In-line Fiber Polarizer

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(ABSTRACT)

Polarizers and polarization devices are important components in fiber optic communication and sensor systems. There is a growing need for efficient low loss components that are compatible with optical fibers. An all fiber in-line polarizer is a more desirable alternative that could be placed at appropriate intervals along communication links.

An in-line fiber polarizer was fabricated and tested. The in-line fiber polarizer operates by coupling optical energy propagating in the fiber to a surface plasmon on a metallic film, which has been deposited onto the surface of the fiber. The device was constructed by polishing a short section of the lateral surface of the cladding to within the evanescent field present around the fiber core. Several thin films including a metal film are applied to the polished section of the fiber. Ionic self-assembled monolayer method was used to coat the polished fiber with thin film.

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Table of Contents

List of figures

1.0 Introduction

The operational characteristics of many fiber optic systems depend on the polarization of the light guided by the optical fiber. Polarization management is essential in fiber optic communications, optical gyroscopes and in interferometric sensors to avoid signal fading and error. To obtain a high accuracy in measurements it is essential to have light with one polarization. It is necessary to have fiber-optic polarizers with high extinction ratio for analysis and filtering in fiber optic systems. Polarizing components are widely used in fiber optic systems. Standard polarizing components used in optical fiber systems have a bulk structure making it difficult to align the optical axis between components. Also the use of bulk optic polarizing arrangements suffer from a high cost, lack of mechanical and thermal stability and high losses. Hence it is desirable to develop optical components with fiber-like structure.

In-line fiber components are desirable in most of the fiber optic systems. They have been successfully used in fiber optic compensators, beam splitters, faraday rotators and filters. Several components involving polarization selective coupling to structures arranged to interact with the evanescent field of the fiber have also been studied. The light from the guide must be removed to use this method in optical fibers.

Many techniques exist for increasing the degree of polarization of light waves. Fiber optic polarizers have been fabricated by using a crystal close to the core of the fiber or using thin films over the fiber core. In the former type a birefringent crystal is placed along the length of the fiber from which the cladding has been removed. The evanescent field of the light guided by the fiber interacts with the birefringent crystal, causing the light with the unwanted polarization to couple into the crystal and is not guided by the fiber. The light with the desired polarization remains unaffected by the crystal and is guided by the fiber. Fiber optic polarizers based on the differential attenuation of the two polarization modes or the cutoff of one of the mode have been demonstrated. However these devices have a high insertion loss when operated as a cutoff polarizer. This loss has been attributed to the use of thick metal film. By using thin films interacting with the evanescent field of a wave propagating through the fiber many components can be devised. Such devices are based on the factor of producing a highly polarized surface

plasmon wave on the metal. Evanescent field coupling from a fiber to a surface plasmon polariton supported by a metal/dielectric interface has been of particular interest in these studies.

The optical energy propagating in the fiber is coupled to a surface plasmon on a metallic film, which has been deposited on the polished lateral surface of the fiber. There are numerous methods to deposit the metallic film on the polished section of the fiber. The energy from the fiber is resonantly coupled from the fiber's core into an optical mode in the metal film. The metallic mode is the surface plasmon and the coupling of the energy is called the surface plasmon resonance. The phenomenon of surface plasmon affects only the TM polarization mode and hence provides the polarization selectivity. Several methods have been used to coat the fiber with a thin film. But such components have not come in the market due to manufacturing difficulties.

In this work a fiber optic polarizer is realized which has a thin metal film deposited on the polished lateral section of the fiber. The fiber with the metal film is further coated with several thin layers of iron oxide using the ionic self-assembly method.

In the ionic self-assembly method (ISAM) thin films are created based on the electrostatic attraction between opposite charges. Alternate adsorption of cations and anions from aqueous solutions forms a thin film. The thickness of the film depends strongly on the ionic strength of the solution. It can also increase with the number of the adsorbed layers.

The optimum thickness required for the successful operation of the fiber optic polarizer can be easily achieved by the ISAM method. Also a fiber based surface plasmon device is simpler and faster to fabricate and is disposable. ISAM method provides an easy way to coat the fiber with a thin film.

The fabrication and the working of the fiber polarizer are discussed in detail in this study. Also the various other components that can be fabricated by this method are proposed.

2.0 Background

2.1 Concept of Polarization.

Polarization is a common property of electromagnetic waves. If the electric vectors of a group of transverse waves are at random angles, in all directions, the light is said to be unpolarized. Conversely, if the electric vectors are all along the same plane, the light is polarized. Polarization refers to the behavior of the electric field E with time. The time variation of the electric field in a monochromatic wave is sinusoidal. Some materials can introduce phase differences between two sets of polarized waves, to separate them or to analyze their states of polarization. Other materials, called polarizers, transmit only waves with electric vectors in one plane the remaining waves are either reflected or absorbed.

2.2 Polarizers

The first light polarizer used calcite prism and was devised by W. Nicol in 1828. The spectral range of this polarizer was about 0.23 to 3.0 μm. The optical constants of the calcite crystal posed limitations on the application of this polarizer and were substituted by dichroic[14] polarizers.

If natural light falls on some homogeneous media the emerging light is partially polarized, either circularly or linearly. Such media are called dichroic, and are characterized by unequal absorption for two oppositely polarized beams of incident light. In one case the two beams of light are linearly polarized at right angles to each other, in the other case the beams are circularly polarized in opposite senses. Numerous observations have been made on dichroic polarizers for well over hundred years but relatively few quantitative measurements of linear dichroism have been made on the widest variety of materials. However in the last decade much progress has been made in the application of dichroic polarizer.

Herapathite crystals are ground in a ball mill to make synthetic[15] polarizers. The crystal suspension is placed in a glass cylinder and placed in a gap of magnet. Other polarizers like the K polarizer and H polarizer are commonly used sheet polarizers.
Thin film[16] polarizers are suitable in a narrow wavelength range. A dielectric periodic stack is irradiated by a beam of polarized light at an angle of incidence greater than 45^0. The reflectance bandwidths for the S plane polarization and the P plane polarization are different. One plane is perpendicular to the incident plane and the other is parallel to the incident plane. In the region of the reflectance bands edge, appears the high reflectance for S-polarization and high transmittance for p-polarization. Thin film polarizers are made using this difference.

Polarizers and polarization devices are important components in fiber optic communication and sensor systems. There is a growing need for efficient low loss components that are compatible with optical fibers. The use of integrated optics offers an attractive solution, but there is considerable loss in removing the signal from the single mode fiber. The best solution consists in interacting with the evanescent field of the guided signal. There has been a rapid development of other types of polarizers, but this discussion is confined to in-line fiber polarizers.

2.3 In-line fiber polarizer

Fiber–optic polarizers are integral components in optical communications systems and polarization dependent sensors. One method of constructing fiber polarizer is from bulk optics. Another approach that is simpler and has less loss is an all fiber device, such as a side polished fiber fabricated to have polarizing properties. A side-polished fiber is an optical fiber device that has a portion of the cladding polished away and replaced with a thin film overlay. This overlay acts as a multimode slab waveguide that can couple to the optical fiber and allows light at certain resonant wavelengths to be removed from the fiber. The light in the fiber interacts with the TE and TM modes of the overlay at different wavelengths and hence the side-polished fiber can be used as a polarizer. This device reduces losses and is simpler to package as the fiber is continuous.

Metal films[7], birefringence crystals[9], liquid crystals[17] and semiconductor doped glass thin films[20] have been used as overlays in a side-polished fiber to make polarizers. Birefringence crystals, liquid crystals and metal films have only one guided Polarization State, and the other state is not supported and is absorbed or radiated away.

In the crystal-based polarizer, a birefringent crystal is placed on top of the polished fiber so that the evanescent field of the light guided by the fiber interacts with the birefringent overlay. By properly choosing the indexes of the birefringent crystal, one polarization mode sees the high index and is not waveguided, whereas the orthogonal one sees the low index and remains guided in the fiber. The fabrication of these devices involves preparing the overlay or film and then applying it to the side polished fiber with index matching fluid at the interface of the side polished fiber and the overlay. This can be complex because the overlay must be secured to the side-polished fiber while the index matching fluid has to be maintained at the interface. Polarizers with liquid crystal overlays are also complex, as electrodes are needed. Metal clad polarizers based either on the differential attenuation and the TE_o mode cutoff of a thick metallic layer or on the evanescent coupling between the optical field and surface plasmon polariton within a thin metallic layer have been widely studied.

The first stage in the construction of the fiber polarizer is the polishing of the fiber to within a few microns of the core. Then a metal film is added and a dielectric medium is usually added to enhance the polarization extinction ratio. In the following section the different methods and materials used to deposit the metal and the dielectric are discussed. Figure 2.1 shows the general schematic of the fiber polarizer.

2.4 Fiber Polarizer Overlay

A polarizer is formed by deposition of a metal film[7] about 1500 Angstrom thickness on the polished surface of the fiber by vacuum deposition. This polarizer is based on the properties of metal–clad waveguides. The extinction ratio measured in this polarizer was about 14 dB.

In a metal-clad fiber cutoff[3] polarizer a thin silver film is deposited onto the flat surface of an optical quality fused silica superstate. The superstate with the thin silver film is placed upon the polished fiber surface, and index-matching oil is allowed to flow

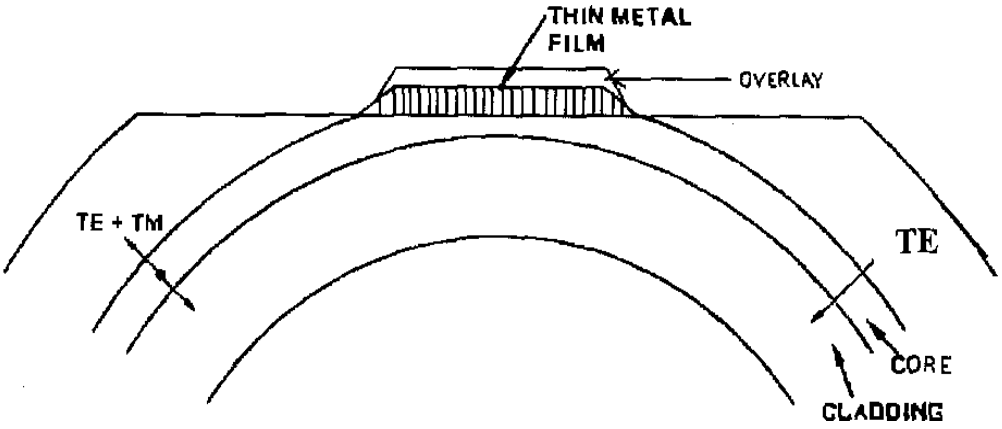


Figure 2.1 Schematic of the fiber polarizer[3].

between the two by capillary action. In this method it was difficult to monitor the thickness of the index matching oil precisely but the experimental results indicated a high extinction ratio and low insertion loss for the cutoff polarizer.

