Evanescent field Mach-Zehnder interferometer sensor for concentration measurement

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Abstract:

Optical fibers have been widely used in the field of sensing. In this paper, Mach-Zehnder interferometer is designed and constructed for detecting the concentration of solutions based on the excitation of the evanescent wave at the cladding/core interface. Laser diode (LD) with wavelength of 810 nm has been used. 3 cm of cladding has been removed in the middle of 1 m (SMF-28) for the two arms by using hydrofluoric acid (HF). One arm is isolated from the external perturbation, and the other arm is immersed in different concentrations of sucrose solutions range from 10% to 50% and sodium chloride (Nacl) solutions range from 5% to 25%. As the concentration of solution increases the output power decreases and the wavelength shifts toward the red region. The sensitivities of this sensor for different concentration of sucrose solutions and Nacl solutions are 0.017 nm/(% w/v) and 0.0474 nm/(% w/v) , respectively.

Key wards: Mach-Zehnder interferometer (MZI), evanescent field, concentration, wavelength shift, sensitivity.

متحسس المجال الزائل ماخ زندر لقياس التركيز

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قسم هندسه الليزر والالكترونيات البصريه / الجامعه التكنلوجيه [1,2] , كليه التقنيات الهندسيه الكهربائيه والالكترونيه / الجامعة التقنية الوسطى[3]

الخلاصه:

قد استخدمت الالياف الضوئية على نطاق واسع في مجال التحسس.في هذه الورقة تم تصميم وبناء "ماخ زندر التداخل" للكشف عن تركيز المحاليل على اساس تحفيز الموجه الزائله على السطح الفاصل للقلب/القشره.قد استخدم ليزر الصمام الثنائي(LD) مع طول موجي 810 نانومتر. تم ازالة 3 cm من القشره في منتصف 1 m (SMF-28) للذراعين باستخدام حامض الهيدروفلوريك (HF). يتم عزل ذراع واحد من الاضطراب الخارجي, وغمر الذراع الاخر في تراكيز مختلفة من محاليل السكروز تتراوح من 10% الى 50% وتتراوح محاليل كلوريد الصوديوم من 5% الى 25%. كما يزيد تركيز المحلول تقل الطاقة الخارجه ويتحرك الطول الموجي نحو المنطقه الحمراء. الحساسيه لهذا المتحسس لتراكيز مختلفه من محاليل السكروز ومحاليل كلوريد الصوديوم هي 0.017 nm/(% w/v) و 0.0474 nm/(% w/v) , على التوالي.

الكلمات المفتاحيه: ماخ زندر التداخل , المجال الزائل , التركيز ,تحرك الطول الموجي , الحساسيه.

Introduction:

Optical fiber sensors have been used in several applications such as chemical, biological, and environmental industries, for the measurements of temperature, liquid level, strain, and Refractive index [1].

Optical fiber sensor offers several advantages compared to electronic sensor due to their features like light weight, robust to environment, non-electrical devices, immune to electromagnetic interference (EMI) and radio frequency interference (RFI), high resolution, dynamic range, high sensitivity, allow remote sensing, allow to access into inaccessible areas, small size[2-4].

The refractive index (RI) is the very essential parameter in these applications particularly in bio-sensing for biochemical reactions or controlling molecular bindings and in food industries or chemical in order to control the quality [5].

In the past various refractive index sensors such as Abbe and Rayleigh refractometers were demonstrated to measure the RI but they have the disadvantages of weight and big size [6]. Nowadays fiber optic refractive index sensors are widely used for these applications [7] .

Recently, Fiber optic Mach–Zehnder interferometer (MZI) sensors are widely used in various chemical and physical sensing applications. In this paper, MZI is used because of several advantages such as simple structure, ease of fabrication, ability of responding to various measurands, and low cost [8].

Mach-Zehnder Interferometer Sensor:

Mach-Zehnder Interferometer sensor is one of the most sensitive configurations of fiber optic sensors [9], which can be used as an evanescent field sensor. The emitted light from the source is divided by the first 3dB coupler into two equal parts, transmitting in different paths, and then they are combined by the second 3 dB coupler. The reference arm isn't exposed to the measurand, and the sensing arm is exposed to the measurand which is introduced as cladding, this induces a phase difference between the signals resulted in an interference, the output signal shows a sinusoidal variation is directly proportional to the refractive index change of the measurand [10-12].The schematic diagram of Mach-Zehnder interferometer is shown in Figure (1) [13].

