June. 2015. Vol. 7. No. 01 ISSN2305-8269
International Journal of Engineering and Applied Sciences

www.eaas-journal.org

EFFICIENT OPTICAL METHOD FOR MUSCULOSKELETAL STRAIN MONITORING IN PHYSICAL ACTIVITIES

[1]FATEMEH MAKOUEI, [2]SOMAYEH MAKOUEI*
[1, 2] Department of Electrical and Computer Engineering, University of Tabriz, Tabriz 51664, Iran.
E-mail: [1]f.makouei92@ms.tabrizu.ac.ir, [2]makouei@tabrizu.ac.ir*

ABSTRACT

In this letter, the biomechanical aspect of strain measurement, regarding the attractive technology of optical fibers, for sport performance attitudes is considered. The single mode step index optical fiber is designed for strain sensing proposes. Mode field diameter (MFD) of the fiber is employed as the indirect parameter and it is endeavored to maximize the MFD alteration due to applied axial strain. By the means of the linear relationship between MFD and induced axial strain the transfer functions for the designed fiber structures are identified. The natural thermal resistivity of the proposed fibers is investigated, either. Furthermore, the effect of layering on fiber strain sensitivity is inspected. The results admit that layering, whether exploiting depressed or raised inner clad, positively affects the fiber strain response. The highest achieved strain sensitivity is 21.47 $pm\mu\varepsilon^{-1}$*using depressed inner clad. This article offers an opportunity to switch between simple structure of step index fiber and multilayer fiber with a more complex structure according to strain sensitivity requirement.*

Keywords: ***Axial Strain, Step Index Fiber, Mode Field Diameter (MFD), Sport, Genetic Algorithm (GA)***

1. INTRODUCTION

Biomechanical aspects of sport performance and physical training provide basic sport science insights into mechanisms of musculoskeletal anatomy. Sport biomechanics, addressing problems related to human health and performance, is useful for physical education teachers, physical therapists, physicians, sport coaches, and etc. [1-3].

Internal tissues provide forces to either withstand forces imposed on the body from the environment or to create forces to move the body. Monitoring of the response of bones, tendons, ligaments, being the reactionary tissues and the response of muscles, as the force creators for movement of the body, is of great importance [1]. An important concept to consider is that force leads to motion that leads to energy that leads to injury. The body's tissues have physiological/biomechanical restrictions that, if exceeded, will lead to injury. When an external force is applied to the human skeleton, several factors influence whether an injury occurs: Magnitude and direction of force, Area over which force is distributed, Load-deformation curve, Yield point (elastic limit), tissue failure point [3].

Biomechanics also helps professionals in clinical settings not only to understand how to improve movement and how problems in the musculoskeletal system can be compensated for, but also to determine the extent of injury and to monitor progress during rehabilitation [2, 4, 5].

The exercises prescribed must match the biomechanical needs of the healing patient. Exercises must effectively train the muscles that have been weakened by injury and inactivity. Biomechanical research on therapeutic exercise is even more critical since therapists need to know when internal loadings may exceed the mechanical strengths of normal and healing tissues [3].

Sports medicine professionals often prescribe prosthetics or orthotics to treat a variety of musculoskeletal problems [3, 4]. Sports medicine professionals use biomechanical principles to understand injury mechanisms, select appropriate injury prevention and rehabilitation protocols, and monitor recovery [5]. Knowledge of the biomechanical causes of certain injuries can assist an athletic trainer in these situations, in that diagnosis of the particular tissues injured is facilitated [2, 3].

Musculoskeletal anatomy and its motion terminology are important in kinesiology and sports medicine, but it cannot be the sole basis for determining the function of muscles in human movement. Medical doctors specializing in sports medicine found that their extensive training in anatomy was not enough to understand injuries and musculoskeletal function in the athletes they treated [6].

Professionals are concerned with analyzing the actions of muscles and the strain amount they experience in movement and need the most accurate information on the biomechanical function of specific areas of the human body [3].

