# DETECTING AND LOCATING PARTIAL DISCHARGES IN TRANSFORMERS

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# Executive Summary

A collaborative research between the Oak Ridge National Laboratory (ORNL), the American Electric Power (AEP), the Tennessee Valley Authority (TVA), and the State of Ohio Energy Office (OEO) has been formed to conduct a feasibility study to detect and locate partial discharges (PDs) inside large transformers. The success of early detection of the PDs is necessary to avoid costly catastrophic failures that can occur if the process of PD is ignored. The detection method under this research is based on an innovative technology developed by ORNL researchers using optical methods to sense the acoustical energy produced by the PDs.

ORNL researchers conducted experimental studies to detect PD using an optical fiber as an acoustic sensor capable of detecting acoustical disturbances at any point along its length. This technical approach also has the potential to locate the point at which the PD was sensed within the transformer. Several optical approaches were experimentally investigated, including interferometric detection of acoustical disturbances along the sensing fiber, light detection and ranging (LIDAR) techniques using frequency modulation continuous wave (FMCW), frequency modulated (FM) laser with a multimode fiber, FM laser with a single mode fiber, and amplitude modulated (AM) laser with a multimode fiber. The implementation of the optical fiber-based acoustic measurement technique would include installing a fiber inside a transformer allowing real-time detection of PDs and determining their locations. The fibers are nonconductive and very small (core plus cladding are diameters of 125 μm for single-mode fibers and 230 μm for multimode fibers).

The research identified the capabilities and limitations of using optical technology to detect and locate sources of acoustical disturbances such as in PDs in large transformers. Amplitude modulation techniques showed the most promising results and deserve further research to better quantify the technique's sensitivity and its ability to characterize a PD event. Other sensing techniques have been also identified, such as the wavelength shifting fiber optics and custom fabricated fibers with special coatings.

# List of ACRONYMS

| | |
|---|---|
| AM | Amplitude modulation |
| AEP | American Electric Power |
| FMCW | Frequency modulated continuous wave |
| FM | Frequency modulation |
| LIDAR | Light Detection And Ranging |
| OEO | State of Ohio Energy Office |
| ORNL | Oak Ridge National Laboratory |
| PD | Partial discharge |
| SNR | Signal to noise ratio |
| TVA | Tennessee Valley Authority |

# 1. Introduction

Accurately predicting impending failures in large transformers is of significant benefit to the power industry for three reasons. First, unplanned outages can be reduced, which improves the system's reliability. Secondly, since catastrophic failure of transformers can be very expensive, knowledge of the start of transformer degradation and the internal location of the fault allows corrective actions to be taken in a timely manner. This failure prediction will reduce the likelihood of catastrophic failures. Thirdly, equipment failures can result in exposure to potential injury and toxic release for operating personnel, the public, and the environment. Partial discharges (PD) are early indicators of faults within transformers and could provide an early warning system to operation personnel.

Partial discharges are sparks generated by the flow of electrons and ions that are generated when small volume of gas breaks down. This phenomenon mostly occurs in voids or cracks within the transformer's winding system. The voids, the windings, and the core structure can be viewed as a series of capacitances with different dielectric constants. The stress on the gas within the void may become high enough for breakdown to occur. This degradation process depends on the size of the void, the dielectric constant, the temperature, and the local field strength (sharp points increase the local field strength). In most cases, the electric field will not be uniform and this tends to lower the break down voltage, which can be in the range of 200 to 300 volts.

PD activity can be detected by the evolution hydrocarbon gases produced in the insulating oil, measurement of the electrical activity during PD, and acoustic measurements of the energy expended during a PD event. Hydrocarbon gas measurement is effective, but depends on having time to produce a volume of gas indicative of the developing problem. In addition, hydrocarbons are likely to be produced inside the windings where they become difficult to detect (perhaps trapped) and localization is impossible. Electrical activity during transformer based PD is significantly lower intensity than the other forms of discharges on an electrical system. It can be difficult to separate and interpret in the working environment.