The advantages of MZI sensors are reduced noise due to intensity fluctuations, reduce undesired feedback effect, and any small change in the optical path length of the sensing arm will produce a large change in the output. The optical path length of the sensing arm is changed by changing the physical length of it (under the effect of temperature or pressure) or by changing the effective refractive index of it (by changing the refractive index of the cladding or the refractive index of the guiding layer) [11].

The input signal E_{in} splits into two identical parts, the signals in the two arms of the interferometer are described by [11]:

$$E_r = \frac{E_{in}}{\sqrt{2}} \quad (1)$$

$$E_s = \frac{E_{in}}{\sqrt{2}} \quad (2)$$

Where E_r and E_s are the signals in the reference and sensing arm respectively. The two signals transmit with different paths, until they reach the second coupler. $\Delta\phi$ is the additional optical phase, which is introduced in the sensing arm. Before the second coupler, the two signals are given by [11]:

$$E_r = \frac{E_{in}}{\sqrt{2}} e^{j\omega t} \quad (3)$$

$$\frac{E_{in}}{\sqrt{2}} e^{j(\omega t + \Delta\phi)} \quad (4)$$

Where ω is the angular frequency.
At output, the two signals are recombined, E_{out} is given by [11]:

$$E_{out} = E_r + E_s$$
$$= \frac{E_{in}}{\sqrt{2}} (e^{j\omega t} + e^{j(\omega t + \Delta\phi)})$$
(5)

The interference of two beams is given by [14]:

$$I = I_r + I_s + 2\sqrt{I_r I_s} \cos(\Delta\emptyset)$$
(6)

Where I_r and I_s are the intensities of reference and sensing arm.

Output power of Mach-Zehnder Interferometer is described by [15]:

$$p_{out} = p_{in} \cos^2(0.5\,\Delta\emptyset)$$
(7)

The phase difference between the sensing arm and reference arm is described by [16]:

$$\Delta\phi = \frac{2\pi}{\lambda} L\, \Delta n_{eff}$$
(8)

Where L is the interaction length (the sensing area length), λ is the wavelength in the vacuum, and Δn_{eff} is the change in the effective refractive index of the mode.
Each solution is referred to as the mode of structure. Each mode is described by its effective index, the effective index it's a parameter that governs the electromagnetic wave as it transmits along the fiber [11].

Experimental Method:

Sodium chloride (Nacl) and sucrose have been used as guiding liquids with various concentrations. The concentrations of Nacl solutions range from 5% to 25% and for sucrose solutions range from 10% to 50% .The refractive index for Nacl and Sucrose solutions at each concentration is measured by using Abbe refractometer.

For the sensing and reference arms, 3 cm of outer plastic jacket in the middle of 1 m of SMF-28 has been removed by immersing the fiber in acetone; the buffer is also removed by acetone. The cladding is partially etched by using hydrofluoric acid (HF) with 40% concentration for 35 minutes to obtain high sensitive region to the surrounding concentrations. The schematic diagram of a Mach-Zehnder interferometer concentration sensor is shown in Figure (2).

The system consists of laser diode (LD) with wavelength of 810 nm, the first (3dB) optical coupler (splitting ratio 50:50) is used to split the light into two identical beams, the coupler is connected with two identical SMF-28 (equal etching length) using (FC to ST) adapter, to combine the light beams the two ends of the fibers are connected to the second (3dB) coupler also with (splitting ratio 50:50) using (FC to ST) adapter .The output of the coupler is connected to a power meter (Fiber Optic Communications Training System EF-970/R promax) and/or Optical Spectrum Analyzer model (HR 2000). The experimental setup of the (MZI) concentration sensor is shown in Figure (3).

When the emitted light entered the first optical coupler, the light beam is divided into two equal beams, the first beam entered in the reference arm, which is isolated from perturbation and the second beam entered on the sensing arm which is immersed in distilled water and different concentrations of Sucrose and Nacl solutions. The beam, then suffer a phase shift due to the external concentrations where the output interference pattern between the two beams is taken by an Optical Spectrum Analyzer, and the output power is taken by the power meter. All measurements are carried out at room temperature.

