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Applied Science and Engineering Technology



INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 9 Issue: XII Month of publication: December 2021

DOI: <https://doi.org/10.22214/ijraset.2021.39539>

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Simulation of Fibre Bragg Grating as Strain Sensor for Property Intrusion

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Abstract: This study will demonstrate a strain sensor based on the optical Fibre Bragg Grating (FBG) sensing technology as it is known to have stable and reliable wavelength and response as function of the applied strain. This kind of sensor can perform accurate measurements of small ground vibration and monitor seismic activity thanks to their high sensitivity to dynamic strains induced by acceleration variation which can use to prevent property intrusion or burglary. To understand the FBG sensor more, few of its characteristics such as strain, spectral reflectivity and bandwidth and their connection with the fibre grating length and refractive index is being studied.

Keywords: Fibre Bragg Grating (FBG); strain sensor; strain; spectral reflectivity; bandwidth; fibre grating length; refractive index; safety; property intrusion.

I. INTRODUCTION

The optical Fibre Bragg Grating (FBG) was first demonstrated by Hill et al. in 1978 where the discovery of its photosensitivity is discovered. By introducing periodic changes in the refractive index profile of the fibre core, FBGs can be formed in the fibre core. The resonance or Bragg wavelength (λ_B) of FBG is

$$\lambda_B = 2n_{\text{eff}}\Lambda \quad [1]$$

Where Λ is the periodicity (pitch) of the grating, and n_{eff} is the effective refractive index of the core. The shifts in Bragg wavelength are due to the applied strain (ϵ) and temperature changes (T) which is

$$\frac{\Delta\lambda_B}{\lambda_B} = K_\epsilon \epsilon + K_T T \quad [2]$$

The physical elongation of the grating pitch and strain-optic coefficient of the fibre will determine the strain effect on the fibre and hence the coefficient, K_ϵ .

When the FBG sensor is installed on the surface of the mechanical structure or embedded in the mechanical structure, the K_ϵ and K_T values are different from those of the bare fibre. They are affected by and usually determined by the mechanical and thermal properties of the structural material and the properties of the fibre protective coating, and the material used to bond the fibre to the structure [3]. There are many papers that discuss the various aspects of FBG sensor technology which are by Kersey et al. [4], Othonos and Kalli [5], and Lau [6].

Fibre optic sensor technology has been exploited by the research community over the past two decades and still actively being explore because of its relatively simple design, low power consumption and relatively low maintenance cost, and therefore the flexibility it offers for both commercial and military applications [7][8]. Other than that, as the FBG technology sensor have been widely used, many improvements have been done especially on the measurement accuracy of FBG sensor arrays where multiple gas absorption lines are used as the absolute reference [9-13] and by using multiple signal processing techniques to enhance the output signal and mixing multipoint FBG sensor systems [14][15].

This study will demonstrate a strain sensor based on the optical FBG sensing technology as it is known to have stable and reliable wavelength and response as function of the applied strain. This kind of sensor can perform accurate measurements of small ground vibration and monitor seismic activity thanks to their high sensitivity to dynamic strains induced by acceleration variation [16][17].

FBG sensors require no electrical power in the sensor head as they transfer signals that are all optical which is confined in the optical cables and intrinsically immune to electromagnetic interference [18][19]. These characteristics makes it more favorable. Furthermore, fibre optic Bragg grating sensors are lightweight and compact. The typical sizes are only several centimeters long and 125 μm in diameter. As it has a small size, multiple FBGs which is usually more than 20 can be monitored in one single optical fibre. Additional to that, special interrogator techniques are done where it allows for more than 1000 FBG sensors to be available on a single fibre. FBGs also exhibit a good corrosion resistance. These advantages are very useful and crucial to ensure that the sensor can be implanted underground or other bad conditions [20][21].

II. METHODOLOGY

These are the methods, parameters and techniques used in this study to obtain required data and results. This framework is based on simulation by using the software MATLAB which can simulate the optical sensor.

A. System Design

The main components used for this FBG design are :

- 1) Parameters used for simulation of FBG designs are effective refractive index (n_{eff}), Bragg wavelength (λ_B), grating period (Λ) and the strain optic constant (p_e).
- 2) Using the single mode fibre with core cladding of diameter ratio 9/125 μm .
- 3) Measuring the shift in Bragg wavelength using the Optical Spectrum Analyser (OSA).

