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# Hybrid Distributed Sensing System for Dynamic Strain and Temperature Measurement

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**Abstract:** We propose a novel hybrid sensing scheme over a single optical cable using time-division-multiplexing of two interrogation technologies to perform distributed acoustic measurements over a frequency ranging 100Hz−1kHz and temperature measurements with uncertainty below 0.2$^0$C. 

## 1. Introduction

With the ever-growing threat from climate change and increasing industrial use of the sea for renewable energy, the need to monitor marine environment has never been greater. Distributed acoustic sensing (DAS) is emerging as an attractive technology for underwater sensing, offering numerous advantages over traditional hydrophones. The benefits include extended spatial coverage, enhanced spatial resolution, cost-effective maintenance, better sensitivity, immunity to electromagnetic interference, and the ability to operate effectively in harsh environmental conditions. Researchers have recently actively pursued the DAS technique to detect various acoustic signals from natural sources, mammals, and anthropogenic activities [1]. Water temperature is another critical indicator of marine ecosystem health. Even a small temperature change of ~0.2°C can adversely affect coral reefs, phytoplankton, and fish habitats, risking irreversible ecological transformation.

Detecting temperature and strain from the same DAS data is challenging as both parameters induce phase changes in the received signal. The use of chirped pulse Brillouin optical time domain reflectometry (OTDR) and chirped pulse phase OTDR for temperature and strain sensing, respectively, on non-uniform cable was proposed by Wang *et al.* to solve this issue [2]. However, the strain accuracy and temperature uncertainty were 4.3 με and 0.32$^0$C, which is not ideal for underwater sensing applications as much higher accuracy is needed [1]. In recent years, ultraweak fibre Bragg gratings (FBG) were proposed for distributed temperature and strain measurements. The scheme senses temperature using FBG's narrow filter edges to translate temperature-induced wavelength shifts into a simple intensity measurement, while distributed vibrations are observed by detecting phase variation between two adjacent broadband ultraweak FBG interference pulses [3]. However, edge-filter-based temperature sensing is prone to errors from laser intensity fluctuations, bending loss, splice loss, etc. Inscribing scattering dots in an optical fibre cable to enhance backscattering and simultaneous measurement of temperature gradient and strain is also proposed [4]. However, this article only provides information on temperature gradient measurement and no information on its accuracy. Sidenko *et al.* proposed the use of distributed temperature sensing (DTS) and DAS technology on two different cables for temperature and strain measurements which is a reliable method, however, needs two different optical cables [5].

High speed, high precision, and reliable tunable laser based FBG interrogators are commercially available for quasi distributed temperature sensing with 0.1°C resolution [6]. In this paper, we propose and experimentally demonstrate the feasibility of a new scheme combining two different technologies for hybrid sensing i.e., temperature sensing using a tunable laser based FBG interrogator and a DAS interrogator on a single sensing cable accessed using a fast optical switch. The sensing cable consists of standard single-mode optical cable and uniform apodized FBGs.

## 2. Proposed Hybrid Sensing Scheme

The proposed hybrid sensing scheme for underwater applications shown in Fig. 1(a) consists of a fast tunable laser based FBG interrogator for temperature sensing and a coherent phase optical time domain reflectometer (Φ-OTDR) to detect Rayleigh backscattering and perform distributed acoustic sensing. The interrogators use an optical switch to access the sensing cable in a time-division multiplexed manner. The proposed sensing cable is a standard single mode fibre of up to 10 km total length, with a lead-in section of (0 – 7 km) followed by a sensing section up to 3km length with high reflectivity FBGs spaced every 100 m. The FBGs act as discrete sensing elements offering temperature measurement every 100 m along the fibre, while the entire fibre can act as a distributed acoustic sensor with a spatial resolution (in the order of ~10 meters) determined by the launched OTDR pulse width. Fig. 1(b) shows the wavelength allocation of the FBG's reflected wavelengths, $\lambda_{FBG,1..n}$, and a single fixed wavelength for DAS interrogator $\lambda_{DAS}$ in

