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Contents

Volume 82
Issue 8
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Research Articles

Sensor Signal Conditioning
David Cheeke 1381

Sensor Interfaces for Private Home Automation: From Analog to Digital, Wireless and Autonomous
E. Leder, A. Sutor, M. Meiler, R. Lerch, B. Pulvermueller, M. Guenther.......... 1389

Bio-Techniques in Electrochemical Transducers: an Overview
Vikas & C. S. Pundir 1405

Design of a Novel Capacitive Pressure Sensor
Ebrahim Abbaspour-Sani, Sodabeh Soleimani 1418

A Ppb Formaldehyde Gas Sensor for Fast Indoor Air Quality Measurements
Hélène Paolacci, R. Dagnelie, D. Porterat, François Piuzzi, Fabien Lepetit, Thu-Hoa Tran-Thi....... 1423

Modeling and Analysis of Fiber Optic Ring Resonator Performance as Temperature Sensor
Sanjoy Mandal, S.K.Ghosh, T.K.Basak.......... 1431

An Optoelectronic Sensor Configuration Using ZnO Thick Film for Detection of Methanol
Shobhna Dixit, K. P. Misra, Atul Srivastava, Anchal Srivastava and R. K. Shukla.......... 1443

Enhanced Acoustic Sensitivity in Polymeric Coated Fiber Bragg Grating
A. Cusano, S. D'Addio, A. Cutolo, S. Campopiano, M. Balbi, S. Balzarini, M. Giordano.......... 1450

Lactase from Clarias Gariepinus and its Application in Development of Lactose Sensor
Sandeep K. Sharma, Neeta Sehgal and Ashok Kumar 1458

Prism Based Real Time Refractometer
Anchal Srivastava, R. K. Shukla, Atul Srivastava,Manoj K. Srivastava and Dharmendra Mishra 1470

Development of a micro-SPM (Scanning Probe Microscope) by post-assembly of a MEMS-stage and an independent cantilever
Zhi Li, Helmut Wolff, Konrad Herrmann 1480

Design, Packaging and Characterization of a Langasite Monolithic Crystal Filter Viscometer
J. Andle, R. Haskell, R. Sbardella, G. Morehead, M. Chap, S. Xiong,J. Columbus, D. Stevens, and K. Durdag.......... 1486

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Modeling and Analysis of Fiber Optic Ring Resonator Performance as Temperature Sensor

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Abstract: A novel temperature sensor using multiple fiber optic ring resonator is presented in the present article. The sensor operates by means of monitoring the changes in the transmission spectrum of a high finesse fiber optic ring resonator. Delay line signal processing technique, developed by a few previous researchers is used to develop the signal flow graph of fiber optic ring resonator and Mason's rule is implemented to determine its overall transmittance in discrete domain. Simulations in MATLAB environment were carried out to obtain the sensor design and the transfer characteristics of the ring resonator based temperature sensor. The simulated frequency response of the single ring resonator is compared with those of previously published results by Heebner et al. [1], which are in very close agreement. Sensitivity of the resonator can be improved by introducing double ring resonator. A simple design methodology to improve the performances of the sensor is also introduced in the article. *Copyright © 2007 IFSA.*

Keywords: Mason's rule, Ring resonator, Temperature sensor, Free spectral range

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1. Introduction

Fiber optic ring resonators has many applications in optical switching[2], photonic biosensor[3], laser resonators[4], add-drop filters[5], Brillouin ring laser gyroscopes[6], optical spectrum analyzers[7] and filters with tailored response[8]. The objective of this paper is to describe a novel temperature sensor using fiber optic ring resonators. Delay line signal processing technique is being used for analysis of ring resonator temperature sensor performance in the present analysis, which was first developed by Moslehi et. al [9-10]. In delay line signal processing technique the optical path length is typically integral multiple of smallest path length, known as unit delay length. The frequency response of ring resonators is generally periodic in nature and one period is defined as free spectral range (FSR). The mathematical relation between FSR and unit delay is given by [11]

$$\text{FSR}=\frac{1}{T}=\frac{c}{nL_u}, \tag{1}$$

where L_U is the smallest path length and termed as unit delay length, n is refractive index and c is velocity of light, T is unit delay time.

