XVII IMEKO World Congress
Metrology in the 3rd Millennium
June 22-27, 2003, Dubrovnik, Croatia

STUDY OF ELECTRO-OPTIC AND ELECTROSTRICTIVE EFFECTS ON POLARIZATION IN SINGLE MODE FIBER

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Abstract - If the rotational symmetry of single mode (S.M.) fiber is disturbed, either during manufacturing or through some external perturbation the polarization modes have different propagation constant. Due to this generated birefringence, the linear polarized light through S.M. fiber is distributed in two orthogonal eigenmodes. As a result, the state of polarization (SOP) is changed at the exit end of the fiber. In the present paper, electro-optic effect on S.M. fiber has been induced by placing the fiber coil under electric field. Investigation shows that the developed birefringence in fiber arises mainly due to bending and electrostriction/Kerr effect. So, by varying the electric field, the developed anisotropy or birefringence ultimately can be utilized to control the state of polarization (SOP) at the output. Experimental study has been carried out on 40m. and 48m. coiled fiber under D.C. voltage (0 to 280 volts). Results show that SOP of two prototype polarization controllers, become circular i.e. λ/4 plate at 235 volts and 143 volts respectively. The external effect acting upon SM fiber is directly calibrated with respect to phase and ellipticity of light. The correction in calibration equation in particular case where ellipticity change is considerable, has been reported in the present paper. Experiment has been performed to verify the theoretical studies and error has been computed.

Keywords fiber optic sensor, wave plate, ellipticity

1. INTRODUCTION

A calibration equation for AC voltage (Range 0-800 volts r.m.s.) impressed upon sufficient length of SM fiber has been presented in earlier work [1]. In single mode fiber input output polarization relationship is maintained. In coherent optical communication system the received and local oscillator signals must have identical polarization states. Any mismatch between polarization states will result reduced output level and associated errors [2].

The induction of birefringence phenomena in single mode fiber may be caused due to the manufacturing process of the fiber or may originate from the outer causes acting on fiber. The main manufacture induced causes are defects in fiber or birefringence generated due to shape of the core. In polarization maintaining fiber the shape of core is purposefully made elliptical to reduce the beat length to a few millimetres rather than 8-9 cm for circular core single mode fiber [3]. A few other effects that may cause or modify birefringence in single mode fiber may be noted as :

i) Mechanical stress induced birefringence. [3]
ii) Induced elastic birefringence. [4]
iii) Birefringence generated due to bending. [5]
iv) Birefringence induced due to torsion. [6]
v) Birefringence due to electric stress [1]
vi) Birefringence generated by electro optic means. [7]

H.C. Leferve utilized the third effect to develop a mechanical fiber optic polarization controller [5]. The electro-optic and electrostrictive effect [1] on sufficient length of S.M. fiber due to voltage has been reported. In the medium D.C. voltage range, a significant change in birefringence has been obtained. In view of that two prototype polarization controller devices have been made to investigate the state of polarization at the output by transmitting polarized light through S.M. fiber. Theoretical study on birefringence due to different induced fields has been carried out and explained briefly. It has been observed through practical set up that the bending of the fiber, as well as, the electrostriction effect contributes the major birefringence changes and which is ultimately manifested by SOP at the output end.

2. THEORETICAL BACKGROUND :

It has been observed that change in azimuth of the polarized laser beam passing through the fiber optic electrometer with direct voltage excitation is due to 1) electrostriction 2) Kerr effect. [1]. Again, due to Kerr effect the principal axes of the system rotate and with the joint effect of change in phase and new alignment of principal axes, ultimately the ellipticity change its value in the system. Though Kerr effect is prominent in glass fiber under electrical stress, Pockel's effect contributes little to the change in birefringence. The additional remarks on Kerr effect is discussed below.

2.1 Generation and control of birefringence

A. Through bending

The change in refractive index along two orthogonal axes in single mode fiber due to bending is [4] :

$$|\Delta n| = \frac{\lambda^2}{N^2 m^2 4\pi^2 a r^2} \quad (1)$$

where, Δn : change in refractive index, N : Number of turns, m = 2,4,8…., a = 0,133, r : core radius of S.M. fiber [4].

In mechanical polarization controller designed and fabricated by H.C. Lefevre, the measure of birefringence due to bending (bending radius 0,85 cm) is obtained as :

$\Delta n = 2{,}35 \times 10^{-4}$ /two loops

With r = 9μm and λ= 633 nm.

