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DESIGN AND DEVELOPMENT OF A FIBER OPTIC INTRINSIC VOLTAGE SENSOR

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Abstract – A direct and alternating voltage measurement scheme utilizing optical polarization phenomena has been reported. Accordingly a single mode fiber optic sensor has been developed which is intrinsic in nature. A polarization phase shift can be observed between input and output laser light when S.M. fiber of sufficient length is subjected to optimum electric field. The phase shift is due to electrostriction and electro optic Kerr effect. The phase shift is measured through polarization sensitive detection. Voltages (DC & AC) are calibrated in terms of phase shift. Theory has been formulated to depict the variation of phase shift with impressed alternating voltage on the set-up. Closeness between theoretical and experimental results is encouraging. The range of voltage measured through this technique is up to a few hundred volts for DC and AC with resolution of 1 Volt. As per construction of the fiber sensor sensitivity is dependent on the length of the fiber and spacing between electrodes. To minimize the measurement error referencing technique is preferable, at the same time to remove the nonlinear relationship between input and output ANN based linearization technique has been employed.

Keywords: Fiber optic sensor, Electrostriction, Kerr effect, polarization.

1. INTRODUCTION

Electrical measurements for quantities like resistance and voltages etc., may be performed in absolute sense in terms of the length, mass and time, with permeability and permittivity of free space [1] involving also one or other material constant. In absolute instruments the measurement accuracy is very high as the precision measurement in length, mass and time is possible. In present investigation after the design and development of fiber-optic voltage sensor or electrometer, the setup is successfully studied for measurement of direct and alternating voltages.

Since optical fibers have the advantage of providing single path measurement medium, they allow either line-integration or line-differentiations to be performed over any chosen path. The line integration property provides the means for attaining large sensitivity via a long and easily tailorable path of optical interaction with the measurand. Rogers (1979)[2] reported the measurement of electric current via the loop integration of its surrounding magnetic field and of voltage via line integration of the electric field of power system. The optical procedure for electrical field measurement problem demands careful investigation. To solve this problem, he suggested a set up in which the electric field act transversely to the spiralling fiber axis and POTDR (Polarizing optical time domain reflectometer) may be used to measure the distribution of electric field along the fiber axis.

The first possibility of detecting magnetic fields by magnetostrictive straining of optical fiber was investigated by Yariv et. al [3]. Based on these suggestions A. Dandridge et. al [4] developed and successfully tested a high sensitivity fiber optic magnetic sensor. Similarly, in the present work, an attempt has been made to measure the voltage based on electro-optic effect and electrostriction.

In view of that a voltage sensor (electrometer) has been designed and developed. The basic idea is that electric field directly induces change in polarization angle of a plane polarized light beam passing through the single mode fiber, ultimately changes the output phase due to electro optic effect (Pockel's effect and Kerr effect) and electrostriction. The contemporary mathematical developments in this field has helped the author to design a single mode fiber optic system with at least 30-50 m of single mode fiber subjected to a minimum electric field 2×10^4 V/m to get considerable change in phase of the polarized laser light coupled to the fiber. A length of fifty meters of fiber has been wound spirally in between two circular aluminium electrodes. Spiral winding of single mode fiber can accommodate large length of fiber in a small place whereas its winding thickness is minimum along the direction of electric field. Measurements have been obtained for direct and alternating voltages up to a few hundred volts.

2. THEORY

For DC voltage applied on the sensor set up, the theoretical deviation of phase shift between two orthogonal polarizations through the SM fiber with change in voltage has been formulated as

$$\Delta\varphi = K_2 V^2 \qquad (1)$$

Where K_2 is the instrument constant and $\Delta\varphi$ is the phase shift.

The polarization phase change depends on the electric field applied to the fiber optic voltage sensor. Now if the initial phase of the sine square variation starts from mid intensity point i.e. at $\pi/4$, the output intensity of the laser beam from a developed electrometer which is subjected to alternating voltage in the form of $V_m \sin\omega t$ can be expressed as [5] [6]

$$I = I_{max} \sin^2 (\pi/4 - K_2 V_m^2 \sin^2 \omega t) \tag{2}$$

Where I_{max}: maximum intensity, V_m: amplitude of alternating voltage, ω : angular frequency of AC and K_2 is the instrument constant which may be delineated as [7]

$$K_2 = \frac{\pi \varepsilon n_{co} l}{\sigma Y \lambda d^2} + \frac{2\pi l K}{d^2} \tag{3}$$

Where, ε: dielectric constant of silica glass, n_{co}: core refractive index of fiber, l: length of fiber winding, σ: poission's ratio of silica glass, Y: Young's modulus of silica glass, λ: wave length of He-Ne laser, K: Kerr constant of silica glass and d: separation between electrodes of the sensor. The first term of (3) arises due to effect of electrostriction whereas the second term is due to Kerr effect [7].