B. Simulation Tools

GNU Octave (GUI) which is an open source that develop is used in running the simulation such as MATLAB software of version R2021a has been used. By declaring the theoretical expression and identified parameters, MATLAB software will be able to generate a mathematical operation where data and graphs are obtained.

C. Parameters Setting

Table below shows the details of main parameters that is used in this simulation. These parameters will help to show how the sensor will behave or react upon sensing changes due to the changes in strain.

Table 1 Parameter and values used in simulation

Parameters	Values
Effective refractive index (n_{eff})	1.46
Bragg wavelength (λ_B)	1550nm
Grating period (Λ)	530nm
Strain optic constant (p_e)	0.22

D. Formulas Identification

1) Strain

$$\varepsilon = \frac{\Delta l}{l}$$

The change of length of the fibre will calculated using the above equation. The changes of fibre length used for the calculation is from 0.000 mm to 0.550 mm with the increment of 0.050 mm.

2) Bragg Wavelength Shift

$$\Delta\lambda_B = \lambda_B(1 - p_e)\varepsilon$$

$\Delta\lambda_B$ is the Bragg wavelength shift, λ_B is Bragg wavelength, ϵ is the strain of the grating and pe is the effective strain-optic constant which is fixed at 0.22. For every strain, the Bragg wavelength is assumed to incrementally increase at 0.20 nm ranging from 1549.40 nm to 1551.60 nm.

3) Spectral Reflectivity

The spectral reflectivity is calculated using the following equation.

$$R(L, \lambda) = \tanh^2(\gamma L)$$

The grating length used for the simulation is set to L=2, 4, 6, 8 and 10 mm. While for the refractive index $\Delta n = 0.0003, 0.0005, 0.0008, 0.0012, 0.0015$ and 0.0020 is used.

4) Bandwidth

The bandwidth for a uniform FBG is expressed as:

$$\Delta\lambda = \frac{\lambda_B^2}{n_{eff}\pi L} \sqrt{\pi^2 + (\kappa L)^2}$$

Where $\Delta\lambda$ is the bandwidth of FBG, λ_B is Bragg wavelength, n_{eff} is effective refractive index, L is the length of FBG and κ is coupling coefficient. Same as in 2.4.3, the values used for grating length, L and refractive index Δn remains unchanged.

III. RESULTS AND DISCUSSION

This simulation demonstrates the FBG characteristics of a strain sensor. When strain is applied, the Bragg wavelength experience changes to it. Other than that, the reflectivity, and the bandwidth of FBG is also affected when there are differences in the grating length, Δl and the refractive index, Δn . The result of the simulation is shown in Table 2 until Table 4.

A.

1) Strain Measurement

Table 2 Applied strain due to changes in fibre length

$\Delta l (\pm 0.05\text{mm})$	Strain ($\mu\epsilon$)
0.000	0.000
0.050	1111.11
0.100	2222.22
0.150	3333.33
0.200	4444.44
0.250	5555.56
0.300	6666.67
0.350	7777.78
0.400	8888.89
0.450	10000.00
0.500	11111.10
0.550	12222.20

As shown in Table 3.1, the strain measured changes due to the difference in length of fibre. The strain measured increase as the change of fibre length increases. When the fibre is at its original length, the strain measured is zero. However, when the length changes increase by 0.550mm, the strain measured is 12222.20 $\mu\epsilon$.

2) Bragg Wavelength Shift

Table 3 Shift in Bragg wavelength due to applied strain

Strain ($\mu\epsilon$)	Bragg wavelength, λ_B ($\pm 0.10\text{nm}$)	Bragg wavelength shift, $\Delta\lambda_B$ ($\pm 0.10\text{nm}$)
0.000	1549.40	0.00
1111.11	1549.60	1.34
2222.22	1549.80	2.67
3333.33	1550.00	4.03
4444.44	1550.20	5.37
5555.56	1550.40	6.72
6666.67	1550.60	8.06
7777.78	1550.80	9.41
8888.89	1551.00	10.75
10000.00	1551.20	12.10
11111.10	1551.40	13.45
12222.20	1551.60	14.79

It is shown that the Bragg wavelength shift increase as the strain applied increase. It shifted to 14.79nm when 12222.20 $\mu\epsilon$ is applied.

