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Contents

Volume 83
Issue 9
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ISSN 1726-5479

Research Articles

IEEE 1451.4 Standard and Practice
Mario Orizabal 1495

Biotechniques in Electrochemical Determination of Cholesterol: Review
*Vikas & *C. S. Pundir*.. 1504

Seismometers and Accelerometers Calibration System (STASI) Prototype
Aldo Terrusi, Roberto Silvestro, Renzo Romagnoli.. 1513

Study of a Modified Anemometer Type Flow Meter
S. C. Bera, B. Chakraborty and D. N. Kole 1521

Modeling of Potential Distribution of Electrical Capacitance Tomography Sensor for Multiphase Flow Image
S. Sathiyamoorthy, J. Saratchandrababu, T. K. Radhakrishnan... 1527

Fabry-Perot Interferometer Performance as Temperature Sensor for Use in Electrical Power System Applications
Sanjoy Mandal.. 1535

Efficient Probes for a Fast Detection of Chlorine Gas at ppb Level
Philippe Banet, Dominique Porterat, Fabien Lepetit and Thu-Hoa Tran-Thi 1541

Influence of Pt Gate Electrode Thickness on the Hydrogen Gas Sensing Characteristics of Pt/In2O3/SiC Hetero-Junction Devices
S. Kandasamy, W. Gao, A. Holland, W. Wlodarski, T. Katsube 1549

Cholesterol Biosensor Based on Polyvinyl Formal Membrane Bound Cholesterol Esterase and Oxidase
Ashok Kumar and Suman.. 1555

Performance Enhancement of the Patch Antennas Applying Micromachining Technology
Mohamed N. Azermanesh, Ebrahim Abbaspour-Sani, Kaveh Purmokhtar 1564

Design of a Opto-Isolator Circuit for Analogue DC Signal
S. C. Bera, B. Chakraborty.. 1574

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Fabry-Perot Interferometer Performance as Temperature Sensor for Use in Electrical Power System Applications

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Abstract: Transfer function model of the loss less Fabry-Perot cavity (FPI), developed in Z-domain is presented in this paper. Frequency response analysis of the model was carried out in MATLAB environment to explain the behavior of the interferometer and its potential as temperature sensor was studied. Analysis reveals a highly sensitive temperature sensor that can be used in electrical engineering power system applications. *Copyright © 2007 IFSA.*

Keywords: Fabry-Perot interferometer, Temperature sensor, Fabry-Perot cavity

1. Introduction

Optical filters can be considered to be linear time invariant system and digital signal processing technique can be used for analysis of optical filter performance. Fundamental relationship between digital filters and optical wave , first developed by Moslehi et. al. [1] is adopted in the present analysis. Optical path lengths may be considered as integer multiples of the smallest path length. The unit delay correspond to smallest path length is generally defined as $T_u = \frac{L_U n}{c}$, where L_U is the smallest path length and termed as unit delay length , n is refractive index and c is velocity of light [2]. A discrete signal is generally obtained by sampling a continuous signal at $t = nT_u$ where n is the sample number and T_u is the sampling interval. For digital filter T_u is generally considered as unit delay associated with the discrete impulse response. Total delay then can be expressed as an integer multiple of the unit delay and the impulse response of an optical filter can now be described as discrete sequence. The fabry-perot interferometer in the present analysis is represented by a discrete model with the help of Z transform technique.

2. Modeling Methodology

A simple Fabry-Perot interferometer cavity constructed from two parallel, highly reflective surfaces separated by a variable distances [3]. Theoretical model of a reflective Fabry-Perot interferometer cavity is shown in Fig. 1. I_{in} is input light signal, I_{out} is reflected light signal r_1 and r_2 are reflectivity of the inner surface and outer surface of the cavity.

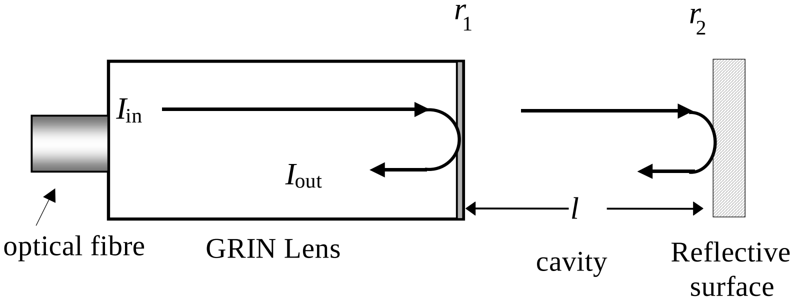


Fig.1. A simple Fabry Perot Interferometer cavity.

