Chapter 2
The Background Theories

2.1 Introduction

In this chapter, the background theories are reviewed and discussed. In the first section, the development of plastic optic fiber ranging from the fabrication techniques to the optical properties is discussed. In the following section, the multi-mode optical fiber waveguide theory is analyzed from its dispersion, absorption loss and rays propagation. In third section, a short introduction of Fiber Optic Sensors (FOSs) is depicted. In the last section, the development of Fiber Optic Displacement Sensor (FODS) and its major components are described. This chapter ends with a summary.

2.2 Historical Background on Plastic Optical Fiber

Over the past 10 years, the research of Plastic Optical Fibers (POFs) has received many attentions particularly in the improvements of its transparency and bandwidth for high-speed data telecommunication. It was first discovered by Pilot Chemical of Boston in year of 1960. Compared to the conventional data transmission media such as copper cable and glass fiber, POFs offer many advantages such as cheap, light, electromagnetic immunity, large bandwidth over short distances (up to 1000m), potentially low cost associated with easy installation, splicing and connecting. Additionally, POFs are not
brittle but ductile. It will stretch rather than break under increased tension, even a thick bundle of POFs is more flexible than a bundle of glass fiber [1-2]. These advantages make the POFs technology are very suitable for many new applications in data communication, industrial sensing and etc. The fiber core and cladding are generally made from polymethylmethacrylate (PMMA) as core and perfluorinated PMMA as cladding [3]. The first PMMA POFs were first commercially developed by DuPont in US and Mitsubishi Rayon in Japan in the year of 1970. In the POF, the refractive index difference between core and cladding comes to about 0.1 which results to a high value of 0.5 in Numerical Aperture (NA). The high NA of POF offers a high acceptance angle as compared to glass fiber with an acceptance angle of 16° corresponding to an NA of 0.14. These properties of POF allow the low precision plastic connectors to be used to reduce the cost of system and improve the light coupling efficiency from the light source to fiber.

The first step-index (SI) POF with a bandwidth of 50Mbps over 100 meters using 650nm light was first developed by Mitsubishi Rayon in 1980. At the same time, Kaino and co-workers [4] pioneered the study of the loss mechanisms in a multimode POF. The series of peaks in the loss spectra are reported, which are originated from harmonic oscillations of hydrogen atoms in the plastic chain. The most common modes are called C-H stretch modes which are associated with carbon. While those modes are following in the infrared portion of spectrum the overtones continue throughout the visible. The
hydrogen stretch modes become more intense in the infrared and the Rayleigh scattering decreases as the inverse of fourth power of wavelength. The minimum loss in most of the POFs is found in the visible wavelength. Fig. 2.1 shows the loss characteristic in two types of multimode POFs; polystyrene (PS) and PMMA. As shown in the figure, the lowest loss is observed in the wavelength range of near 650nm, which is considered as “transparency window”.

![Fig.2.1: Measured loss and contribution of Rayleigh scattering loss for PMMA and polystyrene [5].](image)

Single-mode POFs were first developed by Kuzyk and co-workers in the early of 1990 [6]. The core and cladding diameters of the single mode POFs are about 8μm and 125μm, respectively. These fibers had used the Disperse Red 1 Azo dye, Squarylium dyes and Pthalocyanine dyes doped cores that were responsible for the elevated refractive index as well as potentially having a large intensity dependent refractive index. However, the single-mode POFs have much larger attenuation than that of single-mode glass fibers therefore POFs remains less competitive for telecommunication applications.
Fig. 2.2 shows the loss spectra for various POFs, which are also compared to a silica-based fiber [5]. As shown in Fig. 2.2, the PMMA POF has the highest attenuation loss in the wavelength range of 300nm to 1500nm and therefore only a very limited research is focused on this range. The important landmarks in the development of POF are summarized in Table 2.1 [5].