Current systems that detect PD typically monitor for the acoustic energy from the outside of the transformer. This remote acoustic measurement results in two problems: a low energy signal with background noise contamination and a significant difficulty in determining the location of the PD because of multiple sound paths. ORNL researchers proposed to develop and demonstrate a laboratory-scale, on-line transformer fault early warning system by applying an *in-situ* novel fiber optic-acoustic measurement technique to detect the sound energy from PDs within large power transformers. A standard optical fiber is used as a line microphone within the transformer to detect acoustic waves. Acoustic waves, generated by PDs, exert pressure forces on the optical fiber resulting in a change in the fiber's index of refraction. By placing the fiber in an interferometer leg, the acoustic signals appear as amplitude modulations at the interferometer's light detector. Initial tests with this methodology in a simple experiment showed that the technique is quite sensitive. In addition to the detection of a PD event, a method has been devised to pinpoint the location along the fiber where the acoustic energy arrives and thus, the location of the PD and transformer fault. These optical fibers contain no conductive materials and therefore can be located inside the transformer to enhance the ability to detect very small discharges, their location, and provide diagnostics and prediction of transformer failures.

Early in the project, functional requirements were developed to provide guidance in subsequent innovation and experimentation of an acoustic-fiber detection system for transformer partial discharge. The requirements are included as an Appendix to this report.

## 2. Fiber Optic Sensing Background

The field of fiber optics has undergone significant growth and advancement over the last four decades; where the technology advanced from the ability to carry light and images for medical endoscopic applications to carrying information for telecommunication application, and most recently the use of optical fibers in sensing and control applications. Optical sensing techniques have long been associated with precise and non-intrusive measurements. In conventional optical instruments, considerable mechanical stability is required in order to maintain alignment, thus restricting applications to controlled environments. In the past decade, there has been considerable development in the field of fiber optic technology. The availability of high quality optical fibers and fiber components has facilitated the realization of fiber optic based sensors. Their inherent high resolution, lightweight, and immunity to EMI give optical fiber sensors an advantage in diverse industrial applications.

Fiber optic sensors are widely used in industrial, scientific, and military applications to measure various physical properties, such as but not limited to, displacement, temperature, pressure, rotation, sound, strain, magnetic field, flow, liquid level, vibration, and chemical composition. Applications requiring a high degree of measurement sensitivity employ fiber optic sensing techniques known as phase-modulated sensors as compared to intensity-modulated sensors, which are usually far less sensitive. The high sensitivity of the phase-modulated sensors is attributed to the ability to measure small phase differences between two light beams carried in two separate fibers. One of the fibers is exposed to the perturbation under measurement (sensing fiber) while the other fiber is used as a reference (reference fiber). In general, a beam of light is fully characterized by its wavelength, phase, intensity, polarization state, degree of polarization, and degree of coherence. In optical sensors, any one, or a combination of these parameters, may be modulated in response to external stimuli. In this measurement technique, known as interferometry, a phase shift results from changes in the length and the refractive index of the sensing fiber as given by

$$\Phi = nkL, \qquad (1)$$

where $n$ is the refractive index of the fiber core, $k$ is the optical wave number in vacuum ($2\pi / \lambda$, $\lambda$ is the wavelength), $L$ is the physical length of the fiber, $\Phi$ is the phase shift, and $nL$ is the optical path length. It follows from (1) by differentiation that

$$\frac{d\Phi}{\Phi} = \frac{dL}{L} + \frac{dn}{n} + \frac{dk}{k}, \qquad (2)$$

which indicates that small variations in phase delay can be measured in terms of physical changes in the fiber, mainly the fiber length and index of refraction, caused by the perturbation being measured.

If the paths of the sensing and reference fibers are exactly the same length or differ by an integral number of wavelengths, the recombined beams are exactly in phase and the beam intensity is at its maximum. However, if the two beams are one half a wavelength out of phase, the recombined beam intensity is at its minimum value. This reflects 100% modulation occurring over ½ wavelength change in fiber length. This sensitivity allows variations as small as ~ $10^{-13}$ to $10^{-15}$ meters to be detected.

Optical instruments designed to perform such measurement (interferometers) are commercially available in four different configurations, Michelson, Fabry-Perot, Sagnac, Mach-Zehnder. Figure 1 illustrates the interferometric measurement using the Mach-Zehnder interferometer. In this configuration, the laser output beam is split by using a 3 dB fiber-to-fiber coupler (beam splitter), where 50% of the light is injected into the single-mode-sensing fiber and 50% into the reference fiber. The light beams are recombined by using a second 3 dB fiber-to-fiber coupler where the combined beam is detected by photodiodes that convert the optical signal into an electrical signal. The signal is then conditioned and processed to correlate the resulting phase shift with the corresponding perturbation (gas leak).

