ANALOG TO DIGITAL CONVERSION USING FIBEROPTIC INTERFEROMETRY AND BY DETECTING ELECTRO OPTICALLY MODIFIED POLARIZED LIGHT

by

GARY THOMAS FINA

BS (Physics), BA (Mathematics) KANSAS STATE UNIVERSITY
May, 1973

MS (Physics) UNIVERSITY OF ILLINOIS
at URBANA-CHAMPAIGN, January, 1975

A MASTER'S THESIS

submitted in partial fulfillment
of the requirements for the degree

MASTER OF SCIENCE

Department of Electrical and Computer Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1989

Approved by:

Donald H Lenhert
Major Professor

ACKNOWLEDGEMENTS

The research effort described herein was sponsored in part by the Base and Installation Security Systems Program Office, Electronics Systems Division of the Air Force Systems Command, Hanscom Air Force Base, MA 01731 through the Engineering Division 5238, Sandia National Laboratories, Albuquerque, New Mexico.

Steve Draving, Kenton Harbour and I began our investigation of analog to digital conversion methods in May, 1985. Kenton and I investigated a switched capacitor circuit for use in an A/D converter. At this time I approached Professor M.S.P. Lucas with the germ of my idea that interferometric methods might be used to do analog to digital conversion. Somewhat later I also proposed that the Pockels Electrooptic effect would offer the possibility of very high speed conversion. These ideas formed the basis of the ensuing investigation.

A full list with proper thanks to all with whom I have discussed this research is nontrivial. Prominent among them are Professors Donald H. Lenhert and M.S.P. Lucas, whose advice and encouragment have been invaluable. Dr. Lenhert became my major advisor when Dr. Lucas went on leave for a year. Professor Kenneth Carpenter, an engineer with a Doctorate in physics has been an excellent consultant. Dr. Christopher M. Sorensen, a Professor with

the KSU Physics Department, deserves thanks for completing my advisory committee, and for his efforts as instructor of the courses in Laser Physics and Optics, in which I enrolled primarily because he was teaching them. His review of that body of knowledge was enjoyable and quite worthwhile.

Mr. Michael J. Pankratz deserves my thanks for the invaluable help he gave me in using the Hewlett-Packard 'PIGLET2' graphics system to produce most of the drawings contained herein. This saved me a rather significant amount of time and effort.

Dr. Douglas D. Rhoads, a biologist at Kansas State University, who has been a friend for several years, helped me complete my work by drawing figures 5, 6, and 8 from sketches which I sent him from my home in Rowlett, Texas. He deserves my sincerest thanks for sitting at his computer for several hours, preparing graphics files which I could use to print the figures. Without his help I would probably still be working on the completion of this Thesis.

Contents

Figures

ANALOG TO DIGITAL CONVERSION USING FIBEROPTIC INTERFEROMETRY AND BY DETECTING ELECTRO OPTICALLY MODIFIED POLARIZED LIGHT

Introduction

Results of allowing someone versed in Physics to consider analog to digital conversion are described herein. The ideas presented were conceived by this author in response to his desire to try developing something new, and to the encouragement of Professors M.S.P. Lucas, and Donald H. Lenhert.

Interferometers exist in various configurations, but they all share the same physical principles of operation. If two beams of light, having the same frequency (they must be longitudinally coherent for more than the maximum difference in length between the two paths which they traverse) are combined, they will exhibit interference phenomena characteristic of their wave nature. The most intelligent means of preparing two beams of the same frequency is to generate a single beam and split it into two parts; as nearly equal in intensity as is possible. Two basic methods for doing this are referred to as 'wavefront splitting' and 'amplitude splitting'. Then there exist various means of causing the optical paths traversed by the two beams to be of different lengths.

So it is possible to make the interference pattern (relative to some arbitrary fixed point of reference) vary periodically from brightness maxima through minima. The path length change required to cause one variation from a light (maximum) fringe to a dark (minimum) fringe is equal to one-half wavelength of the light being used. This is quite small, and also exceedingly precise. Detection of the fringes is very easy via photodiodes, etc.. Counting of the fringes is an intrinsically digital process. The interferometer becomes the actual analog-to-digital conversion device.

The challenge is to cause some type of interferometric set-up to vary its (actual or effective) path length in response to some analog signal; pressure, sound, an electric field, or magnetic field, for example. The process of counting fringes requires that a count as high as 32,768 must be performed (for 15 bit resolution) within the time constraints of one conversion. This fact coupled with the 34 Mhz upper limit for low-power, high-speed CMOS counters, gives a practical upper limit for the sampling rate of such a device of a few kilohertz. Naturally, if power usage is not a limitation, emitter coupled logic or gallium arsenide devices can do better by a factor of at least ten. Power usage is a constraint here; the desire is to minimize power used, and hence the intended reliance is on CMOS devices. The Motorola 68HC11 would be the choice for a control microprocessor.

There also exists a possibility of 'track-and-hold' operation; which could be done via subtracting the previous input from the current one and cumulating the digitized differences (the Analog-Digital Conversion Handbook discusses such operation for A/D converters in chapter 18).[1] This would reduce the counting to be done for each conversion, and hence the power. Correction for nonlinearities would be best done by way of a ROM look-up table based scheme.

One means for causing the path length variation to occur is based on the variation of a material's index of refraction as a function of the electric field experienced by the material. This is known as an 'Electrooptic Effect'. It is described in the texts by Haus, and Hecht.[2,3] Research into the fabrication of crystalline fibers is being actively pursued, as noted by authors like Cherin and Yariv, and in periodicals such as Laser Focus.[4,5,6] Naturally this is likely to result in fibers with a high degree of optical activity.

For the present another possibility exists: the process of 'poling' (letting the material cool in the presence of fairly strong electric fields, such as in the manufacture of electrets) can cause a noncrystalline material to have (both piezo-) and optoelectric properties. Liquids can manifest a second order electrooptic effect (the Kerr effect) when in the presence of an electric field. The liquid then behaves as if it has crystalline properties, with respect to optical propagation, with an optic axis defined by the electric field; see Yariv, page 220-238.[5]

Essentially what happens is that the various molecular configurations that interact with electromagnetic fields to produce these effects, are aligned by the external field, and as such their individual contributions are constructively additive, as opposed to cancelling one another when randomly aligned. This is true because of the physical processes giving rise to these effects. And if the material thus prepared is a glass (effectively a supercooled liquid), its molecular alignment can be expected to persist. Hecht mentions the connection between piezoelectric and optoelectric effects.[3] Of the 32 crystal symmetry classes, 20 of them are 'noncentrosymmetric', they have no center of symmetry for a unit crystal cell (see Hecht, or Yariv, or Haus).[3,5,2] Because of this fact, an externally applied electric field will not have the same effect on the crystal for all possible field directions. Application of an external field distorts the electronic structure of the crystal, which gives rise to different interaction probabilities for electromagnetic waves propagating in different directions within the crystal. In particular, the index of refraction will no longer be the same in every direction, and the differences between the index in one direction versus another is a function of the applied electric field strength. So the effect may be varied by external agents; electric fields in particular.

There is another effect whose physics is closely related to that of an electric field dependent index of refraction. It exists in liquids and solids with molecular structures that do not possess mirror symmetry. In particular a helix does not have mirror symmetry. Rather, helices exist either as right- or left-handed objects. This classification is in exact analogy with the fact that a mirror image of one's right hand is a left hand, and vice-versa. Hecht gives a very good introductory discussion of the effect to be described here (section 8.10, page 255, also see page 309ff).[3] The principal idea is that, since photon interaction with such objects results in rotation of their planes of polarization, and since the effect can be used in conjunction with a simple polarizing filter to analyze the resultant rotation, a series of periodic brightness maxima and minima can be produced if a polarizing filter is used to analyze the results. These are not interference fringes, but are detectable in the same fashion as fringes are, and can therefore be counted. The rotation effect is very likely to be modifiable with an electric field. Refer first to Hecht and then to Haus for an introduction and a more advanced treatment of these electrooptic effects. As one might reasonably expect, the amount of variation in optical properties which an external electric field can cause, is dependent on the ratio of the applied electric field intensity to that of the interatomic electric fields which bind the electrons and ions together. Yariv mentions this on page 223, and also gives an order of magnitude for the interatomic electric field intensity, namely 10^8 volts per centimeter.[5]

Given a typical fiber diameter of 140 microns, as compared to the centimeter-sized dimensions of conventional electrooptic devices, one can expect the effects to be larger in such a fiber. In addition, the possibility of using very long path lengths with optical fibers can be expected to yield a still larger overall effect. If the effect is induced in optical fibers, whose diameters are usually made near 140 microns or so, only a rather small voltage would be needed across this distance to produce rather large field intensities, hence large numbers of rotations for counting (see Appendix A).

Additionally, a related electrooptic effect can be used to cause the plane of polarization of an electromagnetic wave to be rotated through reasonably large angles (up to 180 degrees,at least) in response to an applied voltage. The effect used on a beam of light launched with its plane of polarization oriented in a specific way is known as the 'Pockels effect' in crystals.[3] It is exceedingly fast, since the physical entities being rotated are nearly massless. So the rotation can be extremely fast. In fact electrooptic devices are capable of performing in the 'D.C. to 30 GHz' domain.[3] Clearly such a device could form the basis of a very fast ADC. Also very fast is the effect known as Faraday rotation. It is a magnetooptic polarization rotating effect and would be very useful for direct sensing of currents instead of voltages.[3] Following is a brief discussion of interferometers and optical fiber technology, then descriptions of some possible implementations of the above ideas.

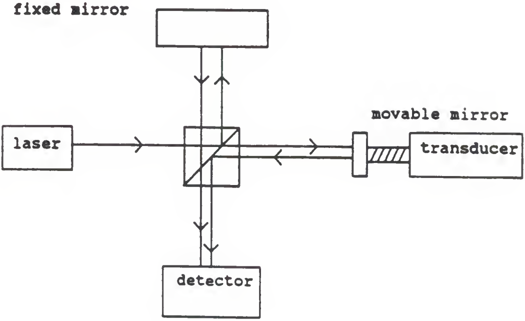
Interferometers and Interferometry

Many excellent texts exist wherein detailed presentations of interferometers and analyses thereof are done. Among these is one of the standard optics references: Max Born and Emil Wolf, Principles of Optics .[7] The reader is referred to this source for any additional detail desired. There exists at least one handbook which gives quick reference for fiberoptic interferometers.[8] The principle underlying the operation of any interferometer is that light has wavelike properties. The majority of analyses of interferometers concentrate on the wave nature of light and do not dwell upon its particle nature. Lightwaves are vector waves. The electric and magnetic vectors of a stream of photons are of critical import to anyone who would try to cause two light beams to interfere with each other. Usually (for linear media) if the electric vector is specified, the magnetic vector is also determined, and hence it is ignored in most analyses of interferometry. The same convention is used herein. Following are diagrams of three common interferometers. They are shown in their classical forms and then in their more recent optical fiber implementations (Figure 1, Figure 2, and Figure 3).