3) Spectral Reflectivity

Table 4 shows the spectral reflectivity dependency with the fibre grating length and the change in refractive index.

Table 4 Shift in Bragg wavelength due to applied strain

Grating length, L (mm)	$\Delta n = 0.0003$	$\Delta n = 0.0005$	$\Delta n = 0.0008$	$\Delta n = 0.0012$	$\Delta n = 0.0015$	$\Delta n = 0.0020$
	R (%)					
2.0	59.78	79.42	92.76	98.48	99.55	100
4.0	94.60	99.98	99.98	100	100	100
6.0	99.50	99.98	100	100	100	100
8.0	99.96	99.99	100	100	100	100
10.0	99.99	99.99	100	100	100	100

4) *Bandwidth*: The data shows that the bandwidth values will differ with the grating lengths. As the grating length increases, the bandwidth will decrease. For when $\Delta n = 0.0005$, when $L=2.0$ mm, the bandwidth is 1.16nm. As the L increases to 10.0 mm, the new bandwidth is 0.26.

Table 5 Changes in bandwidth due to grating length and refractive index changes

Grating length, L (mm)	$\Delta n = 0.0003$	$\Delta n = 0.0005$	$\Delta n = 0.0008$	$\Delta n = 0.0012$	$\Delta n = 0.0015$	$\Delta n = 0.0020$
	Bandwidth(nm)					
2.0	1.16	1.25	1.43	1.74	2.01	2.44
4.0	0.55	0.70	0.96	1.36	1.66	2.17
6.0	0.43	0.61	0.90	1.31	1.62	2.15
8.0	0.38	0.57	0.88	1.29	1.61	2.13
10.0	0.26	0.55	0.87	1.28	1.60	2.12

B.

1) *Bragg Wavelength Shift*

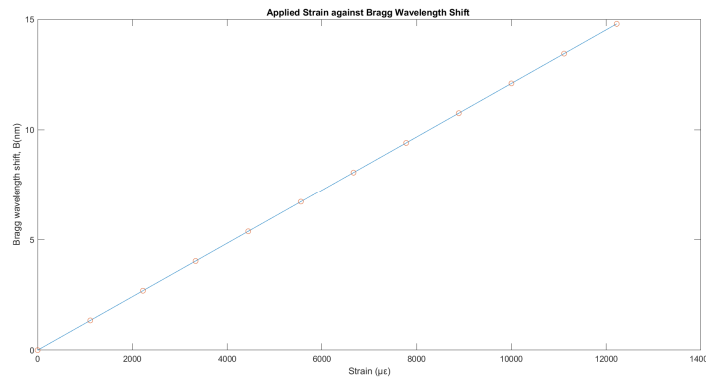


Figure 1 Graph of applied strain against Bragg wavelength shift

Figure 1 shows the relationship between the applied strain and the Bragg wavelength shift. As shown in the figure, the variables are directly proportional to each other. It is shown that the Bragg wavelength shift increases as the strain applied increases. It shifted to 14.79nm when 12222.20 $\mu\epsilon$ is applied.

2) *Spectral Reflectivity Dependence On Refractive Index Change*

A graph of spectral reflectivity of FBG with different refractive index change is plotted based on the data obtained in Table 4.

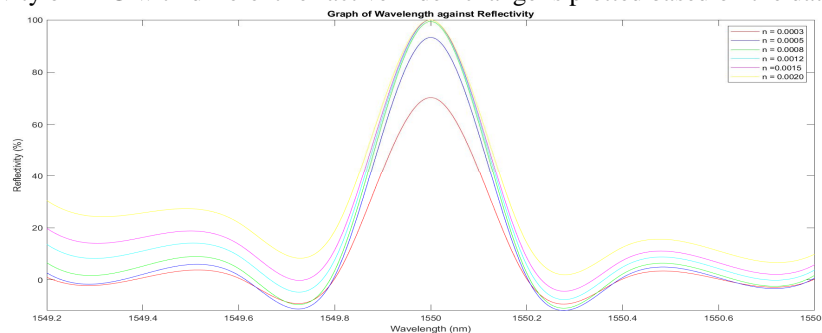


Figure 2 The reflection spectrum of FBG with various refractive index change at grating length of $L = 2$ mm

It is shown that as refractive index changes increase, the reflectivity increases too. It increases to 100% with $\Delta n = 0.0020$ when the grating length was 2.0 mm.