The output signal $I$ representing the interference between the two mutually coherent beams of an interferometer can be expressed as

$$I = I_o ( 1 + V \cos \Phi(t)), \quad (3)$$

where $I_o$ is an intensity constant that includes factors such as the conversion efficiency of the photo detector, $V = 1$ is the visibility of the fringes at the output of the interferometer, and $\Phi(t)$ is the time dependent differential phase between the two arms of the interferometer. As indicated by Equations (2) and (3), the induced phase change $\Phi$ results in intensity modulations at the output of the interferometer.

## 3. Technical Approach

ORNL researchers experimentally investigated various optical approaches to determine the best approach for detecting and locating the source of low energy level acoustical signals. In all approaches, optical fibers (including single mode and multimode) were used as the sensing element and a modulated laser beam (including FM and AM) as the sensing signal. The PD was simulated by two methods: (1) by manually squeezing the fiber at various points along its length and (2) applying an ultrasound signal with a known energy using an ultrasound generator. The following is a description of each investigated method. For any of discussed methods to be deployed in the field, one or more fibers would be installed inside the transformer to allow real-time monitoring of the PDs.

## *3.1. Interferometry*

### 3.1.1. Approach

In this approach, an acoustic energy similar to what is typically produced by PD event was sensed as a phase shift between two light-beams applied to two single-mode optical fibers. As shown in Figure 1, the two beams were transmitted into the fibers by splitting the same light from a coherent light source; a diode laser with 852 nm wavelength. An interferometer receives the light beams from both fibers and determines the phase shift by analyzing the resulting pattern of light and dark bands (fringes). When one fiber is disturbed relative to the other, a phase shift occurs which can be detected precisely by the interferometer. If the light beams in both fibers are exactly in phase upon recombining, they constructively interfere with an increased light intensity. If they are out of phase; however, a destructive interference occurs and the received light intensity is reduced. ,A fringe pattern is produced as this process is repeated that is directly modulated by the acoustical disturbance caused by a PD.

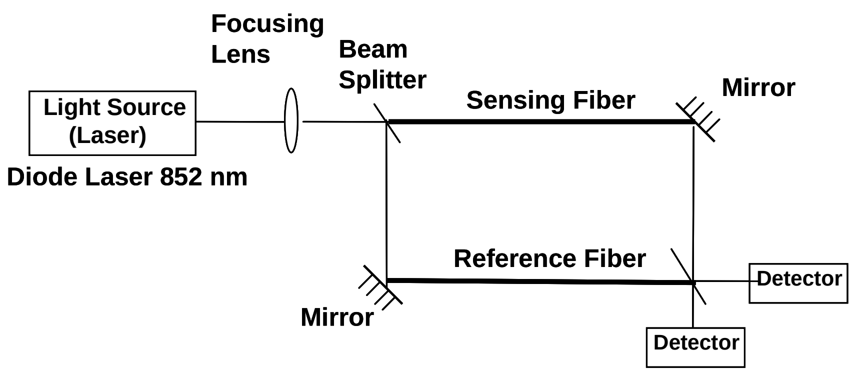


**Figure 1. Schematic representation of an all-fiber Mach-Zehnder interferometer.**

### 3.1.2. Results

Numerous measurements were made and exhaustive investigation proved this approach to be not suitable for detecting and location acoustical disturbance along the sensing fiber. The signal to noise ratio (SNR) turned out to be quite small over a large frequency range. In addition, a very small phase shift was observed as an acoustic signal was applied at various points along the fiber. This phase shift was too small to provide the sensitivity required to make a reliable judgment about the location of the acoustic source.

## *3.2. FM laser with multimode fiber (LIDAR)*

### 3.2.1. Approach

In this approach, a laser is driven from a signal generator with a linear frequency-modulated (chirp) signal, which is a signal whose frequency increases linearly as a function of time over period T, as shown in Figure 2. The laser diode, 852 nm, converts the chirp current waveform into a light waveform where the frequency is proportional to the driving current. The light is collected by a lens, collimated, and directed to a target, which in this case is a reflecting mirror. When the fiber is exposed to an acoustic disturbance at any point along its length, part of the transmitted signal is reflected back. The reflection occurs due to the change in the index of refraction at the point of disturbance due to flexing the fiber created by the pressure waves. The reflected light is then combined by the light that is reflected by the reference mirror and collimated by a lens, and directed into a photodiode.

