Heliyon 11 (2025) e44120

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Athermally packaged fiber Bragg grating for sensor and DWDM applications using liquid carbon

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ARTICLE INFO

Keywords:
Fiber Bragg grating
Athermal packaging
Temperature compensation

ABSTRACT

Highly stable central wavelength with temperature variations is crucial for Dense Wavelength Division Multiplexing (DWDM) multiplexers/demultiplexers, filters, laser sources, sensors, and any equipment that uses fiber Bragg grating (FBG) filters. The wavelength stability prevents channel drift and interference with other channels and thus enables the increase of DWDM channels inside a single fiber. It also ensures the accuracy of the measured values in relation to the reference FBG of the sensors. Stable FBG wavelength is traditionally achieved by athermal packaging which is a complex process involving preloading or bonding under elevated temperatures to compensate for any wavelength shifts caused by temperature variations. Since FBGs are sensitive to both temperature and strain, temperature-induced shifts in the central wavelength can be compensated by athermal packaging. This packaging minimizes axial strain on the FBG as temperature increases, thereby canceling the temperature effect using strain-induced wavelength changes. In this article, we propose and experimentally validate a simple and straightforward athermal packaging solution for FBG to counteract the changes in the central wavelength due to temperature variations. The proposed FBG package involves coating the FBG with two layers of Liquid Carbon material, which possesses a negative thermal expansion (NTE) coefficient of -4×10^{-6} at room temperature. The results demonstrate that the central wavelength is maintained within a narrow range of 0.06 nm over a wide temperature span, from 24 to 96 °C. These findings significantly advance FBG packaging by providing a simpler and more efficient method to achieve central wavelength stability. The practical applications of this research are vast, potentially improving the performance and reliability of DWDM systems and other optical devices that rely on FBG filters. This advancement could lead to more robust and higher-capacity optical communication networks.

1. Introduction

Fiber Bragg gratings (FBG) are important for controlling transmitted light wavelengths in optical sensing systems due to their small and compact size, high sensitivity, stability, high resolution, ability to multiplex, and immunity to electromagnetic interference. Because the central wavelength is influenced by both temperature and strain [1], FBGs find extensive use in various sensing applications for measuring strain and temperature [2,3]. Additionally, they are employed in manufacturing FBG-stabilized laser sources [4],

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https://doi.org/10.1016/j.heliyon.2025.e44120
Received 11 April 2023; Received in revised form 26 August 2025; Accepted 30 October 2025

Dense wavelength division multiplexing (DWDM) multiplexers, demultiplexers, and optical add–drop multiplexers (OADM) [5–7].

Recent studies have demonstrated the effectiveness of FBG sensors in physical, chemical, and electrical fields. They are used in humidity and water content detection [8], flow rate measurements [9], displacement and structural monitoring [10], pressure detection [11], electrical current measurements [12], and other fields. This highlights the broad applicability of FBG sensors beyond traditional telecommunications and strain sensing applications [8,13,14]. Furthermore, the integration of IP-over-DWDM solutions has revolutionized optical transport networks, providing cost-effective and scalable solutions for high-capacity data transmission [15]. This convergence of IP and optical transport networks eliminates the need for external DWDM transponders, simplifying network architecture and reducing costs.

However, it is important to note that FBGs are extremely sensitive to temperature variations [16], experiencing a 1 nm wavelength shift in the c-band over a 100 °C range without fracturing the fiber [17,18]. This Bragg wavelength shift, resulting from temperature changes, introduces errors in measuring strain. Hence, ensuring a stable central wavelength in athermally compensated FBGs under varying temperatures holds significant importance, particularly in applications like strain sensing [19,20]. This stability is crucial for distinguishing shifts caused by strain from those induced by temperature changes. Additionally, maintaining a consistent wavelength is essential in telecommunications to prevent drift due to temperature variations [21]. Athermal packaging is the ideal solution as it does not require any additional power for stability purposes [22].

