RESEARCH NOTE

WEIGHT MEASUREMENTS BY USING SIMPLE OPTICAL-FIBER SENSORS

H. Golnabi

Institute of Water and Energy, Sharif University of Technology
Tehran, Iran, golnabi@sina.sharif.ac.ir

(Received: December 3, 1997 - Accepted in Revised Form: March 14, 2000)

Abstract The use of different optical-fiber sensors for weighing measurements is described. By using three different mechanical stressing mechanisms, the operation of the fiber-to-fiber transducer systems are tested and the results are presented. Parameters such as sensitivity, hysteresis, resolution, and dynamic range are measured. A comparison of the results has shown that the sensor system made with a cantilever steel beam offers a better overall performance. It shows a sensitivity of about 4.8 mV/gm, a maximum hysteresis of 4%, and has a resolution of 0.2 gm for a dynamic range of about 140 gm. The reported systems offer simplicity in design and can be implemented for force/pressure measurements.

Key Words Sensor, Optics, Fiber, Weight, Measurement

pBw pA ²jB´TwA BI /SwA²k{ x nIq£¬p° ºo¼£¦²pAk¯A ºAoI ³ ¦Th« ºn±¯ ºBµo¢ve joInB½ ³§B¸« Ë¼A nj **²k¼ña**
Bµ y ½BÇ«pC [½BT¯ /k¯A²k«C SwkI [½BT¯ Ë¼A ºn±¯ ³T{n - ³I - ºn±¯ ³T{n x°n° °o¼¯ ¤BªîA ³ ¦Th« ºBµnB½°
S¼wBve /jnAj ²k{ x nIq£o¢½j ª±¯°j ³I SLv¯ ºoT´I joñ¦ªî ºj¿±µ ³d´æ pA²jB´TwA x°n³½ k®µj»« ¬Bz¯
14å ºnB½²j°kd« ºAoI ¨o£å.2 ³I ð½jq¯ ð¼ñ´U Rnk¹BI° SwA ¨o£oI S§°»¦¼« 4.8 j°ke nj ©Tv¼w Ë¼A
nBñI £w±T« ºBµ°o¼¯ B½° ¬p° ºo¼£¦²pAk¯A ºAoI k¯A±U»« »£jBw KLw ³I ²k{ x nIq£bo¥/SwA ²jB´TwA ¥IB¹ ¨o£¦
/j±{ ³Tµo£¦

INTRODUCTION

For many years a number of methods have been developed in order to devise transducers for force and, in particular, for weight measurements. The first attempts have been the use of a spring system. This device is very simple and cost effective for mass production. However, stability, accuracy, and other parameters needed for higher precision experiments motivated the development of more reliable transducers.

The new weighing apparatus uses the more sophisticated load cell, which is based on a strain gauge transducer element [1]. The load cells can measure static and dynamic tensile and compressive loads almost without requiring any displacement. A rapid development in the scale industry has become possible by using this type of sensors. These kinds of transducers are now widely used for medical scales, packaging scales, and others [2].

In design and construction of a sensor one must consider accuracy, resolution, repeatability, linearity, hysteresis, and the response time [3]. To meet all the requirements described is not a simple task because one must consider the specifications in relation to the production cost for the real applications. On the other hand, in most cases to obtain the best result for one particular parameter one has to sacrifice for others. Some of the specified parameters are related to the transducer itself, some defined by the measuring system, and many others are related to the both systems.

In recent years, some researchers have attempted to improve the transducer performance while others have focused on the methods and processing the output signals. These efforts include: amplification, averaging and smoothing, and digitizing the output signal in order to obtain a stable, reliable, and reproducible results with a high accuracy.

