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Investigation of Performance for a Two Regions Superstructure Fiber Bragg Grating

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ABSTRACT

A Superstructure Fiber Bragg Grating (SFBG) with a two grating regions has been studied experimentally and analytically. Both transmitted and reflected spectra for SFBG were investigated in a constant temperature (room temperature). Data that archived by Spectrometer & Detector was analyzed. In the same circumstances, a set of equations considered to simulate the experimental configuration. The SFBG spectrum characterized by important parameters: Bragg wavelength, bandwidth and efficiency. Bragg wavelength is very popular and has been used by the researchers to determine the physical quantities, it represent the reflected wavelength which satisfy Bragg condition. The behavior of these spectral parameters are presented and studied in this paper. The effect of grating region on the bandwidth and efficiency of SFBG was also studied. The SFBG has been found worked as a filter for the laser source wavelengths, which is used. Furthermore, this special FBG can be developed to optimize a sensor for temperature and pressure.

Keywords**:** Fiber Bragg Grating, Superstructure, Mode Coupling Theory, Bragg wavelength, Sensor

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1. INTRODUCTION

Over 40 years ago generally, Fiber Bragg Grating (FBG) technology has been continuously developed and has used in standard optical components such as; wavelength filters, sensors, fiber lasers, in communications, as reflectors, mode converters, chromatic dispersion compensators [1], and the recent applications of the FBG is the Optical amplifier, such as erbium-doped fiber amplifier, Wavelength Division Multiplexing (WDM), pump laser stabilizer and flattening filter [2].

The grating inside FBG can be described as an intrinsic sensor which due to variation the spectrum of an incident wave by coupling energy between optical fiber modes. In the simplest state, the incident signal is coupled to a counter propagating like mode and therefore reflected. Characteristics of the grating filter can be understood and modeled by several methods. Mode Coupling Theory (MCT) is the basis for many of these calculations [3]. In this paper we will deals with the concept of solution of MCT for the transmitted and back reflected modes inside the optical fiber also study reflectivity of FBG sensor and bandwidth of it.

In compare FBG sensor with other kinds of sensors, FBG sensor is compact, small in size and relatively cheap, self-referencing with a linear response also insensitive to electrical power fluctuations and EM radiation. In this paper explained who FBG based sensor and study the photosensitivity of it. Also explain what the light exposed through propagation inside FBG are presented in this paper.

1. 1. Solution of Mode Coupling Theory (MCT)

The expression grating is used almost to describe any device whose operation encompasses interference among multiple optical signals creating from the same source but with different relative phase shifts. Any periodic perturbation in the propagating medium works as a Bragg grating. This perturbation is commonly a periodic variant of the medium refractive index. Wave propagation in an optical waveguide can be analyzed by the Maxwell's equations solution forced to suitable boundary conditions. Can be simplified to found solutions for the wave-propagation equations resulting, that assumed weak "guidance", which allows the decay of the modes into an "orthogonal set of transversely polarized modes". This solution affords the basic distribution fields of the radiation and bound modes of the waveguide. But if it not found any perturbation the modes propagated without coupling [4].

The coupling in propagating modes take place if the waveguide has an amplitude (or / and) phase perturbation that is periodical with a perturbation amplitude / phase, it is constant near to the difference or sum between the modes propagation constants. Solution of (MCT) is usually applied for solving this type of practical problems. This solution assumed that the unperturbed fields of mode of the waveguide stay without changed, that in state of weak perturbation. This method offers a set of "first-order differential equations" to the amplitude change of the field through the optical fiber, which has analytical solutions for sinusoidal periodical uniform of perturbations [4].

Solution of MCT is great mathematical tool in studying and analyzing the wave propagation even when interactions with material in optical waveguide. Since FBG is one of the weakly guiding structures, solution of MCT can be used to analyze its optical behavior [4]. In this case solution of MCT considers the grating structure as the perturbation into an optical waveguide due to occurs coupling of guided modes.

The advantages of this theory are straightforward, accurate and intuitive for most practical fiber gratings. Also it is used to describe the relation between spectral response of the FBG and its structural parameters.

1. 2. The Bragg Condition

It is basically and simply requirement to satisfies both momentum and energy conservation. Energy conservation demands that the incident radiation frequency equal to the reflected radiation frequency ($\hbar\omega_f = \hbar\omega_f$). Momentum conservation demands that the grating wave vector (K), plus the incident wave vector (k_i), equal the scattered wave vector (k_f) as fallowing [5]:

$$K + k_i = k_f \qquad (1)$$

The wave vector of grating (K) has a normal direction to the grating levels with a magnitude ($2\pi/\Lambda$). The wave vector diffracted radiation has same value but in opposite direction with respect to the vector of wave of incident radiation and the momentum conservation condition can be written as [5]:

$$2\left(\frac{2\pi}{\lambda_B}\right) n_{eff} = \frac{2\pi}{\Lambda} \qquad (2)$$

For the first order Bragg condition:

$$\lambda_B = 2n_{eff}\,\Lambda \qquad (3)$$

where: λ_B the Bragg grating wavelength.