An aluminium-coated mirror[4] was placed in contact with the polished fiber. This is shown in figure 2.2. A suitable mixture of glycerol and water was used as the buffer layer sandwiched between the fiber mirror and the fiber. The buffer thickness was measured using a differential micropositioner.

The TE polarization reaches its maximum when the mirror is in contact with the fiber and the TM attenuation reaches its peak when the distance between the mirror and the fiber is 0.8 μm.

Fiber optic polarizers have been made by depositing CaF_2-film[5] as the buffer layer and an AL-film on the polished surface of the fiber. This polarizer had a high extinction ratio (45 dB) and low insertion loss (1 dB).

In another type of polarizers high birefringent fibers[8] were used. A thin aluminum layer (10 nm) was deposited on to a glass block and oil was used as the buffer layer between the fiber and the metal. In this polarizer the power transmitted is dependent on the buffer layer thickness and in certain regions of transmission denoted by A and B in Figure 2.3 the transmitted power are not known because of the lack of buffer layer of appropriate thickness. In another technique a birefringent crystal[20] is used to replace the removed portion of the fiber cladding. If the refractive index of the crystal is greater than the effective index of the waveguide the guided wave excites the bulk wave in the crystal and light escapes from the fiber. By properly using the birefringent crystal one polarization can be radiated and the other guided.

The common type of fiber polarizer uses liquids of various indexes on top of a metal deposit to serve as the superstrates. In the proposed method a thin metal film is deposited on the side polished fiber by vapor deposition and then using the Ionic self-assembled monolayer method layers of thin films are deposited on top of the metal layer.

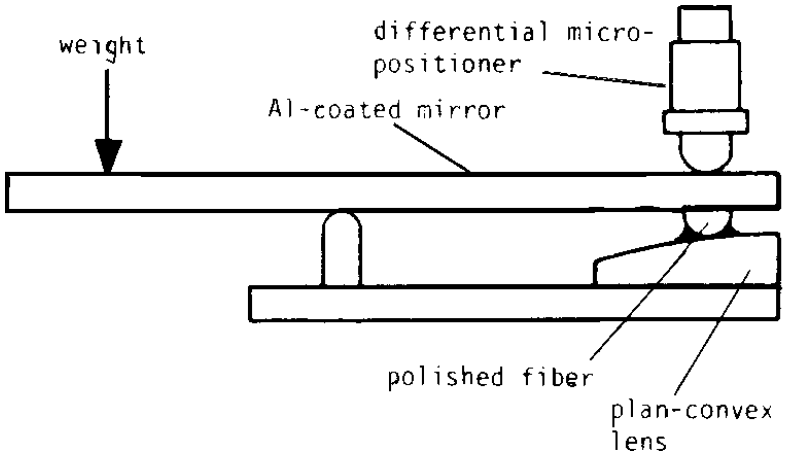


Figure 2.2 Fiber polarizer with metal-coated mirror and the experimental setup[4].

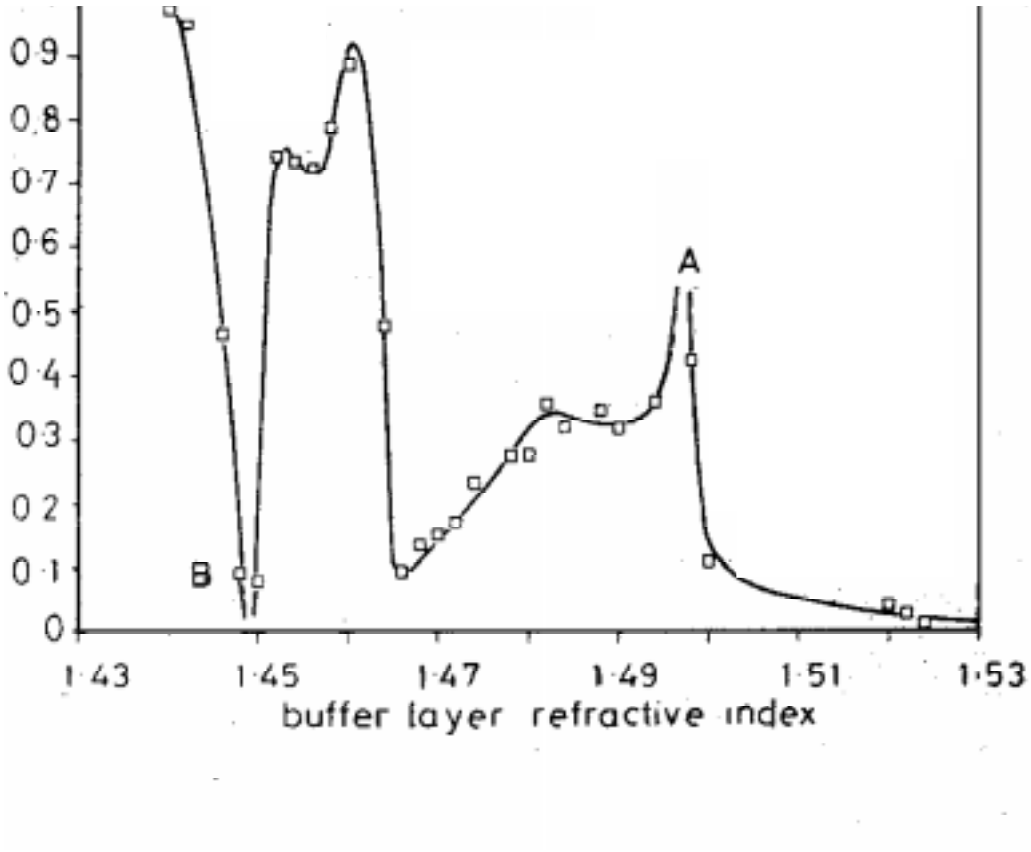


Figure 2.3 Transmitted power against buffer layer refractive index[8].

3.0 Theory

3.1 Surface Plasmon Resonance

3.1.1 Introduction

A Surface plasmon is an electromagnetic wave that propagates along the interface of two materials, one of which has a negative dielectric constant. Surface plasmons are oscillations of electrons that occur on the surfaces of solid materials that contain free electrons. When an external electric field is applied at the boundary between a metal and a dielectric, plasma is generated in the free electron cloud present on the surface of the conductor. Raether[1] deals with the theory of surface plasmons in detail.

The surface plasmon resonance depends upon the coupling of light incident upon a thin metal film, into surface modes associated with collective electron oscillations within the film. Surface plasmon resonance is achieved by using an evanescent wave resulting from a light beam being totally internally reflected inside a medium of high dielectric constant. A Surface plasmon field is commonly generated by using a thin, planar, conductive film, which supports the plasmon. The plasmon is generated by coupling the transverse-magnetic (TM) polarized energy contained in an evanescent field to the plasmon mode on a metal film. The coupling is dependent on the refractive indices of the dielectric materials on both sides of the film. The resonance condition is dependent upon the optical characteristics of the thin film, its thickness, the refractive index of the dielectrics on both sides of the film and the angle of incidence of light upon it.

The plasmon is a transverse magnetic effect and exhibits the property of strongly attenuating one polarization component from an optical beam while the other polarization is unaffected. Thus only the TM polarization is coupled to the plasmon and the TE polarization is unaffected.

3.1.2 Nature of Surface Plasmon Polaritons

Surface plasmon polaritons are wave like phenomena comprising electromagnetic fields coupled to electron density oscillations at a metal/dielectric interface. The waves are guided by the interface. The wave equation for this geometry yields a guided transverse magnetic mode and a radiative TM mode. This exhibits exponentially growing fields in both the metal and the dielectric with no localized field peak as shown in Figure 3.1[10]. The electric field distribution peaks at the interface and decays exponentially into both the metal and the dielectric material. A metal/dielectric interface thus is a planar waveguide, which can support coupled electromagnetic waves known as surface plasmon polaritons.

A thin metal film of few nm thicknesses is regarded as a pair of coupled plasmon waveguides. The coupled modes of the two interfaces defined by thin-film boundaries are the waveguide solutions for such a structure. The coupled modes are the in-phase combinations of the bound modes for each interface, giving a symmetric bound mode s_b, the antiphase combination yielding an antisymmetric bound mode a_b, and the combinations of the bound mode of each interface giving a symmetric leaky mode s_l and an antisymmetric leaky mode $a_{l,}$ as shown in Figure 3.2. The leaky mode peaks on one interface, then decays across the metal film and grows exponentially into the dielectric in contact with the other interface. For a metal bound by materials with different refractive indices the leaky modes which peak at the high index/metal interface is the antisymmetric leaky mode a_l and the one that peaks on the low index side is the symmetric leaky mode s_l.

3.1.3 Dispersion Relation

The electron charges on a metal boundary can perform coherent fluctuations, which are called surface plasma oscillations. A dispersion relation $\omega(K_z)$ ties the frequency of these longitudinal oscillations to the wave vector K_z. These charge fluctuations are accompanied by a mixed transversal and longitudinal electromagnetic field, which disappears at $|x| \to \infty$ and has a maximum at the surface x=0 (Figure 3.3).

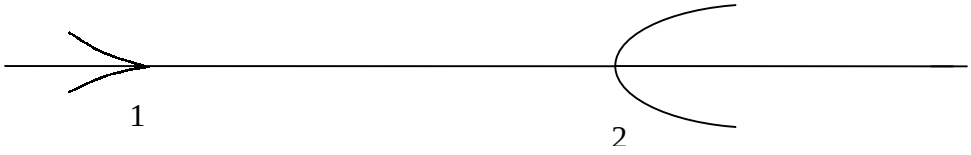


Figure 3.1 Electric field distribution supported by a metal dielectric interface[10] (bound (1) mode and radiative (2) mode).