OPTICAL-FIBERSENSORS

Beside the load cell devices, optical sensors have the potentials to be used for weighing measurements especially in hazardous process control areas. Optical-fiber sensors can be devised based on the extrinsic, intrinsic, and evanescent processes [4]. Evanescent sensors rely on the measurable loss of guidance from an optical fiber as a means of detecting external changes. For example, when the effective refractive index of surrounding material around an optical fiber changes the intensity modulation can be measured. At a liquid-to-air interface the change of refractive index can be used for measuring the specific gravity of the liquid or measuring chemical parameter such as pH of a solution. In intrinsic sensors [5,6], the effect of micro bending and the resulting transmission loss can provide a means of detecting pressure or strain. Extrinsic optical-fiber sensors can also be used in which the radiation is released from the transmitted fiber and modulated externally by some induced changes. One common method in extrinsic sensor design is the intensity modulation of the radiation.

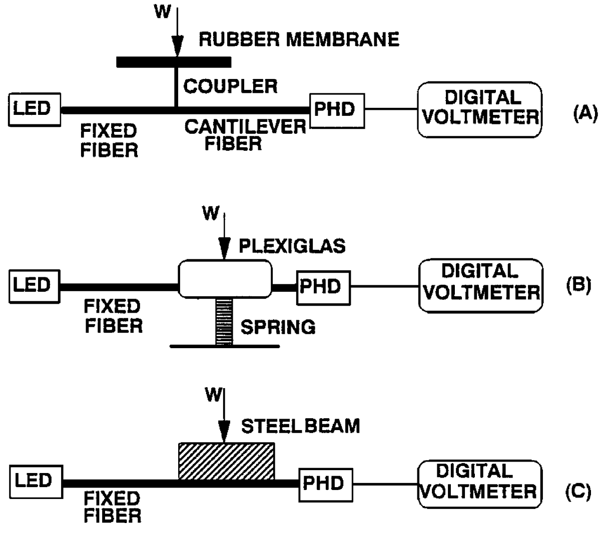
To avoid some of the problems existing in intensity modulation, the method of development of transducers that directly transmit frequency-out information, as a function of the strain applied has been introduced. The various options of frequency-out sensors are : vibrating wire [7], quartz crystal, micro machined silicon [8], and micro machined GaAs devices [9]. Among these devices, a vibrating wire is often used for applications like remote sensing and differential pressure measurements. Quartz crystal cantilever beams can be optically excited into resonance and the frequency varies with axial stress loading. Devices made by this mechanism have a measurement range of 1 kg and a resolution of 0.5 gm. However, design and construction of such devices are very complicated and requires thin film and integrated electro-optics technologies [10-13].

In this study the goal is to focus on the use of optical fibers and to develop simple sensors with compatible characteristics. For this purpose, several mechanical stressing means in the fiber-to-fiber configuration have been tested and the obtained results are reported. All the reported systems function as a fiber-to-fiber intensity modulator but the external changes are induced by different methods.

EXPERIMENTAL ARRANGEMENTS

Design and operation of a single and double fiber-to-fiber sensors were described in the previous study [14]. By using this type of sensor a precise measurement of the displacement, gas pressure, and the linear thermal expansion of a metal rod were reported [15]. Using the same idea of transducing mechanism several sensors were constructed, which are displayed in the block diagram shown in Figure 1. For convenience, hereafter we refer to these three arrangements as sensor A, sensor B, and sensor C, respectively.

The first design shown in Figure 1(A) which consists of: a LED as radiation source, a fixed fiber, and a cantilever fiber which is free to



Figrue 1. Experimental Arrangements of the sensors: (A) a cantilever fiber that is connected to a rubber membrane by a thin coupler, (B) The second fiber is fixed to a Plexiglass plate, which can move, down and return up by a spring restoring force and (C) The cantilever steel beam geometry in which the second fiber and photo detector are connected to the free end of the steel beam.

move according to external changes or environmental perturbations. As indicated in Figure 1(A), the first fiber is coupled to the radiation source and the second fiber is located in an axial distance of about 50 μm from the first fiber. The cantilever fiber is connected to a rubber membrane by a thin coupler. The membrane is a disk of 30 mm diameter and 3 mm thickness fixed in position while the thin coupler is connected to its center from one side. The other side of the coupler is connected to the second fiber, as shown in Figure1(A).

