APPLICATION OF FIBER OPTICS TO EMI/EMC PROBLEMS

Fiber optic lines which propagate light or infrared signals are electrical insulators that provide an alternative to wire communication systems.

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INTRODUCTION

Using light signals to transmit information is not a new concept. It was first demonstrated by Alexander Graham Bell in 1880 with his photophone invention. The photophone used a narrow beam of sunlight focused on a thin mirror that was vibrated by the sound waves of human speech. Thus modulated, the reflected beam was focused onto a selenium detector causing a corresponding change in its resistance, and, consequently, a corresponding change in the current driving a telephone receiver. Bell was able to transmit signals up to 700 feet by this invention.

Today, more sophisticated modulation equipment is available, including efficient transmitters and receivers of light and low-loss optic fibers to transmit signals over many kilometers with no significant loss in signal. Yet, the principles involved are essentially the same as Bell utilized over 100 years ago.

With the advent of inexpensive electro-optic devices and fiber optics, the EMC engineer has another tool for controlling EMI/EMC problems. Fiber optic lines which propagate light or infrared signals are electrical insulators that provide an alternative to wire communication systems. Moreover, some fiber optic equipment currently being advertised promises up to 6 GHz bandwidth, which far exceeds any wire communication links.

Although fiber optic communications offer many advantages, they also provide significant disadvantages, the most important being the added complexity they introduce. Another disadvantage is the reduced liability associated with the electro-optical components. However, the advantages outweigh the disadvantages in many applications.

Wire communication links provide a simple and inexpensive means for the propagation of signals from one point to another, but with severe limitations. For example, wire links provide a ready path to conduct noise and in a noisy environment may also act as an antenna to radiative noise. Typically, techniques such as balanced lines, isolation transformers and shielding are required to separate the signal from the noise. For digital signals, error correcting codes which restrict the transmission bit rate and use less sensitive Manchester codes are common practice. However, these solutions further restrict the rate of information transfer of wire communication links.

In order to understand the advantages and limitations of fiber optic communication systems, a basic understanding of the principles of their operation is required. The basic building blocks of a fiber optic system are shown in Figure 1.

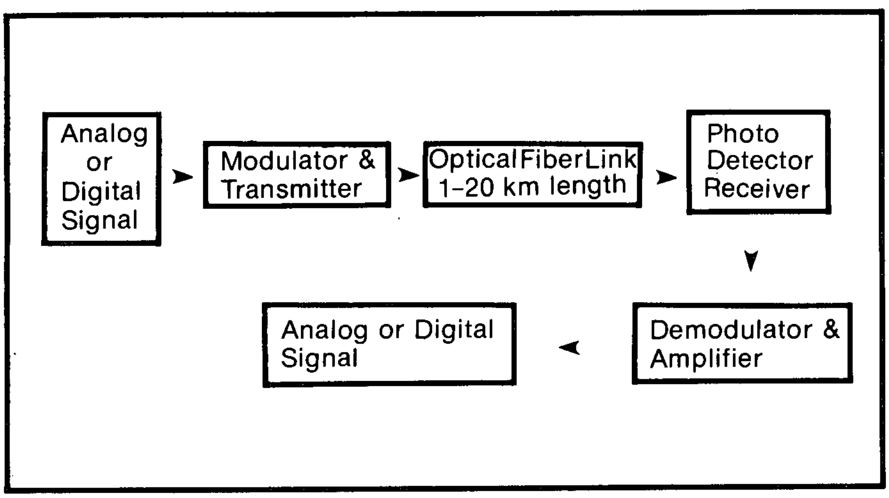

Figure 1. Block Diagram of a Fiber Optic Data Link.

Of course, this system is simplified in that optical power splitter/combiners and active repeaters are not shown. These would be necessary if multiple terminals and lengthy fibers are required. Each of the basic elements of the fiber optic systems will be discussed separately.

FIBER OPTIC CABLES

Optical fibers provide a low-loss channel for light signals; in fact, when compared to twisted wire pairs or coaxial lines, the optical fiber transmission loss is far less for signal frequencies above a few megahertz. Table 1 illustrates the comparable loss characteristics versus digital transmission rates for different transmission media. These data may be somewhat misleading in that coupling and splice losses are not included. However, these topics will be considered later.

