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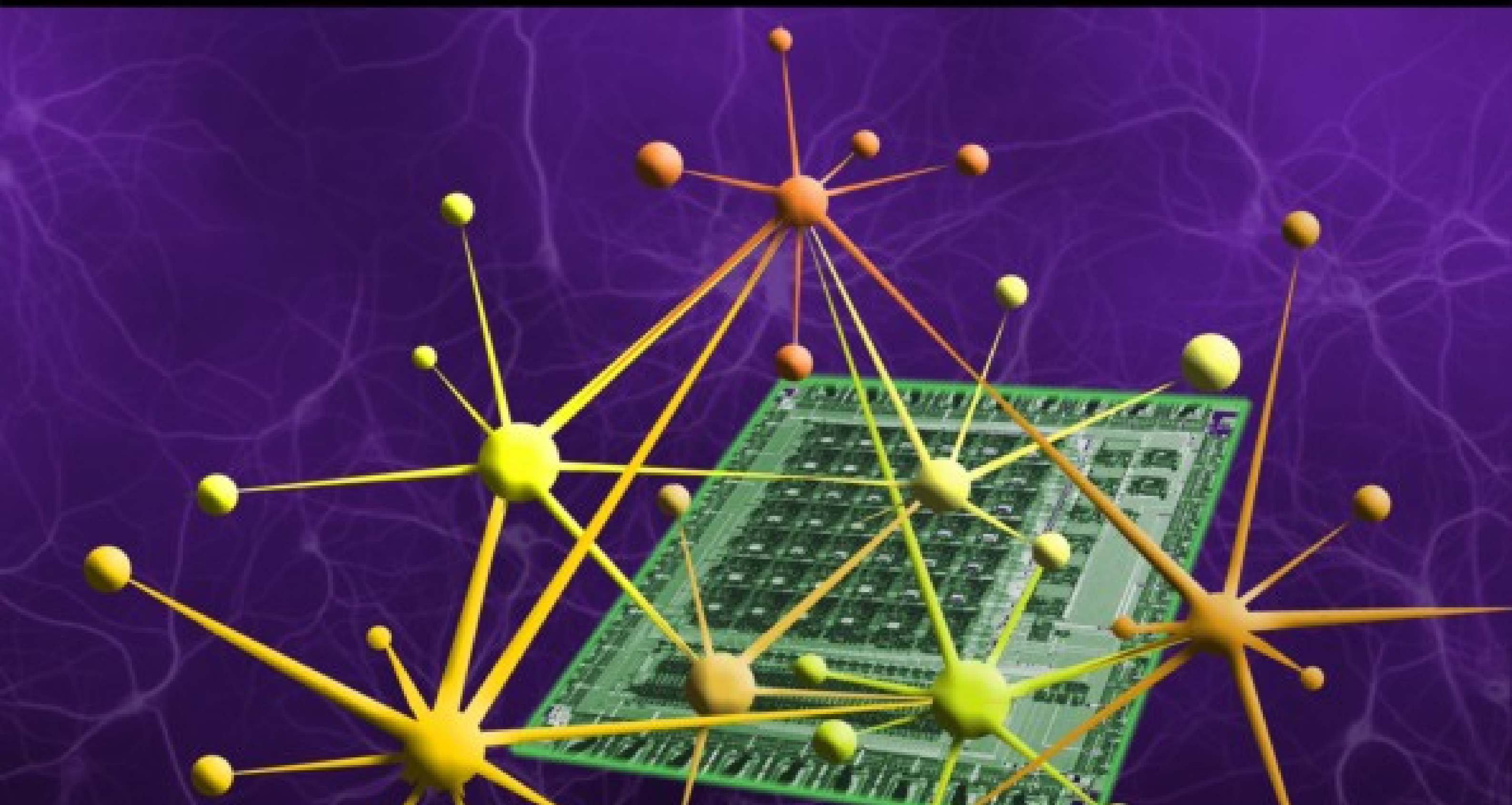

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Transformer Temperature Measurement Using Optical Fiber Based Microbend Sensor