The wavelength which is reflected and has maximum efficiency is called the Bragg wavelength [5]. In other words, the Bragg grating wavelength can be defined as the free space center wavelength of the input signal which back reflected from the FBG [5, 6].

n_{eff} is the index of effective refractive of the fiber core at the free space center wavelength, which normally ($n_{\text{cladding}} < n_{eff} < n_{core}$) [7]

Now, for N ≥ 1 can be described number of grating period and its integer number, equation (3) called Bragg condition or the phase matching condition again can be written as [8]:

$$N\lambda_B = 2n_{eff}\,\Lambda \qquad (4)$$

Therefore, any change in the index of effective refractive (n_{eff}) or the period of grating (Λ) can be lead to a shift in the reflected Bragg wavelength (λ_B). While other wavelengths will try out weak reflection at each of the levels of grating as of the phase mismatch over the grating length [5]. That mean the Bragg condition is not satisfied, the reflected light from each of the following levels be gradually out of phase and will finally cancel out [6]. Can be change the grating spacing through manufacturing, to get on Bragg gratings with different center wavelengths [5].

1. 3. Bragg Grating Reflectivity

An FBG contains of a periodic modulation of the refractive index in the single mode core optical fiber. Figure (1) explain basic FBG in structure with highly wavelength-selective reflection filter with the peak reflectivity of wavelength. When laser source which is incident from one side of the FBG, only reflected a specific wavelength which fulfils Bragg condition whilst the remaining wavelengths is transmitted through grating regions without any loss [5].

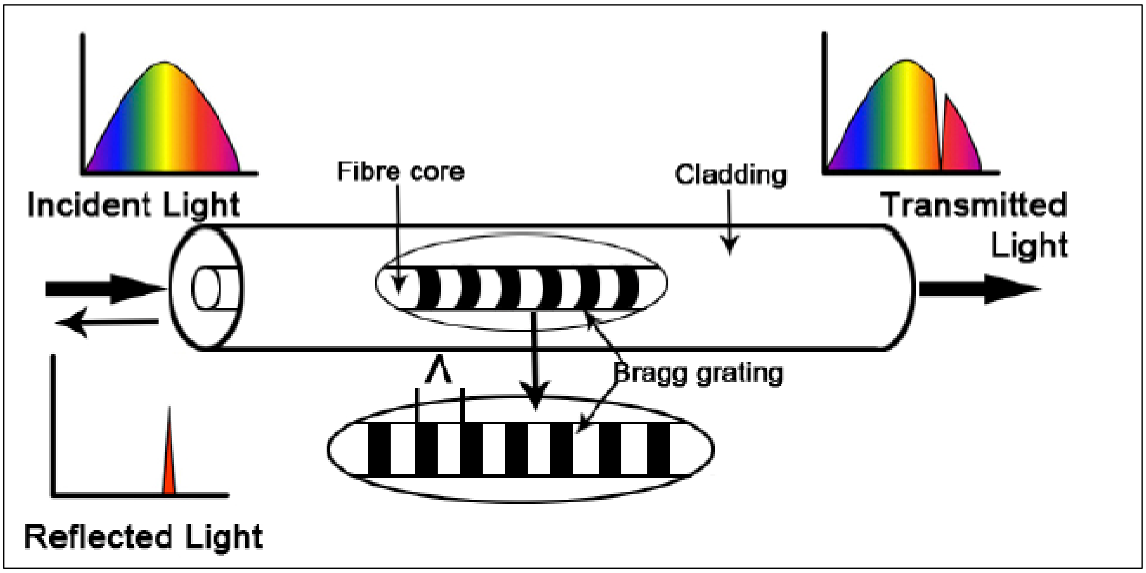

Fig. 1. Schematic presentation of a FBG inside the optical fiber core [5].

The power reflection coefficient (reflectivity) can be expressed as [9]:

$$r = |\rho^2| \quad (5)$$

The solution of the mode coupling equations for uniform FBG will lead to the calculation of the amplitude and power reflection coefficients given as: [5, 9]:

$$\rho = \frac{-k \sinh(\sqrt{k^2-\hat{\sigma}^2}L)}{\hat{\sigma} \sinh(\sqrt{k^2-\hat{\sigma}^2}L)+i\sqrt{k^2-\hat{\sigma}^2}\, cosh(\sqrt{k^2-\hat{\sigma}^2}L)} \quad (6)$$

After using equation (5) can be obtain:

$$r = \frac{\sinh^2(\sqrt{k^2-\hat{\sigma}^2}L)}{cosh^2(\sqrt{k^2-\hat{\sigma}^2}L)-\frac{\hat{\sigma}^2}{k^2}} \quad (7)$$

At resonance there is no detuning i.e. $\delta = 0$, therefore reflectivity is maximum. According this conditions, the reflectivity given as [4, 6]:

$$r_{max} = tanh^2(kL) \quad (8)$$

The reflective ratio increases when the induced refracted index change and the grating length increasing. A calculated reflected spectrum as a function of uniform FBG wavelength is displayed in Figure (2). The side parts of the resonance are due to multiple reflections to and from opposite grating area ends. Mathematically, the sine spectrum rises during a harmonic signal for transform of Fourier; if an infinitely long grating would convert to an ideal delta function response in the wavelength field [6].