In case of prototype developed, the birefringence generated due to bending as calculated from eqn (1) is :

$\Delta n = 1{,}66 \times 10^{-4}$ / two loops

where, $R_{effective}$ (effective bending radius) = 1,22 cm.

B. Through electrostrictive stress :

S.M. fiber is helically coiled and placed between two electrodes in single layer i.e. one fiber dia separation (≈0,185 mm). The mechanical stress on the capacitive set up due to impressed D.C. voltage (V) may be delineated as [8].

$$P = \frac{\varepsilon V^2}{2d^2} \ (N/m^2) \quad (2)$$

where, ε : dielectric constant of silica glass ≈ 3,81 x 8,85 x 10^{-12} F/m, d : separation between two electrodes ≈0,185 mm. The corresponding longitudinal strain (l_o) produced in the coiled S.M. fiber due to electrostrictive stress is [1]:

$$l_0 = \frac{P}{\sigma Y} \ \text{/ metre of fiber} \quad (3)$$

where, σ : poission's ratio of silica glass ≈0,19

Y : Young's modulus of silica glass ≈68 G.Pa

Birefringence (Δn) due to electrostrictive stress is [3] :

$$\Delta n = \tfrac{1}{2} n_{co}^3 (p_{12}-p_{11})\, d_0 \quad (4)$$

where, p_{11} (optical constant) = 0,121, p_{12} (optical constant) = 0,370, n_{co} : core R.I. of glass fiber = 1,452 d_0 : diametric deformation [5].

The longitudinal strain created along the fiber (l_0) when integrated over l metres of S.M. fiber should satisfy the relation for λ/m wave plate :

$$l_0 . l + \Delta n . l = \lambda/m \quad (5)$$

where, m = 2, 4, 8….

Calculation has been carried out with V_{DC} = 200 volts and separation between two electrodes as 0,185 mm i.e. one fiber dia. It is obtained that 40 metres of fiber length is sufficient to realize one λ/4 effect for D.C. voltage range 0-280 volts.

C. Kerr Effect

Optically isotropic medium like silica glass fiber characterized by its second order electro-optical matrix (S), which is under influence of electric field E has been considered. The medium has rotation symmetry, hence the E vector may be chosen along the axis Oz of the set reference frame such that E=Ez (Fig.1) [3].

Due to Kerr effect the variation of coefficient of ellipsoid may be expressed as [3].

$$\Delta[1/n_{ij}^2] = r_{ij}E_j + S_{ik}E_k^{(2)} \quad (6)$$

Where,

$E_1^{(2)} = E_x^2$ ……. and, $E_4^{(2)} = 2E_xE_y$

This equation leads to the equation for index of ellipsoid, such as :

$$x^2[1/n^2+S_{12}E^2]+y^2[1/n^2+S_{12}E^2]+z^2\,[1/n^2+S_{11}E^2] = 1 \quad (7)$$

Single mode fiber which is normally isotropic in nature becomes birefringent under the application of electric field for electrostrictive and electro optic effects [3]. The corresponding change in polarization due to Kerr effect is [3] :

$$n_o = n-(1/2)n^3S_{12}E^2$$
$$n_e = n-(1/2)n^3S_{11}E^2 \quad (8)$$

Where the ellipsoid is revolving around the axis Oz and the terms $S_{11}E^2$ and $S_{12}E^2$ being very small with respect to $1/n^2$.

For an incident linear state of polarization, having an angle θ (θ between - π/2 to π/2) with the slow axis of the λ/4 wave plate, the emerging SOP is elliptical. An important particular case is θ=π/4, when the emerging SOP is circular. Through calculation it may be shown that minimum 80 metres of fiber winding is necessary for control of ellipticity at the output upto λ/4, for a D.C. voltage range of 0-280 volts when only Kerr effect is considered.