When the separation between two electrodes is one fiber dia i.e. upper electrode touches the fiber winding, the phase shift between two orthogonal states of polarizations depends on both electrostriction effect and Kerr effect. Whereas for greater value of d, i.e. the upper electrode is not in touch with the fiber winding, change in phase shift due to electrostriction effect is zero and only Kerr effect is responsible for change.

$$K_2 = \frac{2\pi l K}{d^2} \tag{4}$$

Other electro-optic effects such as Pockel's effect, photoelastic effect are neglected during analysis as these effects contribute little to the change in phase.

As output intensity I in (2) is integrated over a time period, the r.m.s. response of detector output will be $R x I_{rms}$ [8], where R is the detector responsively and I_{rms} is the r.m.s detector output which is formulated as:

$$I_{rms} = \left[\frac{I_{max}^2}{8} - \frac{I_{max}^2}{8} J_0(2K_2V_m^2)\cos(2K_2V_m^2)\right]^{1/2} \tag{5}$$

Jo $(2xK_2V_m^2)$ is the Bessel function of order 0. The r.m.s. output intensity is modulated with the Bessel function of order 0 and cosine of the square of amplitude of voltage.

The measurement process is disturbed by a few sources of errors; 1) dielectric heating of the sensor 2) microbending effect for spiralling fiber. An attempt has been made to minimize these stray effects through differential transducer arrangement. Also nonlinear relation exists between output r.m.s. intensity and input r.m.s. voltage. An ANN based linearization technique has been adopted for corrections against these stray effects. Maximum percentage error for unknown voltage prediction is reduced to a low of 3 % with inclusion of this technique. The associated development in this regard is given in section 6.

3. SENSOR DESIGN

The design of the sensor is shown in Fig. 1. Two annular shaped aluminium plates are taken with inner radius 2,5 cm. and outer radius of 10 cm. The surface of the plates are made flat by proper machining. Single mode fiber of core diameter 9 μm with a coating of 200 μm is wound on one plate in single layer in concentric spiral fashion. A stick adhesive with less amount of hardener is used to stick the fiber 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 the two ends of the fiber winding for launching the light and detection purpose. Fiber has been wound spirally on one plate with no overlapping. In the design of the fiber sensor, the microbending loss has been minimized by keeping the winding radius of the fiber (about 3 cm.) always greater than critical radius of microbending (8 mm). During experiment sensor is maintained at constant temperature by controlled heat bath to control the temperature in ±0,2 ^{0}C. Experimental studies have been carried out for three different make of the sensor by controlling minimum radius of fiber winding. The outer plate is placed over the first one and electrical contacts are made to apply the voltage.