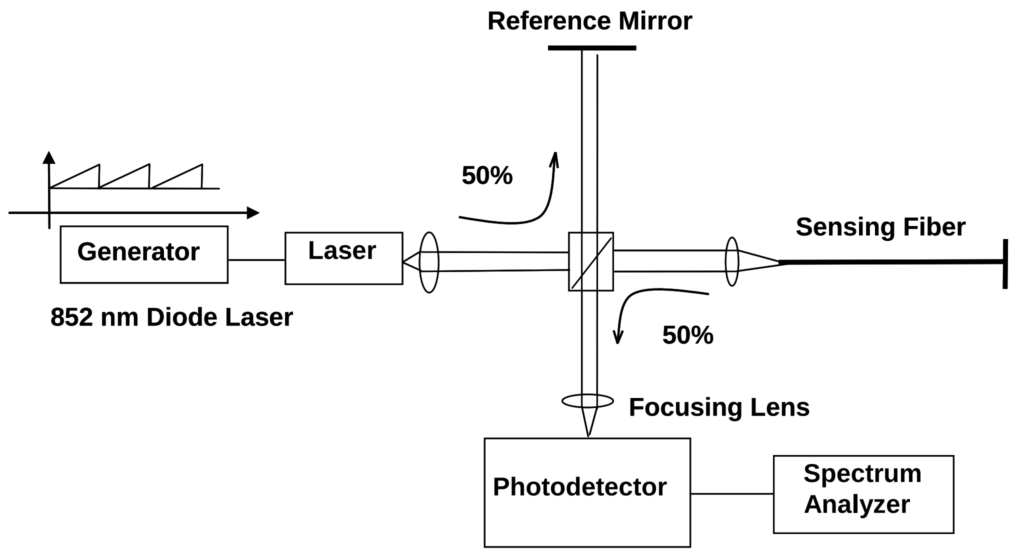


**Figure 2. Simplified schematic diagram of the FM LIDAR System developed for these tests.**

The distance from one end of the fiber to the point at which the acoustic disturbance occurred can be estimated in a similar way as in the case of the FM radar applications. The difference between the start and stop frequency, ΔF (also known as the beat frequency), is chosen to establish the LIDAR resolution ΔR according to the well known equation:

$$\Delta f = \alpha\,(2\,\Delta R)/C \qquad (4)$$

Where:

$\Delta f$ ≡ beat frequency, $\Delta R$ ≡ Distance from one end of the fiber to the point of disturbance, α ≡ factor related to laser chirp, and C ≡ Speed of light. The distance $\Delta R$ can then be estimated by measuring the beat frequency $\Delta f$.

### 3.2.2. Results

Measurements were taken over a 100 kHz frequency range; the results indicated a high degree of sensitivity to acoustic disturbance. However, phase shift information was lost (as it was an extremely small signal) due to the mode conversion when the fiber received a simulated acoustic disturbance. Consequently, the LIDAR approach was considered unsuitable for PD detection due to the inability to locate the PD source.

### 3.3. FM laser with single mode fiber

#### 3.3.1. Approach

To avoid the problem of mode conversion that was encountered in the FM LIDAR concept with a multi-mode fiber, the LIDAR set up was modified. As shown in Fig. 3, the sensing fiber was replaced with a single-mode type and two photo-detectors were used; one at each end of the fiber. One detector is used to monitor the reflected signal and the other to monitor the transmitted part of the signal resulting from exposing the fiber to an acoustical disturbance. Using the single mode fiber ensures that the light being transmitted through the fiber will travel in one path and when the fiber is exposed to acoustical disturbance, the change in the index of refraction will cause part of the light to reflect back toward the laser and part will be transmitted through. Comparing the phase shift of the transmitted signal to the light that was originally generated by the laser should provide the information necessary to estimate the location where the perturbation took place.

#### 3.3.2. Results

The experimental results form this concept revealed a very unusual phenomenon. By introducing a mechanical disturbance through squeezing the fiber, at any point along its length, very little light was detected at either end of the fiber; i.e., not much light was reflected and likewise not much light was transmitted past the point of perturbation. After thorough investigation of the results, it was suspected that most of the light was escaping from the fiber by scattering at the point where the fiber was squeezed. This was confirmed by replacing the IR diode laser (852 nm) with a visible light laser (620 nm). In addition, analyzing the signal from the spectrum analyzer, Figure 4, indicated that phase shift information is not useful for detecting the event location for two reasons: (1) the SNR is very low and (2) the peak produced by the event is rather wide in frequency. Any estimation of the location based on frequency information will produce significant uncertainties.