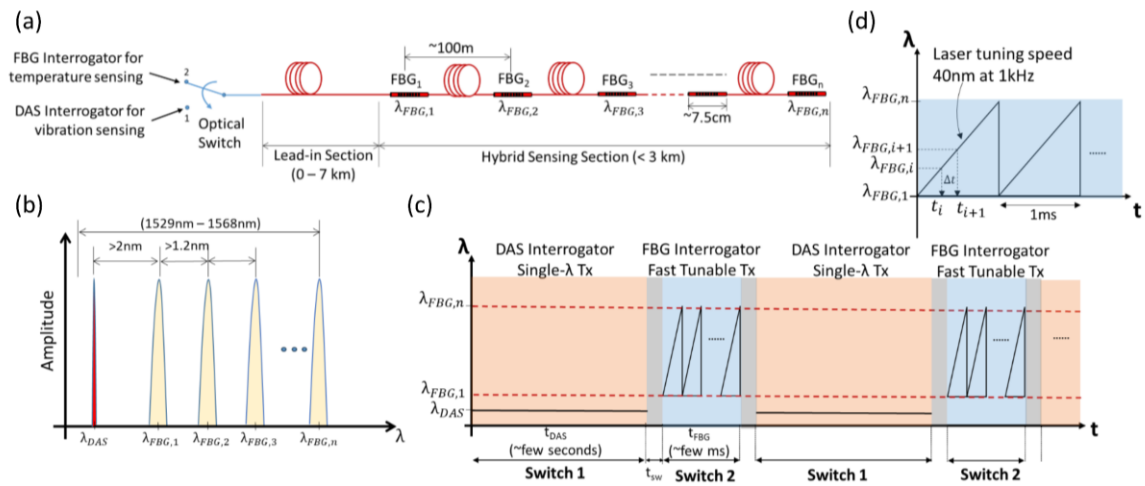


Fig. 1. (a) Proposed hybrid sensing scheme using two different interrogation technologies over a single sensing cable. (b) Wavelength allocation of DAS and FBG wavelengths in the C-Band. (c) Time-division-multiplexed operation of DAS and FBG interrogator enabled by a bidirectional optical switch and (d) shows linear sweep of the fast tunable laser in the FBG interrogator.

the C-Band. To avoid cladding mode loss, $\lambda_{DAS}$ must not be placed in the vicinity of 2 nm of FBG's Bragg wavelengths [7]. The intended dwell times of the optical switch positions for DAS (Switch 1) and FBG (Switch 2) interrogators are indicated in Fig. 1(c). To measure low frequency vibrations (~100Hz range) reliably, the Switch 1 position will require a time slot in the order of a few seconds, while the temperature measurements from all the FBGs along the sensing cable will only take a few milliseconds.

FBGs are the Bragg grating inscribed at the core of the optical fibre, whenever a broadband signal is passed through these gratings the reflected signals are coupled at a particular wavelength ($\lambda_{FBG,i}$) due to the Bragg condition that depends upon the grating period ($\Lambda_i$) and effective index ($n_{eff}$). Hence, only one wavelength that satisfies $\lambda_{FBG,i} = 2.n_{eff}.\Lambda_i$ is reflected while other wavelengths propagate with negligible loss. As temperature changes in the vicinity of these gratings, their periodicity and the effective index of fibre change, resulting in a shift in Bragg wavelength [8]. For accurate wavelength-to-time mapping of the reflected light to estimate temperature from all the gratings along the fibre, the following condition needs to be satisfied between the sensing cable and the interrogator parameters, $\lambda_{FBG,i+1} - \lambda_{FBG,i} > r_{Tx} . [2.L_{fibre}.n_{eff}/c]$ where the expression inside square brackets is the round trip time of light over the sensing cable, $r_{Tx}$ is the laser tuning speed, $L_{fibre}$ is the length of the sensing section of the fibre, and $c$, is the speed of light in fibre. For a 3 km sensing section and a laser tuning speed of 40nm over 1ms, we get the minimum wavelength spacing between any two FBG's peak wavelengths, $\lambda_{FBG,i}$ *and* $\lambda_{FBG,i+1}$ to be 1.2nm. With a tunable laser of 40nm coverage, we can have ~30 FBGs along a 3km fibre section, which suggests we can have a temperature measurement for every 100 m, which is acceptable for the intended application as the temperature gradient over distance is gradual in underwater environments. The standard length of commercial FBGs, including an encapsulated metal layer to isolate from external strain, is around 7.5mm. The impact of the proposed inscription of FBG array in the sensing fibre has negligible impact on DAS because of the following reasons: compared to the typical spatial resolution of ~5m for DAS, the discontinuity from the 7.5 mm FBG elements is a negligible fraction, the FBG elements are sparsely located (every 100 m), and they have negligible insertion loss (0.1−0.2 dB). Additionally, the time slot for the FBG interrogator only needs to be a few milliseconds in duration to measure temperature across the entire FBG array, resulting in a short interruption for DAS measurements.

