FIBER OPTIC HYDROPHONE

ELE 490 SENIOR DESIGN PROJECT

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TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

FIGURES

List of Symbols

η	Index of Refraction.
θ	Angle relative to material interface.
ω	Angular frequency (rad/s).
ε	Permittivity (Farad/m)
μ	Permeability(Henry/m)
k_c	Cutoff wave number in dielectric waveguide.
E_z	Electric Field propagating in z direction.
h	Decay constant of evanescent field outside of a waveguide.
λ_o	Wavelength(m).

ABSTRACT

Optical fiber technology has become one of the most important new developments in communications. Telecommunications and broadcast communications have become the most visible applications of fiber optics. The computer terminals in the lab at Northern Illinois University communicate over a fiber optic local area network (LAN). These and many other applications illustrate the utility of fiber optics in electrical engineering.

What is it about fiber optics that makes them so useful in communications? How can light transmit a telephone call or a television program? The answers to these questions lies in the fact that light is no different from microwaves and radio waves except for the frequency. In other words, light is another form of electromagnetic energy that can be harnessed.

The optical region of the electromagnetic spectrum is from $3*10^{12}$ Hz to $6*10^{15}$ Hz.[1] This is higher than radio frequencies and microwave frequencies. And because light is the carrier in optical communication, it follows that optical systems offer a wider bandwidth than RF and microwave communication systems.[2] In a typical system where the bandwidth is a fraction of the carrier frequency, it is possible to attain bandwidths on the order of 10^6 Hz. This is why a single optical fiber can carry thousands of telephone and television channels simultaneously.

Another advantage of optical communications is the immunity to interference. Because optical fibers are dielectrics, they do not conduct electricity and are thus immune to electrical discharge. The extremely high frequency of optical signals prevents

most electromagnetic interference from distorting the signal. Thus, fiber optic telephone lines offer clearer transmission than coaxial cables.

A third advantage of fiber optics is that glass fibers offer low attenuation compared to some media. At certain wavelengths it is possible for some fibers to have attenuation as low as 0.5 dB/km. This makes it practical to use fiber optics for long-distance communication links. Fiber optic cables have even been laid on the ocean floor to carry telephone channels between Europe and the United States.

FIBER OPTIC SENSORS

Another more specialized application of fiber optics is in sensors. This project is intended to demonstrate one example of a fiber optic sensor. In this experiment, I will demonstrate a moving-fiber displacement sensor to measure the amplitude and frequency of acoustic signals. This simple sensor is useful for detecting sounds in air or under water. This is one design for a sensor called a hydrophone. It can be used like a microphone to listen under water or to make measurements on sound waves in the water, similar to those performed by sonar.

In this report, I will give a brief introduction to fiber optic technology and discuss their application to sensing. I will then talk about the specific components used in this experiment and give a summary of the tests performed. This paper will conclude with a brief discussion of the interferometric sensor concept used on board surface vessels and submarines in the Navy.

BACKGROUND

Fiber optics have only come into widespread use within the last 20 years in the telecommunications industry. The operating principle is very simple to understand. Using concepts from light and optics, the following brief introduction will show how optical fibers transmit light.

SNELL'S LAW

Most everyone has seen light travel from air into water and observed that light is bent, or refracted, by the water. This happens because water has a higher **index of refraction** than air. The angle at which the light bends is governed by Snell's Law, which reads:

$$\eta_1 \sin \theta_1 = \eta_2 \sin \theta_2. \tag{1}$$

When light travels from water into air, the opposite effect occurs. In this case, incident light is refracted away from the normal. At a certain angle, light passing from water into air will propagate along the surface of the water, or 90 degrees with respect to the normal. This angle is called the **critical angle.** For the case of water-to-air propagation with $n_2=1$, $\theta_2 = 90°$, and $n_1=1.33$, the critical angle is

$$\theta_1 = \arcsin \frac{1}{1.33} = 48.75° \; . \tag{2}$$

If light hits the boundary at any angle greater than the critical angle, it will be reflected back into the first medium. This is called **total internal reflection.** Fiber optics are constructed to take full advantage of this concept.

