Attenuation in Fiber Optics

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Table of Contents

- 1 Introduction
- 2 Transparency in optical fibers
- 3 Optical amplifiers
- 4 Decibels
- 5 Frequency
- References

1 Introduction

In optical fibers communication, it is really important to consider all elements that affect the transmission of signals through optical fiber. There are several elements which relates to the attenuation in optical fiber transmission, including transparency of optical fibers, optical amplifiers, decibels, frequency and other variable dependencies. All of them will be covered respectively in this wiki page.

2 Transparency in optical fibers

Optical fibers have held a key role in making growth of world-wide communications and internet. The creation of very pure glass which is sufficiently transparent that makes possibility of long distance transmission of light through glass fibers. In 1960, working in research laboratory in California, Theodore Maiman produced the first operating laser which has very pure nature, well-defined color and is very bright. The special properties of laser create opportunities to expand the usefulness of optical communication links. In addition, the creation of a reliable, affordable channel for long distances data transmission is required to advance optical communication. In 1854, in London, John Tyndall shown that light can be guided along a stream of flowing water that proves light needs not to travel in straight lines.[1]

An optical waveguide must be made from a transparent material which can be plastics or glasses. Optical attenuation in plastics is much higher than the attenuation in glasses. Materials such as polystyrene or polymethacrylates (PMMA) are often used plastic fibers with losses in range of 100-1000 dB/km. However, plastic fibers are easy to manufacture so that is an economic solution for short-range communication. Nevertheless, glasses are excellent materials for optical waveguides as those have very low loss.[2,128]

Total internal reflection theory was applied in guiding light in optical fibers. When a light ray passes from a transparent medium to another, it bends at the boundary of two media. The bending phenomenon can be described by Snell’s law mathematically:
As figure 1 shows that is $n_2$ is less than $n_1$, there is restriction of the angles that light ray can go cross the border. Light goes from medium 1 to medium 2 with condition that $\theta_1$ is greater than the critical angle so light cannot refract across the boundary (because $\theta_1$ cannot greater than 90). The critical angle is defined by sine of $n_2/n_1$. A light ray goes to the boundary at an angle which is greater than the critical angle, it reflects and does not cross the border.[1]

Figure 1: Refractive indices of media and Snell’s law. Copied from [1]

$$\text{first sense } \theta_1 = n_2 \sin \theta_2$$

Figure 2: Total internal reflection. Copied from [1]
Figure 2 shows typical structure of an optical fiber with the capability of guiding light ray inside by applying the total internal reflection between the core glass and the less dense glass surrounding.

In 1958, fiber imaging bundles were developed for medical imaging. In that bundle, a large number of optical fibers are bonded together. Optical image is relayed from one end of bundle and appears at the other end, where it can be seen. It was concluded that about 80 percents of the original light is transmitted to other end with a bundle 1m long. However with 100m long bundle, only a ten billionth part of the light reaches the far end. The attenuation of bundle was measured as 1000 dB per km, which can be considered useless for long distance light transmission.[1]

In 1966, Charles Kao and George Hockham pointed out that glass attenuation has reason in the impurity with appearance of metal ions, such as iron, copper, vanadium and chromium and a glass with attenuation of 20 dB/km can make 1% of input light reaches the other end of a 1 km-length fiber. In 1979 the attenuation of 0.2 dB/km was achieved in optical fiber.[1]

3 Optical amplifiers

Optical link has limit in range as there is always attenuation of propagating light in a normal fiber. One method to solve the problem is to detect the optical signal before the critical low value and convert it back to electrical domain and create new copy of optical signal. Another method is using optical amplifier. Without need of converting back optical signal to electrical domain, an amplifier can be used in different applications. It can be use as an inline amplifiers to compensate the attenuation of optical signals as well as pre-amplifiers in optical detectors to improve sensitivity of the receiver or as power boosters to raise output power of an optical transmitter. [2,149]

