

The potential application of a fibre-optic icing sensor in identifying water content in planetary atmospheres

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ABSTRACT

The aim of the present work is to present to the research community a potential space application of an icing sensor based on fibre Bragg gratings (FBGs) or long-period gratings (LPGs). These icing sensors, developed by the National Institute of Aerospace Technology, can detect the phase transition from supercooled water to ice. When supercooled water droplets strikes a surface, it freezes and adheres to it. This process modifies the aerodynamic shape of the surface, thereby affecting its aerodynamic performance. In addition, sensitive instrumentation located on the spacecraft surface may be affected by ice accretion, potentially compromising its operation. These ice sensors can operate in conjunction with heating elements that are activated as soon as ice is detected, thereby removing the accumulated ice. The sensors have been tested in aeronautical field for icing detection under flight conditions with promising results. They also have applications in other areas where ice formation can cause problems for structures, such as wind turbine blades or power lines. It is therefore expected that they may also be applicable to planetary exploration missions.

Keywords: Supercooled water, phase transition, icing sensor, optical fibre sensors.

1. INTRODUCTION

Several studies provide evidence for the existence of oceans of liquid water beneath the icy shell of several bodies in the Solar System, such as Europa, Titan, and Enceladus. The scientific evidence supporting these findings has been reported by Lunine, J. I.¹, and Nimmo, F., et al.² The work of Hansen, C.J. et al.³ presents observations of Enceladus obtained by Cassini's Ultraviolet Imaging Spectrograph (UVIS) and other instruments designed to study its plumes, and concludes that water vapor is the main component of the plumes emerging from the "tiger stripes" on the Enceladus surface. In their paper, Parkinson, C.D et al.⁴ discuss the possibility of finding "extremely high" temperatures on the surface of Enceladus compared with its surroundings, ranging from -23 °C to 0 °C. These observations suggest that an icing sensor could potentially be a useful tool for investigating the presence of water in other environments within the Solar System. Furthermore, a system that includes an ice-formation sensor could be very useful for scientific instruments used in planetary atmospheric exploration missions, as it can detect ice formation on their surfaces and activating an anti-icing system only, when necessary, thereby reducing energy consumption.

Supercooled water can happen in the Earth's atmosphere under appropriate environmental conditions, temperatures ranging from 0°C to -30°C. It is a metastable state in which water remains liquid at a temperature below its freezing point, 0 °C. Icing is the accumulation of ice on the surface of structures that occurs when supercooled water droplets impacts them and rapidly undergo a phase transition from the liquid to the solid state. This transition is exothermic and releases the latent heat of crystallization, which increase the temperature of the water. If the volume of water is sufficiently large, the temperature increases until it reaches 0°C; if the water volume is small, a temperature increase of a few degrees can be detected. The icing sensor described in this work detects this temperature increase resulting from the phase transition of supercooled water by means of the wavelength shift of an FBG.

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FBGs and LPGs are highly sensitive to temperature increase caused by phase transition of supercooled water, even when this phase transition occurs with volumes of only a few microlitres. FBG and LPG based sensors can provide more accurate measurement of ice formation than conventional sensors, such as thermocouples, due to fast response to small temperature variations. The proposed icing sensor is based on the use of two FBG or LPG sensors. The advantages of the proposed icing sensor include its low weight, immunity to electromagnetic interference (EMI), the stability under space radiation environment^{5,6} and the low power consumption of its electronic interrogation system. These characteristics make the proposed icing sensor a promising candidate for integration in planetary exploration missions, where ice accumulation on structures and scientific instrumentation could interfere the operation of the spacecraft mission.

The current paper is structured as follows. Firstly, the theoretical background on FBGs and LPGs is outlined to introduce the operating principle of the proposed icing sensor. Next, the icing wing tunnel (IWT), which is the key facility used to characterize the icing sensor sensors, is presented. Finally, the results of three icing experiments carried out in the icing wind tunnel are presented and described.