Z-transform method has been so far used to determine the performance of single ring resonators and its cascaded architectures only. For multiple ring resonators transfer matrix and chain matrix formulation are currently being used. The method involves matrix manipulations and become laborious for complex photonic circuits. A novel attempt is made to introduce a different mathematical tool for convenient and easy analysis of multiple ring resonator temperature sensor.

2. Theory

Simple fiber optic ring resonator using one directional tapered fused fiber coupler is shown in Fig. 1.

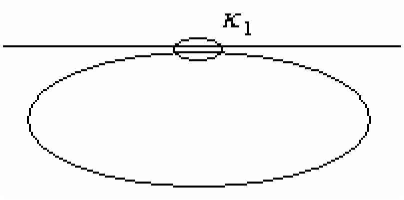


Fig. 1. Fiber optic ring resonator.

The Z transform schematics of the simple ring resonator is represented in Fig. 2.

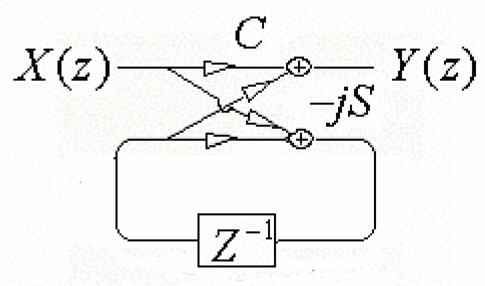


Fig. 2. Z-transform schematics of fiber optic single ring resonator.

Power coupling ratio κ is generally associated with optical directional coupler. When two optical waveguides are coupled with each other the relationship between input and output can be expressed as a 2x2 transfer matrix [11]

$$\begin{bmatrix} E_1^0 \\ E_2^0 \end{bmatrix} = q \begin{bmatrix} C & -jS \\ -jS & C \end{bmatrix} \begin{bmatrix} E_1^i \\ E_2^i \end{bmatrix} \tag{2}$$

Here E^i_1, E^i_2 represent coupler input, E^o_1, E^o_2 represent coupler output, q is amplitude transmission coefficient of the coupler, κ is power coupling ratio of the optical directional coupler. The through port transmission is represented by $C = \sqrt{1-\kappa}$ and the cross port transmission is designated by $-jS = -j\sqrt{\kappa}$.

In the transfer matrix of equation (2) it has been assumed that the coupling ratio should be wave length independent. Through out the analysis it has been assumed that the effective group index is constant and doesn't vary from its nominal value.

A discrete signal is generally obtained by sampling a continuous signal at t=kτ where k is the sample number and τ is the sampling interval. For digital signal processing technique τ is generally considered as unit delay associated with the discrete impulse response. Total delay then can be expressed as an integral multiple of the unit delay and the impulse response of an optical circuit can now be described as discrete sequence. Transfer function of simple fiber optic single ring resonator in Z-domain may be expressed as [11]

$$\frac{Y(Z)}{X(Z)} = \frac{C - \gamma Z^{-1}}{1 - \gamma C Z^{-1}} \tag{3}$$

The round trip loss of the ring is denoted by $\gamma = \exp(-\alpha L)$ where α is average ring loss per unit length and L is the ring perimeter. The quality of resonance is governed by finesse which is basically a function of loss and coupling coefficient of the fused tapered coupler within the resonator and may be defined as $F \approx \pi/(1-\gamma C)$ [1]. Z^{-1} is generally known as unit delay in Z-domain and the entire ring perimeter represents unit delay length for single ring resonator.

Mason's Rule [12, 13] is used to determine overall transmittance of the double ring resonator. The overall transmittance (transfer function) T_f of any signal flow graph (SFG) as per the rule is given by

$$T_f = \frac{\sum T_n \Delta_n}{\Delta}, \tag{4}$$

where T_n is the transmittance of nth forward path and Δ is the determinant of the graph given by