It became obvious at this phase of our research that the FM concept would not be useful in detecting PD events due to its inability to estimate locations. Further investigation lead into undertaking the AM concept, which will be described next.

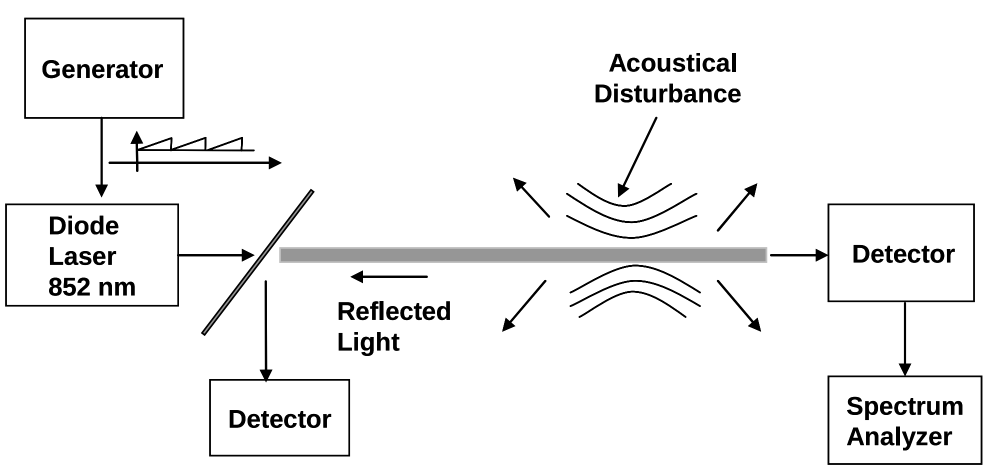


**Figure 3. Modified FM LIDAR concept using single-mode fiber.**

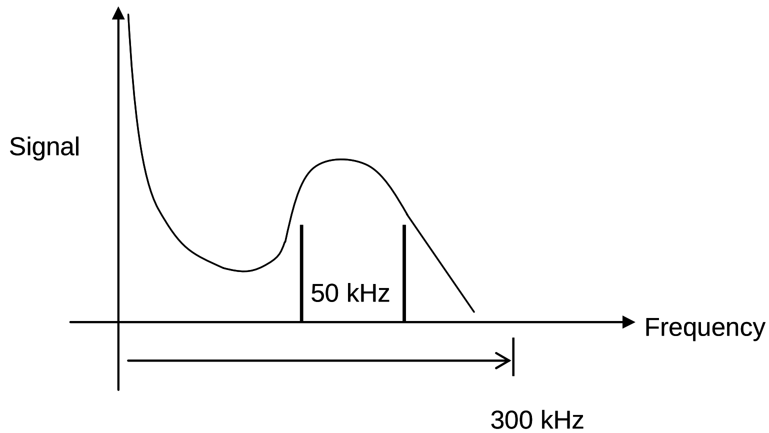


**Figure 4. FM Laser Phase Shift with Wide Frequency Range.**

## *3.4. AM laser with multimode fiber*

### 3.4.1. Approach

Several experiments were conducted using an amplitude modulated laser with multimode fiber, as shown in Figure 5. The tests have shown promising results in the detection sensitivity and location capabilities by using a timing technique. However, in order to enhance the capability of estimating the location of the perturbation source along the fiber, several ideas were identified, as shown in Figure 6.

