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A Finite Element Analysis of Fiber Optic Acoustic Sensing Mandrel for Acoustic pressure with Increased Sensitivity

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Abstract: **-** This paper investigates the influence of material properties on the performance of an optical fiber wound mandrel composite fiber optic interferometer mandrel by using the ANSYS Cad tool, The acoustic sensitivity of an optical fiber considered analytically, High sensitivity obtained with low young modulus, very thick polymer coatings. The thick coating realized by embedding optical fiber in polyurethane. A flexible composite fiber-optic interferometric acoustic sensor has been developed by wrapping single mode fiber in a winding manner and then embedding a fiber in a thin polyurethane layer. The acoustic sensitivity has to be found more in a frequency range of (2.5-5.0 KHz). In this paper we studied the structural and material properties of a mandrel sensor with foaming layer in such way to get the optimal performance. The sensor was found to be compatible with water. Also the performance of optical fiber is analytically verified using the MATLAB software. In this paper the design was simulated in ANSYS Cad Tool, to verify the sensitivity of the Optical Mach-Zehnder Interferometric Sensor for increased sensitivity. The main objective and focus of the above work is concentrated on choosing the optimal foaming layer material by varying the Young Modulus E to choose the perfect foaming material for implementing in the design of mandrel.

Keywords: *Young modulus (E), Interferometer, Mandrel, ANSYS, Sensitivity.*

I. INTRODUCTION

Mach–Zehnder interferometer is a device used to determine the relative phase shift between two collimated beams (sensor arm & reference arm) from a coherent light source by using light modulation technique, to measure small phase shift in one of the two arm caused by a small sample or the change in length of one of the paths. Interferometric fiber optic sensor exploits the changes in an optical path length induced by transverse load in the optical fibers [1]. MZI sensors modulate the phase of the electromagnetic waves propagating within the optical waveguide. One of the major areas of application for MZI is in defense. There are numerous reasons for this interest which range from cost and performance to the geometric versatility of the sensing head. In coated fiber sensors the optical fiber is wound in a coil as a sensing element and the size is comparatively large. Since the optic coupling of the fiber waveguide is weak, a long fiber is generally used to increase the induced phase change. Pressure sensitivity is a complex function of a Young's modulus, Poisson's ratio, and the cross-sectional area of an outer coating. In the case of a mandrel sensor, a thin jacket fiber is typically wrapped around a compliant mandrel. The optical fiber then measures the pressure-induced strain in the mandrel. It is important to maximize the scale of the sensor in order to maintain a high sensitivity and a flat pressure response. So composite concentric mandrel has some improvements over the fiber wound mandrel even though bounded by some structural limitations [9].

The basic design of a hydrophone consists of two single-mode optical fibers. One fiber carries the signal light beam and the other carries the reference beam. Transduction in such a device depends directly on the acoustically induced phase modulation of the signal beam. After modulation both beams are combined and sent to a photomultiplier tube for detection. When the two beams are adjusted so that they are 120 degrees out of phase of each other and at the output of the 3x3 coupler we get the three different output waveforms, these outputs are feed as inputs to the photo Multiplier Tube which processes the signal to detect the impact of the differential pressure caused by the acoustic events.

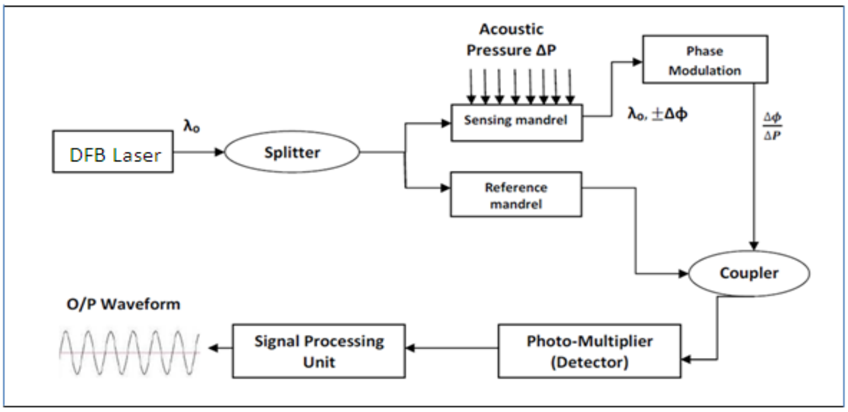


Fig 1 – Basic block diagram of Fiber Optic Hydrophone based on MZI.

