Design and Simulation of Waveguide Bragg Grating based Temperature Sensor in COMSOL

Vigneshwar Dhavamani¹, Srijani Chakraborty¹, Ramya S¹ and Somesh Nandi²

¹ Department of Electronics and Communication Engineering, Rashtreeya Vidyalaya College of Engineering, Bengaluru, Karnataka-560059, India
² CISCO - RVCE Center of Excellence in IoT, Rashtreeya Vidyalaya College of Engineering, Bengaluru, Karnataka-560059, India

E-mail: vigneshwar.dhavamani@gmail.com, chakraborty.srijani189@gmail.com, ramyas@rvce.edu.in and someshnandi@rvce.edu.in

Abstract.

With the advancements in the domain of photonics and optical sensors, Fibre Bragg Grating (FBG) sensors, owing to their increased advantages, have been researched widely and have proved to be useful in sensing applications. Moreover, the advent of Photonic Integrated Circuits (PICs) demands the incorporation of optical sensing in waveguides, which can be integrated on silicon photonic chips. In this paper, the design of a sub-micron range Waveguide Bragg Grating (WBG) based temperature sensor with high peak reflectivity and thermal sensitivity is proposed. The flexibility of COMSOL Multiphysics software is explored to simulate the sensor and the results are verified with the analytical values calculated using MATLAB. The simulation is carried out for the proposed design having 16000 gratings and a corresponding peak reflectivity of 0.953 is obtained. A thermal sensitivity of 80 pm/K is achieved, which is approximately eight times better than that of FBG based sensor.

1. Introduction

The field of photonics has taken a significant forward leap since the invention of laser in 1960. Moreover, the constraints of Moore’s law in integrated electronic circuits has inspired the scientific community to push boundaries that has led to several breakthroughs in the field, especially integrated photonics circuits [1]. Integrated photonics involve optical waveguides as the fundamental interconnect between different components, which has led to waveguide based sensors as a new development.

Bragg grating filters, which are a type of Bragg reflector that reflects a narrow band of wavelengths and allow light transmission in all other wavelengths, was first demonstrated by K.O. Hill in 1978 [2]. The Fiber Bragg Gratings (FBG) are the most common Bragg grating filters, where the refractive index is periodically modulated in the core of a photosensitive fiber. The Bragg gratings can be extensively used in sensing technology [3, 4]. In [5], the temperature dependence of FBG is presented by gradually changing the incident temperature from 0°C to 60°C in 10°C increments and thereby showing the corresponding frequency shift in both Radio Frequency (RF) and optical spectrum. A comprehensive review of the FBG sensing technique for various physical parameters like pressure, temperature, refractive indices, strain,
liquid level, displacement as well as shape is provided in [6]. Another application involving the FBG based temperature sensor as a tunnel fire detector in structural health monitoring is explored in [7]. Though the application of Bragg grating based optical sensors can be dictated by various parameters, the temperature sensitivity remains of significant importance due to the necessity for the compensation of temperature cross-response in sensing any other parameter [8].

With recent advancements in silicon photonics, the Bragg gratings are integrated onto the widely popular silicon-on-insulator (SOI) slab, as demonstrated first in [9]. Photo-induced Bragg gratings are fabricated into integrated waveguides using similar techniques, since waveguides are essential building blocks of every photonic circuit. With the emerging research in PICs, the integration of Bragg gratings into SOI waveguides instead of optical fiber is of high importance. In [10], different types such as strip, rib and slot corrugated waveguides were integrated with Bragg gratings.

Owing to the feasibility of Bragg grating sensors as well as importance of waveguides in emerging PIC industry, a sub-micron range planar WBG temperature sensor design is proposed and simulated in COMSOL Multiphysics software for the first time. This software finds applications in wave optics simulations due to its user friendly interface using Finite Element Analysis. Here, a silicon symmetric slab waveguide based WBG with 16000 gratings is designed and the corresponding simulation is carried out for two temperatures - 295 K and 300 K. A peak reflectivity of 0.953 is obtained and a thermal sensitivity of 80 pm/K is achieved, which is approximately eight times better than that of FBG based sensor. This paper begins with a brief summary on the basic fundamentals that forms the base of the simulation followed by the modelling and implementation of the design. The obtained results upon simulation are discussed and the major deliverables are highlighted.

2. Theory
The WBG sensors work on the basis of Bragg reflection and are formed by varying the core refractive index periodically in the direction of propagation of the lightwave [10]. The travelling light wave gets reflected at each boundary of the gratings and these reflected waves interfere constructively only in a narrow band around the Bragg wavelength, and interfere destructively at the other wavelengths. The Bragg wavelength ($\lambda_B$) having peak reflectivity is given by the Bragg’s equation as

$$\lambda_B = 2Pn_{\text{eff}}$$

where $P$ is the grating period.