Optical fibers are threadlike structures made of silicate glass or, less commonly, plastic. Typically, the diameter of the fiber is about 125μm, the thickness of human hair. Although glass is intrinsically a very strong and durable material, optical fibers require a protective coating. Since the typical softening temperature of glass is about 600°C and the refractive index change in temperature is about 0.0001/°C, the fiber optic cable can be operated over a temperature range exceeding

-250°C to 500°C. Generally, it is the coating material that limits the operating temperature range. As the volume of production increases, it is expected that the eventual cost of a fiber optic cable will be comparable to a pair of 22-gauge copper wires.

TRANSMISSION LINK	Loss in dB/km		
	Digital Transmission Frequency		
	1.5 Mb/s	6.3 Mb/s	45 Mb/s
26 Gauge Twisted Wire Pair	24	48	128
19 Gauge Twisted Wire Pair	10.8	21	56
RG 217/U Coaxial Cable	2.1	4.5	11
Optical Fiber (.82 μm wavelength carrier)	3.5	3.5	3.5

Table 1. Transmission Loss in dB/km at Half Bit Rate Freqency for Various Transmission Links.

The operating principle of a fiber optic cable is quite simple. It is based on a reflection of light phenomenon that occurs at an interface between media with different dielectric properties. When a light beam strikes the interface at the so-called critical angle (or at an angle of incidence that exceeds the critical angle), total reflection occurs. This critical angle occurs only when the incident medium has the greater index of refraction. By having two parallel interfaces, a light ray launched at an angle to obtain total reflection from one interface would be reflected back to the other interface in such a way as to be totally reflected again. Furthermore, if the separation of the interfaces is such that constructive interference results, the ray will propagate unattenuated, trapped between the parallel interfaces. By controlling the refractive index change at the interface and the separation of the two interfaces, it is possible to control the frequencies for which propagation will occur. This process is completely analogous to the mode propagation inside the conventional waveguide.

Step-Index Fiber. Even though optical fibers are cylindrical, the multiple reflection concept of signal propagation is still appropriate. However, the solution for the modal fields and cutoff frequencies requires the solution to Maxwell's equations in cylindrical coordinates. Generally, the cutoff frequency is expressed in terms of the so-called V number of the fiber

where:

$$V = \frac{2\pi f}{c}\sqrt{n_1^2 - n_2^2} \quad a$$

where c is the speed of light in a vacuum, a is the radius of the core (see Figure 2), and f is the frequency of the light signal.

The lowest cutoff frequency is zero and occurs for the HE_{11} (a hybrid mode), and the next lowest frequency occurs for the TE_{01}, TM_{01} modes (Transverse Electric and Magnetic modes) where V = 2.405. By a judicious choice of parameters, it is possible to design a single-mode fiber that supports only the HE_{11} mode. This is desirable in that modal delay distortion does not occur. Generally, each propagating mode has a distinct propagation velocity; when several modes are propagating, the different arrival times of the transmitted signal at the end of the fiber will result in signal distortion. Note that this dispersion is a function of the length of the fiber.

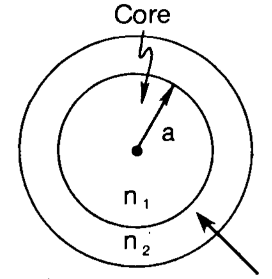

Figure 2. Cross Section of an Optic Fiber.

For the *single mode fiber* with a step change in the refractive index as shown in Figure 2, very large bandwidths are possible (up to 50 GHz/km). However, this type of fiber requires a very small core radius; for a 1.3μm (wavelength) laser source, typically, a $\leq$5μm radius is required. Fibers with these dimensions are more expensive and more difficult to handle. Also, it is more difficult to couple light into such small fibers.

A measure of the light power that can be coupled into a fiber is the numerical aperture. It is defined as

$$NA = \sqrt{n_1^2 - n_2^2} = \sin\theta$$

where θ is the maximum angle from the fiber axis from which the light can enter the fiber; i.e., it is one-half the fiber's cone acceptance angle. A typical single mode fiber would have a core radius of about 3μm, and a numerical aperture of 0.1 for operation at a wavelength of 0.83μm.