$$\Delta = 1 - \sum L_1 + \sum L_2 - \sum L_3 + \dots \tag{5}$$

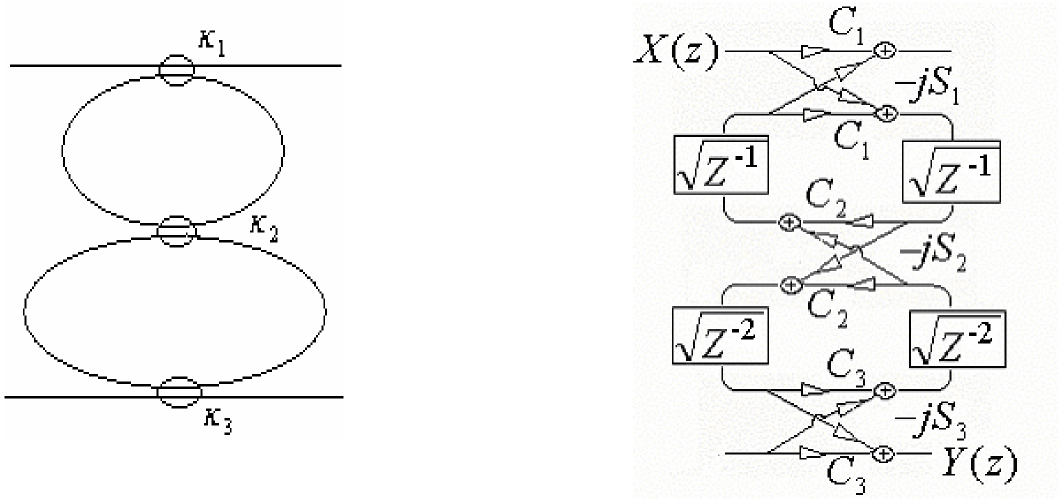
in which

$\sum L_1$ is the sum of the transmittance of all individual closed paths (loops) of the graph;

$\sum L_2$ is the sum of the products of transmittance of all possible combinations of two non touching closed paths;

$\sum L_3$ is the sum of the products of transmittance of all possible combinations of three non touching loops and so on, and Δ_n is the value of Δ for that part of the graph which doesn't touch the nth forward path.

Schematics of double ring resonator and its signal flow graph (SFG) of is shown in Fig. 3 (a) and (b). $X(z)$ is considered as input node signal and $Y(z)$ is considered as output node signal.



(a) (b)

Fig. 3. (a) Schematics of a double ring resonator using three directional fused fiber coupler; (b) Z transform schematics (SFG) of the double ring resonator.

Forward path transmittance of the graph is given by

$$T_1^2 = (-jS_1)\sqrt{z^{-1}}\,(-jS_2)\sqrt{z^{-2}}\,(-jS_3) = j\sqrt{\kappa_1\kappa_2\kappa_3}\sqrt{z^{-3}}\ , \tag{6}$$

where

$$\begin{cases} S_1 = \sqrt{\kappa_1} \\ S_2 = \sqrt{\kappa_2} \\ S_3 = \sqrt{\kappa_3}. \end{cases} \qquad j = \sqrt{-1} \tag{7}$$

Individual loop transmittance of the graph is given by

$$L_1^2 = C_1 C_2 z^{-N} \tag{8}$$

$$L_2^2 = C_2 C_3 z^{-M}\ , \tag{9}$$

where

$$\begin{cases} C_1 = \sqrt{1-\kappa_1} \\ C_2 = \sqrt{1-\kappa_2} \\ C_3 = \sqrt{1-\kappa_3}. \end{cases} \tag{10}$$

and

$$L_3^2 = C_1\sqrt{z^{-1}}(-jS_2)\sqrt{z^{-2}}C_3\sqrt{z^{-2}}(-jS_2)\sqrt{z^{-1}} = -C_1C_3{S_2}^2z^{-3} \tag{11}$$

Transmittance for all possible combinations of two non touching loops are given by

$$L_{12}^2 = C_1C_3{C_2}^2z^{-3}. \tag{12}$$

Since all the loops touch the forward path, the value of $\Delta_1 = 1$.