Michelson Interferometer

The Michelson interferometer (Figure 1) is a classic device, originated to demonstrate and measure interference phenomena (see Born and Wolf, p 300ff, and the Fiber Optic Technology Handbook, p 4-1ff, for detailed treatment). It is possible to fix one path length for the light and vary the second. While the path length is varied through one wavelength, the interference pattern undergoes one complete sinusoidal variation. This results in the appearance at the detector of both a brightness maximum and a minimum. If the light source is coherent and if the two beams are of equal intensity the minimum will be of zero intensity. This idealized situation can actually be rather closely approached in practice. If one uses the usual definition of 'fringe visibility' (see Hecht page 519, section 12.2), namely the ratio, $V = (I_{max} - I_{min}) / (I_{max} + I_{min})$, values of $V = .9$ are readily obtainable.

CLASSICAL CONFIGURATION



(rays deliberately displaced for clarity)

FIBEROPTIC EQUIVALENT

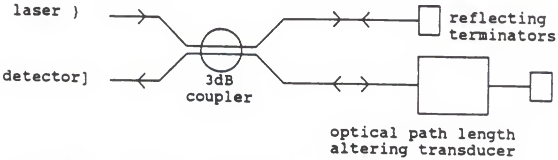
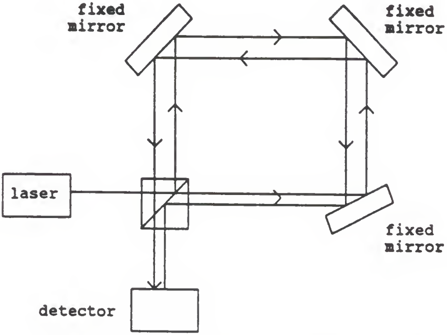


Figure 1 The Michelson Interferometer

Sagnac Interferometer

The Sagnac interferometer has been used to implement devices known as 'ring laser gyroscopes' (see the Fiber Optic Technology Handbook, p 4-2ff, for detailed treatment). In its case the two beams are traveling in opposite directions. And as light propagates in a fixed reference frame, regardless of whether or not the interferometer's components are rotating, the device will sense the motion of the interferometer relative to the fixed frame in which the light propogates. By timing/counting the passage of fringes across a photodetector, rotational rates from thousands of revolutions per second down to a few millidegrees per month can be measured in an intrinsically digital manner.

CLASSICAL CONFIGURATION (used in ring laser gyroscopes)



(rays deliberately displaced for clarity)

FIBEROPTIC EQUIVALENT

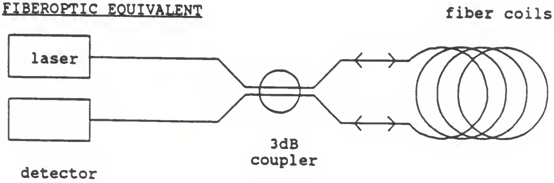


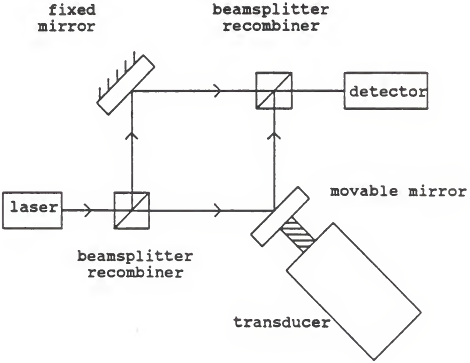
Figure 2 The Sagnac Interferometer

Mach-Zender Interferometer

The Mach-Zender interferometer is of interest here because of its fiber optic implementation, and because of the existence of electrooptic effects (see Born and Wolf, p 312ff, and the Fiber Optic Sensor Technology Handbook, p 4-1ff, for detailed treatment). Since the anticipated light source is a semiconductor laser diode, careful account of the coherence length available from such a device must be taken. If the difference between the optical path lengths of the two interferometer 'arms' exceeds or even approaches the coherence length of the light, the visibility of interference fringes will be very poor. So a reference fiber as long as the sensor fiber must be used. An error in length of a meter will not be too serious, as the coherence length of a diode laser is usually about three meters. Once a few important notes regarding optical fibers are made, the possibility of doing analog to digital conversion with a Mach-Zender interferometric technique can be considered.

CLASSICAL CONFIGURATION

excellent coherence length
match without compensators



FIBEROPTIC EQUIVALENT

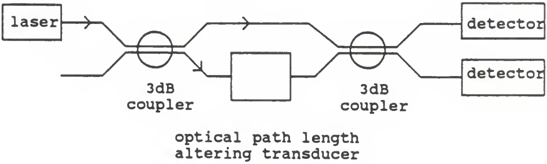


Figure 3 The Mach-Zender Interferometer

Optical Fibers and Associated Considerations

The phenomenon of total internal reflection has been known since Snell's law was discovered. It is true that for a light ray incident at an interface between two media having unequal indices of refraction, the angles of incidence and refraction are related by the equation: n_1 x Sine(i) = n_2 x Sine(r). The angles of incidence (i), and reflection (r) are defined relative to the normal to the surface. If one now considers what happens when the incident ray is within the medium of higher refractive index, and is at an incidence angle such that the angle of refraction is 90^o, one gets the notion that for angles of incidence greater than this 'critical angle of incidence', something other than refraction into the medium of lesser index will occur. Then one can consider what happens when the angle of incidence is very near 90^o. A complete treatment of this problem can be found in Hecht or Born & Wolf (page 104ff, and page 47ff, respectively).[3,7] The result is that for angles of incidence greater than the critical angle, the ray is reflected internally. The critical angle is given by: i_c = Arcsine(n_2/n_1). Clearly if one considers fabricating a long thin piece of transparent medium, such as glass, with a rectangular cross-section for simplicity; it should be obvious that certain light rays will remain within the medium if they enter an end at an angle which would result in total internal reflection at the interfaces between the medium and its surroundings (usually taken as air; n = 1.00033). Rays which enter with an initial angle nearer to the normal to the boundaries will be refracted out of the 'fiber'.

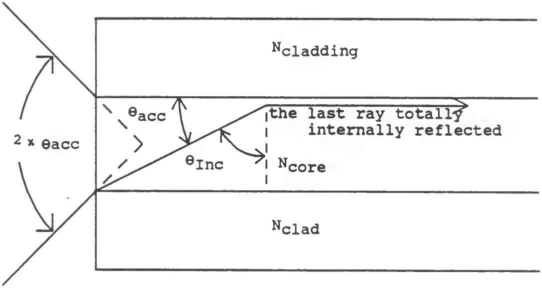
Fiber Modes / Analysis Thereof

It should also be clear that there exists a range of angles for which the entrant ray will be 'accepted' and remain within the fiber. Inasmuch as fibers of circular cross-section are much easier to produce, analysis should proceed to that kind of fiber as soon as the initial concepts are obtained. Very similar physical reasoning applies to circular fibers when they are viewed in longitudinal cross-section, and when the fiber's diameter is much larger than that of the wavelengths of light which it is to conduct. Such is not always the case, but it serves well to introduce the more difficult problem of analyzing 'singlemode' fibers, whose diameters are only a little larger than the wavelengths they conduct, and sometimes smaller. These are crucial to the success of fiberoptic interferometers. They are discussed below. One of the more important characteristic parameters of optical fibers is the 'angle of acceptance' associated with each type of fiber. This angle depends upon the physical characteristics of the fiber and the material of which it is made. Analysis via Snell's law is used to determine the acceptance angle, and fibers are usually described not by the angle but instead by their 'numerical aperture', which is the sine of the 'half angle of acceptance' (times the index of refraction of the medium in which the fiber is immersed, usually air for which the index is about 1.00033, and is taken as 1.0). This is easiest to understand if a drawing of the situation is considered (Figure 4)

NUMERICAL APERTURE

(obtained via geometric ray analysis)

$$\text{Sine}[\ \theta_{acc}\ ] = \text{N.A.} = \text{Sqrt}[\ N^2_{core} - N^2_{clad}\ ]$$



Use Snell's Law

$$N_{Inc}\ \text{Sine}[\ \theta_{Inc}\ ] = N_{Refr}\ \text{Sine}[\ \theta_{Refr}\ ]$$

1: At Core Internal Reflection Point; with $\theta_{Refr} = 90^o$ to get θ_{Inc} ... Then get θ_{acc}

2: At Point Of Entry; with $\theta_{Refr} = \theta_{acc}$ to get the angle of acceptance

Figure 4 Illustration of angle of acceptance for optical fibers

That there exist several possible paths for light rays to follow within a fiber is clear from Figure 4. This situation is sometimes unimportant. But it can cause extreme difficulty for some applications. The fact that there are several paths means that, unless they are all of identical length (or effective length, if the medium's index of refraction is not constant along all paths), the transit time for a photon will not be invariant from path to path. A pulse of light will be (wavefront) split into as many different fractions as there are modes of propagation for it to follow. The extreme variation between path lengths for these different modes can be as much as a factor of 1000 times the shortest path length (consult Marceuse or Cherin for an explanation of this phenomenon).[9,4] The result of this is that a pulse of some initially fixed duration will be 'stretched' to one having a duration at least as long as the difference in propagation times for the shortest versus the longest mode. This means that such a multimode fiber will degrade the effective bandwidth of the pulse generating device by at least the path length ratio mentioned above. Bandwidths of optical pulse generation mechanisms are usually in the Gigahertz range. If possible, one would certainly want to correct the path length variation problem of a multimode fiber in order to make the most use of the available bandwidth. Various heuristic analyses can be applied to provide perspective and physical intuition for the student of this problem. For instance, it can be observed how the various paths derive their existence.

Classically the wavelength is taken as zero. Thus the various angles of acceptance, must be continuously variable from maximum to minimum. So there may exist an infinite number of possible paths. One could choose any path length between minimum and maximum, and find its corresponding path. When the light is realized to have a small but finite wavelength, it follows that the assumption of an infinitude of paths is not reasonable. Rather there should be a very large number of such paths for a fiber whose diameter is much larger than the wavelength of the light it will conduct. The exact number of such paths is not easy to derive, especially when the fiber's index of refraction is continuously variable rather than a constant or a step function. The actual methodology used is one developed by three physicists who were interested in extending 'particle-in-a-box' calculations of quantum mechanics to more physically realistic situations where the potential barrier to be penetrated was not simply a constant or a Heaviside step function. The next most reasonable assumption was that the potential varied slowly as compared to the characteristic length of the matter wave of the confined particle. The method is called the WKB method after the names of the three: Wentzel, Kramers, and Brioullin. It is far too involved to discuss here. Marcuse, chapter two is a very good starting reference.[9] Cherin, chapter six contains an excellent WKB based analysis of graded index fibers.[4] The WKB method is well developed in the texts by Merzbacher, and Gottfried.[10,11] This is not light reading. But the method turns out to be exactly what is needed for rigorous analysis of fiber propagation modes. Although, approximations, notably the paraxial approximation to the general Maxwell wave equations, are still needed. The paraxial wave equation is commonly used in classical optics.