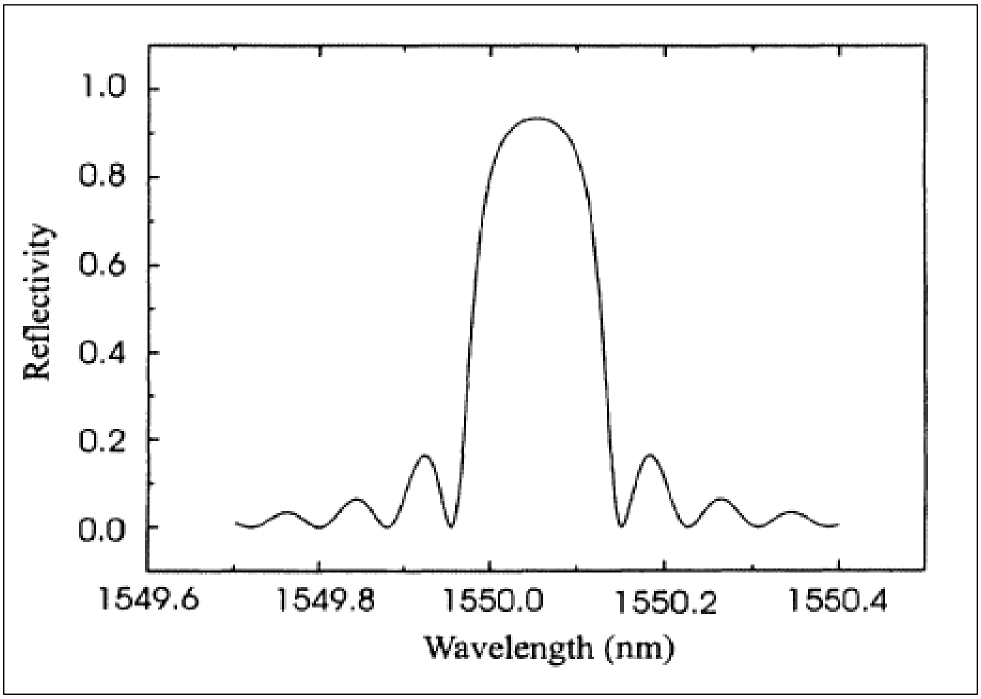

Fig. 2. An ideal reflected spectrum of a FBG centered at 1550 nm as a function of wavelength [6].

1. 4. The FBG Bandwidth

The "Full Width at Half Maximum (FWHM)" of grating or grating bandwidth can be defined as the difference between two wavelengths on either side of "Bragg wavelength" where drops of reflectivity to half of its maximum. An increased in the grating length leads to reduced FWHM [5].

The FWHM of a grating can be expression by [9, 10]:

$$\Delta\boldsymbol{\lambda} = \lambda_B s\sqrt{\left(\frac{\Delta n}{2n_\circ}\right)^2 + \left(\frac{1}{L}\right)^2} \quad (9)$$

where;

L - is the number of the grating levels.

s - is known a grating parameter approximately equal to 1 (high reflectivity for grating) (i.e. near 100% reflection) and 0.5 (weak reflectivity for gratings) [9].

1. 5. FBG Simulation by MATLAB Program

A computer simulation by Matlab program is a very important instrument in the fiber optical research field. Matlab program is a mathematically interpreter language can use to simulation and study optical fiber problems. The theoretical results can be obtained by Matlab program. Also can be studying the differences between the theoretical results and the experimental values. The Matlab program can be used to analyze the spectral characteristics of SFBG have been simulated by this program. The reflection spectra, FWHM can be obtained. Grating's variables as (length of grating, the period of the grating and effective refractive index) explained in Table (1), and the output spectrum values as (coupling coefficient, the power reflectivity, FWHM and center wavelength) can be calculated by this program using instantaneous changes in the number of regions of grating.

Table 1. Simulation parameters.

Effective refractive index (n_{eff})	1.444
Bragg wavelength (λ_B)	SFBG (2 grating regions): 1530.466, 1536.247
Index difference between core and cladding (Δn)	0.0036
Radius of core (a)	4.1 μm
number of grating regions in FBG (N)	1 ,2,3,4
Grating length (L)	10 mm

The simulations by this program of the SFBG was based on the solution of (MCT). The grating equation (Bragg condition equation) for perturbation to (n_{eff}) of the guided mode is given in equation (4). The Matlab simulated SFBG reflection spectrum based on the above MCT equation. The Matlab code of FWHM was adopted from reference [11].

2. EXPERIMENTAL / RESULT

2. 1. Efficiency setup

To study the effect the efficiency of SFBG sensor with two grating regions. It was fabricated on Acrylate- single mode (SMF-28e). It is worth mentioning that the specifications of the SFBG sensor were sent to the manufacturer according to the specifications that satisfy the desire to apply this study in practice. Table (2) explained all details of FBG sensor which used.

Table 2. Details of used FBG sensor.