![Fig. 2.2: Transmission loss spectra for various fibers: PMMA, D-PMMA (deuterated), CYTOP (which is an amorphous fluorinated polymer), PCS and silica [5].](image)

Table 2.1: The important landmarks in the development of POF during the past 40 year

<table>
<thead>
<tr>
<th>Year</th>
<th>Organization</th>
<th>Landmarks</th>
</tr>
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<tbody>
<tr>
<td>1968</td>
<td>Dupont</td>
<td>First SI POF with PMMA core</td>
</tr>
<tr>
<td>1972</td>
<td>Toray</td>
<td>First SI POF with PS core</td>
</tr>
<tr>
<td>1982</td>
<td>KeioUniv.</td>
<td>First GI POF (1070dB/km at 670nm)</td>
</tr>
<tr>
<td>1990</td>
<td>Keio Univ.</td>
<td>First high speed transmission with a PMMA core GI POF (300MHz*Km at 670nm)</td>
</tr>
<tr>
<td>1994</td>
<td>NEC</td>
<td>Transmission at 2.5Gb/s over 100m by means of a GI POF at 650nm</td>
</tr>
<tr>
<td>Year</td>
<td>Institution</td>
<td>Description</td>
</tr>
<tr>
<td>------</td>
<td>------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1995</td>
<td>Mitsubishi Rayon</td>
<td>Transmission at 156Mb/s over 100m by means of a low NA SI POF and a fast red LED</td>
</tr>
<tr>
<td>1996</td>
<td>Keio University, KAST</td>
<td>First perfluorinated GI POF (50dB/km at 1300nm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Theoretical estimation of the transmission speed in a GI POF optical link (PMMA:4Gb/s over 100m; PF:10Gb/s over 1 km)</td>
</tr>
<tr>
<td>1997</td>
<td>Keio University</td>
<td>Transmission at 2.5Gb/s over 200m by means of a PF-core GI POF at 1300nm</td>
</tr>
<tr>
<td>1998</td>
<td>COBRA, Eindhoven Univ.,</td>
<td>Transmission at 2.5Gb/s over 300m by means of a PF-core GI POF at 645nm</td>
</tr>
<tr>
<td>1999</td>
<td>COBRA, Eindhoven Univ.,</td>
<td>Transmission at 2.5Gb/s over 500m by means of a PF-core GI POF at 840nm and 1310nm</td>
</tr>
<tr>
<td>2000</td>
<td>Asahi Glass</td>
<td>GI POF (Lucina) with an attenuation of 16dB at 1300nm and 569 MHz*km</td>
</tr>
<tr>
<td>2001</td>
<td>Nuremberg IEEE</td>
<td>First “POF application center” is established</td>
</tr>
<tr>
<td>2002</td>
<td>Fuji film</td>
<td>IEEE 1394B standard ratified, IDB-1394 for automobiles completed</td>
</tr>
<tr>
<td></td>
<td>Chromis</td>
<td>Announces the GI-POF is available</td>
</tr>
<tr>
<td>2005</td>
<td>Fiber optics</td>
<td>First commercially PF GI-POF available</td>
</tr>
</tbody>
</table>

Note: SI, Step-index; GI, graded-index; PS, polystyrene; PF, perfluorinated fiber

### 2.3 Optical loss characteristic of the POF

In general, the optical losses of POF can be divided into two major categories: intrinsic and extrinsic losses. The intrinsic losses originate from the material and are independent from the manufacturing process while the extrinsic loss arises from impurities during materials processing. The intrinsic losses can be treated as the
ultimate transmission loss limit, which cannot be eliminated by improving fabrication technologies. Basically, they are caused by the molecular vibrational absorption of the groups C-H, N-H, and O-H, by the absorption due to electronic transitions between different energy levels within molecular bonds and by the scattering arising from composition, orientation, and density fluctuations [7]. As mentioned above, the hydrogen atoms in a plastic act like masses on a spring and hence, absorb light at the characteristic frequency of the “spring” and its harmonics. As such, this type of loss can be lowered by replacing the hydrogen atoms with heavier ones such as deuterons to push the absorption resonance further into the infrared [8]. However, this technique has several disadvantages such as the deuterons diffuse to the surface of the material by exchanges between sites where they are replaced with hydrogen nuclei would cause humidity absorption which in turn increases the attenuation significantly as a result of the strong vibrational absorption of the groups O-H, especially in the near infrared region. On the other hand, the hydrogen can also be replaced by the fluorine atoms to form the fluorinated plastic which is less susceptible to diffusion because of the greater mass of the fluorine atom as well as the fact that fluorine is not an isotope of hydrogen, making it impossible for the two nuclei to exchange while conserving energy [9]. However, the fluorinated plastics have more severe problem of being brittle if compared with the hydrogenated plastic. All materials absorb light at wavelengths corresponding to electronic or nuclear resonances in the molecules. As such, aside from meticulously
choosing molecules with the desired windows of transparency when they are used in manufacture a material, these losses cannot be affected by processing [9].

