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NON LINEAR PROPERTIES IN MATERIALS OF OPTICAL WAVEGUIDE: NONLINEAR OPTICAL EFFECTS IN SILICON OF OPTICAL WAVEGUIDE

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ABSTRACT

Materials with nonlinear properties are a basic ingredient of any device that can efficiently switch and amplify optical signals. The need for such materials has increased with the growing use of optical frequency waves as carriers of information over long distances. A particularly desirable type of nonlinear property is bistable behavior, i.e. having two possible steady states under the same external conditions and the option of switching between them. Many proposals for achieving this type of behaviorhave been made, but they often involve a special material where bistability is found only in a narrow, well defined frequency range and above a certain intensity threshold, both of which cannot be altered. One way of possibly avoiding such limitations is to achieve bistable behavior in composite materials. Itis important to realize that optical communications is not like electronic communications. While it seemsthat light travels in a fibre much like electricity does in a wire this is very misleading. Light is an electromagnetic wave and optical fibre is a waveguide. Everything to do with transport of the signal even to simple things like coupling (joining) two fibres into one is very different from what happens inthe electronic world. The two fields (electronics and optics) while closely related employ different principles in different ways. Some people look ahead to "true" optical networks. The present research paper focus on Non Linear Properties in Materials of Opticalwaveguide: Nonlinear Optical Effects in Silicon of Optical Waveguide

INTRODUCTION

Materials with nonlinear properties are a basic ingredient of any device that can efficiently switch and amplify optical signals. The need for such materials has increased with the growing use of optical frequency waves as carriers of information over long distances. A particularly desirable type of nonlinear property is bistable behavior, i.e. having two possible steady states under the same external conditions and the option of switching between them. Many proposals for achieving this type of behavior have been made, but they often involve a special material where bistability is found only in a narrow, well defined frequency range and above a certain intensity threshold, both of which cannot be altered. One way of possibly avoiding such limitations is to achieve bistable behavior in composite materials. Intrinsic Optical Bistability (IOB) in nonlinear composite materials was first discussed by Leung in 1986 and has since then attracted growing interest due to its potential uses in materials for optical devices and to a number of interesting theoretical problems associated with it. It has been recognized that to obtain such behavior the composite medium should include a dielectric component together with a metallic or semiconducting component, the dielectric constant of which has a negative.

This requirement is essential for obtaining bistability since it can be shown that the internal electromagnetic fields in a dielectric material are uniquely determined by the incident field whenever the local dielectric constant ε is either field independent or is a monotonic increasing function of the field intensity. The employ of light to send messages is not new. Fires were used for signaling in biblical times, smoke signals have been used for thousands of years and flashing lights have been used to communicate between warships at sea since the days of Lord Nelson. The idea of using glass fibre to carry an optical communications signal originated with Alexander Graham Bell. However this idea had to wait some 80 years for better glasses and low-cost electronics for it to become useful in practical situations. Development of fibres and devices for optical communications began in the early 1960s and continues strongly today. But the real change came in the 1980s. During this decade optical communication in public communication networks developed from the status of a curiosity into being the dominant technology. Among the tens of thousands of developments and inventions that have contributed to this progress four stands out as milestones:

1. The invention of the LASER (in the late 1950's)
2. The development of low loss optical fibre (1970's)
3. The invention of the optical fibre amplifier (1980's)
4. The invention of the in-fibre Bragg grating (1990's)

The continuing development of semiconductor technology is quite fundamental but of course not specifically optical. The predominant use of optical technology is as very fast “electric wire”. Optical fibres replace electric wire in communications systems and nothing much else changes. Perhaps this is not quite fair. The very speed and quality of optical communications systems has itself predicated the development of a new type of electronic communications itself designed to be run on optical connections. ATM and SDH technologies are good examples ofthe new type of systems. It is important to realize that optical communications is not like electronic communications. While it seems that light travels in a fibre much like electricity does in a wire this is very misleading. Light is an electromagnetic wave and optical fibre is a waveguide. Everything to do with transport of the signal even to simple things like coupling (joining) two fibres into one is very different from what happens in the electronic world. Thetwo fields (electronics and optics) while closely related employ different principles in different ways. Some people look ahead to “true” optical networks. These will be networks where routing is done optically from one end-user to another without the signal ever becoming electronic. Indeed some experimental local area (LAN) and metropolitan area (MAN) networks like this have been built.