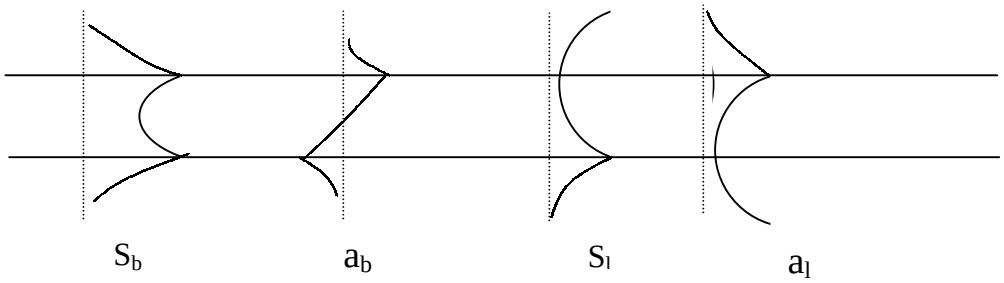


Figure 3.2 Bound and leaky symmetric (s_b, s_l) and antisymmetric (a_b, a_l) modes in a thin metal film 8.2b.

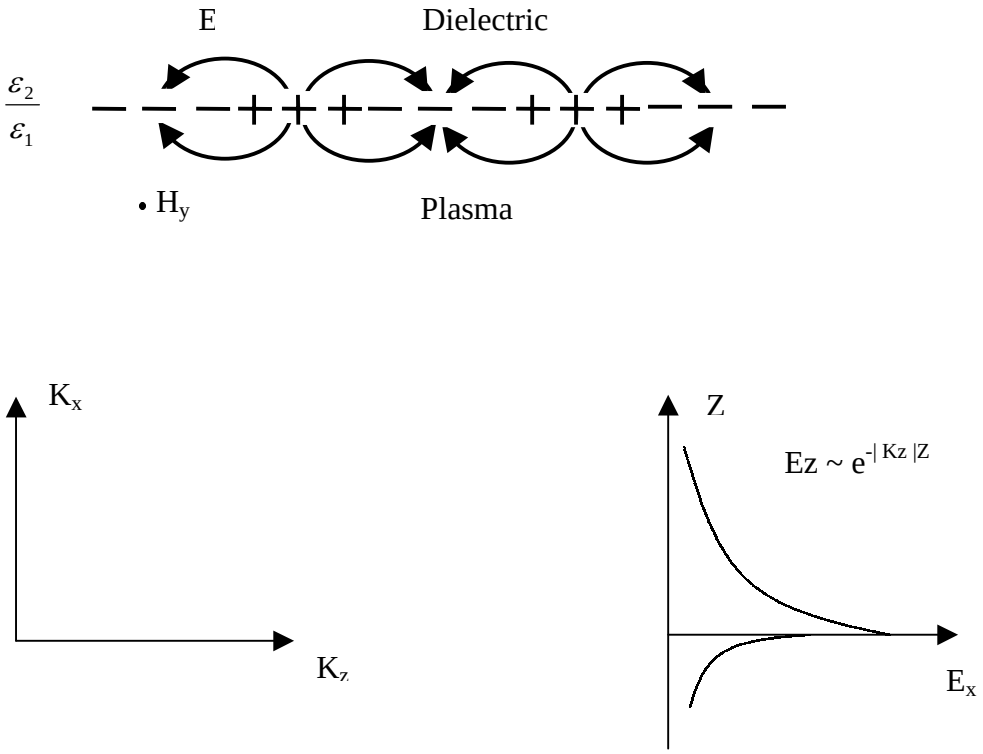


Figure 3.3. The charges and the electromagnetic field of surface plasmons propagating on a surface in the z direction. H_y is the magnetic field in the y direction of the p-polarized wave[2].

This explains their sensitivity to surface properties.

The electric field[19] of a surface plasmon propagating along the interface x=0 in the z-direction is given by

$$E(x,z,t) = E^{o}(x)\exp(i\omega t - k_z z), \qquad (2.1)$$

where ω = angular frequency, and $k_z = k_z' + ik_z''$, the propagation constant.

The field amplitude reaches a maximum value at the interface and decays exponentially in the adjacent half spaces. The decay constants are in the range of 10^{-1} – 10^{-3} nm^{-1}, corresponding to a large field concentration in the transducing layer. The propagation constant of a surface plasmon propagating along the interface of two semi-infinite layers depends on the dielectric properties of the constituting layers and is given by the dispersion relation[19]:

$$K_z = \frac{\omega}{c}\left(\frac{\varepsilon_A \varepsilon_D}{\varepsilon_A + \varepsilon_D}\right)^{1/2}, \qquad (2.2)$$

where c is the velocity of light and ε_A, ε_D are the dielectric constants of the metal film and the dielectric layer, respectively.

The surface plasmon resonance supported by a metal film will be excited by the incident light beam only if the condition

$$K\sin\theta = k_z, \qquad (2.3)$$

is satisfied, where $K = 2\pi n_p/\lambda_o$, n_p is the refractive index of the prism and λ_o is the laser beam wavelength in vacuum.

3.1.4 Fiber based Surface Plasmon devices

The three-layer and four-layer systems are two possible configurations for fiber based surface plasmon devices. The three-layer system requires the metal layer to be deposited on the polished lateral surface of the fiber and the iron oxide or other material coated on the metal layer. The three layers are fiber, metal and the coating material. The four-layer system consists of the polished lateral surface of the optical fiber coated with a metal and a dielectric overlay upon which another material is coated. The dispersion

equation is used to predict the occurrence of surface plasmons from the refractive index and thickness of the considered three or four layers. The choice of metal is very crucial in producing surface plasmons. The sensitivities for different metals vary with the wavelength of operation. In this work the three-layer system was used hence only the three-layer system is discussed below and gold was used as the metal layer over the lateral surface of the fiber.

The coordinate system used for the derivation of the dispersion equation of the three-layer system is shown in Figure 3.4. The factors that play an important role are the refractive index of the cladding, the metal and the coating material and the thickness of the metal layer. The effective index of the single mode and the wavelength of operation of the source are other variables in the dispersion equation.

The three layers are defined by parallel planes, the x direction and the propagation of light is in the z direction. The fiber/metal interface is arbitrarily chosen at x=0 while x = t implies the metal/sample interface as represented in Figure 3.4.

Bender[21] derived the dispersion equation by using the following assumptions. The polished fiber is assumed to be an approximation of a planar waveguide and the coating material and cladding layers are assumed to extend to infinity in thickness.

$$t = \ln\left\{\frac{\left(-\alpha^2/n_s^2 + \Delta/n_m^2\right)\left(\rho/n_c^2 - \Delta/n_m^2\right)}{\left(-\alpha^2/n_s^2 - \Delta/n_m^2\right)\left(\rho/n_c^2 + \Delta/n_m^2\right)}\right\} \Big/ 2\Delta, \qquad (2.4)$$

where t is the thickness of the metal layer, n_s is the coating material refractive index, n_m is the metal refractive index, n_e is the effective modal index, $K = 2\pi/\lambda$, $\beta = n_e K$, $\alpha = i(n_s^2K^2-\beta)^{1/2} = (\beta^2 - n_s^2K^2)^{1/2}$, $\Delta = i(n_m^2K^2-\beta)^{1/2} = (\beta^2 - n_m^2K^2)^{1/2}$ and $\rho = i(n_c^2K^2-\beta)^{1/2} = (\beta^2 - n_m^2K^2)^{1/2}$

3.1.5 Fiber to plasmon mode coupling

Efficient fiber to plasmon mode coupling and hence a high polarization extinction ratio is obtained if the plasmon effective index equals the fiber effective index. Polarization analysis is based on the coupling theory. The modal properties of each waveguide in isolation and the planar surface plasmon guide are considered, and it is predicted that the

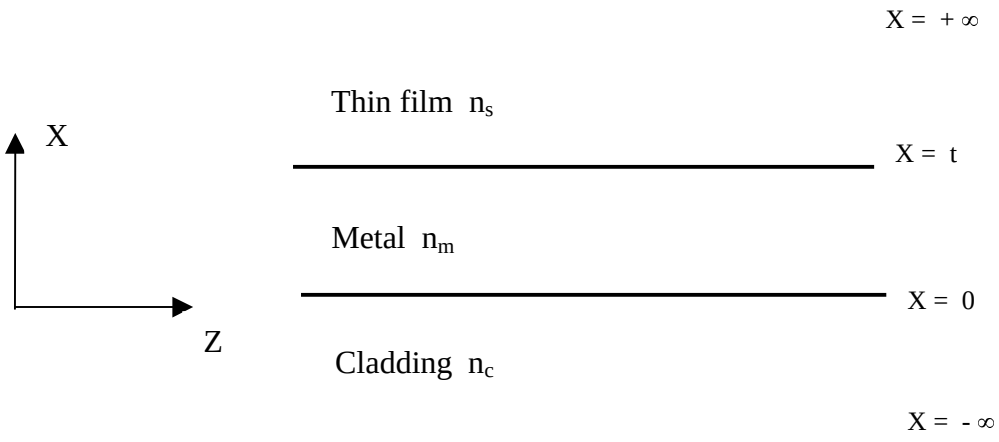


Figure 3.4 the three-layer fiber surface plasmon configuration[22].

coupling takes place when their effective indices match. There are two distinct regimes of efficient coupling between the fiber field and the symmetric TM plasmon modes of the thin film and these are the regimes of device operation. Coupling occurs to the bound symmetric modes over a continuous range of combinations of overlay index n_3 and metal thickness for which $n_e=n_{ef}$ (Figure 3.5). The thickness of the metal is around 100 to 300 angstrom. The effective index of the overlay is between 1.440 and 1.451. As the metal thickness is increased the overlay index has to be decreased to achieve coupling. The suitable thickness and index can be obtained by plotting the dispersion curve for the symmetric bound and leaky plasmon modes of the thin metal film.

The effective index (n_{ef}) of a 1.3-micron fiber is indicated as a line on Figure 3.6. The figure also indicates that the antisymmetric modes do not play a role in device operation and coupling takes place to the symmetric modes only. The symmetric bound mode exhibits a cutoff thickness at the point where $n_e = n_3$. Hence coupling cannot occur to the symmetric bound modes when the overlay index is greater than the fiber effective index $n_{ef} = 1.451$. This establishes the lower limit of the thickness for coupling to the bound mode. This thickness is the cutoff thickness for $n_3 = n_{ef}$ and from the figure 3.6 it is 100 angstrom. The coupling occurs to the leaky symmetric mode when $n_e>n_{ef}$ and the thickness of the metal is less than 100 angstrom.