If the fiber length can be short and the bandwidth smaller, then the multimode step-index can be used. Modal delay distortion is the primary dispersion mechanism which limits the bandwidth to less than 100 MHz/km. However, much larger numerical apertures are possible with values up to about 0.5. A typical multimode step-index fiber constructed from high silica glasses would have a core radius of about 50μm and a cladding radius of about 65μm, with a numerical aperture of about 0.3.

Graded-Index Fiber. By introducing a radial variation of the refractive index in the core, the difference in propagation delays of the different excited modes is significantly reduced. This type of fiber is called the graded-index fiber. Since the index of refraction of silica can be controlled by dopants (such as GeO_2, P_2O_5, and B_2O_3), a radial variation is easily produced by a deposition process.

An optimum radial profile for the refractive index is near a parabolic contour, as shown in Figure 3. The maximum index of refraction occurs in the center of the core. Thus, the signals with a more direct propagation path spend more time in the region of high index of refraction. The higher order mode signals that suffer more reflections within the core spend more time in the region of lower index of refraction. Consequently, their propagation time delays are somewhat equalized, which, in turn, reduces the modal delay distortion.

A typical multimode graded-index fiber constructed from high silica material would have a core radius of about 25μm, a cladding radius of about 35μm, and a protective coating radius of 62.5μm. It would have a numerical aperture of about 0.2 and a bandwidth 1 GHz/km. This is a high quality fiber with excellent bandwidth and loss characteristics.

Plastic-Clad Fibers. A more economical optical fiber can be manufactured by using a plastic cladding over a silica core. The core could have a graded-index profile. However, this type of fiber has a number of limitations. It has significant losses (several dB/km), small bandwidth (typically, 20 MHz/km), and a limited temperature range.

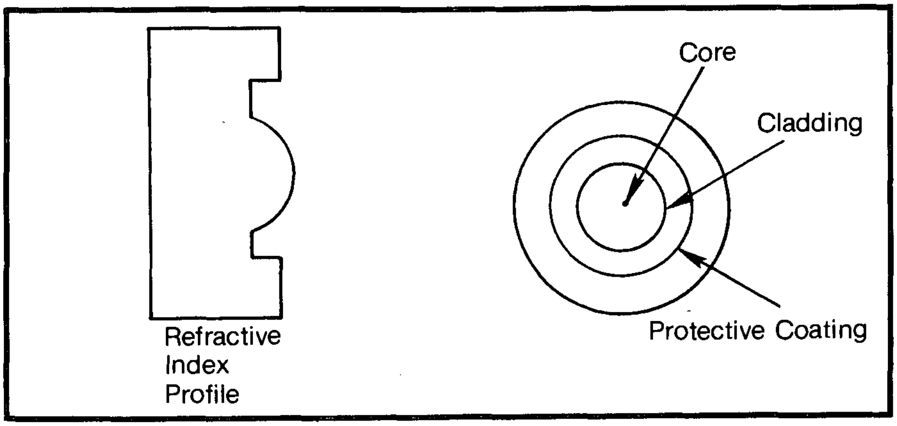

Figure 3. Illustration of a Graded-index Optic Fiber.

FIBER-OPTIC TRANSMITTERS

There are two types of optical sources generally used with fiber optic systems, semiconductor light-emitting diodes (LEDs) and solid state injection-laser diodes (ILDs). Both are dimensionally compatible with the optical fibers and emit light signals at frequencies where the fiber losses are low. Moreover, they are easy to modulate and offer reasonable reliability (mean time between failures exceeding 10^6 hrs.). Although LED's and ILD's are similar in many ways, there are notable differences and these should be considered in selecting a suitable source for an application.

The term laser is an acronym for *Light Amplification by Stimulated Emission of Radiation*. Lasers can be realized in many forms. Semiconductor lasers such as GaA1As and the InGaAsP, are the ones that are ideal for fiber optic systems. Both devices can be fabricated by using the techniques developed for integrated circuits.

A GaA1As laser can provide emissions in the wavelength region from 0.8 to 0.9μm, and InGaAsP provide wavelengths from 1.0 to 1.7μm. Both devices emit a near beam of light that has a very narrow spectral width. Since lasers are threshold devices, their outputs are proportional to the input drive curve only above threshold. Unfortunately, the threshold drive is not constant and depends upon age and temperature. Consequently, feedback control techniques are required to stabilize their operation.