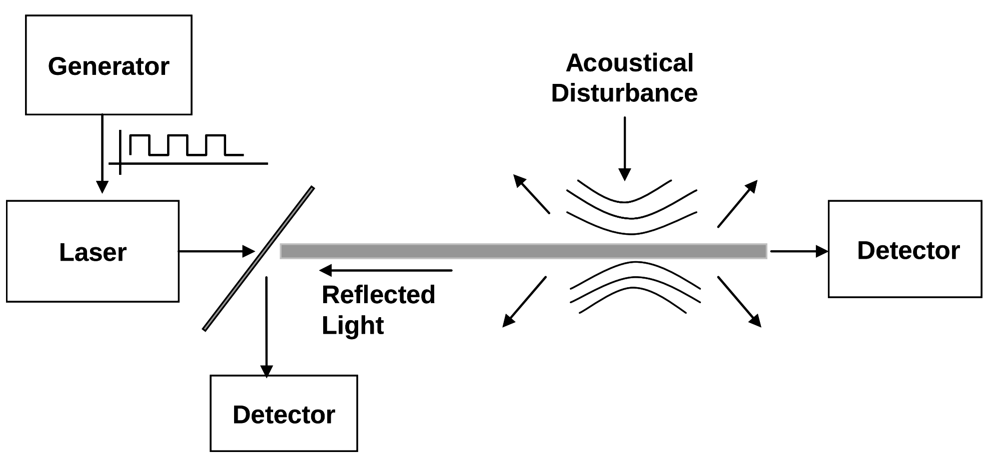


**Figure 5. Modified AM LIDAR concept using single mode fiber.**

- Reflect the light scattering out from the fiber back into the fiber. This can be accomplished by using special fibers with reflection coating, or by using other fibers surrounding the sensing fiber. This later method is mostly suited for pipeline leak detection. This method would allow the FM laser with a single mode fiber to function.

- Using wavelength shifting fiber as a sensing fiber. Wavelength shifting fibers would be placed around the sensing fiber. When light leaks out of the sensing fiber due to a disturbance, the wavelength shifting fibers would receive this leaking light. This would require a simple and cheap blue light source, such as light emitting diodes (LEDs) for driving the sensing fiber. The wavelength shifting type of fiber is commercially available and is used in nuclear technology applications to detect radioactive decay in scintillation-type radiation detectors. When the fiber is exposed to blue light, almost 95% of the light is coupled into the fiber and is converted into a longer wavelength (green light). The green light transmits equally in both directions along the fiber. The timing of the green light received at the two ends of the fiber provides a means of estimating the location of the disturbance with reasonable accuracy.

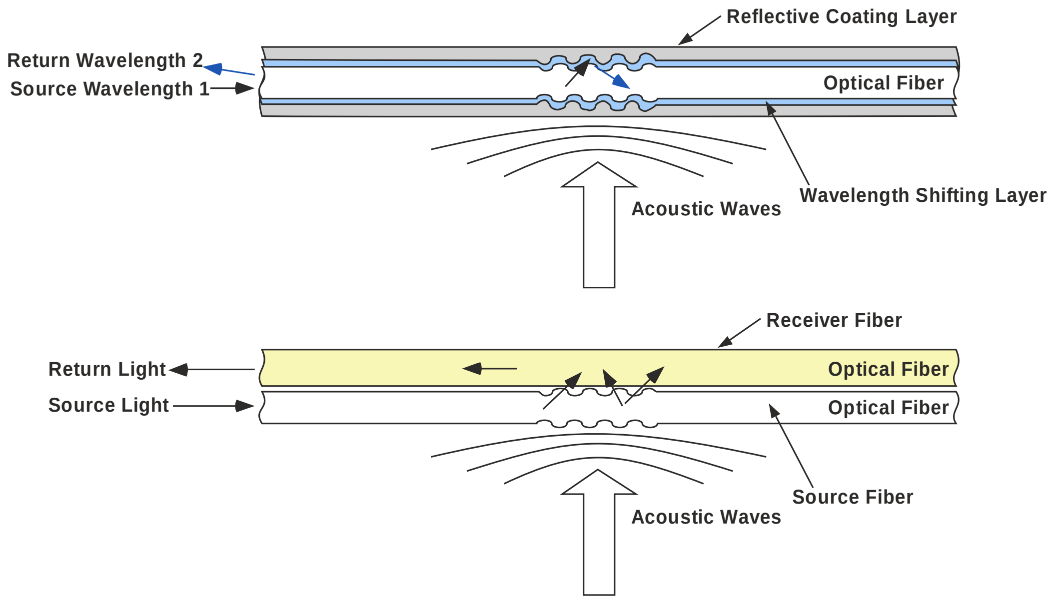


**Figure 6. Special multi-mode fiber concepts for acoustic disturbance detection with spatial location features.**

# 4. Project Results

The results of this research have shown that for the methods tested, the optical sensing of acoustical perturbations using a laser and optical fibers as the sensing element has significant sensitivity. Most methods attempted however, do not function well in determining the location of the acoustical disturbance. Bench top experiments and analytical concepts did show that two techniques have promise in detecting and locating acoustical energy. The FM laser with a single mode fiber that is coating with a reflecting film should allow both detection and location of a disturbance. A disturbance will cause light to leak form the single mode sensing fiber and the coating will reflect that light back into the sensing fiber. A disturbance will cause light to be reflected back toward the source and some will transmit on to the end of the fiber. The resulting phase shift can be used to determine the location. The AM laser method with multi-mode fiber can also be used to detect and locate acoustic disturbances.  This AM technique offers some significant advantages such as (1) the multi-mode fibers are more rugged than single-mode fibers, (2) multimode fibers are easier to align and (3) the AM technique should result in a lower cost system.