2.2 Representation of Polarization

It is assumed that the axes of the elliptical state of polarization are aligned with those of laboratory's reference frame O_{xyz}. If a and b are respectively the values of half axis, the Jone's representation of polarization [3] :

$$J = \frac{1}{\sqrt{a^2+b^2}}\begin{bmatrix} a \\ \pm ib \end{bmatrix} \quad (9)$$

Where J is the standardized Jones vector [3] corresponding to elliptical polarization. The +/- sign denotes clockwise or anticlockwise sense of the ellipse. Whenever polarizer is rotating, the transmitted intensity through the polarizer oscillates between two extreme values I_{max} and I_{min} such that

$$I_{max} = a^2/(a^2+b^2)$$
$$I_{min} = b^2/(a^2+b^2) \quad (10)$$

Where I_{max} and I_{min} are the intensities along the major and minor axis of the ellipse respectively. In Fig 1, the transmitted intensity is plotted as a function of analyzer rotation for an elliptical SOP incident at the input of the analyzer. The variation of elliptical SOP with the ratio (a/b) may be shown in Fig. 1.

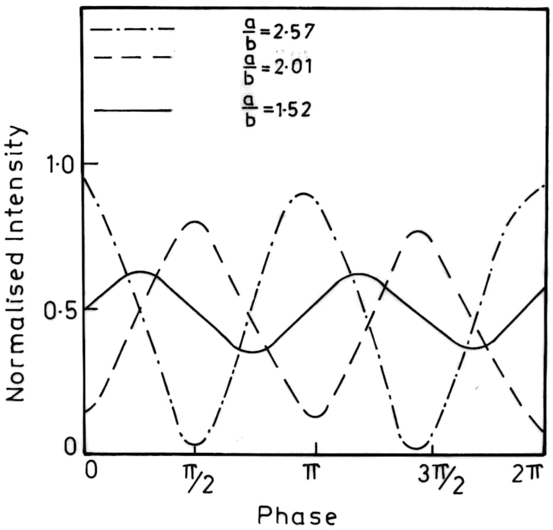

Figure 1 : Intensity transmitted by an analyzer for rotation angle of θ with respect to incident state of polarization (SOP).

2.3 Change in Phase :

The force exerted due to electric field E on a nonhomogeneous fiber dielectric with dielectric constant ∈ may be given as [9] :

$$F = \tfrac{1}{2}\,\epsilon_0\,(\epsilon\nabla|E_1|^2 + |E_2|^2\,\nabla\epsilon) \qquad (11)$$

Where the first term in the equation is governed by the weak change in refractive index due to light intensity and E_1 is the electric field due to laser beam propagating in the fiber. The second term is evolved when E_2 is externally applied electric field [1,9].

Change in phase of laser beam through coiled S.M. fiber caused by electrostrictive stress on the set up may be depicted as [1] :

$$\Delta\varphi_E = \left(\frac{\pi\varepsilon n_{co}}{\sigma Y\lambda}\right) x \left(\frac{lV^2}{d^2}\right) \qquad (12)$$

where V : impressed voltage

l : coiled fiber length

d : separation between electrodes i.e. one fiber dia.

The change in phase due to Kerr effect for impressed DC voltage on the coiled fiber is [10]

$$\Delta\varphi_k = \frac{2\pi KlV^2}{d^2} \qquad (13)$$

The integrated effect of electrostriction and Kerr on the capacitive setup for impressed D.C. voltage V is :

$$\Delta\varphi_T = \left(\frac{\pi\varepsilon n_{co}}{\sigma Y\lambda} + 2\pi K\right) x \left(\frac{lV^2}{d^2}\right) \qquad (14)$$

The transmitted intensity through analyzer polarizer combination follows I_{max} $Sin^2\theta$ variation [1]. When operating point (Q) is at $\theta = \pi/4$, for AC voltage of magnitude V_mSinwt which is applied on sufficient amount of coiled S.M. fiber the corresponding intensity variation is [1] :

$$I = I_m + (1/2)\times(I_{max} - I_{min})\,Sin^2(\pi/4 - K_2V_m^2Sin^2wt - \alpha) \qquad (15)$$

I_m:Constant, K_2 : change in phase / unit voltage. Where I_{max} and I_{min} are optical power along major and minor axes of elliptical polarization at the output and α is change in phase due to spurious effects arising from sensor design like bending of fiber, dead weight of the upper electrode. For change in ellipticity $\left(\varepsilon = \sqrt{\frac{I_{max}}{I_{min}}}\right)$, the operating point Q is shifted to a new curve (Fig 1) with different slope and (15) is invoked.