By applying a weight of W on the rubber membrane, the force is applied to the second fiber, which causes modulation in the intensity of the radiation, which is received from the first fiber. The modulated transmitted light by the second fiber is collected by a photo diode (Centronics, BPX 65) and then the produced electrical signal is measured by a digital voltmeter. Although, photon multiplier or electron multiplier detectors could make a more precise detection system rather than the simple device used here, they were unavailable and costly, which increase the sensor cost.

The BPX 65 detector is a planar silicon (PIN type) photodiode with excellent sensitivity and wide bandwidth capability suitable for a great variety of signal detection. It has an active area of $1mm^2$ and a low dark current of about 1 nA. The noise equivalent power at 900 nm is $3.6*10^{-14}$ W/(Hz)$^{1/2}$. Spectral response of this detector is from 400 nm (quantum efficiency of 0.4), with maximum quantum efficiency of 0.8 at about 830 nm, and it has a quantum efficiency of 0.35 at 1000 nm. The quantum efficiency of this photodetector for green light (500 nm) is about 0.62 while for red light (600 nm) it is 0.7. Typical responsivity for 450 nm is 0.2 A/W, for 900 nm 0.55 A/W, and for 1064 nm is around 0.15 A/W.

Figure 1(B) shows a different stressing mechanism for the weighing measurements. Here, the second fiber was fixed in a Plexiglass (kind of glass with high degree of flexibility) plate, which is able to have a precise movement in the vertical direction. A spring-loaded screw in a precise fashion controlled this movement (see Figure 2b). Since the second fiber is fixed to this plate, then by putting a weight of W on the top of it, the displacement causes some modulation in the intensity of the radiation, which is ultimately collected by a photo diode. The output signal is then measured by a digital voltmeter as shown in Figure 1(B). Therefore, sensing of the applied weight was possible by recording the output voltages. For this experiment, we have tested the system with different springs of different force constants (k=200-1000 N/m).

The final design for weight measuring is illustrated in Figure 1(C) refered to as sensor C. This apparatus uses a fiber-to-fiber arrangement similar to those of sensor A and sensor B, but uses a steel beam in a cantilever configuration. Schematic perspective of the weighing

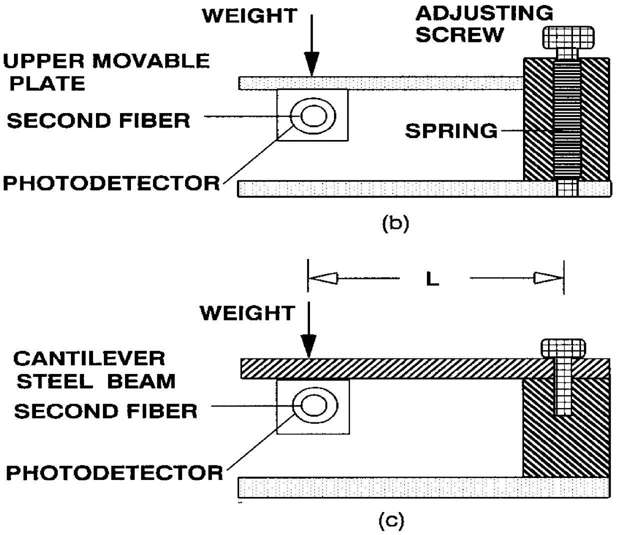


Figure 2. Schematic representation of the weighing apparatus used in this study. Part (b) shows sensor B, which uses the spring mechanism, and (c) shows the cantilever steel beam geometry for sensor C. Weight placing distance, L, is shown for sensor C.

apparatus for sensors B and C are shown in Figures 2b and 2c, respectively. As indicated in Figure 2c, the second fiber in this case is fixed to the tip of the steel bar that is free to move and the other end of the bar is tightly fixed in position. This piece of metal bar (steel) has a dimension of 96 mm*28 mm*1 mm and the pivot length is about 90 mm. The collecting photo diode is also fixed to the steel beam and the output voltage is again recorded by a digital voltmeter.