Silicon is one of the fundamental materials in the semiconductor industry. The techniques to fabricate silicon-based electronic devices are mature and cheap for mass production. With the advances in fabricating silicon electronic devices, it is now possible to fabricate silicon photonic devices using the same complimentary-metal-oxide semiconductor (CMOS) technology, especially with the help of the mature silicon- insulator (SOI) wafer technique and nano-scale photolithography. The fact that silicon photonics is truly CMOS compatible, and that silicon is transparent in the wide spectral regions extending from near to mid infrared, make it very promising for making passive and active opto-electronic components [1–9]. Recent research papers show that silicon photonics enables applications in optical interconnects, data communications, telecommunications, specialized signal processing, switched networks,imaging, displays, radio frequency/wireless photonics, electronic warfare, photonics for millimeter-wave/microwave/radio-frequency systems, laboratory-on-a-chip, medical diagnosis, spectrometer-on- a-chip, photonic sensing of chemical/biological/physical variables, sensor fusion, neural networks, bionics, analog-to-digital conversion, optical storage, optical logic, electro-optical logic, and testing of CMOS circuits. Other than linear applications, several kinds of nonlinear optical effects have also been observed using silicon waveguides in recent years. Comparing with fused silica, silicon is promising for making nonlinear optical devices for five reasons. First, silicon is transparent in the spectral region beyond 1.1 mm up to 6 mm. Second, the refractive index of silicon (around 3.5) is much larger than that of fused silica (n = 1.45). This implies a much stronger light confinement inside SOI waveguides, which is beneficial for both nonlinear light interactions and for controlling the size of optical devices. Third, the nonlinear refractive index n2 of silicon is about 200 times larger than that of silica. Fourth, the Raman gain coefficient of silicon is about 3000 times larger than that of silica, and is strongly polarization dependent. Fifth, SOI waveguides are CMOS technology compatible and enable low-cost large-scale integration. However, comparing with silica, silicon has some additional complications, such as two-photon absorption, free-carrier absorption, and free-carrier-induced change in the refractive index. Also, the polarization properties of silicon are different from silica because of its lattice structure. These aspects have been studied extensively and can be easily incorporated into our theoretical model.

This theorem is circumvented in composites where the dielectric has a ε which is a function of the electric field intensity E such that ε (E)E2 is a non-decreasing function of E , and ε of the metal is field independent and negative. The nonlinear component can exhibit either cubicor quadratic nonlinear response. The local electric field in certain regions inside such composites can be greatly amplified, in comparison with the volume averaged applied field, when the system is in the vicinity of a sharp isolated quasistatic resonance. Such resonanceshave been predicted to appear in metal dielectric composites that are either very dilute collections of similarly shaped inclusions embedded in an homogeneous host, or else have an accurately periodic microstructure These resonances can only occur when the applied field is an ac field with a frequency in the range where the dielectric coefficient of the metallic or semiconducting component has a negative real part. When carefully tuned to the vicinity of such a resonance, the bulk effective nonlinear behavior of the composite is enhanced and bistable behavior can appear, i.e. different solutions for the local field can be found thatcorrespond to the same value of applied field. Close enough to a resonance are an extreme manifestation of the so called local field effect, whereby the local electric field can be increased above its ambient or average value in the vicinity of a conducting inclusion which is embedded in a dielectric host medium. Such local field effects have been invoked in connection withoptical bistability in other systems too. The problem of calculating the bulk effective properties of nonlinear composite materials is in general quite intractable, since it involves the solution ofa nonlinear partial differential equation with coefficients that depend on position in a way that reflects the detailed micro geometry. Therefore, the analysis of the IOB is limited to a few very simple micro geometries in the quasistatic limit, namely assuming that the characteristic scale ofinhomogeneity in the system is much smaller than the wavelength and the skin depth of the local electric field. One type of these materials is dilute mixtures of small spherical, possibly multilayered, inclusions in which the local nonlinear behavior is restricted to the innermost core of the inclusion. The calculation is based on the fact that the filed in the nonlinear core is uniform when the inclusion is subject to a uniform external field. Layered micro geometries, with two or more components, can also be solved exactly since the field in the layers of each component, including the nonlinear one may also assumed to be uniform. In this review we discuss the phenomenon of IOB in composite materials of various micro geometries'. Some of these examples are exactly solvable but others can only be analyzed in an approximate way. For these cases we use a variation approach based on the fact that near a resonance bistability appears even though the nonlinear behavior is everywhere weak, thus allowing it to be treated as a small perturbation to the leading linear behavior.