The overall transmittance of the DRR is given by

$$T_{f2}(z) = \frac{j\sqrt{\kappa_1\kappa_2\kappa_3}\sqrt{z^{-3}}}{1-(C_1C_2z^{-1}+C_2C_3z^{-2}-C_1C_3S_2^2z^{-3})+C_1C_3C_2^2z^{-3}}.$$

By using the relations $S_2^2 + C_2^2 = 1$, $T_{f2}(z)$ simplifies to

$$T_{f2}(z) = \frac{j\sqrt{\kappa_1\kappa_2\kappa_3}\sqrt{z^{-3}}}{1-C_1C_2z^{-1}-C_2C_3z^{-2}+C_1C_3z^{-3}}. \tag{13}$$

Considering the ring loss the overall transmittance will be modified as

$$T_{f2}(z) = \frac{j\sqrt{\gamma_1\gamma_2\kappa_1\kappa_2\kappa_3}\sqrt{z^{-3}}}{1-C_1C_2\gamma_1z^{-1}-C_2C_3\gamma_2z^{-2}+C_1C_3\gamma_1\gamma_2z^{-3}}, \tag{14}$$

where γ_1 and γ_2 are the ring losses of the smaller and the larger ring respectively.

3. Principle of Operation of the Temperature Sensor

When the optical fiber of length L undergoes a temperature change of $\Delta\tau$ the unit delay length will vary and may be represented as [14]

$$\delta(nL) = [L\frac{dn}{d\tau} + L\Delta n_{Strain} + n\Delta L]\Delta\tau \tag{15}$$

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

$$\Delta n_{Strain} = \frac{n^3}{2}[(p_{11}+p_{12})\nu - p_{12}]\frac{\sigma}{E} \tag{16}$$

p_{11} and p_{12} are photo elastic constants of silica and ν is poison’s ratio and. σ and E are respectively the axial stress and Young’s modulus of each fiber layer. Equation (15) may be rewritten as

$$\delta(nL) = [\frac{dn}{d\tau} + \Delta n_{Strain} + n\beta]L \times \Delta\tau \,, \qquad (16)$$

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

considering $\frac{dn}{d\tau} = 1.1\times10^{-5}/^{o}\mathrm{C}$, $p_{11} = 0.121$, p_{12}=0.27, $n = 1.46$, $\beta = 0.24$ [15]

$$\delta(nL) = 0.44\times10^{-4} \times L \times \Delta\tau \,. \qquad (17)$$

When the unit delay will vary due to temperature change Z^{-1} of equation (3) 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 modulated with temperature as $\tau' = \tau + \frac{0.44\times10^{-4}\times L\times\Delta\tau}{c}$.

For the purpose of sensing temperature, modulation applications of ring resonator are implemented in the article. It can be possible to obtain a large modulation in transmitted optical power by small variation of the unit delay length. This nature of modulation is useful if the resonance wavelength shift remains within the bandwidth of the resonator. Such shifts can be achieved due to change in optical path length, which is a function of resonator physical length subjected to temperature variation and effective refractive index as described by equation (15). Fig. 4 shows the transmission spectrum of a fiber optic single ring resonator, and the modulation concept. When the ring resonator is designed with high finesse, the modulation is dramatic due to sharp fall of the transmission dip.

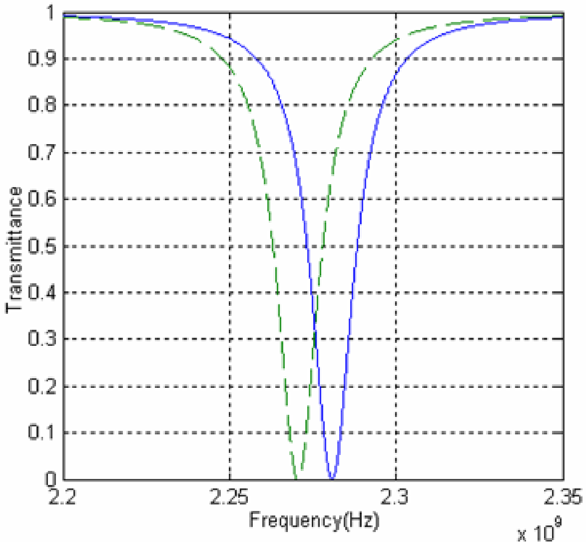


Fig. 4. Sensor concept based on a ring resonator. Optical power modulation takes place as the position of the resonance dip shifts due to temperature variation of the ring fiber.

4. Sensor Design and Results

A ring resonator could have high finesse when design to work at the critical coupling regime. To determine performance of ring resonator as temperature sensor, a fiber ring resonator of circumference 31cm is considered in the present analysis, which was used by Heebner *et. al* [1].