Results and Discussion:

Figures (4) and (5) show the relationship between refractive index and concentration of Nacl and Sucrose solutions, respectively.

From the Figures the refractive index is directly proportional to the concentration, as concentration of guiding liquid increases refractive index increases.

The reference arm is isolated from any external perturbation, the variation which is induced in the sensing arm is due to the change in the concentration of Nacl solutions range from 5% to 25%, and Sucrose solutions range from 10% to 50%. Figures (6) and (7) show the interference pattern for different concentration of Sucrose and Nacl solutions, respectively.

According to Equation (8) as the concentration of solution increases (the refractive index of the guiding layer increases) the effective refractive index of propagation mode in the sensing arm increases, this will lead to increase the shift towards long wavelength (red region), also the curves show that as the concentration of Nacl and Sucrose solutions increase the intensity decreases. The sensitivity of this sensor (s= $\frac{\Delta\lambda}{\Delta C}$) for sucrose and Nacl solutions is 0.017 nm/ (% w/v) and 0.0474 nm/ (% w/v), respectively, as shown in Figures (8) and (9).

According to Equation (7) as the concentration of solution increases (the refractive index of the guiding layer increases), the phase shift increases this lead to decrease in the output power. The relationship between concentration of Sucrose and Nacl solutions and output power are shown in Figures (10) and (11), respectively.

Conclusion:

A Mach-Zehnder Interferometer sensor based on the excitation of evanescent field has been demonstrated where the variation of the surrounding concentration is detected by measuring a shift in the wavelength. A red shift in the output spectrum is observed with increasing of concentration. The sensitivity of this sensor for sucrose solutions in the range of 10% to 50% is 0.017 nm/(% w/v) and for Nacl solutions in the range of 5% to 25% is 0.0474 nm/(% w/v). This sensor can be used for measuring concentration in various applications such as medical, food industry, pharmaceutical, environmental controlling systems, and monitoring the quality of drinking water.

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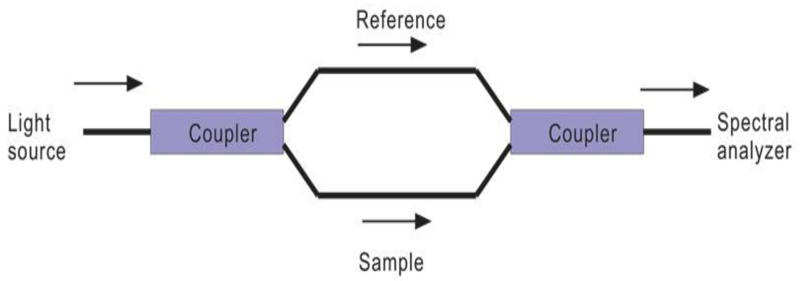

Figure (1): The schematic diagram of Mach-Zehnder Interferometer [13].

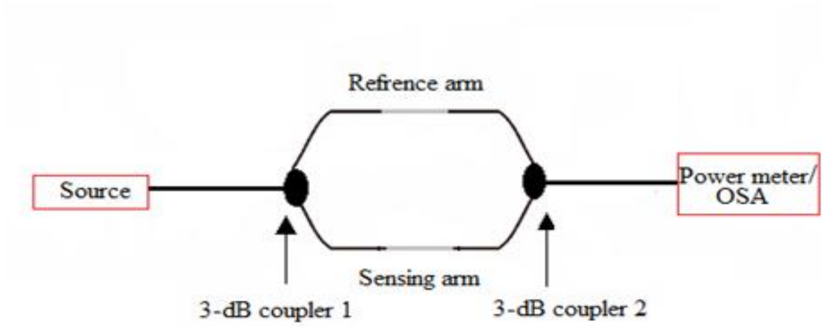

Figure (2): The schematic diagram of a MZI concentration sensor.