A GaA1As LED can also provide radiation in the same region as the corresponding ILD. In addition, the LED output is almost linear to the drive curve, making this source suitable for analog applications. But, in contrast to the ILD, the LED sources provide a much broader radiation pattern and a much wider spectral width. Also, the LED is much slower than the ILD, making the ILD more suitable for high-speed data transmission.

Typical operating characteristics for the ILD and the LED sources are shown in Table 2.

In addition, ILDs are the sources compatible with single mode fibers. However, they are not as reliable as the LEDs and are more expensive.

OPTICAL RECEIVERS

Optical receivers are transducer devices, detecting optical signals and converting them into electrical signals. Generally, the output of the receiver-photodetector must be amplified and filtered to be usable. Today, there are two types of photodetectors used - semiconductor PIN (positive-intrinsic-negative) photodiode and the APD (avalanche photodiode) photodiode. The PIN converts one photon to one electron, whereas the APD produces a number of electrons per incident photon. Consequently, the APD is a more sensitive receiver.

A comparison of the properties of the two photoreceivers is shown in Table 3.

In addition to these properties, noise is another important consideration. When the PIN diode is combined with the FET front-end amplifier, the effective noise is dominated by the amplifier noise. On the other hand, the APD device introduces an additional noise term arising from the randomness of the avalanche process which increases with the intrinsic gain of the device. Consequently, for the optimum low-noise design, the gain must be balanced by the additional noise it introduces. Typically, the PIN detector provides greater signal-to-noise-ratio (SNR) for received powers $\leq$-20dBm, and the APD device is superior for received powers

BASIC CHARACTERISTICS	ILD	LED
Output power (mW)	1 to 10	1 to 10
Power launch into fiber (mW)	0.5 to 5	0.03 to 0.3
Spectral widths (nm)	2 to 4	15 to 60
Modulation Speed (MHz)	~1000	~100

Table 2. Comparison of the Light Emitting Diodes with Laser Diode Sources.

PROPERTY	PIN	APD
Internal Gain	0dB	20dB
Dark Currents	10^{-9} A	10^{-10} to 10^{-11} A
Sensitivity		
at 100 Mb/s	-48dBm*	-42dB
at 300 Mb/s	-41dBm*	-37dBm

*Combined with FET front-end amplifier

Table 3. Properties of the PIN and APD Photodetectors.

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$\leq$-30dBm. For an APD with a gain of 20dB, a typical range in SNR for a 4 MHz bandwidth receiver is 25dB at -55dBm to 83dB at 0dBm.

CONNECTORS AND SPLICES

Connectors and splices are inevitable in the deployment and maintenance of a fiber optic system. Recent advances now provide connectors and splicing techniques that yield very small insertion losses ($\leq$1dB). However, the precision required makes the field use of these devices difficult. Connectors and splices for single mode fibers require more attention than for graded-index types. Over the lifetime of a fiber link, it should be expected that the connector/splice losses will be the dominant losses and this should be taken into account in the system design.

FIBER OPTIC NETWORKS

Up to this point, only one-way communication links have been considered. For bidirectional communication, either two independent links are used, or a coupler configuration is incorporated with a multiplexing scheme. As an example, Figure 4 illustrates a bidirectional wavelength division multiplexing (WDM) that is analogous to frequency division multiplexing used in microwave radio and satellite systems.

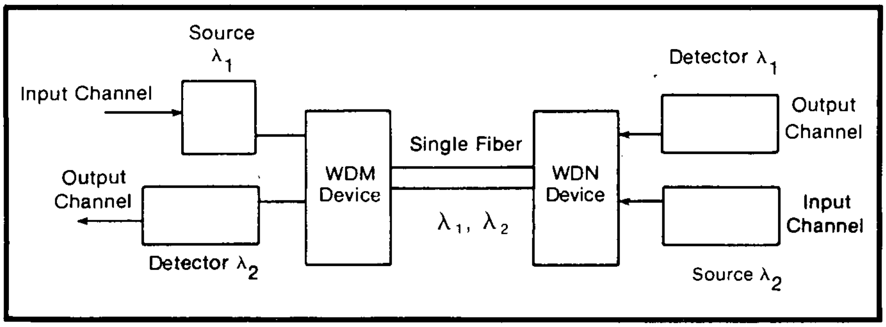

Figure 4. Block Diagram of a Wavelength Division Multiplexing Scheme.

