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Work Package 1: Devices and Subsystems

Deliverable D1.1 (D01): Prototype for FBG sensor array

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Executive Summary

In this report, the progress on Task 1.1 of work package 1 is presented.

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1. Work Package Objectives

As part of OWIN6G network, WP1 objectives are shown below:

Design, and development of novel sensor networks (SNs) with (i) distributed biochemical optical sensor for environmental monitoring, and medical diagnostics; (ii) standalone mobile electro-optical sensor nodes for indoor applications; (iii) solar-cell-based power units; and (iv) hybrid radio frequency (RF)-optical transceivers.

Towards this goal the major tasks are: T1.1- Distributed optical sensor systems; T1.2- Portable electrical/optical sensor devices; T1.3- High performance flexible solar cells; T1.4- RF-optical Transceiver. For the current period, D1.1 presents the recent progresses in prototype of Fiber Bragg Grating (FBG) sensor array for distributed sensor system, achieved through collaborations between several partners from OWIN6G.

2. Specific Progress

2.1 FBG Sensor

The FBG sensor array is a powerful fiber-optic sensing technology enabling quasi-distributed sensing along an optical fiber with high precision and fast response [1, 2]. It supports real-time remote monitoring of various physical parameters such as temperature, strain, pressure, and refractive index. These features make FBG sensors widely applicable in fields such as structural health monitoring, oil and gas industries, etc.

FBG is created by inscribing periodic changes in the refractive index along the core region of an optical fiber. When broadband light passes through the fiber, a certain wavelength of light is reflected by these periodic changes, and the rest of the light continues to propagate. The reflected wavelength depends on the grating period and effective refractive index of the fiber core. When the FBG sensor is exposed to strain or temperature changes, the effective refractive index, and the grating period will be altered, resulting in the changes of reflected wavelength. By monitoring the changes in reflected wavelength, the precise measurement of strain or temperature can be achieved.

An FBG sensor array consists of multiple FBG sensors inscribed along a single fiber, each with a unique reflected wavelength. This setup allows multi-point sensing along the fiber, facilitating monitoring at multiple locations simultaneously. Since FBG sensors operate entirely through optical signals, they are immune to electromagnetic interference, making them ideal for harsh environments. Additionally, multi-parameter sensing (e.g., temperature and strain) can be achieved using reference FBG sensors.

The FBG interrogator system is the core of the sensor system and is responsible for detecting and processing changes in reflected wavelengths. Among several interrogation schemes, the most common method uses a tunable laser and a photodetector to capture the reflected spectrum. A stable tunable laser requires precise control of current and temperature. Also, fast algorithms are used to track the peak wavelengths in real time. A computer processes the spectrum data received from the FBG interrogator and outputs the calculated peak wavelengths.

The interrogator setup shown in Fig. 1 is based on collecting the reflection spectrum, which is suitable for FBG sensors. By adjusting the interrogator structure, transmission spectra can be measured, enabling compatibility with other types of fiber-optic sensors for broader application scenarios (e.g., whispering gallery mode resonator-based sensors for bio-chemical sensing).

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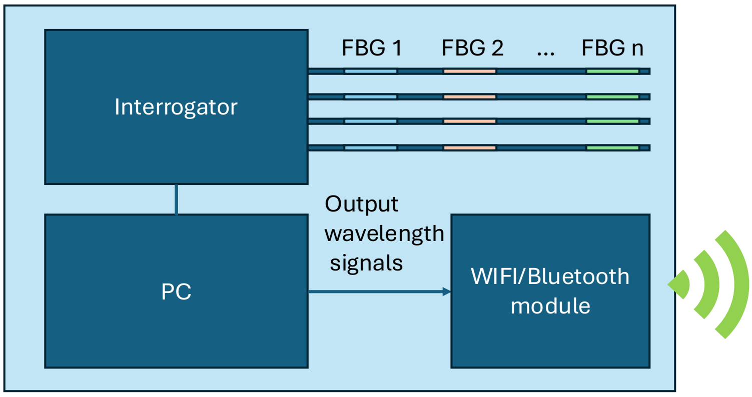

Fig. 1. Schematic diagram of sensor node structure

The exported electrical signal from the computer will then be connected to the communication modules (e.g., WIFI, Bluetooth, etc.), forming a wireless sensor node. By combining these components, the distributed optical sensor system can deliver reliable, precise, and real-time monitoring across a wide range of environmental and industrial applications.