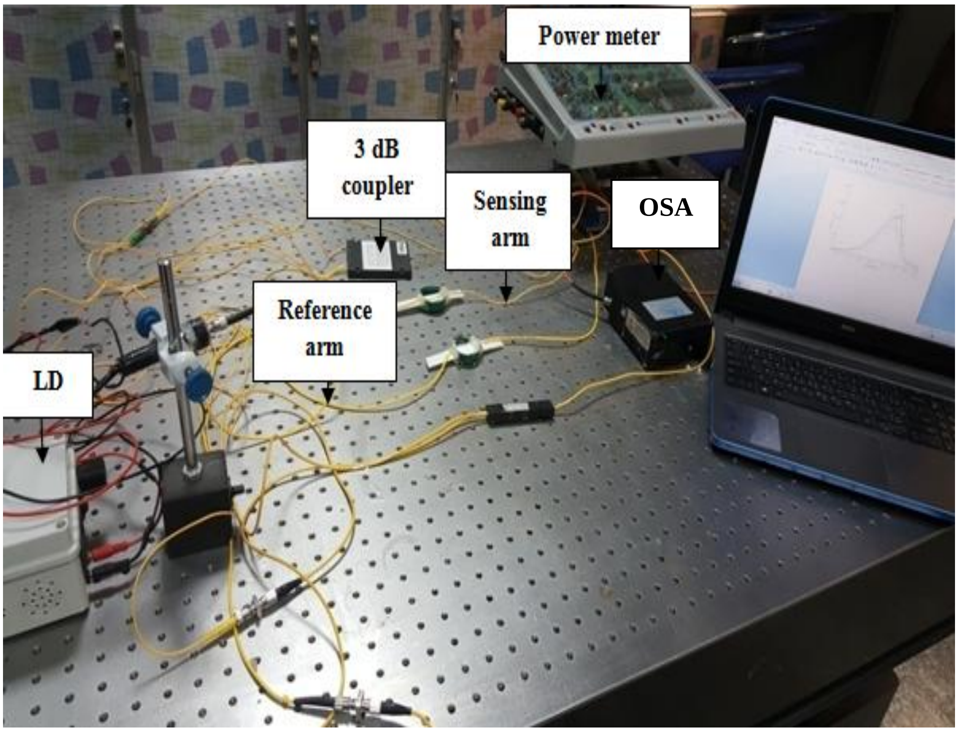

Figure (3): The experimental setup of the MZI concentration sensor.

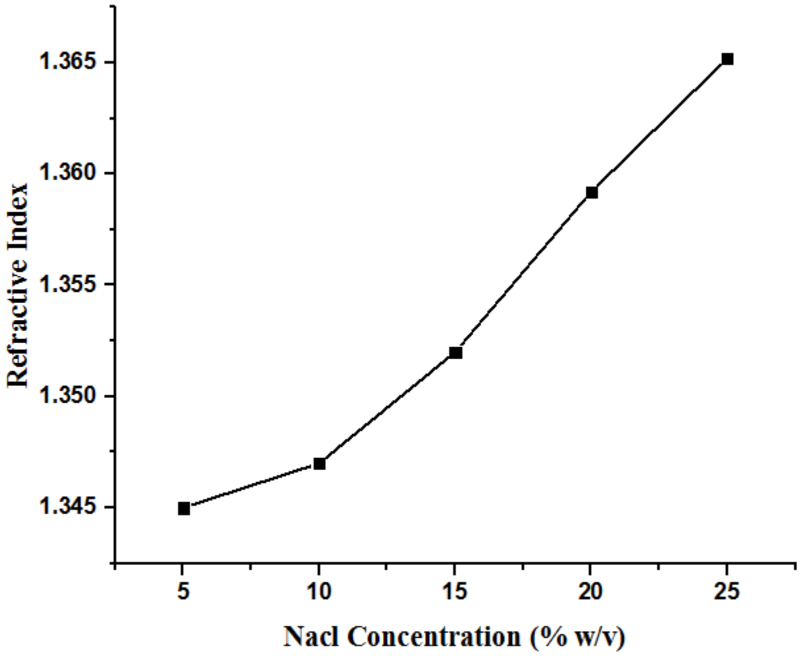

Figure (4): The relationship between concentration and refractive index of Nacl solutions.