Additionally, there is another type of intrinsic loss: Rayleigh scattering which is caused by fluctuation in the density, orientation, and composition of the material. The density fluctuations (thermal excitation of compressional modes) are depending on the compressibility $\beta_p$ and on $\frac{\partial \varepsilon}{\partial \rho}|_T$, where $\varepsilon, \rho,$ and $T$ are the dielectric constant, the density, and the temperature, respectively [5]. The orientation fluctuations are caused by the anisotropy of the monomer, the crystallinity of the plastic links and the addition of substances to achieve the desired refractive index profiles. These can also increase the composition fluctuations. Thereby, the minimum transmission losses are contributed by the absorption loss, and Rayleigh scattering loss [10,12]. The various loss factors and the theoretical attenuation limits for PMMA, PS, and CYTOP POFs are summarized in Table 2.2 [10-15]. As shown in the table, PMMA has low loss characteristic at visible wavelength.

Table 2.2: Loss factors and theoretical attenuation limits for POF with different cores [5]

<table>
<thead>
<tr>
<th>Loss factors (dB/km)</th>
<th>PMMA (568nm)</th>
<th>PS (672nm)</th>
<th>CYTOP (1300nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total loss</td>
<td>55</td>
<td>114</td>
<td>16</td>
</tr>
<tr>
<td>Absorption</td>
<td>17</td>
<td>26</td>
<td>10</td>
</tr>
<tr>
<td>Rayleigh dispersion</td>
<td>18</td>
<td>43</td>
<td>2</td>
</tr>
<tr>
<td>Structural imperfections</td>
<td>20</td>
<td>45</td>
<td>4</td>
</tr>
</tbody>
</table>
The extrinsic losses are caused by the impurities in the fiber core, fundamentally comprise of transition metal ions and the hydroxyl group. However, in addition to these impurities, the most important extrinsic losses are induced by the structural imperfections of POF, which are originated from the manufacturing process [10]. Co ions as one of the most dangerous transition metal ions that can increase the attenuation up to 10dB/km for small concentration of just 2 ppb [5]. Besides, the water absorption during and after manufacturing process can leave high hydroxyls (OH) in the fiber which increase the light absorption in the infrared region, except for fluorinated POFs and CYTOP POFs which are almost free from water absorption [16]. The extrinsic losses resulted from the structural imperfections of POF which induce of the change in the diameter, eccentricity, ellipticity, and core index profile, as well as bubbles, cracks, dust in the core or cladding, and defects at the core-cladding interface, etc. These structural imperfections emit a total scattering loss which is independent of the wavelength. Thereby, it can be counted by adding a constant loss contribution from 4dB/km at 1300nm for the best quality CYTOP and 20dB/km for a PMMA POF at 680nm [5].

The bending loss of POF can be determined by the geometrical optics where the power loss at turning or reflection points is described by the leaky ray paths within the core of the bent waveguide based on appropriate power transmission coefficient [17].
The total loss is the sum of these losses along the each leaky ray path [18, 19]. Additionally, the bending losses can be ignored from the bend radius as it is generally enormous compared with the core dimensions. A bend fiber can be thought of as a segment of ring, or torus, and the leaky ray paths are shown in Fig. 2.3. The meridional rays are either tunneling rays or refracting rays, and skew rays lose power at successive reflections or turning points either by tunneling or refraction. The generalized Fresnel transmission coefficient $T$ can be used to measure the transmitted power within a curved interface between two dielectric media. $T$ is given by [17],

$$T(\theta) \approx 4 \left(1 - \left(\frac{\theta}{\theta_c}\right)^2\right)^{\frac{1}{2}} \exp\left(-\frac{2}{3}k\rho \left(\theta_c^2 - \theta^2\right)\right)$$