3) Spectral Reflectivity Dependence On Grating Length

Graph of spectral reflectivity of FBG for different grating length is plotted as shown in Figure 3.

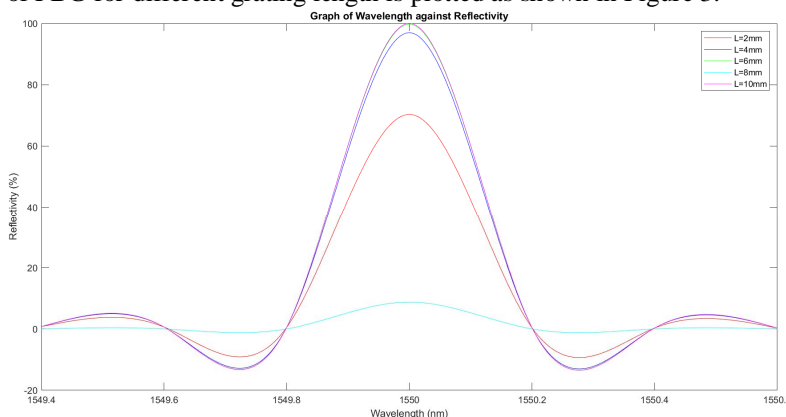


Figure 3 The reflection spectrum of FBG for various grating length at reflective index change of $\Delta n = 0.0003$

It is shown that reflectivity of FBG changes with different grating length when the refractive index changes is fixed at $\Delta n = 0.0003$. The reflectivity is at 59.78% when the grating length L is at 2.0mm. However, at L=10.0mm, the reflectivity increases until 99.99%.

4) Bandwidth

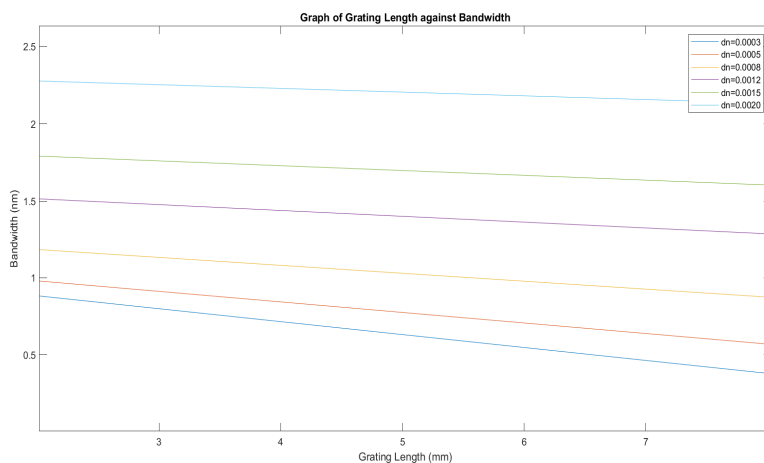


Figure 4 Relationship between FBG bandwidth and grating length with different refractive index

IV. CONCLUSIONS

The study is to propose the applicationS of FBG using strain sensor in detecting for intrusion in private properties with the help of MATLAB software for the simulation. It also aims to bring new technique for other researchers in analyzing the characteristics without limiting the simulation techniques that can be implemented.

The results obtained in this study is similar to the previous studies. By using simulation, FBG characteristics can easily be analyzed. Characteristics such as the strain, spectral reflectivity and bandwidth and their connection with the fibre grating length and refractive index have been successfully analyzed.

Based on what is obtained from the simulation, strain is available when there are changes to length of the fibre. As the strain increase, the Bragg wavelength shift increases too. Hence, as the length increase, the reflectivity of FBG increase too which also cause the refractive index to increase. As for the bandwidth, it will decrease as the grating length and refractive index increase.

V. ACKNOWLEDGEMENTS

The author would like to thank the Ministry of Higher Education of Malaysia (MOHE) and Universiti Teknologi Malaysia, UTM for providing GUP (2020/2021) grants in order to conduct this research and developing the paper. The author report no conflicts of interest in this work.

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