Due to prominent change in I_{max} and I_{min} i.e. change in ellipticity value $\left(\varepsilon = \sqrt{\frac{I_{max}}{I_{min}}}\right)$ for variation in impressed A.C. voltage on the sensor, the calibration equation for AC voltage measurement, in case of sufficient amount of coiled S.M. fiber, is obtained as :

I_{rms} =

$$\left[\frac{A^2}{8} - \frac{A^2}{8} J_0(2K_2V_m^2 + \alpha)Cos(2K_2V_m^2 + \alpha)\right]^{1/2} \qquad (16)$$

Where, $A = (1/2)\times(I_{max} - I_{min})$, J_0 : Bessel function of order zero. Intensity is modulated by Bessel and Cosine function of square to amplitude of AC.

2.4 Thermal Effect :

Beside the various effects on fiber, electrostrictive stress also generates heat inside the medium. The maximum electrostrictive stress on the prototype developed is of magnitude 30 Pa [1] for impressed D.C. voltage of 280 volts. A $1{,}5^0$C rise in temperature of the set up is obtained theoretically for dissipation of 30 Pa of mechanical stress for about 30 minutes. Though a slight rise in temperature causes a deformation in the coiled fiber of magnitude comparable to a fraction of He-Ne laser wavelength which may cause significant change in birefringence. The temperature sensitivity may be significantly reduced by carrying out experimentation in a controlled temperature environment.

3. WAVE PLATE DESIGN

Two annular shaped aluminium plates are taken with inner radius of 2 cm and outer radius of 10cm. The surface of the plates are made flat by proper machining. Single mode fiber of core diameter 9μm and coat dia 175 μm is wound on one plate in a concentric spiral fashion. The schematic diagram of the electrometer is shown in Fig.2. A stick adhesive with less amount of hardener is used to stick the fiber on one plate in single layer. During the process the length of winding on the aluminium plate has been estimated. Nearly one metre of fiber is kept free at ends of fiber winding for launching of light and detection purposes. Single mode fiber is wound spirally on one plate with no overlapping. In the design of the wave plate the microbending loss has been minimized by keeping the minimum winding radius (2cm) of the fiber always greater than critical radius of microbending (8mm) [5]. During experiment, waveplate is maintained at constant temperature by placing it in a temperature controlled (±0,2^{0}C) environment. The outer plate is then placed over the first one and electrical contacts are made to apply voltage. For experimental study, two wave plates are made with 48 metres and 40 metres of SM fiber.

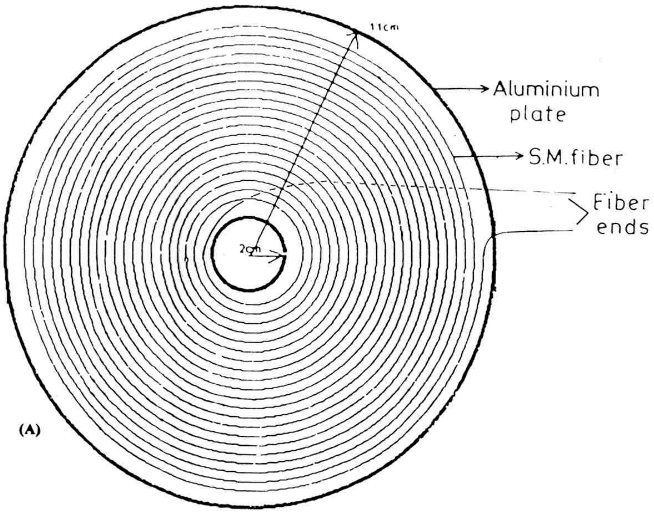

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Figure 2 : (A) Optical fiber layout on the electrode plate

4. EXPERIMENTAL SET UP AND PROCEDURE

The experimental set up is shown in Fig.3. He-Ne laser is first passed through a polarizer which linearly polarizes the beam and then focussed by the microscope objective to the single mode fiber for efficient coupling. The laser output beam is passed through an analyzer and detected by a photodetector for measurement of optical power. Low noise power meter has been used for recording the data.

The polarizer and analyzer are positioned in crossed condition and adjusted to minimize the detected signal. After application of voltage to the fiber optic controller, linearly polarized input beam becomes elliptically polarized at the output.

The phase change in polarization i.e. azimuth can be determined by rotation of the analyzer in the direction of major axis. At the same time, by measuring the power in orthogonal direction or in minor axis, ellipticity can be determined and is followed in the present work. The ellipticity is precisely the square-root of the ratio of power carried through two axis i.e. I_{max} and I_{min}.