A closer look at the mode structure of an optical waveguide will lead into the discussion of how to couple sources and detectors to fibers. For this report, it will suffice to simplify the geometry and talk about a dielectric sheet waveguide. The cylindrical geometry of fiber optics makes such an analysis much more difficult. It will be considered only briefly following the slab waveguide analysis.

Consider the dielectric slab waveguide shown in Fig. 2. It is considered to be infinite in the y and z directions, and extends to $\pm d/\ 2$ in the x direction. The region above and below the dielectric is air. The analysis of this waveguide is similar to that of metallic waveguides except for a change of boundary conditions at the dielectric-air interface. At the interface, the tangential electric fields, E_z and E_y must be continuous, but do not have to go to zero(0). The dielectric waveguide can support **transverse electric (TE)** and **transverse magnetic (TM)** waves. TM waves have no magnetic field vector in the direction of propagation (the z direction), and the electric field in the z direction must satisfy the wave equation. If the magnetic field varies only in the x direction, then the wave equation reduces to:

$$\left(\frac{\partial\wedge 2}{\partial x\wedge 2}+(\omega\wedge 2\cdot\mu\varepsilon-k_z\wedge 2)\right)E_z=0 \qquad (3)$$

If we look at the region inside the waveguide, $\omega\wedge 2\mu\varepsilon > k_z$ and the second term in (3) is positive. If we then solve the equation and equate the second term to k_c, the solution is of the form

$$E_z=A\cdot\cos(k_c x)+B\cdot\sin(k_c x) \qquad (4)$$

Each mode that propagates through a waveguide has a cutoff wave number, k_c. The first term in (4) corresponds to even-ordered modes, while the second corresponds to odd-ordered modes.

than the cutoff for the TM_{01} mode. [5] It is also useful to find a core radius and the indices of refraction so that the fiber only supports one mode at a specified wavelength.

The index profile refers to what the index of refraction is as a function of core position. The fiber described above is called a step-index fiber because the core-cladding interface looks like a step function. Another useful fiber is called graded-index fiber. Its index profile is approximated by an inverted parabolic curve. Graded-index lenses are also useful in fiber optics and are used in this experiment. They will be discussed in detail in the next section.

OPTICAL SOURCES AND DETECTORS

The two most common light sources for fiber optics are light-emitting diodes and laser diodes. The following is a brief discussion of both. LED's are made of gallium arsenide and can emit power over a wide range of wavelengths. They are relatively inexpensive and are fairly insensitive to temperature extremes. Laser diodes emit over a narrower range of wavelengths and can be switched on and off much faster than LED's. Thus, laser diodes are more useful for large (GHz) bandwidth systems whereas LED's are suitable with smaller bandwidth systems. Laser diodes are useful with single-mode fibers because of their coherence.

Once light is launched into one end of an optical fiber, it must be detected at the other end. In the presence of light, a photodetector must act as a current source for other parts of the circuit. Photodiodes are the most common types of detectors used. The PIN photodiode and the avalanche phododiode (APD) are the most common detectors used in fiber optics. A PIN diode is much like any other diode except for the intrinsic layer between the anode and cathode. When light hits the intrinsic layer, electron-hole pairs are formed. These charge carriers then separate to create a current. The APD also creates a current in the presence of light, but each electron-hole pair undergoes avalanche multiplication, and thus acts as a signal amplifier. Photodetectors with preamplifier outputs are available.

In order for any fiber optic link to work, one end must be coupled to the source and the other end must be coupled to the detector. This is where graded-index (GRIN) rod lenses can help. GRIN lenses work exactly like graded-index fibers, but are generally only a few millimeters long and perhaps one or two millimeters in diameter. These lenses are specified in terms of pitch, or fractions of a wavelength. For example, a 0.29-pitch lens is 0.29 wavelengths long. This type of lens is useful for focusing light from a point source at one end onto a focal spot a few microns from the other end. If a fiber is placed at the focus, the light is coupled into the fiber. Another useful GRIN lens application will be discussed in the design section of this report.