Once the difficult work is done correctly, one result is the expression below for the number of modes, N, a fiber will support as a function of its parameters. The expression is $N = 0.5(n_1ka)^2[(n_1{}^2-n_2{}^2)]/n_2{}^2$. Where n_2 is the maximum core index, and n_1 is the minimum cladding index of refraction. The core radius is symbolized 'a'. The propagation number of the waves is 'k', namely two pi divided by the wavelength in the medium. This is rigorously correct only for step-index fibers, not for fibers with a continuous variation of index as a function of the radial distance from the fiber center. Still it is a good formula for doing estimations, whereas the general WKB results are a bit too complex. The idea of adjusting a fiber's index profile so that multimode dispersion effects are minimized leads to an assumption of a power law for the index' radial dependence, and analysis leads to an optimal value for the exponent used. It is usually just a bit less than 2.0. WKB analysis leads to the number of modes for multimode fibers with a not too rapidly varying index of refraction. Once the results are gotten, one can deduce that a single mode fiber will result if the fiber core is made very small, sometimes smaller than the wavelength it will conduct; and if the difference between the maximum core index and the cladding index is also small. This results in a fiber with, among other properties, a rather small numerical aperture. Typically this is around 0.1. So the full angle of acceptance is about 10 degrees. This poses some problems in launching light into such a fiber, but they have been solved. One can construct an interferometer using singlemode fibers. Because multimode fibers will variably distribute light among many or all of their modes, and because this distribution will usually change randomly with time, there is little hope of making interferometers with multimode fibers.

It is correct to note that because there exist two mutually orthogonal polarizations for any lightwave travelling through a fiber, a singlemode fiber is really a two-mode fiber. These two are degenerate eigenmodes. Light from one can scatter somewhat randomly into the other mode. This is especially true as fibers become longer than a few meters or so. Clearly this is the likely case for most practical applications. It is because the modes can have large probability of transition from one to the other in fairly short lengths of fiber that this situation occurs. This would make interferometric devices nearly useless, because their interference effects depend so completely on the constructive and destructive interference of vector lightwaves which must be everywhere parallel for such effects to occur. And as one might expect, if some means is used to cause the two modes to have much less degeneracy, there will obtain a fiber which preserves the polarization of the light launched into it. Such polarization preserving fiber does exist (see page 4-5 of Davis et al).[8] The means of its preparation is simple and clever. The preform from which the fiber is drawn has some of its material cut away along two parallel tracks, diametrically opposed on its surface, for its entire length. Then the form is heated to its softening or annealing point, and so returns to nearly its original circular cross section. Thus the core, which is deliberately and carefully not cut into, deforms to an elliptical cross section. Whereas the circular cross section of an unmodified preform will have nothing to distinguish one polarization mode from the other, the elliptical cross section will indeed have different propagation constants for its two polarizations. And if these propagation constants are made enough different, by reforming to get an elliptical core with significantly different semiaxes, the probability of transition from one polarization mode to the other will be made rather small. Although it is a bit confusing at first, such fibers are referred to as 'birefringent' and are said to have 'high birefringence'. This refers to the different propagation numbers, and hence effective indices of refraction, for the now differentiated polarization modes. The greater this difference, the stronger the polarization preserving effect of these fibers. So the fiber will preserve the ratio of the energies of one mode to the other, and hence the polarization of any light launched into the fiber. The propagation velocities of the two orthogonal modes are different, but the probability of scattering from one mode to the other is extremely small. Once launched, the ratio of these two modes will be preserved no matter what it is.

Now we can make a fiberoptic interferometer which will not suffer unacceptable fringe visibility problems.

Beam Launching

Launching light into fibers varies in difficulty from complete triviality to very hard. Fibers with a large numerical aperture are very easy to launch light into. They usually have fairly large cores as well. Singlemode fibers are the most difficult to launch light into since they will accept only one mode. The limiting case would suggest that only one angle of incidence, namely zero degrees, would suffice. In fact, it is nearly as bad as that. The numerical aperture for a typical singlemode fiber, or a polarization preserving fiber, is about 0.1, which means that its angle of acceptance is a total of ten degrees or so. In addition to this, the cladding of such a fiber comprises the vast majority of the fiber. The core which actually conducts the light is typically about five to ten microns in diameter (Cherin, page 45).[4] So one of the first devices used to focus light on the small core, and give it an angle of incidence from zero to (±)five degrees was a microscope objective lens. Currently several manufacturers, Kodak in particular, are producing precision molded lenses which will accept a beam of much larger diameter than the five to ten micron core, and will compress that beam to about one core diameter. These lenses are fabricated from glass or from plastic. They can be made either spherical or aspherical. A lens is made an integral part of a plastic channel which serves to guide a fiber along the lens' optical axis. Thus these 'beam expansion' couplers make it fairly easy to launch light into a fiber, and to splice it with similarly equipped fibers if desired. Index matching cements can also be used.

Splicing Optical Fibers

There are other problems to be dealt with when working with optical fibers. Most have been solved, but they bear at least a brief mention. Among them are the problems of joining two fibers so that the light lost at the joint is minimized. A good 'splice' will have a loss of not more than 0.5 dB (power), and can have as little as a 0.1 dB loss. Basically the method is to be sure the two fibers to be joined are cut to produce end faces perpendicular to the axes of the fibers, and polished extremely smoothly. This can be accomplished quickly with a 'cleaving' tool. Good ones can produce a cleavage which is within 0.5 degrees of perpendicular. The fiber almost always leaves a nearly optically flat surface when it is nicked with a very sharp edge (usually tungsten carbide) and placed under tensile stress, then gently bent away from the nick. If the splice is to be permanent it may be finished with a cement whose index of refraction is matched to that of the fiber. This would be a perfect solution for fibers with a constant index of refraction, or even a step profile. The parabolic profile of a singlemode fiber presents matching problems. Some average of the core index values has to be chosen for the cement's index. Yet the results are still better than for not having attempted index matching at all. The Fiberoptic Sensor Technology Handbook discusses this.[8]

Beamsplitting Devices

The final problem associated with making an interferometer with fiberoptic components is the development of suitable beamsplitting apparatus. Various methods have been used. The Fiberoptic Sensor Technology Handbook gives a good description of these.[8] The only one of these to be mentioned here is the most intriguing and arguably the most sophisticated of the methods. It is also the most rugged and simple, from the viewpoint of the user. The problem to be solved is that of causing a lightwave traveling along a fiber to divide (preferably equally) between two fibers. Conceptually one might imagine cutting or grinding away exactly half of the thickness of a fiber along some convenient length, repeating the procedure for the other fiber, and somehow joining the fibers along this length, perhaps with index matching cement. Then a beamsplitter would result. This has actually been done.[8] Reproducibility of such splitters is a problem, as is their mass production. The problem was solved, for all practical purposes, by research workers who understood that when a lightwave meets an interface between two differing indices of refraction (and under conditions of total internal reflection) there is not actually a discontinuity in the electromagnetic fields present at the interface. In fact there is an exponentially damped wave present which extends beyond the interface, and which makes the fields across the interface satisfy the electric and magnetic boundary conditions that electromagnetic theory says they must. Such a wave cannot transport energy very far, since its extent beyond the interface is usually only a wavelength or two before it is essentially gone. But if it is able to extend into another medium of the same index of refraction as that from whence it came, then it will indeed continue to propagate through said medium. The term for this effect is 'frustrated total internal reflection'.[3] The electromagnetic disturbance which extends beyond the interface is often referred to as an 'evanescent wave'.[4] Such an effect can be very nicely exploited by taking two singlemode fibers and twisting them together along a convenient length (usually a few centimeters) and heating them carefully so that although their cores are not disturbed, their claddings melt together. When carefully done, this process will bring the cores very close together. Then if the length of near core contact is sufficient, half of the light from one fiber will transfer to the other. The device thus produced is referred to as an 'evanescent mode coupler', or a 3 dB beamsplitter/recombiner, or simply as a 3 dB coupler. These are now commonly available. They are made both with what is still called 'singlemode' fiber (really two mode fiber) and with 'polarization preserving fiber', to prevent interaction of the two orthogonal polarization modes. This last kind of coupler is what is needed for construction of a reliable fiberoptic interferometer. It is important to note that such a device has two possible input 'ports', and two output ports. There is no preferred direction of propagation for light through the device; no distinction, other than for convenience, between inputs and outputs. It will either split one input beam into two equal energy halves, or if two beams are each launched into a respective port on one side of the fused fiber pair, each resultant output port will contain a half-and-half mix of both beams. Usually one output port is simply ignored in favor of the other, because most interferometers need only one of the two recombined beams.

Light Sources Used For Optical Fiber Illumination

Light sources for different optical fibers are chosen according to the fiber requirements. Multimode fibers are usually illuminated with incoherent light from various sources. Since it is unrealistic to build an interferometer without a coherent light source, and since coherence is best had from a laser source, the only likely source for singlemode fibers is a laser. Diode lasers have been developed for optical fibers. They are usually supplied with integral devices for accepting the fiber and aligning it to launch the maximum possible light energy into the fiber. Since any source other than a monochromatic one will introduce several different frequency modes into the fiber, it is best to use the most nearly monochromatic source possible; a laser.

A/D Using Polarization Rotation Effect

There exist molecular structures which are 'left-' or 'right-handed'. Their images in a mirror are not the same as the objects themselves, but bear the same relationship to each other as do right- and left-hands. Morrison and Boyd discuss this subject at great length (see chapter 3, on optical activity).[12]

When photons interact with such structures, their planes of polarization undergo rotation proportional to the path length traversed, and to the concentration of such structures that exist in a medium. Hecht on page 309ff gives a good description and model of the phenomenon.[3] It is important to know that the orientation of such structures is less important than their handedness. The orientation of the symmetry axes of the helices may be entirely random within the medium. Solids and liquids exist which exhibit this phenomenon. If equal proportions of both right-handed and left-handed structures exist in a medium, their net effect will be no rotation at all. Preparation of such a racemic mixture would destroy the effect. Elimination of one or the other handedness in favor of its opposite would foster the effect. In fact, chemists have developed analytical methods based upon this phenomenon.[12]

The Polarization Rotation Effect

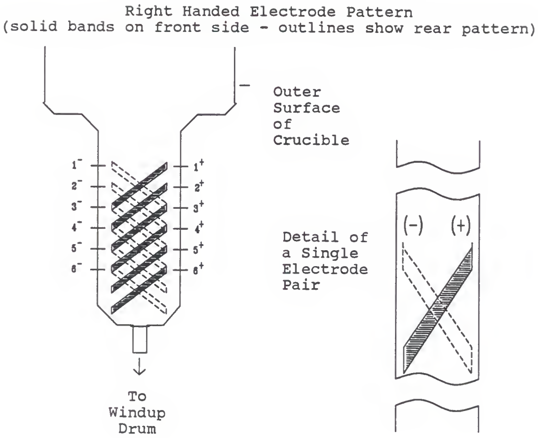
Optical fibers are usually made of doped silica glasses, the primary constituent of these is silicon dioxide. Quartz (SiO_2) may be crystallized in either a right or left handed form. Glass is amorphous and correctly described as a supercooled liquid. Right and left helical structures with silicon dioxide as their fundamental repeating unit, exist naturally in equal abundance within silica glasses. But if a relative excess of one species could be made to exist, then rotation of the plane of polarization of (linearly polarized) light would occur. This phenomenon has been known since Louis Pasteur's initial inquiries, and is well understood today (see Hecht, Morrison and Boyd).[3,12] The specific rotation (rotation per unit of path length, and concentration for compounds in solution) might not be as high as it is for many compounds. The effect is also wavelength dependent; so wavelengths are chosen as close as could be found to the target wavelength of 850 nanometers. Typical numbers for specific rotations of selected compounds follow: Cinnabar (HgS); +32.5 degrees/millimeter at 589.3 nm, lead hyposulfate; +5.5 deg/mm at 589.3 nm, and quartz (SiO_2) for various wavelengths, to indicate some of the nature of the wavelength dependence; +21.684 deg/mm at 589.5 nm, +15.746 deg/mm at 686.7 nm, and +12.668 deg/mm at

760.4 nm. The plus sign convention is to indicate clockwise rotation of the polarization plane as observed by someone looking in the same direction that the light propagates. This data is found in the CRC Handbook of Chemistry and Physics on page E-412.[13] For certain special forms of matter the rotation can be rather large. Liquid crystals (cholesteric liquid crystals in particular) have rotatory powers on the order of 40,000 deg/mm. This is because molecular orientations are preserved when the liquid flows, rather than disrupted, and because the pitch of the helical arrangements of molecules is much smaller than usual (see the footnote on p 313 of Hecht).[3] The important fact to gather from the above is that if there is no solid crystalline structure to dictate the pitch and quantity of helices, but also some means to preserve the helices from disruption when the liquid flows or is subject to thermal agitation (which exists at any temperature above zero Kelvin), then the rotatory power can be very large indeed. Then one should note that glass is an excellent candidate for this effect. Glass is actually a supercooled liquid; very little thermal agitation, as evidenced by the consistency of glass near room temperatures. So once helical structures are formed they may be expected to persist for rather long periods of time, probably comparable to the time intervals during which glass may be observed to flow (hundreds of years). The classic example of this is the stained glass windows in the French Cathedral of Notre Dame: the windows are much thicker at the bottom than at the top. The Cathedral is over 400 years old. The explanation of how such structures could be formed will be deferred for a while.

