Integration of chirping and apodization of Topas materials for improving the performance of fiber Bragg grating sensors

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Abstract. The discovery of the fiber Bragg grating (FBG) is an early milestone in developing optical fiber technology, such as optical communication to monitoring material health structures as sensors. For optical communication, the FBG components are capable of filtering functions. As a sensor, it has a high sensitivity immune to electromagnetic wave interference, is small in size, and is resistant to extreme environmental conditions. The sensitivity of the FBG sensor is obtained from the shift in the peak wavelength of each of the temperature and strain quantities. However, the performance of the FBG sensor can be improved by engineering the distribution of the refractive index on the grid with the apodization and chirp functions. Apodization is a technique to improve the performance of the FBG to eliminate noise, narrow the full width half maximum, lower the side lobes of the main lobe, and improve the spectrum ripple factor. Apart from apodization, the chirp function also affects the sensor sensitivity and the refractive index distribution on the grid. Numerical experiments were carried out in designing the FBG component as a sensor using Gaussian apodization and Topas (cyclic olefin copolymer) for several chirp functions. The results show that the Gaussian apodization Topas for all chirp functions as a strain sensor has the same sensitivity, namely 0.84 pm/μstrain while for temperature sensors with the highest sensitivity is obtained at cubic root chirp of 13.82857 pm/°C followed by square root chirp of 13.74286 pm/°C, quadratic chirp 13.71429 pm/°C, and linear chirp 13.4 pm/°C. The Bragg wavelength shift was greater for 1 °C than for the 1 μstrain.

1. Introduction
The invention of the fiber Bragg grating (FBG) has resulted in many remarkable applications in the world of research and industry. These very wide applications range from optical communication, optical sensing, data filters, dispersion compensators, and monitoring of material health structures to applications in the medical world as biosensors. In the field of optical communication, the FBG component is used as a dispersion compensator to produce a long-range of data transmission [1], either with an amplifier or not, but it is also applied as an optical filter for different wavelengths [2-4]. Transmitted as a result of changes in the grating periodic, as well as the add and drop of wavelengths in communication wavelength division multiplexing, which is a technology that is able to combine a number of optical signals into one fiber, using various wavelengths of light or laser to allow two-way communication in one fiber on optical sensing or monitoring applications [5,6]. FBG sensors are
sensitive to changes in physical quantities and have better performance than conventional or electronic sensing. FBG can be built on a fiber core that can detect changes in physical parameters such as strain [7,8], temperature [9,10], and pressure [11,12]. The advantage of FBG over other mechanical or electronic sensors is the encoding of information measured in nanometer wavelengths, thereby reducing connector losses and power losses and being more sensitive to physical changes [13-15].

FBG optical sensors have developed and become a topic that has been widely researched in the last two decades and several developments in applicable research on FBG have been reported such as FBG as a smart textile in real-time human respiratory monitoring [16-18], heart frequency monitoring [19], and in monitoring. Temperature and pressure were bridged with woven thermoplastic composite fabrics [20]. Numerical experiments in improving the performance of the FBG sensor have also been widely researched as it was reported that FBG with Topaz material has higher sensitivity compared to Tera Flex and pure silica materials [21], and it was reported that apodization was able to narrow the full width half maximum (FWHM) in FBG, as reported [22], a $\pi$ phase with several apodization functions such as Gaussian, sinus, Nuttall, Blackman, and raised cosine is recommended for high-temperature monitoring sensors in electric transformers. FBG with Nuttall apodization has a high sensitivity to temperature sensors at sea level with a hydrophobic polymer-coated material [23]. Fiber optical sensor based temperature sensing methodology includes interferometric sensors [24,25], photonic crystal fiber sensors [26], and FBG [27,28].

FBG can be seen as an optical filtering component along with the optical fiber core of a specific wavelength. Based on the shape and structure of the grating, FBG is generally classified as homogeneous and apodization. Uniform FBG is inherently sensitive to changes in external strain and temperature. This sensing property is viewed as a shift in wavelength in the reflected spectrum of the sensing unit. The shown spectrum of a homogeneous FBG is characterized by the presence of more side lobes and the energy is very close to the peak wavelength thereby reducing the detection accuracy of the sensor [29].