To arrive at the transcendental equation for getting the propagation constant ($\beta$) for different modes in the symmetric slab waveguide and a the Maxwell’s equations for a linear, non-conducting, non-magnetic and isotropic medium are considered [11]. The refractive index profile $n(x)$ is

$$n(x) = \begin{cases} n_1; & |x| < d/2, \\ n_2; & |x| > d/2 \end{cases}$$

where $n_1$ and $n_2$ are the core and cladding refractive indices, respectively, with $n_1 > n_2$ and $d$ is the core thickness. By solving the Maxwell’s equations for Transverse Electric (TE) modes and applying the refractive index profile given by equation (2), the transcendental equation is obtained as

$$m \tan m = \left( \frac{V^2}{4} - m^2 \right)^{1/2}, \quad \text{where} \quad m = \frac{d}{2} \left( k_0^2 n_1^2 - \beta^2 \right)^{1/2}$$

Here, $k_0$ is the free space wave number and $V$ is known as the dimensionless waveguide parameter,
commonly referred to as $V$-number, and is calculated using

$$V = k_0 d \left( n_1^2 - n_2^2 \right)^{1/2}$$  \hspace{1cm} (4)

When calculating the modes, the guided modes are to be considered such that the fields are confined to the core and decay in the cladding. Furthermore, the boundary conditions must be satisfied at $x = \pm d/2$ [11]. This is maintained by the inequality condition

$$n_2^2 < \left( \frac{\beta}{k_0} \right)^2 < n_1^2$$  \hspace{1cm} (5)

For single mode waveguide designed for wavelength $\lambda$, $0 < V < \pi$. This gives rise to the condition for core diameter as

$$0 < d < \frac{\lambda}{2 \left( n_1^2 - n_2^2 \right)^{1/2}}$$  \hspace{1cm} (6)

The mutual lightwave interaction between contrapropagating modes in case of Bragg gratings is dealt with using the coupled mode theory [11]. The coupled mode equations are solved for a single mode waveguide and the expression for the reflectance $R$ of the waveguide for a grating length $L$ is obtained as

$$R = \frac{\kappa^2 \sinh^2 \gamma L}{\gamma^2 \cosh^2 \gamma L + \frac{\Gamma^2}{4} \sinh^2 \gamma L}, \text{ where } \gamma^2 = \kappa^2 + \frac{\Gamma^2}{4}$$  \hspace{1cm} (7)

Here, $\kappa$ is the coupling coefficient defined by [10]

$$\kappa = 2 \frac{\Delta n}{n_{\text{eff}} P} = \frac{2 \Delta n}{\lambda_B}$$  \hspace{1cm} (8)

and $\Gamma$ is the phase mismatch defined using the wave vector of periodic modulation $K$ [11] as

$$\Gamma = 2 \beta - K$$  \hspace{1cm} (9)

The Bragg gratings are widely used for sensing technology, working on the basis of detection of the wavelength shift [4]. If either or both the effective refractive index $n_{\text{eff}}$ and grating period $P$ of Bragg gratings change due to parameters such as temperature, strain, pressure, etc., there will be a shift in the Bragg wavelength $\lambda_B$ [6]. For Bragg grating based temperature sensor, the Bragg wavelength shift with temperature variation $\Delta T$ [12] is given by

$$\Delta \lambda_B = 2 \left( P \frac{\partial n_{\text{eff}}}{\partial T} + n_{\text{eff}} \frac{\partial P}{\partial T} \right) \Delta T$$  \hspace{1cm} (10)

Here, $\frac{\partial P}{\partial T} = \alpha P$ and $\frac{\partial n_{\text{eff}}}{\partial T} = \xi \cdot n_{\text{eff}}$, where $\alpha$ and $\xi$ represents the thermal expansion and thermo-optic coefficients of the waveguide gratings, respectively. This leads to a change in the refractive index of core and cladding with respect to the value of the thermo-optic coefficient of the material, and a change in the grating period with temperature, given by the linear thermal expansion coefficient. Moreover, the thermo-optic coefficient itself also varies with respect to temperature and the relation is derived using the Sellmeier’s equation [13] given by

$$n^2(\lambda, T) - 1 = \sum_{i=1}^{3} \frac{S_i(T) \cdot \lambda^2}{\lambda^2 - \lambda_i^2(T)}, \text{ where } S_i(T) = \sum_{j=0}^{4} S_{ij} \cdot T^j, \lambda_i(T) = \sum_{j=0}^{4} \lambda_{ij} \cdot T^j$$  \hspace{1cm} (11)