2. MATERIALS AND METHOD

FBGs and LPGs as temperature sensors: Measuring principle

Both FBGs and LPGs are fibre-optics sensors that consist of a periodic modulation of the refractive index of the fibre core. The main difference between FBGs and LPGs lies in the grating period. For FBGs, typical grating periods range from 0.5–0.55 μm , whereas for LPGs range from 100–1000 μm . This physical difference is also reflected in their operating principle. FBGs reflect a narrow spectral band known as the Bragg wavelength. This reflected band appears as a peak when is measured in reflection mode or as a valley if it is connected in transmission⁷. The Bragg wavelength, λ_{FBG} , is determined by the effective refractive index of the core, n_{eff} , and the grating period, Λ_{FBG} , according to the following expression:

$$\lambda_{FBG} = 2n_{eff}\Lambda_{FBG} \quad (1)$$

In LPGs, the energy typically couples from the fundamental guided mode to discrete, forward-propagating cladding modes. The cladding modes are quickly attenuated, and this result is a set of loss bands in the transmission spectrum of the grating. There is no reflection spectrum for LPGs. Each of these attenuation bands corresponds to the coupling of different cladding modes, each with a different effective refractive index. The values of the effective refractive indices depend on the specific parameters of the fibre. For a specific LPG grating, with period Λ_{LPG} , the wavelength λ_{LPG}^m at which the mode coupling occurs is given by:

$$\lambda_{LPG}^m = (n_{core} - n_{cl}^m)\Lambda_{LPG} \quad (2)$$

where n_{eff} and n_{cl}^m are the effective indices of the guided mode and the LP_{0m} cladding mode, respectively⁸. Table 1 and Figure 1 present the key features that determine the performance of FBGs and LPGs:

Table 1. FBGs and LPGs measurement properties.

Feature	FBG	LPG
Grating period	0.5–0.55 μm	100–1000 μm
Grating length	2 – 10 mm	20 – 50 mm
Coupling	Core – core	Core – Cladding
Measuring capacity	Temperature, strain.	Temperature, strain, refraction index
Temperature sensitivity	8 – 13 $\text{pm}/^\circ\text{C}$	Depending on the guided mode

Without any mechanical deformation, a change in temperature causes a change in the length of the fibre due to thermal expansion. Furthermore, the thermo-optic effect also causes a change in the refractive index of both the core and the cladding. By applying infinitesimal temperature variations Equations 1 and 2, the variation of the resonance wavelength

peak with wavelength can be determined. The mathematical expressions of the wavelength shift of an FBG is presented below^{7,8}:

$$\Delta\lambda_{FBG} = \lambda_{FBG}(\alpha + \xi)\Delta T \quad (3)$$

where α is the thermal expansion coefficient ξ is the thermo-optic coefficient respectively, ΔT is the change in temperature, $\Delta\lambda_{FBG}$ the variation in the resonance wavelength of the FBG and λ_{FBG} the resonance wavelength of the FBG at a reference temperature.

The wavelength shift in the case of an LPG is given by:

$$\Delta\lambda_{LPG} = \lambda_{LPG} \left(1 + \frac{1}{n_{eff,LPG}} \frac{d(n_{eff,LPG})}{dT} \right) \Delta T \quad (4)$$

where $n_{eff,LPG} = n_{core} - n_{cl}^m$, $\Delta\lambda_{LPG}$ the variation in the resonance wavelength of the LPG and λ_{LPG} the resonance wavelength of the m-th cladding mode of the LPG at a reference temperature.