By polishing the fiber, the evanescent field of the core that permeates into the cladding can be used for the surface plasmon resonance devices. Another fabrication method involves the total removal of the cladding and the deposition of the metal on the core of the fiber. This method makes use of the reflections at the core/cladding surface of the fiber. When these reflections come in contact with the metal layer at the surface of the core of the fiber the light is attenuated, depending on the refractive index of the coating material on the surface of the metal layer. This method of fabricating the surface plasmon element is relatively simpler because removing the cladding is easier than polishing a fiber to couple the evanescent field the surrounding environment.

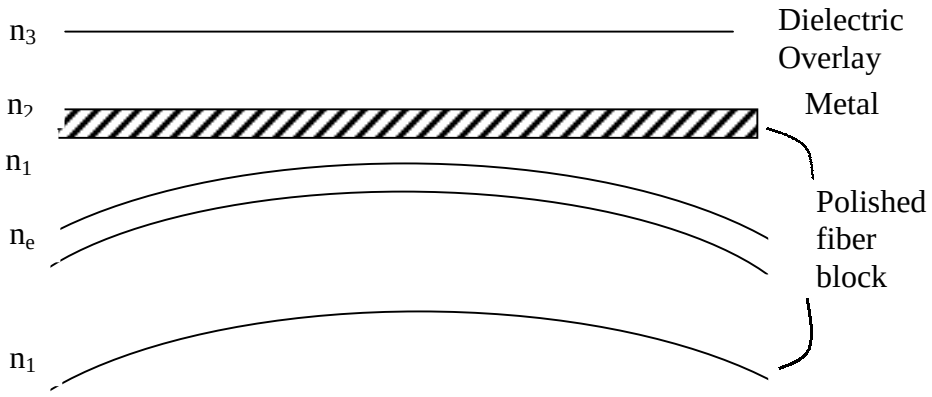


Figure 3.5 Schematic diagram of the thin metal film plasmon polarizing structure[10].

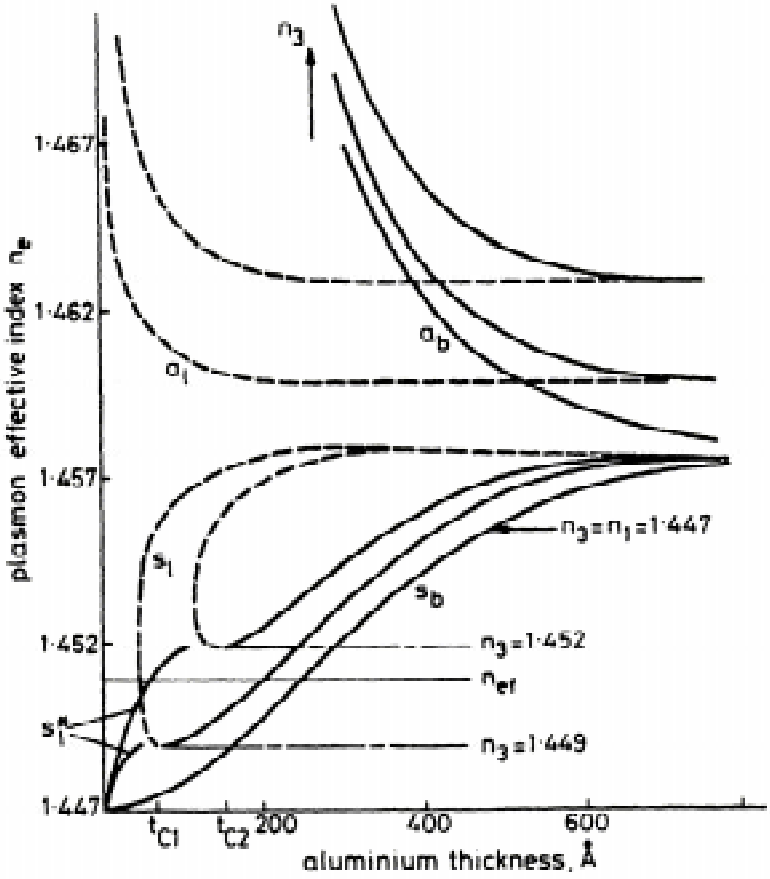


Figure 3.6 Dispersion curves for the plasmon modes[3].

3.2 Ionic Self-Assembled Monolayer (ISAM) Method.

In the last decade much attention has been paid to thin films. These films are built-up of one or more layers, where the individual layers may consist of different molecules. The large number of molecules with varying functions and structures that are used in the build-up of the thin films leads to the realization of tailor-made systems with specific properties. The fabrication of dense and homogeneous thin-films of very small particles with improved properties is possible.

One of the promising approaches is the deposition of the individual layers by adsorption from solution because there is no limit to the substrate size. Sequential self-assembly of oppositely charged polyelectrolytes from solution has received attention as a simple but yet a powerful approach for making thin films. The use of materials that provide multiple electrostatic interactions between the layers offers significant advantages for fabricating multilayer films with reduced defect formation and propagation, in contrast with most films prepared by the Langmuir-Blodgett or by other conventional methods. Individual layers are controllable by factors including concentration, molecular weight, and ionic strength. Polyelectrolyte self-assembly can produce coatings on essentially any solvent accessible surface from environmentally friendly aqueous solutions. In addition there are the advantages in the low cost instrumentation and high throughput of layer fabrication in comparison with the physical vapor deposition or Langmuir-Blodgett techniques.

The ISAM method has received attention as a simple fabrication procedure for the synthesis of multilayer thin films. This method allows detailed molecular-level control over the film composition and thickness. The use of polyelectrolytes that provide alternating electrostatic attractions between layers offers significant advantages for the fabrication of multilayer films with reduced defect formation.

The ISAM technique is based on the electrostatic attraction between opposite charges. Alternating adsorption of anionic and cationic polyelectrolytes from aqueous solutions forms multilayer assemblies. The attraction between the positive and negative charges of polyelectrolytes forms strong interlayer adhesion. The self-assembly process

of monolayers is by physisorption[26]. The connection between monolayers is due to the weak and directional bonds, such as ionic, hydrogen, or van der Waals forces.

The ISAM process, shown in Figure 3.2[25], involves the alternate dipping of a charged substrate into an aqueous solution of the oppositely charged ions at room temperature. By then dipping the substrate in oppositely charged solution in a cyclic fashion, alternating multilayer assemblies can be obtained [26, 27].

One important advantage of the ISAM technique is that there is no substrate size limitation since the deposition is done by adsorption of individual layers from solutions. Another advantage of the ISAM technique is the possibility of building composite multilayer structures. The process only requires two oppositely charged particles. Consequently, deposition of more than two kinds of oppositely charged molecules is feasible. Thus, one can simply immerse the substrate in as many solutions of polyelectrolytes as desired, as long as the charge is reversed from layer to layer.

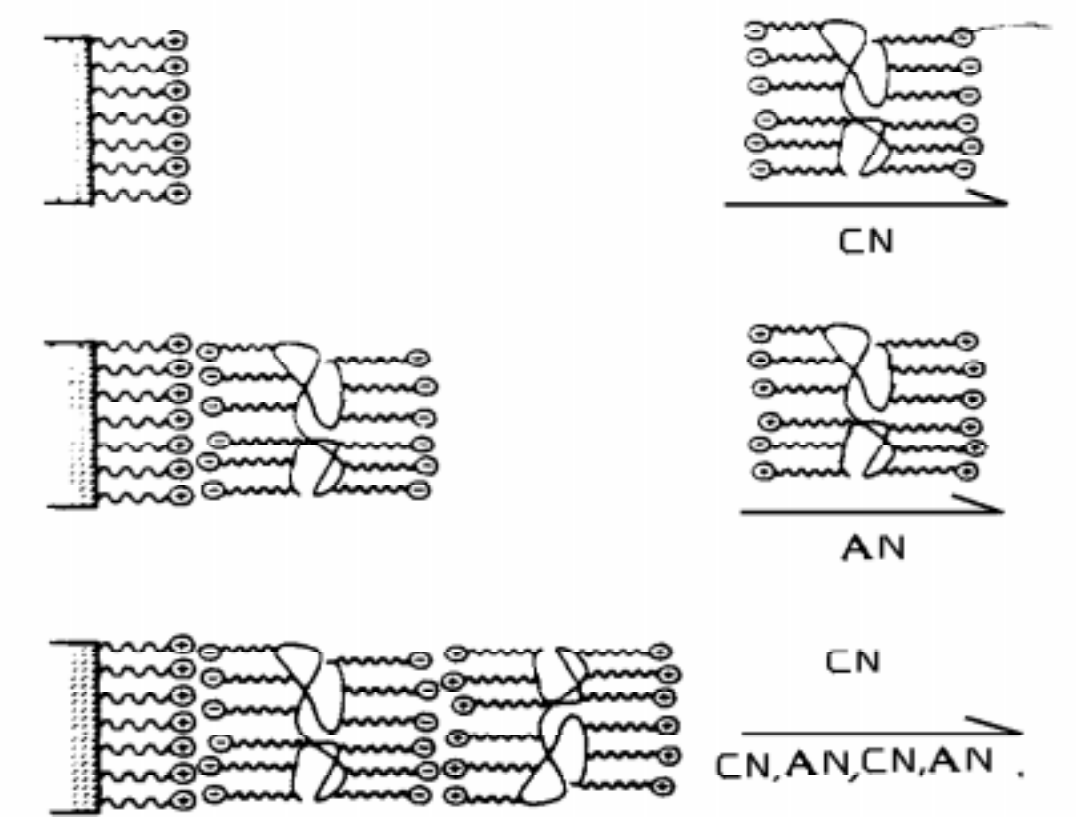


Figure 3.7 Ionic Self-Assembled Monolayer Method (ISAM), buildup of multilayer assemblies, (AN-anion, CN-cation).

4.0 Polarizer Construction

Introduction

To construct the polarizer, commercially available optical fibers are modified by polishing a short section of the lateral surface of the fiber to within the evanescent field penetration depth, followed by the application of one or more thin films to the polished surface. The construction of the in-line polarizer is discussed in detail below.