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Abstract: Breakdown of transformers proves to be very expensive and inconvenient because it takes a lot of time for their replacement. During breakdown the industry also incurs heavy losses because of stoppage in production line. A system for monitoring the temperature of transformers is required. Existing sensors cannot be used for monitoring the temperature of transformers because they are sensitive to electrical signals and can cause sparking which can trigger fire since there is oil in transformers cooling coils. Optical fibers are electrically inert so this system will prove to be ideal for this application. Results of investigations carried out by simulating a configuration of Optical Fiber Temperature Sensor for transformers based on microbending using Matlab as a simulation tool to evaluate the effectiveness of this sensor have been communicated through this manuscript. The results are in the form of graphs of intensity modulation vs. the temperature. *Copyright © 2007 IFSA.*

Keywords: Generic microbend sensor, Hot spot monitoring, Direct temperature monitoring, Bending loss

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1. Introduction

1.1. Importance of Optical Fibers

Optical fiber cables are used in modern telecommunication for the transmission of information. Light waves being conducted over great distance by glass fiber of capillary thickness. Glass fiber or optical cable offers significant technical and economical advantage compared to standard telecommunication cables with copper conductors.

The most important advantages are:

- Wide transmission bandwidth;
- No interference from external electromagnetic stray-fields;
- No potential problem with non-metallic cable;
- Optical fiber cables are thin, light and flexible.

These advantages are the special features of glass fiber make the optical transmission of information interesting not only for the public telecommunication network, but also for other application areas such as:

- Telecommunication network of energy supply companies;
- Cable television networks teleconferencing;
- Industrial process control;
- Data processing in interconnected computer networks;
- Military use (high interception security).

Another application which the fiber is being used for in the recent times is for sensing temperature. Generally plastic clad silica is used for this application. In the case of transformers it is not possible to use electrical contact type of sensors like RTD etc since they themselves being electrical conductors increase the chances of short circuit on overheating. Moreover they are prone to electromagnetic interference.

1.2. Fiber Optics in the Field of Sensing

Optical fiber sensors have been demonstrated to be attractive for the measurement of a wide variety of physical, chemical, biological, biomedical parameters because of a number of inherent advantages Some of the major advantages over conventional electrical and electronic sensors include immunity to electromagnetic interference, small size and light weight, avoidance of ground loops, capability to respond to a wide variety of measurands, avoidance of electric sparks ,resistance to harsh environment ,remote operation, capability of multiplexing and many more .Because of these inherent advantages ,a variety of fiber sensors have been developed in the past two decades.

Most of the fiber sensors developed to date may be classified in two large groups based on their configuration as:

1) Extrinsic FOS;
2) Intrinsic FOS.

Extrinsic FOS are basically optical sensor where we deliver (and collect) light signal by optical fiber, while the modulation of the light signal occurs outside optical fiber. Intrinsic FOS is “true” fiber optic sensors, meaning that the modulation of light takes place inside fiber in accordance to measured parameter. According to principle of operation both sensor groups can be further divided in two large categories:

1) Intensity modulated FOS;
2) Phase modulated FOS (fiber interferometers).

In intensity modulated FOS, measured parameter induces light intensity change at the detector i.e. optical intensity is modulated. Intensity modulated FOS can be found in variety of intrinsic and extrinsic configurations. In interferometers optical phase is affected. In general, interferometric sensors have the advantages of ultra high resolution, accuracy, and configuration versatility. However they have disadvantages of relative measurement, costly signal processing. In contrast to fiber interferometers, the intensity based devices have the advantages of simple signal demodulation, absolute measurement, high frequency response.

1.3. Microbend Sensors

The microbend sensor (Fig.1) is one of the earliest intrinsic fiber-optic sensors. Microbend loss has always been a curse to the cable designer, but it is this very same microbend loss effect in optical fibers which is exploited by the microbend sensor designer who has adopted the microbend effect in the measurement of many physical parameters and physical variables such as temperature, pressure, displacement, etc. The early interest in microbend sensors was for hydrophone applications. Since that time, over 100 different studies on microbend sensors have appeared in the literature, and the sensors have been adapted to many different measurement applications. Microbending in simplest terms can be explained as follows: the mechanical perturbation of a multimode fiber waveguide causes a redistribution of light power among the many modes in the fiber. The more severe the mechanical perturbation or bending, the more light is coupled to radiation modes and is lost. Thus, the important characteristics of a microbend sensor are that it uses a multimode optical fiber, it is a light intensity sensor and the light intensity decreases with mechanical bending. The basic design is shown in figure above. Corrugated plates, called deformer plates, squeeze optical fiber under measured perturbation and thereby induce microbending. This causes coupling between guided and continuum of cladding modes, which results in irreversibly leak of the optical power from the fiber. The microbend sensitivity