(2-1)

where $\theta = (\pi/2) - \theta_N$, $\theta_N$ is the inclination angle to the normal, $\theta_c$ is the critical angle of the fiber, $\rho$ is the radius of curvature in the plane of incidence, $k = 2\pi n_1/\lambda$, $\lambda$ is the wavelength in vacuum and $n_1$ and $n_2$ are the indices of refraction for the fiber core and cladding, respectively. The transmission loss in Eq. (2-1) is a ray propagates along a
bend at one reflection. To determine the attenuation of a ray the transmission loss $T$ should be sum at its each reflection. The dimensionless attenuation coefficient $\alpha$ equals to the number of reflections in an interval multiplied by the power loss $T$ at each reflections [17],

$$\alpha(\theta) = \frac{T(\theta)}{\Delta\phi} \quad (2-2)$$

where $T$ is given by Eq.(2-1) and $\Delta\phi$ is the angle subtended between two successive reflections and is given by [17],

$$\Delta\phi = 2\theta - 2\sqrt{2\left(1 - \frac{\rho_o}{\rho_i} \left(1 - \frac{1}{2} \theta^2\right)\right)} \quad (2.3)$$

The dimensionless attenuation coefficient $\alpha$ is given [17],

$$\alpha = \frac{\eta(\theta) \rho_o \theta^2}{\rho_o - \rho_i} \left(\frac{T}{2\theta}\right)_{\rho=\rho_o} \quad (2-4)$$

Only rays angle that is near to the critical angle suffers from the significant bending loss. Then $\eta(\theta) \approx \frac{1}{2} k(\rho_o - \rho_i)(\theta_i^2 - \theta^2)^{1/2}$, so that $\alpha$ can be derived from Eqs. (2-2) and (2-4) as [17],

$$\alpha = k\rho_o \sqrt{\theta_i^2 - \theta^2} \exp\left(-\frac{2}{3} k\rho_o (\theta_i^2 - \theta^2)^{3/2}\right) \quad (2-5)$$

According to the Eq. (2-5), a different amount of lights is lost at each reflections because $T$ is a function of the radius of curvature $\rho$ in the plane of incidence, and $\rho$ is the function of position. The attenuation decreases as either the radius of the fiber or the bending radius increases [17].
The analysis described above is based on the only meridional rays contribute to the bending loss within the fiber. This analysis is not very accurate because some parameters are ignored such as refractive index. Therefore Bløtekjær studied the refractive index change in the portion of fiber bent due to stress-optic effects [20]. Actually, there are two effects that can cause the light to couple out when the fiber is bent. Firstly, only from the geometrical change some of the rays that were confined in the straight fiber will be beyond the critical angle around the bend. Secondly, the bending induces stress in the plastic thus a birefringence. The effect of birefringence is shown in Fig. 2.4 (a) while the conventional ray tracing analysis method is shown in (b).

![Fig. 2.4: (a) Ray tracing in a bent fiber for a refractive index gradient at the bend that is positive, negative, and zero; (b) Tracing rays from a point source that are within the critical angle for the straight fiber. Note that all the rays considered are in a plane that contains the fiber axis [9].](image)

In Fig. 2.4 (a), the solid ray represents the geometrical limitation where there is no refractive gradient. In the presence of refractive gradient, the ray will bend in the direction of larger refractive index as shown in the figure. The two dashed rays show
that for a positive gradient the ray will couple out of the fiber core while the negative gradient results in the ray being refracted toward the axis and therefore the ray is not lost. In case of no refractive index change five representative rays are systematically analyzed as shown in Fig. 2.4 (b). The loss from this contribution can be calculated numerically from above basic analysis.

Thereby, compression along the inner half of fiber towards the center of the bend and tension along the outer half, cause the magnitude of the birefringence is given by [21],

$$\Delta n = -\frac{p_{11} - p_{12}}{n^3} (1 + \sigma) \frac{r}{R}$$

(2-6)

where $p_{11}$ and $p_{12}$ are the elastooptic constants, $n$ is the stress free refractive index, $\sigma$ is the Poisson ratio, $r$ and $R$ are the radius of fiber and bending curvature, respectively. Consequently, by combination of the geometrical effects and birefringence, it is possible to calculate the bending loss in a multimode fiber using above ray tracing method.

Normally, the bending losses are categorized from macrobending loss and microbending loss. The theoretical analysis described above is based the macrobending of fibers where the radius of curvature is larger compared to the radius of POFs. In contrast, the microbending means that the scale of refractive index variations that are comparable to or smaller than that size of fiber region. The microbending loss is very important in the design of optical fiber system, however, it is too complex to analyze because the
microgeometry is not always easy to quantify. Such as, the plastic jacket is placed on the fiber induces the stress which result in microsized variations in the refractive index or radius of fiber. These fluctuations cause the scatter of the light while the larger fluctuation can be imprinted at the interface of core and cladding due to impurities, imperfections in the material, or fluctuations due to processing, such as differential cooling [21].