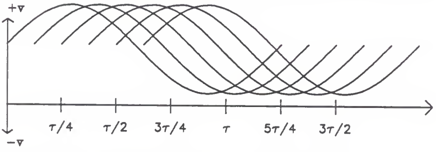
From the twenty-three values given for quartz from 318 nm to 760.4 nm one can extrapolate across the small interval to 850 nm and obtain an estimate of about 12 deg/mm for its optical rotary power (Appendix B). Let's use 10 deg/mm for an example; to get some feel for the problem. Then taking a full 360 degrees of rotation as equal to one count, or unit, a fiber 1,180 meters long would give 32,778 units (a little more than 15 bits). This ignores the fact that we can at the very least resolve the rotation into 180 degree parts, and probably more like 90, or 45 degree parts. That the compounds contain essentially only right- or left-handed species is the case for these numbers. Rotation is caused only by whatever excess of one species exists. This excess may be large or small depending upon the substance. However with optical fibers one has the option of using rather long paths to obtain sufficiently large rotational effects.

How to Cause the Effect

Silicon dioxide molecules have a natural tendency to orient themselves in helical configurations. In fact it is possible to prepare crystals of either right- or left-handed quartz. The first individual to take really careful notice of the formation of left- and right-handed crystals was probably Louis Pasteur. The compound was tartaric acid. Hecht shows the configurations of right-handed and left-handed quartz crystals on page 309.[3] Then he points to the fact that the crystalline structure of quartz seems to account for its optical activity. Further, he states that some substances are optically active in solid form or in solution. The reason is easy to see: the right- or left-handed structures are intrinsic to the molecules themselves in the case of some compounds, and are imposed on the SiO_2 molecules by the crystalline structure of quartz. But the essential difference between quartz as a crystal and as a glass after being fused, is just the disruption of the crystalline structure upon melting. It is not necessary that the material be crystalline in order that it be optically active, if another means can be found to induce the helical structures. Such a means is fairly easy to develop. Silicon dioxide molecules do have permanent dipole moments; thanks to the fact that silicon and oxygen atoms have different affinities for electrons. The molecular orbitals which the bonding electrons occupy are not symmetrically distributed over the positive nuclear charge centers. Instead the electrons spend more time near the oxygen nuclei than near the silicon nuclei. This gives rise to a permanent electric dipole moment because of the effective (time averaged) charge separation. Such a permanent electric field localized about the SiO_2 molecule will naturally interact with external fields. As such, this author believes, it would be fairly easy to use static electric fields to compel SiO_2 molecules to become oriented to a greater extent in either right- or left-handed helices. A drawing should help clarify this a bit (Figure 5). What is proposed here is quite comparable to a process currently used to compel a nonlinear organic polymer (para-dimethylamine-nitrostilbene) to form a thin-layer noncentrosymmetric molecular structure, which is used to form the fundamental, active part of a single-mode phase modulator. The device is made by Pilkington Guided-Wave Optics, Glasgow, U.K..[14]



Timing for the Six "+" Electrodes
The "-" Electrodes are Exactly Opposite in Phase



τ is Chosen to Match Apparent Motion of Field to Actual Transport Rate of Fiber Material

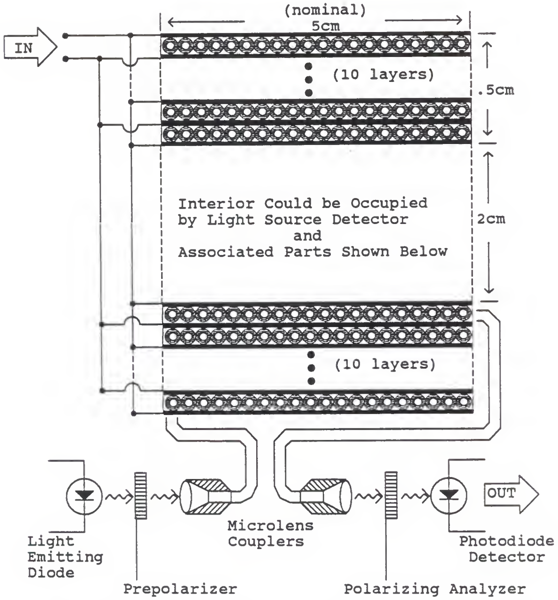
Figure 5 Illustration of a means to induce helically oriented chains of SiO_2 molecules in optical fibers.

The method of manufacturing optical fibers rather nicely lends itself to the application of external electric fields while the molecules are liquid and thus free to move into orientation. The fibers are drawn from a fiber 'preform' also referred to as a 'boule', which is progressively melted to allow the drawing process to occur. The glass supercools very quickly after leaving the melted region maintained by a heating element, thus fixing the molecular orientations. It would be fairly easy to equip the region in which the glass is melted with pairs of electrodes having right- or left-helical configurations. (see Figure 5). Then application of potential differences on the order of a few hundred volts or so would cause strong electric fields to exist within the glass. These would tend to force some fraction of the SiO_2 molecules into helical orientations. The pitch could be altered, up to a point, by altering the pitch of the helical pairs of electrodes. Clearly one could either use electrodes placed so that the shortest path from one electrode to its oppositely signed counterpart is either through the central axis of the cylinder just containing the helix, or is on the surface of that cylinder. It would be a matter of experiment to determine the most effective setup to use. If even a small proportion of SiO_2 molecules could be thus aligned the fiber would have optical rotatory properties. The question then arises as to whether or not the pitch of the helices would be near that of those in crystalline quartz. If greater, this would be more than acceptable. If less, then we should ask how much less is still acceptable. A good estimate can be made based upon the facts that: fiber lengths up to 30,000 meters can be used in communications systems without losses that degrade the signal below detector limits, so a limit of 10,000 meters is reasonable; and since 360 degrees of rotation of the polarization plane will result in a detected intensity variation which has two maxima and two minima, it is trivial to resolve the rotation into 90 degree increments. So a fiber 10,000 meters in length would need to vary from some initial rotation through 8192 rotations under the application of some external controlling agent (for 15 bits of resolution). This requires a change in rotatory power of 295 degrees per meter, or 0.295 degrees per millimeter. Compared to the rotation of about 12 deg/mm for crystalline quartz; this seems to be well within reach. It would seem apparent that the great lengths of fiber which can be used, enable one to gain a rather significant advantage over the situation: even a 1000 m fiber would need just 2.95 deg/mm.

One would also require that the rotatory property could be modified by some external agent. The obvious candidate is an electric field. The example of Appendix A shows that fields of the same magnitude as that of the (relatively large) interacting lightwaves themselves are quite easy to apply to optical fibers without resorting to very large voltages to generate these fields. This is primarily due to their rather small diameters, which are in the 100 to 200 micron range, as per the drawing on page 4 of Cherin.[4] This characteristic has been exploited to produce fiberoptic devices which use external electric fields to alter the fiber's optical properties (see section 12.4, p 334 of Haus).[2] So there is excellent reason to believe that the polarization plane rotating effect can be externally manipulated. The breakdown voltage of the fiber material sets the upper limit to the voltage used. But, as the photon fields do have significant interactions with the material, it is likely that an external electric field of about the same magnitude will also have significant effect on the medium. Such a field corresponds to eight or ten volts across the fiber's diameter (see calculation in Appendix A). What the field would do is distort the electronic orbitals of the SiO_2 molecules so that their probabilities of interaction with photons would change. Thus the optical rotation effects would change. This would be in much the same fashion as externally applied fields cause other related 'electrooptic' effects in various media. The low frequency dielectric constant of fused quartz, or silica glass is about 3.8 (page E-60 of CRC Handbook of Chemistry and Physics).[13] This also indicates how significant the interaction of SiO_2 dipole fields and external fields is. A rigorous analysis of any effect involving photon interactions with matter must be a quantum mechanical one. But the foregoing reasoning does seem to provide sufficient motivation for further investigation.

Construction of the Transducer

In order that this effect be useful in analog to digital conversion, a transducer which converts a voltage impressed across the fiber to rotation of the plane of linearly polarized light must be constructed (Figure 6). The construction is fairly simple. A suitable length of optically active fiber should be wound around a cylindrical conductor. If 100 meters is the chosen length, then the allowance of an overall diameter of 200 microns (to give a 125 micron fiber a protective coating, as is usually done) will result in a 2 centimeter diameter cylinder of about 32 centimeters in length. Naturally the fiber could be wound in successive layers to shorten the cylinder to a convenient length. Each layer would have to be exposed to the electric field, so between each fiber layer there would have to be a conductive layer. Mylar metallized on both sides (with both sides electrically connected) would be a good choice. Very thin metallic sheets wrapped around each successive fiber layer would also be good. Then a light source, a pre-polarizing filter and a beam launching lens/coupler would constitute the 'front end' of the transducer.



Layers of Wound Fibers
Separated by Conductive Layers
With Electrical Connections as Indicated

Figure 6 Construction of the polarization rotating transducer.

How to Obtain Digital Output from Transducer

The light exiting the fiber would be passed through another polarizing filter, and the transmitted light would be detected with a photodiode. Every time the polarization plane rotates 360 degrees the intensity detected would go through two brightness maxima and two minima. This is at least four counts, but could easily be resolved into more by simple comparison of the photodiode output with more than only maximum and minimum references. Explanation for the intensity variation's two maxima and minima for each rotation of the plane of polarization is in Hecht, on page 277ff. It is often referred to as 'The Law of Malus'.[3] To complete an analog to digital converter would (in general) require some input buffering and sample-and-hold circuitry. Followup to the photodetector would be: comparator and references to resolve the output into pulses, the counter, and any needed latches for the count. The actual analog to digital conversion would be intrinsic to the fiberoptic device itself.