l is the cavity length. When a wave is entered into the cavity the optical delay for successive reflections gives additional phase differences, which correspond to double passage through the cavity [4]. The round-trip phase-lag φ within the cavity is given by [5]

$$\varphi = \frac{2\pi(2nl\cos\theta)}{\lambda}, \tag{1}$$

where n is the refractive index of the medium between the mirrors, θ is angle of incidence and λ is the propagating wavelength. If the incident illumination is normal to the inner surface i.e (θ=0), and considering total path length inside the cavity $d=2l$ equation (1) becomes

$$\varphi = \frac{2\pi nd}{\lambda}. \tag{2}$$

The situation is a condition of positive feed back [4] and can be represented as Fig. 2.

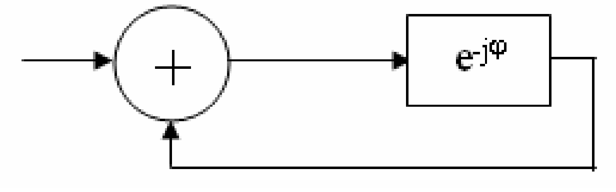


Fig. 2. Block diagram model of Fabry-Perot cavity.

Using the relation $\lambda = \frac{c}{f}$ and $\omega = 2\pi f$, where f is frequency in Hz and ω is the frequency in rad/sec, equation (2) can be represented as $\varphi = T\omega$, where $T(=\frac{nd}{c})$ can be considered as unit delay. In the above equation c is the velocity of light. Using relation $s = j\omega$ and $Z = e^{ST}$ [6] block diagram model in Fig. 2 can be transformed to block diagram model in discrete domain as shown in Fig. 3.

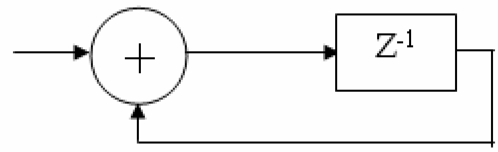


Fig. 3. Block diagram model of Fabry-Perot cavity in discrete domain.

The interference takes place between the reference input and the output of the Fabry-Perot resonator cavity. If we assume r_1=0.25 ,then 25% of the input is allowed to interfere with the output of the resonator cavity. In such case the overall block diagram may be represented by Fig. 4 [7].

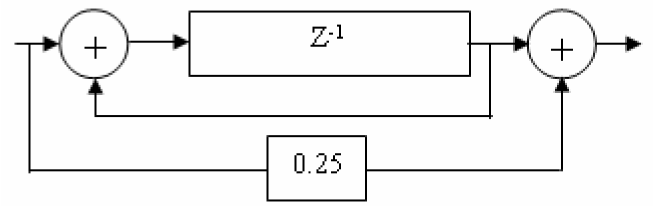


Fig. 4. Block diagram model of the FPI in discrete domain.

Overall transfer function of the FPI in Z domain is calculated as

$$T_f = \frac{0.75Z^{-1} + 0.25}{1 - Z^{-1}}. \tag{3}$$

3. Principle of Operation

A simple fiber with one end coated with silver and other end connected with 25% partial reflector will act as cavity as well as sensor probe. A schematic of the sensor configuration is shown in Fig. 5.

When the fiber probe of length L undergoes a temperature change of ΔT the unit delay length will vary and may be represented as [8]

$$\delta(nL) = [L\frac{dn}{dT} + L\Delta n_{Strain} + n\Delta L]\Delta T\ , \tag{4}$$

where Δn_{Strain} represents the strain induced change in the refractive index of the core given by the expression:

$$\Delta n_{Strain} = \frac{n^3}{2}[(p_{11} + p_{12})\nu - p_{12}]\frac{\sigma}{E} \tag{5}$$

p_{11} and p_{12} are photo elastic constants of silica and ν is Poisson's ratio and σ and E are respectively the axial stress and Young's modulus of each fiber layer.