2.2 Distributed Sensing

Due to their unique design, FBG sensors exhibit distributed sensing capabilities, enabling multi-point measurement along a single optical fiber. In a cascaded approach, each FBG reflects a specific wavelength based on its grating period and refractive index, allowing simultaneous monitoring of various points.

The length of the FBG sensing region is typically around 1 cm, enabling precise localization of sensing points. Additionally, the low attenuation of single-mode fibers at the 1.55 μm wavelength (~0.2 dB/km) makes FBG sensors particularly suitable for remote sensing applications, supporting monitoring over long distances with minimal signal loss. To enhance scalability, the FBG interrogator can be designed to connect to multiple channels, enabling even broader sensing coverage.

FBG-based distributed sensing systems offer several advantages, including:

- Long-Range Sensing: Monitoring over several kilometers with minimal signal loss.
- Multiplexing Capability: Supporting dozens to hundreds of sensors on a single fiber.
- Electromagnetic Immunity: Ensuring reliable operation even in harsh environments.
- Real-Time Data Collection: Providing continuous monitoring with high precision and fast response times.

2.3 Experimental Implementation

In our experiment, an optical spectrum analyzer (OSA) is employed to calibrate the FBG sensor. A broadband laser serves as the light source, providing a wide spectral range. The corresponding reflection spectra from the FBG sensor are recorded, and the peak wavelength is tracked in real time.

The experimental setup is illustrated in Fig.2. To accurately measure the sensor's response to temperature changes, a heating stage is used to control the temperature of the FBG sensor. Simultaneously, a thermocouple monitors the actual temperature in real time, ensuring precise temperature reference data for calibration. As shown in Fig. 3, the sensitivity of the FBG for temperature is 12.68 pm/°C. This indicates that the reflected Bragg wavelength shifts by 12.68 pm for every 1°C increase in temperature. This linear relationship confirms the sensor's reliability for temperature monitoring applications.

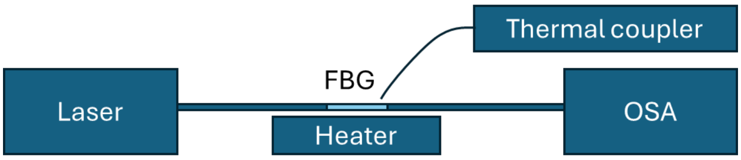

Fig. 2. Experimental setup for calibration of the FBG

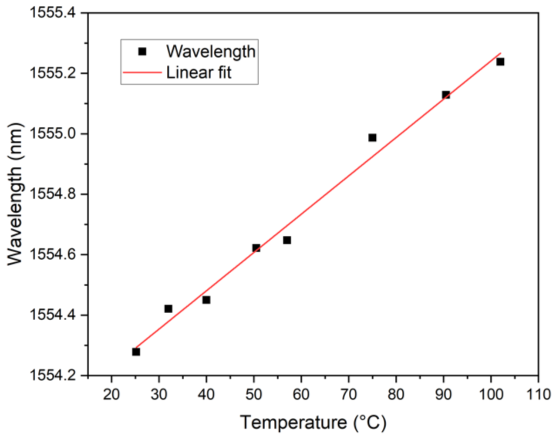

Fig. 3. Dependence of peak wavelength on temperature

A commercially available FBG interrogator is used to capture the reflected signals from the FBG sensors and convert them into digital signals for further processing. This setup enables real-time monitoring and data acquisition. As shown in Fig. 4, a simple distributed sensing system is demonstrated with two FBG sensors configured for temperature sensing. Each FBG has a distinct Bragg wavelength, resulting in two reflection peaks observed in the reflected spectrum. The intensity difference between the two peaks arises from the use of different types of FBG sensors with varying reflectivity. This reflectivity depends on the inscription process and the grating length of each FBG. Despite this difference, both sensors effectively contribute to multi-point temperature monitoring within the same optical fiber.