In a composite fiber wounded mandrel of MZI Sensor, a thin jacket fiber is typically wrapped around a compliant mandrel and thin elastic polyurethane of 1cm thick, is coated over the fiber as protection during operation. The optical fiber measures the pressure-induced strain in the mandrel and protecting layer. Mandrel sensors are important because they are easy to produce and they exhibit a high sensitivity and amenability to spatial shading. Consider the cross section view of the mandrel sensor shown in Fig 2. A hollow cylindrical composite mandrel of length L_{eff} and radius Rm is radially wrapped with a single-mode fiber of length 150 meter over a length Lm[9].

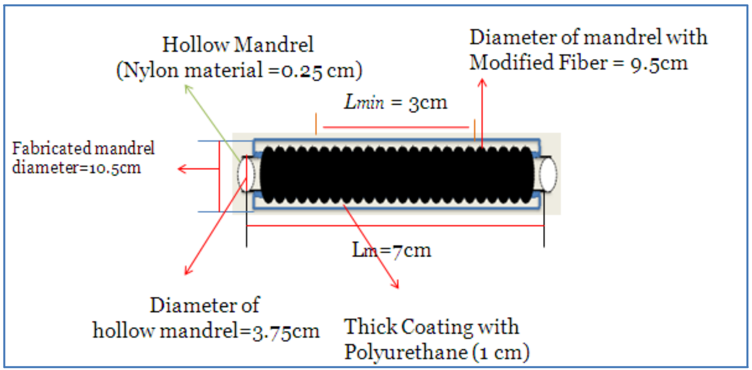


Fig 2. Cross Section of the concentric Composite Mandrel.

II. NOVEL DESIGN CONSIDERATIONS

The Novel MZI Optical fiber wounded concentric composite mandrel as shown below in Fig 3 consists of mainly five layers made up of different materials, the basic layer is Nylon which is coated in the inner diameter of the mandrel with a thickness of 0.25Cm, then the core of the mandrel is made of Aluminum (Al) metal which acts as a supporting structure for the entire mandrel the thickness of Al layer is 2Cm, above the aluminum layer consist of one of the important constituent material i.e., the foaming layer, this acts as flexible material supporting the Optical fiber, here the optical fiber is actually sandwiched between foaming layer with a thickness of 1Cm and the elastic Polyurethane coating of 1 Cm thickness [4],[7]. So when an acoustic event strikes or impacts on the effective length $L_{eff}$of sensor, the pressure exerted by the acoustic wave on the sensor is experienced by the elastic polyurethane coating and this makes an efficient impact of stress & strain on the optical fiber which causes some slight deformation on the fiber, Consequently makes a considerable change in length and diameter of the optical fiber this in turn causes change in optical path length and changes the phase of the light emitted from the Laser source. Hence this is the technique of finding the change in phase shift for the Mach-Zehnder Interferometric based sensors.

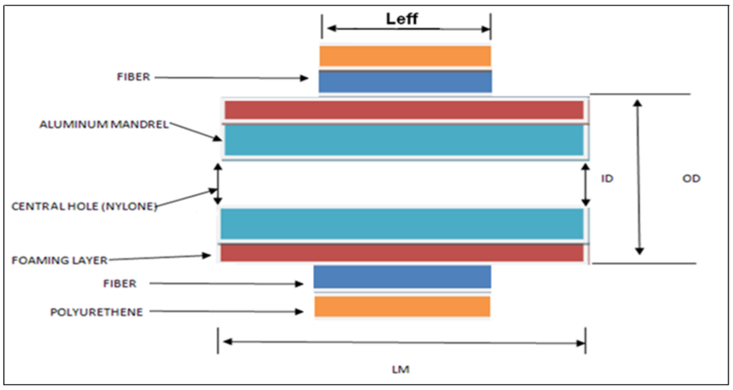


Fig 3: Schematic Structure of Novel MZI optical fiber wounded concentric composite mandrel.