Comment on Track and Hold Operation

Track and hold operation would reduce the work load on the counter rather significantly, and hence its power usage. The primary obstacle to such operation is the stability of the rotational effect from sample to sample, and over the long term, since the intent is to cumulate the differences between the previous and the current sample. Random variations of phase and polarization do affect optical fibers. Typically they occur over intervals of time measured in seconds, and result from mechanical, thermal, and other variations in the fiber. They plague development of fiberoptic ring laser gyros, since they usually cause shifts of many tens of degrees, and the gyros must measure shifts in the millidegree range in order to sense small angular speeds. Automatic recalibration, under the control of a microprocessor could be done every second or so without much difficulty. So the possibility of track and hold operation seems to be good. The most likely way of obtaining such operation would be to sample and hold the current and the previous inputs, then apply their voltage difference to the unit, then cumulate the (signed) result with the previous digital output. The sign of the difference would have to be determined via a second comparator. As this would use power and add complexity to the device, perhaps the better prospect is to let the counter do the work. It certainly results in a much simpler device. But tradeoffs of this sort are best determined experimentally.

Along the same lines of reasoning as those of differencing two samples, goes the idea of doing an eight-bit conversion for the most significant bits, followed by differencing of the sample and the partial conversion, scaling of that difference, and subsequent eight-bit conversion to get the least significant bits. This would necessitate only two (maximum) counts of 256 each, and would greatly shorten the fiber length required. It would require the use of an eight-bit digital-to-analog-converter which is trimmed so that its 256 levels are precise to 16 bits. Then the residual could be accurately obtained.

Analysis of Performance

To begin analysis of the potential performance of this device, one should note that the transducer is a capacitor. Using the 1000 meter fiber length and a dielectric constant of 4.0 the capacitance of the 2 cm diameter transducer would be about 71.4 nF. If made multilayered so that it is a little less than 7 cm long, it would be about 89.3 nF. The device has its own built in sample and hold capacitor. This capacitance does limit the speed of the device. With a semiconductor device such as an analog switch there would be about 50 ohms of resistance involved. To charge to within one-half part in 32768 of full voltage requires 10.4 RC time constants. So a sample rate of not more than 21.5 kHz could be used. However, the conversion would be done simultaneously with the sample acquisition. And in fact it is absolutely necessary that the electric field in the transducer not change more rapidly than the counter can count pulses. So the built in capacitance is useful. Based upon a high speed CMOS counter's maximum performance limitation of 34 MHz. The maximum sample rate for such a device would be 1.039 kHz (see Appendix C). Other devices, such as gallium arsenide based counters, would enable higher speed performance. The sample rate scales directly with the performance limit of the counter.

The error rate is another important performance specification. It will be affected primarily by the fluctuations in the light source used to illuminate the optical fiber of the transducer. The choice of how many parts in which to resolve one 360 degree rotation will specify the performance needed from the light source. If the logical initial choice of 90 degrees as one unit is made, then the detector has only to discriminate between an intensity maximum and a minimum. Consistency with CMOS standards is one possible choice for specifications. Thus the detector would be specified to consider any intensity up to 30% of maximum to be 'low' and any intensity greater than 70% of maximum to be 'high'. If the light source in a simple implementation would not be allowed to fluctuate more than 30%, ever, then the probability of error would be vanishingly small. The actual case is that the intensity would fluctuate randomly about its mean. Some measure of the fluctuation, such as a standard deviation, would then give the probability of fluctuation outside of the acceptable ranges. To give an error rate of one part per million would require a probability of 10^{-6} or less that such an excursion took place. This corresponds to a standard deviation of a little less than 7.7%, obtained by looking in a table to find the number of standard deviations which encompass .999999 of the total area under a gaussian curve. This is a fairly easy goal to strive for. But it seems wasteful to use only 90 degree increments of rotation. It should at the least be worthwhile to either obtain 16 bits resolution, or halve the required fiber length for 15 bits, by using 45 degree increments. Then three levels of comparison will be necessary. If the above intensity standard is used, only 3.85% fluctuation can be allowed.

A better approach would be to sample and hold the maximum intensity, the average, and the minimum. This can be done at intervals dictated by the rate at which the light source fluctuates. Then the pertinent specification is the probability that the light will fluctuate 3.85% before the next minimum, average, maximum determination is done. Clearly this can be made small by frequent determinations.

Possible Applications

There are several possible applications for this kind of device. It could directly sense electric fields whose intensities were in the range of the 54,000 volts/meter (Appendix A). It would be particularly useful for measurements done where there is a requirement of essentially complete electrical isolation between the input being measured and devices subsequent to any input buffer used. The electrical isolation would be considerable. The possibility of using the polarization rotating unit as a remote sensor is good. What could be done is to mount the sensor, equipped with optics to focus its light output beam a distance away from the device. This light could be intercepted by what would amount to a small telescope, with a photodetector where a human observer would place his eye. Conversion would proceed as with an integrated unit. This would make possible remote sensing in the presence of an intervening noise environment. It would also be possible to use several remote sensors to provide data for a single processor, and multiplex the optical signals received by the set of telescopes to a single photodiode. This would allow the processor to be given a fairly secure location while the relatively simple and rugged sensor is in the harsher environment of the signal of interest.

Interferometric A/D Using Electrooptic Effect

The Electrooptic Effect

Several related phenomena exist which are referred to loosely as 'electrooptic effects'. The meaning intended is that: material properties which have to do with the propagation of visible electromagnetic waves (optical radiation) may be altered by the application of an external electric field. This external field may be static or time dependent. But its highest frequency component is (currently) not more than 50 GHz, whereas optical frequencies range from about 4 x 10^{14} Hz to about 7.5 x 10^{14} Hz. So the external field is ten-thousand times more slowly varying than the optical fields also present. Since the Kerr and Pockels effects were discovered first, it is these to which the term 'electrooptic effect' is usually meant to refer. Our concern here is with solid media, the Kerr effect occurs primarily in liquids. The Pockels effect occurs in solids. It is strongest by far in crystals. There are actually two such effects: the 'transverse Pockels effect' and the 'longitudinal Pockels effect'. Hecht and Haus, read in that order will provide an excellent introduction and advanced look at the Pockels Effect.[3,2] The Fiberoptic Sensor Technology Handbook mentions a few numbers on page A-7 that serve to establish perspective.[8] Its explanation of 'electrooptic coefficient' states that said coefficient is a measure of the extent to which a material's index of refraction changes with an applied 'high electric field'. Then an example: an index change of 'several parts per 10 thousand' for applied fields 'of the order of 20 V/cm', is given. Clearly the motivation for further research derives from consideration that relatively enormous path lengths may be had through the use of optical fibers, and that this can easily compensate for a change in refractive index of only a few parts per 10 thousand.

What is sought is some physical effect that may be resolved into a nominal 32768 parts, or more. Then a 15 bit conversion is feasible. A few quick figures can demonstrate the idea. If 850 nm light is used, and if one wavelength is taken as a single unit, then a path length change of a little less than 2.79 cm is needed for an interferometer to produce 32678 fringes. These are fairly trivial to detect and count via photodiodes, etc. With minimized faith in the 'few parts per 10 thousand'; calling it one part per 10^4, an optical path of 279 meters is needed to have a path length change of 2.79 cm. The index of refraction of optical fibers is near 1.5. So an actual fiber length of 186 m would suffice. Then if a field of 20 V/cm is to be applied to a fiber (transversely) which is around 200 microns in diameter, an actual voltage of only a few millivolts would suffice. This author is skeptical about the quotation of 20 V/cm. Most electrooptical devices require voltages in the kilovolt/cm range. And if the field is more like 20 kV/cm, then the required voltage across the diameter of the fiber is 2.0 V. This seems reasonable. Still the small diameter and large fiber length that can be easily obtained will strongly support efforts to achieve the desired goal of a fiberoptic interferometer whose effective optical path length may be varied by at least 2.79 cm by an applied electric field of around 10 V.

The Pockels effect was discovered in crystals. The regular orientation of molecules in a crystal makes their responses to external fields constructively additive as opposed to randomly additive to a net response of zero. Because there are many crystals which are 'anisotropic' (structured differently when viewed along different axes) the response of the molecular fields is not the same for external fields of equal magnitude, but applied in different directions. So typically the Pockels effect is not the same along all crystal axes. This is simply a fact to be kept in mind.

What happens when the crystal is exposed to an external electric field is that the molecular orbitals (there is no electronic band structure here, these crystals are nonconductors, like quartz: SiO_2) are distorted and as such will have different interaction probabilities with photons. Since propagation of lightwaves through media consists of repeated interactions with bound electrons resulting in absorption and reradiation, one should intuitively see that changing the interaction probabilities will alter the speed of propagation in a medium. Hecht and Born & Wolf are good classical references.[3,7] Study of the quantum nature of these processes is needed for a rigorous understanding of them. Gottfried; Volume One is authoritative.[11]

There is no special reason why the medium must be crystalline, except that the requirement of molecular alignment must be kept in order that the medium have a nonzero resultant for the separate molecular effects. Naturally since an optical fiber is rather thin, and its manufacture requires it to be drawn from a molten reservoir, it is fairly easy to apply strong aligning fields to the molten glass. Since the fiber material supercools rapidly when drawn there is little liklihood of having thermal agitation destroy the alignment before solidification takes place. In any event, the fields can be applied well past the region in which the fiber medium is molten. When done to fused quartz to regenerate the piezoelectric effect lost by melting, this process is called 'poling'.

Such a process has not yet been tried on optical fibers, but this author believes that scaling down to fiberoptic sizes should not alter the physics involved in aligning the molecular dipoles to an externally applied electric field. Even if an effect ten times weaker than in crystalline media can be had, it should be entirely sufficient. A device using about 2,000 meters of fiber would be feasible. Voltages up to 40 V could be used. And a path length change of one wavelength for an interferometer corresponds to detection of both a maximum and a minimum intensity. So another factor of two is easy to get. And resolution of the (sinusoidal) intensity variation into four parts is easy enough, if needed.

Construction of the Transducer

The construction would be exactly the same as in the polarization rotating transducer. Probably 1,000 meters of fiber would be wound around a mandrel and metallized mylar would provide the necessary means of applying an external field, which would be the analog signal to be digitized.

Use in a Fiberoptic Mach-Zender Interferometer

The rest of the instrument would be more complex than the polarization rotating A/D. This is an interferometric device. A reference path, whose optical length does not change is needed, and could be furnished with a second length of fiber wound as in the transducer, but shielded from external fields by grounding of both conductive plates. The length of one fiber would have to be within about a meter of the other. This is because an interferometer will not work at all if the path length difference is in excess of, or even gets near the coherence length of the light source used. A laser diode light source is anticipated. These devices have coherence lengths of about 3 meters. The two fiber windings would make up the two 'arms' of a Mach-Zender fiberoptic interferometer. As the applied voltage varied the photodetector would generate countable pulses.

Comment on Track and Hold Operation

The considerations here are essentially identical with those for the polarization rotating A/D. Recalibration needs to be done every second or so; and if a ROM based look-up table for correction of nonlinearities is used, updates could be done via a piecewise-linear approximation determined from actual referenced measurements. A microprocessor like the Motorola 68HC11 would be a good choice for automated calibration, and for controlling the device in order to make it more flexible. The trade-off is as before, greater complexity for more performance.

Analysis of Performance

This analysis is the same as for the polarization rotating transducer. The capacitance and maximum counting rate would limit the sampling rate to about 21.5 kHz and 1.07 kHz respectively. Counters faster than high speed CMOS, such as gallium arsenide devices could give tenfold better sampling rates. If an eight-bit conversion for the most significant bits were followed by a second eight-bit conversion of the scaled-up residual between the sample and the first conversion were done, only two successive counts of at most 256 would be needed. Naturally this would speed the system up considerably, and make the fiber length required fully 256 times shorter. Although this would make the system more complex, this trade-off would probably be a very good one.