In all case, it is assumed that the quasistatic limit is valid, i. e.$\nabla \times E = 0$, where E is the local electric field. This assumption is generally adequate provided that the grain sizes are all small in comparison to both the wavelength of the electromagnetic field in the surrounding medium, and the skin depth of the electromagnetic fields in the grains, so that electromagnetic scattering can be neglected.

HISTORICAL REVIEW OF PREVIOUS WORK

Past to about 1980 most communication technologies involved some type of electrical transmission mechanism. The era of electrical communications started in 1837 with the invention of the telegraph by Samuel F. II. Morse. The telegraph system used the Morse code, which represents letters and numbers by a coded series of dots and dashes. The encoded symbols were conveyed by sending short and long pulses of electricity over a copper wire at a rate of tens of pulses per second. More advanced telegraph schemes, such as the Baudot system invented in 1874, enabled the information speeds to increase to about 120 bits per second (b/s) hutz required the use of skilled operators. Shortly thereafter in 1876 Alexander Graham Bell developed a fundamentally different device that could transmit the entire voice signal in an analog form and which did not require any expertise to use. Both the telegraph and the analog voice signals were sent using a baseband transmission mode. Baseband refers to the technology in which a signal is transmitted directly over a channel. For example, this method is used on standard twisted-pair wire links running from an analog telephone to the nearest switching interface equipment. The same baseband method is used widely in optical communications. That is the optical output from a light source is turned on and off in response to the variations in voltage levels of an information-bearing electrical signal. In the ensuing years an increasingly larger portion of the electromagnetic spectrum was utilized to develop and deploy progressively more sophisticated and reliable electrical communication systems with larger capacities for conveying information from one place to another. The basic motivations behind each new system application were to improve the transmission fidelity so that fewer distortions or errors occur in the received message. to increase the data rate or capacity of a communication link so that more information can be sent, or to increase the transmission distance between in-line repeater or amplification stations so that messages can be sent farther without the need to restore the signal amplitude or fidelity periodically along its path. These activities led to the birth of a wide variety of communication systems that are based on using high-capacity long-distance terrestrial and undersea copper-based wire lines and wireless radio frequency (RF) microwave and satellite links. In these developments the basic trend for advancing the link capacity was to use increasingly higher channel frequencies, The reason for this trend is that a time-varying base band information-bearing signal may be transferred over a communication channel by superimposing it onto a sinusoidal electromagnetic wave, which is known as the carrier nave or simply carrier. At the destination the base band information signal is removed from the carrier wave and processed as desired. Since the amount of information that can be transmitted is directly related to the frequency range over which the carrier operates, increasing the carrier frequency theoretically increases the available transmission bandwidth and consequently, provides a larger information capacity.