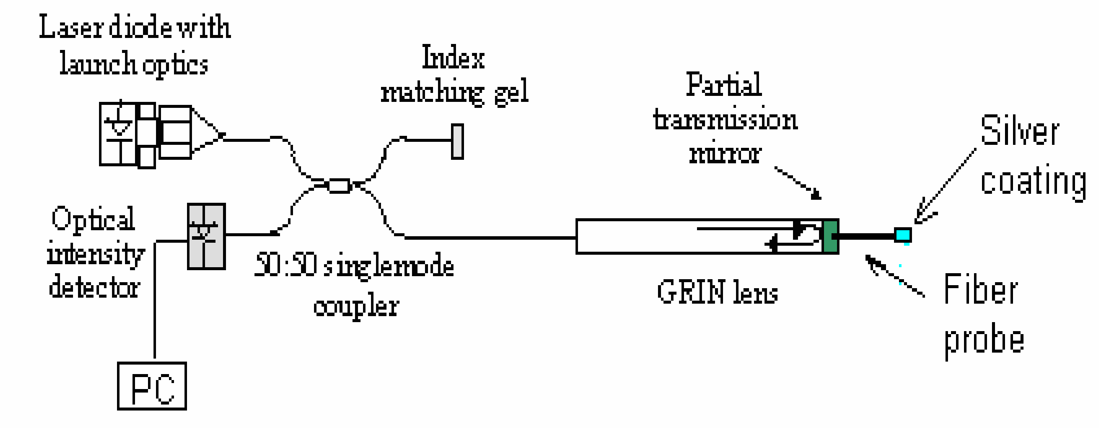


Fig. 5. Fiber optic temperature sensor configuration.

Equation (6) may be rewritten as

$$\delta(nL) = [\frac{dn}{dT} + \Delta n_{Strain} + n\beta]L \times \Delta T\,, \tag{6}$$

where $\beta = \frac{\Delta L}{L}$

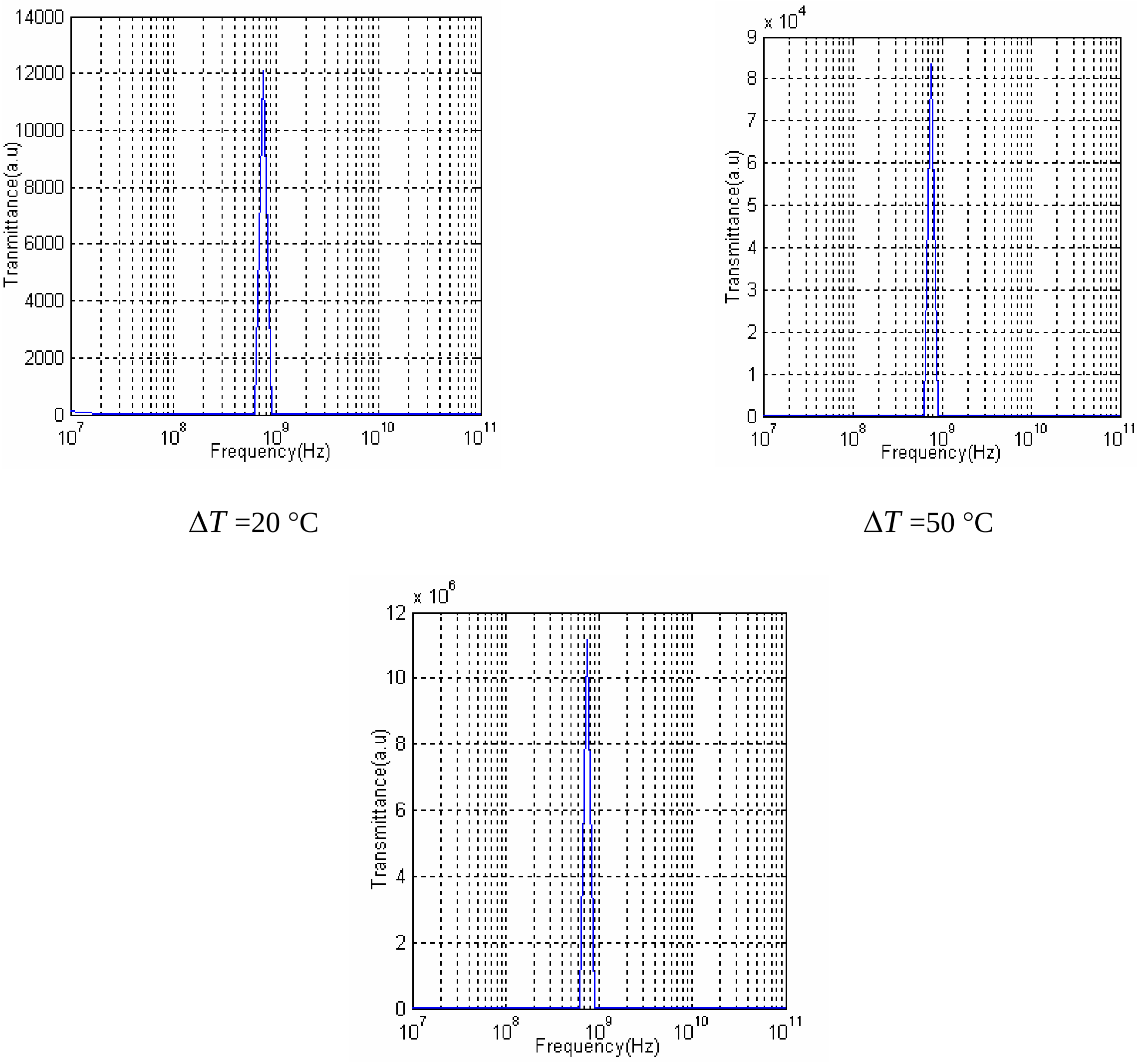
considering $\frac{dn}{dT} = 1.1\times10^{-5}/^{o}\text{C}$, $p_{11} = 0.121$, p_{12}=0.27, $n = 1.46$, $\beta = 0.24$ [8]