Possible Applications

These are identical with those for the polarization rotating A/D. Since an interferometer is required for the production of countable intensity variations, it is obvious that this device will not be as compact as the previous one can be.

Here the concern is not to obtain a large path length shift for use in an interferometer, but to obtain a shift of about one or two halves of a wavelength ... a very fast shift. Explanation can be found in Haus, and Hecht.[2,3] What happens, basically, is that the crystal is not isotropic, at least in the presence of an external electric field. When the field is applied, (and in some cases even when not) the crystal's properties, namely its photon interaction probabilities, and hence its indices of refraction, are not the same in all directions of propagation within the crystal. Usually there are two indices of refraction; one for two axes of propagation, and one for the third. The third axis is usually referred to as the 'extraordinary' axis, and it observes the 'extraordinary' index. What is particularly important is that the index of refraction may be varied linearly with the external field strength.

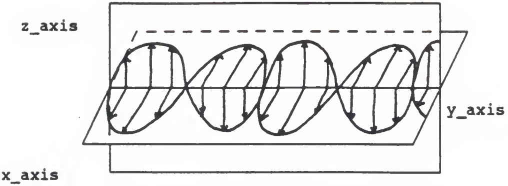
More on the Pockels Effect

The classic 'Pockels Cell' is constructed of a piece of (cubic) crystal, cut and polished so that there exist plane surfaces perpendicular to the intended direction of application of the external electric field. If the longitudinal effect is to be used, transparent metal oxide coatings are applied to either end of the crystal. As this effect requires a certain voltage be applied to get a desired shift, regardless of the crystal length, it is not very useful here. The desire is to use the transverse effect, which benefits greatly from miniaturization, if reduction of the voltage is a goal. Haus discusses this fact on page 331ff.[2] The transverse effect requires a voltage of 2h/l times the longitudinal voltage, if h is the transverse 'height' of the crystal, and l is its length.

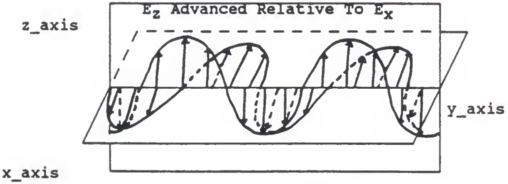
Rather significant research efforts have been directed toward the production of crystals which require as little voltage as possible, and as little power. The best currently available are potassium dideuterium phosphate (KH_2PO_4); referred to as KD^*P, or cesium dideuterium arsenate; referred to as CD^*P. These efforts are ongoing, and expected to produce further results (see Hecht or Yariv).[3,5]

When the field is applied, two lightwaves having orthogonal polarizations will observe different indices of refraction. This means that the effective wavelengths of the two are not the same within the crystal. The one partaking of the smaller index will have the longer wavelength. During transit it will therefore undergo a smaller total phase shift (relative to the other). Upon exiting the crystal the wavelengths will be identical and the two waves will have been shifted relative to their original phase relationship.

The most intelligent means of preparing two such waves is to prepare a beam of linearly polarized light. A polarizing filter does this. The orientation of the polarizing axis should be 45 degrees between the two polarizations one wants launched into the crystal. A cubic crystal is envisioned here, for simplicity. Remembering that any electromagnetic vector may be resolved into two orthogonal components; that is exactly how to view the situation. The components will be of equal magnitude if the 45 degree angle is observed. One component can thus be shifted with respect to the other. In general, the result will be elliptically polarized light when linearly polarized light was input.



Both Component Electric Fields In Phase



Elliptical Polarization Results In General

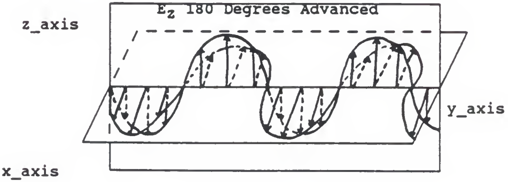


Figure 7 The effect of a phase shift on the polarization of a lightwave.

Consider the effect this shift has on the initial polarization of the light (Figure 7). From the drawings it should be apparent that if the wave having its electric field along the z-axis is advanced by one-half wavelength, then the resultant total field will have its polarization rotated through ninety degrees. The direction of the rotation is clockwise from the viewpoint of someone looking through the Pockels cell **in the direction the light is propagated.** If a more detailed analysis is done it will show the light to be elliptically polarized for shifts in between zero and one-half wavelength (see Yariv or Haus, regarding "the polarization ellipse").[5,2] From the viewpoint of a polarizer placed with its axis perpendicular to the initial polarization, the intensity transmitted by the polarizer varies from near zero to a maximum about equal to the initial maximum. There are losses in the polarizing medium, and it does not perfectly absorb perpendicularly polarized light, so the minimum and maximum are not exactly equal to zero and the initial intensity. For a polarizer oriented with its axis somewhere between zero and ninety degrees, relative to the initial beam's polarization, there will be a periodic variation in transmitted intensity. It will be a function of the shift which the Pockels cell causes. The variation from maximum to minimum will not be independent of the angular position of a sensor relative to the initial polarization of the input lightwave, but individual sensor calibration can be done.

Comment on Speed

Pockels cells are used to amplitude and phase modulate lightwaves for communication and other purposes. They function at frequencies ranging from DC to 30 GHz.[3] Clearly this speed could be used to great advantage in analog to digital conversion.

The fastest A/D units currently made are referred to as 'Flash A-to-D Converters'.[1] They function by comparing the input simultaneously to 2^n references. This requires 2^n comparators (for n bits). The resultant output of the comparators is (from the least to the most significant bit) a series of logic 'high' outputs, up to the first reference level that exceeds the input. Once the comparators have all settled their outputs may be decoded to a digital word which represents the analog signal. The process of switching and settling is the most time consuming part of the flash operation. The comparators are also the most power consumptive part of the device. They are also the more complex part of the A/D, and consume the most significant amounts of the chip area on an integrated device. The decode logic is the simpler part of a flash A/D, and its design is not really much of an issue anymore, although improvements are always being considered.[1] If an electrooptic device could effectively replace the comparator section of a flash A/D then a significant speed advantage could be had, primarily because the electrooptic device can perform at far higher speeds. The Pockels cell can modulate light at 30 GHz or more. It can follow an input sinusoid at 30 GHz. And the smaller the device is, the faster it is, and the less power it consumes. The challenge is to use the Pockels cell to generate some sort of output that logic devices can use. The Pockels cell is not the only candidate for this application. Faraday rotation is a well known effect.[3] It is akin to optical activity in solids with left- and right-handed structures (as discussed above). It is explainable in detail only if a quantum mechanical treatment is used. Devices using Faraday rotation do exist, and are used to modulate lightwaves for communication (and other) purposes.[15] The attainable rotation of the polarization plane is in the range of one to two hundred degrees per centimeter of medium. The value of such a device is that the plane of polarization is rotated, while the lightwaves remain in a plane polarized state, instead of becoming elliptical. This would somewhat simplify calibration efforts for the proposed device. Also, it is an effect caused by magnetic fields instead of electric fields; a current is required to cause the rotation instead of a voltage. For the usual Faraday rotator material (Yttrium-Iron-Garnet) a rotation of about 198 degrees per centimeter of a YIG crystal's length is typical.[15] So it would be easy to obtain sufficient rotation in a short path length.

Construction of the Electrooptic A/D

Referring to the drawing (Figure 8), what is needed is an array of photodiode receptors, which are preceded by polarizing filters. The polarizing axis of each filter must be parallel to the radial line which passes through the center of the associated photodiode. Then the intensity seen by a photodetector will vary as $\sin^2(A_1 + a_2*E)$, where A_1 and a_2 are constants; see equation (12.17) in Haus.[2] The constant A_1 will vary with the position of each photodetector. And in order to avoid the occurrence of a detector at exactly 45 degrees from the first one, a small offset in position must be used. This is because there is no variation in detected intensity at the 45 degree point, due to fact that whatever electric field component is lost from the initial direction is gained by the perpendicular direction; so that (both angles being equal to 45 degrees) the sum of the two contributions remains constant. However, this would be exactly the proper location for a reference detector. Such a detector could be used to give a light-source-intensity normalized reference. It could supply a threshold to which all other detector outputs could be compared. Or it could be used as feedback to control the light source intensity.

Clearly the best construction would have small polarizing filters placed on top of photodiodes in the semicircular array shown (Figure 8). This would require some custom fabrication. It is desirable to prove the concept first. So a couple of other approaches are possible for prototyping efforts.

First, a semicircular array of radially oriented polarizers could be fabricated. Then simple multimode optical fibers, with large numerical apertures could be used to conduct the light to a linear array of photodetectors. Once the light has been filtered by the polarizers, there is no longer a need to worry about its polarization.

Second; if the array of small polarizers is difficult to make, one could use polarization preserving optical fibers, also radially oriented (probably with the major axes of their elliptical cores made radial), to conduct the light to a strip of simple polaroid. Behind the polaroid would be the linear array of photodiodes. There is only one problem with this. The cores of polarization preserving fibers are about five to ten microns in diameter, nominally. They would gather very little light. So each would have to be spliced with a device known as a 'GRIN rod' (GRaded INdex), which can be as large in diameter as is necessary, up to the maximum diameter permitted by the physical constraints of the array's radius, and the number of bits the array is designed to give. Its radial index profile is chosen such that entering light rays follow a sinusoidal path along the rod. A 'quarter pitch' rod is needed to accept incoming rays across its entire face and focus them to a very small region at the center of the other end. Its length is one fourth of the sinusoidal period (which is usually a centimeter or two). The GRIN rod is a rather clever and compact way of launching light into small aperture fibers. This option is not as easy as the first, so it should be the last tried. But it does bear mention, especially in view of the fact that progress in manufacture of such devices is evidently quite rapid; one has only to note the commercial advertisements in such publications as LASER FOCUS, and PHOTONICS SPECTRA.

Illustration for 10° Detector Separation
(18 Detectors / 4.17 Bits)
Separation of 0.7° Would Give 258 Detectors / 8.01 Bits

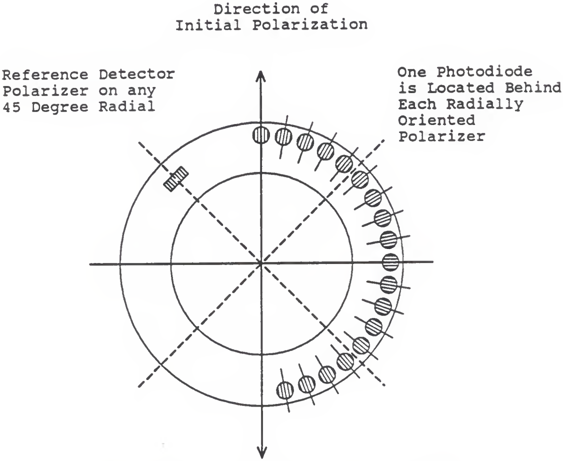


Diagram Shows Orientation of Polarizer Preceding Each Photodiode Detector

Region in Center is Not Needed by Detectors and Could be Used For Balance of Circuitry

Figure 8 Construction of the front end of the electrooptic A/D.