2.4 Other properties of POF

Dispersion

Dispersion in POFs may be separated into two main types: chromatic dispersion and modal dispersion. The chromatic dispersion is related to the dependence of the index of refraction on the wavelength. Due to various wavelengths in the waveguide, the variants spectral components of each mode are propagating at a different velocity in the fiber. This different propagating velocity causes a pulse broadening or dispersion. The modal dispersion is related to the spreading of the pulses as a result of the difference in propagation delays among the modes as well as dispersion from intermodal effects such as power mixing between modes and mode dependent loss. Besides, the modal dispersion is dependent on how the modes are excited (the lunching condition), the spectral characteristics of the light source and on the effects of micro-bending, among others.
**Chemical resistance properties**

The polyethylene jacket serves to protect the POF when they are in contact with chemical liquids. Without the jacket protection, the polycarbonate POFs can only last for 5mins when they are immersed in 85-octane petrol whereas with the jacket protection they are able to withstand oil and battery liquid for a much longer time [22]. The polyethylene jacket of PMMA POFs can resist the liquids such as water, NaOH, sulfuric acid (34.6%) and engine oil. Furthermore, the fluorinated POFs do not show any sign of change in attenuation within a week immersed into chemical solutions, such as 50% HF, 44% NaOH, and 98% H₂SO₄ or organic solvents such as benzene, hexane, MEK, and CCL₄ [23].

**Thermal properties**

Without the protection of jacket, the POFs can operate at the temperatures up to 80-100ºC. However, the POFs lose their rigidity and transparency above the limitation. If the POFs are protected by the jacket made of cross linked polyethylene or of a polyolefine elastomer, its temperature limitation can be increased to 125ºC and possibly up to 135ºC [24, 25]. On the contrary, the resistance of temperature of POFs is strongly influenced by the degree of moisture in surrounded environment. The relative humidity level around 90% results in the attenuation increase of more than 0.03dB/m [26]. This can be explained from the strong OH⁻ absorption band in the visible range. The fluorinated fibers have ability to resist the water absorption. Thereby, the fluorinated
fibers are a better choice in the applications than when they are used in humid environments [27]. In comparison with the conventional optical materials, thermo-optic coefficient of silica glass material is an order of magnitude lower than that of plastic materials and the refractive index of plastics decreases rapidly with temperature at a rate of $10^{-4}(°C)^{-1}$. The value of the thermo-optic coefficient for variants classes of plastics varies from $-1.5 \times 10^{-4}$ to $-5 \times 10^{-4}(°C)^{-1}$.

**Mechanical properties**

Most studies on the mechanical properties of POFs mainly focused on the attenuation induced by bends and tensile or torsion stresses [28, 29]. The Young's modulus of POFs is nearly two orders of magnitude lower than that of a silica fiber. Even a 1mm diameter POF has a greater bending flexibility than that of a silica fiber with smaller diameter due to the ductility of plastic. The bending radius of POF can be made smaller than that of silica fiber[30].

### 2.5 Fiber optic sensors

Fiber optic technology offers the possibility for developing variants sensors for a wide range parameter measurement. The use of optical fiber as the sensor probe provides fast response innumerous parameters (displacement, pressure, temperature, electric field, refractive index and surface roughness) compared to conventional transducer. To date, numerous types of FOS based on different techniques have been
studied and proposed but only a limited number of techniques and applications have been successfully commercialized [31].

2.5.1 Fiber optic sensor classifications

There are many varieties of FOSs which can be categorized according to the detection techniques such as intensity (amplitude), phase, frequency, or polarization sensor. On the other hand, FOS can also be classified in accordance to the basis of their applications: physical (e.g. measurement of temperature, stress, etc.), chemical sensor (e.g. measurement of pH content, gas analysis, spectroscopic studies, etc.) and biomedical sensors (inserted via catheters or endoscopes for the measurement of blood flow, glucose content and etc.) [32]. Hence, in this section the intensity modulation, Spectral modulation, Interferometeric, as well as Multiplexing FOSs are briefly introduced.