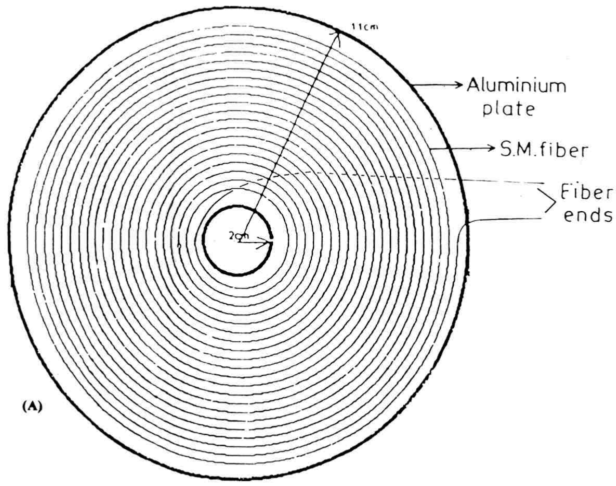


Fig. 1. Optical fiber Layout on the Electrode Plate

4. EXPERIMENTAL SET UP AND PROCEDURE

The experimental set up is shown in Fig. 2. A He-Ne laser is polarized via polarizer and launched to the single mode fiber with the help of microscope objective (40X). The microscope objective is used to focus the laser beam, to increase the power coupled to the fiber. The set up also consists of a mechanical polarization controller which is placed in series with the sensor and laser beam is ultimately detected by a photodetector after passing through sensor and polarization controller. The phase of polarized laser light propagating through fiber of the electrometer changes when direct voltage is impressed on the electrometer and this phase change is experimentally measured with the help of an analyzer and photodetector. The mechanical polarization controller ensures linear polarization at the output of the sensor. Direct voltage measurement with 30 m of fiber winding, is performed to measure the instrument constant. The electrometer is now subjected to alternating voltage and the method of measurement is as follows: at first with 0 V alternating voltage on the electrometer the polarization controller is adjusted to get linear polarization and analyzer is set to crossed position. So intensity of laser light coming out from the analyzer is made nearly zero, with the rotation of the analyzer. From this it is inferred that linearly polarized laser light is emanating from the polarization controller. The analyzer is then adjusted at mid-intensity position i.e. 45^0 to the input. Output intensity is linear in this region and sensitivity i.e. change of output with applied voltage, is high. The detector output now changes with the impressed alternating voltage and r.m.s. detector output is noted. The alternating and direct voltage impressed on the electrometer is precisely measured by an electrodynamometer instrument with high sensitivity. The study has been made for direct voltage range (0 V - 240 V) and for alternating voltage range (100 V - 600 V).

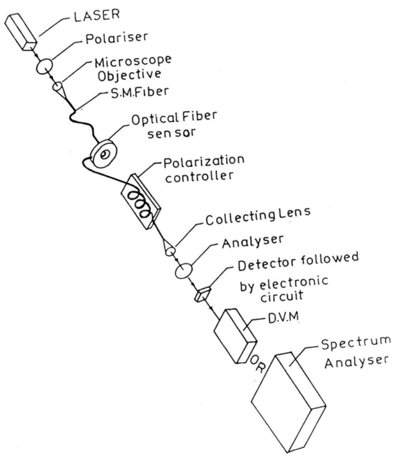


Fig. 2. Schematic optical layout for the fiber optic sensor

5. RESULTS AND DISCUSSIONS

Salient features of direct and alternating voltage responsivity of the sensor with 30m of fiber winding is hereby discussed. The instrument constant K_2 is calculated with the help of (3) and (4) for the two cases i.e. experiment without spacer (separation between electrodes = 0,227 mm) and with spacer of thickness 0,168 mm and 0,271 mm respectively. From experimental result it is inferred that the phase shift between two orthogonal polarizations varies with the square of impressed electric field. The experimental value of instrument constant, K_2 (K_2 = 13,38x10^{-4}/V^2 for minimum spacing between electrodes and K_2 = 0,72x10^{-4}/V^2 when separation between electrodes is 0,498 mm) is closely matched with the theoretical value (K_2 = 13,51x10^{-4}/V^2 for minimum separation and K_2 = 0,732x10^{-4}/V^2 when separation is 0,498 mm). The corresponding graph showing phase shift between two orthogonal polarizations vs. applied DC voltage for separation between electrodes 0,227 mm is shown in Fig. 3.

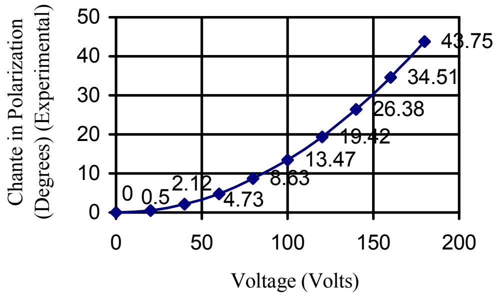


Fig. 3. Phase shift between two orthogonal polarizations for different direct voltage on the electrometer for experiment without spacer. (For 30 m of fiber winding) (d = 0,227 mm).

Study of the performance of the same electrometer for alternating voltage measurement has been performed. In this case the r.m.s. intensity value shown by the detector is mapped with r.m.s. alternating voltage at mid intensity region. The theoretical results of alternating voltage responsivity is analyzed from (5) and it shows that experimental results are in close conformity with the theoretical results for both experimental set up without and with glass spacer (thickness = 0,168 mm and 0,271 mm respectively). The corresponding curve is shown in Fig. 4.