For a better comparison, in the construction of all of the sensors we have used similar fibers, photo diodes, and digital voltmeter. Although, similar types of LEDs were used in sensors A, B, and C, but the first two were emitting the green light while for sensor C the emitted red light was used for measurements. The first and the second fibers for all the systems are picked up from silicon fibers with step index profile, a core diameter of 400 μm and an overall diameter of 1 mm.

In order to minimize the light source fluctuations, care was taken to provide a relatively constant voltage for the LEDs. For this purpose, a high quality power supply (Hewlett-Packard model HP 6115A Precision Power Supply) was used to provide a well-regulated voltage of 3V. With this power supply it was possible to control the supply voltage within a precision of 1 mV. The LED supply current was also monitored which was constant of the order of 2.5 mA at this voltage level.

RESULTS

For data collection, variations of the output voltage as a function of the weight changes were measured. By using sensor A, several weight measurements were accomplished, and the average values for the five series of measurements are shown in Figure 3. This sensor shows a sensitivity of about 1.5 mV/gm for a dynamic range of about 200 gm (rubber membrane of 3 mm thickness). By using the rubber membranes with different thicknesses, it is possible to change both the sensitivity and the dynamic range. However, when the dynamic range is increased, the sensitivity of the system will decrease in a reverse way.

The resolution of the sensor A with the mentioned parameters was about 0.5 gm, but it

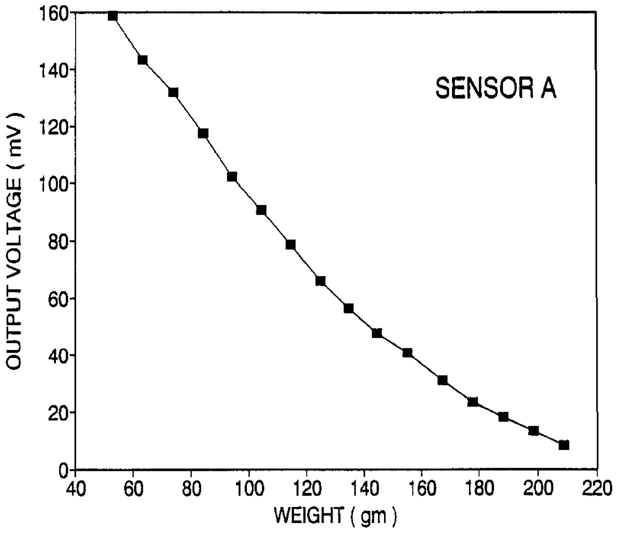


Figure 3. Variation of the output signal as a function of weight (increasing weight) for sensor A.

could be further improved by using another thinner rubber membrane. The output of the sensor is nonlinear which is true for the case of fiber-to-fiber modulation, but for a weighing range of 60 gm to 180 gm it is nearly linear. It should be mentioned that with the option of digitizing, the nonlinearity of the output should not be a serious problem because it would be easy to use a nonlinear calibration curve to correct the data.

In another measurement, to show the hysteresis effect, the output signals for the case of increasing and decreasing weights are recorded and the difference in the averaged results are shown in Figure 4. The slight difference can be explained by the fact that the output measurement is related to the weight force and the restoring force, which are not acting exactly in the same manner. However, the maximum hysteresis for this case is about 9% that is not so bad for such a simple design. Another source of error in this respect might be due to the intensity drift of the LED. Hence, for precise applications, the LED light source can be replaced by a more stable laser diode for more accurate results.

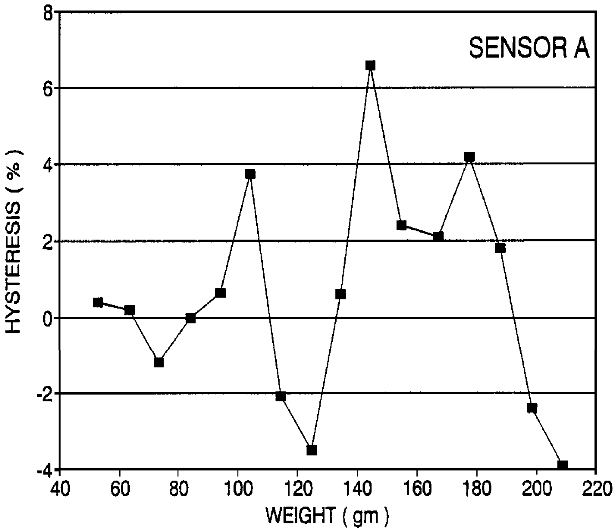


Figure 4. The effect of the increasing and decreasing weight (hysteresis) in the operation of sensor A.