## 5. Future Research and Development

The AM laser with multimode sensing fibers and wavelength shifting fibers has been demonstrated at the bench-top level as a viable technique for detecting and locating PDs in transformers.  There is still significant work to be accomplished to make this technique a robust field measurement system. In order to achieve this goal of a robust system, several steps must be taken.

a. Development, design, and fabricate a prototype AM laser system
b. Quantify and improve the SNR of the AM laser technique
c. Quantify the sensitivity for acoustic detection levels and accuracy of disturbance locating technique using a calibrated high-voltage discharge in an oil bath
d. Test the prototype in a simulated field environment
e. Pilot test the system in a real transformer

In addition to the application of the partial discharge detection, this fiber optic-acoustic measurement system has the potential to detect and locate leaks in pressurized piping over relatively long distances, ~15km per system.  The measurement system may also be able to be configured to measure temperature in transformers or piping systems as well and be used as a infrastructure protection system that can detect intruders or abnormal acoustic or vibration around critical infrastructure.  These additional potential applications can also save significant energy through rapid detection of steam or natural gas leaks, temperature changes indicating insulation loss or degradation, security issues at critical infrastructure locations such as power plants and electrical substations.  It would be desirable to demonstrate the technology to a point where the potential of these applications, as well as others, could be clearly evaluated.

# Appendix

## Functional Requirements for Acoustic-Fiber Detection of Transformer Partial Discharge

March 19, 2004

These functional requirements reflect the desirable characteristics of a commercial fieldable acoustic-fiber partial discharge instrument. The laboratory prototype being developed in this project will demonstrate acoustic detection and localization capability. We expect to prototype in such a manner that a path forward to meeting these functional requirements is commercially realizable. Not all of these functional requirements will be met by the prototype.

### Detection Parameters

*Minimum detectable acoustic level (sensitivity)*
20 dBm at the fiber surface (this reference is for an ultrasonic source in air). Although this is an important parameter, field experience has been with piezoelectric sensors external to the transformer tank. Additional experimentation is necessary to determine a relationship to sensitivity in oil, inside the tank, in close proximity to the partial discharge sources.

*Response time of overall system*
We would expect that the optics, electronics, and algorithms would yield a time delay from event to report of less than five seconds. The response time comes about because signals derived from spectrum analysis of the detector have to be processed. With high-speed digital signal processing (DSP) much can be accomplished in five seconds. It is quite possible that less that one second would be sufficient. Time stamping would be possible, which makes the delay inconsequential. PD data can be subsequently correlated with data from other recording transformer diagnostic sensor systems, for dissolved gas, EMI, alarm contact closures, etc. Time stamping can be synchronized to GPS or SCADA.

*Range of acoustic frequencies*
2 kHz to 2 MHz

*Minimum spatial resolvability along fiber*
5.0 cm

*Detection of Multiple Discharges*
A challenge to meet is detection and separation of signals from multiple acoustic sources. Detection of discharges from various locations but having different non-coincident times is a minimum capability. A more difficult capability is to separate simultaneous discharges from differing locations.

## Component Placement

*Fiber*

The entire optical fiber is operating as a sensor; however, the active portion is that part inserted in the transformer. Optical fiber outside the transformer should be protected with standard fiber jacketing. A penetration is required where the fiber enters the transformer. A penetration is also required where the fiber passes into the opto-electronics package. Figure 1 below illustrates the fiber connecting the opto-electronics package with the transformer.

*Opto-Electronics Package*

The opto-electronics package is mounted external to the transformer up to several meters from the transformer penetration point. The package can be mounted stand alone or placed in a rack mount. Not shown in Figure 7 are the output signals, which can be provided in a compatible format for the utility, and the power connections.

The opto-electronics box shows the internals of the device. The optical components are the interferometer, laser, and detector. Electronic systems are the modulation system, spectrum analyzer, and spatial analyzer, which assigns signals to bins for further analysis.