Many proposals are introduced for wavelength shift compensation using athermal packaging of the FBG filter. Some methods use different thermal expansion coefficients of two materials to make a bimetal strip with mechanical system to achieve the compensation [23,24]. In this method, the FBG needs to be loaded and fixed from both sides under specific tension for the lifetime of the FBG, which needs highly skilled person and special adhesive materials that keep its behavior over exceptionally prolonged period. Other systems need connecting moving metal blocks to the fiber beside the FBG [25]. Mechanical motion during operation can pose problems in certain applications, and the lifetime of this technique depends on the adhesive used and the installation of the moving block. A drawback of mechanical methods is their complexity, as the fiber must be packaged under elevated temperature. Another technique involves metal coating, eliminating the need for preloading [26–28]. However, this method requires complex wavelength demodulation to separate the effect of temperature and strain. Additionally, at elevated temperature metal coating makes the FBG more brittle and may cause mechanical failure [29]. Another technique is based on using two FBGs, one is fixed in a way to measure both strain and temperature and the other is positioned nearby but in a way to be unaffected by strain [30,31]. This technique needs two FBGs to find the difference in central wavelength shift and separate the shift related to strain from that related to temperature.

A negative thermal expansion coefficient material is considered a satisfactory solution to decrease the shift of the FBG wavelength as reported early in Ref. [22]. Thermal expansion is an important phenomenon in many applications when a material is exposed to elevated temperatures. Most materials have positive thermal expansion coefficient and expand when heated; nevertheless, few materials experience negative thermal expansion (NTE) coefficient and thus contract when heated. NTE is also essential for preventing thermal expansion of conventional materials, particularly in high-temperature or precision applications [32,33]. In this article, compensation for temperature effects is achieved by applying Liquid Carbon, an NTE coefficient material, on the entire FBG before it is hardened [34]. The thermal expansion coefficient of Liquid Carbon material depends on temperature, and it equals at room temperature -4×10^{-6} [35]. This technique of FBG athermal packaging is a simpler and more efficient method compared to traditional techniques.

2. Methodology

The dual sensitivity of Fiber Bragg Gratings (FBGs) to both temperature and strain simultaneously is a significant drawback. Any temperature variation results in a central wavelength shift that could be interpreted as strain readings, or as channel drift, introducing a potential source of error. The wavelength of the FBG is proportional to temperature, an increase in temperature causes an increase in the central wavelength of the FBG. The FBG central wavelength is also proportional to the axial strain, when the axial strain increases, it causes the central wavelength to increase as well. The proposed method mitigates this dual sensitivity of FBG to both temperature and strain by packaging the FBG with NTE material that contracts with increasing temperature and thus applying a compression on the FBG and generating a negative strain. An increase in temperature shifts the central wavelength and contracts the hardened NTE material bonded to the FBG. This compression cancels the temperature induced central wavelength shift and makes the FBG only sensitive to external strain. In DWDM applications, the FBG can be bonded to a solid material to prevent any external strain, therefore maintaining a stable central wavelength despite any changes in both temperature and strain.

When the ambient temperature increases, it affects the FBG wavelength, causing an incremental shift by influencing the Bragg period (Λ_B). The Bragg wavelength is given by Equation. (1):

$$\lambda_B = 2n_{eff}\Lambda_B \tag{1}$$

where n_{eff} is the effective refractive index of the fiber. Mathematically, the wavelength shift due to the thermal effect can be expressed as shown in Equations. (2) and (3) [3,26]:

$$\Delta\lambda_{\mathrm{B}} = \lambda_{\mathrm{B}}\left(\frac{1}{\Lambda_{\mathrm{B}}}\frac{\partial\Lambda_{\mathrm{B}}}{\partial T} + \frac{1}{\mathrm{n_{eff}}}\frac{\partial \mathrm{n_{eff}}}{\partial T}\right)\Delta\mathrm{T} \tag{2}$$

and

$$\frac{\Delta\lambda_B}{\lambda_B}_{Thermal} = (\alpha_f + \chi)\Delta T \tag{3}$$

Where $\alpha_f = \frac{1}{\Lambda_B}\frac{\partial\Lambda_B}{\partial T}$ is the fiber thermal expansion coefficient; $\chi = \frac{1}{n_{eff}}\frac{\partial n_{eff}}{\partial T}$ is the fiber thermo-optic coefficient, and ΔT is the temperature variation.