Recall that the electrooptic, or Pockels effect reduces simply to the variation of a material's index of refraction, for lightwaves with a particular plane of polarization relative to the Pockels cell's orientation. In general the relationship is tensorial.[2] If a polarizing filter is used to prepare light with the special plane of polarization, then such light will be subject to the variation of its wavelength, in the crystal, as a function of the control voltage used. Naturally the transverse effect is anticipated, the longitudinal effect requires voltages in the 7.6 kilovolt range to cause a shift of 180 degrees, regardless of the crystal's length. A crystal whose length is 30 millimeters, and whose height is .26 millimeters would cause a shift of 180 degrees for a transverse voltage of 133 V. See Haus, p334-5 for details of the calculation.[2] This is a reasonable voltage to work with. It could be made quite a bit lower if the device is made smaller. A device 5 millimeters long and 3 microns in diameter requires about 1.7 volts to have a 180 degree shift (see Haus, page 335).[2] This is probably too small a device, as there is a requirement that enough light be passed through the device to sufficiently illuminate the photodetectors. Still, the illumination can be improved by using an aspheric lens to focus the light in an annular region, centered about the arc of photodetectors. This would eliminate the waste of light not incident on the detector array with no lens to refocus it there. So the possibility of reducing the required voltage to tens of volts is quite real.

Calibration of the Unit

The photodetector circuitry could be fairly simple (Figure 9). If the photocurrent is too small to fire the diode series; chosen to give compatible logic levels, there will be no output. When the current is sufficient, the circuit outputs a logic 'high'. Individual calibration is made possible by the two variable resistors. The likely implementation for production would be laser trimmed resistances, so that the threshold level and output voltage could be set with automated equipment. Naturally the unit would be calibrated by generation of a reference voltage corresponding to the digital output desired, followed by trimming of the resistors until the photodetector circuit output just transitions 'high'. One point to be made is that detectors placed between 0 and 45 degrees see intensity decreasing with increased applied voltage, so their outputs will have to be logic inverted to be consistent with the outputs of the detectors from 45 to 90 degrees.

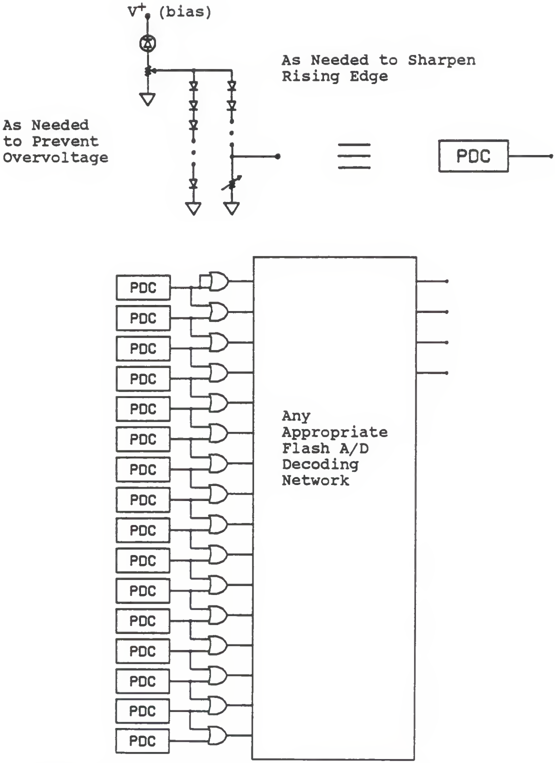


Figure 9 Photodetector circuitry for the electrooptic A/D. Illustration for 4-Bit Converter.

The additional difference between the output of the proposed device and that of a flash A/D comparator section is that the photodetectors will not always remain at 'high' when the voltage increases beyond their transition points, because the intensity increases, then decreases past a maximum. Instead of imposing unworkable limitations on the calibration, it is much easier to use the series of OR gates at the outputs, connected as shown (Figure 9). With them, the output of all preceding detectors is forced 'high' for any given detector. Yet the output of subsequent detectors is still allowed to be low until each one transitions in turn. Now the output of this A/D is identical with that of a Flash A/D, and may be decoded in exactly the same manner. Thus decoding will not be discussed herein. See reference 11 for any needed explanation. One final comment is appropriate. The most logical implementation for the decode logic is a gallium arsenide integrated logic circuit. There is nothing faster currently available, and it makes no sense to use the electrooptic device with logic circuitry that slows the overall performance obtainable.

Other Implementations Using the Pockels Effect

Other means of using the electrooptic effect to cause intensity variations on an array of photodiodes could be used. The Pockels cell is a standard item. So are what are called 'optical beam deflectors'.[16] Their problem is that the deflection angles attainable for reasonable voltages are mostly in the millidegree range. Yet larger angles could be gotten via diverging lenses or mirrors. Perhaps they could be made large enough to illuminate a fraction of a linear photodiode array, which fraction could be varied from zero to unity by a control voltage. This would eliminate the need for polarizers as the detectors would simply respond to the presence or absence of light.

Analysis of Performance

The process by which a flash A/D does a conversion is essentially that its analog front end must compare the sampled input to the 2^n reference voltages. Then enough time must be allowed for the slowest of the comparators to complete its transition and settle. The next step is the decoding of the sequence of: 'high's' up to the last reference less than the input, followed by 'low's' up to the highest order bit. Latching of the output is sometimes done by the A/D, sometimes by the followup circuitry. The time needed for the comparison is the largest part of the conversion time.

What is accomplished by using the electrooptic device to replace the comparator section is as follows. First, this author knows of no comparators that can perform reliably at or near 30 GHz. The single electrooptic device does the conversion comparison for the entire range, so there does not exist the problem of ensuring matched characteristics for 2^n comparators. The price paid for substituting the Pockels cell is the addition of the OR gate array. Clearly this adds one level of circuitry for the digital signals to propagate through. Three levels is about the minimum number for a flash decoding circuit.[1] The time for the OR gate to switch must be added to the time for the electrooptic device to settle, and this total compared to the switching/settling time for the comparator array. It is really not a contest if the logic circuitry is comprised of gallium arsenide devices. Even if not, the time for a high speed comparator to switch is typically much longer than for a gallium arsenide logic gate (on the order of 130 picoseconds).[17] So the trade off is indeed a good one.

The question of how many bits of resolution can likely be achieved should be answered next, since this is part of the performance specifications of such devices. If the radius of the array of photodetectors is two centimeters, and if ninety degrees of arc is used for the photodetector array, then seven bits worth of detectors would require about 0.70 degrees of arc per detector. With a two centimeter radius, this is about 0.245 millimeters per detector. If optical fibers are used to carry the light away to a linear array of detectors the nominal fiber diameter (with cladding and protective sheathing) is about 200 microns, or 0.2 millimeter. A GRIN rod for additional light gathering could be up to the 0.245 millimeter diameter. But clearly the space available is enough to accommodate an element of an integrated photodiode array.[18,19]

Possible Applications

This device is obviously a candidate for use wherever exceedingly high speed A/D conversions are needed. It is intended to compete with flash A/D converters. As such it is likely to outperform them in speed of conversion. It is also likely to be able to do higher resolution conversions. This is particularly likely in view of the anticipated speed: two step conversions should be possible. Perhaps converting five bits, using a five bit DAC to provide the subtrahend for differencing away the most significant part of the sample value, amplifying and converting the difference, and digitally combining the two results for nine or ten bits of resolution, would require more than two conversion times, but less than three. This would definitely outstrip any current high speed analog to digital converters in existence today, and probably in the future as well (at least for a while).

When signals propagate through an integrated circuit, such as a flash comparator array, they take the form of electronic currents. These go no faster than the currently obtainable electron drift speeds in gallium arsenide devices; about 5×10^7 meters/second.[17] The actual distance that the electrons must travel is several times the physical dimensions of the chip. By comparison, the Pockels cell responds after three things happen. First and second, the control field must propagate completely through the crystal, and the electrons in their bound states must alter their time averaged spatial distributions (become polarized). The field propagates at the speed of light in the crystal; about $(3 \times 10^8$ m/s)/1.5. The electronic states are best described in terms of their transition lifetimes. These are on the sub picosecond level for electrons bound to small molecules like SiO_2. Third, the light traversing the cell must have time to do so before its effect can be sensed. This is also a phenomenon which occurs at about $(3 \times 10^8 \text{ m/s})/1.5$. So the process has at least a factor of four speed advantage. This ignores the fact that the actual path traveled by the electrons in an integrated circuit is probably several times the optical path length for the Pockels cell based device. The decode logic and subsequent processing circuitry can be identical for both kinds of A/D considered here.

Conclusions and Recommendations

The proposed analog to digital conversion methods above seem to this author to have more than a fair chance of being useful. The exact applications most suited to any of the methods is not so easy to foretell. But the first two devices would be particularly adaptable to instrumentation purposes in unpleasant environments, and in noisy ones, where their signals could be transmitted across some appropriate distance as optical signals, thereby isolating most of the processing circuitry from the environment. Both the polarization rotation sensor and the interferometric sensor could be used to directly sense sufficiently strong electric fields. As such, they would be useful in research-oriented applications such as particle accelerators or other high voltage producing devices. They would also be useful in monitoring electric fields produced by high voltage power generation, transformation, and transmission equipment. In all cases the link between the sensor and followup circuitry could be the optical fibers themselves. This would provide excellent electrical isolation. An average field intensity over a fairly large area or volume, could be measured by a fiber sensor which is not wound on a mandrel, but distributed throughout the region of interest. One additional possibility is the monitoring of lightning prestroke and poststroke fields, for both research and hazard warning purposes.

The third device is likely to be able to compete with the best gallium arsenide based devices, in speed and resolution for quite some time to come. It will not satisfy requirements of small size as well as integrated circuits can, but a little reflection on the physics of the processes involved should convince one of the speed comparison. Others have recognized the potential of electro optic devices where extremely fast devices are desired. In particular there exist three articles, in Laser Focus, Design News, and Electronic Design, all discussing the device testing equipment designed and built by Photon Dynamics, of San Jose, California.[20,21,22] This test equipment is based upon a Pockels effect crystal. It is able to test very high speed integrated circuitry at the rate of several hundred thousand test states in 250 milliseconds. It owes its speed to the same Pockels effect this author proposes to exploit for very fast analog to digital conversion. Extremely low loading of the device under test is also possible because of the Pockels effect crystal's use as the interface between the tested device and the test circuitry. It seems reasonable to pursue development of the above discussed devices.

APPENDIX A

Calculation of Average Electric Field Strength Within an Optical Fiber

To compute an estimate of the average electric field strength present in an optical fiber which carries electromagnetic radiation, we can use an expression relating the irradience within the fiber to the average electric field intensity, the speed of light, the index of refraction, and the permittivity of the fiber medium.

Expression for average irradiance: $\langle I \rangle_t = \epsilon V \langle E^2 \rangle_t$

where $\epsilon = \epsilon_o \epsilon_r$ is the relative permittivity of the medium times the permittivity of free space

and $V = C/n$ is the speed of light in a vacuum divided by the medium's index of refraction

MKSA units: m(eters), s(econds), c(oulombs), n(ewtons), v(olts), w(atts)

Accepted values are: $C = 2.9979 \times 10^8$ m/s

$\epsilon_o = 8.8542 \times 10^{-12}$ $c^2/n\ m^2$

A good nominal index: $n = 1.5$

At optical frequencies (around 10^{15} Hz), the relative permittivity will tend toward unity. Using a value of 1.0 will increase the voltage estimate a little, which is actually good for this illustration.