$$\wedge = \frac{\pi a}{\sqrt{\Delta}}$$

can be enhanced by the proper constriction of deformer plates.

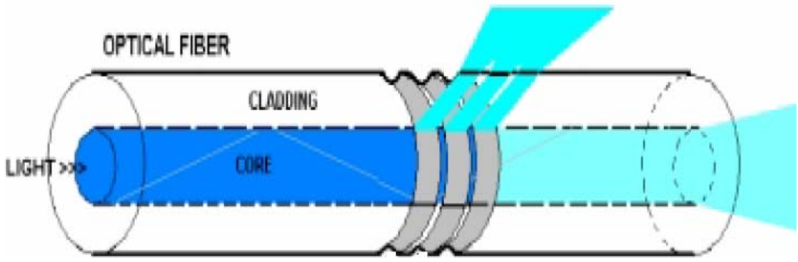


Fig. 1. The Fiber Microbend Sensor.

It was shown that mechanical period of the deformer must match expression in the case of graded index fiber in order to achieve maximum microbend sensitivity, where a is the core radius and Δ is the refractive index difference. Over the years, microbend sensors have been configured for measurement of many different parameters including pressure, temperature, acceleration, flow, local strain, and speed. Microbend sensors arrays have been used in tactile sensing systems, and in distributed sensing systems for temperature, strain, structural monitoring, and water detection. In some of these areas, prototypes have been built and tested, and in a few of the areas, commercial products have been offered.

1.4. Macrobend Sensors

Macrobend sensors are another type of intensity modulated, intrinsic FOS (Fig.2). They are certain similarities to microbend sensors, however there are also significant differences between both concepts. In macrobend sensors, single mode fiber is usually used and is bend at relatively large diameters (typically bend radius is in order of few centimeters). Regular telecommunication fiber is usually not enough sensitive to macrobending therefore it is usually necessary to use specially bend sensitive single mode fibers. Those fibers are usually operated at low V numbers (V is normalized frequency). The principle of operation can be explained as follows.

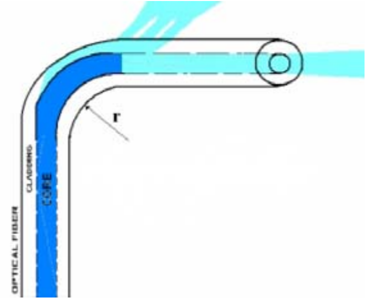


Fig. 2. The Fiber Macrobend Sensor.

Consider the schematic representation of a single-mode fiber shown in figure below. In the straight region of the fiber before the bend, the fiber is considered as lossless and the transverse mode of power P0 is confined to propagate along fiber axis. In the bend region of radius *R* and angle Φ, the confining path is assumed to be circular. In the bend the modal wave front will propagate with a phase velocity linearly dependent on the radial distance from the center of curvature of the bend. The propagation constant of the mode β, will thus be in proportion to *1/r*. For radial positions on the wave front larger than a characteristic value *rc*, a radiation caustic occurs where the angular phase velocity of the wave front equals the velocity of light in the propagation medium and the power in the shaded tail *Pc* dissociates itself from the wave front and propagates in a tangential path to the dissociation point and radiates away. Macrobend sensors can be used in applications similar to microbend sensor.

2 Mathematical Model of Generic Fiber Microbend Sensor

An idealized generic microbend sensor as depicted in Fig. 3.