$$\delta(nL) = 0.44\times10^{-4} \times L \times \Delta T\,, \tag{7}$$

when the unit delay will vary due to temperature change Z^{-1} of equation (5) will be replaced by $e^{-j\psi}Z^{-1}$ where $\psi = \frac{2\pi}{\lambda}\delta(nL)$ [2]. Hence the unit delay of the fiber will be modified as $T' = T + \frac{0.44\times10^{-4} \times L \times \Delta T}{c}$. Therefore temperature change will modifies the unit delay length and the response of the FPI also will be altered.

4. Simulation Results

The developed FPI model was simulated in MATLAB environment to determine its square magnitude with different values of temperature. The fiber probe length is considered as 27 cm. Frequency response of the FPI model for temperature changes ΔT =20^{o} C, 50^{o} C, 70^{o} C is shown in the Fig. 6. Only one peak at frequency 0.65GHz indicates constrictive interference and its intensity changes with variation of temperature. Variation of peak amplitude with temperature is shown in Fig. 7.



ΔT =20 °C

ΔT =50 °C

ΔT =70 °C

Fig. 6. Frequency response of FPI for different temperature.

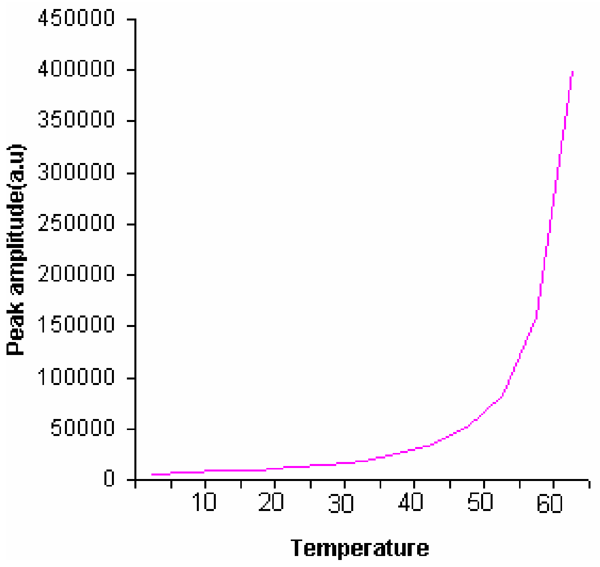


Fig. 7. Optical intensity variation of the FPI against temperature (°C).

5. Conclusion

Mathematical model of FPI in Z-domain is developed and its behavior is studied. Thermal characteristics of the FPI are investigated. The analysis reveals that the FPI is very sensitive due to the variation in the temperature. It can be concluded from Fig. 7 that the FPI will be very much suitable as temperature sensor for power transformer applications. The sensor output can be easily communicated to the control room due to inherent advantages of the optical fiber. The fiber is immune to electromagnetic interference, and this is an added advantage for its use in power system applications. Since the FPI is sensitive for vibration, proper precaution is to be taken for its use in actual applications.

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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;
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- Technologies and materials;
- Nanosensors;
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