In another experiment, sensor B shown in Figure 1(B) was employed for weighing measurements. For this arrangement, a transitional stage was used in which the fine movement of the second fiber in the vertical direction was possible. The measuring weight was placed on the top of the Plexiglass plate as shown in Figure 2b, and the restoring force was provide by a spring. For this case, using springs with different force constant values made several measurements. The spring with a higher force constant provided a higher dynamic range while the sensitivity of the sensor was decreased. Experimental results for a typical spring (force constant, k= 980 N/m) are presented in Figure 5. This device shows a sensitivity of about 2.6 mV/gm for a dynamic range of 70 gm.

Two major points can be seen from Figure 5: first similar to the case of sensor A, its output is not linear, even more nonlinear than that of sensor A. It must be pointed out that the nonliearity observed in the optical fibers is due to the fact that output intensity changes with the square of the offset distance of the two fibers. The second problem is that the output response for the case of increasing and

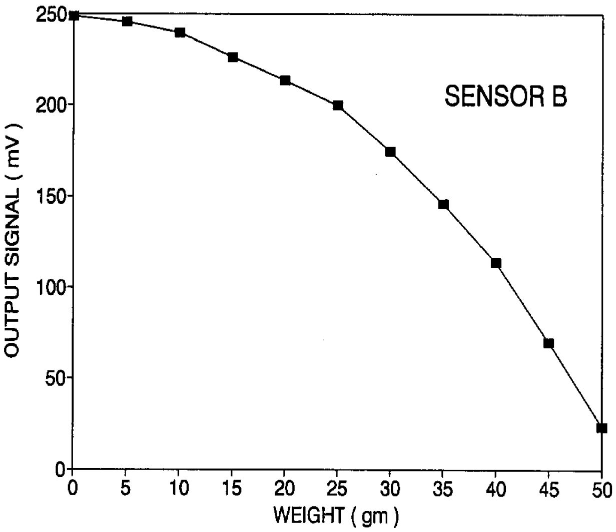


Figure 5. Output signal versus weight for sensor B.

decreasing weights was slightly different. This problem was mainly due to the structure of the spring. The construction of the spring in such a way that it is either compressing or stretching. Hence, under restoring force, the spring was not acting exactly the same as the compressing force. The maximum hysteresis for this sensor was even more than that of sensor A and is about 13%. At first it was thought it might be due to some defect in a particular spring, but several springs were experimented and more or less the same effect was noticed in all of the spring-loaded systems.

In sensor C presented in Figure 2c, a steel beam is used as the perturbing system for the intensity modulation. Weighing measurements for this sensor was accomplished by placing the weight at different places on the steel bar (L= 6.5 cm, 4 cm, and 2.5 cm. see Figure 2c) and the output results were measured accordingly. The flexibility of this sensor permits to employ just one system for a wider measuring range and at different sensitivity levels.

The result of such measurements for different weight placements, L, is illustrated in Figure 6. As can be seen in Figure 6, increasing L will decrease dynamic range, but the slope of the curves or sensitivity will increase in a reverse manner. To show this effect for the case of L=6.5 cm, the weighing measurements were performed at higher resolution and the results are shown in Figure 7. In this experiment the weight increase at each step was 0.5 gm, but the best resolution of this sensor was found to be 0.2 gm at this range of operation. For this study we used a container and varied the weight by adding small amount of water using an accurate micropipette. Our system was sensitive to a small drop of water corresponding to 0.2 gm weight.