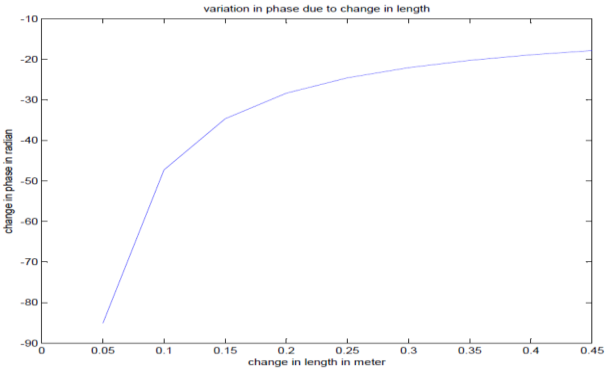
In the above the layout and design of above mandrel has significant changes, i.e. as we know from the basic concepts of the physics that as area increases pressure exerted decreases and as area decreases pressure exerted increases, in the above mandrel the polyurethane and optical fiber layers have been specifically placed at the center of the overall length of the mandrel and its design is restricted for the effective length L_{eff} so that whenever an acoustic even has occurred the acoustic pressure exerted by the wave will strike the L_{eff} effective length of the mandrel and we get a good sensitivity of detecting the sound underwater as compared to the other designs where in the polyurethane and optical fiber are spread across the overall length of the mandrel.
A pressure P interacting with the fiber induces a change in phase Δϕ/P and is given by

$$\frac{\Delta\Phi}{P} = k_0 n\Delta L + Lk_0\Delta n_0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where the first term corresponds to the change in the length of the fiber and the second term corresponds to the photo elastic effect. This photo elastic effect describes the relation between the mechanical strain in the fiber and the resulting change in the refractive index.
Therefore, the pressure sensitivity of the mandrel sensor per unit of air pressure becomes.

$$\frac{\Delta\Phi}{\Phi} = \varepsilon_z - \frac{n^2}{2}[(P_{11} + P_{12})\varepsilon_r + P_{12}\varepsilon_z]\ldots\ldots\ldots\ ..(2)$$

Equation (2) means that the phase change of the mandrel sensor can be found once we determine the appropriate strain distribution in relation to the unit of applied pressure, which then leads to the analysis of the transducer performance. In this paper, the strain distribution is calculated by using the MATLAB. Eq. (2) is written in the form of a summation of the strains distributed over all the discrete elements in the MATLAB. The values for Pockel's coefficients of the unclad fiber are assumed in the calculations of the pressure sensitivity with the MATLAB; we came at a reference that the wavelength (typically 850 - 1550nm) has the level of highest sensitivity [5].Therefore, MATLAB Simulink gives a mathematical analysis of interferometer-which keeps a promise to give accuracy in the measurement of all the parameter and higher possibility of sensitivity. Here parameters like phase, Wavelength for MZI and optical fiber length shown in the following graph as seen in Fig 4are simulated by MATLAB, gives the pressure sensitivity. Interferometric arms differ by virtue of the perturbation in one of the fiber legs, and the phase shift between the two light signals provides the measurement.



Because the measurements are made with the interference of two light signals with a small

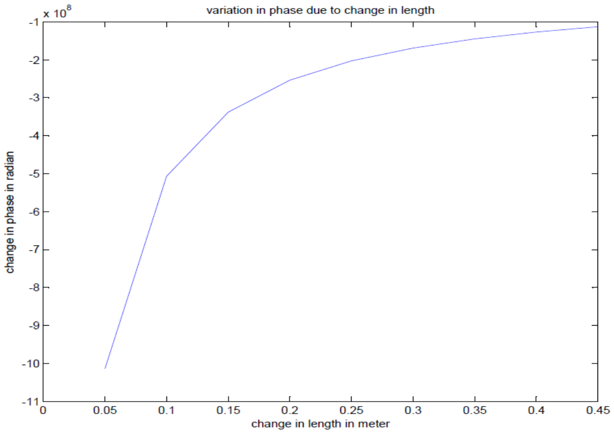


Fig 4: MATLAB graph of Variation in phase due to change in length.