This research will design, simulate and analyze performance as a component of temperature and strain sensors to produce sensitive FBG and will be optimized with some chirping and apodization such as Blackman, Hamming, and Gaussian which are techniques to reduce side lobes, so that it will produce a narrow and sensitive signal. The parameters that will be considered to determine the effect of sensitivity are the length of the grid and the variation of chirping and apodization with Topas material [21]. The methodology uses a simulation of the FBG sensor component with OptiGrating with a shift in the peak of the Bragg wavelength for each change in temperature and strain, then it will optimize the performance of the sensor against several apodizations that will be validated with OptiSystem.

2. Theory
Optical fiber is a light transmission medium and can carry information in the form of voice and video data [30]. Light is transmitted through fibers made of silica [31]. Since the discovery of optical fiber, many developments have occurred, it is efficient in transmitting light besides silica, there are also germanium, Topas, Tera Flex, plastics, and polymers. This optical fiber can be used to replace conventional cables which function as power cables. Optical fiber has many advantages over conventional electronic cables mainly because the data transmitted is modulated by laser or light so that it is not dangerous. Another advantage is the transmission of data that is very fast, accurate, and relatively stable to environmental conditions compared to conventional cables. It is not surprising that optical fibers can be used to transmit data across continents with susceptibility to electromagnetic waves which result in no wave interference, are resistant to high temperatures, small transmission attenuation, and large bandwidth [32].

FBG can reflect certain wavelengths called Bragg wavelengths and transmit other wavelengths due to the presence of a periodic grating in the core of the fiber. When the light hits the grating, it is scattered, which is called the Bragg effect. The wavelength of the Bragg $\lambda_b$, depending on the grating
period, and the guiding properties of the FBG such as the refractive index $n_{\text{eff}}$, can be mathematically expressed as follows [33],

$$\lambda_B = 2n_{\text{eff}}A$$  \hspace{1cm} (1)

the distribution of the refractive index $n_{\text{eff}}(z)$ along the FBG is written as,

$$n_{\text{eff}}(z) = n_0 + f(z)\Delta n_{\text{ac}} v \cos \left( \frac{2\pi z}{\lambda} + \theta(z) \right)$$  \hspace{1cm} (2)

where $z$ is the position, $n_0$ the initial refractive index FBG, the period is $A$, the amplitude of the modulation refractive index, the apodization function is $f(z)$, $\theta(z) = 2\pi C z^2$ is the chirp function where $C$ is the chirp parameter, $v$ the fringe visibility.

Equations (1) and (2) are directly related to the grating variable at temperature ($T$), strain ($L$), and ($\Delta \lambda$) changes in wavelength, by taking $X$ mathematically as follows,

$$\Delta \lambda_b = \frac{d \lambda_b}{dX} \Delta X = \lambda_b \left( \frac{\delta n_{\text{eff}}}{n_{\text{eff}}} + \alpha \right) \Delta X$$  \hspace{1cm} (3)

where $\delta n_{\text{eff}}/n_{\text{eff}}$ is the normalized sensitivity of the modal refractive index and is the coefficient of change in physical length depending on the parameter $X$. FBG acts as a sensor when changes in physical parameters can shift the Bragg wavelength to a measured quantity such as temperature, strain, hydrostatic pressure or the refractive index of cladding whose function is in Equation (3) [34].

The shift of the Bragg wavelength in measuring temperature and strain is influenced by the thermo-optical coefficient and thermal expansion of the material used, and can measure temperature and strain simultaneously as in Equation (4).

$$\Delta \lambda_b = \lambda_b (\alpha + \delta) \Delta T = \lambda_b \left( \frac{1}{n_{\text{eff}}} \frac{\Delta n_{\text{eff}}}{\Delta T} + \frac{1}{\lambda} \frac{\Delta \lambda}{\Delta T} \right) \Delta T$$  \hspace{1cm} (4)

The shift of the Bragg wavelength to temperature is influenced by the coefficient $\alpha$ thermo-optic and $\delta$ coefficient of thermal expansion. While in sensitivity to strain, the shift in wavelength of Bragg is influenced by the optical strain coefficient, the Poisson ratio, the refractive index, and the coefficient of thermal expansion as shown by Equation (5) below,

$$\Delta \lambda_b = \lambda_b (1 - \rho_e) \delta$$  \hspace{1cm} (5)

with $\rho_e$ represents the optical strain coefficient defined as,

$$\rho_e = \frac{n_s^2}{2}(\rho_{12} - \nu(\rho_{11} + \rho_{12}))$$  \hspace{1cm} (6)

where $\rho_s$ is the Poisson ratio, $\rho_{11}$ and $\rho_{12}$ stress-strain.