Conclusively, in order to attain highly permissible data, an appropriate modern strain measurement system is on demand. Fiber optic sensors, due to their sophisticated superiorities such as lightweight, easy installation, biocompatibility, multiplexity, and etc. [7-9], have entered various fields of technology and are of potential to significantly affect the sport biomechanics, either. However, in recent years, the use of magnetic resonance imaging (MRI) for assessing severity of muscle strain and predicting prognosis has become more prevalent [10, 11] and the fiber optic strain sensors are the only sensor types that can be used simultaneously with MRI since these sensors are, uniquely, immune to electromagnetic interferences [7-9].

In this paper, the strain response and also the temperature sensitivity of the step index fiber is inspected. Moreover, the effect of adding layers to the clad with two distinct profiles are investigated.

2. THEORETICAL BACKGROUND

In order to investigate the performance of an optical strain sensor based on the well-known single mode step index fiber, firstly, the fiber response to strain should be inspected. In this paper, for the material environment, which here is silica, the continuum mechanics is considered and hence the complications of edge effects are whisked away [12].

Application of force to a solid body leads to movement or deformation or both of them in it. Strain is a description of deformation in terms of relative displacement of particles in the body that excludes rigid-body motions [13]. Axial strain is the type depicting the length change relative to a reference length and so is a dimensionless number. If there is an increase in length of the material line, the axial strain is called tensile strain, otherwise, if there is reduction or compression in the length of the material line, it is called compressive strain [1, 12]. It is generally thought that compressive and tensile strains are the main component for most kinds of activities [1]. Axial strain, which is our case of interest, is defined as

$$\varepsilon = \frac{\Delta L}{L} \qquad (1)$$

Where ΔL is the length change and L is the initial length of the body.

In a continuous body, here optical fiber, strain results from a stress field induced by applied forces or is due to changes in the temperature inside the body. When silica is exposed to strain, its band-gap and hence the absorption coefficients face a change. Based on the Kramers-Kronig relation, the change in the absorption coefficients lead to the alteration in refractive index of silica [14]. Moreover, temperature change consideration could be made through the method introduced in [15, 16]. Assuming the homogeneity and isotropic behavior of silica and also the application of force perpendicular to the fiber cross section, the change in refractive index as a result of strain can be deduced to be [12]

$$\Delta n_i = -\frac{n_i^3}{2}\left(p_{12} - \upsilon\left(p_{11} + p_{12}\right)\right)\varepsilon + \frac{\partial n_i}{\partial T}\Delta T \qquad (2)$$

Where n_i is the refractive index of the ith layer in the fiber, ε is the strain tensor element, ΔT is the temperature variation, and for the pure silica, p_{11}=0.113, p_{12}=0.252, and υ =0.17

Since the field of the fundamental mode of a circularly symmetric fiber is bell shaped and has circular symmetry, its extent could be well described by a single parameter: this parameter defines the mode field diameter (MFD) [17].

$$MFD^2 = 8\frac{\int_0^\infty \left|\psi\left(r\right)\right|^2 rdr}{\int_0^\infty \left|\frac{d\psi\left(r\right)}{dr}\right|^2 rdr}, \qquad (3)$$

where $\psi(r)$ is modal field distribution and r is the radius position of the optical fiber.

Since the direct effect of strain is observed on the effective refractive index and the electrical field distribution is managed through this parameter, mode field diameter is an appropriate variation to be employed as an indirect parameter for strain sensing. In other respects, according to Equation (3), it can be claimed that MFD is another definition of field distribution.

3. SIMULATION RESULTS AND DISCUSSION

3.1 Strain and Temperature Response of a Step Index Single Mode Optical Fiber

The step indexed silica fiber reported here has an outer diameter of 125 µm and the fiber is single-moded in the 1550 nm window. The magnitude of the applied strain is considered to be [-3500, +3500] µε, since this range contains almost all the possible axial strain that the body may experience [1] which are outlined in Figure 1.