As can be seen from Equations (3) and (4), the shift in the resonance wavelength with temperature is linear for temperature variations of a few degrees, but in practice, the thermal expansion and thermo-optic coefficients exhibit temperature dependence over a wide temperature range⁹, meaning that Equations (3) and (4) are no longer linearly dependent on temperature. In addition, the sensitivity of identical fibre-optic sensors is not the same, due to slight differences introduced during their manufacturing; therefore, in order to determine the temperature correctly each sensor must be calibrated individually by linear regression for small temperature ranges and with higher-order polynomials for wide temperature ranges.¹⁰

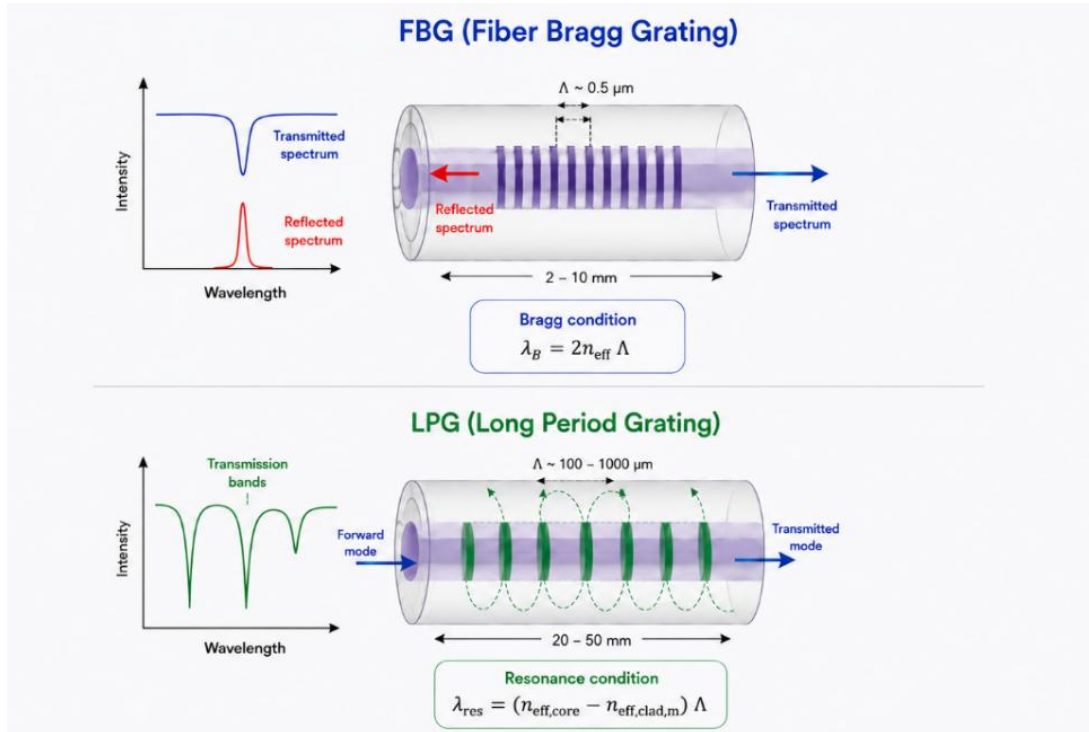


Figure 1. Schematic representation of the operation of FBG and LPG.

Icing sensors and probes

FBG and LPG sensors can operate as temperature sensors, but they must be configured in such a way that they are insensitive to mechanical strain. Figure 1¹¹ shows an FBGs sensor design that ensures isolation from mechanical deformations and cross-sensitivity. The FBG sensor must be located close to the end of the fibre. The fibre is in a stainless steel microtube, and it must move freely inside. After manufacturing, it is crucial to check whether the fibre moves freely inside the tube. To ensure this, first, an initial calibration is carried out to determine the sensitivity of the sensor over the operating range. In Equation 3, this sensitivity is represented by $(\alpha + \xi)$. Once the sensor has been manufactured, it is recalibrated. If the sensor sensitivity has changed, this indicates that the movement of the fibre within the tube is restricted, resulting in cross-sensitivity between temperature and strain; In this case, the sensor must then be discarded for temperature measurements. Only the sensors that have the same sensitivity before and after manufacturing are suitable for temperature measurements.