The experimental fabrication was done with Corning Flexcore 850 nm optical fiber. The Flexcore fiber is singlemode at the wavelength of operation and has the following properties.

Core Index: 1.4603 Core diameter: 6 microns

Cladding Index: 1.4537 Cladding diameter: 125 microns

Other fibers can also be used for the construction of the fiber device.

4.1 Fiber polishing

The central portion of the optical fiber of length one-meter is bonded to a polishing substrate using fingernail hardener and allowed to cure for 24 hours. The amount of hardener used must be sufficient to anchor the fiber firmly to the substrate and at the same time should be thin enough to allow reasonable polishing time. The polishing substrate is a piece of polymer approximately 8 cm long, 1 cm in height and 0.2 cm wide. The top surface of the substrate is curved along the length of the substrate such that its height is only 0.6 cm at the ends. The radius of curvature of the substrate is around 25 cm.

After the fiber is suitably bonded to the surface of the substrate, the ends of the fiber are cleaved. The fiber is now ready to be polished. The aim of the polishing procedure is to remove a short section of the fiber's jacket and cladding so that the evanescent field around the core can be reached. Figure 4.1 shows the polishing substrate and the fiber attached to it. The polishing process must be sufficiently vigorous to remove the hardener, fiber jacket and cladding, but should be gentle enough so that it can be

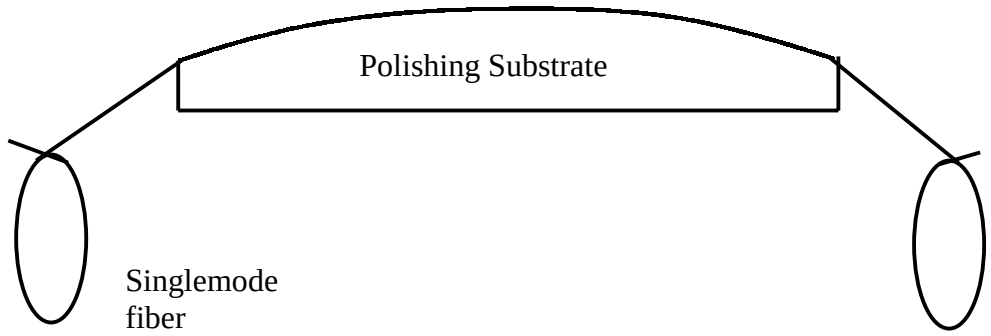


Figure 4.1 Polishing substrate and configuration of the single mode fiber polarizer.

terminated before the core of the fiber is penetrated.

One end of the fiber is connected to an LED and the other end to an optical spectrum analyzer to monitor the polishing process. The experimental setup used to monitor the optical intensity during polishing is shown in Figure 4.3. The output is monitored carefully to ensure that the core is not penetrated.

The polishing is done using a Litton Corporation polishing wheel and a 1 μm grit-polishing pad and is shown in Figure 4.2. The polishing substrate with the attached fiber is mounted on to the cart in the polishing wheel. The cart is gently moved back and forth over the rotating polishing pad. The output is continuously monitored through the optical spectrum analyzer. The output shows some fluctuations initially, and then a significant drop (3-dB drop) in intensity indicates that the evanescent field has been reached. The output intensity that was observed using an optical spectrum analyzer during polishing is shown in Figure 4.4.

In order to verify that the evanescent field of the fiber has been reached a liquid with refractive index considerably larger than water is applied on the polished surface of the fiber. If the evanescent field has been penetrated then nearly all the light out the fiber attenuates. If the core is penetrated the light seen through the optical spectrum analyzer reduces drastically and the whole procedure from bonding the fiber to the substrate and then polishing has to be repeated.

4.2 Metal Deposition

The fiber is now ready for the deposition of the metal layer. Gold was deposited onto the polished surface of the fiber using the vacuum vapor deposition chamber. Based on the type of fiber used the appropriate thickness of the metal deposition has to be chosen. Figure 4.5 shows the graph of the dependence of the metal thickness on the wavelength as derived from equation 2.4. As 850-nm single mode fiber was used, 30 nm of gold was deposited on the polished fiber. Except the polished section of the fiber the other portion of the fiber is masked to ensure that only the polished section of the fiber is coated with gold.

Figure 4.2 Polishing wheel.

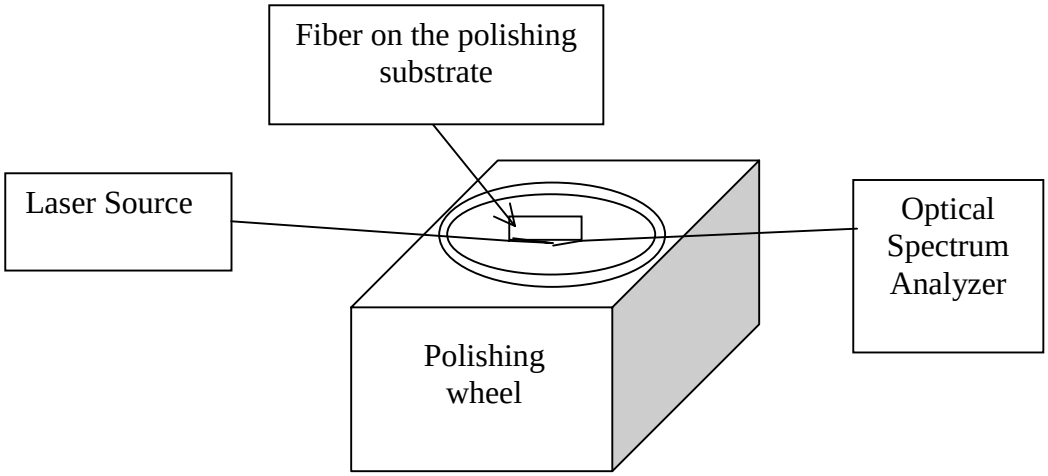
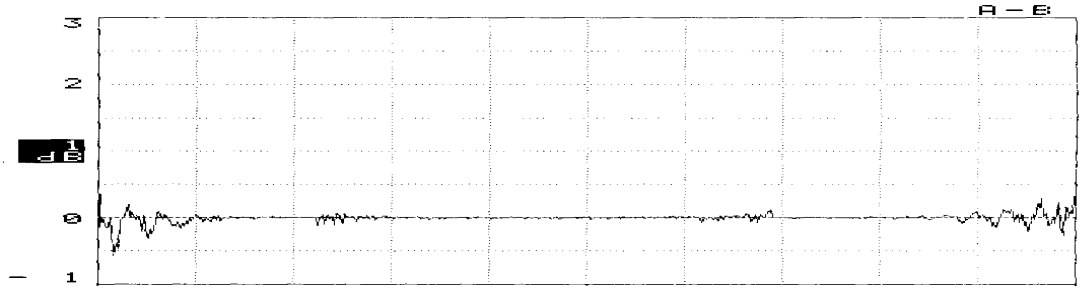
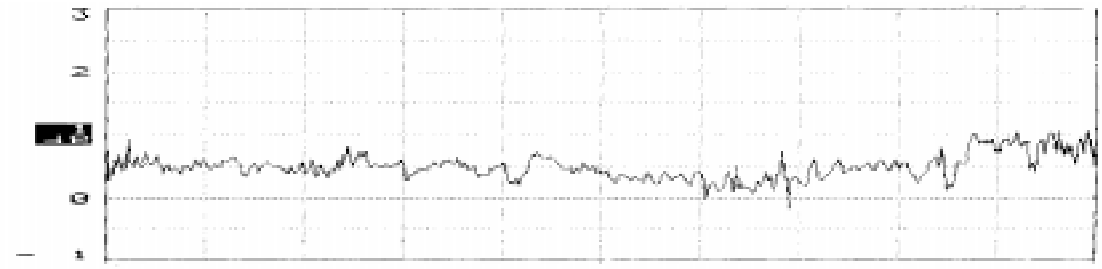


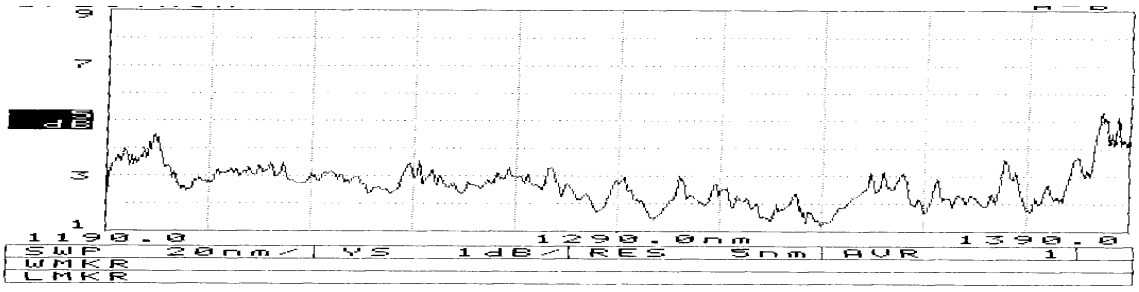
Figure 4.3 Experimental setup for polishing.



(a) Initial output before polishing.



(b) Drop in output intensity during polishing.



(c) 3-dB drop in output intensity when the evanescent field is reached.

Figure 4.4 the output of the fiber while polishing.

4.2.1 Vapor Deposition

The metal coating on the polished fiber was done using the process of thermal vapor deposition. An Edwards sputtering system was used to deposit the thin metal film. The technique of thermal evaporation is useful for the application of thin films of material that are capable of withstanding the thermal shock of melting. Metals such as gold and silver used in this work are easily formed into films by using the Edward system.

The polished fiber is attached to the sample holder in the chamber. The coating material is placed on the wire filament holder, located below the sample holder. In this work the coating material used was gold and 0.15 gram of gold was placed in the filament holder. The wire filament holder is attached to two leads of a high voltage source.

The deposition process begins by sealing and evacuating the chamber. The pressure inside the chamber is brought to around $6*10^{-6}$ torr by the diffusion pump in the system. Slowly the variable transformer is turned on to give a current below the evaporation value that will sufficiently wick the evaporant material into the wire filament holder. After all the material is wicked into the wire filament, the current is increased to the evaporation level. 15 amperes of current is applied for 60 seconds. As the material melts some of the atoms ejected from the filament holder strike the polished fiber on the substrate. Figure 4.6 gives an illustration of the vapor deposition process. The rate at which the atoms strike the substrate is given by the equation [28] 4.1.

$$N = 3.513*10^{22}\frac{P}{\sqrt{MT}}\ \text{mols cm}^{-2}\ \text{sec}^{-1}, \qquad (4.1)$$

where N is the rate of evaporation of the material with atomic weight M and a vapor pressure P at a temperature T.