Reflectivity (%)	Bandwidth (nm)	Wavelength (nm)	Two regions of grating of fiber
98.88	0.238	1530.466	Frist region
99.64	0.311	1536.247	Second region

The conditions which the experiment was run were to constant temperature at room temperature (25 ºC). Design more than one setup to suit the requirements of the research and achieve its purpose. So that to response of the efficiency of FBG sensors with different regions of grating used different experimental setups shown in next sections:

2. 2. Transmitted spectrum setup

The efficiency of SFBG sensors can be calculated by two methods: by measure input and output power of laser source with output power (-6.2dBm) by power meter by this relation [12]:

$$\eta(\%) = \frac{p_{out}}{p_{in}} \times 100 \qquad (10)$$

where

η = efficiency (Greek letter "eta")
p_{out}= output power. Unites are (Watt)
p_{in} =input power. Unites are (Watt)

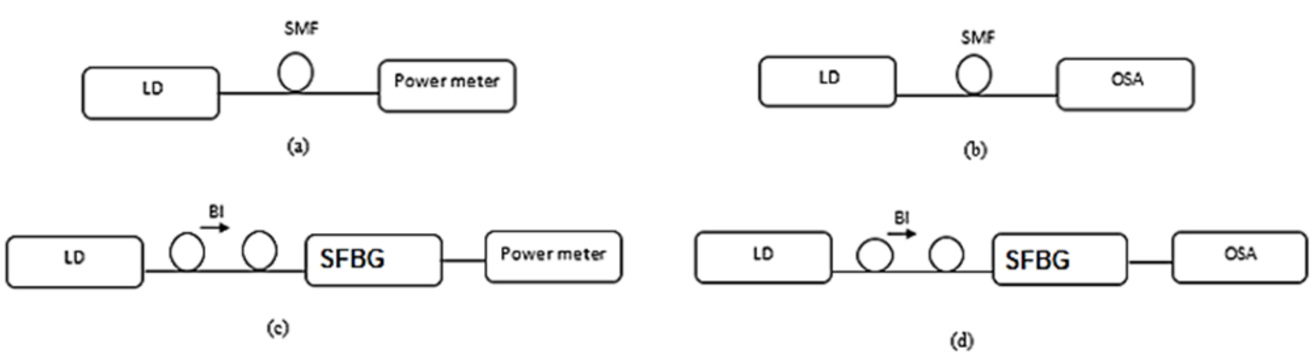

Fig. 3. Setup of transmitted spectra and efficiency of SFBG to measure: (a) Input power by unites (-dBm or mWatt), (b) Input spectra by OSA, (c) Transmitted spectra (output power), (d) transmitted spectra (output power).

where:

LD: Laser Source, SMF: Single Mode Fiber, BI: Beam Isolator, OSA: Optical Spectrometer Analysis.

Figure (3a, 4c) shows the setup for efficiency measurements using the optical power meter. The measured power converted the power from dBm to Watt by using the following relation [13]:

$$mW = 10^{\left(\frac{dBm}{10}\right)} \quad (11)$$

Another power measurement can be satisfied by scope (counts) from AvaSpec spectrometer software version 8, (XP/Vista/Windows7 x64 (64-bit O/S)) as shown in Figure (3b) and Figure (3d).

2. 3. Reflected spectrum setup

The reflectance spectra of the FBG sensors determined by experimental setup which shown in Figure (4). Used beam optical isolator connected with optical broadband source to protect from the reflected spectrum return from SFBG sensor which due to occurs interference and confusion in laser spectra, has been compered used without used beam optical isolator and is found little deference about (0.54± 0.2-dBM) in output spectrum.

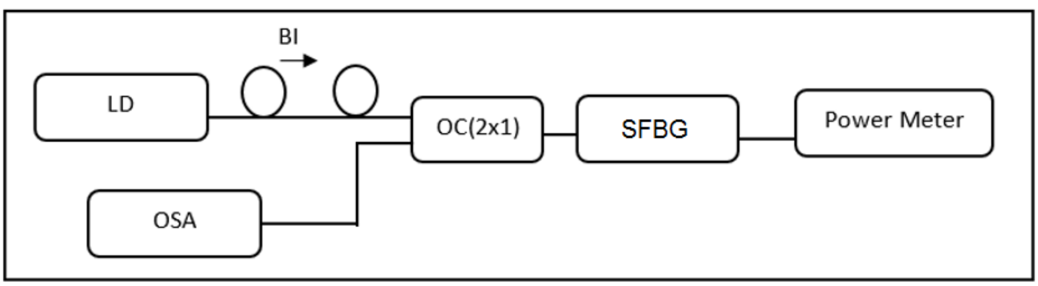

Fig. 4. Setup to measure reflection spectrum of FBG, OC (2 × 1) is SMF optical coupler (50:50).