Simultaneously, the NTE material undergoes shrinkage, influencing the Bragg period (Λ_B) and, consequently, the Bragg wavelength. Consequently, the NTE material exerts a negative strain on the FBG to counteract the increase in the Bragg wavelength induced by the temperature rise. This negative strain leads to a decremental shift in the central wavelength. Therefore, the wavelength shifts caused by the temperature change are balanced by the negative strain introduced by the NTE material. Mathematically, the wavelength shift due to the strain effect can be expressed by Equation (4) [3,26]:

$$\frac{\Delta\lambda_B}{\lambda_B}_{strain} = (1 - P_e)\epsilon_{strain} \tag{4}$$

Where ϵ_{strain} is the axial strain applied on the FBG because of the packaging; and P_e is the effective strain optic coefficient. As mentioned previously, the wavelength shift due to the temperature effect is in the opposite direction of the wavelength shift due to the strain effect, hence,

$$\frac{\Delta\lambda_B}{\lambda_B}_{Thermal} = -\frac{\Delta\lambda_B}{\lambda_B}_{strain} \tag{5}$$

Thus,

$$(\alpha_f + \chi)\Delta T = -(1 - P_e)\epsilon_{strain} \tag{6}$$

The strain applied to the FBG can be given as:

$$\epsilon_{strain} = \alpha_{eff}\Delta T \tag{7}$$

Where α_{eff} is the effective thermal-expansion-coefficient of the Fiber and FBG area coated with Liquid Carbon, and it is in the opposite direction of that of the fiber. Thus, it can be expressed as:

$$\alpha_{eff} = \alpha_f + \alpha_{carbon} \tag{8}$$

And thus, the thermal expansion coefficient of the packaging material should be:

$$\alpha_{carbon} = -\frac{(\alpha_f + \chi)}{(1 - P_e)} - \alpha_f \tag{9}$$

We present a straightforward and effective solution. Our proposed method involves compressing the FBG by applying a negative axial strain and rectifying any shifts in the central wavelength caused by temperature fluctuations. This compression helps to counteract the effects of temperature-induced strains on the FBG by reducing the Bragg period (Λ_B). When an FBG is subjected to compressive forces, the Bragg period decreases, which can offset the expansion caused by temperature increases. This balancing act helps maintain the accuracy of central wavelength by minimizing the wavelength shifts that would otherwise occur due to temperature changes.

This is achieved by directly applying material with a NTE coefficient onto the exposed FBG, as illustrated in Fig. 1. NTE materials, unlike conventional materials, contract upon heating. The innovation lies in utilizing liquid carbon with a negative NTE for athermal packages, countering temperature effects on FBGs. Liquid carbon's NTE induces FBG shrinkage, creating a negative strain and decreasing the central wavelength with rising temperature. This compensates for the typical central wavelength increase when temperature increases in FBGs, ensuring athermal behavior. The NTE induces a strain on the FBG, counterbalancing the Bragg wavelength increase due to temperature, resulting in a decremental shift in the central wavelength. This mechanism effectively offsets temperature-induced wavelength shifts.

The preparation of FBGs before applying the Liquid Carbon material involves several critical steps to ensure a strong and uniform coating. Initially, the FBGs are thoroughly cleaned with alcohol to remove any contaminants, such as dust, oils, or residues, which

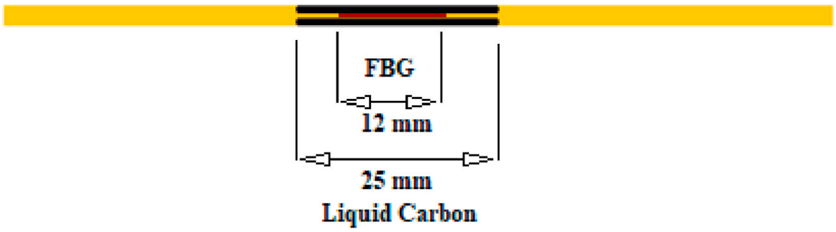

Fig. 1. FBG covered by NTE material.

could obstruct the bonding process. The cleaning process ensures that the surface of the FBG is free from any impurities that could affect the adhesion of the Liquid Carbon material.