The sensing fiber which is sandwiched between a pair of deformer plates is somehow constrained to bend in a regular pattern with periodicity Λ. The deformer in response to an appropriate environmental ΔE, applies a force ΔF to the bent fiber causing the amplitude of the fiber deformation X to change by an amount ΔX. The transmission coefficient for light propagating through the bent fiber T is in turn changed by an amount ΔT so that

$$\Delta T = (\Delta T/\Delta X) D\Delta E \, , \tag{1}$$

where

$$D\Delta E = \Delta X \, . \tag{2}$$

Here D is the constant which depends on the environmental change ΔE.

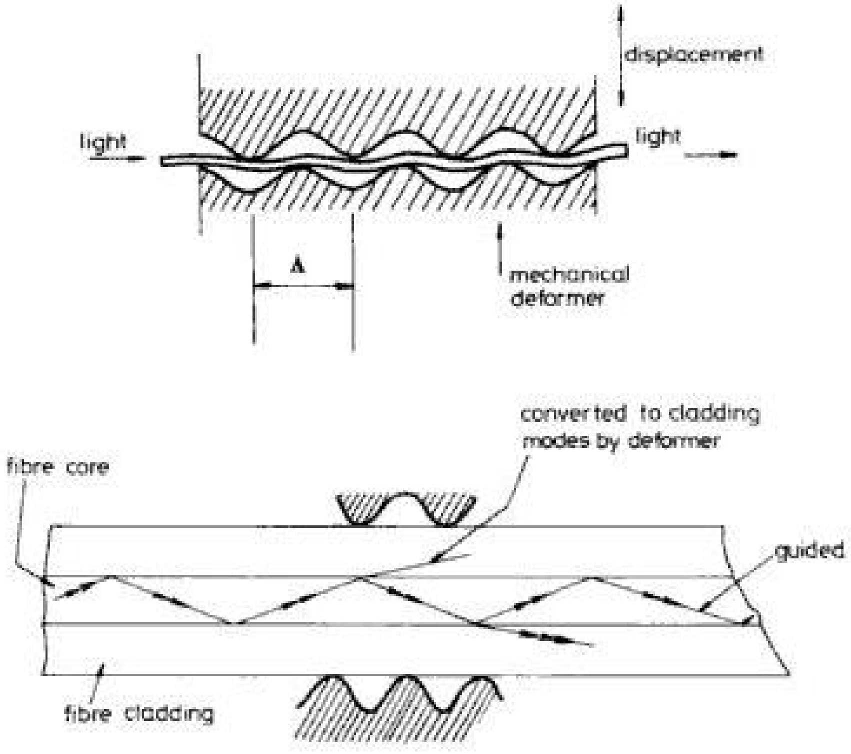


Fig. 3. The principle of Fiber Microbend Sensor.

In terms of the applied force ΔF, Equation (1) becomes

$$\Delta T=(\Delta T/\Delta X)D\Delta F.\ (K_f+A_sY_s/L_s)^{-1} \tag{3}$$

The deformer converts the change in the environmental parameter ΔE to a force ΔF on the bent fiber i.e,

$$\Delta F=\Delta EC.$$

For generic deformer depicted in fig the parameter c can be expressed as a simple function of deformer parameters for various environmental sensors

For a temperature sensor, C is equal to $A_S\ \acute{\alpha}_s\ Y_S$, where, $\acute{\alpha}_s$ is the thermal expansion coefficient of the spacers.

Then equation (3) becomes

$$\Delta T=(\Delta T/\Delta X).A_S\ \acute{\alpha}_s\ Y_S\,(K_f+A_sY_s/L_s)^{-1}\Delta\theta, \tag{6}$$

where $\Delta\theta$ is the temperature change. For sensitive temperature sensor equation (6) implies that one should have $L_s\ \ K_f \ll A_sY_s$. In this condition equation (6) becomes simply

$$\Delta T=(\Delta T/\Delta X).\ \acute{\alpha}_s\ L_s\ \Delta\theta \tag{7}$$

3. Role of Fiber Optic in Monitoring Dry Transformer

The new overheating protection system overcomes these disadvantages. Both high and low voltage coils as well as the core can be guarded against overheating. The principle of operation is based on a temperature dependant shift of the optical transmission properties of a fiber optical cable. An optical sensor does not cause any electromagnetic interference or influences the operation of the transformer in any other way. If a light signal is injected into one side of the fiber optic sensor it can be detected at the opposite end with an optical receiver. If the surface temperature of the optical fiber rises the light transmission is interrupted by deformer plates in response to temperature.

