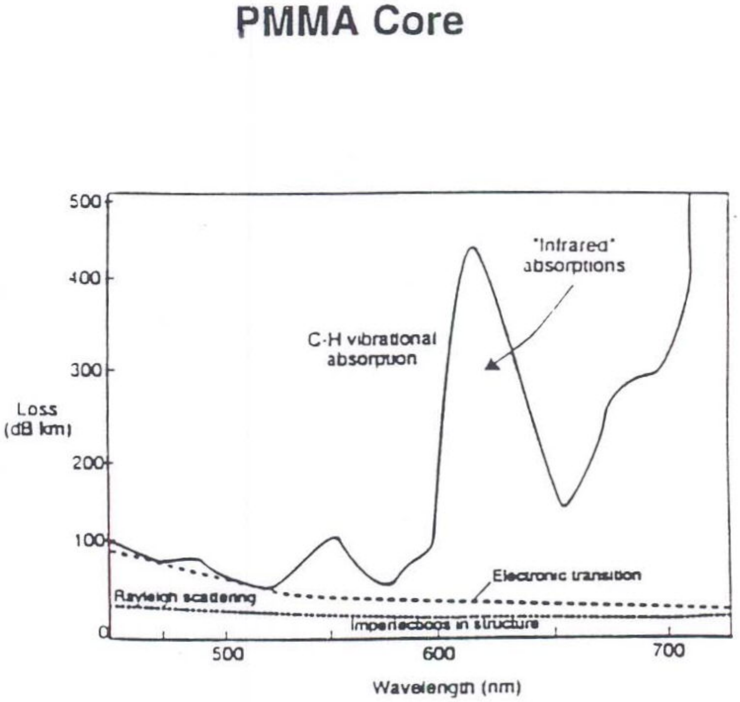
3. Materials and losses

   a. Materials

In this section I will introduce mainstream materials that are broadly used for MM fibers. The first material is of course Silica (with Germanium dopant) and the second is polymethyl methacrylate (PMMA). Silica fibers are ubiquitous thanks to the huge boom they facilitated in telecommunications. However one should keep in mind that although their very low (3 db/km for Silica MM fibers) attenuation coefficient was at the origin of the fiber optics telecom revolution, this low attenuation is achieved in the infrared and consequently the sources used in telecom are around the minimum loss i.e. in the infrared around 1.3-1.5 microns. For the visible wavelengths the story is completely different and for that reason I looked also into the Plastic Optical Fibers (POF) that although more lossy they are available of the shelf for a fraction of the cost and are more lightweight and resilient to bending, shock and vibrations.

The following graph and table compare the performances of the 2 materials


Silica Core


PMMA Core

(From Product Information Sheet: Mitsubishi-Rayon Co. Inc.)

Characteristics	Glass	Plastic
Fiber core diameter, microns	50-200	250-5000
clad diameter	125-500	450-6000
Attenuation at 650 nm, dB/km	4.0	150
Maximum transmission distance for 75% power loss, meters	1,500	53
Usable spectral range	UV,VIS,IR	VIS

Numerical aperture	.1-.4	.3-.65
Acceptance angle (cone)	35 degrees	60-75 degrees

For silica the attenuation for visible light is from 45 db/km to 3 db/km. In the case of POF we have attenuation factor ranging from 100 db/km to more than 400 db/km.

Conclusions pertinent to our application: with such attenuation factors transport of light over long distances using optical fibers without the use of repeaters seems impractical. Even taking into account the lowest attenuation (3 db/km) in silica fiber @ 750 nm, the intensity is divided by 2 after 1 km, after 10,000 km not much is left…

b. Loss factors:

Loss of signal strength in an optical fiber can result from absorption or scattering of the light. Absorption is caused by impurities in the fiber, such as metals and water molecules. Light can scatter off impurities in the material, defects in the fiber such as voids, and at core-cladding interfaces and end faces. Each of these loss mechanisms is a function of the wavelength.
In the case of silica those loss mechanisms are know we great accuracy. The basic loss mechanisms are universal and I list here just few of them:

i. Ultraviolet (UV) Absorption: this absorption is of electronic origin. That means that incoming light at UV wavelength matches the energy needed for electrons in the Silica to jump from an energy state to a higher one. This is a resonant process and as such it has some width in the spectrum. This resonance and its tail is broad enough to yield appreciable attenuation in the visible and that the tail that we see in the graph in the previous page.

ii. Infrared absorption: in this case energy from the incoming light is transferred to the lattice this is why this absorption is referred to as the vibrational absorption.

iii. Rayleigh scattering: simply put, this effect is about light bouncing off (elastic scattering) some impurities that are much smaller than the wavelength of the light. When light propagate along the fiber this scattering sums up to a net loss of energy at the output of the fiber. This is the main source of loss in the POF.

iv. Coupling losses: this mechanism is due to the size and angle mismatch between the focused light at the fiber's input and fiber's core size and cone of acceptance.

Conclusion pertinent to our application: as we can see, the attenuation figures introduced in the previous section derive from fundamental processes that take place at the atomic scale where the light-matter interaction occurs. As a consequence reducing this attenuation figures in the visible range requires an extensive R&D effort similar to the one that took place in the 60's that led to significant reduction of the attenuation factor in silica fibers in the IR.

4. Conclusion

In this report I have introduced some basic concepts in fiber optics. In the light of those concepts it appears that guiding daylight over long distances (hundreds of kilometers) using commercially available optical fibers is impractical due the th e extremely high attenuation that visible light experiences as it propagates inside a fiber. It is worth noting that daylight transport using fibers has found some niche in the architecture and interior design (http://www.parans.com/eng/). In this specific application light is transported over few meters and the attenuation is still acceptable.