## 3. Experimental setup and results

The experimental setup shown in Fig. 2 consists of three main units; sensing cable, FBG interrogator and DAS system. The FBG unit is a commercial interrogator (I4G FBG Interrogator from Optics11 FAZ) which uses an electronically tunable laser that scans between 1529nm to 1568.2nm with a repetition rate of 1 kHz to observe the back reflected Bragg wavelengths from different FBGs using direct detection. It has a wavelength precision of <0.1pm and wavelength accuracy of 1pm which theoretically corresponds to ~$0.1^0$C temperature accuracy for FBG based temperature sensors. To test the proposed scheme, we built a sensing cable consisting of three single mode fibre spools with a combined length of 2.3km and two FBGs having Bragg wavelengths at 1560 and 1565nm with full width half

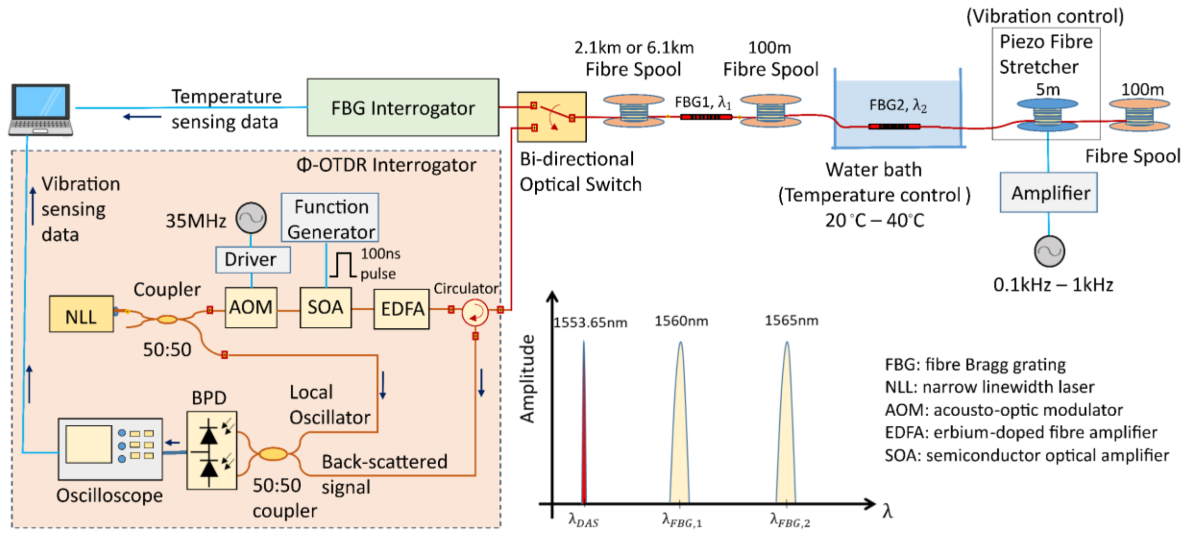


Fig. 2. Experimental setup with controlled temperature and vibration to test the performance of the proposed hybrid sensing scheme using a commercial FBG Interrogator I4G from Optics11 FAZ for temperature sensing and a coherent Φ-OTDR laboratory testbed for distributed acoustic sensing (DAS).

maximum (FWHM) of 0.3nm, uniformly apodised and reflectivity 50% to 75%. To test the capabilities of the hybrid scheme, a temperature-controlled water bath and a piezo fibre stretcher (PFS) were used to vary the temperature ($20^0$C − $40^0$C) and induce vibrations (100Hz – 1kHz) at known locations along the sensing fibre. An opto-mechanical 1×2 bi-directional switch connects the FBG and DAS unit to the fibre. The switch provides 60dB crosstalk isolation between the two interrogators. The DAS unit is a Φ-OTDR setup built from commercial components consisting of a narrow linewidth laser (NLL), acousto-optic modulator (AOM) to shift the laser light by 35 MHz, a semiconductor optical amplifier (SOA) to carve 100 ns pulses with high extinction ratio (50 dB) followed by an erbium-doped fibre amplifier (EDFA) to boost the launched interrogation pulses. Optical bandpass filters (not shown in the figure), with 0.4 nm bandwidth, were placed after the SOA and EDFA to remove ASE from the launched signal. A balanced photodiode (BPD) coherently beats the local oscillator and the Rayleigh backscattered light. The inset in Fig. 2 shows the operating wavelength of the DAS and the centre wavelengths of the two FBGs incorporated in the sensing cable. The narrow linewidth fibre laser provides a maximum power of 14.2dBm at 1553.65nm (6.35nm away from the nearest FBG Bragg wavelength). An optical coupler splits the source light and sends one path to an acousto-optic modulator (AOM) and SOA pulse carver, and the other path acts as a local oscillator for coherent detection. The Rayleigh backscattered signal that travels back from all points along the fibre is routed via a circulator to the BPD. The received signal is phase demodulated in the digital domain to determine the frequency and amplitude of the applied dynamic strain. Although we have experimentally demonstrated only two FBGs and a shorter sensing range due to implementation constraints in the laboratory, the FBG interrogator and DAS system used in the setup can support the sensing scheme configuration with ~30 FBGs proposed in Fig. 1.