Naturally, the FBG sensor cannot be separated only to measure one temperature parameter or strain only. The FBG measures both quantities simultaneously as shown by Equation (7).

$$\Delta \lambda = k_t \Delta T + k_e \Delta \delta + \Delta k_t \Delta k_e \Delta \delta$$  \hspace{1cm} (7)

FBG can be improved in performance by apodization, which is a technique of removing unfavorable parameters from the reflected light spectrum, but there are some disadvantages including a reduction in the amplitude of the reflectivity peak of the spectrum. Some of the applications that apply different apodization are filtering, dispersion compensation, wavelength adjustment, and sensing.
in optical and optoelectronic communications as well as improved performance in temperature and range sensors [21]. The results of previous research showed that the best profile apodization in the performance of FBG as a temperature and strain sensor is the Gaussian function apodization with a sensitivity of and [21]. Gaussian apodization function is given by Equation (8).

\[ A(x) = \exp \left( -\ln 2 \left( \frac{2(x-\frac{L}{2})^2}{0.5L} \right) \right), \quad 0 \leq x \leq L \]  

Equation (8)

Apart from the apodization function, the chirp function also affects the sensitivity of the FBG sensor. The following are the types of chirp functions [35],

a. Linear

\[ A(z) = A_0 - \frac{2z-L}{2l} \Delta, \Delta \ll A_0 \]  

Equation (9)

b. Quadratic

\[ A(z) = A_0 - \left( \frac{z}{L} \right)^2 \Delta, \Delta \ll A_0 \]  

Equation (10)

c. Square root

\[ A(z) = A_0 - \left[ \sqrt{\frac{z}{L}} - \frac{1}{\sqrt{L}} \right] \Delta, \Delta \ll A_0 \]  

Equation (11)

d. Cubic root

\[ A(z) = A_0 - \left[ \sqrt[3]{\frac{z}{L}} - \frac{1}{\sqrt[3]{L}} \right] \Delta, \Delta \ll A_0 \]  

Equation (12)

where \( A(z) \) grid period over a specified distance, \( A_0 \) grid start period, \( \Delta \) total chirp.

Apodization is a technique to increase the sensitivity of the FBG sensor. Many studies have been reported on the effect of modifying apodization [35], such as the apodization of the Nuttall-Blackman function to suppress the lobe side of the reflection spectrum compared to no apodization or uniform type. The smaller or narrower the side of the lobe will give a high sensitivity to the FBG sensor. Further reported in monitoring the high temperature of the electric transformer [22], FBG with phase obtained results that FBG was superior to Sinusoidal type for each apodization. In this study, the performance of the temperature and strain FBG sensor will be optimized with variations in apodization, grating length and reflection peak for respiratory monitoring applications in humans.

3. Research Methods

The FBG component of Topas (cyclic olefin copolymer) is designed with parameters and quantities that affect the performance of the FBG sensor. The simulation results will provide an overview of changes in the Bragg wavelength to the varied parameters. Furthermore, the data obtained from FWHM will be analyzed to produce the best FBG sensor components. The simulation is operated at OptiGrating. The spectral profile will be obtained and then will be seen the change in the peak of the reflection wave with respect to temperature and strain.

FBG is designed based on the geometry and refractive index of the core, cladding, and grating shape according to the parameters of the Topas material which has a refractive index of a core of 1.53 and a refractive index of a cladding of 1.525. Then the signal peaks and left and right-side lobes of the
resulting spectrum are defined. The temperature is measured using FBG where the wavelength of the light source after passing through the Bragg grating will be filtered. Analysis of the results of the Bragg wavelength spectrum for each chirp period will be analyzed including linear chirp, quadratic root, square root, and cubic root.