Structures for Making SOIWaveguides

The widely used SOI waveguides may take the form of a channel waveguide, ridge waveguide, photonic-crystal waveguide, or slot waveguide, as shown in Fig. 1.1 [3]. Researchers usechannel waveguides to reduce the sidewall roughness resulting in reduced propagation losses. However for a waveguide with thickness and width of 1 mm or more the number of modes will be large. For single-mode operation in an SOI waveguide, for example at a wavelength of 1.55 mm, its dimensions need to be less than or close to 240 nm [2]. The rib waveguides are a littlebit different. Calculations show that a large rib waveguide can be single-moded if its aspect ratio satisfies the following equation:

$$\frac{a}{b} \leq 0.3 + \frac{r}{\sqrt{1-r^2}}, \qquad (1.1)$$

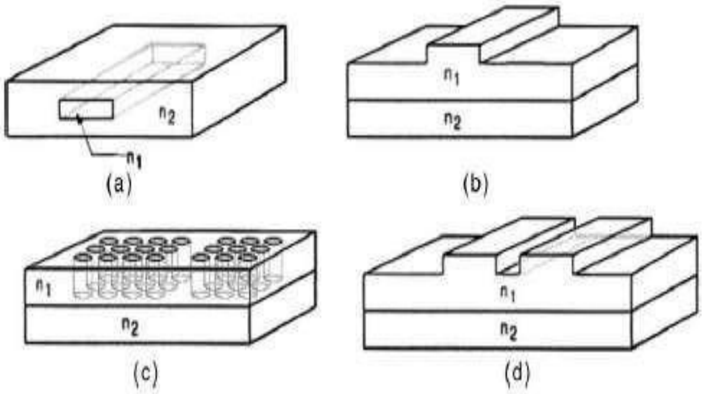

Figure 1.1: Four configurations for making waveguides in silicon: (a) Channel waveguides; (b) Rib waveguides; (c) Photonic-crystal waveguides; (d) Slot waveguides. (From Ref. [3].)

where a=b is the ratio between width and height, and (1�) is the ratio of etch thickness and waveguide height. For a typical ridge waveguide where r = 0:5, the waveguide is single-mode as long as a=b<0:96. A reasonable set of dimensions will be b=400 nm, a =385 nm. There are advantages of using rib waveguides. First, free carriers dissipate faster into the wings of the waveguide, which reduces the free-carrier effects. Second, a p-i-n structure with metal contacts is easily fabricated using this structure. A photonic-crystal waveguide is another option for making SOI waveguides. The refractive indices of the left and right sides of the cladding in Fig. 1.1(c) can be flexibly engineered by varying the diameter of the holes and the lattice constants. The disadvantage is a high propagation loss due to the roughness of sidewalls. Recently, the slot waveguide has been proposed and fabricated as another candidate for silicon photonics [3, 10, 11].

Low-loss SOIWaveguide Manufacturing

Silicon waveguides have great potential for use as nonlinear optical devices. However, two manufacturing challenges are high propagation losses and high fiber-to-waveguide coupling losses [3, 4]. The main origin of the propagation loss in a silicon submicron waveguide is scattering at its sidewalls. By reducing the sidewall roughness, scattering losses can be reduced significantly. Lithography and etching are the keys to making a smooth silicon pattern. Researchers employ electron-beam lithography and plasma etching for the silicon submicron- size waveguides. A relatively low propagation loss of 2.8 dB/cm for a 400 nm _ 200 nm corehas been achieved [4]. An oxidation procedure can further improve the smoothness of sidewalls.For example, losses in channel waveguides typically range from 0.2 to 5 dB/cm. Losses in photonic crystal and slot waveguides are even higher. Rib waveguides have typically lower losses of less than 0.1 dB/cm due to their larger dimensions [3].

The most difficult problem with silicon waveguides is how to connect them to external circuits, where optical fibers are generally used. An SOI waveguide is very small, and its core is about 500 nm wide. On the other hand, the fundamental mode of single mode fiber is about 9 mm in diameter. Moreover, the air gap between the facets causes interference and puts some wavelength dependent characteristics on top of the original spectra [4]. The coupling element can be either a microscope objective lens or a tapered fiber lens. The latter is widely used nowadays for convenience. The waveguide itself can be either un-tapered, or tapered with normal tapering or inverse tapering [3]. The advantage of inverse tapering is that the modeindex at the narrow tip is much smaller than that of bulk silicon and the effective mode area is larger than that of the silicon region, both of which offer better mode matching and more efficient coupling. The disadvantages are that the coupling is very sensitive to environmental vibrations, and also a bigger portion of the optical field is propagating along the sidewalls sothat scattering loss from the sidewalls is huge. Since the coupling of inverse tapering is not as stable as normal tapering, in our experiments, we used the waveguides with normal taperings.