It can directly sense hot spot-temperature unlike conventional sensors.

At still higher temperatures the light transmission is interrupted, and, no signal can be received any more. This state is used for providing an overheat alarm.

The most important advantages of the new developed overheating protection system (Fig. 4) can be summarized as follows:

- Overheating of both insulation and core can be detected online;
- In case of a local temperature extension an alarm reduces the risk of fume, fire or damage of the insulation;
- No electromagnetic interference, surface discharges or any other impairment of the environmental conditions;
- Safe overheating detection in a range of 80°C up to 170°C which is well tried in practical operation;
- Cost efficient and easy to install;
- Processing unit enables due to an intelligent design self control and supports several interfaces as well as remote access.

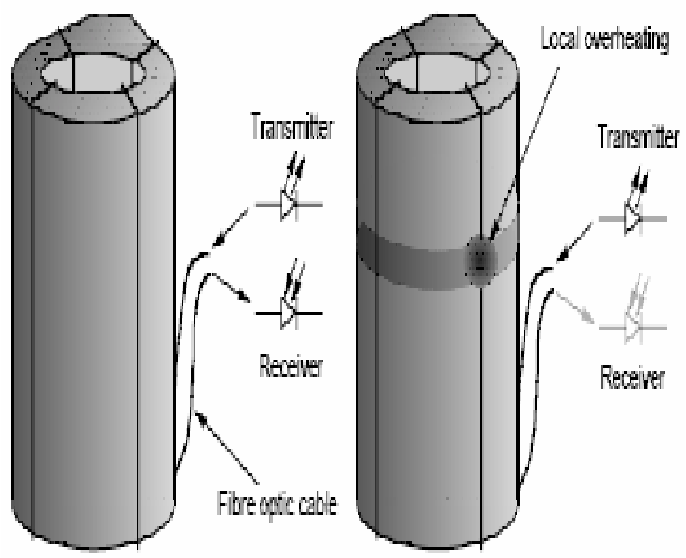


Fig. 4. Direct Winding Temperature Measurements Using Fiber Optics.

The proposed set up for this optical fiber based temperature monitoring of transformer has been shown in this block diagram in Fig. 5 along with Fiber Optic Transmitter & Receiver in Fig. 6.