2.5.2 Intensity modulation FOSs

Among all sensor modulation techniques, intensity based technique has received a great deal of consideration mainly due to its high performance and low cost. Microbend sensor is one of earliest FOS intensity modulation based intrinsic sensor as shown in Fig. 2.5. In the figure, the microbend transducer squeezes optical fiber under measured perturbation and thereby induces the microbending of optic fiber. This causes the irreversibly leaky in the optical power from the fiber. Over the years, many
configurations of microbend FOSs have been developed for measurement the different parameters, such as pressure, temperature, acceleration, flow, local strain, and speed, etc.

Quite similar to microbend FOS, macrobend sensors is another type of intensity modulated intrinsic FOS. Basically, both FOSs share almost the same operating principle but differ in several aspects. Bend-sensitive single-mode fibers are commonly used in macrobend FOS which operates with relatively large bending radius (typically in order of few centimeters) [33]. Besides that, there are many other types of intensity modulate sensors, such as the chemical and temperatures sensors which are based on the mechanisms of absorption, fluorescence, changes in refractive index, or polarization. For absorption based temperature sensors, generally, the core glass is doped with some material to achieve different peaks and temperature sensitive. Fluorescence time and intensity are temperature dependent and can be used for temperature measurement [34].

Fig. 2.5: The configuration of microbend FOS [33].

2.5.3 Spectrally based FOSs

Spectrally based FOSs are dependent on a light beam being modulated in wavelength by an environment effect [35]. Blackbody sensor shown in Fig.2.6 is one of
the FOSs based on this technique. It is the simplest blackbody sensor where an optical fiber end is placed in a blackbody cavity. It collects the emission from the cavity when the temperature of cavity rises and begins to glow. The narrow band filter and detector are then used to determine the profile of the blackbody curve and in turn the temperature [35].

![Narrow Band Filter](image)

**Fig. 2.6:** One of simplest blackbody sensor [35].

Fiber Bragg Gratings (FBGs) find many applications in optical fiber communication systems, fiber lasers and optical fiber sensors since the late 1980s. The FBG is formed based on the photosensitivity of silica fiber doped with germanium when illuminated with UV light, usually from high power excimer lasers, as shown in Fig. 2.7. A fiber grating has proven its ability as a sensing element in a range of chemical, pressure sensing, and accelerometers applications. This section provides a brief introduction to the FBG.
The basic principle of operation of an FBG-based sensor system lies in the monitoring of the shift in wavelength of the returned “Bragg” signal, as a function of the measured (e.g., strain, temperature). The Bragg wavelength, $\lambda_B$, is related to the effective refractive index of the material, $n$, and the grating pitch, $\Lambda$,

$$\lambda_B = 2n\Lambda$$

A narrow spectral component centered at the Bragg wavelength is reflected by a FBG, when the light from a broadband light source is injected into the fiber. In the transmission spectrum, as shown in figure 2.8, this component is missing.
FBG sensors are well suitable for quasi-distributed point measurements of strain or temperature at known positions in an optical fiber network. The operation of the sensor is very simple, such as the strain response is occurring because of the physical elongation of the sensor and the change in fiber index due to photoelastic effects. In the strain monitoring, the fiber Bragg gratings are particularly used where a comparison the wavelength shift of grating is essential measured.

2.5.4 Interferometry FOSs

Interferometric FOSs have always been the most attractive products in the development of high performance FOSs, such as Sagnac interferometers, Mach-Zehnder, Michelson and etc. The Sagnac interferometers have been developed over 20 years and it is mainly used for the measurement of rotation rate. The Mach–Zehnder interferometer is a device used to determine the relative phase shift between two collimated beams from a coherent light source. The interferometer has been used, amongst other things, to measure small phase shifts in one of the two beams caused by a small sample or the change in length of one of the paths. The principle difference is that in the Michelson the beam splitting optic is also used to recombine the beams. Commercial examples of these interferometers have been proven to be successful in aerospace control systems such as missiles and aircraft. These interferometers, such as Sagnac interferometers, are employed in luxury cars coupled with commercial global positioning systems (GPS) for navigation purpose.
2.6 Fiber optic displacement sensors

One of the applications of FODS is the high-precision noncontact displacement measurement, which is the key to micro-nano technologies. Displacement sensors are used wherever it is necessary to acquire the exact position or distance between two subjects. Several types of displacement sensors are proposed for such purpose such as optical and magnetic displacement sensors for detecting the amount of a linear displacement are commonly used in stages of machine tools and three-dimensional measuring instruments [36].