Low-loss, low-reflection, mode-field converter can be used to solve the coupling problem even better. The converter has a silicon adiabatic taper that gradually becomes thinner toward the end, and a second low-index waveguide covers the taper. Coupling losses can be made as low as 0.5 dB per connection with this approach [4]. In our preliminary trial, mode-field converters improved the couplings significantly by reducing the coupling loss from around 20 dB to around 8 dB.

Characteristic optical physics in the solid state

The previous section has given a brief overview of the optical properties of several different classes of solid state materials. It is natural to ask whether any of these properties are exclusive to the solid state. In other words, how do the optical properties of a solid differ from those of its constituent atoms or molecules? This question is essentially the same as asking what thedifference is between solid state and atomic or molecular physics. The answer clearly depends on the type of material that we are considering. In some materials there will be a whole range of new effects associated with the solid state, while with others, the differences may not be so great. Molecular materials are an example of the second type. We would expect the absorption spectra of a solid film and that of an forces between the molecules in the condensed phase are relatively weak compared to the forces within the molecule itself. The appeal of the solid statein this case is the high number density of molecules that are present, and the possibility of incorporating them into solid state electronic devices. With many other materials, however, there will be substantial differences between the condensed phase and the gaseous or liquid state. It is obviously not possible to give a full catalogue of these effects in an introductory chapter such as this one. Instead, we highlight here five aspects that make the physics of thesolid state interesting and different, namely

- Crystal symmetry
- Electronic bands
- Vibronic bands
- The density of states
- Delocalized states and collective excitations.

There are many others, of course, but these themes occur over and over again and are therefore worth considering briefly in themselves before we start going into the details.

Nonlinear Applications

Silicon is also promising for making nonlinear optical devices, because of its high Kerr and Raman nonlinearities [9]. Nonlinear applications in SOI waveguides are based on self-phase modulation (SPM), cross-phase modulation (XPM), stimulated Raman scattering (SRS), and four wave mixing (FWM). In addition, two-photon absorption (TPA), free-carrier absorption (FCA) and free-carrier induced dispersion (FCD) should also be taken into consideration in silicon. These are the research areas this thesis is going to focus on.

Self-phase modulation is a very efficient process in SOI waveguides [21]. SPMinduced spectral broadening is found to be significant at coupled peak powers of even a few tens of milli-watts. In Refs. [22, 23], a twofold increase in the spectral width was observed. XPM was used to demonstrate strong modulation instability in silicon waveguides in the pump-probe configuration [24]. The result showed modulation instability gain spectrum that is 2 to 3 orders of magnitude larger than that achieved in optical fibers [24]. XPM in a silicon Mach-Zehnder interferometer was shown to work as an optical modulator. The dependence of XPM on walk- off was also observed experimentally [25]. Raman amplification in an SOI waveguide is promising because the Raman gain peak is about 3000 times stronger than in silica fibers. Using stimulated Raman scattering, many nonlinear optical functions have been demonstrated, including Raman amplification [26], optical modulation [32] and wavelength conversion [33]. Net Raman gain was observed by several groups [26, 27]. Silicon Raman lasers [28–30] and a cascaded silicon Raman laser [31] have also been demonstrated. They provide the ability to generate coherent light in wavelength regions that are not easily accessible with other conventional types of lasers. Four wave mixing is promising for all-optical signal processing, and has been studied widely [34–39]. Applications of FWM include wavelength conversion [34,35], parametric amplification [36,37] and photon-pair generation [38,39]. Kuo et al.demonstrated wavelength conversion at 40 Gb/s data rate in silicon waveguides [35]. Net gain from FWM is not promising when CW pumps are used to pump a signal in an SOI waveguide because of the effect of free-carrier absorption. However, net gain in the case of pulsed pumpsis achievable [37]. Lin et al. even proposed to achieve highly tunable optical parametric oscillation using silicon micro-resonators [40]. The pump was chosen to beyond 2.2 mm to get around the issues of two-photon absorption and the consequent free-carrier effects. The carrier- induced plasma-dispersion effect makes use of an electric field applied across the waveguide [41]. An alternative way to generate free carriers is through photon-absorption process using optical pumps [42–44]. This is faster than using external electrical field because the free carriers are generated locally. Applications based on this effect include carrier-induced optical bistability in silicon ring resonators [42], all-optical switching [43], optical modulation [41,44], wavelength conversion [45], and silicon photonic memory [46, 47].

