STEWART, C., JOSEPH, C.S.J., JOHNY, J., ERDOGAN, N., FOUGH, N. and PRABHU, R. 2023. Optical fibre-based sensors for monitoring offshore floating photovoltaic farms. In *Proceedings of 2023 IEEE Oceanic Engineering Society conference and exposition (OCEANS 2023): blue ocean planet earth*, 5-8 June 2023, Limerick, Ireland. Piscataway: IEEE [online], document number 10244737. Available from: https://doi.org/10.1109/OCEANSLimerick52467.2023.10244737

Optical fibre-based sensors for monitoring offshore floating photovoltaic farms.

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2023

Optical fibre-based sensors for monitoring offshore floating photovoltaic farms

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***Abstract*— Solar photovoltaic farms are seeing increasing expansion into new domains (offshore) in order to harvest the sunlight as society pushes towards reaching Net Zero by 2050. However, photovoltaics are bound by physics, parameters such as temperature and strain varying result in changes in efficiency. Predictive maintenance through remote sensing can also save resources particularly in a domain where equipment and personnel are relatively expensive. This work represents the first investigation into the utilisation of Fibre Bragg Gratings (FBG) for offshore floating solar farms. It proposes a robust multiplexed network of FBG sensors to monitor these parameters in the harsh oceanic environment where equivalent electromechanical equivalents would fail. Using Super luminous LED (Light Emitting Diode), FBG interrogators, multiplexing techniques and the sensors themselves reliable, effective strain and temperature measurement can be made. A series of MATLAB simulations into how FBGs can be engineered to achieve these results were carried out. The findings suggest that applied to a select case study, 2 strain and 49 temperature sensors can be multiplexed on a single line of fibre. An experiment was also carried out that placed FBGs on an aluminum solar panel frame that suggests a bandwidth of 13.32µm would be needed to encompass the range in that specific study.**

Keywords*— *Offshore Solar Farm, Fibre Bragg Gratings, Photonics, Photovoltaics

I. INTRODUCTION

Solar energy is predicted to be a significant contributor in the grid of the near future if the 2050 goals for Net Zero are to be achieved. There are sizable terrestrial solar farms in countries such as India, China and the United States producing GW of electricity at its extremes under the right conditions. Beyond the manufacturing and mining processes which does produce significant carbon footprints, it does not produce greenhouse gases to produce electricity itself, therefore, it is going to be relied upon towards achieving these 2050 goals. It is safe to conclude therefore, if social and political attitudes do not shift, there will be continued solar farm expansion. However, terrestrial development of solar farms brings significant challenges legally and politically, given that this same land is competed for by other anthropomorphic interests such as farming etc and are often fraught with legal and licensing issues. In response to this, these solar farms traditionally earmarked for terrestrial development are being shifted into other domains such as the oceans [1] and even space [2].

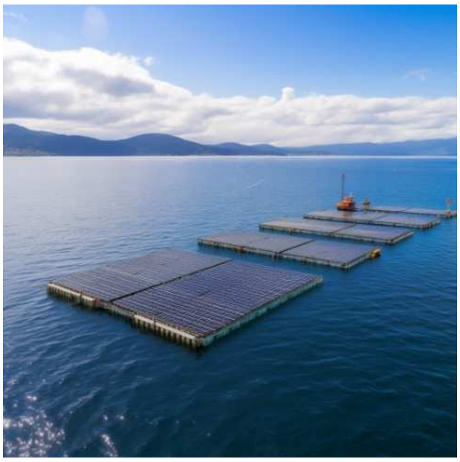

Figure 1. A floating solar farm

However, the process of developing electricity using solar panels is not a predictable process. Not only does weather play a role but the physics of the system do also, temperature plays a major role in the efficiency of these systems [3] and, to a lesser extent, does the mechanical strain on the system [4]. Given that monitoring of the grid and subsequent balancing are significant roles, even small changes on the efficiency of these farms can result in significant shifts in the amount of energy output. Also, to be considered is the fact that the equipment used in these systems must be monitored for faults that could interrupt supply or cause catastrophic damage to the investment, vibration and excessive heat is a common signifier of faulty equipment. Given that vessels and trained staff are expensive services and that offshore solar farms are relatively harder to access compared to terrestrial systems, often, careful, predictive management is required in order to be both time and cost effective.