As shown in Fig 4. Changing the length causes variation in phase and from another Fig. beside, another parameter also keeping the promises of more sensitive like pressure (transverse load) occurs with the change in phase w.r.t the different optical source wavelength (890 nm – 1550 nm) [3], [6].

III. PRESSURE SENSITIVITY CALCULATION

To prove the novel design consideration of the Concentric Composite mandrel as designed & simulated in ANSYS Cad tool the following calculations are shown as a proof for the new design. From Equation (2) we have, from [2]

$$\frac{\Delta\Phi}{\Phi} = \varepsilon_z - \frac{n^2}{2}[(P_{11} + P_{12})\varepsilon_r + P_{12}\varepsilon_z] \ldots\ldots\ldots\ldots(2)$$

Where $\text{€}_r = 0.575*10^{-4}$, $\text{€}_z = 0.001975$
and $P_{11} = 0.121$, $P_{12} = 0.27$

$$\frac{\Delta\phi}{\phi} = 0.001975 - \frac{(1.46)2}{2}[(0.121+0.27)*0.575*10^{-4} + (027*0.001975)]$$

$$\frac{\Delta\phi}{\phi} = 1.382700302*10^{-3}*\pi/180$$

We know that $\phi = 1.54*10^7$ radians

$$\Delta\phi = 371.643 \text{ radians}$$

As we know that,

$$\text{Sm} = \frac{\Delta\phi}{\text{P}} \ldots\ldots\ldots\ldots\ldots (3)$$

Assume P= Pressure (2Mpa)

Sm = 371.643/2
Sm = 185.8215
Sensitivity =20 log (Sm/Sr)………….. (4)
Sr = 1rad/µPa
S (dB) = 20 log (185.8215/1 µPa)

So, Pressure Sensitivity = -74.61 dB

IV. FINITE ELEMENT ANALYSIS IN ANSYS

The analysis & performance evaluation of the MZI interferometric composite concentric optical fiber based mandrel is analyzed in the commercial available software ANSYS 11.0; this is based on FEM nodal analysis. A static analysis of the MZI based mandrel for hydrophone was performed by applying a pressure of 2 Mega Pascal to depict the real underwater environmental conditions. By the above analysis made we achieved,an improved sensitivity nearabout 9dB. The foaming layer is more soft and flexible than the base layer that is Al, by sandwiching the optical fiber in between the foaming layer and the outer polyurethane elastic layer improved the sensitivity of the designed mandrel radial pressure sensitivity due to its superior compliance.

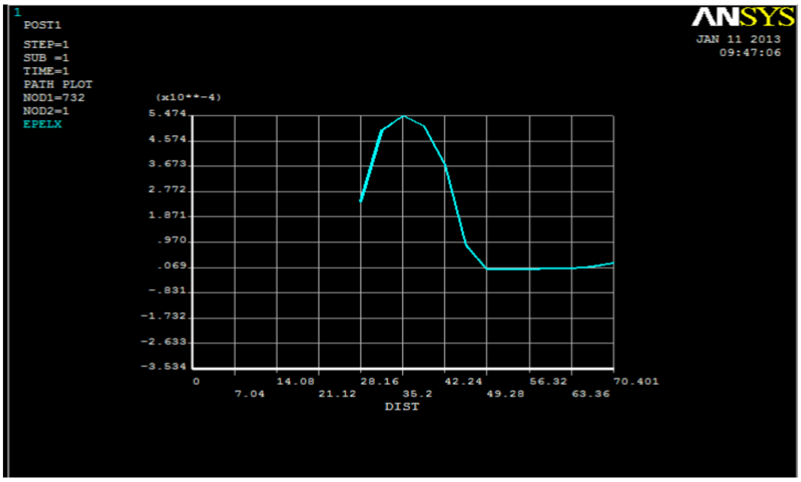


Fig 5.Graph of Radial Strain Vs. length of mandrel.

In the above graph of Strain Vs. length of mandrel graph of ANSYS we have shown that at the X axis we have the overall length of the mandrel and Y axis we have taken the Strain, the graph clearly indicates that exactly at the effective length L_{eff} the strain is maximum at the center of the overall length of mandrel. This graph response strongly supports the proposed design.