Figure 2. FBG temperature sensor layout ¹¹: (1) Tube lid; (2) Optical fibre; (3) Stainless-steel tube (4) protection tubing; (5) FBG sensor.



Figure 3.. FBG temperature sensor, insensitive to external deformation.

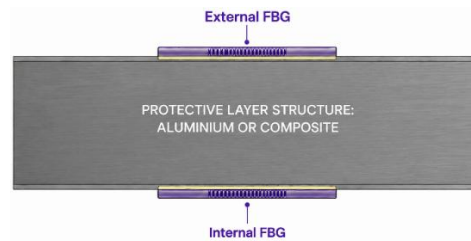


Figure 4. Icing sensor layout.

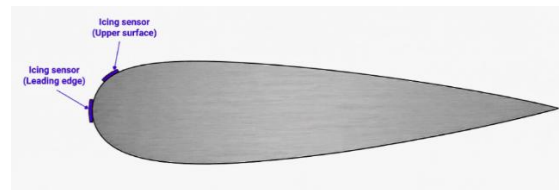


Figure 5. Wing profile with two icing sensors: one on the leading edge and the other on the upper surface of the profile.

Supercooled water can exist in the Earth's atmosphere at temperatures between 0 °C and -30 °C. During the phase transition to ice, energy is released. The icing sensor presented in this paper is based on the measurement of the increase of temperature of the water mass and its surroundings due to the energy released during the phase transition of the supercooled water. The icing sensor proposed by INTA (Figure 4), is composed of two temperature sensors of the type presented in Figure 2. An internal FBG (λ_a), isolated thermally for a layer of composite or aluminium, monitors changes in the ambient temperature. The importance of the internal FBG lies in preventing false positives resulting from very rapid changes in external conditions that could be misunderstood as an icing process. The protective layer structure isolates the sensor from the energy released during the phase transition. The second sensor is installed on the external surface of the protective layer structure and detects the phase transition as a sharp increase in temperature (λ_c). Such increase occurs in fractions of a second. The icing signal is defined as the difference between the temperature of the phase-transition sensor and that the reference sensor ($\lambda_c - \lambda_a$).

In this experiment two icing sensors have been installed in a wing profile (Figure 5. Wing profile with two icing sensors: one on the leading edge and the other on the upper surface of the profile. Figure 5). The profile has been manufactured in the Composite Department of INTA. The core of the profile is made of polystyrene, and its outer layer is made of a composite material. Once the profile has been manufactured and the icing sensors installed, preliminary measurements were performed to check the response of the sensors. These measurements were carried out using an industrial freezer and the data have been collected by means of a LUNA interrogator, model si255, with four interrogation channels and a data acquisition rate of 100Hz.