DESIGN

CONCEPT AND PHILOSOPHY

There are many design concepts useful for acoustic sensing using fiber optics. Almost every type of fiber is useful in at least one configuration. In this section, I will talk about the moving-fiber sensor used in this project. In the discussion section, I will talk about some other designs for comparison.

The moving-fiber sensor looks very similar to a communication link except for the break in the fiber. The fiber from the source is fixed in place while the fiber leading to the detector is allowed to move back and forth. The discontinuity allows sound waves to displace the loose fiber. This offset lowers the coupling efficiency between the fibers and thus reduces the power reaching the detector. In this way, the moving fiber acts like an external modulator in the presence of pressure or sound.

INTRODUCTION TO THE NEWPORT FKP-COM

This experiment is performed using the FKP-COM Fiber Optic Communications Project Kit. This kit was used to build and demonstrate a short model (about 500 meter) fiber optic communication link in 1990.[6] The kit includes a number of optical components that made it possible to complete this project.

F-MLD-50	100/140 optical fiber	
FK-LED	Infrared LED	
FK-DRV	LED-laser diode driver	
F-925	GRIN Rod Lens-Fiber Coupler	(2)
FK-GR29	0.29 Pitch GRIN rod lens	
SP-2	Posts	(4)
	Newport optical experiment table.	

815	Power Meter	
FK-DET	Infrared detector.	
F-IRC1	Infrared sensor card.	
FP-1	Fiber Positioners	(5)
FPH-S	Fiber Chuck (<200 micron)	
FPH-DJ	Fiber Chuck (>250 micron)	

NSG FIBER COLLIMATOR

The fiber cables used in this design are worth talking about by themselves. The fiber is actually a beam collimator manufactured by Nippon Sheet Glass, Inc. The collimator is a fiber cable pre-aligned to a quarter-pitch GRIN rod lens. When light comes out of the fiber through the lens, it forms a collimated beam. The lens can also focus collimated light into the fiber core. One application of this technology is to use two collimators with the lenses facing each other. This arrangement is called an expanded-beam connector. This is the other application of GRIN lenses useful in this project. GRIN lenses were introduced in the background material.

The collimators used in this experiment are designed for efficient coupling at the source and detector. They have a large core diameter of 200 microns and a cladding diameter of 250 microns. The peak operating wavelength is specified at 820 nm, which is well into the infrared range. The fiber is a plastic clad silica (PCS) fiber, which means the cladding is plastic and the core is glass. The fiber is inside a cable and can thus be used in harsh environments, such as under water.

EXPERIMENTAL SETUP

The experimental setup for this experiment is fairly easy to understand. The first step is to try to couple light from the LED into one end of the input fiber. To do this, I use a source-to-fiber coupler with a 0.29-pitch lens between the LED and the end of the fiber. Using a fiber holder inside the optical stage allows me to make fine adjustments of the fiber position in order to couple as much power in as possible. Using the infrared sensor card at the other end (the collimator end), I was able to see the beam coming out of the fiber. I verified this using the power meter.

Once the source is coupled to the fiber, the next thing to do is to use another coupler to set up an expanded-beam connector. This time, the beam is coupled from the lens of the input fiber to the other lens, which faces the first. Using a 0.25" O.D. tube will help hold the cable in place while allowing the lens to move a small distance if it is disturbed. The other end of the output fiber is then coupled to the power meter to verify its operation. Once the expanded beam connector works, I am ready to perform some tests on the sensor.

TESTS TO BE PERFORMED

The moving-fiber sensor works on a principle of changing the coupling efficiency when the fibers become misaligned. With this in mind, a simple place to start is by moving the output fiber lens to one side and measuring the power at the meter. This can be done using a screw on the optical stage. The procedure is to align the lenses, turn the screw a quarter turn at a time, and measure the power that gets through on the meter. Each axis on the fiber positioner has a range of 3.2mm.[7] I was able to turn the screw 10 full turns, making each turn a distance of 320 microns. Each quarter turn is then 80 microns. This test should give me an idea of what the beam profile looks like coming out of a broken fiber. The output power is plotted as a function of lateral offset in Fig. 4.