To sum up the results of our experiments for different sensors the related parameters are compared in Table 1 in terms of the numerical values. Since the fiber-to fiber method is nonlinear in nature, so all these sensors behave nonlinearly on which we did not elaborate in our comparison. However, in terms of linearity, sensor C has the best performance (compare Figure 6 with Figure 5, and Figure 3) and is sensor A the next. Considering these results in terms of sensitivity, hysteresis, repeatability, resolution, and dynamic range it is noticed that sensor C has the superior performance. This

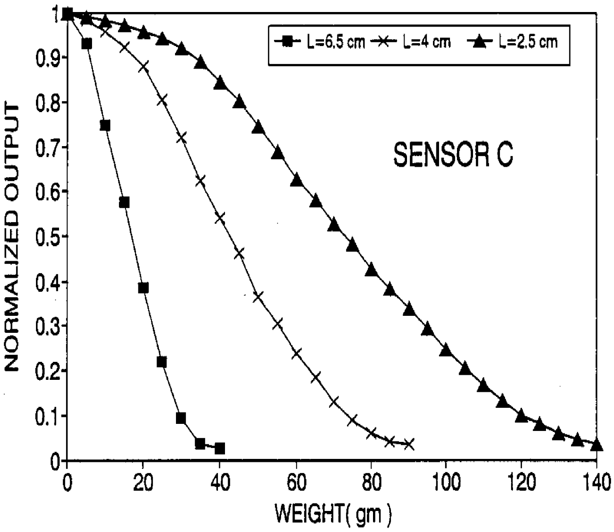


Figure 6. Variation of the normalized output as a function of weight for different placing positions, L=2.5, 4, and 6.5 cm in sensor C.

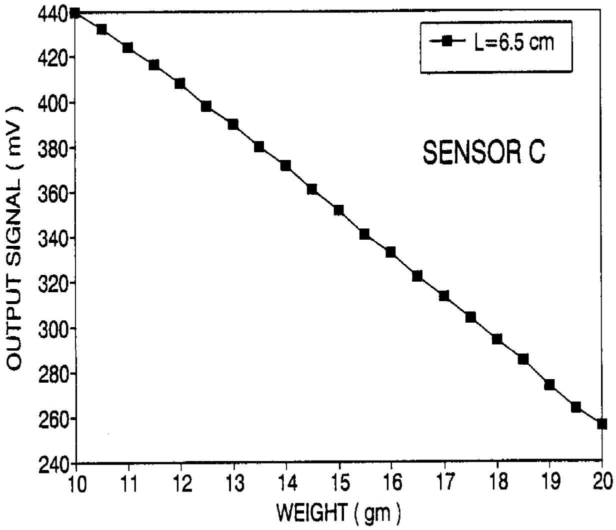


Figure 7. Resolution of the sensor C for the weight placement value of L=6.5 cm.

TABLE 1. Comparison of the Different Sensor Systems (k=980 N/m for Sensor B).

Sensors	Sensitivity (mV/gm)	Hysteresis (%)	Repeatability (%)	Resolution (gm)	Dynamic Range (gm)
A	1.5	9	5	0.5	180
B	2.6	12	6	0.5	70
C	4.8	4	3	0.2	140

sensor is more stable and provides the means to construct a reliable system that can be used for different weighing ranges with an acceptable sensitivity and dynamic range.

FURTHER DEVELOPMENTS

The preliminary results reported here indicate that sensor C can be effectively used for force and pressure measurements. However, sensitivity and its overall performance can be improved by considering several points. First, for radiation source we used the available LEDs, for sensors A and B the green LED, and the red one for sensor C. So using a high power LED or a laser diode emitting at a wavelength that matches the highest quantum efficiency point of the detector will greatly improve the sensor sensitivity. It seems that for the present detector the wavelengths in the RED-NIR (830 nm)should be the best choice for the optimum operation.

As indicated by others, there are some loss of light in coupling the LED to the first fiber. In our case the coupling was done in a casual way, but there are better means and mechanism for a more efficient coupling. Because of the limitations on the optical fibers, we just tested the available silicon fibers, but one can try different fibers in order to select the best one in terms of fiber material, index profile, and core and cladding dimensions.