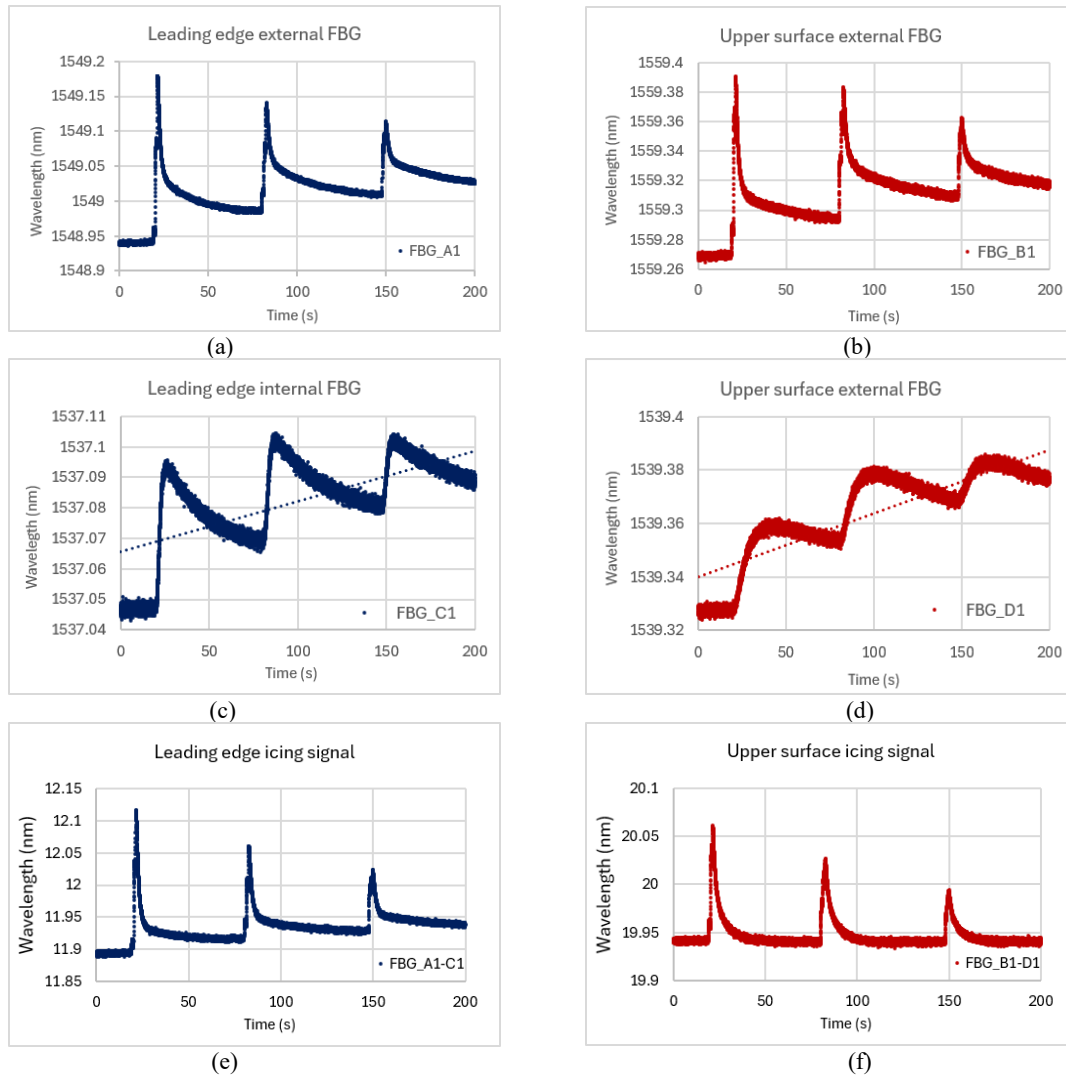


Figure 6. Wing profile preliminary measurements. The response of FBGs has been presented in nm. (a) and (b) present the response of the external sensors; (c) and (d) the response of internal sensors and (e) and (f) the icing signal.

The freezer temperature was set to -33°C . The wing profile was also placed inside the freezer until its temperature had stabilised. A spray bottle containing distilled water was also placed inside the freezer. The water in the sprayer was allowed to cool down while remaining in a liquid state. The spray bottle was used to spray the wing profile in the area where the sensors were located. The spraying was repeated three times. The graphs show an exothermic peak coinciding with each of the three spray applications.

Figure 6 (a) and (b) show how the external sensors can detect each spray discharge. A layer of ice forms on the surface of the profile after each spray discharge. This layer provides thermal insulation between the internal sensor and the

environment. The layer of ice causes the external sensor to become progressively less sensitive to icing; this is reflected in the graphs as a decrease in the peak height corresponding to the successive sprays. Figure 6 (b) and (c) show the response of the internal sensors. In Figures (c) and (d), a linear fit has also applied to the data, indicating changes in ambient temperature. In this case, the ambient temperature is rising. Figures 6(e) and 6(f) present the icing signal without the contribution to the background change in temperature. These FBGs are also capable of detecting icing, but with even lower sensitivity. This is an area that can be improved in the design of the icing sensor. For future tests, the thickness of the composite skin should be increased.