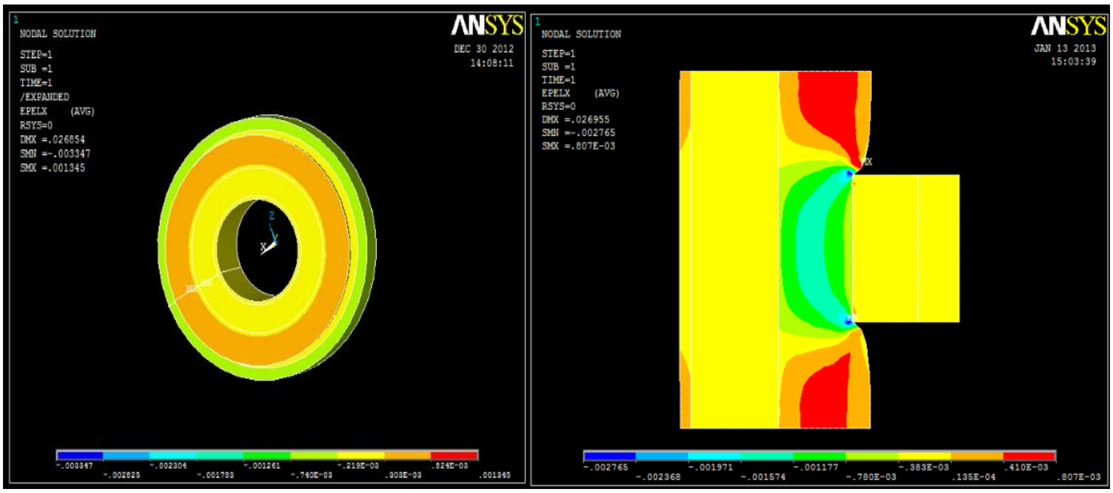


Fig 6.ANSYS Simulation of Radial strain (€r).

The figure’s 6 & 7 are the snap shots of the designed mandrel in the ANSYS Cad tool, the simulation results of both axial strain and radial strain were obtained in ANSYS by using the material properties as shown in Table 1.

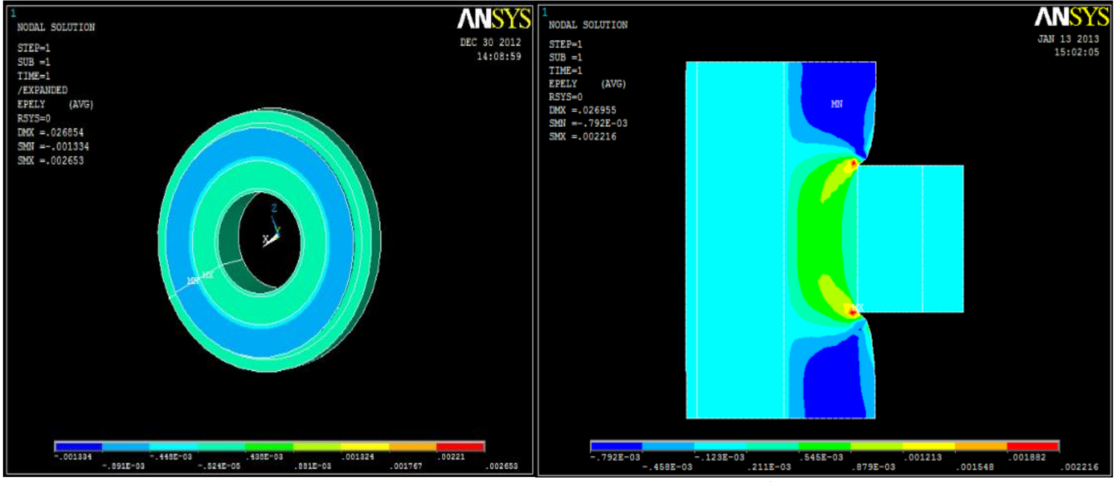


Fig 7.ANSYS Simulation of Axial strain (€z).