As was described for the source of radiation, for the appropriate detection one must choose a high efficiency low noise photo detector that matches the light source wavelength. In our case the BPX 65 photo detector has a quantum efficiency of about 70% at 600 nm and a maximum of about 80% at 850 nm, which is reasonable. Considering all the parameters of this photo diode its operation is satisfactory.

Another parameter is the mechanical stressing mechanism that plays an important role in sensor operation Even though, the steel bar showed a good performance, we did not study other materials in this connection. The dimension and the geometry of the cantilever beam are the two factors that can be optimized for a better operation.

The signal recorded here is just the direct output of the photo detector measured by a digital voltmeter. For more precise applications one can improve the S/N ratio by using amplifying, averaging methods and digital techniques. In fact the response time of the system is defined to some extent by the detection circuit and the signal processing technique. However, for static measurements such as weight measurements accomplished here this factor is not a crucial one.

In summary, with some of the mentioned improvements this simple sensor can be employed effectively in force and the related measurements in order to meet the increasing demand for the sensors offering a good price and quality performance ratio. However, it requires some more efforts to compete with the load cells of fixed positions that are widely used in precise applications.

ACKNOWLEDGMENTS

This work was supported in part by the Sharif

University of Technology research program. The author, therefore, likes to thank the Research Council for the grant to this project. The assistance given by the staff of the mechanical workshop is also appreciated.

REFERENCES

1. Strain Gauges, Application Note Vol. G 24.01.8e, HOTTINGER BALDWING MESSTECHNIK Company, Darmsdt, (1995).
2. How to Solve Measurement Problems, Application Guide, Vol. F 01.05.0e, HOTTINGER BALDWING MEASSTECHNIK Company, Darmsdat, (1995).
3. Jacob, J. M., "Industrial Control Electronics", Prentice-Hall International, NJ, (1989), Chap. 3.
4. Allard, F. C., "Fiber Optics Handbook", McGraw-Hill, New York, (1989), Chap 8.
5. Tracey, P. M., "Intrinsic Fiber-Optic Sensor", ***IEEE Trans. on Industry Applications***, 27, (1991), 96-98.
6. Hocker, G. B., "Fiber-Optic Sensing of Pressure and Temperature", ***Appl. Opt.***, 18, (1976), 1445-1448.
7. Jones, B. E. and Philp, G. S., "A Vibrating Wire Strain Sensor", ***Eruopean Conference on Sensors and their Applications***, UMIST, Manchester, Technical Notes, (1983), 86-87.
8. Malki, A., Lecoy, P., Marty, J., Renouf, C. and Ferdinand, P., "Optical Fiber Accelerometer Based on a Silicon Micromachined Cantilever", ***Appl. Opt.***, 34, (1995), 8014-8018.
9. Venkatesh, S. and Culshaw, B., "Optically Activated Vibrations in a Macromachined Silicon Structures", ***Electronic Letters***, 21, (1985), 315-317.
10. Senior, J. M., "Optical Fiber Communications", Prentice-Hall International, UK, (1992).
11. Giallorrenzi, T. G., Bucaro, J. A., Dandrige, A., Sigel, G. H., Cole, J. H., Rashleigh, S. C. and Priest, R. G., "Optical Fiber Sensor Technology", ***IEEE J. of Quantum Electron.***, QE-18, (1982), 626-663.
12. Greenwood, J. C., "Silicon in Mechanical Sensors", ***J. of Phys. E: Sci. Instrum.***, 21, (1988), 1114-1128.
13. Hunsperger, R. G., "Integrated Optics: Theory and Technology", Springer-Verlag, Berlin, (1991).
14. Golnabi, H. and Ashrafi, A., "Design and Construction of a Reliable Fiber Optic Sensor", ***Proc. of the 5th. International Conference on Flexible Automation and IntelligentManufacturing*** FAIM 95, Begell House Inc., New York, (1995) 910-917.
15. Golnabi, H., "Fiber Optic Sensing of Thermal Expansion", ***International Journal of Engineering***, Vol. 9, No. 2, (1996), 37-43.