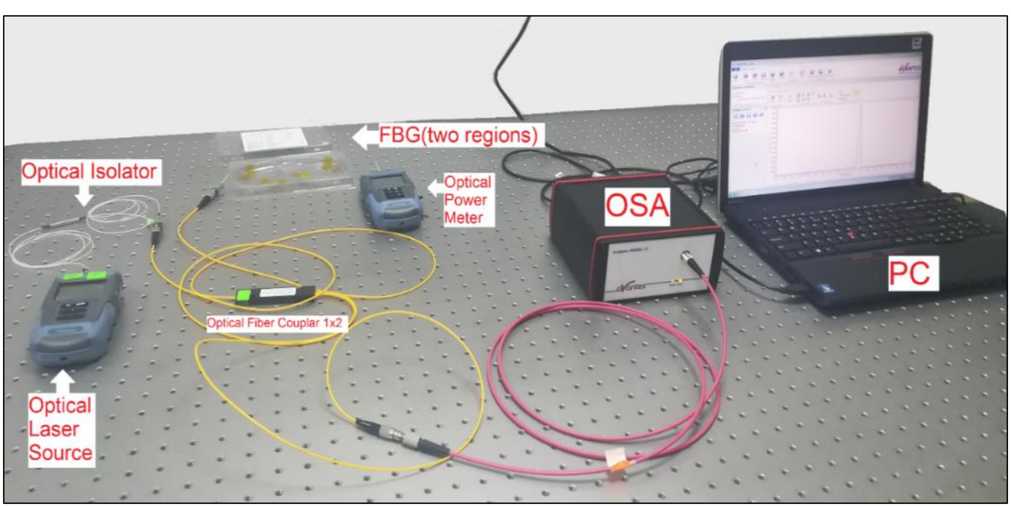

Fig. 5. Setup to measure reflected spectrum of SFBG sensor with two grating regions.

The optical laser spectrum routed to the SFBG sensor through a SMF (2×1) optical coupler (50:50) so that a portion of the light reflected by the SFBG sensor can be routed to the input of the OSA. Used power meter to measure output power to determine the efficiency of power for this setup. This setup is agreement with the setup in this work for Jianfeng Zhao to measure reflected spectrum of SFBG in Figure (5) shown setup to measure reflected spectrum of SFBG sensor.

The SMF(2 × 1)1 optical coupler (50:50) has been verified to work correctly by connection the tip to the laser source and the other two tips sides to power meter as shown in Figure (6). It found two sides have convergent power.

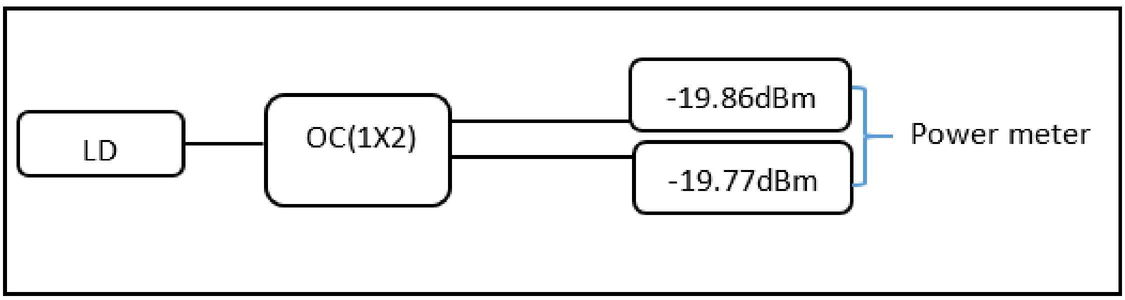

Fig. 6. Setup to check SMF coupler (50:50).

2. 4. Transmitted and reflected spectrum setup

In another experimental setup for response of the SFBG sensor is presented in Figure (7). It consists of a broadband light source guided into the core of a SM F (2 × 1) optical coupler (50:50), a portion of which is reflected back after its encounter with the SFBG sensor, and is routed to the OSA through the optical coupler (OC (2 × 1)). The transmitted light signal was also sent to the OSA via the same optical coupler. The presence of an optical coupler (OC 2 × 1) collecting reflected spectra from SFBG and portion of transmitted spectra which arrived to OSA. Subsequently, optical signal recorded by the OSA.

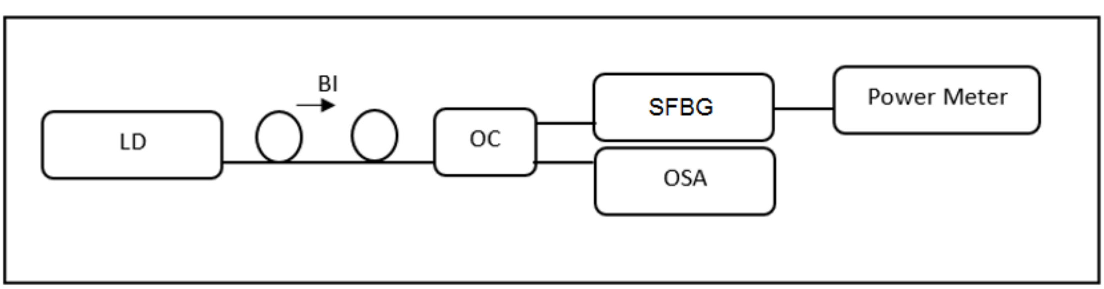

Fig. 7. Setup of collecting reflected spectra from FBG and portion of transmitted spectra that arrived to OSA.

The aim of this setup shown in Figure (7) is to verify the presence reflected spectrum so make sure of work FBG sensor and compare the results between the transmitted spectrum and the reflected spectrum. Where it was detected spectrum and measured FWHM and compare with transmitted spectrum and the reflected spectrum for SFBG. The spectrum data get from spectrometer software as Excel format, then it analysis and graphed by Origin computer program software (2018) also used to curve fitting.

2. 5. Filter setup

To Filtered the light sources within specific wavelengths, needs to many techniques based on active filtering depend on the ability of finely tuning a filter. Whereas the SFBG sensor is basically a filter that proved in many papers [9]. In several configurations of setups which depended to get transmitted and reflected spectrum of FBG sensor checked it work as filter.