The optimization tool used for management and determination of structural parameters of the fibers is Genetic Algorithm (GA) with the cost function presented below:

$$\textit{Cost function}= MFD\big|_{-3500\mu\varepsilon} - MFD\big|_{+3500\mu\varepsilon} \qquad (4)$$

Employment of this cost function leads to the better strain response of the fiber while MFD is as the indirect parameter. As a result of the linear nature and behavior of MFD in 1550nm, the transfer function of step index fiber with respect to strain in the absence of temperature fluctuation is

$$MFD = 12(1+0.89\varepsilon) \qquad (5)$$

Where, ε is the axial strain. However, temperature changes are inevitable in all natural events. Considering the thermal effect on refractive index of the fiber and hence the MFD leads to the following relation.

$$\Delta MFD = 10.82\Delta\varepsilon + 3.86\times10^{-7}\Delta T \qquad (6)$$

Based on Equation (6), step index fiber, designed by the means of GA, shows the strain sensitivity of 10.82 $\mathrm{pm}\mu\varepsilon^{-1}$ and also temperature sensitivity of $3.86\times10^{-7}\mathrm{pmC}^{-1}$.Comparing to the conventional optical strain gauges based on fiber Bragg gratings (FBGs) with strain and temperature sensitivities of 1.2 $\mathrm{pm}\mu\varepsilon^{-1}$ and 13.7pmC^{-1} [7], respectively, the results accomplished in this subsection admit more satisfactory strain response of the designed single mode step index structure and also unremarkable thermal sensitivity in step index fiber which is clarified better throw Figure 2. This behavior eliminates the temperature compensation complexity.

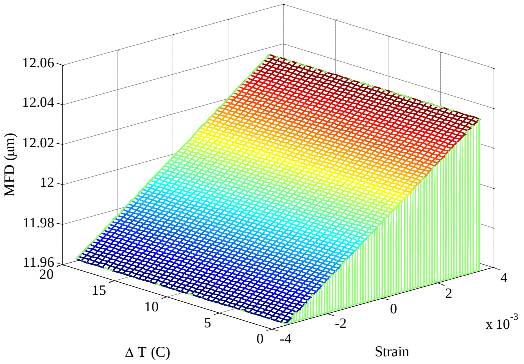

Figure 2. MFD as a Function of Strain and Temperature in Step Index Fiber.

Conforming to the figure presented, the linear relationship between MFD variation and applied axial strain is obvious.

3-2 Effect of adding layers to the clad

In this section, aimed to study the impact of adding layers to the cladding of optical fiber in MFD response of the fiber to the applied axial strain, the achieved results and the simulation outcomes are exhibited. For this purpose, two main types of layer could be added to the step index fiber; depressed and raised inner clad which are of the most important classes of layering in modern multilayer optical fibers for modification of the transmission behavior of the fiber. Figure 3 illustrates the refractive index profile for the proposed multilayer structures.

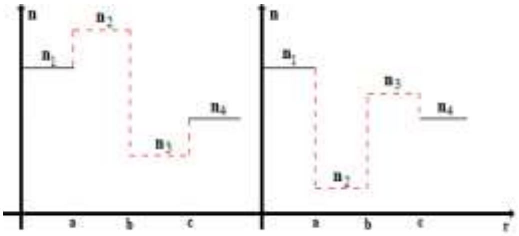

Figure 3. Added Multilayer Cladding; (Right) Depressed Inner, (Left) Raised Inner.

Parameters controlling the added layers are well-introduced in [9, 16]. The additional depressed and raised layers lead to different influences on the electrical field distribution and can be investigated with respect to strain. The GA cost function for step index fiber with additional layers is as follows.

$$\textit{Cost function}= (MFD|_{-3500\mu\varepsilon} - MFD|_{+3500\mu\varepsilon}) + |MFD|_{0\mu\varepsilon} - M| \qquad (7)$$

Where M is the mode field diameter in the designed step index fiber in absence of application of strain. Utilizing this cost function, the influence of alteration in the cladding profile for the identical mode field diameter to the step index fiber is studied. In other respects, this cost function provides the procedure with exactly same conditions for the indirect parameter which is MFD.

The attained mathematical relations for raised and depressed inner clad with respect to strain and temperature are as follows.