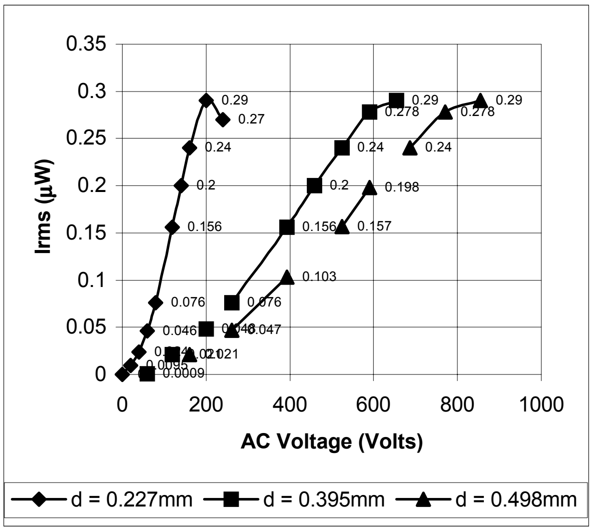


Fig. 4. Change in AC responsivity with different AC voltage on the electrometer for different separation between electrodes of sensor. (30 metres of fiber winding)

The range of alternating voltage which could be measure by the developed instrument is 20 V – 230 V for experiment with minimum separation between electrodes, 50 V – 350 V and 100 V – 600 V for experiment with separation between electrodes 0,395 mm and 0,498 mm. respectively with a resolution of 1 V. The resolution and range for AC measurement can be varied by using different thickness of glass spacer between the electrodes of the electrometer, which ultimately changes the value of instrument constant.

The different types of noises may affect the resolution of the system. The noise limited resolution of the electrometer is 0,5 V when maximum output power is 2,1 μW and bandwidth = 150Hz, T=300 K and detector resistance is 60 kΩ. Measurement system is modified by replacing the DVM with a spectrum analyzer. The spectrum analyzer can isolate the electronic circuit noise from the detector output at angular frequency 50 Hz.

Dielectric heating of the electrometer for alternating voltage analysis is also a limitation to the measurement accuracy. To minimize this effect of dielectric heating with alternating voltage the electrometer temperature is controlled at ±0,2 °C from ambient temperature by placing it inside a temperature controlled heat bath.

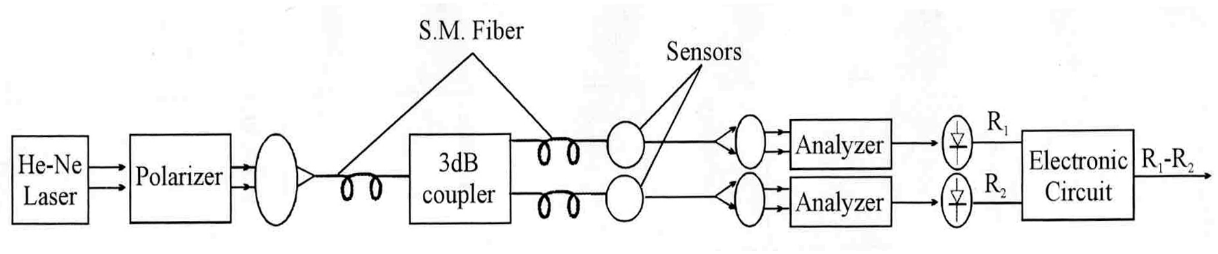


Fig. 5. Differential transducer layout

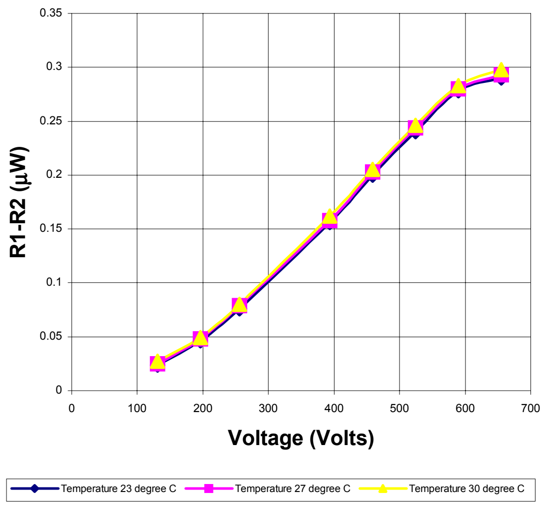
6. ANN BASED LINEARIZING TECHNIQUE

The reliability of measurement of voltage through developed sensor depends on how accurately the results of the experiment are analyzed to predict a particular value of r.m.s. voltage and also whether the experiment provides corrections against stray effects arising from physical effects other than the measurand. For the present set up these stray effects are due to bending of fiber and temperature of electrometer. P. Arpaia et. al [9] recently developed a method for reducing multiple error effects for experimentally modeled sensors through ANN based technique. In this method difference in characteristics of two nearly matched sensing element (differential scheme) with variation of auxiliary quantities like supply voltage and different make of the sensor give independent information. This method has been carried out by multilayer perceptron (MLP) of ANN topology.