2. 6. Analysis of FBG simulation

MATLAB program was developed to get two important FBG sensor parameters are the central Bragg wavelength and bandwidth of the measured reflection spectrum. SFBG for two grating regions can be simulated by Matlab program developed in this work .Has been enter the wavelength SFBG for two regions of grating depending on the wavelength of the factory which made it, addition to the grating's variables: length of grating, the grating period and (n_{eff}) explained in table (1), and the output spectrum values: coupling coefficient, the power reflectivity, FWHM calculated by this program using changes in the number of regions of grating. Reflected spectrum analysis for SFBG as displayed in Figure (8). The Matlab code to simulations bandwidth of reflected spectrum in appendix A. the wavelengths which used to simulation reflection spectrum are: SFBG sensor two grating regions (λ_{B1} =1530.466 nm and λ_{B2} =1536.247 nm) as shown in Figure (8).

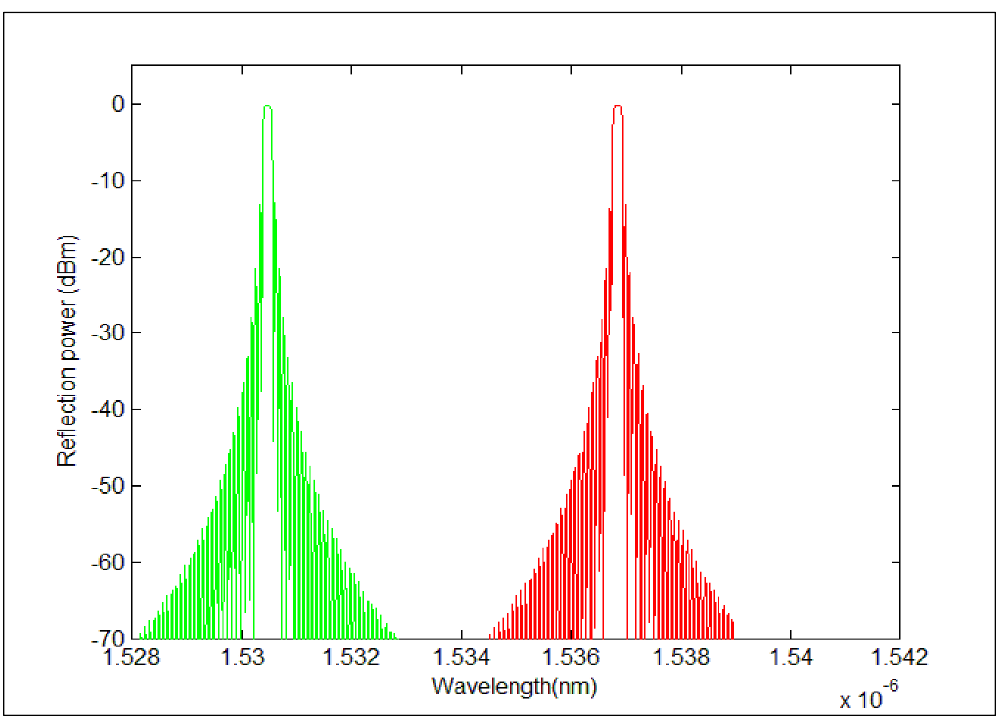

Fig. 8. Simulation Reflection spectrum of SFBG sensor two grating regions.

The reflectivity is plotted with respect to the wavelength for different values of grating regions for assuming n_{eff} = 1.444 and L = 1 cm. Appear at Bragg wavelength, sharp beaks from grating regions. These beaks satisfy Bragg condition equation (4). We investigated the influence of the bandwidth of reflectance spectral for two grating regions number of SFBG sensor.

Table 3. FWHM simulation of two grating regions number of FBGs.

Number of regions of FBGs	Bragg wavelength	FWHM
SFBG	1530.466	0.211
Two regions	1536.247	0.288

Convergences of result of the reflected spectrum bandwidth with FBG sensor factory results, can be compared it with table (2).

2. 7. The efficiency of SFBG spectrum

A SFBG sensor is made by an eternal periodical modulation of the index of refractive along its core. When illumination fiber by a laser source, a thin "narrow" wavelength be reflected back [14]. Different experimental setups are designed to calculate many of FBG sensor variables as transmitted and reflected spectral, also calculate center wavelength (Bragg wavelength), FWHM and efficiency for these spectrum.

The power efficiency of the spectrum of transmitted of SFBG sensor with two grating regions number calculated by used eq. (10). Experimentally, measured Laser transmitted and reflected spectrum parameters relative to SFBG two grating regions number are included in this Table (4). The recorded data of peak wavelength, output power, intensity, efficiency of power and the bandwidth of the FBG sensor (Full-width at half-maximum (FWHM)) of transmitted and reflected spectrum achieved used experimental setups as shown in Figure (4). In another work was mixed reflected and portion of transmitted spectrum using optical coupler (OC 2X1) using experimental setup (7). We obtain the reflected part from fiber Bragg as well as a portion of transmitted spectrum where appear in the spectrometer spectrum. The advantage of this work is to check whether there are wavelengths reflected or not and compered with reflected spectrum of FBG sensors, details this work also putted in Table (4).