Therefore, adequate remote sensing of these systems is often an effective method of performance analysis and pre-emptive maintenance. Optical fibre sensors such as fibre Bragg grating (FBG) are apt for this application in these environments compared to traditional electro-mechanical devices [5]. A subtype of Distributed Bragg Reflector, FBGs are popular research subjects for several advantageous properties in application such as structural health monitoring [6], acoustics [7] and beyond [8, 9]. Careful selection of these sensors can result in robust, accurate, reliable sensing of both temperature and strain on the same line of fibre without direct interference from the effects of one another whilst utilising multiplexing. This work presents a simulation and experiment into how many FBG sensors can be integrated on a single silica fibre within the output range of a common super luminous LEDs with a 1550nm centre frequency, thus providing robust temperature and strain measurement in a challenging environment using modern FBG interrogation equipment utilising Spatial (SDM) and Wavelength Division Multiplexing (WDM).

II. FBG SENSOR PRINCIPLES

FBGs are simple devices in principle. They are periodic refractive index perturbations along a line of otherwise uniform single core fibre caused by significant exposure to a pattern of optical interference [10]. A specific portion of a transmitted spectrum of light will be reflected by the series of gratings, the centre frequency of which will be determined by the equation 1.

$$\lambda_B = 2n_{eff}\Lambda \quad (1)$$

Where λ_B is the reflective Bragg wavelength, n_{eff} is the effective index of the fibre core and Λ is the grating period. The key controllable parameter here in the context of implementing multiple sensors is the shift of grating period which can be attained through utilisation of an ultraviolet laser to precisely create the gratings into the fibre core.

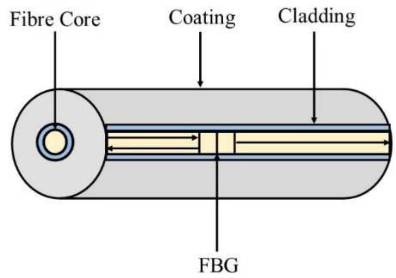

Figure 2. Simple FBG sensor illustration (not to scale)

Relevant to this application is the effect of strain and temperature on the physical properties of the fibre, the physical deformation caused by these shift the Bragg wavelength in a linear predictable manner, making them ideal for utilisation as sensors according to several relationships. This extent of deformation affects this wavelength shift which is due to several mechanical properties inherent in the material called the "opto-thermal" and "opto-elastic" coefficients. Therefore, in addition to equation 1, a change in these physical constants defined by the core material can give rise to a change in performance parameters such as sensitivity. The relationships are given as follows:

A. Strain

The strain induced Bragg wavelength shift on an FBG is given by equation 2 [11].

$$\Delta\lambda_{B|S} = \lambda_B(1 - P_e)\varepsilon_z \quad (2)$$

Where ε_z is the applied strain to the sensor and P_e is an effective strain-optic constant given as equation 3.

$$P_e = \frac{n_{eff}^2}{2}[P_{12} - v(P_{11} + P_{12})] \quad (3)$$

Where P_{11} and P_{12} are the photo-elastic constants otherwise known as Pockel's Constants whereas v is Poisson's ratio. Pockel's constants generally need to be determined experimentally, for common materials however, such as silica there are approximations commonly used within the academic community that can be used for numerical analysis.

B. Temperature

The temperature induced Bragg wavelength shift $\Delta\lambda_{B|T}$ is given by equation 4:

$$\Delta\lambda_{B|T} = \lambda_B(\alpha + \xi)\Delta_T \quad (4)$$

Where Δ_T is the temperature change, α is thermal expansion coefficient for the fibre and ξ is the thermo-optic coefficient. α is given by equation 5 and ξ is given by equation 6:

$$\alpha = \frac{1}{\Lambda}\frac{\partial \Lambda}{\partial T} \quad (5)$$

$$\xi = \frac{1}{n_{eff}}\frac{\partial n_{eff}}{\partial T} \quad (6)$$

Where Λ is the grating period. Table 1 is a derived table of some relevant coefficients of various glass constituents [12].