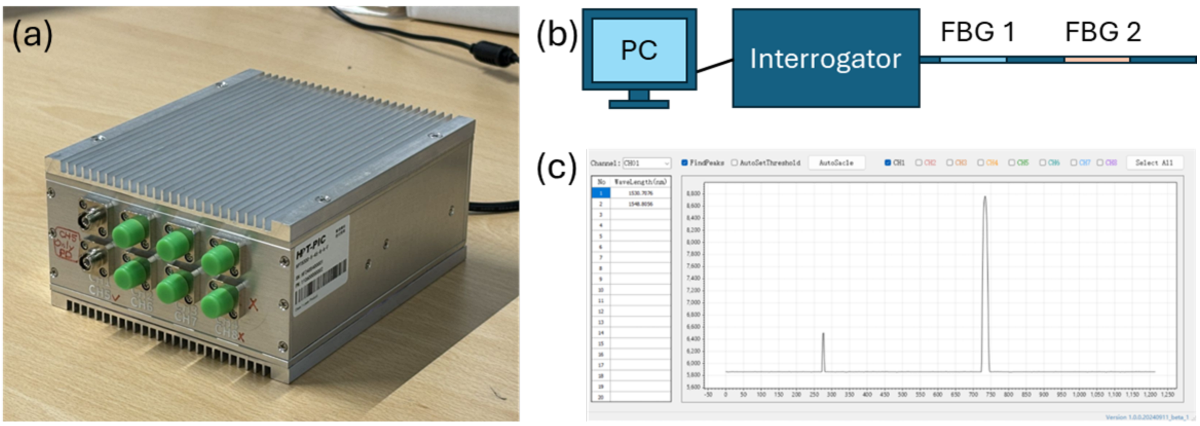

Fig. 4. (a) Interrogator with 8 channels. (b) Distributed sensing system with 2 cascaded FBGs, 2 FBGs are connected to 1 channel of the interrogator. (c) Reflection spectrum obtained from the interrogator.

To evaluate the system's performance, we monitored the peak wavelengths of the two FBG sensors over time. The results are shown in Fig. 5. The wavelength shift is induced by applying a finger to the back of the glass plate, ensuring the strain remains unaffected. The exported data from the FBG interrogator will be further utilized for hybrid communication in future work, enabling real-time wireless transmission and remote monitoring in distributed sensing applications.

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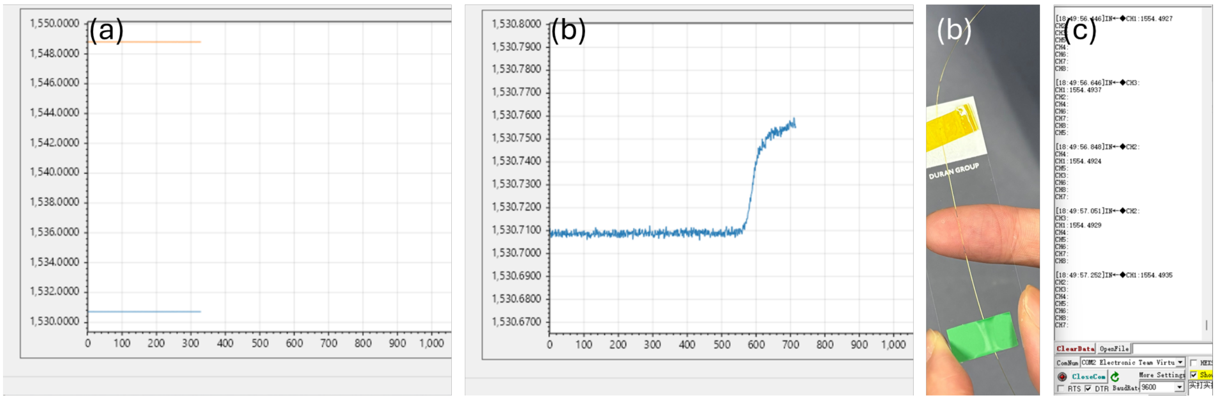

Fig. 5. (a) Tracked peak wavelengths of both FBG sensors over time. (b) Zoomed-in view of the wavelength variation. (c) Placement of a finger on the back of the glass plate with the FBG on the opposite side. (d) Output data from the interrogator with 5 Hz.