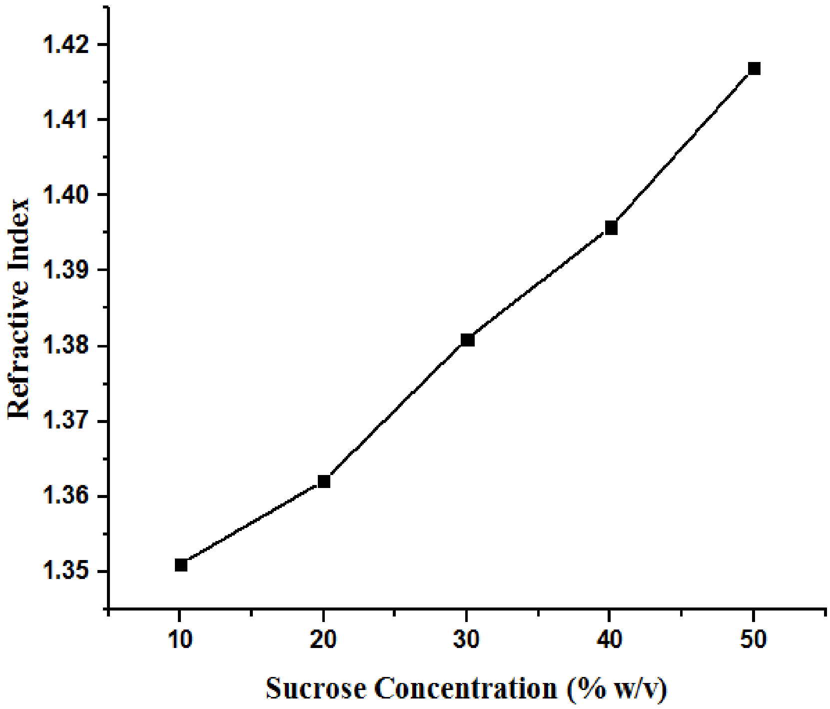

Figure (5): The relationship between concentration and refractive index of sucrose solutions.

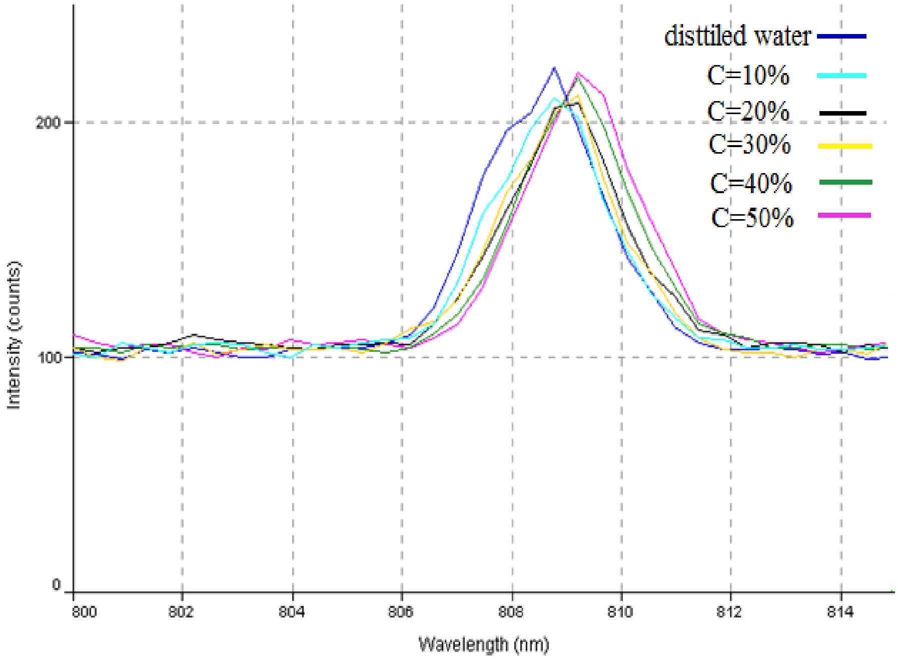

Figure (6): Interference spectra of MZI sensor for different concentrations of Sucrose solutions.