Table 1 parameters of various glass constituents

Value	SiO_2	Al_2O_3	SrO
R Index (1534nm)	1.444	1.653	1.810
ξ (10^{-6} K^{-1})	10.4	10.5	-12.4
α (10^{-6})	0.56	10.9	13.92
P_e	0.174	0.039	-0.120
P_{11}	0.098	-0.237	-0.296
p_{12}	0.226	-0.027	-0.245
v	0.16	0.25	0.231

III. Modelling Of FBG

A common numerical method for analysing the behaviour of FBG is to utilise Coupled Mode Theory (CMT). This method allows for analysis of wave propagation and how it interacts with the waveguides. CMT has been utilised successfully to model fibre gratings. To obtain the characterisation of an FBG's reflectivity for a given wavelength equation 7 can be used[11].

$$r = \frac{\sinh^2(\sqrt{\kappa^2-\hat{\sigma}L})}{\cosh^2(\sqrt{\kappa^2-\hat{\sigma}L})-\frac{\hat{\sigma}^2}{\kappa^2}} \quad (7)$$

Where $\hat{\sigma}$ and κ are the ac and dc coupling coefficients respectively given by equations 8 and 9.

$$\hat{\sigma} = \delta + \sigma - \frac{1}{2}\frac{d\varphi}{dz} \quad (8)$$

$$\kappa = \frac{\pi}{\lambda}\delta\overline{n_{eff}} \quad (9)$$

The detuning coefficients δ and σ in equation 8 are given by equations 10 and 11 respectively.

$$\sigma = \frac{2\pi}{\lambda}\delta\overline{n_{eff}} \quad (10)$$

$$\delta = \beta - \frac{\pi}{\lambda} = 2\pi n(\frac{1}{\lambda} - \frac{1}{\lambda_d}) \quad (11)$$

IV. FBG Multiplexing

There are several possible methods of multiplexing the information being received at the FBG Interrogator from the gratings installed on the fibre. SDM is possible. This would be limited, however, by the number of channels for the interrogator in question. WDM involves engineering the gratings in such a way that each grating has a specific bandwidth allocated to be utilised by each sensor considering the expected range of parameters the FBG is likely to face. This will allow several sensors to be implemented on the same fibre core of fibre. In addition to utilising each multiplexing convention individually, they can be combined to increase the number of sensors connected to each FBG interrogator. In this study, SDM and WDM has been considered.

V. Simulation and Experiment

These calculations were utilised in a MATLAB program in order to evaluate how many strain and temperature sensors can be expected to be implemented in an offshore solar farm scenario. For several single mode fibres engraved with FBG sensors given the available bandwidth of a standard super luminous LED that would be a candidate for use in this scenario. In this case the Thorlabs SLD1005S was selected. Several calculations were utilised to understand different grating lengths, effective indices, grating periods and reflective index changes effected the characteristics response of the FBG. In addition, some alternative materials were explored with different strain-optic and thermo-optic coefficients to understand how this could be utilised to enhance the sensitivity of the sensor as well as manage the available bandwidth of the super luminous LED that supplies to the fibre. The materials selected were various ceramics commonly found in the glass doping and fibre development literature, specifically silica (SiO_2), alumina (Al_2O_3) and strontia (SrO). Also crucial to this specific discussion is the bandwidth of the FBG response, given that this will impact how many sensors can be multiplexed using WDM on a single interrogator channel.

In addition, an experimental investigation of FBGs was performed to find out its' response to monitored physical parameters such as strain. The strain analysis experiment was conducted with the aid of traditional rigid and flexible PV panels, optical spectrum analyser (OSA) and light source. A rectangular cantilever beam comprised of aluminium material is utilized to mimic the sides of PV panels.