In order to measure the contribution of electrostriction and Kerr effect experiments have been performed with varying voltages. In this experiment it has been tried to maintain the input and output optics free from strain to avoid influencing the measurement with their own birefringence.

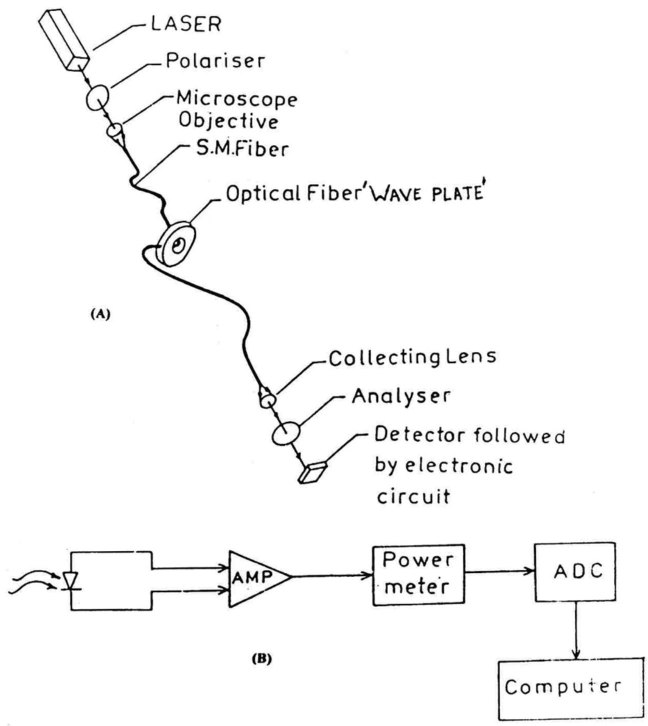

Figure 3 : (A) Schematic optical layout for the fiber optic sensor
(B) Schematic electronic circuit for data processing

5. RESULTS AND DISCUSSIONS

As it has been discussed earlier that ellipticity at the output changes as well as orthogonal axes rotate in space due to applied voltage on the fiber wave plate. With the increase of DC voltage from 0V to 280 volts, ellipticity changes. It is to be noted that as the voltage increases, ellipticity of the polarization decreases and at 143 volts the SOP becomes circular for 48 metres of coiled fiber (table 1).

Table 1 : Change in ellipticity at different D.C. voltages on the wave plate.
Fiber wound = 48 metres
Core dia. of S.M. fiber used = 9 micro-metres
Clad dia of fiber used = 125 micro-metres
Separation between electrodes : 0,185 mm

Voltage in Volts (D.C.)	I_{max} micro-watt	I_{min} micro-watt	Ellipticity
0	1,36	0,26	2,28
20	1,35	0,27	2,21
40	1,33	0,28	2,19
60	1,28	0,31	2,01
80	1,24	0,32	1,97
100	1,20	0,35	1,92
120	1,17	0,38	1,75
140	1,10	0,42	1,60
150	1,02	0,60	1,30
160	1,13	0,43	1,62
180	1,15	0,28	2,02
200	1,27	0,26	2,18
220	1,30	0,27	2,19
240	1,33	0,26	2,24
260	1,25	0,29	2,06
280	1,26	0,33	1,95

For further increase of voltage it becomes elliptically polarized. Hence the prototype can be used as a electrostrictive / electro-optic λ/4 retarder at 143 volts DC. The azimuth change at 143 volts is 43^0. It is calculated value on the basis of measured intensity of optical beam at the output of the wave plate with 5^0 rotation of analyzer from 0^0 to 180^0. Extrapolating the ellipticity Vs. voltage curve for higher voltages it can be shown that the λ/2 characteristic voltage is about 230 volts and near this voltage the ellipticity factor is high and the SOP changes from elliptic to linear. Similarly for λ/8 plate the characteristic voltage is 104 volts. The same experiment is repeated for 40 metres of S.M. fiber wound and λ/4 effect sets in at a voltage of 210 volts and the azimuth change at this voltage is 92^0. The change in SOP of linearly polarized laser beam during its passage through the wave plate which is subjected to different direct voltages for experiment with 40m of helically wound fiber is shown in Table 2.