RESEARCH METHODOLOGY

Methods for Calculating Waveguide Modes

It is important to know the modes and dispersion of an SOI waveguide in order to carry out the research on its optical nonlinear properties. The calculation of dispersion reduces to the calculation of mode index since nth order dispersion is related to the nth order derivative of the mode index. And the mode profile can also be calculated if the mode index is known [53]. There are many ways to calculate the mode index. One way is to solve the two Maxwell curl equations in the frequency domain using the method called Finite Difference in Frequency Domain (FDFD) [60]. There are free software packages available online. For example Optical Modesolver is a free FDFD simulation software package developed at the University of Maryland [61] that solves the mode indices and mode profiles directly. A second method is to solve the Maxwell equations in the frequency domain using the method called Finite Element in Frequency Domain (FEFD) [62]. The third method is the finite-difference Beam Propagation Method (BPM) that solves the scalar Helmholtz equations [62], which is also readily extendableto the vector form to include both of the TE and TM modes. Rsoft’s BeamProp package [63] is such an example. The fourth one is the effective index method (EIM) [53]. The EIM treats a rectangular waveguide as two one-dimensional waveguides that are placed vertically to each other, where the index of the core region of the second waveguide takes the value of the calculated effective mode index of the first waveguide. This method is applicable for waveguides whose one dimension is larger than the other dimension. In the case of the rib waveguides that we are interested in, it is still acceptable to use the EIM. In the case of waveguides whose two dimensions are comparable to each other, an option is to treat the waveguide as a two-dimensional rectangular waveguide [64]. These will be discussed in more detail later in this chapter. Although many methods can be used to calculate the modes and dispersion of an SOI waveguide, in this chapter we only discuss three of them in detail: FDFD, BPM, and EIM. We treat FDFD method as the most accurate one, and compare the results using the other two methods with those obtained using FDFD to discuss their accuracy. The issue of time consumption is another factor we will discuss later in this chapter.

OBJECTIVE OF RESEARCH

This research is intended to provide a comprehensive study of the optical properties of SOI waveguides with an emphasis on nonlinear properties, including a theoretical model of nonlinear light-material interaction covering both electronic and Raman responses, coupling loss and propagation loss measurements, mode calculations, dispersion analysis and dispersion tailoring, self-phase modulation, two-photon absorption, free-carrier absorption, free-carrierinduced index change, influence of pulse trains with high repetition rate, continuous spectral blue shift, super continuum generation, cross-phase modulation, birefringence and nonlinear polarization rotation. The basic objects of research are-

- to improve the transmission fidelity so that fewer distortions or errors occur in the received message.
- to increase the data rate or capacity of a communication link so that more information can be sent, or
- to increase the transmission distance between in-line repeater or amplification stations so that messages can be sent farther without the need to restore the signal amplitude or fidelity periodically along its path.