The Liquid Carbon material is applied to the FBGs using the spin-coating method. The FBG is placed on a spin-coater, and a small amount of Liquid Carbon material is dispensed onto the center of the FBG. To achieve the desired coating thickness, two layers of Liquid Carbon material are applied. Each layer is dried before the next layer is applied, ensuring a smooth and uniform build-up of the coating.

The purpose of curing the FBGs coated with Liquid Carbon material is to solidify the coating and ensure its stability and adhesion. The coated FBGs are subjected to a controlled heat treatment process to dry. This typically involves placing the FBGs in an oven at a specific temperature between 60 °C and 120 °C, for 3 h. The heat treatment causes the Liquid Carbon material to undergo a chemical reaction, leading to the formation of a solid, stable coating. After the heat treatment, the FBGs are allowed to cool gradually to room temperature. This step is important to prevent any thermal stress that could affect the integrity of the coating.

3. Experimental results and discussion

In this study, a Liquid Carbon, which is a NTE coefficient material is applied over a 2.5 cm stripped photosensitive fiber, with 1.2 cm of FBG inscribed at the center. The FBG is annealed by exposing it to high pressure for approximately 12 h at a room temperature of 24 °C. This high-pressure annealing process achieves thermodynamic stability, relieves stress, and ensures a uniform structure for long-term stability. After annealing, the FBG characteristics are measured using a setup shown in Fig. 2 and it possesses the following characteristics: a central wavelength of 1540.48 nm, a bandwidth of 0.2 nm, and a reflectivity of 96 %.

The experimental setup of the system explained above is shown in Fig. 3. It involved subjecting the coated FBG to temperature variations between 24 °C and 96 °C. A VENUS stabilized laser source is used as an Amplified Spontaneous Emission (ASE) broadband light source and injects a C-band broadband light into the FBG through port one of the circulator. The insertion loss of the circulator is less than or equal to 1.5 dB. The reflected light from the FBG is then routed back from port two to port three of the circulator into the Ando AQ6317B Optical Spectrum Analyzer (OSA) to monitor wavelength shifts in response to temperature changes. The temperature of the packaged FBG is controlled and varied within a range from about 20 °C to 95 °C. The athermally packaged FBG exhibited remarkable stability.

The application of Liquid Carbon, a material with NTE coefficient of -4×10^{-6} at room temperature, played a critical role in stabilizing the FBG's central wavelength. As the temperature increased, the Liquid Carbon coating contracted, introducing negative strain on the FBG. This strain counterbalanced the Bragg wavelength shift typically induced by thermal expansion in the fiber. Consequently, the central wavelength of the packaged FBG remained constant, demonstrating a minimal shift of 0.06 nm, a significant improvement compared to the unpackaged FBG, which experienced a shift of 0.63 nm. This result underscores the efficacy of the NTE material in compensating for temperature-induced variations, ensuring the reliability and accuracy of the FBG in practical applications.

The relationship between temperature and wavelength shifts in both coated and uncoated FBGs is shown in Fig. 4. As expected, the uncoated FBG exhibited a linear wavelength increase as the temperature rose, reaching a peak shift of 0.63 nm at 96 °C. The athermal packaging with Liquid Carbon, however, maintained the wavelength shift within 0.06 nm. This small variation can be attributed to the NTE properties of the Liquid Carbon, which exerted a compensatory force on the FBG as the temperature increased. The experimental results align well with the theoretical model described by Equations (1)–(9), confirming that the applied coating mitigates the temperature effect by inducing negative strain on the FBG. A notable observation is a small dip in the wavelength shift at approximately 60 °C, which could be due to a transitional phase in the Liquid Carbon material or a minor shift in the structural integrity of the FBG under these thermal conditions.