Typical WDM devices fall into two categories - angular dispersive devices and filter-based devices. Angular dispersive devices include prisms and gratings that separate the wavelength components of the composite signal. Filter-based devices most often utilize a reflective filter consisting of a flat glass substrate upon which multiple layers of dielectric materials are deposited. By selection of appropriate indices of refraction and layer thicknesses, pass bands and reflection bands are formed. Multiple selection bands can be accomplished by series stacking of two or three filters.

Generally, multiplexing of the fiber optic signal introduces some insertion loss. For a prism device, the insertion loss is typically 1 to 3dB, with cross-talk levels between -20 and -30dB. Reflective filters are preferred over absorption-types that normally have high insertion losses.

For local area networks (LAN), a network of multiple transmitters and receivers, recent advances have made fiber optic systems a viable choice. Two types of optical buses that have been developed for LAN are the "star" configuration and the "T-coupler" configuration. These are illustrated in Figure 5.

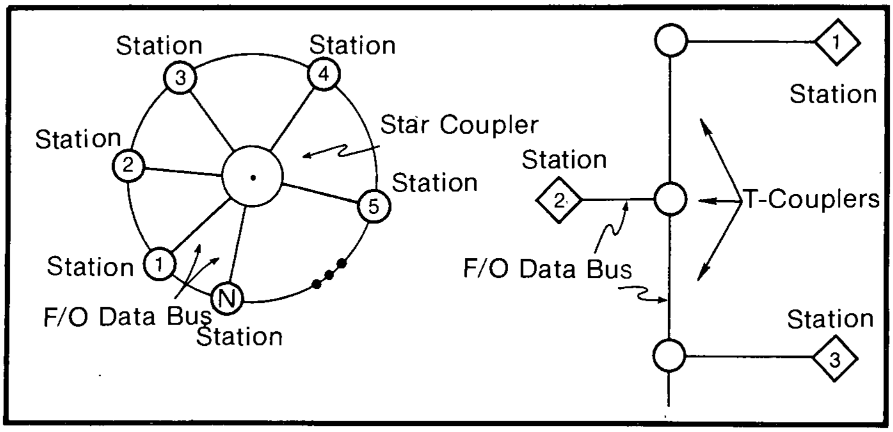

Figure 5. Block Diagram Illustrations of Two Types of Fiber Optic LANs.

APPLICATION FOR EMI/EMC PROBLEMS

Fiber optic communication links may provide a solution for problems of electromagnetic interference (EMI) and electromagnetic compatibility (EMC). Because fiber optic cables are dielectrics, their use can eliminate ground loops. However, the designer must be aware that the transmitters, receivers, repeaters, etc. are active devices and require power supply wiring. Therefore, these devices are susceptible to EMI, and should be well shielded with power lead filtering. When the fiber optic cable passes through a shield, a feed-through configuration should be used, as shown in Figure 6.

SIGNAL SECURITY

For signal propagation on copper-wire lines, external sensors can remotely detect the signals with virtually no disturbance of the signal propagation. The use of well shielded lines can prevent this problem to some extent. However, a probe inserted through the shield can defeat the shield. This indicates that the privacy of wire communication links is not high.

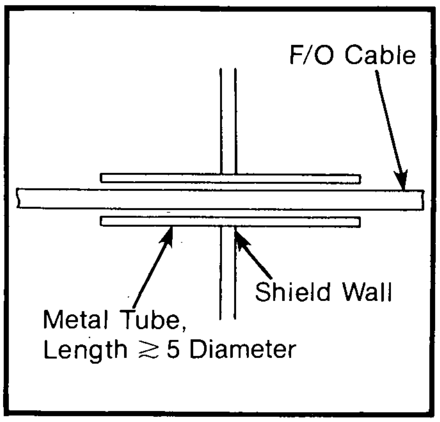

Figure 6. Fiber-Optic Feed-through Configuration.

In contrast, the fiber optic link provides good privacy of communication. In order to detect the F/O signal, the sensor must be placed within a wavelength of the core which is surrounded by the cladding. Generally, this type of tampering requires physical access, and schemes can be devised to detect it. ■

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