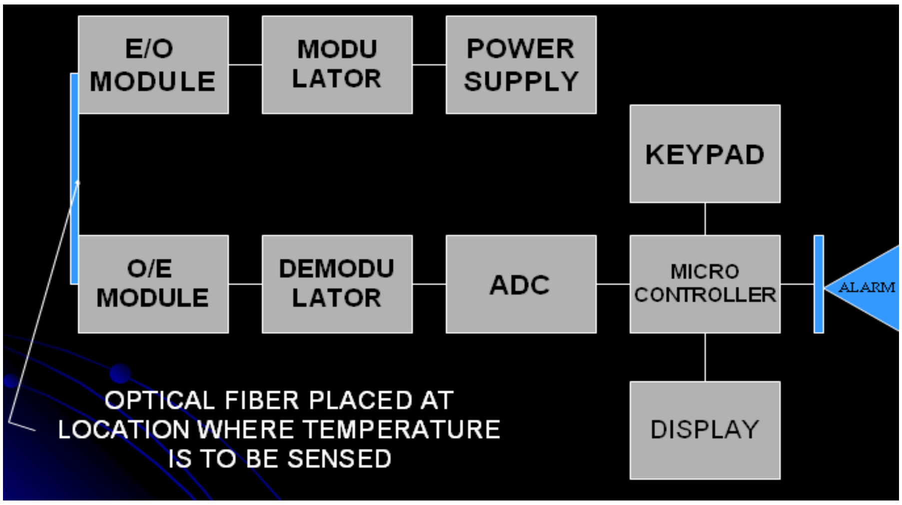
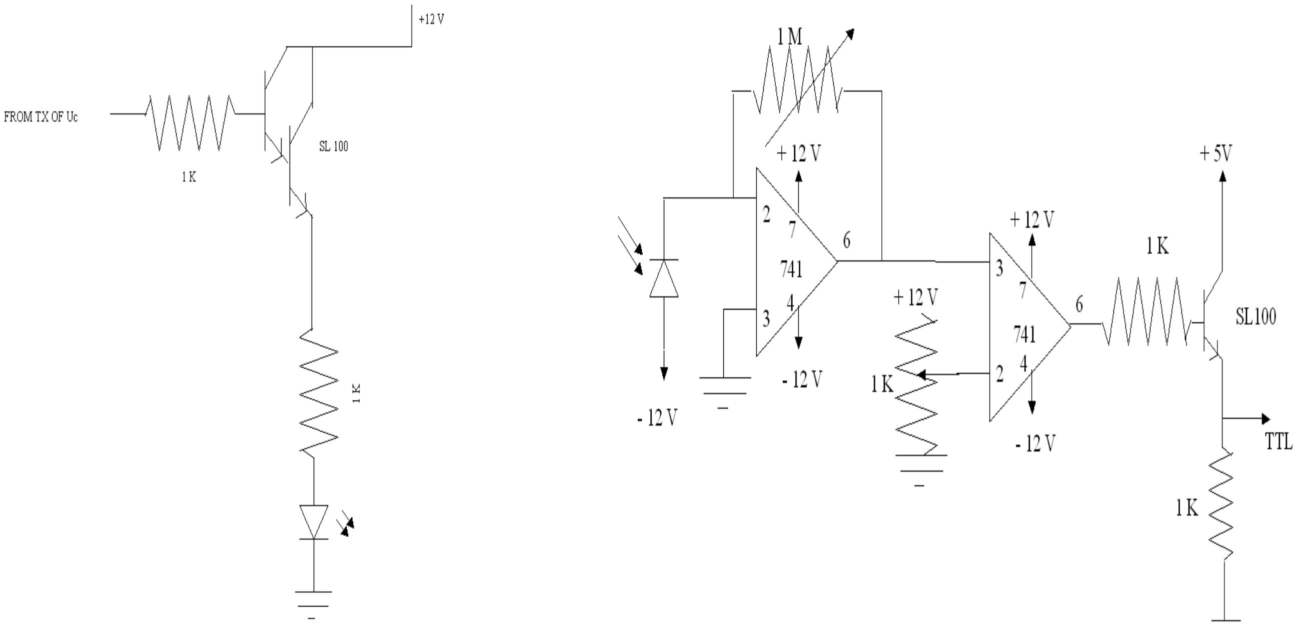


Fig. 5. Block Diagram for Hardware Prototype.



(a) (b)

Fig. 6. Fiber Optic (a) Transmitter & (b) Receiver.

4. Methodology

Since there is proof that optical fiber has the potential to be used as a Fiber Optic Temperature monitor, Investigation will be carried out by simulating a configuration based on microbending and macrobend simulation tool to evaluate the effectiveness of this sensor. Performance analysis by characterizing the sensor through simulation using Simulink toolbox of Matlab has been carried out to arrive at the optimal design of the sensor (Fig.7).

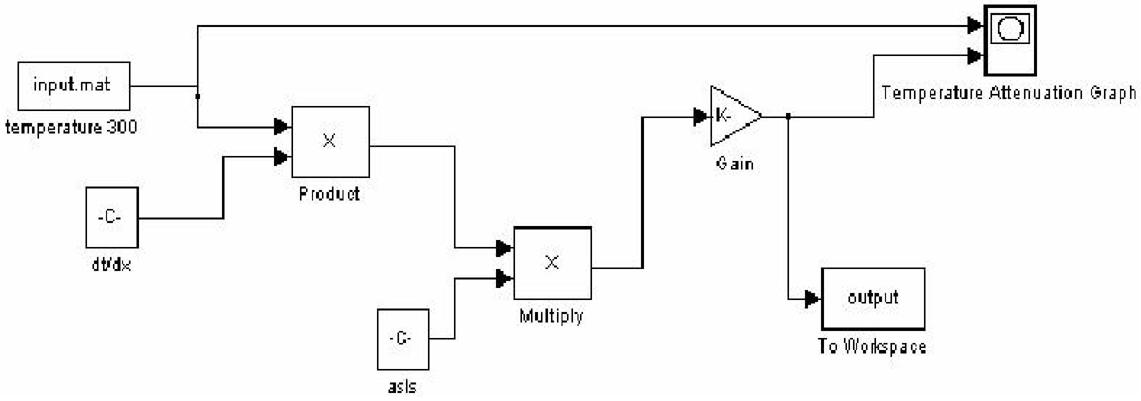


Fig. 7. MATLAB-SIMULINK Model for Generic Fiber Optic Sensor.

