Fundamentals of Fiber Optics

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Contents

1 A Brief Introduction and History

In 1854 a British physicist by the name of John Tyndall discovered that light could be bent around a corner through a curved spout of running water. In this experiment he permitted water to spout from a tube, the light on reaching the limiting surface of air and water was totally reflected and seemed to be washed downwards by the descending liquid [2]. What he had discovered was the idea know as total internal reflection. It is this idea that is the basis of fiber optics.

The first practical application of this was used in the UK during the 1930s in the medical field. An un-coated plastic "channel" was used to guide light to an area of interest for inspection [2]. Also during the 1930s, other ideas were developed with this newly found technology such as transmitting images through a fiber. The idea of transmitting an image through bundles of glass fibers was introduced in the 50s. This idea of light propagating through a fiber was rapidly expanding. During the 1960s, LASERS were introduced as efficient light sources and in the 70s the refinement of pure low-loss glass fibers was established [9]. With these developments, fiber-optic transmission became practical and advantageous for many applications.

Today fiber optics is used in a variety of applications from the medical environment to the broadcasting industry. It is used to transmit voice, television, images and data signals through small flexible threads of glass or plastic. These fiber optic cables far exceed the information capacity of coaxial cable or twisted wire pairs. They are also smaller and lighter in weight than conventional copper systems and are immune to electromagnetic interference and crosstalk. To date, fiber optics has found its greatest application in the telephone industry [4]. Fiber optics are also used to link computers in local area networks (LAN). It is quite apparent that fiber optics is, at the moment, an invaluable resource but the technology does have its limitations. For one thing, there is no standardization of fiber optic components which makes interchangability difficult. Also, costs are currently a limiting factor, though believed to be going down daily. The future of fiber optics does look promising, for its advantages far out weigh its disadvantages.

2 Theory of Operation

The main principle behind the method of wave guidance in a fiber optic cable is the idea of total internal reflection. It is known that if a light ray passes from one medium with a refractive index of n_1 to another medium with a refractive index of n_2 , and n_2 is larger than n_1 , such as air to glass, the refracted wave in the second medium will bend towards the normal. If n_2 is less than n_1 , the wave will be bent away from the normal to the surface. There is one instance, where the penetrating ray will not deviate from its original path at all, that is, if it enters the medium perpendicular to the surface or head on. In the case of n_2 being less than n_1, there is a point when the incident ray will be totally internally reflected, that is, the ray will not enter the second material. If the angle of incidence, measured from the normal, for the n_2 ¡ n_1 case, is gradually increased the transmitted wave will continually bend away from the normal. There is an angle, however, in which the refracted wave will be placed along the surface of the boundary between the two media, and will not enter the second material, this is called the critical angle, θ_c. A light ray will be reflected at the boundary for all angles of incidence greater than the critical angle. As the incident angle of the ray is further increased, the refracted wave is actually turned back into the first medium, and total internal reflection is achieved.

We can find the critical angle by putting $\theta_2 = 90$ deg in Snell's law of refraction:

$$n_1 \sin\theta_c = n_2 \sin 90\ deg \tag{1}$$

$$\theta_c = \sin^{-1}\frac{n_2}{n_1} \tag{2}$$

3 Sources and Transmitters

A basic fiber optic communications system consists of three basic elements: A light source, fiber media and a light detector. The majority of light sources used in fiber optics emit light at one of three different wavelengths: 850nm, 1300nm and 1550nm [9]. These wavelengths are desired because they exhibit the least amount of attenuation in the glass fiber.

Of the light sources, there are mainly two types used today: the light-emitting diode (LED) and the current injection laser diode (ILD). Both sources are similar in that they are both made of aluminum-gallium-arsenide (AlGaAs) and are both semiconductor's diodes that are directly modulated by varying input current. The actual choice of one source over another depends on the type of application, cost, desired output as well as temperature considerations.

LEDs can be broken into two types: edge-emitting and surface-emitting. LED's, in general, are very practical when cost effectiveness is in order.

They are priced well below the cost of ILDs and are believed to have a life expectancy of around 107 hours [4]. An LED's power output, usually measured in microwatts, is quite linear, meaning that the amount of current in the LED is directly proportional to the light output. ILDs, on the other hand, have a non linear output, usually measured in milliwatts (mW). They have a threshold associated with them or point at which the diode turns on or lasses, the output then increases exponentially. The output of an ILD is very narrow, with a spectral spread on the order or 1 to 10 nm, compared to an LED that may have a spread as high as 100nm. LEDs actually have a tendency to spew light in all directions, thus decreasing the coupling efficiency to a fiber and increasing signal loss. Because ILDs have a higher output potential and coupling efficiency, they are well suited for long distance transmissions. LEDs have a lower bandwidth, or information capacity, than ILDs because of dispersion. That is, because the velocity of light through glass varies with frequency, the high spectral spread of the LED (emitting many frequencies) will cause dispersion or so call "material dispersion." This is also referred to as chromatic dispersion. This dispersion will cause different frequencies to travel at different speeds and ultimately be received at the detector end at different times. If the source were truly monochromatic, there would not be any material dispersion. An ILD can significantly reduce material dispersion due to there low spectral spreads. ILDs are also very sensitive to temperature changes. A slight temperature can make the output drift as much as 20nm. So it is important to keep ILDs cool during operation.

4 Optical Fibers

Optical fibers are the actual media that guides the light. They can be made of glass or plastic. The plastic fibers exhibit much loss and tend to have low bandwidths so glass fibers are usually preferred. A typical fiber is made up of a core, cladding and a jacket. The core is the center or the actual fiber where the light propagates. It has dimensions on the order of 5 to 600 μm. The cladding surrounds the core and has an index of refraction lower than that of the core, in this way the light will propagate through the core by means of internal reflection. Surrounding the cladding is the jacket, the outer most part of the fiber. The jacket serves to protect the entire optical fiber.