Table 2 Parameters for each variable in the simulation

Parameter	**Value**
Grating Length	2mm
Effective Refractive Index	1.447
Grating Period	535.59nm
Change in Effective Index	0.0005
Bragg Wavelength	1550nm

A single-mode glass optical fibre with a reflectivity wavelength of 1550 nm was adhered to the cantilever beam as demonstrated to verify its' suitability for Structural Health Monitoring of offshore FPV systems. Figure 3 shows the experimental set-up for this study.

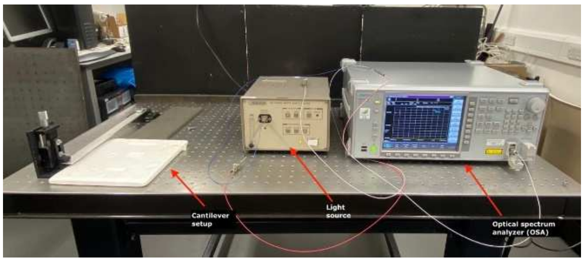

Figure 3. Experimental set-up.

VI. RESULTS

The results of these calculations informed how these sensors can be engineered in order to minimise bandwidth, thus maximising the number of sensors on a single fibre. Figure 4 shows how changing the grating lengths, whilst keep the other variables constant, effected the reflectivity and bandwidth with longer gratings reducing the bandwidth and the expense of increasing the amplitude of the lobes.

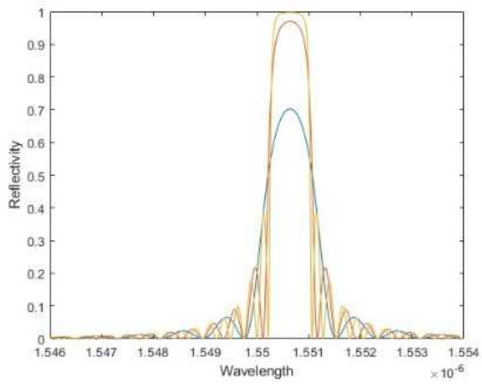

Figure 4. FBG response for varying Grating Lengths: 1mm (blue), 2mm(orange) and 3mm (yellow)

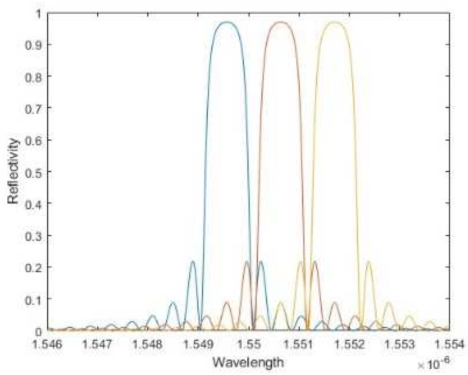

Figure 5. FBG response for varying effective refractive indices 1.446 *(blue)*, 1.447 *(*orange*)* and1.448 *(*yellow*)*

Figure 5 shows how changing the refractive index of the fibre core shifts the centre wavelength proportionately to the change whereas figure 6 shows the bandwidth of the signal is also affected by the how the shift in grating refractive index with the core. This is another variable that can be controlled to manage the effective bandwidth for each FBG.

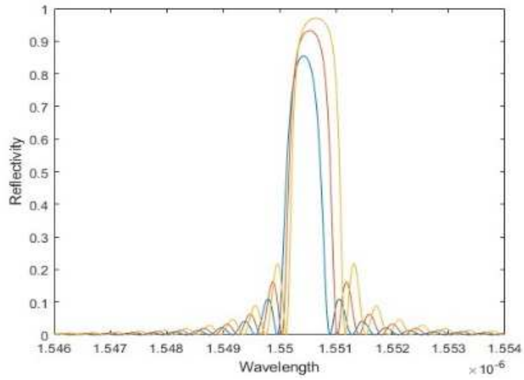

Figure 6. FBG response for varying effective refractive index changes at the gratings where the blue line is 0.0004, orange is 0.0005 and yellow is 0.0006