2.6.1 Interference based FODS

In a fiber-optic displacement sensor, two methods are commonly adopted, namely interferometry and reflective intensity modulation techniques. For the interferometry FODS [35] which is based on the fringe counting method has high resolution and stability, but its precision and stability is depending on the operating wavelength. A general configuration of interference based FODS system is shown in Fig.2.9[37]. In this figure, a multimode fiber (MMF) was fused splice to a single-mode fiber to act as the sensing element. In this concept, the fiber end facet of MMF can be used as a lensing effect. In light intensity distribution with in the MMF starts to converge to a ON axis point at the end facet of the MMF. Cleaving the MMF slightly shorter, the light exciting the fiber converges to a point in the air outside the fiber. If a mirror is placed at this point where the reimaging point occurs, the coupling of the light
reflected back through the fiber would be a maximum comparison with any other location in the near vicinity. The single reimaging position is wavelength dependent, so varied the longitudinal positions of the mirror will be induces the variants wavelength corresponding to maximum back coupling [37].

![Diagram of displacement sensing based on interference technique](image)

Fig.2.9: One of displacement sensing based on interference technique [37].

### 2.6.2 Reflective intensity modulation based FODS

Comparatively, the reflective intensity modulation technique is a simpler method for non-contact displacement measurements while at the same time being able to provide high resolutions. In this type of sensor the reflected light from the mirror is coupled back into a fiber from a reflecting surface and this power is compared to a portion of the power emitted by the same light source. The interest in this type of sensor is based on its inherent simplicity, small size, mobility, wide frequency capability, extremely low displacement detection limit and ability to perform non-contact measurements. These properties have led to a variety of applications, not only as a displacement or vibration sensor, but also as a secondary transducer for measuring
physical properties that correlate to the amount of displacement such as temperature, pressure, and sound [33].

Some main components, such as, laser source, photodetector, optical fibers, as well as the lock-in amplifier are normally used to form an intensity modulation based FODS system. A diagram of intensity modulation based FODS is simply shown in Fig. 2.10. In this configuration of FODS, each of these components contributes to the noises which are heavily influence the performance of FODS. In the next subsection, short reviews on He-Ne laser, silicon detector, and lock-in amplifier will be presented. The noises associated with these devices are also analyzed and some techniques to remove the noises will be reviewed.

![Diagram of intensity modulation based FODS](image)

Fig.2.10: A simply configuration of intensity modulation based FODS.

### 2.6.2.1 He-Ne laser

A helium-neon laser, usually called a He-Ne laser, is a type of small gas laser which have many industrial and scientific uses, and are often used in laboratory. The gain medium of the laser, as suggested by its name, is a mixture of helium and neon gases, in a 5:1 to 20:1 ratio, contained at low pressure in glass tube. The energy or pump
source of the laser is provided by an electrical discharge through an anode and cathode at each end of the glass tube. A current of 5 to 100 mA is typical for CW operation [38]. The optical cavity of the laser typically consists of a plane, high-reflecting mirror at one end of the laser tube, and a concave output coupler mirror of approximately 1% transmission at the other end. He-Ne lasers are normally small, with cavity lengths of around 15 cm up to 0.5 m, and optical output powers ranging from 1mW to 100mW.

The lasing process in this laser starts with collision of electrons from the electrical discharge with the helium atoms in the gas. This excites helium from the ground state to the $^{23}S_1$ and $^{21}S_0$ long-lived, meta-stable excited states. Collision of the excited helium atoms with the ground-state neon atoms results in transfer of energy to the neon atoms, exciting neon electrons into the $^3s_2$ level [39] as shown in Fig.2.11. This is due to a coincidence of energy levels between the helium and neon atoms. This process is given by the reaction equation:

$$\text{He}(21S)^* + \text{Ne} + \Delta E \rightarrow \text{He}(11S) + \text{Ne}3s2^* \quad (2-8)$$

where (*) represents an excited state, and $\Delta E$ is the small energy difference between the energy states of the two atoms, of the order of 0.05eV or 387 cm$^{-1}$, which is supplied by kinetic energy. The number of neon atoms entering the excited states builds up as further collisions between helium and neon atoms occur, causing a population inversion. Spontaneous and stimulated emission between the $3s_2$ and $2p_4$ states results in emission of 632.82 nm wavelength light, the typical operating wavelength of a He-Ne laser. After
this, fast radioactive decay occurs from the 2p to the 1s ground state. Because the neon upper level saturates with higher current and the lower level varies linearly with current, the He-Ne laser is restricted to low power operation to maintain population inversion [40].