Raised inner clad:

$$\Delta \mathrm{MFD}=15.96\Delta\varepsilon-6.97\times10^{-7}\Delta \mathrm{T} \qquad (8)$$

Depressed inner clad:

$$\Delta \mathrm{MFD}=21.47\Delta\varepsilon-8.2\times10^{-7}\Delta \mathrm{T} \qquad (9)$$

According to the results expressed in this subsection, it is evident that adding layers to the clad of step index fiber, whether depressed or raised, results in enhancement of the strain response of the MFD in the fiber. However, the outcomes admit the higher impact of adding depressed inner clad. Furthermore, in spite of the addition of layers to the clad, the order of thermal sensitivity is unaltered and the fiber preserves the temperature insensitivity. Figure 4 and Table 1 are advantageous for better comparison of strain response in simple step index fiber and step index with two distinct multilayer cladding profiles.

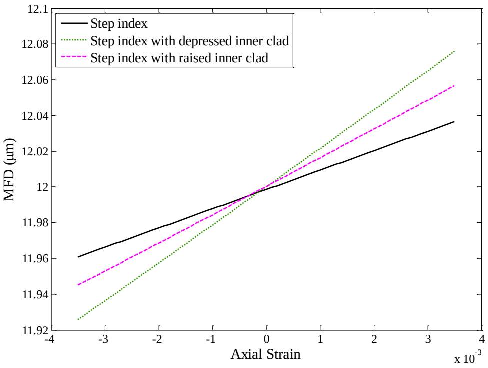

Figure 4. MFD as a Function of Axial Strain at 1550nm.

The curve trends in Figure 4 apparently admit the linearity in MFD alteration of the fiber due to strain application.

Table 1. Strain and Temperature Sensitivities of the Three Designed Fiber Structures

Fiber Type	S_{strain}***(pmμε^{-1})***	S_T***(pmC^{-1})***
Step index	10.82	3.86×10^{-7}
Step index with depressed inner clad	21.47	8.2×10^{-7}
Step index with raised inner clad	15.96	6.97×10^{-7}

To sum up, it is apparent that the complexity in fiber structure through adding layers to the clad leads to a better strain sensitivity. Therefore, regarding the specific strain range for the applications and also the required sensitivity, a trade-off should be considered to accomplish a logical decision for selection of the fiber structure type.

4. Conclusion

In this article, the requirement of strain monitoring in physical activities and sport performance is considered. The single mode step index optical fiber designed by the means of GA for strain sensing purposes exhibits a strain sensitivity of 10.82pmμε^{-1}. However, we have shown that a step index fiber containing additional cladding layers can identify the applied strain with much more sensitivity. The fiber comprising of extra depressed inner clad and the one containing raised inner clad hold the sensitivity of 21.47pmμε^{-1} and 15.96pmμε^{-1}, respectively. Furthermore, the low impact of temperature fluctuation on strain response in optical fibers, has led to the successful solution of the cross-sensitivity issue in strain measurement systems. The attained results admit the potential of optical fibers to be designed for strain measurement with required sensitivities due to the specific applications.

REFRENCES

[1] P. F. Yang, G.P. Bruggemann, and J. Rittweger, "What do we currently know from in vivo bone strain measurements in humans?", *Muskuloskelet Neuronal Interact*, Vol. 11, 2011, pp. 8-20.

[2] S. J. Shultz, P. A. Houglum, and D. H. Perrin, *Assessment of athletic injuries*. Champaign, IL: Human Kinetics, 2000.

[3] D. Knudson, "Fundamentals of Biomechanics", *Springer*, 2nd Ed., 2007.

[4] B. Heiderscheit, J. Hamill, and D. Tiberio, "A biomechanical perspective: Do foot orthoses work?" , *British Journal of Sports Medicine*, Vol. 35, 2001, pp. 4–5.

[5] S. A. Herring, J. A. Bergfeld, J. Boyd, *et al.* "The team physician and return-toplay issues: A consensus statement" , *Medicine and Science in Sports and Exercise*, Vol. 34, 2002, pp. 1212–1214.

[6] R. R. McGregor, and S. E. Devereux, " The McGregor Solution for Managing the Fitness Pains", 1st Ed., 1982.

[7] P. Roriz, L. Carvalho, O. Frazao, J. L. Santos, J. A. Simoes, "From Conventional Sensors to Fiber Optic Sensors for Strain and Force measurements in Biomechanics applications: A review", *Biomechanics*, Vol. 47, 2014, pp. 1251-1261.