5. Results and Discussion

From the expression for the change in transmission coefficient of optical fiber for generic configuration of generic microbend sensor model and the simulation results are shown below.

Subsequently a model was constructed for application of the sensor at higher temperature range from 0 to 100 ^{0}C. It was found that the results were linear but the slope was too steep for the instrumentation signals to capture the data. The model constructed is shown below. The graph of the measured values for the transmission constant is as given below which shows that the results are quite linear.

In order to correct the slope iterations were performed to arrive at suitable gain for the amplifier and the desired response is shown in Fig. 8. This can be practically implemented by simply adjusting the feedback network of the instrumentation operational amplifiers in the transducer stage. Similarly for other temperature ranges the gain can be suitably changed so as to get the plots in the measurable range. This model constructed can thus help in designing the temperature sensors effectively for different types of applications to work at different temperature ranges.

The simulation results are:

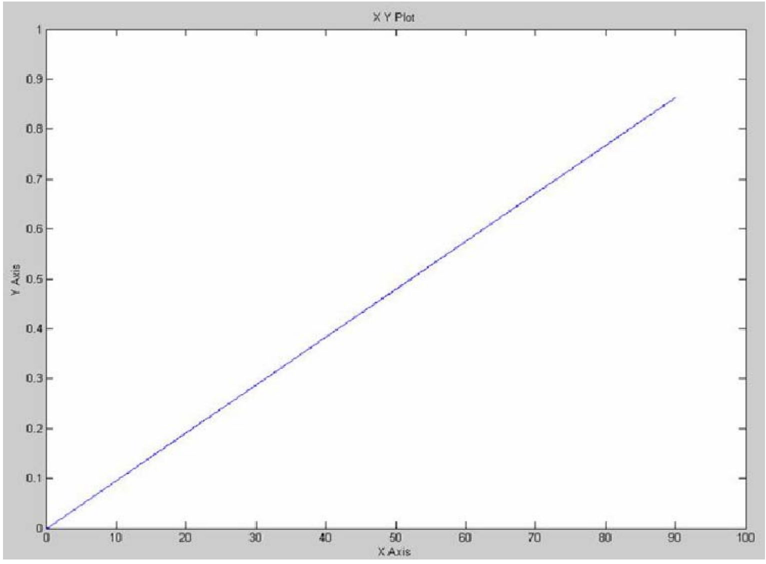


Fig. 8. Temperature-Attenuation Linearity.

6. Conclusions and Scope for Future Work

In the presented thesis simulation of microbend configuration of fiber optic sensor has been simulated and results discussed to arrive at an optimal design for temperature sensor for dry type transformer. It has been found that graph of the measured values for the transmission constant is quite linear.

The continuous monitoring of the transformer aims at improved reliability, at early stage detection of problems, at reduced maintenance cost, and also extension of its life expectancy. Present application of instruments does not provide consistency neither accuracy in their indications of winding temperature. Indirect measurement WTM'S i.e, Thermowell simulating WTM system are slow to respond to step load changes. Aging of power transformers is mainly driven by winding temperature. More frequent loading to full capacity has shown need for better control of winding temperature Fiber optic sensor have reached a level of dependability that makes them a natural choice for this important function . As it avoids catastrophic failure and emergency shutdowns by monitoring long-term, gradual transformer deterioration. For future we can use various technologies like: Nano-tech based, autonomous, self-navigating thermal sensors and also, technology like Winding temperature algorithms. Moreover, imaging sensors can also be located internal to the tank. We can also make use of neural network and neuro-fuzzy in future use.

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726- 5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

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