Here, $S_{ij}$ and $\lambda_{ij}$ refer to the Sellmeier’s coefficients. The linear thermal expansion coefficient $\alpha$ for silicon is extremely small (in range of $10^{-6}$) as seen in [14, 15]. Furthermore, the thermo-optic coefficient of silicon (in range of $10^{-4}$ at 300K) varies significantly with temperature [13]. This shows that the Bragg wavelength shift is majorly due to refractive index variation and hence, the contribution of $\alpha$ is ignored here.
3. Design and Simulation

The Si WBG is designed having Si core and SiO$_2$ cladding. The schematic of the same is shown in figure 1. The design parameters of WBG must facilitate only single light propagation mode for sensing application. Thus the design equations are solved iteratively in MATLAB to arrive at optimal parameter values as shown in Table 1. The Bragg wavelength is fixed at 1550 nm owing to its wide applications in optical systems, availability of feasible interrogation systems and low loss communications. The number of gratings is set to 16000 to obtain a high reflectivity at the Bragg wavelength, for easier detection of shift in reflectance spectrum. The core and cladding refractive index at 295K is found out to be 3.4788 and 1.4444 respectively, using equation (11). Similarly, the core and cladding refractive index at 300K is 3.4797 and 1.4445.

![Figure 1. Schematic of Waveguide Bragg Grating. Blue: Cladding, Orange: Core and Red: Gratings](image)

| Design Parameters                  | Notations | Values   |
|------------------------------------|-----------|----------|
| Bragg wavelength                   | $\lambda_B$ | 1550 nm  |
| Waveguide core thickness           | $d$       | 220 nm   |
| Waveguide cladding thickness       | $D$       | 1.5 $\mu$m |
| Difference between grating and core refractive index | $\Delta n$ | 0.0004 |
| Grating period                     | $P$       | 271.8735 nm |
| Number of gratings                 | $N$       | 16000    |
| Grating length                     | $L$       | 4.35 mm  |

3.1. Model Definition

Having obtained the design parameters in table 1, the model is required to be defined on the basis of geometry and respective materials. In the MODEL WIZARD window, 2D (x-z plane) design...
was selected for ease of computation as the WBG is symmetric along y-axis. The respective dimensions were taken from table 1. The resulting geometry is illustrated in figure 2.

![Figure 2. 2D design of Waveguide Bragg Grating. Gray: Cladding, Blue: Core and Yellow: Gratings](image)

3.2. Physics Interface

The next important step in simulation is assigning the physics to the defined model. This is done by choosing the appropriate physics interface. Here, Electromagnetic Waves, Frequency Domain (EWFD) under wave optics module of COMSOL was selected as the physics interface. It computes many parameters like transmittance, reflectance, electric field, power, etc. For single mode propagation, the lightwave can be restricted in either TE or Transverse Magnetic (TM) modes, provided the fundamental equations used are modified accordingly [16]. Here, the wave propagation is restricted to only TE mode.

Hence, the solution was computed for only the out-of-plane electric field component. To enable boundary mode analysis, the numeric ports were added at the input and the output of the WBG, such that the lightwave is excited at the input port (port excitation is set to ON) while the output port acts as the listener port (port excitation is set to OFF). The geometry was meshed with physics controlled element size, having maximum element size as that of Bragg wavelength (1550nm).

3.3. Study Interface

A parametric sweep study was performed for refractive indices at temperatures 295K and 300K. This was followed by the boundary mode analysis for both the ports to find the propagation constant and the effective refractive index of the WBG. Frequency domain study was added for the propagation of the input lightwave in the waveguide for the specified frequency range corresponding to wavelength range from 1548 nm to 1552 nm to obtain the reflectance spectrum.

4. Results and Discussions

With the defined parameters and the selected modules, the simulation successfully calculated the effective refractive index by the boundary mode study to be as 2.8514. The resulting out-of-plane electric field distribution is shown in figure 3.
It can be seen that there is a single (fundamental) mode of light wave propagation for sensing application. The reflectance spectrum computed at 295K and 300K is represented in figure 4. There is a peak reflectance of 0.953 and Bragg wavelength shift of 0.4 nm due to temperature change from 295K to 300K. This shift in the spectrum leads to sensing of the temperature difference. This is usually detected using interrogation systems like Mach-Zehnder Interferometer, Fabry-Perot Interferometer, etc. The temperature sensitivity for the designed WBG is 80 pm/K which is eight times better than the FBG sensitivity shown in [5, 17].