To make a workable moving-fiber transducer, it was necessary to put together a similar setup using bare fibers instead of cabled fibers. Using two 100 micron fibers

EXPERIMENTAL RESULTS

In the first step of this project, I set the expanded-beam connector up and measured the power getting through to the detector. Table I is the power as a function of the axial offset of the lenses. The graph of these data shows that the power resembles a raised-cosine function. Using 50 milliwatts as a reference, the half-power points are at about 720 microns. The lenses are approximately 1mm in diameter. The response is fairly linear up to about 1mm offset, which means the moving fiber will measure transmitted power as long as there is some core (or lens) overlap. This information should be useful when the real hydrophone is tested.

Using the F-MLD optical fiber included in the fiber optics kit, the moving fiber hydrophone is simple to put together on the optical table. The only problem is to prepare the ends of the two fibers that form the sensor and to couple them to the LED and the photodetector. It is easy to displace the receiving fiber by blowing on or fanning the assembly. This was readily visible on the oscilloscope. Using this sensor in air on the table made the sensor fairly responsive to air movements near the fiber. If the hydrophone were used in water, it may also be useful for sensing currents under water. Undersea currents may come from waves or from a submarine traveling past the sensor.

To get an idea of how sensitive this hydrophone is to sound pressure, I brought a speaker near the output fiber. This required setting the power meter to measure down to 3 decimal places. One problem this creates is that the power at the detector must be less than 2 milliwatts, or the reading will be out of range. Using an audio generator, I generated tones on the speaker between 100 Hz and 1 kHz. This procedure is similar to a hearing test. Over this range, the response was very consistent, showing power drops of up to 50 microwatts each time. The frequency response is probably pretty flat over this range. The small power changes made it impossible to see waveforms on the oscilloscope, but the power readings show that the fiber is moving under the pressure of acoustic waves.

DISCUSSION

There are ways to improve the sensitivity of this type of hydrophone. One way would be to attach a flexible diaphragm to the receiving fiber. This would increase the sensor's effective area. It would also change the resonant frequency of the device, making it closer to that of the diaphragm than to the glass fiber. It is also possible to control the resonance point of the glass itself by measuring how long the moving fiber is. Another design change can be to use single-mode fibers rather than multimode. This would make the sensor more responsive because of the much smaller (about 3-5 micron) core diameter. It would take much smaller axial offset to misalign the cores. However, single-mode fibers are more difficult to handle and align. In short, while the moving-fiber sensor is relatively simple to understand and to put together, it is limited in its application by its sensitivity.

To make this device useful under water, it would be necessary to package it so that the fibers remain aligned in the absence of stimulus. One consideration is whether or not the fibers are to be in the water. Optical fibers are useful under water, unlike some electrical transducers. The coupling efficiency at the gap would be improved because the index of refraction of water is closer to that of glass than air is. However, water has a high fluid viscosity and would damp the movements of the fiber, further reducing its sensitivity. The fibers remained aligned in the absence of pressure very well in air, but I do not know if this would happen in water as well. A speaker cone may help correct the moving-fiber hydrophone's problem.

CONCLUSION

This fiber hydrophone design has been a very interesting project for me because it is something out of the scope of my academic work here at NIU. I would not have learned so much about fiber optics without doing this project. I expect that this experience will only help me when I join the Navy.

This is not the only method of modulating light in an optical fiber by any means. There are many other fiber optic sensor devices.[8] Because of its sensitivity problem, the moving-fiber sensor is not a very useful one in military applications. Before I conclude this report, I will give a brief discussion of the fiber optic interferometer.

The interferometer is easily the most sensitive sensing device available, and this is the concept used in hydrophone design by the U. S. Navy. Unlike the moving-fiber sensor, the interferometer is a phase-modulation scheme. Because optical wavelengths are on the order of 1 micron, it is possible to see phase changes due to very small changes in the effective path length of the wave.