Transmission spectrum single ring with circumference of 31cm and finesse 30 is shown in Fig. 5. The transmission spectrum is of very close agreement with the published results of Heebner *et. al*.

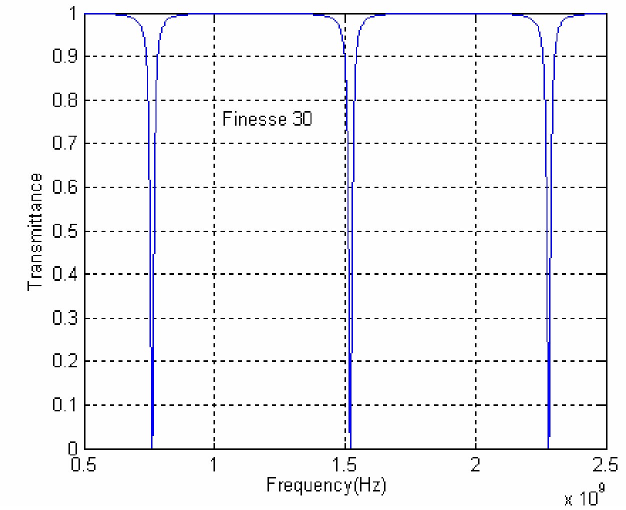


Fig. 5. Transmission spectrum of the ring resonator with circumference of 31cm.

The current of the detector is proportional to the light falling on it.

$$i = \frac{\eta I_t}{h\upsilon}, \tag{17}$$

where η is the quantum efficiency of the photo detector, I_t is the detected optical power, υ is optical frequency of the light and h is plank constant.

Therefore

$$\frac{\Delta i}{i_o} = \frac{\Delta I}{I_o}, \tag{18}$$

where I_o is the incident optical power.

Therefore the detected power depends on the transmission characteristics of the fiber optic ring resonator.

Output optical intensity variation due to variation of ring length temperature is shown in Fig. 6. The variation is almost linear between temperature range of (0-90)° C.

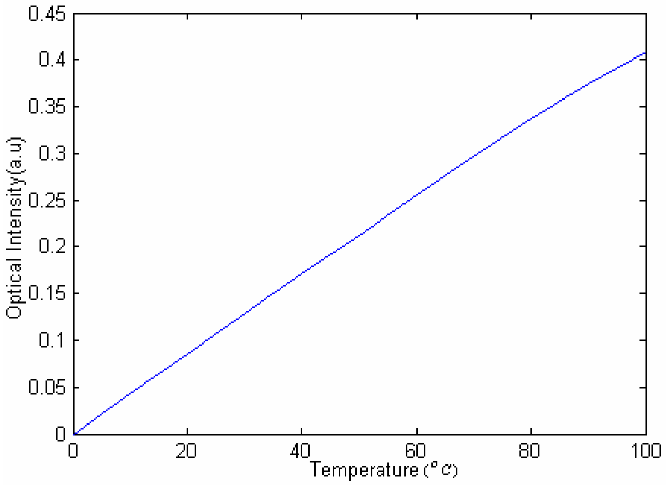


Fig. 6. Output optical intensity variation of the detector due to variation of temperature of the ring length in single ring resonator.

The sensitivity obtained in the single ring resonator can be improved greatly by introducing double ring resonator mainly due to improvement of finesse. The smaller ring length is considered as 31 cm and larger ring length of 62 cm. Coupling coefficients of the double ring resonator for unitary transmission can be estimated from equation (13). Condition of unitary transmission can be determined from equation (13) by imposing $T_{f2} = 1$. A choice of $\kappa_3 = \kappa_1$ is considered in the present study. The equation (13) can be expressed in frequency domain using relation $z = e^{j2\pi\nu T}$, where ν is the optical frequency. The equation (13) can be further simplified by approximating the exponential series up to 1st order and since the imaginary part will vanish in resonance condition the value of κ_2 for which $T_{f2} = 1$ is given by the condition

$$\kappa_2 = \frac{\kappa_1^2}{2 - \kappa_1^2} \tag{19}$$

in which κ_2 is the critical coupling coefficient which minimizes the resonant loss [16].

The transmission spectrum of double ring resonator with, smaller ring length 31cm, larger ring length 62cm, $\kappa_1 = \kappa_3$=0.37, κ_2=0.073, refractive index 1.46 and ring loss 0.01 dB/cm [16] and q=1 is presented in Fig. 7.