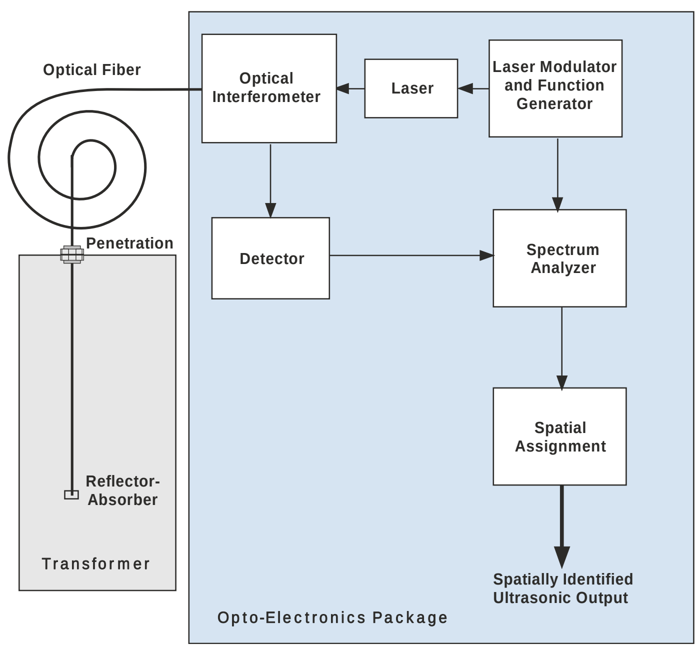


**Figure 7. PD Detection Apparatus Block Diagram.**

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## Physical Parameters

*Fiber size/type*

Fiber diameters will be less than one mm including cladding and any jacketing. We expect the optical fiber length to be 10 m; however, longer can be accommodated. The glass fibers will not be electrically conductive. The fiber should have the applicable physical characteristics (e.g., strength, durability, flexibility, brittleness, and bending radius) to be suitable for 1) retrofitting it into an existing transformer surrounding the coils, 2) winding it with the conductor as part of the transformer coil manufacturing process. Loose tube fiber would not be appropriate because of the likely attenuation of acoustic signals. The optical connection between the sensor fiber and the opto-electronics package may require jacketed fiber in a Kevlar 3mm loose-tube. This would be for handling purposes and general ruggedness. The actual fiber would necessarily need to be consistently the same diameter and type throughout to maintain mode stability and minimize reflections.

*Interferometer vibration withstand*

The apparatus will be moderately sensitive to external vibration. The maximum vibration withstand of the package will depend on the internal shock mounting effectiveness. It may be necessary to incorporate internal shock mounting and provide vibration isolation at the cabinet level. Manufactured instruments resulting from these experiments will use cast components and fabrication methods that enable field use, whereas the laboratory apparatus is assembled from standard optical components on a breadboard.

*Operating temperature range*

Optical/Electronic apparatus: We expect external field environments to be from -40°C to 60°C with 0 to 100 percent RH. An enclosure can be developed to meet these temperature specifications. A moderate amount of active cooling of specific components (e.g., laser diode and certain optical components) may be required to permit reliable functioning at the elevated temperatures.

Optical fiber: Fiber will withstand continuous oil bath from ambient to 70°C. Sensing fiber can be mounted in most any location within the tank since voltage conductivity is not a consideration. Fiber should be secured so that continued flexing from vibration or oil velocity does not cause fatigue or generate large signals that exceed the system's dynamic range, which might obscure the PD acoustic signal. A small amount of flexing and contact with other surfaces will generate a signal; however, we expect the resulting spectrum to be oriented to low frequencies and not have much at PD frequencies.

*Equipment Size*

A commercial version should be able to fit in a box of 20x40x80 $cm^3$ including electronics. These dimensions are fluid. This box is external to the transformer and should be mountable in a 2U standard EIA 19 inch rack

*Portability*
A commercial version can be made with precision cast and locked optical components and be easily portable. Weight will be less than 14 kg.

*Fiber penetration interface*
The transformer fiber penetration will be air-, water-, and oil-tight.

*EMI/RFI immunity*
The fiber is non interactive with EMI or RF energy. However, the optical/electronic package will be susceptible at the component level; therefore appropriate shielding will be required. Conversely, the instrument will not emit significant radiation to cause interference with other equipment. The electronics system's enclosure can be reasonably designed to 60db attenuation. The input penetration is the optical fiber, which does not provide an EMI conduction path. The power and output connections need separated isolation to achieve maximum noise attenuation.

*Electrical Power*
Power requirements are 120 VAC 60Hz up to 2 amps for the laser, laser cooling, electronics, and DSP. Cooling apparatus for the entire package is an additional power requirement and could be up to 120 VAC 60Hz 5 amps.