A fiber interferometer has two coils of fiber, a sensing coil and a reference coil. The sensing coil is exposed to the environment and the reference coil is isolated and stabilized. Basically, the interferometer splits the light it carries between the sensing coil and the reference coil and couples the light from the two together at the output end. When the two combine, they interfere with each other constructively or destructively, depending on the phase difference. The output is the superposition of the two waves.

A diagram of an all-fiber Mach-Zehnder interferometer is shown in Fig. 5.[9] A laser launches power into the fiber, and a beam splitter divides the beam between the sensing coil and the reference coil. The sensing coil is designed so that when the two beams recombine, they are in quadrature, or 90 degrees out of phase. Thus in the absence of disturbance, the recombined interference pattern will be of the form

$$A_o[\sin\phi + \cos\phi]. \tag{9}$$

If the sensing coil has a pressure-sensitive jacket, it will experience strains in the presence of sound. If the fiber is stretched or compressed by the sound wave, the phase change can be measured relative to the reference coil. Again, the small wavelengths of optical signals means small changes in the length of the sensing coil are visible in the interference pattern.

The interferometer hydrophone requires some special design considerations. The light must be highly monochromatic, which immediately mandates a single-mode laser diode as a source. It also means single-mode fiber is most suitable. Because of their small core size, single mode fibers are more difficult to handle than multimode fibers. They are also more difficult to couple to sources and detectors. In addition, it is necessary to maintain quadrature between the sensing coil and the reference coil. This is perhaps the biggest challenge for optical fiber designers, and is an area of research the Navy supports.

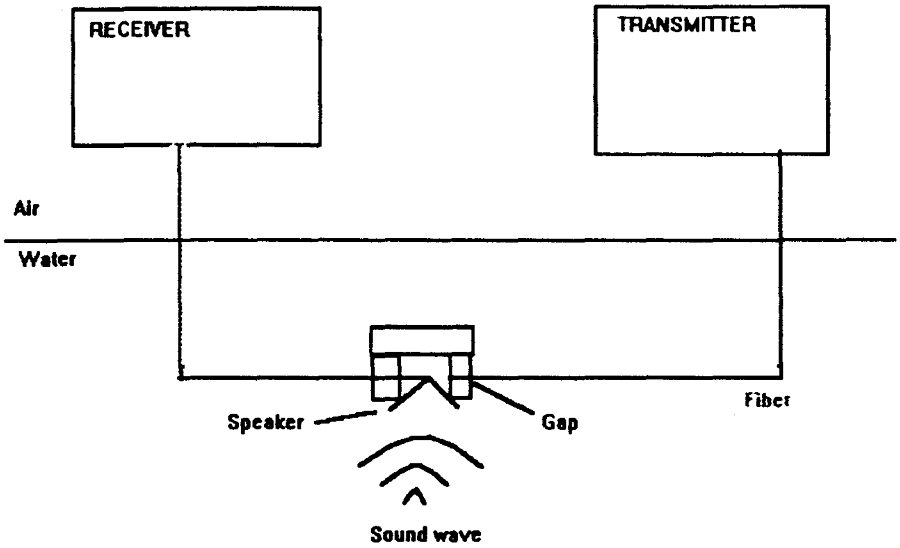


Fig. 1 Fiber Hydrophone block diagram.