Output optical intensity variation due to variation of ring length temperature is shown in Fig. 8. Although the sensitivity is improved to a great extent the range of the sensor for a particular tuned resonant frequency is very small.

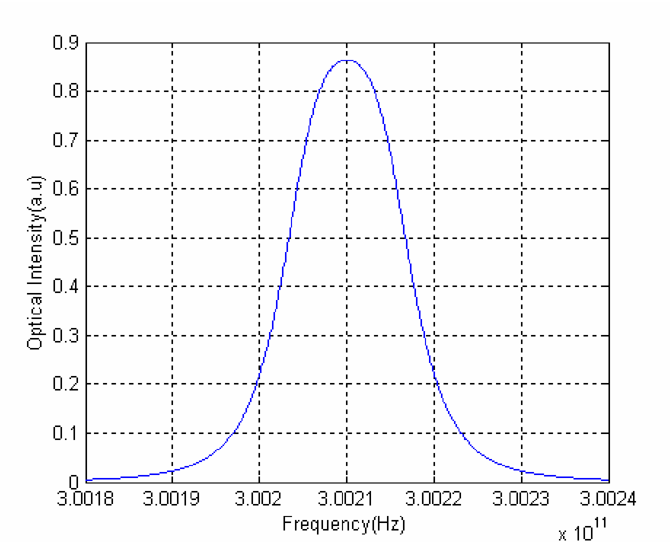


Fig. 7. Transmission spectrum of double ring resonator with ring circumference 31cm-62cm.

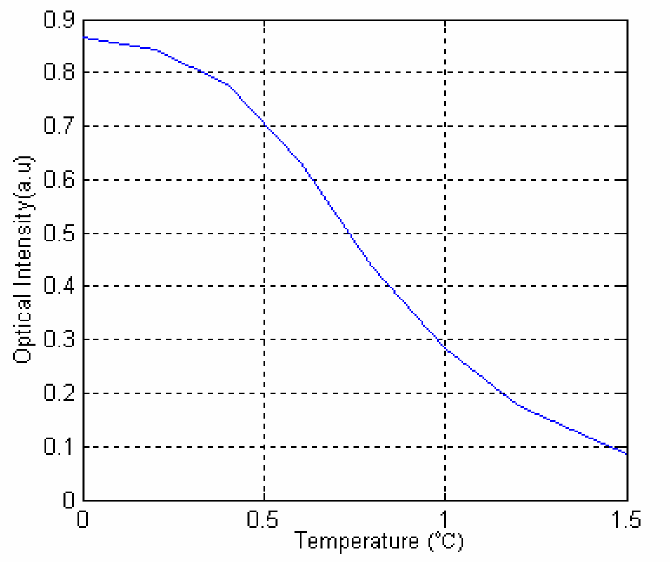


Fig. 8. Output optical intensity variation of the detector due to variation of temperature of the ring length in double ring resonator with ring circumference 31cm-62cm.

The range of the sensor can be increased by suitable design of the ring circumference. The finesse can be expressed by the relation [16, 17]

$$F = \frac{FSR}{\Delta f}, \tag{19}$$

$$FSR = \frac{c}{nL}, \tag{20}$$

where F is the finesse, FSR stands for free spectral range, c is velocity of light, n is refractive index, L is ring length, Δf is half maximum width of transmission spectrum at resonance. From equation (19) and (20) if appears that Δf is inversely proportional to the ring length since all other parameters are assumed to be constant. In order to increase the operating range of the proposed sensor by 5 times in comparison with the presented double ring resonator the ring length is required to be reduced by 5 times.

The transmission spectrum of double ring resonator with, smaller ring length 6cm, larger ring length 12 cm, keeping all other parameters same as before, is presented in Fig. 9. Output optical intensity variation due to variation of ring length temperature is shown in Fig. 10. From Fig. 10 it is evident that the sensor range has also increased approximately 5 times.