V. RESULTS AND DISCUSSION

In this paper, various performance evaluation parameters with respect to pressure sensitivity are studied and simulated the performance parameters include such as length of Mandrel, Wavelength, Young Modulus (E) of foaming layer for radial pressure.This analysis reportgives the proof for highest possible value of sensitivity of optical fiber based on interferometer principle which shows the optimized performance of the mandrel w.r.t Young modulus of the foaming layer. As Pressure increases, changes in light path i.e., phase modulation will occurs depending on the radial load in the sensor arm which in comparisons with reference arm will be more so, the effective changes in the fiber length (Δl) will be more and *vice-versa.* In this paper, we concluded, pressure increases which changes in Δl *w.r.t*length of the fiber wrapped around the mandrel 'L' will be more and consequently the phase related to optical signal will be more depending on the wavelength of the optical signal.

Structure	Central Hole	First layer	Second layer	Third layer	Elastic layer
Composition	Nylon	Aluminum	Foaming Layer	Si - glass	Polyurethane
Diameter (mm)	2.5	20	20	15	10
Young modulus	2.14e3	73e3	0.45e3	19.6e3	1.3e3
Poisson's ratio	0.48	0.33	0.45	0.34	0.45
P_{11}				0.126	
P_{12}				0.27	
Refractive Index				1.458	

Table1: Specifications of Material Properties.

The above Table 1 provides the information of the designed mandrel material properties and its composition ration which help to enhance the pressure sensitivity [2]. The foaming layer works as a real compliance material layer that supports & actuates more deformations on the optical fiber when it is exposed to an external acoustic pressure, the base material Al of the mandrel supports the overall structure of sensor. For the foaming layer, the material properties that have efficient effect on the acoustic sensitivity of the mandrel are mainly the Young's modulus & the Poisson's ratio. In a composite concentric mandrel the foaming layer should be more soft and flexible than the Al base material to get more enhanced sensitivity. [2] The Young's modulus of the foaming layer is found to be lying in the range of 0.1 to 10Gpa, and its Poisson's ratio 0.35 to 0.45 and is as shown in the Table 1. The Higher sensitivity for this novel design was obtained and verified by considering the optimized design parameters as shown in Table 3.

Table 2 lists the material properties of the constituent parts of the proposed mandrel design. Other design features were selected to increase sensitivity and were associated with the mandrel properties and thickness of the foaming layer.

Layers	Material	Young's modulus(Gpa)	Density (kg/m^3)	Poisson's ratio
Base layer	Aluminum Al	73	2700	0.33
Foaming layer	Polystyrene	0.45	1208	0.85
Fiber	Si-glass	19.6	1404	0.34
Molding	Polyurethane	1.3	960	0.45

Table 2: Material properties of the constituent parts of optical fiber Mandrel for MZI Sensor.

PRESSURE (Mpa)	POISSON'S Ratio	ID (cm)	OD (cm)	LM (cm)	THICKNESS (cm)	YOUNG'S MODULUS (Gpa)	SENSITIVITY (dB)
2	**0.45**	**3.75**	**8**	**7**	**2**	**0.45**	**-74.61**
2	0.45	3.75	8	7	2	0.50	-76.32
2	0.45	3.75	8	7	2	0.55	-77.92
2	0.45	3.75	8	7	2	0.60	-78.87
2	0.45	3.75	8	7	2	0.65	-80.02
2	0.45	3.75	8	7	2	0.70	-81.13
2	0.45	3.75	8	7	2	0.75	-82.21
2	0.45	3.75	8	7	2	0.80	-83.05

Table 3: Tabulation of Young's Modulus Vs. Sensitivity.

The values tabulated in table 3shows the results of the sensitivity Vs. Young's Modulus here as we can infer from the table that only the Young's modulus is varied by keeping constant Pressure, Poisson's ratio, ID & OD and length of the mandrel etc., this clearly gives us the result that as the Young's modulus (E) increases the sensitivity decreases & henceforth good sensitivity is obtained and from this it is easy to find the detection of the sound underwater.

VI. CONCLUSION

From the design and analysis of structural properties of material required for mandrel, As the Young modulus (E) increases the sensitivity decreases & henceforth we got the good optimized sensitivity for the young modulus value 0.45 for the foaming layer material and from this we can detect the sound as well as where it is coming from in underwater medium. In above designed mandrel as we change the material properties and the design for different layers we obtained a significant change of 10dB higher sensitivity as previously designed mandrels.

VII. ACKNOWLEDGEMENTS

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