[8] A. Othonos, "Rev. Fiber Bragg Gratings" , *Sci Instrum*, Vol. 68, 1997, pp. 4309-4341.

[9] F. Makouei, and S. Makouei, "Behavior of Mode Field Diameter in the Depressed Inner Triple-Clad Single Mode Optical Fiber with Applied Tensile Force", *American Journal of Modern Physics and Technology*, Vol. 2, 2015, pp. 21-27.

[10] J. Orchard and T. M. Best, "The Management of Muscle Strain Injuries: An Early Return Versus the Risk of Recurrence", *Clinical Journal of Sport Medicine*, Vol. 12, 2002, pp. 3–5.

[11] K. Speer, J. Lohnes, W. Garrett, “Radiographic imaging of muscle strain injury”, *Am J Sports Med*, Vol. 21, 1993, pp. 89–96.

[12] E. Udd, and W. B. Spillman, “Fiber optic sensors: An introduction for engineers and scientists”, 2nd ed., *John wiley and sons*, 2011.

[13] C. Truesdell, and W. Noll, “The non-linear field theories of mechanic”, *Springer*, 3rd Ed., 2004.

[14] V. Lucarini, J. J. Saarinen, K. E. Peiponen, and E. M. Vartiainen, “Kramers-Kronig Relations in Optical Materials Research”, *Springer-Verlag*, 2005.

[15] G. Ghosh, “Temperature Dispersion of Refractive Indexes in Some Silicate Fiber Glasses,” *Photonics Technol. Lett.*, Vol. 6, 1994, pp. 431-433.

[16] A. Rostami, and S. Makouei, “TEPMERATURE DEPENDENCE ANALYSIS OF THE CHROMATIC DISPERSION IN WII-TYPE ZERO-DISPERSION SHIFTED FIBER (ZDSF)” *Prog. Electromagn. Res. B*, Vol. 7, 2008, pp. 209-222.

[17] M. Artiglia, G. Coppa, P. Di Vita, M. Potenza, and A. Shamra, “Mode Field Diameter Measurements in Single Mode Optical Fibers,” *Lightwave Technol.*, Vol. 7, 1989, pp. 1139-1152.

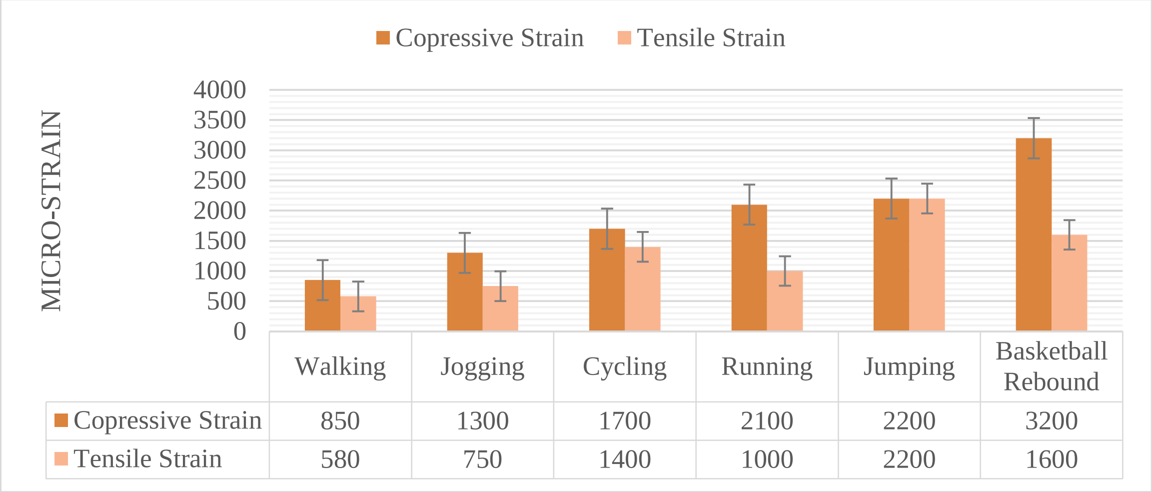

Figure 1. Maximum Axial Strain for Different Physical Activities.