2.4 Optical Fiber Sensor Based on Whispering Gallery Mode Resonator

To achieve sensing with higher sensitivity and resolution, various whispering gallery mode (WGM) resonators have been coupled with a tapered fiber for measuring diverse parameters (as shown in Fig. 6). These resonators confine light through total internal reflection, enabling strong light-matter interactions and resulting in ultra-high sensitivity.

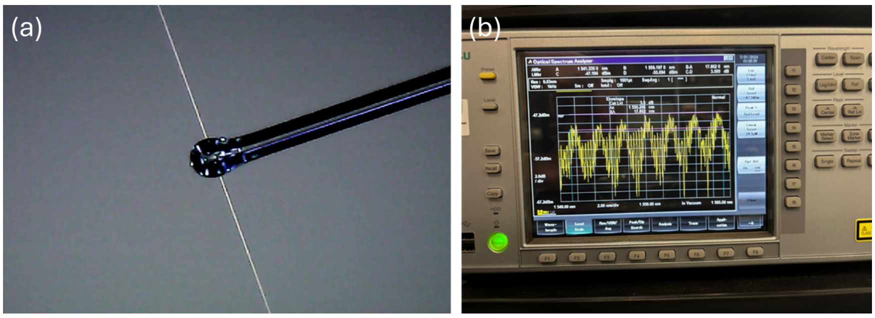

Fig. 6. (a) Coupling of the fabricated microsphere with tapered fiber. (b) Transmission spectrum obtained by OSA.

In our preliminary experiment, we employed a micro-bubble structure (as shown in Fig. 7) to detect subtle force changes with high sensitivity. The calculated sensitivity of the sensor reached 125 pm/mN, with a detection limit of approximately 8 μN. The sensor operates on an all-optical setup, making it inherently immune to electromagnetic interference (EMI). This characteristic ensures reliable operation in harsh environments where electrical sensors might fail. These features make the micro-bubble force sensor a promising candidate for applications in biomechanics, robotics, and structural health monitoring, where accurate and interference-free force detection is essential.

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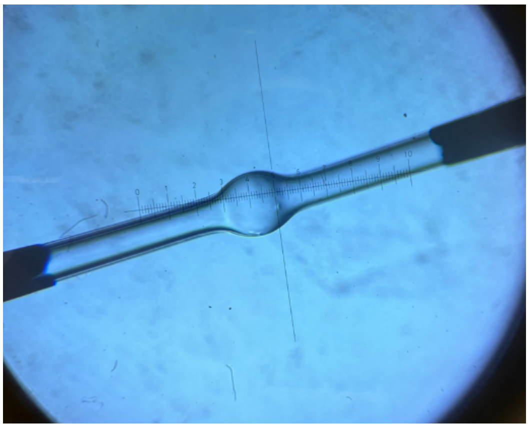

Fig. 7. Microscope image of the fabricated microbubble structure

2.5 Modeling and Optimization of FBG Sensors

The primary goal of optimizing FBGs is to maximize reflectivity at the desired wavelength while minimizing reflectivity at other wavelengths, particularly by suppressing side lobes. This suppression is critical in distributed FBG sensor systems to reduce crosstalk. To achieve this, refractive index modulation is employed to apodize the reflective spectrum of the FBG. This optimization problem is commonly referred to as the inverse scattering problem [3-6], where the objective is to derive FBG parameters (e.g., length, refractive index modulation profile) from the desired spectrum. The problem is treated as a multi-variable optimization task, supported by a detailed review of existing methods in the literature.

A simulation program was developed in Python to compute the reflectivity spectrum of FBGs. Key features of the program include:

- Simulation of various apodization profiles.
- Extraction of optimization variables (e.g., bandwidth, maximum side lobe reflectivity).
- Support for two computational methods: Piece Uniform Approach/Transfer Matrix Method and RK45 numerical solution.
- Simulation of spectral changes induced by temperature variations or linear stress along the fiber length.