4. Results and Discussion
The shift of the Bragg wavelength to temperature was carried out by numerical experiments made from Topas, a clear polymer that is well applied to medical devices and electronic devices [36]. Topas materials FBG sensors also have advantages in measuring temperature and strain. Topas is more sensitive than silicon, germanium, and Tera Flex so that the sensitivity is 14 pm/°C and 0.84 pm/μstrain for temperature and strain [21]. The simulation uses a core refractive index of 1.53 and a cladding refractive index of 1.525 while other parameters on the FBG grid are shown in Table 1.

| Parameter          | Value     | Parameter          | Value     |
|--------------------|-----------|--------------------|-----------|
| Period             | 0.5076    | Grating length     | 50 mm     |
| Grating shape      | Sinus     | Modulation index   | 0.0001    |
| Average index      | Uniform   | Total chirp        | 0.2       |
| Apodization        | Gaussian  | Tapers parameter   | 0.5       |

4.1. Spectrum analysis of Gaussian apodization wavelength of each chirp function
The apodization and chirp functions affect the structure and distribution of the refractive index in the fiber sensor grid as shown in Equations (1) and (2).

Figure 1. Spectrum of the sensor FBG Gaussian no chirp apodization.

Figure 1 shows the spectrum of Bragg wavelengths in the wavelengths of 1550 nm – 1552 nm, it shows an almost periodic increase in the peaks of each wavelength before and after crossing the peak of the Bragg wavelength spectrum.

Figure 2. The wavelength spectrum of the Gaussian Linear chirp FBG Sensor.
The difference between the main lobe and side lobe of the apodization of Gaussian linear chirping as in Figure 2, is not very significant compared to the non-chirping, the parameters obtained from the half peak wavelength of linear chirping are, the bandwidth is 0.232 nm, and the difference between the main and side lobes is 0.228 nm. These results indicate the poor performance of the FBG sensor.

![Figure 3](image3.png)

**Figure 3.** The wavelength spectrum of the Gaussian quadratic chirp FBG sensor.

The bandwidth width of the quadratic chirp wavelength spectrum in Figure 3 is the same as the linear chirp, which is 0.232 nm and the difference in the main and side lobes of the quadratic chirp is smaller, which is equal to 0.206 nm. The reflection spectrum of the quadratic experiences small, regular ripples after reaching its peak wavelength. It is actually great for optical communication applications to remove noise from the wavelength spectrum.

![Figure 4](image4.png)

**Figure 4.** Wavelength spectrum of the Gaussian square root chirp FBG sensor.

The main lobe bandwidth of the square root chirp wavelength spectrum in Figure 4 is narrower than the linear chirp and quadratic chirp, which is 0.171 nm while the difference between the side lobes and main lobes is 0.164 nm. It shows worse performance compared to linear chirp and quadratic chirp periods.

![Figure 5](image5.png)

**Figure 5.** Wavelength spectrum of Gaussian cubic root chirp FBG sensor.
Figure 5 shows the spectrum of cubic root chirping which has the narrowest main lobe of 0.14 nm, while the difference between main and side lobes was 0.124 nm, indicating a smaller difference between main and side lobes compared to linear, square root, and quadratic chirp. The small difference between the main lobe and the side lobe indicates the poor performance of the FBG sensor both with respect to temperature and strain, but the narrow FWHM indicates this sensor is more sensitive.

4.2. Sensitivity of FBG to temperature
As shown in Equation (6), the Bragg wavelength shifts with each change in temperature and strain. Meanwhile, the cross-relationship between temperature change and strain cannot be separated, but using OptiGating software will eliminate the effect of strain change and only review temperature changes. By using a thermo optic coefficient of equal to and a coefficient of thermal expansion in the design, the shifting of the Bragg wavelength of each chirp for Gaussian apodization is obtained as shown in Figure 6.

![Figure 6. The shift in the wavelength of the Bragg chirp function.](image)

The shift of the Bragg wavelength is almost always linear as shown in Figure 6. Meanwhile, the sensitivity value of the chirp function is shown in Table 2.

| Chirp          | Sensitivity (pm/°C) |
|----------------|---------------------|
| Linear         | 13.4                |
| Quadratic      | 13.71429            |
| Cubic Root     | 13.82857            |
| Square root    | 13.74286            |

In Table 2, the chirp function with different sensitivity to the apodization of Gaussian cubic root has the greatest shift in the Bragg wavelength, namely 13.82857 pm/°C followed by square root chirp 13.74286 pm/°C, quadratic chirp 13.71429 pm/°C, and linear chirp 13.4 pm/°C. The results obtained indicate that the performance of the Gaussian cubic root chirp apodization FBG sensor has a better performance than the other periodic chirp. The greater the shift of the Bragg wavelength for each temperature and strain indicates the high sensitivity and good performance of an FBG sensor.