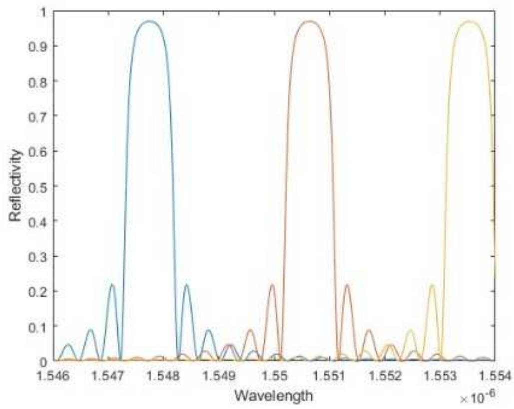

Figure 7. FBG response for grating period changes: 534.59 (blue), 535.59 (orange) and 536.59 (yellow) nm.

Figure 7 shows how the grating period affects the wavelength of an FBG response. This suggests that by engineering the grating period, the FBG sensor responses can be engineered to be at specific wavelengths in the super luminous LED spectrum. If these are carefully considered, along with the sensitivities of each sensor to temperature and strain, then the bandwidth can be allocated accordingly. According to [11], a grating length of 8mm and refractive index change of 0.0005 produces the response seen in figure 8 which corresponds with an FBG bandwidth of 0.6nm, the smallest value found in that investigation.

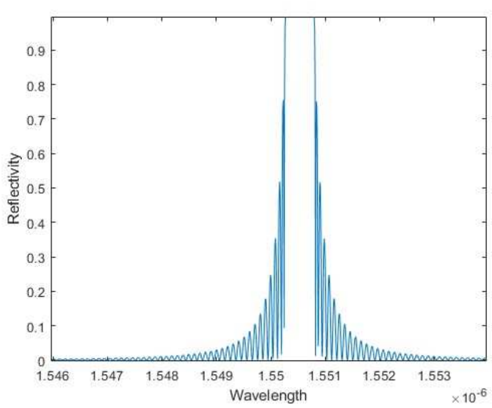

Figure 8. Response of an FBG with an index of 0.0005 and a grating length 8mm

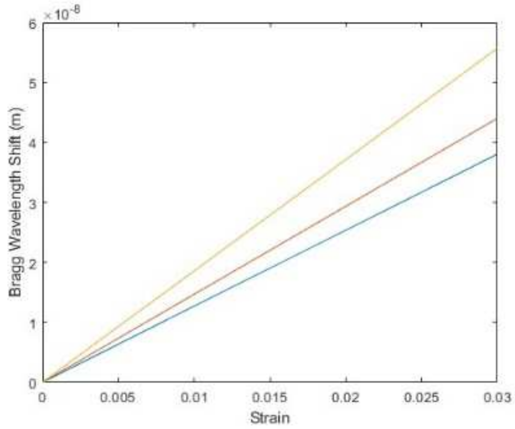

Figure 3. Strain response of FBGs with different core materials silica (blue), alumina (orange) and strontia (yellow)

Figure 9 shows the strain response of several materials that could be utilised in an FBG sensor fibre for purposes of increasing the sensitivity and, thus, reducing the bandwidth each sensor needs to occupy. Between the three materials that the typical optical fibre material, silica, is the least sensitive to strain whereas strontia is the most sensitive to strain. Figure 10 shows the characteristic temperature response of the same three materials. In this case strontia was the least sensitive to temperature whereas alumina had the most sensitive response. Therefore, it can be said that fibre material needs to be considered in order to manage bandwidth, as the more sensitive materials will use more bandwidth for the same ranges of parameters in exchange for a better resolution for a common FBG interrogator.

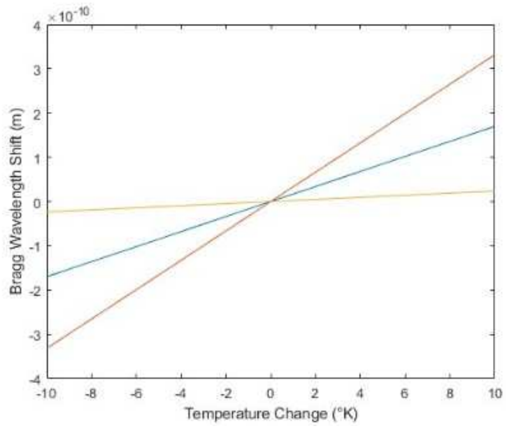

Figure 10. The effect of temperature change on FBG with different core materials; silica (blue), alumina (orange) and strontia (yellow)

In addition, the experimental work provided insight into the performance of the FBG mounted on the solar panel when strain was applied figure 11 shows how the application of strain shifted the Bragg wavelength.