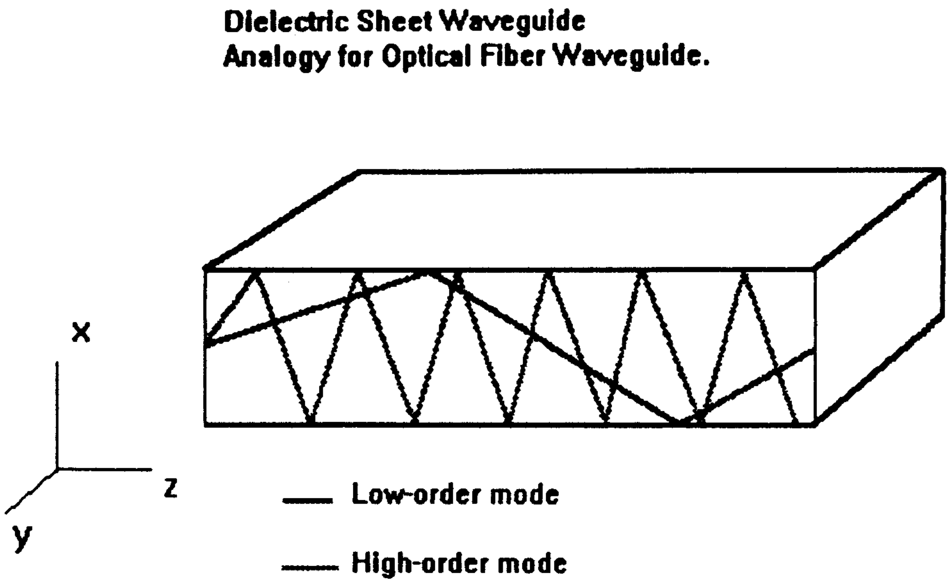


Fig. 2 Dielectric Sheet Waveguide Showing Low and High Order Modes

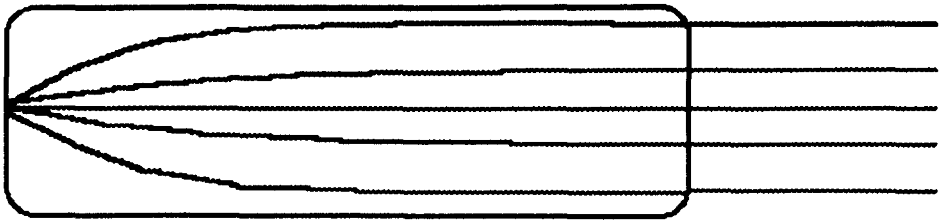


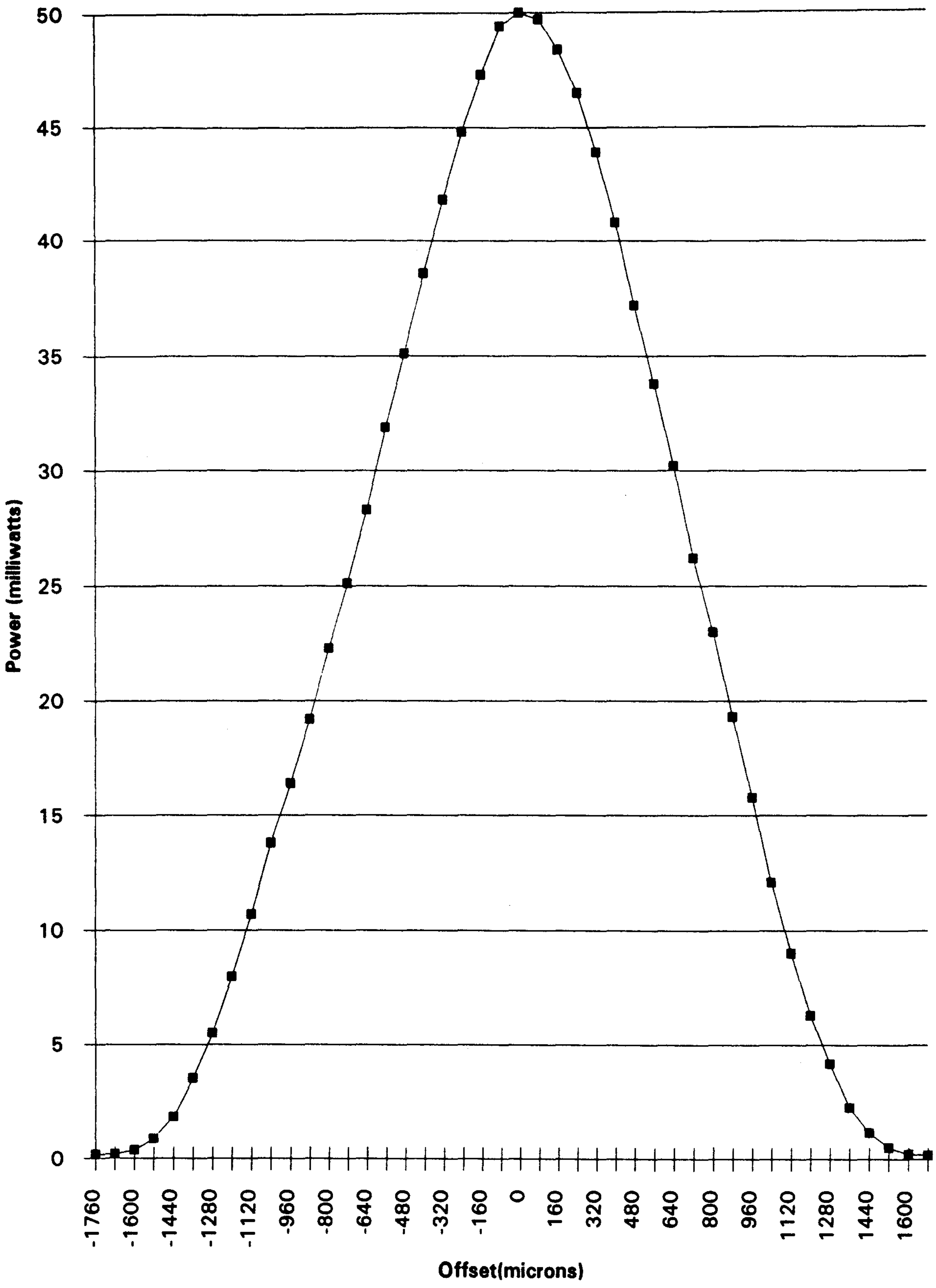
Fig. 3 Quarter-pitch GRIN Rod Lens used as a Collimator.