The variable transformer is reset to zero and the filament is allowed to cool for ten minutes and then the chamber is vent to atmospheric pressure before removing the substrate. From the geometry of the evaporating system it is possible to roughly estimate the thickness of the thin film from equation 4.1, as the thin metal film used to obtain surface plasmon resonance requires very accurate thickness.

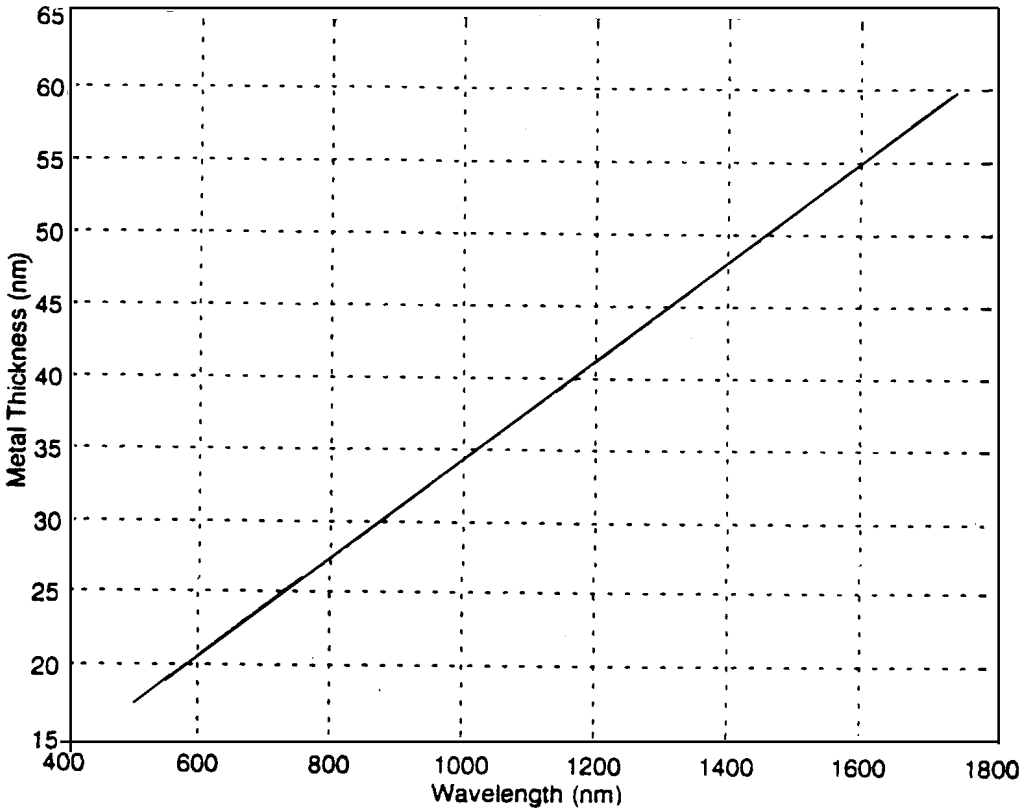


Figure 4.5 Wavelength vs. metal thickness dependence of a 3-layer SPR configuration.

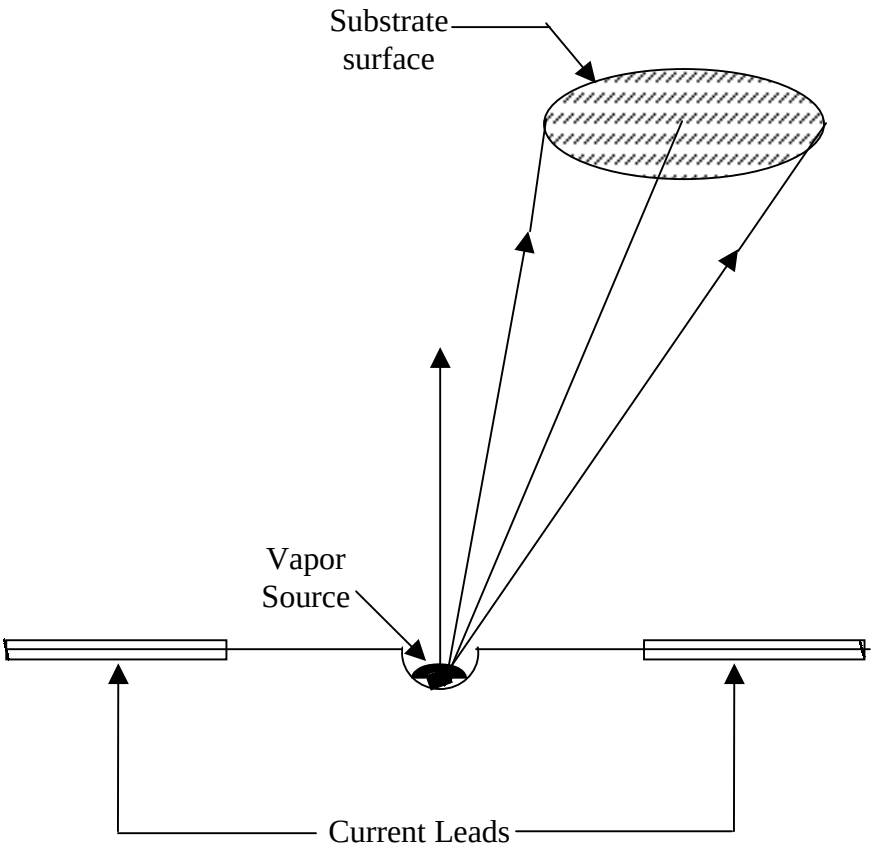


Figure 4.6 Schematic illustrating vapor deposition.

4.3 Experimental setup for the in-line fiber polarizer

The experimental setup used to characterize the polished fiber polarizer is shown in Figure 4.7. The output from an LED at a wavelength of 850 nm is launched in to the fiber polarizer. A linear analyzer was placed at the output end of the fiber to evaluate the polarization dependence of the output. The spectrum of the light from the polarizer was measured using an 850 nm detector attached to a power meter. The analyzer was rotated in steps of 10 degrees. The output was recorded for each successive rotation of the analyzer. The plot of the output light intensity of the metal-coated polished fiber as a function of the angle of the analyzer is shown in Figure 4.8 (b).

4.4 Deposition of thin films

The polished fiber with the metal coating is then coated with thin films using the ISAM process discussed in Chapter 3. Before coating the fiber using the ISAM process, the fiber has to be pretreated to negatively charge the surface of the metal coating on the fiber. This is essential since the ISAM method is based on the electrostatic attraction between opposite charges and the polished surface has to be coated alternatively with anions and cations.

Pretreatment of the fiber surface consists of the following procedure. The fiber is immersed in a solution containing equal parts of hydrogen peroxide (H_2O_2) and hydrochloric acid (HCl). The fiber is removed from the H_2O_2/HCl solution after twenty seconds and is rinsed with water immediately.

About 660 mg of MUA is mixed in 40 ml of chloroform. This mixture is stirred well for over thirty minutes until the solution becomes clear. The fiber is immersed in this solution for over two hours. After removing the fiber from the MUA solution it is rinsed twice with chloroform. The fiber is then placed in a bath containing alcohol and cleaned ultrasonically for ten minutes. Finally the fiber is cleaned five times ultrasonically with water, each cleaning lasting for about 5 minutes. By this procedure the metal surface on the polished fiber is negatively charged and the fiber is ready for thin film deposition by the ISAM process.

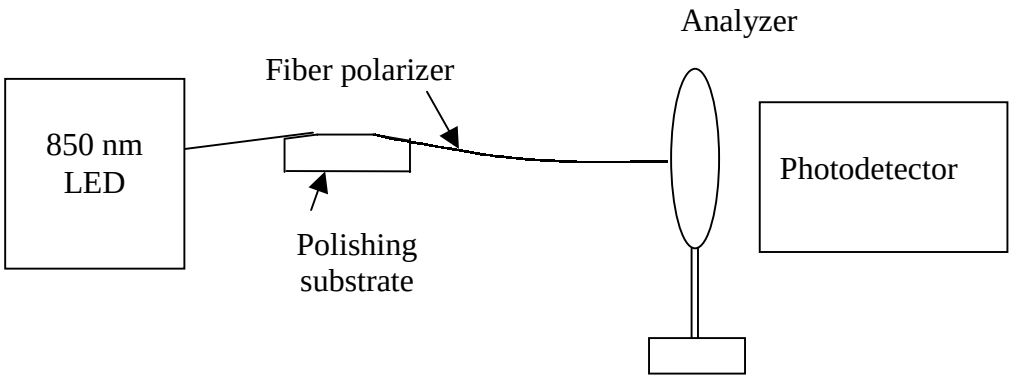
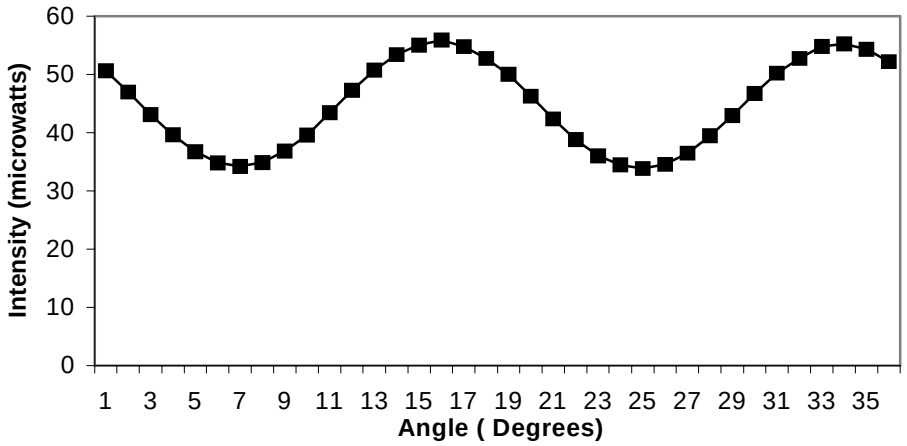
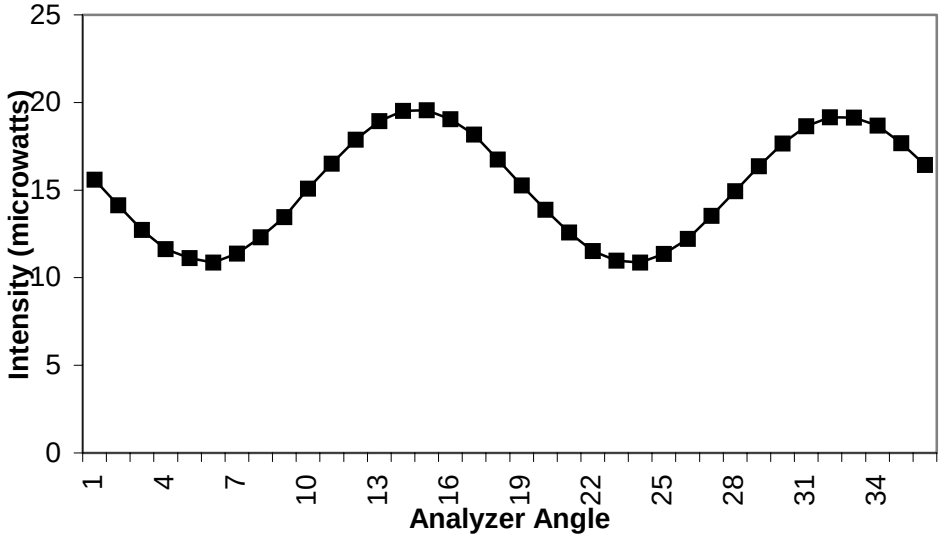