Table 2 : Ellipticity change for different D.C. voltages on the wave-plate.
Fiber wound = 40 metres
Core dia. of S.M. fiber used = 9 micro-metres
Clad dia = 125 micro-metres
Separation between electrodes : 0,185 mm

Voltage in Volts (D.C.)	I_{max} micro-watt	I_{min} micro-watt	Ellipticity
0	1,49	0,26	2,39
20	1,48	0,27	2,34
40	1,48	0,28	2,29
60	1,47	0,30	2,21
80	1,47	0,31	2,17
100	1,43	0,32	2,11
120	1,43	0,34	2,05
140	1,40	0,35	2,00
160	1,38	0,37	1,93
180	1,35	0,38	1,88
200	1,30	0,41	1,78
240	1,20	0,54	1,49
260	1,04	0,72	1,20
280	1,27	0,50	1,59

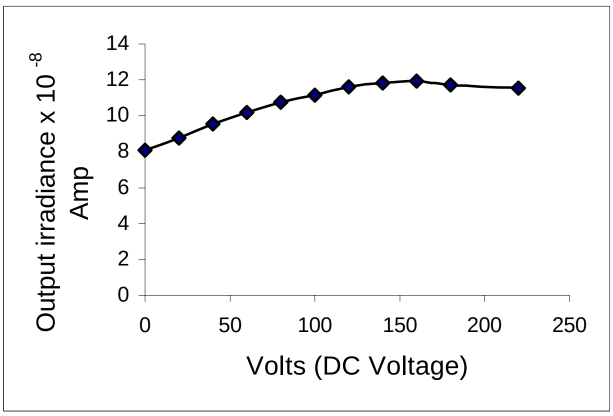

Figure 4 : Transmission voltage characteristics for DC voltage range 0-220 volts; for 40 metres of coiled fiber; input irradiance : $23{,}94 \times 10^{-8}$A, Separation between electrodes : 0,185 mm

5.1. Value of α

The output irradiance of the sensor (for 40 metres of coiled fiber) with applied D.C. voltage when linearly polarized light is ensured at the output of the sensor at 0 volt, is shown in Fig. 4. The calculated value of α as worked out from the curve is 6^0, where α is the correction in phase shift due to bending of fiber and dead weight of the upper electrode of the sensor.

5.2. AC Sensitivity of the sensor

The curve showing variation of output irradiance of the sensor for change in AC voltage (frequency = 50Hz) is given as Fig. 5. The output curve is in close proximity with the theoretical one and error calculated is 2% of the total range.

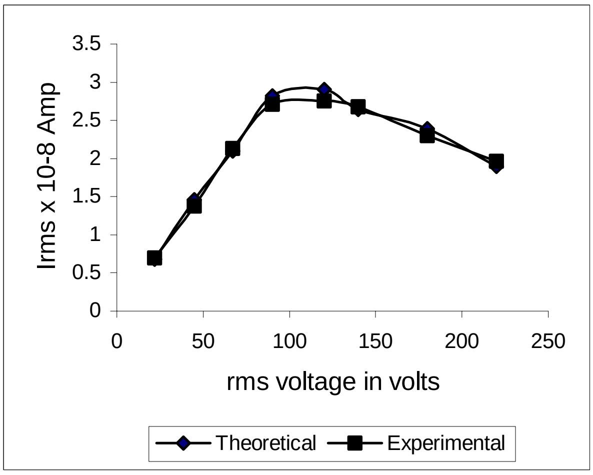

Figure 5 : Incremental output irradiance of the sensor for applied AC Voltage (frequency = 50Hz) on the sensor. For 40m of coiled S.M fiber, separation between electrodes : 0,185mm.

6. CONCLUSION

Study of polarization control on fiber optic device is discussed in this paper. With the application of different DC voltages on the electrometer the stress induced birefringence modification of SM fiber contributes to realization of λ/8, λ/4, λ/2 wave plates. Work has been extended to generalize the calibration equation for AC voltage measurement. The experimental results show change in ellipticity and azimuth of the polarized laser light passing through the device for impressed direct voltage on the wave plate. The SOP of propagating laser light through the device is found to change from elliptic to linear and from elliptic to circular with the change of direct voltage on the device. Outcome of the work also shows that the study can also be used for the assessment of electrical field and so the potential.

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