So suppose 0.1 milliwatts of light is launched into a single mode of a polarization preserving fiber, whose core diameter is as small as 5 microns.

Now the mean squared electric field can be found:

$$\langle E^2 \rangle_t = n \cdot \langle I \rangle_t / \epsilon_o \epsilon_r \cdot C$$

where $\langle I \rangle_t = 10^{-4}$ w / π $(2.5 \times 10^{-6}$ m$)^2 = 5.093 \times 10^6$ w/m^2

giving: $E_{rms} = 53{,}650$ v/m

A typical fiber diameter is 140 microns.

Should one wish to apply an electric field to the fiber of magnitude comparable to that of the light, a potential of about 8 volts across its diameter would be necessary.

$$v = (53{,}650 \text{ v/m}) \cdot (140 \times 10^{-6} \text{ m})$$

$$= 7.511 \text{ v}$$

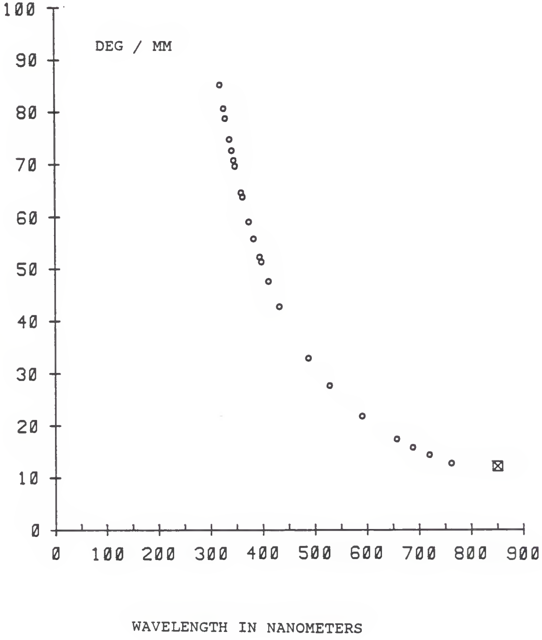
The expression for $\langle I \rangle_t$ is common to all good texts on electromagnetic theory, or optics. It is equation 3.47 on page 44 of Hecht.[2]

Appendix B

Estimation of Specific Rotation of Quartz at a Wavelength of 850 nanometers

Data points indicated by circles. Extrapolated point indicated by an "x" within a square. This estimates the specific rotation for quartz at 850 nanometers.

DEGREES ROTATION PER PATH LENGTH IN MILLIMETERS (Quartz)



(data taken from page E-412 of CRC Handbook[11])

Appendix C

Sampling Rate Calculations for Polarization Rotation A/D

In order to estimate the sampling rate of which the Polarization Rotation A/D is capable, we can estimate the capacitance of the device, and use this to determine its settling time (about 10.4 time constants for 15 bit accuracy).

For a cylindrical capacitor, the capacitance per unit length is given by:[18]

$$C_l = 2\pi\epsilon_o\epsilon_r \;/\; \ln(r_2/r_1)$$

where: $\epsilon_o = 8.8542 \times 10^{-12}$ coul^2/n m^2
$r_1 = 0.02$ m (inner radius)
$r_2 = 0.0202$ m (outer radius)

and let $\epsilon_r = 4.0$ (generous estimate of dielectric constant)

So for a 3.2 m long capacitor: **C = 71.6 nf**

Or if we make a 46 layer device, it will be less than 7 cm long. Mylar 15 microns (6 mils) thick is a more than adequate separator, and can easily be metallized.

Then the nth inner radius = [0.02 + n(0.000215)] Meters
and the nth outer radius = [0.0202 + n(0.000215)] Meters

The summation of 46 of the 7 cm long capacitors gives a value of:

89.3 nF

Using 89.3 nF and anticipating the use of an analog switch to gate the sampled signal, with the usual 50 ohms of resistance of an analog switch, the RC time constant becomes:

$$\mathbf{4.47 \times 10^{-6} \ s}$$

To decay to within one part in 2^{15} of its final value, this RC circuit must go through $\ln(2^{15}) = 10.397$ time constants. Thus a sample period of at least 46.42 microseconds must be allowed.

The reciprocal of this is **21.54 kilohertz.**

An upper limit to the sampling rate, based on the speed limitations of a High-Speed CMOS counter can be obtained.

Assuming a 34 MHz counting rate, and realizing that the maximim slope for an RC circuit's charging function is equal to: V_f/RC. We can quickly determine that the below relation must hold:

$$34 \text{ MHz} \geq 32{,}768/T_{samp}$$

So in this case case: $T_{samp} \geq 963.7$ microseconds.

References

[1]The Engineering Staff of Analog Devices, Inc., Daniel H. Sheingold, ed. Analog-Digital Conversion Handbook, (New Jersey: Prentice-Hall, 1986, ISBN 0-13-032848-0).

[2]Herman A. Haus, Waves and Fields in Optoelectronics, (New Jersey: Prentice-Hall, 1984, ISBN 0-13-946053-5).

[3]Eugene Hecht, Optics, (2nd ed; Reading, Massachusetts: Addison-Wesley, 1987, ISBN 0-201-11609-X).

[4]Allen H. Cherin, An Introduction to Optical Fibers, (New York: McGraw-Hill, 1983 ISBN 0-07-010703-3).

[5]Amnon Yariv and Pochi Yeh, Optical Waves in Crystals, (John Wiley & Sons, 1984, ISBN 0-471-09142-1).

[6]L.M. Holmes, "Sapphire Fibers Transmit Infrared Power", Laser Focus World, p 140, March, 1989.

[7]Max Born and Emil Wolf, Principles of Optics (electromagnetic theory of propagation interference and diffraction of light), (6th ed; Oxford: Pergamon Press, 1980, 1986 corrected reprinting, ISBN 0-08-026482-4).

[8]C.M. Davis, E.F. Carome, M.H. Weik, S. Ezekiel, and R.E. Einzig, Fiberoptic Sensor Technology Handbook, (Herndon, Virginia: Optical Technologies, Inc., 1984).

[9]Dietrich Marcuse, Principles of Optical Fiber Measurements, (New York: Academic Press, 1981, ISBN 0-12-470980-X).

[10] Eugen Merzbacher, Quantum Mechanics, (2nd ed; New York: John Wiley and Sons, Inc., 1970).

[11] Kurt S. Gottfried, Quantum Mechanics, volume I Fundamentals, (New York: W.A. Benjamin, Inc., 1966).

[12] R.T. Morrison and R.N. Boyd, Organic Chemistry, (Boston: Allyn and Bacon, Inc., 1966).

[13] The Chemical Rubber Company, Handbook of Chemistry and Physics, (60th ed; Boca Raton: CRC Press, Inc., 1979-1980).

[14] B. Dance, "Organic Nonlinear Polymers Make Fiberoptic Devices", Laser Focus World, p 143, May, 1989.

[15] A. Shibukawa and M. Kobayashi, "Compact Optical Circulator for Optical Fiber Transmission", Applied Optics, vol. 18, no. 21:3700-3, November 1979.

[16] V.J. Fowler and J. Schlafer, "A Survey of Laser Beam Deflection Techniques", Proc. IEEE, 54, 1437, 1966.

[17] R.C. Eden, A.R. Livingston, B.M. Welch, "Integrated Circuits: the Case for Gallium Arsenide", IEEE Spectrum, December 1983.

[18] S.M. Sze, Physics of Semiconductor Devices, (2nd ed; New York: John Wiley and Sons, 1981, ISBN 0-471-05661-8).

[10] Eugen Merzbacher, *Quantum Mechanics*, (2nd ed; New York: John Wiley and Sons, Inc., 1970).

[11] Kurt S. Gottfried, *Quantum Mechanics, volume I Fundamentals*, (New York: W.A. Benjamin, Inc., 1966).

[12] R.T. Morrison and R.N. Boyd, *Organic Chemistry*, (Boston: Allyn and Bacon, Inc., 1966).

[13] The Chemical Rubber Company, *Handbook of Chemistry and Physics*, (60th ed; Boca Raton: CRC Press, Inc., 1979-1980).

[14] B. Dance, "Organic Nonlinear Polymers Make Fiberoptic Devices", *Laser Focus World*, p 143, May, 1989.

[15] A. Shibukawa and M. Kobayashi, "Compact Optical Circulator for Optical Fiber Transmission", *Applied Optics*, vol. 18, no. 21:3700-3, November 1979.

[16] V.J. Fowler and J. Schlafer, "A Survey of Laser Beam Deflection Techniques", *Proc. IEEE*, 54, 1437, 1966.

[17] R.C. Eden, A.R. Livingston, B.M. Welch, "Integrated Circuits: the Case for Gallium Arsenide", *IEEE Spectrum*, December 1983.

[18] S.M. Sze, *Physics of Semiconductor Devices*, (2nd ed; New York: John Wiley and Sons, 1981, ISBN 0-471-05661-8).

[19]S.M. Sze, *Semiconductor Devices Physics and Technology*, (New York: John Wiley and Sons, 1985, ISBN 0-471-87424-8).

[20]G.T. Forrest, "E-O Instrument Tests Gigahertz ICs", *Laser Focus*, p 28, October 1988.

[21]L.H. McCarty, "System Tests Devices at GHz Rates", *Design News*, p 56, April 10, 1989.

[22]J. Novellino, "Electro-Optic Device Tester Tops 1-GHz", *Electronic Design*, p 55, September 8, 1988.

ANALOG TO DIGITAL CONVERSION USING FIBEROPTIC INTERFEROMETRY AND BY DETECTING ELECTRO OPTICALLY MODIFIED POLARIZED LIGHT

by

GARY THOMAS FINA

BS (Physics), BA (Mathematics) KANSAS STATE UNIVERSITY
May, 1973

MS (Physics) UNIVERSITY OF ILLINOIS
at URBANA-CHAMPAIGN, January, 1975

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment
of the requirements for the degree

MASTER OF SCIENCE

Department of Electrical and Computer Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1989

ABSTRACT

Studies were made to determine the feasability of using interferometric methods, and methods based on several effects, known as 'electrooptic' effects, to perform analog to digital conversion. The three main sections of this thesis are each concerned with one of the proposed methods. The introduction covers some background information about optical fibers and interferometers.

The first section describes an effect where the plane of polarization of a linearly polarized lightwave in a medium may be rotated through a controllable angle. The control parameter is an externally applied electric field. The medium is to be an optical fiber. A means of observing the rotation by using a polarizing filter and a photodiode is discussed. The digitization is to be done via a count of the intensity maxima (and minima) which the photodiode observes as the field is applied.

Section two describes a related effect where the effective optical path length is varied through application of an external electric field. Detection of this variation is done through the use of a fiberoptic interferometer with photodiode detection of the intensity maxima and minima produced in response to the field.

The final section describes how the variation of optical path length may be used to obtain extremely fast

analog to digital conversion by using polarizing filters and photodetectors, followed with an array of OR logic gates to cause the output thus obtained to be identical with that of the comparator array used in a 'flash' A/D converter. Then the decoding process may be the same as that already in use with flash A/D converters. The proposed implementation form for the logic circuitry is a Gallium Arsenide integrated circuit, as this is the fastest available device, and is commensurate in speed with the electrooptic part of the proposed device; known as a 'Pockels cell'.