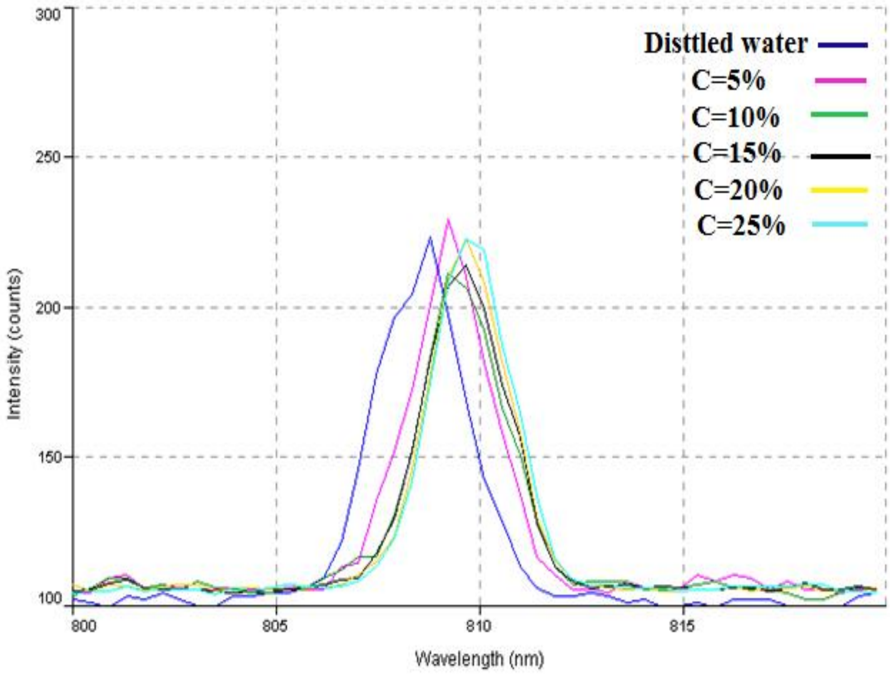

Figure (7): Interference spectra of MZI sensor for different concentrations of Nacl solutions.

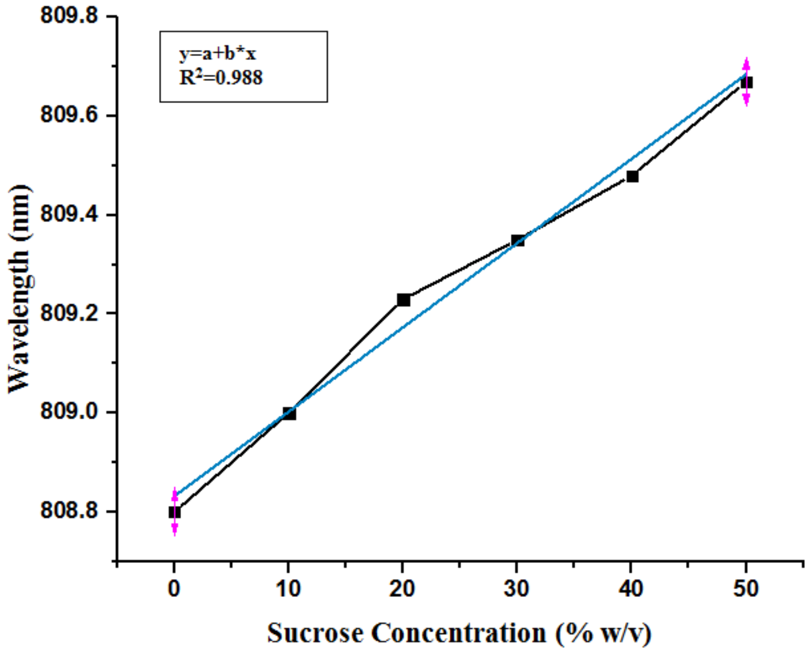

Figure (8): The relationship between wavelength and different concentrations of Sucrose solutions.