The behavior of the intensity and bandwidth for transmitted spectrum of SFBG sensors has high values compared with theoretical results as shown in Figure (9) which plotted by (AvaSpec spectrometer software (version 8)) and by (Origin program (2dimensions and 3dimensions)). In this experimental work used Single Mode Fiber (SMF) for input spectrum to compare changes in spectrum when used SFBG. Note that the spectrum become slimmer with used SFBG with two grating regions. A light reflected from the grating regions according to the Bragg condition, while transmitted the anther wavelengths that did not achieved it, so when there is more than one grating region has different from the effective refractive index n_{eff} will be reflected more than the wavelengths. Therefore, shows the spectral analysis more than a peak depended that on grating regions number.

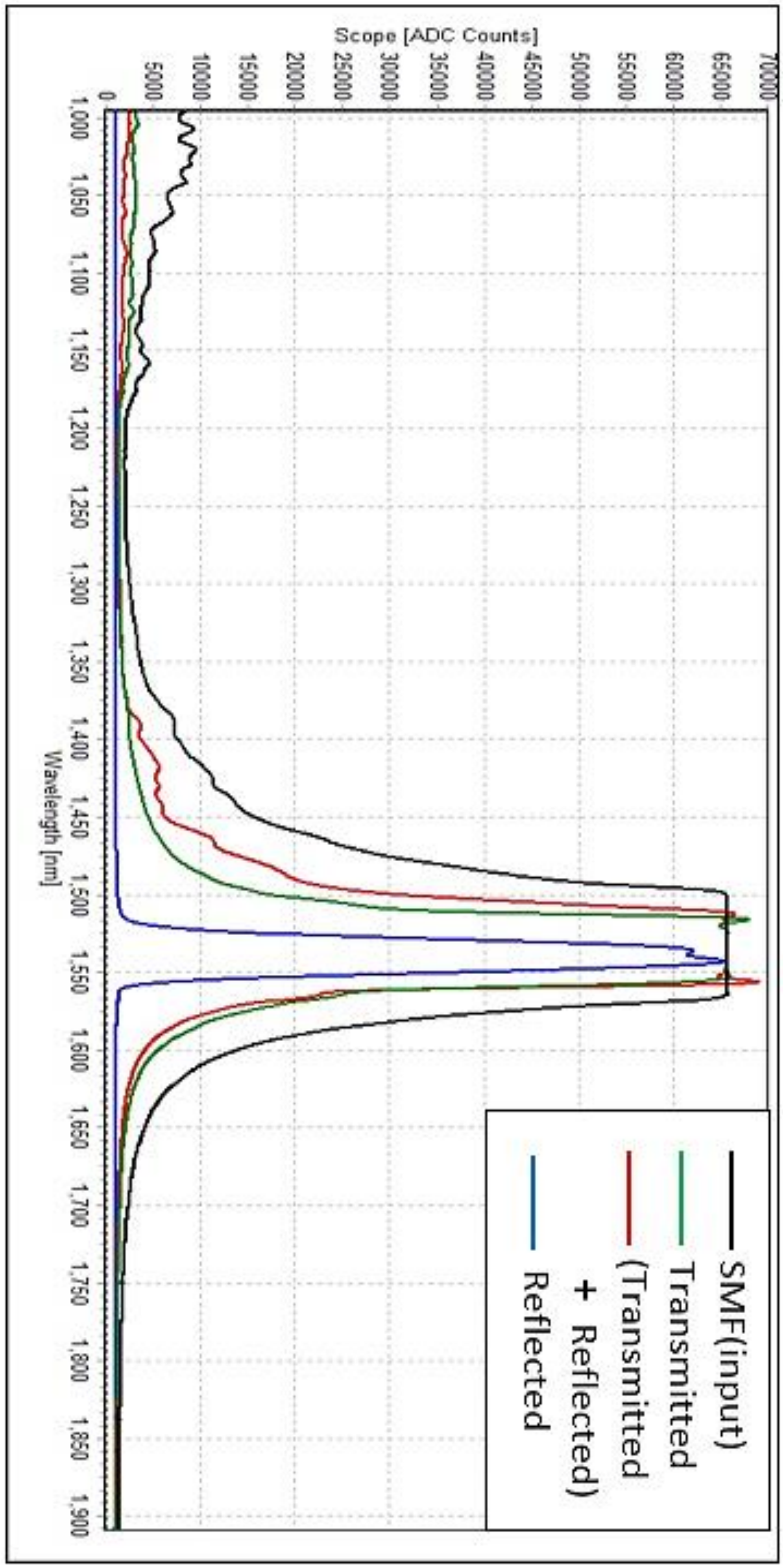

Fig. 9. The spectrum of SFBG (two grating regions) from AvaSpec spectrometer software.