Figure 4.7 Experimental setup to observe the polarization of light.



a) Polished singlemode fiber.



b) Gold coated polished fiber.

Figure 4.8 Graph of output intensity as a function of the angle of rotation of the analyzer.

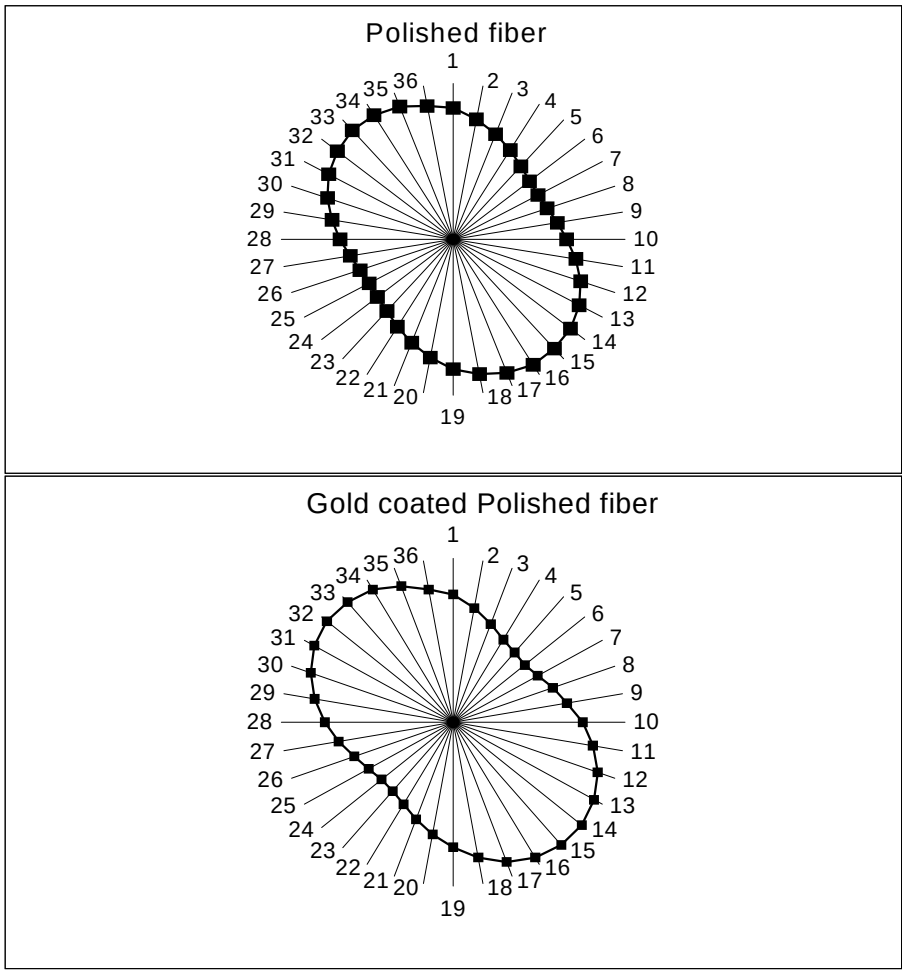


Figure 4.9 Polar plot of output intensity as a function of the analyzer angle.

The fiber is immersed in a solution of iron oxide (Fe_3O_4) for five minutes for anion adsorption. The fiber is then rinsed with pure water. Now the fiber with the metal coating has a layer of positively charged molecules. It is then immersed in a solution of PS119 for five minutes for the cation adsorption. This alternate adsorption of anion and cation forms a layer of thin film on the polished fiber surface.

4.5 Polarization Measurements

The fiber with the film coating is then tested to observe the polarization effect. The ISAM process was continued and after each layer of the thin film the fiber was tested to observe the polarization effect. The observed output is shown in Figure 4.10. Figure 4.11 shows the polar plot of intensity at the detector as a function of the analyzer angle. The solid curve represents the polarization.

As the number of film coatings increases on the fiber the polarization property of the fiber increases. It reaches a maximum with 23 film coatings and the light is polarized at $\sim 1^0$. Further coating reduces the polarization property of the side polished fiber with the coating.

A commercial polarizer was also tested using the same experimental setup. The graphs plotted for the commercial polarizer is shown in Figure 4.12. The results obtained from the polarizer constructed using the side-polished fiber and the ISAM process compare favorably with those of a commercial polarizer.

4.6 Extinction Ratio

The extinction ratio ER is defined as

$$ER = 10 \log_{10}(I_{max}/I_{min}) \qquad 4.2$$

where I_{max} and I_{min} are the maximum and minimum output light intensities measured by rotating the analyzer. Figure 4.14 shows the extinction ratio of the fiber polarizer for each bilayer.

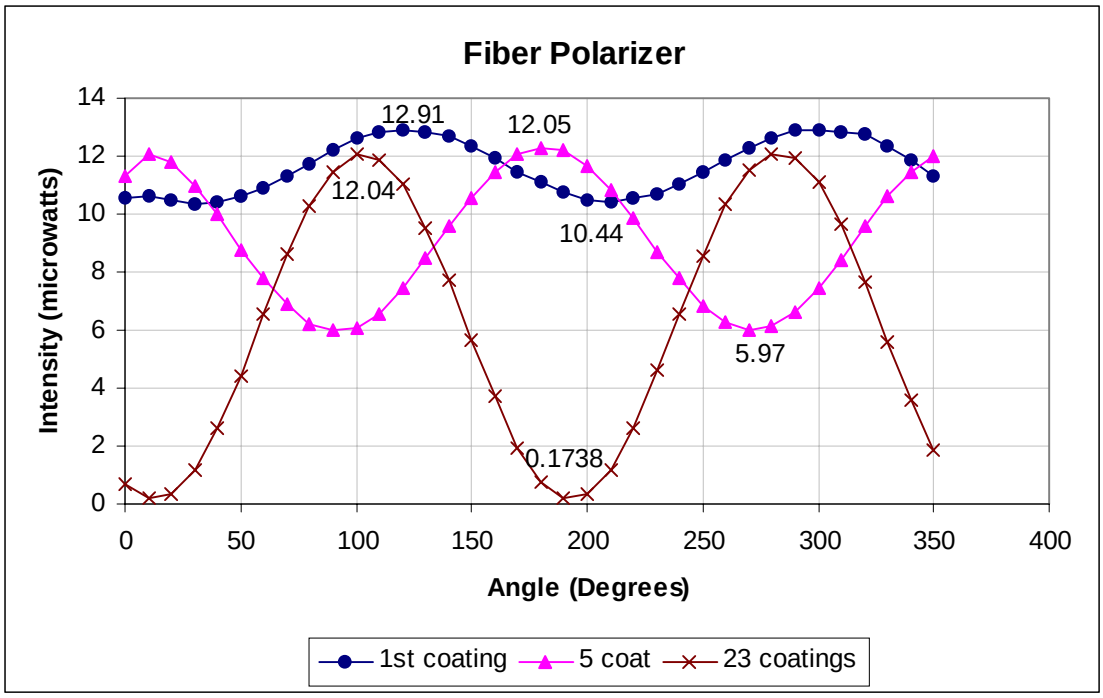


Figure 4.10 Output intensity as a function of the analyzer angle.