Table I

	Data #	Lateral offset	Power(mW)		
Offset left	-22	-1760	0.19		
	-21	-1680	0.21		
	-20	-1600	0.37		
	-19	-1520	0.88		
	-18	-1440	1.83		
	-17	-1360	3.53		
	-16	-1280	5.49		
	-15	-1200	7.99		
	-14	-1120	10.7		
	-13	-1040	13.8		
	-12	-960	16.4		
	-11	-880	19.2		
	-10	-800	22.3		
	-9	-720	25.1		
	-8	-640	28.3		
	-7	-560	31.9		
	-6	-480	35.1		
	-5	-400	38.6		
	-4	-320	41.8		
	-3	-240	44.8		
	-2	-160	47.3		
	-1	-80	49.4		
Aligned	0	0	50		
Offset right	1	80	49.7		
	2	160	48.4		
	3	240	46.5		
	4	320	43.9		
	5	400	40.8		
	6	480	37.2		
	7	560	33.8		
	8	640	30.2		
	9	720	26.2		
	10	800	23		
	11	880	19.3		
	12	960	15.8		
	13	1040	12.1		
	14	1120	9.01		
	15	1200	6.28		
	16	1280	4.18		
	17	1360	2.27		
	18	1440	1.16		
	19	1520	0.5		
	20	1600	0.22		
	21	1680	0.19		
End of data					