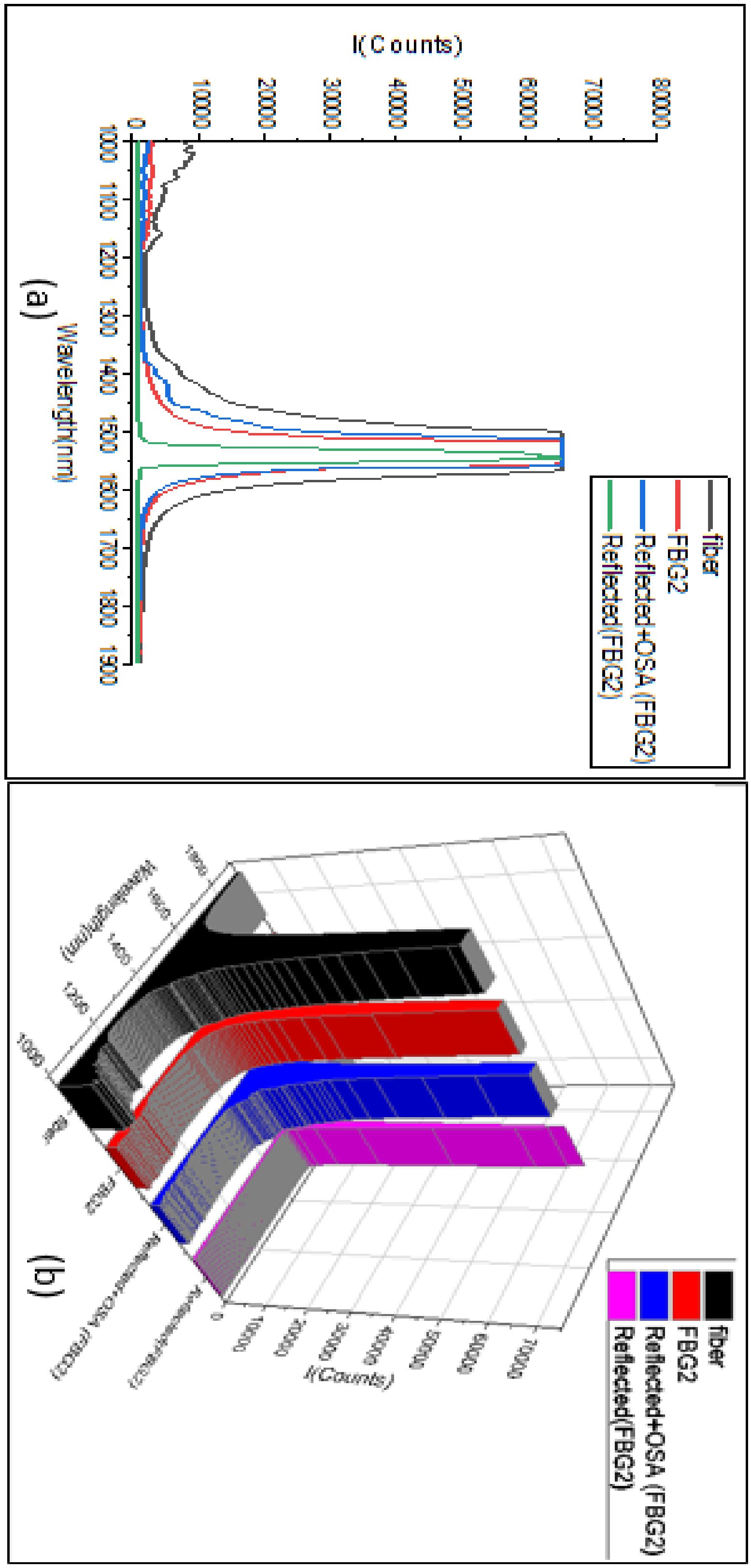

Fig. 10. Spectrum of SFBG (two grating regions) sensors by Origin program: (a) 2D. (b) 3D.

The FBG sensor used in several applications is basically a filter [9]. By scanning spectrum of laser source which used, note that there are short wavelengths at the beginning of the spectrum at wavelength (1000-1200) nm at maximum intensity (10000) Counts, and these wavelengths begin to disappear when using FBG sensor until reaching the reflected spectrum as shown in: Figure (10) for SFBG sensor (two grating regions) from AvaSpec spectrometer software, while (9) plotted by Origin program: (a) 2dimensions. (b) 3dimensions.

Table 4. Spectrum parameters relative to SFBG sensor two grating regions number

Spectrum Type	Peak Wavelength $\boldsymbol{\lambda_p}$(nm)	Intensity (Counts)	FWHM (nm)	Output Power (-dBm)	Efficiency (%)
Single mode fiber (SMF)	1496.847	66350.0	100.141	-6.4	95.50
Transmitted spectrum of SFBG	1542.40	67917.45	49.984	-7.18	83.54
Reflected spectrum of SFBG	(λ_{B1})1536.32 (λ_{B2})1545.23	65861.82 67069.55	24.60	-7.18	98.45 97.32
Mixed of reflected and transmitted spectrum of SFBG	1549.24	67724.1	60. 77	-13.91	17.89

This important result addition to get on reflected wavelength in specific value also get on filtered wavelength that good in communications field. That shown in above figures got slim reflected spectra and put input spectra (used SMF) and transmitted spectra to compare the change [14-22].

3. CONCLUSIONS

SFBG sensor efficiency studied for grating regions both theoretically and experimentally. Transmitted and reflection spectrum have been used to investigate for this fiber. That by used different experimental setups of SFBG. Bandwidth of experimental results large than theoretical result because mixed peaks of spectrum in experimental result also type of laser which used. The efficiency of reflected spectrum increases while decreases for transmitted and for mixed reflected and transmitted spectrum. A good result SFBG worked as filter.

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