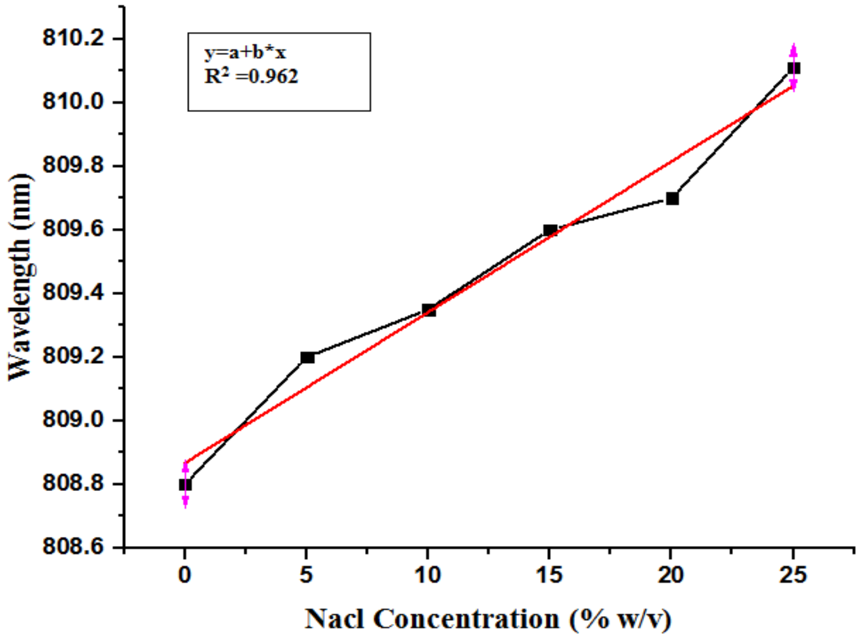

Figure (9): The relationship between wavelength and different concentrations of Nacl solutions.

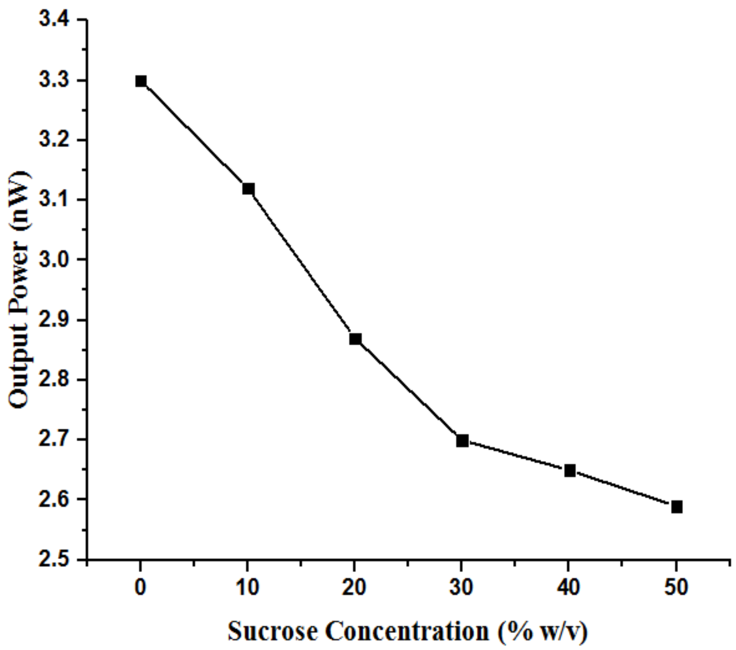

Figure (10): The relationship between output power and different concentrations of sucrose solutions.

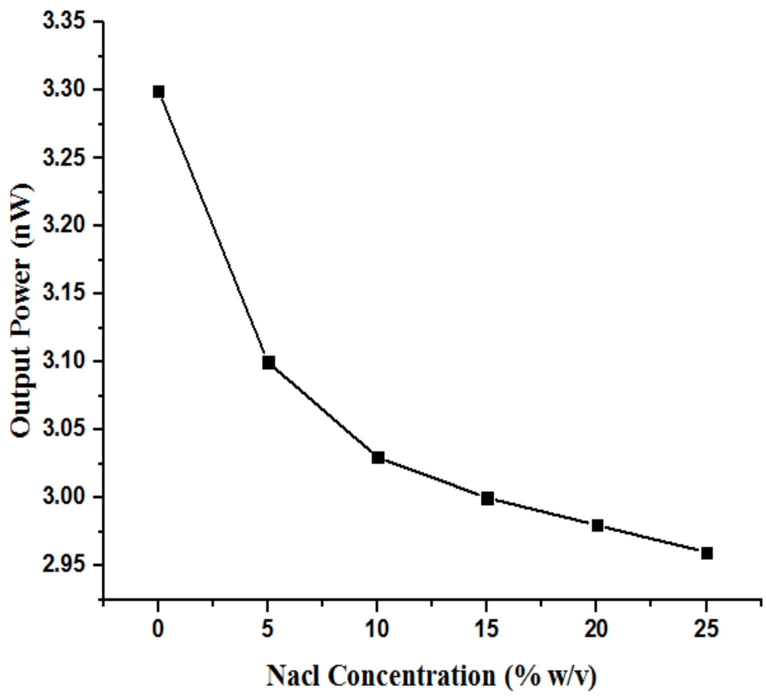

Figure (11): The relationship between output power and different concentrations of Nacl solutions.