Table I

Power vs Axial Offset of Lenses



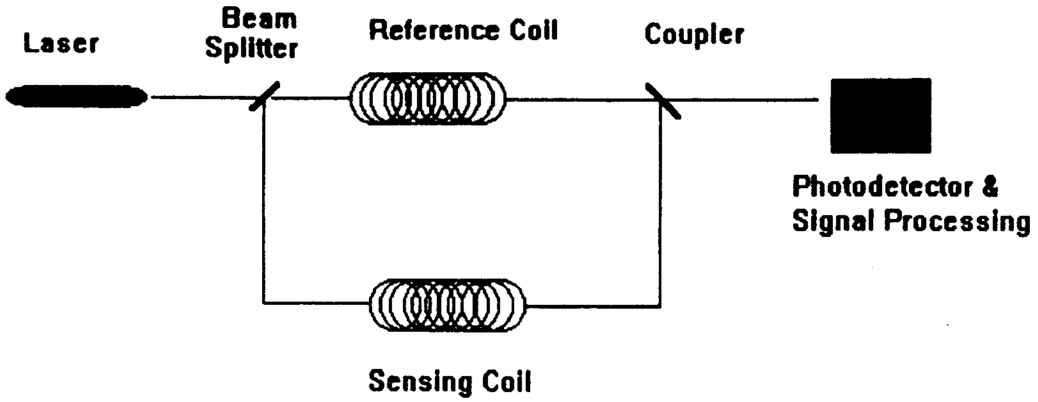


Fig. 4 Fiber Optic Interferometer Diagram.

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Appendix: Dielectric Sheet Waveguide Example

$\eta 1 := 1.5$	Index of refraction of dielectric
$\eta 2 := 1$	Index of refraction of air
$d := 10 \cdot \mathrm{mm}$	Thickness of dielectric sheet
$\lambda := 10 \cdot \mathrm{mm}$	Free space wavelength

The critical angle for propagation of a trapped ray is:

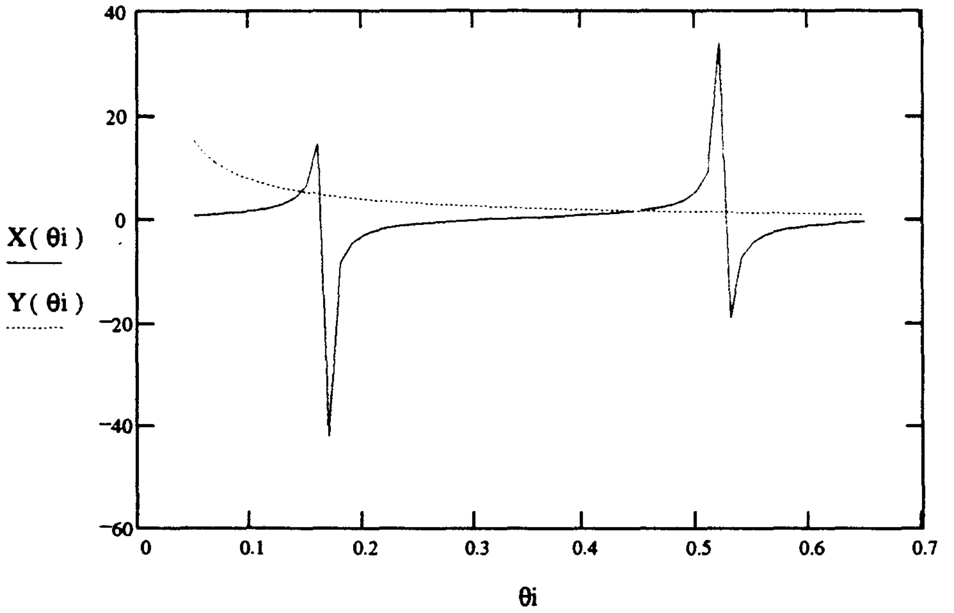
$$\theta := \mathrm{asin}\left(\frac{\eta 2}{\eta 1}\right) \qquad \theta \cdot \frac{180}{\pi} = 41.81$$

Angles to create graph:

$$\theta i := 0.05, 0.06 .. 0.65$$

$$Y(\theta i) := \frac{\sqrt{\eta 1^{2} \cdot (\cos(\theta i))^{2} - \eta 2^{2}}}{(\eta 1 \cdot \sin(\theta i))} \qquad X(\theta i) := \tan\left(2 \cdot \pi \cdot \eta 1 \cdot d \cdot \frac{\sin(\theta i)}{\lambda}\right)$$

$Y(0.84) = 0.044$ This corresponds to a cutoff angle, 0.85 radians.



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