4. Conclusion and future work

The Liquid Carbon packaging of FBG provides an easy and effective means to counteract the central wavelength increase $(\Delta\lambda_{B-temp})$ caused by rising temperature. The NTE liquid carbon induces FBG shrinkage, applying a negative strain that decreases the central

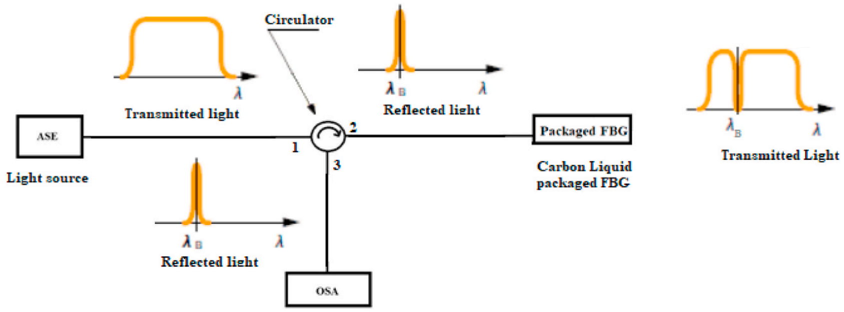

Fig. 2. Setup diagram.

Fig. 3. Experimental setup.

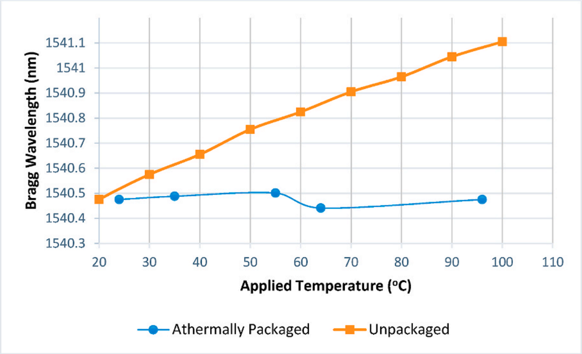

Fig. 4. Wavelength Shift with temperature variation in both unpackaged and athermally packaged FBG.

wavelength $(\Delta\lambda_{B-shrink})$ as temperature increases. The central wavelength change in the packaged FBG is the difference between the two $\left(\Delta\lambda_{B-temp} - \Delta\lambda_{B-temp}\right)$. This packaging method is simple and easily achievable compared to alternatives. Experimental testing reveals only a 0.06 nm change with a 72-degree Celsius temperature variation, demonstrating a 90 % reduction in Bragg wavelength shift. This cost-effective and straightforward packaging method enables the mass production of temperature compensated FBGs for sensing and communication applications with a simple and low-cost compact configuration. While the proposed liquid carbon-based athermal packaging shows effective temperature compensation, it is limited to a temperature range of 24°C-96 °C. Long-term stability and environmental durability of the packaged FBG should also be tested. Future work should explore broader temperature ranges, alternative NTE materials, long-term performance, and integration into practical DWDM and sensing systems.

CRediT authorship contribution statement

Mohammad M.N. Hamarsheh: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing. **Amjad Abu Jazar:** Writing – review & editing, Software, Resources, Funding acquisition, Data curation, Formal analysis, Investigation, Methodology, Visualization, Validation. **Tawfig Eltaif:** Validation, Investigation, Formal analysis, Methodology, Visualization, Writing – review & editing, Data curation, Writing – original draft, Funding acquisition, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was partially funded by the Arab American University–Faculty of Scientific Research, through a seed fund (Grant No. 1601/2/MM). The authors would like also to thank Dr. Mahmoud Manasrah for his support.

Data availability

Data will be made available on request. For requesting data, please write to the corresponding author.

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