Experimental study with the SM fiber optic voltage sensor reveals that the stray effects for a few auxiliary parameters like temperature and make of the sensor particularly microbending effect, is to be properly referenced. In pursuance with the discussed method, the ANN based linearization technique has been adopted for correcting effects from multiple error sources.

It has been tried to devise differential transducer effect by creating a reference path identical to the sensor path. The voltage of the reference sensor is maintained at 0 V. The differential transducer arrangement is shown in Fig. 5. The polarized laser beam is split into two equal power by a 3 dB coupler and coupled to two sensors of nearly similar make. The analyzed power is detected by the photodetectors and processing of signal is performed by electronic circuit.

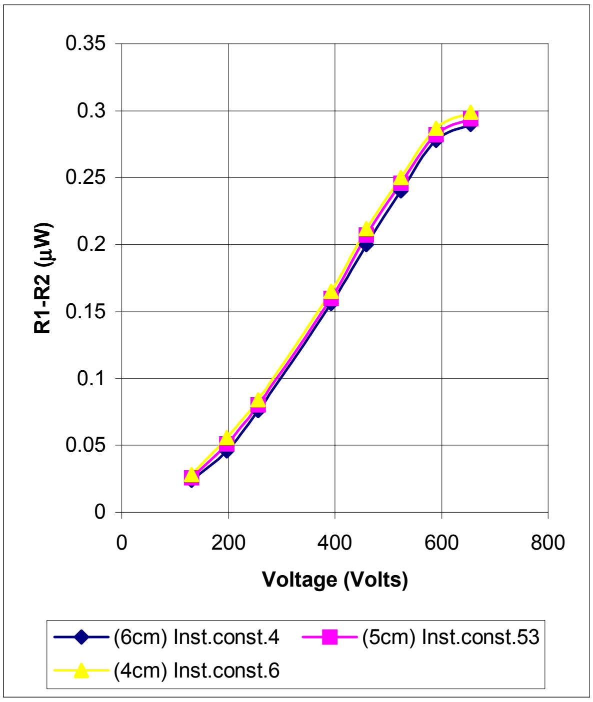
The measurement of a set of difference response of the sensor has been performed for three different temperature of the sensor, three different maximum bending make of the sensor and for three different separation between electrodes. These form a redundant set to train the ANN based structure [9]. The variation of detected output has been plotted for different voltages on the sensor with maximum bending of SM fiber, temperature of electrometer and separation between two electrodes of the sensor, as parameters. The training samples are represented in Fig. 6, Fig. 7 and Fig. 4.



For 30 metres of fiber winding

Fig. 6. Change in AC responsivity for different alternating voltage impressed on electrometer at different temperature of set-up (d=0,395).

A MLP structure has been developed with a set of 45 hidden layer neurons and bias values generated by MATLAB software. The input variables are 1) The difference response 2) Separation between two electrodes of the sensor (0,227 mm, 0,395 mm, 0,498 mm) 3) Instrumental constant specified by microbending effect (0,4, 0,53, 0,6 for minimum bending radius of the fiber, 3 cm, 2,5 cm and 2 cm respectively) 4) Temperature (27 °C, 30 °C, 33 °C) and the target is voltage. Back propagation algorithm has been adopted and for one lacks of epochs, a maximum percentage error of 3 % for unknown voltage prediction, has been achieved.



For 30 metres of fiber winding

Fig. 7. Change in AC responsivity with different AC voltages on the sensor for different make of the sensor in terms of maximum bending of fiber for d=0,395 (temperature 27 °C)

CONCLUSION

Fiber optic based voltage (DC & AC) measurement system has been developed. The process of measurement is significant due to simple design of the sensor and a reliable polarization sensitive detection technique. The variation between experimental and theoretical results is within range of 2 %. The reliability of the measurement process is checked with experiment performed in two different laboratories namely Measurement and Instrumentation laboratory, E.E. Dept., Jadavpur University and Applied Physics Dept., Calcutta University. The vibration induced laser coupling noise is minimized by carrying out experiment on a vibration isolation table.

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