Two approaches were tested to achieve the desired FBG spectrum:

1. Continuous Apodization Profile. The apodization function applied was:

$$\Delta n_{\mathrm{eff}}(z) = \Delta n_{\mathrm{eff}} \exp\left(-\rho \frac{(z - L/2)^2}{L^2}\right) \tag{1}$$

   where L is the FBG length, z is the position along the fiber axis, Δn_{eff} is the spatially averaged refractive index change over a grating period, and ρ is the apodization parameter. The goal was to optimize parameters ρ, L, and Δn_{eff}.
2. Cascaded Uniform Grating Profile. The desired profile was modeled as N cascaded uniform FBGs, each with a distinct Δn_{eff}, as described in [4]. The optimal profile was determined using multi-objective optimization algorithms, with the profile represented as an N-dimensional vector and serving as the parameters to be optimized:

$$dn = \left[dn_1, dn_2, \ldots, dn_N\right] \tag{2}$$

   Suppose we want the reflectivity of the FBG to be 1 for wavelength λ = 1550nm and zero for all other wavelengths. We can define the reflectivity of the desired spectrum as:

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$$R_{\lambda,\ \text{target}} = \begin{cases} 1 & 1549.9nm \le x \le 1550.1nm \\ 0 & \text{else} \end{cases} \quad (3)$$

The cost function can be defined as:

$$e = \sum_{i=\lambda_{\min}}^{\lambda_{\max}} \left(R_i(dn) - R_i^{\text{target}} \right)^2 \quad (4)$$

where $\lambda_{min,max}$ refer to the minimum and maximum wavelengths of the emission spectrum of the light source. To minimize the cost function different meta-heuristic optimization algorithms were tested:

- Particle Swarm Optimization (PSO),
- Staged Continuous Tabu Search [4],
- Gravitational Search Algorithm [7].

The simulation parameters were N = 20, L = 20mm, n = 1.45 and the boundaries of dn were chosen as $dn \in [0, 0.0002]$. Staged Continuous Tabu Search and Gravitational Search algorithm failed to reach a meaningful solution within a reasonable number of iterations. PSO in star topology proved more effective and the FBG reflectivity spectrum after 500 iterations with a particle size of 60 can be seen in Fig. 8.

Both the Staged Continuous Tabu Search and the Gravitational Search Algorithm failed to achieve a meaningful solution within a reasonable number of iterations. In contrast, the PSO method, utilizing a star topology, demonstrated greater effectiveness. The FBG reflectivity spectrum obtained after 500 iterations, with a particle size of 60, is illustrated in Fig. 8.

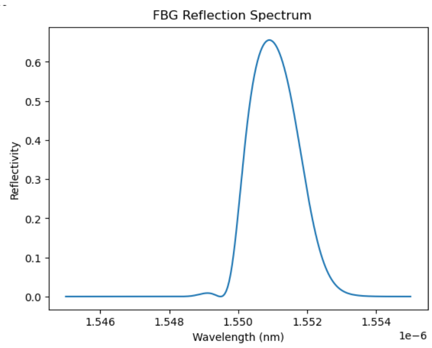

Fig. 8. Optimized Spectrum of FBG

The continuous apodization profile approach provides a computationally efficient solution suitable for achieving general FBG spectrum features.

The cascaded grating profile approach offers greater design flexibility but is computationally intensive, especially for large N, due to the expanded search space. Additionally, manufacturing such profiles is more complex.

2.6 List of Publications

No publications related to T1.1 were submitted at the time of this deliverable.

3. Summary

This deliverable presented the contributions received within the framework of WP1 for the tasks T1.1, focusing on the development and demonstration of the FBG sensor array prototype and related optical fiber sensing techniques.

4. Future works

Based on the progress made in WP1, the next phase will involve:

1. Data Utilization for Wireless Communication:
   The sensing data obtained from the FBG array will be integrated into a wireless communication module, enabling remote monitoring and real-time data transmission.
2. Energy Harvesting with Solar Cells:
   Solar cells will be incorporated to power the system, ensuring sustainable operation in outdoor environments.
3. Development of Sensor Nodes for Environmental Monitoring:
   Combining the FBG array, wireless communication module, and solar power source, a fully integrated sensor node will be developed. This sensor node will enable remote environmental monitoring.

5. References

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Annex A. Acronyms

WPi	**Work Package i**
Ti.i	**Task i.i**
Di.i	**Deliverable i.i**
FBG	**Fibre Bragg grating**
SN	**Sensor Node**
OSA	**Optical Spectrum Analyzer**
WGM	**Whispering Gallery Mode**
EMI	**Electromagnetic Interference**
PSO	**Particle Swarm Optimization**