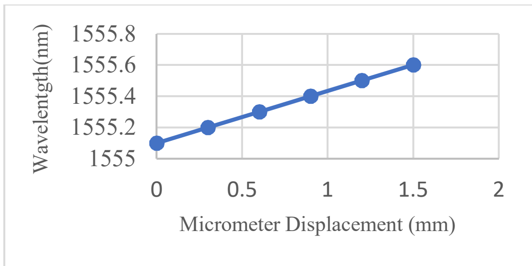

Fig. 11. Impact of strain on the reflected wavelength

It is observed that the reflected Bragg wavelength increases linearly with the strain applied on the cantilever. Table 3 shows the sensitivities of these select materials based on these activities.

Table 3 the sensitivities of the select materials derived from the simulations

Compound	Strain Sensitivity (nm/millistrain)	Thermal Sensitivity (pm/°K)
SiO_2	1.35	16.84
Al_2O_3	1.45	32.87
SrO	1.84	2.29

VII. Discussion

Based on these results, it is possible to anticipate how many of these sensors will be possible over a given range of possible strain and temperature values. An experiment is carried out in [13] that uses temperature ranges of -40°C to 80°C and considers strain from 0% to 4%, for analytical purposes these shall be utilised in this discussion. In addition, silica will be considered as the core material. This gives a temperature range of 120°C considered in this instance and 4% strain. A single FBG for temperature response, therefore, will shift by 2020.8 pm across the given range whereas a FBG sensor for strain will shift by 13.32μm. In this scenario, the wavelength spectrum for the temperature sensors can be divided more than that utilised for the strain sensors for multiplexing purposes as each sensor requires less bandwidth. If the spectral bandwidth to be utilised is that which is above -30dB of the super luminous LED, then this will be 130 nm. Considering the case of the strain sensor and given the bandwidth is 0.6nm, this suggests that the allocated bandwidth will need to be 54.6nm to encapsulate the expected response. Therefore, within this bandwidth two strain sensors can be placed. Considering the case for a core containing temperature sensors, the allocated bandwidth needed will be 2620.8pm for the given range, this suggests 49 FBG sensors can be placed in a single core in this instance. This can be scaled in addition, if spatial multiplexing is used by introducing an interrogator that has the capacity to connect multiple lines of fibre. If two optical connections are utilisable then that would double the capacity of sensors that can be connected to that interrogator. In the case discussed in the experiment, the sensitivity is 333 pm/microstrain therefore a larger bandwidth of 13.32μm would be needed to achieve the same 0.04 strain range on the aluminium panel mount. This would require alternative SLED.

In addition to the discussed multiplexing techniques, machine learning is a field revolutionising many traditional methodologies in many fields [14]. Current literature on the matter of multiplexing suggests that this technology will play a role in this field too, allowing for further gains to occur in the number sensors possible on a single line. For an example, [15] utilises deep learning techniques and Intensity Wavelength Division Multiplexing to achieve this. However, investigations need to be carried out into how this can be adapted for the emerging offshore solar power field.

VIII. Conclusion

This work presented an investigation into how many FBG sensors could be potentially connected to a single line of fibre given a select portion of bandwidth available from a super luminous LED source using a series of MATLAB driven simulations. Assuming WDM and SDM techniques were to be utilised, it was found that, in the given case study, 2 strain and 49 temperature sensors could be connected in a single core utilising WDM alone. This could, in addition, be increased by utilising SDM through connecting additional fibre cores to a single FBG interrogator that allow for the capacity of sensor to increase, scaled, by the number of connectors available.

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