SCOPE OF RESEARCH

The technical breakthrough for optical fiber communications started in 1970 when researchers at Corning demonstrated the feasibility of producing a glass fiber having an optical power loss that was low enough for a practical transmission link. As research progressed, it became clear that many complex problems made it extremely difficult to extend the carrier concept for achieving a super broadband optical communication link. Nevertheless, the unique properties of optical fibers gave them a number of performance advantages compared to copper wires, so that optical links operating in a simple on-off keyed base band mode were attractive applications.The first installed optical fiber links which appeared in the late 1970s were used for transmittingtelephony signals at about 6 Mb/s over distances of around 10 km. As research and developmentprogressed, the sophistication and capabilities of these systems increased rapidly during the 1980s to create links carrying aggregated data rates beyond terabits per second over distances ofhundreds of kilometers without the need to restore signal fidelity along the path length. Starting in the 1990s there was a burgeoning demand on communication-network assets for bandwidth- hungry services such as database queries, home shopping, and high-definition interactive video, remote education, Tele medicine and c-health, high-resolution editing of home videos, bogging, and large-scale high-capacity c-science and Grid computing. This demand was fueled by the rapid proliferation of persona) computers (PCs) coupled with a phenomenal increase in their storage capacity and processing capabilities. (He widespread availability and continuous expansion of the Internet, and an extensive choice of remotely accessible programs and information databases. To handle the cover-increasing demand for high bandwidth services from ranging from home-based PC users to large businesses and research organizations. Telecommunication companies worldwide greatly enhanced the capacity of fiber lines by adding more independent signal-carrying wavelengths on individual fibers and increasing the transmission speed of information being carried by each wavelength.

CONCLUSION

System designers must know the characteristics of each piece of the fiber LAN puzzle in order to understand the whole. Although fiber modal bandwidth is a critical factor, it is not the only one. Transmitter and receiver characteristics are as important as modal bandwidth in determining link length and data rate. Also, as requirements change, so must the system. In the past, those changes have come about through improved transmitters and receivers. As these devices are reaching their limits, we must rely more on fiber capability. Data Link Performance Limitations by Transmission Medium In terms of performance, data links can be either attenuation limited or bandwidth limited meaning link data rate and length are constrained to ensure proper system operation. (Historically, systems have flip-flopped between being attenuation limited and being bandwidth limited.) In the attenuation limiting case, power losses associated with signal propagation are the constraining factor. With bandwidth limited operation, signal distortion, which increases with data rate and link length, is the constraining factor. It is important to distinguish between the terms “bandwidth limited” and “limited bandwidth.” Multimode fiber offers virtually unlimited bandwidth. In discussions of LAN data links, however, it is technically accurate to speak of fiber as bandwidth limited. This is because as data rate and link length increase, signals are distorted, creating an unacceptable level of bit errors before they are attenuated beyond detection. With attenuation in multimode glass fiber extremely small (less than 3 dB/km at 850 nm to less than 0.7 dB/km at 1300 nm) limited bandwidth conditions occur with greater frequency with shorter data links. For example, most data links are shorter than 500 meters, yielding an effective attenuation level of<1.5 dB a level not critical for the successful operation of these links. In contrast, copper-based systems are limited by a combination of attenuation and crosstalk. For standard Category S unshielded twisted pair (LTTP) the crossover between attenuation and crosstalk occurs at 155 MHz, the point at which the signal coupled onto one conductor pair by an adjacent conductor pair is attenuated to the same degree as the original transmitted signal. In other words, the noise signal is as strong as the information signal, and proper operation is impossible.

FUTURE SCOPE

The uses of waveguides for transmitting signals were known even before the term was coined. The phenomenon of sound waves guided through a taut wire have been known for a long time, as well as sound through a hollow pipe such as a cave or medical stethoscope. Other uses of waveguides are in transmitting power between the components of a system such as radio, radar or optical devices. Waveguides are the fundamental principle of guided wave testing (GWT), one of the many methods of non-destructive evaluation. Specific thrust is of research for further research:

- Optical fibers transmit light and signals for long distances and with a high signal rate.
- In a microwave oven a waveguide leads power from the magnetron where waves are formed to the cooking chamber.
- In radar, a waveguide leads waves to the antenna, where their impedance needs to be matched for efficient power transmission.
- A waveguide called stripline can be created on a printed circuit board, and is used to transmit microwave signals on the board. This type of waveguide is very cheap to manufacture and has small dimensions which fit inside printed circuit boards.
- Waveguides are used in scientific instruments to measure optical, acoustic and elastic properties of materials and objects. The waveguide can be put in contact with the specimen (as in a Medical ultra sonography), in which case the waveguide ensures that the power of the testing wave is conserved, or the specimen may be put inside the waveguide (as in a dielectric constant measurement), so that smaller objects can betested and the accuracy is better.

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