There are two categories of amplifiers: semiconductor optical amplifiers (SOAs) and fiber amplifiers. Optical gain in semiconductors is based on forward-biased junction. Fiber amplifier contains optical fiber which is doped with a rare earth element such as neodymium (Nd) and praseodymium (pr) etc… The existence of dopants creates new energy bands within the fiber.
Figure 3 illustrates the dopants ions interact with the pump signal with frequency $f_p$ and goes to higher energy state $E_p$. The ions have short lifetime ($T_p$) and quickly move to lower energy band, $E_1$, in which they have longer lifetime ($T_1$). Because $T_1 \gg T_p$, population inversion is created. Inverted system interacts with main signal of frequency $f$, results in amplification of signal as stimulated emission happens.

The erbium doped fiber amplifier (EDFA) is the most popular type as $E_1 - E_0$ exists in the wavelength of 1550 nm. In consequence, EDFA can amplify signal in lowest range of attenuation of silica fibers, results in the popularity of using in long distance communication. Typical EDFA amplifiers can supply gain in 30nm band (1530-1560 nm) with gain of 20-30 dB.
Figure 4 shows one example of co-directional pumping as the main and pump signals travel in same direction. EDFAs have very important role in long-range optical fiber communication, and subjected to high interest of researching for increase of bandwidth and performance.

4 Decibels

The decibel (dB) is used to measure sound level but it is also used widely in communications, electronics and signals. In communications, the decibel is a logarithm way of describing a ratio between two signal power, such as power, sound pressure, voltage, or current levels. The decibel is a common measurement used in the field of electronics to determine loss or gain in a system.

Suppose we have 2 signals, signal 1 has a power of P1 watts, signal 2 has a power of P2 Watts, then the difference in decibels between 2 signals is defined to be:

\[ 10\log(P2/P1)\text{dB} \quad \text{where the log is base 10} \]

In order to measure optical loss, you can use two units, namely, dBm and dB. While dBm is the actual power level represented in milliwatts, dB (decibel) is the difference between the powers.
Light loss, $L(dB)$, is a commonly used specification for fiber optic attenuation. For example, to determine the light loss of an optical fiber in a cable, a light source is connected to one end of the fiber cable (input). The light output power of the source is known to be 0.1 mW. When an optical power meter is connected to the opposite end of the fiber optic cable under test (output), the meter measures 0.05 mW. Using the decibel power loss formula, the optical fiber loss can be calculated as follows:

$$L(dB) = 10 \log_{10} \left( \frac{P_{out}}{P_{in}} \right)$$

The light power loss of this optical fiber is 3 dB.

The dB unit is a logarithmic ratio of input and output levels and is therefore not absolute (i.e., has no units). An absolute measure of power in decibels can be made in the dBm form. The dBm unit is a logarithmic ratio of the measured power to 1 mW of reference power.
5 Frequency

Attenuation is a loss of intensity in an energy beam as it passes through a substance or object or the energy loss of signal transmission through a given medium. Coefficient is a quantitative measure of either an effect or a property. It is the ratio by which a change in one property will change another property. The attenuation coefficient is thus a ratio comparing the loss of intensity to the distance that the energy beam passes through the material. The units used to express the intensity will depend on the precise energy beam.

The attenuation coefficient is also used in ultrasound. When ultrasound waves propagate in a medium, energy is removed from the ultrasound waves by two main processes, absorption and scattering. The mechanism that removes energy from the ultrasound waves is called “attenuation”. Ultrasound is absorbed by the medium if part of the wave energy is converted into other forms of energy, such as heat. The absorption is frequency dependence. When ultrasound waves propagate, they not only become smaller in amplitude but they also change shape. Absorption in the body has a major effect on the penetration depth. It would limit the detectable penetration of the ultrasound waves in the body or the maximum depth at which tissues can be imaged. The attenuation of ultrasound in a material could be described by the attenuation coefficient in the units of decibels per centimetre per megahertz (dB/cm /MHz).[6]