4.3. Sensitivity of FBG to strain
Like temperature, FBG is also sensitive to changes in the strain as shown in Equation (6). By inputting the photoelasticity coefficient $\rho_{11} = 0.121$, $\rho_{12} = 0.27$ at 0.17 Poisson ratio, the Bragg wavelength crest shift is obtained for each 20 μstrain strain change, which is shown in Figure 7 that the shift in the Bragg wavelength for each.
The shift of the Bragg wavelength to the strain for each 20 μstrain.

The strain unit is not linear enough compared to temperature changes, but for the cubic root chirp and square root chirp, the linearity is better than the other chirp periods. And the least linear is the linear chirp in the 120 – 140 μstrain strain which has a large increase, while in the 160 – 180 μstrain strain the Bragg wavelength crest has decreased compared to before. This indicates the poor strain sensor performance of the FBG. The shift of the Bragg wavelength to strain was the same as that reported [21], with a sensitivity of 0.84 pm/μstrain despite having different linearities.

Table 3. Sensitivity of Gaussian apodization FBG for each chirp.

| Chirp             | Sensitivity (pm/μstrain) |
|-------------------|--------------------------|
| Linear            | 0.84                     |
| Quadratic         | 0.84                     |
| Square root       | 0.84                     |
| Cubic Root        | 0.84                     |

Even though it has different linearity, the sensitivity of FBG to strain for each chirp function is the same, which is 0.84 pm/μstrain. Similar results were obtained on the sensitivity of Gaussian apodization Topas FBG [21]. The findings show that although the peak of the Bragg wavelength at room temperature for each chirp function is different, the gradient of the Bragg wavelength shift in the 100 – 200 μstrain strain range has the same values as in Table 3. The chirp function and the apodization function are two functions that can change the FBG geometry and can also remove noise from the resulting wavelength spectrum.

4.4. Temperature and strain sensitivity of linear chirp Topas

The measurement of the FBG sensor for temperature and strain cannot be separated, the shift in the Bragg wavelength depends on these two quantities. Figure 8 shows the shift of the Bragg wavelength to temperature and strain simultaneously at 200 °C and 20 μstrain, the temperature starts from 25 °C – 105 °C.

Figure 8. Shifting of the FBG sensor to changes in temperature and changes in strain.
From Figure 8, it is obtained that the peak wavelength of the Bragg for the two quantities of temperature and strain. At room temperature and with a strain of 100 µstrain the peak wavelength was obtained at 1550.952 nm, while it can be seen from the results for each temperature of 25 °C and the strain of 100 µstrain obtained 1550.89 nm and 1550.952 nm from these results it is shown that the peak wavelength produced is the same as the peak wavelength of Bragg at 100 µstrain. Meanwhile, if you look at the at a temperature of 65 °C and 140 µstrain, the peak wavelengths are 1551.416 nm and 1551.006 nm, while at the same temperature and strain it is obtained 1551.534 nm. 0.118 nm difference from the peak of the Bragg wavelength at temperature and 0.410 nm in the strain here it is also found that the effect of changes in temperature every 10 °C is greater on the peak shift of the Bragg wavelength than 1 µstrain.

5. Conclusion

The chirp function has a different sensitivity from the Gaussian apodization for temperature sensors at the cubic root chirp which has the greatest Bragg wavelength shift, namely 13.82857 pm/°C followed by square root chirp 13.74286 pm/°C, quadratic chirp 13.71429 pm/°C, and linear chirp 13.4 pm/°C. From the results obtained, the performance of the sensor with apodization Gaussian cubic root chirp has a better performance than other chirp periods. Meanwhile, the sensitivity of FBG to strain for each chirp function was equal, namely 0.84 pm/µstrain. The findings show that although the peak of the Bragg wavelength at room temperature for each chirp function is different, the gradient of the Bragg wavelength shift in the 100 – 200 µstrain strain range has the same value, namely 0.84 pm/µstrain. Furthermore, the peak shift of the Bragg wavelength in temperature every 10 °C is greater than 1 µstrain.

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