There are basically two types of fibers: stepped index and graded index. The stepped index fibers can be broken down into two types: single-mode and multi-mode. The stepped index fibers are fibers that have an abrupt change in refractive index from the core to the cladding while gradded index fibers have a gradual change in index. The multi-mode stepped index fiber has, as one might guess, multiple paths for the light to travel while the single-mode fiber only allows a single light ray to propagate. Because the core diameter is so small, ILDs are usually used to couple light to the fiber. Multi-mode stepped index fibers exhibit what is referred to as modal dispersion. This is because not all the rays travel through the center of the core. Some deviate from the core and are reflected back to the center. This reflected light takes a longer path and will therefore arrive at its destination at a later time. The graded index fibers will exhibit less of this dispersion because they gradually bend light back to the center allowing the light to travel faster when further from the core, making up for the longer distance. The single-mode stepped index fibers do not exhibit modal dispersion because of their small diameter core. Because of this they tend to have much wider bandwidths and lower losses. In general, if the modal dispersion of a fiber is low, then the output signal will be more likely to resemble the input signal. On the other hand, if the fiber has a high modal dispersion, the output signal will actually be spread out due to the different path lengths and therefore will be less likely to resemble the input signal. When such a case is present, repeaters are needed to re-construct the signal and then send it on its way again.

It is important to consider the characteristics involved when coupling a source to a fiber. Fibers have a certain ability to collect light. This light gathering ability of the fiber is called the numerical aperture (NA). A large NA means a larger signal, or ray loss, and larger distortion “of the intelligence being thus conveyed” [7]. Also with an increase in NA comes a decrease in bandwidth. The NA is always less than 1 since it is a function of the refractive indexes of the fiber. There are four parameters that effect the efficiency of source-fiber coupling, the NAs of both the source and the fiber and the dimensions of the source and the fiber core [9]. The NA can be represented by the following Equations:

$$NA = \sqrt{n_1^2 - n_2^2} \tag{3}$$

$$NA = \sin\theta \tag{4}$$

Where n_1 is the index of the core and n2 is the index of the cladding. θ is the half-angle of the acceptance cone of the fiber.

Equation 3 is generally used for step-index fibers while Equation 4 is use for graded index fibers.

If one were given the indices of the core and cladding of a step index fiber and wanted to determine its numerical aperture the equation would break down to:

$$\theta = \sin^{-1}\sqrt{n_1^2 - n_2^2} \tag{5}$$

Another important fiber parameter is transmission or power loss. Signals that travel through fibers are sometimes attenuated. This is due to a variety of things such as impurities in the fiber, scattering within the fiber (variation in the uniformity of the fiber) and micro bending [4], in which radiation escapes because of small sharp bends that may occur in the fiber.

$$P_T = P_0 e^{-\alpha L} \tag{6}$$

Equation 6 represents the transmitted power through the fiber [1]. Where P_0 is the power into the fiber, L is the length of the fiber and α is the attenuation constant, commonly referred to as fiber loss.

Typical fiber loss is measured in units of decibels per kilometer (dB/km) using the relation:

$$\alpha_{dB} = -\frac{10}{L}\log\frac{P_T}{P_0} \tag{7}$$

where α_{dB} is the loss in decibels [1].

Fiber loss is a function of frequency so this means that fibers will have greater losses at some frequencies than others. These losses are usually specified at certain wavelengths rather than at certain frequencies.

Another source of signal loss is at various locations where the light needs to re-enter or exit a fiber. These locations would include coupling to the fiber (the source end), splicing two fibers together and at the detector end of the fiber link. In order to minimize losses at these junctions, great care must be taken with the fiber. Two of the most common forms of splicing are mechanical and fusion splicing, where the fibers are actually fused together. The mechanical splice would consist of a connector matting the two ends of the fiber. Typical real world connectors cause 1 dB of loss each [9]. These losses and other characteristics of the fiber can be measured with instruments such as an Optical Power Meter or an Optical Time-Domain Reflectometer (OTDR).

5 Detectors

On the receiving end of a fiber optic link is the detector. These detectors emit electrons when illuminated by light of short wavelengths, thus generating electric signals. Two types of detectors are positive intrinsic negative (PIN) and avalanche photo diodes (APD). Basically, a PIN detector diode has a layer of intrinsic or undoped material surrounded or sandwiched by a layer of positive and negative doped materials, a semiconductor. It works in the opposite manner that an LED does and does not require much bias voltage to operate. A PIN can be operational with a voltage as low a 5v. The APD, on the other hand, requires a large bias to operate (between 100v - 300v) but offers amplification of the current signal. The APD actually acts as a current source and is operated at the diodes reverse breakdown voltage.

6 Idea of Modulation

When sending information by way of an optical fiber, the information must be encoded or transformed somehow into information that is capable of being transmitted through a fiber. In other words, the signal needs to be modulated. Modulating the signal basically means that the light is varied as a function of time. There are two types of modulation Analog and Digital. Analog modulation deals with changing the light level in a continuous manner while digital deals with pulsing the signal. In digital modulation, each pulse is a bit of information.

There are other things to consider when transmitting signals such as signal-to-noise ratio (SNR) and the bit error rate (BER), which is simply the ratio of the number of incorrect bits to the total number of bits received.

Again, fiber optics is widely used today and is becoming more common in everyday life. To date, it's greatest use is in the field of communications [9]. Fiber optic technology has been around for some time but it is only recently that it has acquired so much growth so fast.

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