Attenuation always serves as a measurement parameter that leads to the formation of theories to explain physical or chemical phenomenon, which decreases the ultrasonic intensity. Attenuation is generally proportional to the square of sound frequency. Quoted values of attenuation are often given for a single frequency, or an attenuation value averaged over many frequencies may be given.[7] The attenuation coefficient () can be used to determine total attenuation in dB in the medium using the following formula.

\[
\text{Attenuation} = \alpha[\text{dB}/(\text{MHz} \cdot \text{cm})] \cdot l[\text{cm}] \cdot f[\text{MHz}]
\]

: attenuation coefficient
: medium length
: frequency of the incident ultrasound beam

The attenuation coefficients of common biological materials at a frequency of 1 MHz are listed below:

<table>
<thead>
<tr>
<th>Material</th>
<th>a (dB / (MHz ; cm))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1.64 (20°C)</td>
</tr>
<tr>
<td>Blood</td>
<td>0.2</td>
</tr>
<tr>
<td>Tissue</td>
<td>Value</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>Bone, cortical</td>
<td>6.9</td>
</tr>
<tr>
<td>Bone, trabecular</td>
<td>9.94</td>
</tr>
<tr>
<td>Brain</td>
<td>0.6</td>
</tr>
<tr>
<td>Breast</td>
<td>0.75</td>
</tr>
<tr>
<td>Cardiac</td>
<td>0.52</td>
</tr>
<tr>
<td>Connective tissue</td>
<td>1.57</td>
</tr>
<tr>
<td>Dentin</td>
<td>80</td>
</tr>
<tr>
<td>Enamel</td>
<td>120</td>
</tr>
<tr>
<td>Fat</td>
<td>0.48</td>
</tr>
<tr>
<td>Liver</td>
<td>0.5</td>
</tr>
<tr>
<td>Marrow</td>
<td>0.5</td>
</tr>
<tr>
<td>Muscle</td>
<td>1.09</td>
</tr>
<tr>
<td>Tendon</td>
<td>4.7</td>
</tr>
<tr>
<td>Soft tissue (average)</td>
<td>0.54</td>
</tr>
<tr>
<td>Water</td>
<td>0.0022</td>
</tr>
</tbody>
</table>

Figure 7: Diffuse reflection. Copied from [5]

6 Other Variable Dependencies

In fiber optic, attenuation is the loss of signal energy or intensity when signal is transmitted in long distance. There are many factors that cause attenuation. In general, attenuation is caused by the medium components such as, cables, connectors. Below are factors that degrade the signal strength in the fiber.

The first phenomenon is optical absorption. When light travel through the optical fiber, photons can be observed by the material structure which result in the higher energy state of the material. Because of photon absorption, light loses its intensity and hence signal is degraded. The travel of light can be described in the following formula:

\[ n^* = n(y) + ik(y) \]

\( n^* \): complex refractive index
\( n() \): real portion of the refractive index
\( n(h) \): extinction coefficient
So, the material structure has an effect on the signal strength through optical absorption.

The next factor is light scattering. If the surface of the material is rough and uneven, propagation of light in the fiber can be reflected in random directions. This kind of reflection is also called as diffuse reflection.

Figure 8: Diffuse reflection. Copied from [8]

As we can see, the blue lights hit the surface of the core. If the surface is rough, the reflected red lights will go in random directions following the law of reflection. This results in the loss of the light power.

Next one is connection loss. It is important to align two fibers correctly because it will minimize the lateral offset of the core, tilt, angular mismatch... Fiber misalignment can have a large impact on the signal loss because the light is not reflected correctly.
The above image shows the misalignment between two fibers that affect the fiber coupling efficiency. Moreover, air between fiber connections may exist and has impact on the medium. Therefore, air should be minimized as much as possible to produce an optimal medium for propagation of light.

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