![Energy-level diagram for the helium-neon laser. The solid line represents the common laser line; the dashed lines are spontaneous [39].](image)

With the correct selection of cavity mirrors, other wavelengths of laser emission of the He-Ne laser are possible. There are infrared transitions at 3.39\(\mu\)m and 1.15\(\mu\)m wavelengths, and a variety of visible transitions, including a green (543.365 nm, the so-called Green He-Ne laser), a yellow (593.932 nm), a yellow-orange (604.613 nm) and an orange (611.802 nm) transition. The gain bandwidth of the laser is dominated by Doppler broadening, and is quite narrow at around 1.5GHz for the 633nm transition lasing on a single longitudinal mode[40]. The visible output of the He-Ne laser, and its
excellent spatial quality, makes the He-Ne a useful source for holography and as a reference for spectroscopy. In most of the works in this thesis uses a yellow He-Ne laser as a light source.

2.6.2.2 Silicon photo-detector

In the silicon photo-detector, the wafers are normally n-type with a high resistivity of about 5 kΩ-cm, and with a low-resistivity p-implant in form of pads, strips or pixels to create a junction. With a reverse bias of less than 100 V, the detectors can then be fully depleted such that only the thermally generated current contributes to the leakage current. Larger thickness requires much higher voltage because the depletion voltage increases with the square of the thickness. The area of the detectors are limited to the standard wafer sizes used in high-resistivity processing by industry, which has increased the wafer size from 4 to 6 in the last two years. Larger area detectors are now routinely made by assembling and wire bonding several detectors into so-called ladders, with fairly long readout strips [41].

2.6.2.3 Lock-In Amplifier

The Lock-In Amplifier plays a role of filter to detect the very small ac signal from noisiness environment. It amplifies the detected signal and rejects the most of the unwanted noises. The Lock-In Amplifier denoise consists of a Low Noise Differential Pre-Amplifier, a First Line Frequency Notch Filter, a Second Line Frequency Notch Filter, a band-pass Filter and a High Gain A.C Amplifier as shown in Fig.2.12. The
output signals of FOS are amplified through the Low Noise Differential Pre-Amplifier.

The amplifier also amplifies the shot noise current at same time but do not amplify the thermal noise current since it is not produced inside the photo detector. After amplification, the signal passes through the first line notch filter to attenuate the line frequency noise and the second line notch filter to remove the first harmonic frequency. First and second filters have the notch width of 6Hz and 12 Hz, respectively. Then, the signal pass through the band-pass filter which adds the 20 dB of dynamic reserve for noise signals outsides the pass band and rejects the second and higher harmonic frequencies. The additional 20 dB of dynamic reserve can increase the sensor stability. After that, the signals are post-amplified by the A.C Amplifier with an amplification gain G. Finally, the denoise signals are output from the A.C Amplifier [42].

![Simply structure of noise attenuation of Lock-In-Amplifier](image)

Fig.2.12: Simply structure of noise attenuation of Lock-In-Amplifier

2.7 Summary

In first section, the plastic optical fibers are simply described in its evolutions and properties. The discussion in this chapter are more focused on the multimode step-index POFs while the single-mode POFs and graded index POFs are beyond our aim
because of most of the studied are carried out by multi-mode step-index POFs in following chapters. In section two, three different types of FOSs are described including the intensity modulation, spectral modulation, and interferometric. In the intensity modulation technique, the microbend and macrobend FOSs have been depicted. Furthermore, many other types of intensity modulated sensors, such as the chemical and temperatures sensors based on the prime mechanisms of absorption, fluorescence, changes in refractive index, or polarization are briefly discussed. In the spectral modulation FOSs, the blackbody sensor and FBG sensors are simply reviewed. In last section, the developments of the FODSs are reviewed from two techniques: interferometry and reflective intensity modulation. The main components, He-Ne laser, photo-detector, and lock-in amplifier used for FODS system are depicted.

References


[41] M. Bruzzi, “Radiation damage in silicon detectors” these proceedings.