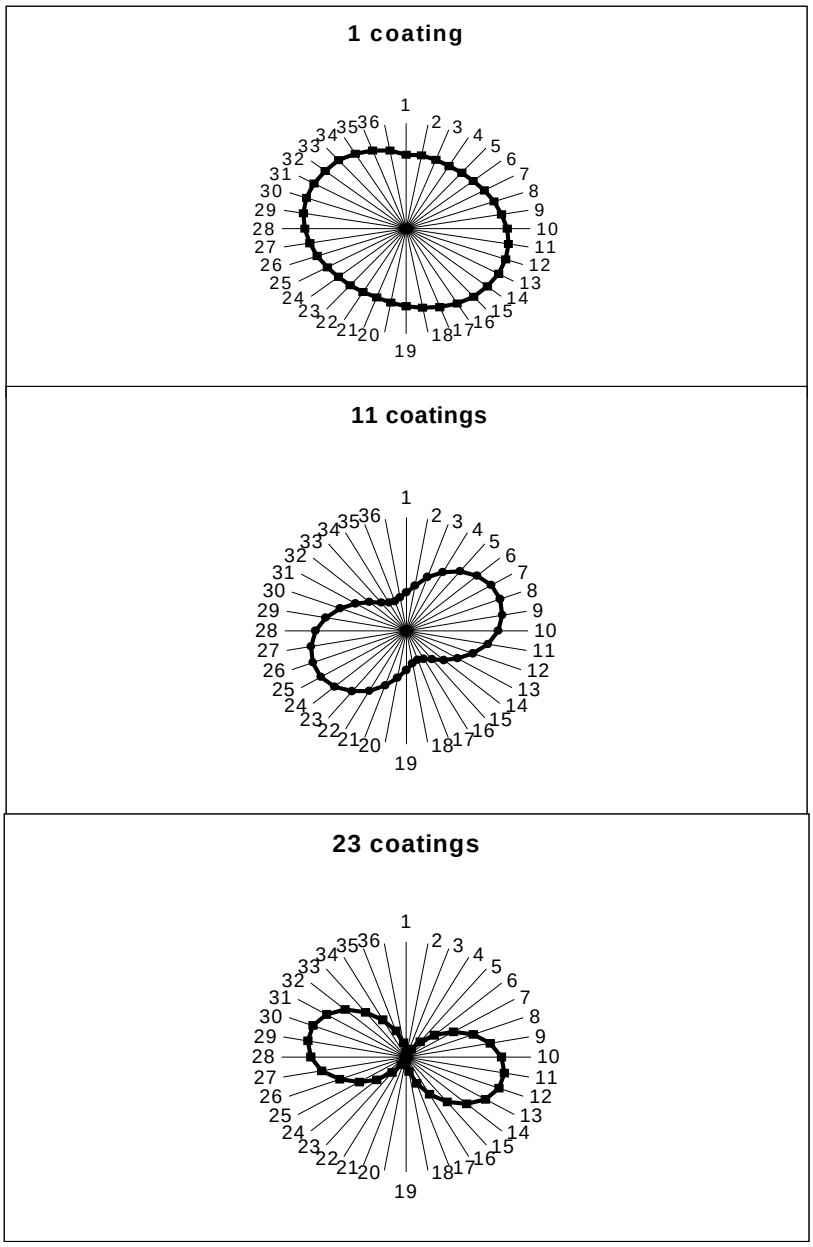


Figure 4.11 Polar plot of intensity at the detector as a function of the analyzer angle.

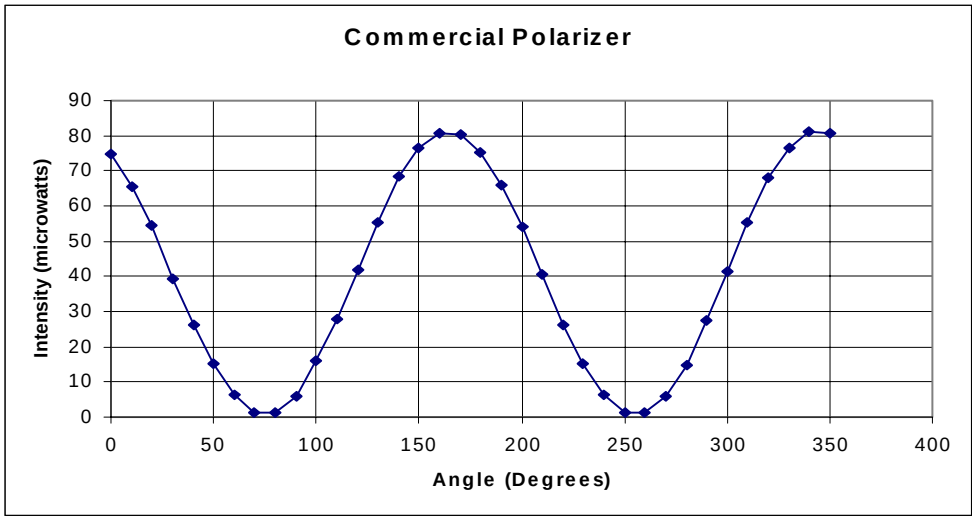


Figure 4.12. Variation of output intensity as a function of analyzer angle for a commercial polarizer.

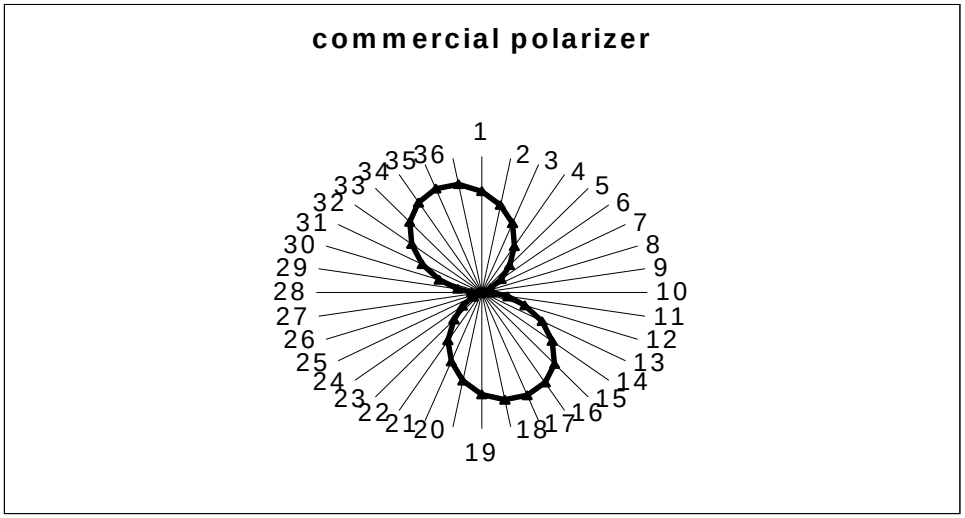


Figure 4.13. Polar plot of the output intensity as a function of analyzer angle for the commercial polarizer.

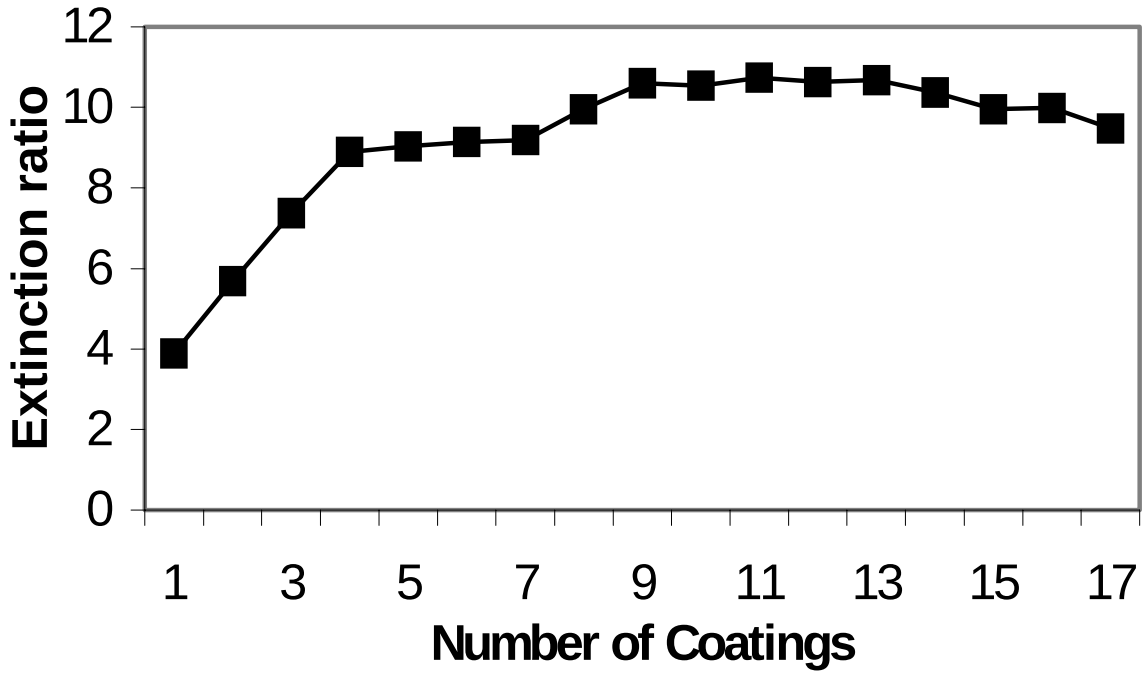


Figure 4.14. Extinction ratio of the fiber polarizer.

Refractive index fluid was applied to the polished side of the fiber and the intensity of the light through the fiber was observed using the detector. The peak intensity at the output of the fiber increased with the increase in the refractive index of the liquid.

5. 0 Future Work and Conclusion

5.1 Future work

The commercial viability and future usefulness of the fiber optic in-line polarizer may depend on several key aspects of the polarizer construction and design. The coupling efficiency between the guided mode and the surface plasmon strongly depends on the quality of the polish of the fiber's lateral surface. An automated method is required to produce consistent, high quality surfaces to deposit the plasmon support and overlay. The best method is to use a D-clad fiber where one side of the fiber is flattened and thin to allow evanescent penetration. This will eliminate the need for polishing the fiber.

The quality and thickness of the deposited layers are the most important characteristics of the fiber optic in-line polarizer. The application of the desired thin metal film is crucial for the development of the device. Apart from using the vapor deposition process to deposit the metal film other processes such as electron beam sputtering could also be employed to synthesis the metal film coating.

Further improvements can be made to the fiber polarizer by proper control of the film thickness at peak polarization. The particle size of the anion and cation solutions used to coat the fiber by the ISAM method can be varied to obtain a better performance through control of thickness.

Other devices such as isolators and modulators can also be constructed on the surface using optical fibers coated with the thin film. An optical switch can be constructed using a side polished fiber with thin film coatings.

5.2 Conclusion

The use of surface plasmon resonance for polarization control has shown to be feasible with a surface modified optical fiber. By polishing the lateral surface of the fiber and applying thin films that support surface plasmon resonance, an in-line fiber polarizer was constructed. Thin metal-clad fiber polarizers with index overlay were experimentally demonstrated by this work. The polarization selective evanescent coupling between a

fiber and surface plasmons supported by thin metal film deposited on to the polished fiber has been characterized experimentally.

Matching the ray angle of the fundamental mode of single mode fibers and the resonant angle of the surface plasmon mode in the interacting region of fiber polarizers can effectively excite the surface plasmon mode. This in-line fiber optic polarizer can be inserted directly into a single-mode fiber line by splicing. The device may find a variety of applications such as in all fiber gyros that require a high quality polarizer in order to reduce the bias offset due to polarization coupling and in fiber optic communication systems.

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Vita

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