A MATLAB program was written using equations (2)-(11) to calculate the effective mode index and reflectance spectrum. This was done to verify the simulation results obtained in
COMSOL. The effective mode index was calculated as 2.8516 which is very close to results obtained using COMSOL. The calculated reflectance spectrum is shown in figure 5 is also similar to that obtained in simulation. This shows that the COMSOL simulation results are having high accuracy.

![Reflectance spectrum](image)

**Figure 5.** Reflectance spectrum obtained in MATLAB at 295K (solid) and at 300K (dashed)

5. Conclusion
In this paper, a WBG based sensitive temperature sensor operating at room temperatures was designed and simulated in COMSOL Multiphysics software. The sensor is based on a single-mode symmetric slab waveguide with planar Bragg gratings and designed with core dimensions in the sub-micron range to accommodate its integration in the advancing miniaturised photonic circuits. The temperature dependence was incorporated in the WBG by considering the fundamental change in refractive index with temperature. The temperature sensed by the model was observed in the form of shift in the reflectance wavelength spectrum. The simulation was performed for two specific temperatures - 295K and 300K and a thermal sensitivity of 0.08 nm/K was observed, which is approximately eight times better than that of FBG temperature sensors [5, 17]. The same design was further validated using MATLAB. The flexibility of COMSOL Multiphysics facilitates simulation of WBG sensors with high accuracy. The physics interfaces in the wave optics module provides features like frequency and wavelength domain analysis, modal analysis and eigen solver.

The successful compilation of a WBG based temperature sensor in COMSOL shown here can serve as a platform and further the inception of waveguide based sensors for various applications by implementing different types of gratings like long, chirped, tilted or phase shifted based on different kinds of waveguides. Moreover, 3D waveguides like channel waveguides can also be simulated in COMSOL, though it would require more computation power.

References
[1] Waldrop, M.M. 2016 More than moore. *Nature* **530** 144–148
[2] Hill K. O., Fujii Y., Johnson D. C., and Kawasaki B. S. 1978 Photosensitivity in optical fiber waveguides: Application to reflection filter fabrication Applied Physics Letters 32 647–649

[3] Venghaus H. 2006 Wavelength Filters in Fibre Optics (Berlin: Springer)

[4] Alvarez-Botero G., Baron F. E., Cano C. C., Sosa O. and Varon M. 2017 Optical sensing using fiber Bragg gratings: Fundamentals and applications IEEE Instrumentation Measurement Magazine 20 2 33–38

[5] Yücel et al 2016 Design of a fiber Bragg grating based temperature sensor IEEE Trans. Signal Processing and Communication Application Conference (SIU) 24 669—72

[6] Sahota J. K., Gupta n. and Dhawan D. 2020 Fiber Bragg grating sensors for monitoring of physical parameters: A comprehensive review Optical Engineering 59 6 60–90

[7] K. Aishwarya and M. Pavithra 2020 Tunnel fire detection using FBG International Journal of Engineering Research Technology 9 3

[8] Liang M., Fang X., and Ning Y. 2018 Temperature compensation fiber Bragg grating pressure sensor based on plane diaphragm Photonic Sensors 8 2 157–167

[9] Murphy T., Hastings J. and Smith H. 2001 Fabrication and characterization of narrow-band Bragg-reflection filters in silicon-on-insulator ridge waveguides Journal of Lightwave Technology 19 12 1938–42

[10] Wang X. 2013 Silicon photonic waveguide Bragg gratings Ph.D. dissertation (University of British Columbia)

[11] Ghatak A. and Thyagarajan K. 1998 An introduction to fiber optics (Cambridge: Cambridge university press) 458–474

[12] Hisham H. K. 2019 Fiber Bragg Grating Sensors: Development and Applications (CRC Press)

[13] Frey B. J., Leviton D. B. and Madison T. J. 2006 Temperature-dependent refractive index of silicon and germanium Optomechanical technologies for Astronomy International Society for Optics and Photonics 6273 62732J

[14] Watanabe H., Yamada N. and Okaji M. 2004 Linear thermal expansion coefficient of silicon from 293 to 1000 k International journal of thermophysics 25 1 221–236

[15] Okada Y. and Tokumaru Y. 1984 J. Appl. Phys. 56 2 314–320

[16] Pollock C. R. 1995 Fundamentals of Optoelectronics (Irwin)

[17] Marcelo M. Werneck, Regina C. S. B. Allil, Bessie A. Ribeiro and Fábio V. B. de Nazaré 2013 Current trends in short-and long-period fiber grating ed Cuadrado-Laborde C. (Argentina: Intechopen) 2–24