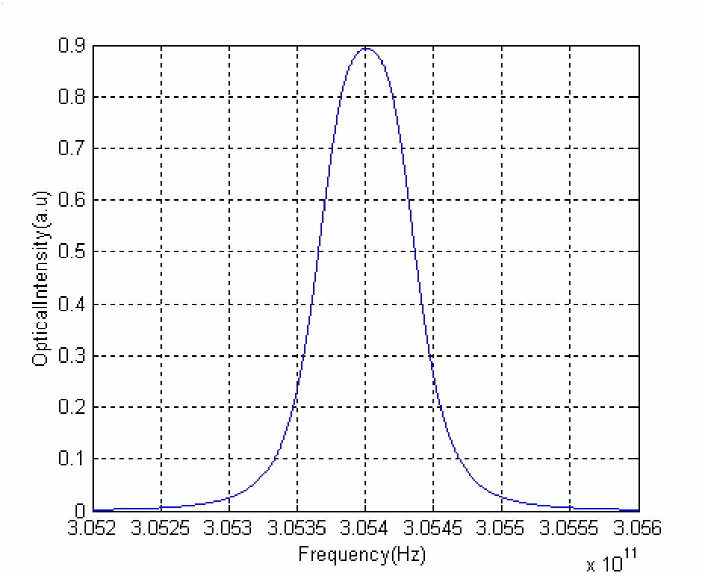


Fig. 9. Transmission characteristic of double ring resonator (ring circumference 6cm-12 cm).

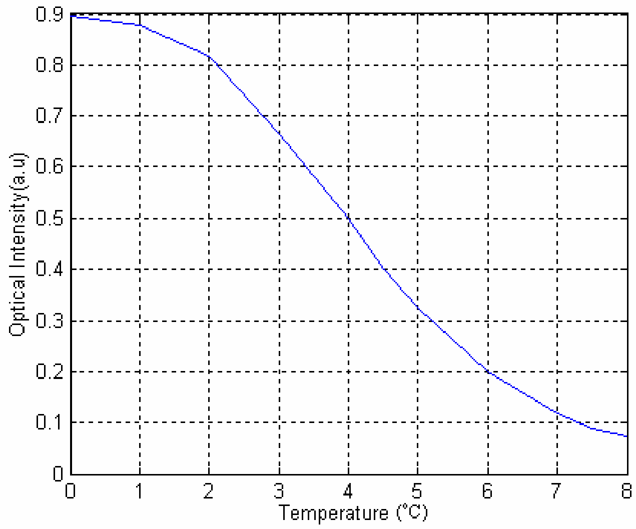


Fig. 10. Output optical intensity variation of the detector due to variation of temperature of the ring length in double ring resonator with ring circumference 6cm-12 cm.

The performance of the proposed sensor is limited by the noise of the system. The laser intensity variation can be one source of noise, which can be eliminated by introducing a reference photo detector and using differential amplification, and the output intensity can be normalized. In this process a tunable laser source is required to produce high intensity and wavelength stability [18].

Another two fundamental noises namely shot noise and thermal noise is generally exists in all optical detection process. In the optical power detection process photons fall randomly on the photo detector and the time average of the received power fluctuates due to this randomness.

The signal to noise ratio can be expressed by the well known equation

$$\text{SNR}=\sqrt{\frac{i}{2eB}}\,, \tag{21}$$

where e is the electron charge and B is the bandwidth. The SNR increases with the received power. A typical value of shot noise current is 6×10^{-10} A, for 100 μW optical power.

Another source of noise in detection electronics is thermal noise. Random thermal motion of the electrons produces a fluctuating current given by the well known relation

$$i_{th}=\sqrt{\frac{4kTB}{R}}\,, \tag{22}$$

where k is the Boltzmann constant, T is the temperature and R is the resistance. A typical value of thermal noise is 4×10^{-10} A.

The total noise is the sum of all individual noise. Out of the all noise the dominant is the shot noise. The SNR can be increased by increasing the optical power.

5. Conclusion

In the present article, a novel multiple fiber optic ring resonator based temperature sensor is proposed. The principle of operation of the sensor based on the elasto optic effect is discussed. The performance of the sensor was analyzed using unit delay formulation technique. The overall transmittance of the ring resonator was determined using Mason’s rule. The transmission spectrum is compared with the previously published results [1] and the results are in very close agreement. A novel design methodology is proposed to improve range and sensitivity of the sensor. The sensor will be useful for detection of small variation of temperature at elevated temperature.

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