Fig. 3(a) shows results from the FBG interrogator operating in time-division-multiplexed mode. While the switch is in position 2, we can measure temperature from all FBGs every 1ms, so in principle, we can reduce the Switch-2 dwell time to a few milliseconds. The rise/fall time of the optical switch in the setup is 100 ms, but faster transitions (~50 μs) are possible [9]. The results in Fig. 3(b, c) show that the hybrid system can perform temperature measurements with uncertainty below $0.2^0$C and perform distributed acoustic measurements over a frequency ranging 100Hz−1kHz. Fig. 3(c) shows the maximum phase shift (peak to peak) that can be detected by the DAS for a range of vibration frequencies. The fibre is monitored by the DAS interrogator while the Switch is in position 1 over a duration of 20 ms with the DAS gauge length set to 20 m. The sensing ranges of 2.3 km and 6.3 km were used to show the impact of the sensing range on the maximum detectable phase. This combination of phase and frequency is encapsulated in a term known as strain rate. The limitation on the strain rate is imposed by the sampling conditions for the reconstruction of the phase change induced by the vibration [10]. Here the sampling rate is determined by the roundtrip propagation. For any sensing range, there is a maximum associated strain rate, which can be satisfied by different combinations of strain induced phase amplitude and frequency. It can be seen in Fig. 3(c) that there is a good fit between the experimental and numerical data at the higher frequencies. The deviation at the low frequency is due to the low-frequency phase noise caused by environmental fluctuations and laser phase noise.

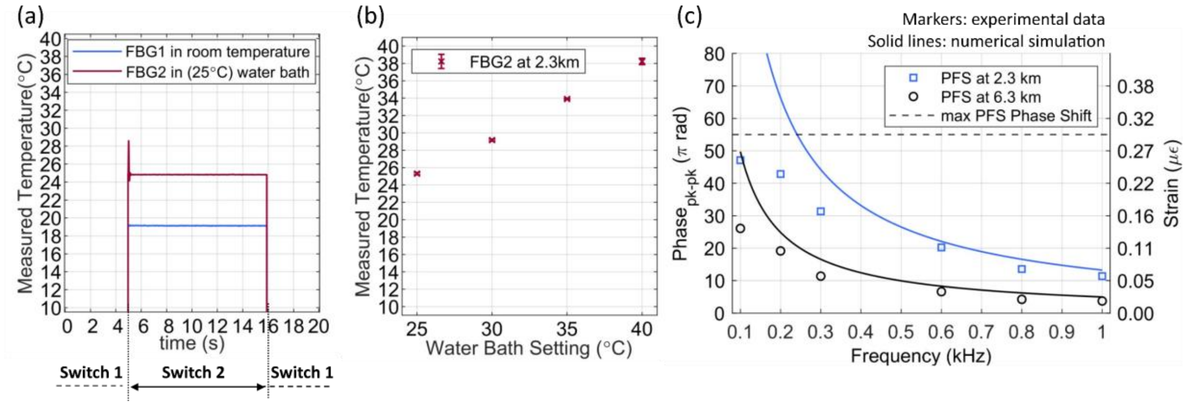


Fig. 3(a) Plot of 20,000 temperature readings from FBG interrogator operating at 1kHz tuning rate (one reading for each of the two FBGs in the setup every 1ms). (b) Measured temperature with error bar from 6000 readings while optical switch is in position 2. (c) Measured peak to peak optical phase while optical switch is in position 1 and various dynamic strain applied to Piezo Fibre Stretcher.

## 4. Conclusion

In summary, we demonstrate a hybrid sensing scheme over a single sensing cable capable of distributed dynamic strain measurements over 100Hz–1kHz frequency range with 20 m spatial resolution and distributed temperature measurements spaced 100 m apart with uncertainty below $0.2^{0}$C. We show that the time-division-multiplexed approach that we employ to switch between the FBG interrogator and the Φ-OTDR to access the same optical cable does not limit the sensing capability and can meet the desired temperature and dynamic strain targets for marine monitoring applications. Both temperature and acoustic measurements are critical for underwater marine environment monitoring and hence the proposed scheme could be an attractive solution to integrate two sensing modalities.

## 5. Acknowledgements

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