Icing Wind Tunnel (IWT) facility

The INTA icing wind tunnel is a facility that enables the simulation of ‘in-cloud’ atmospheric conditions and belong to the Metallic Materials Department. It consists of a wind tunnel installed in a 54 m³ cold chamber, which maintains internal temperature in the appropriate range. The Figure 7 shows the complete facility with the test cell at the centre. The cross-section of the test cell measures 15 × 15 cm². The aerodynamic profile is positioned inside the chamber and, whilst the wind tunnel is in operation, an aerosol consisting of 20 µm diameter droplets is sprayed. The IWT can produce both glaze (transparent and translucent) and rime (white and opaque) ice simply by adjusting the temperature, wind speed, median volume diameter (MVD) and liquid water content (LWC).

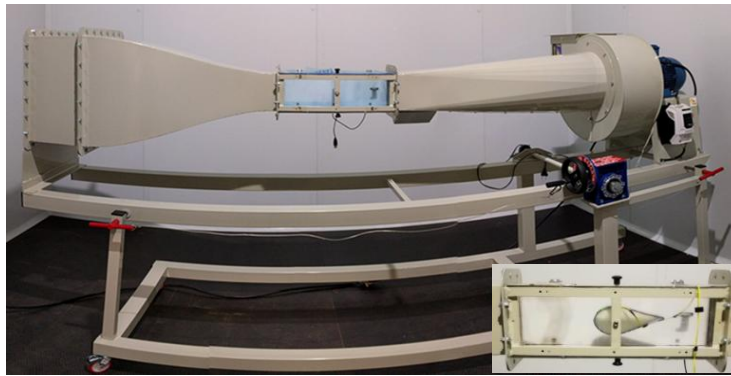


Figure 7. INTA icing wing tunnel and wind profile experimental set up.¹²

3. RESULTS

The following section describes three experiments to detect ice in the IWT. Each of these experiments was carried out under different environmental conditions. The results of these experiments will serve as the basis for improving the sensors and enhancing their overall performance. The results have been acquired by means of a LUNA interrogator, model si255, and with reading frequency of 100 Hz.

These experiments consist of placing the instrumented wing profile inside the wind tunnel, which is maintained at a temperature below 0 °C, adjusting the wind speed to a specific value, and introducing a spray of water droplets of a controlled size into the airflow, so that the water liquid content of the air surrounding the wing profile is controlled.

In this first experiment, the ambient temperature starts at -4 °C. It is not possible to maintain the temperature of the cold chamber constant throughout the experiment. The temperature fluctuations can reach ± 5 °C. This situation reflects a realistic scenario in which the ambient temperature is not constant over time. The airflow velocity is set to 50 m/s, which is equivalent to 180 km/h. During this experiment, the spray system is activated five times. The spray produces droplets with a diameter of 20 µm and a liquid water content (LWC) of 0.65 g/cm³. The figure shows how the sensor can detect each of the spray discharges. The sensor response consists of a rapid increase in wavelength that persists while the spray system remains active. When the spray is no longer applied, the signal measured by the sensor drops sharply, and then increases again with the next spray application. The Figure 8 has the same structure as in Figure 6. The icing signals detected by the sensors are gradually attenuated, which indicates that the ice layer forming on the profile acts as an insulator against the heat released during the phase transition. In this experiment, the volume of water sprayed onto the profile was higher than in the initial measurements shown in Figure 6; as a result, the internal sensor detects a much stronger signal. Unfortunately, the icing signal is close to the noise threshold of the interrogator, and its magnitude should be increased for

easier detection. This fact supports the need to increase the thickness of the insulating layer between sensors in future sensor designs.

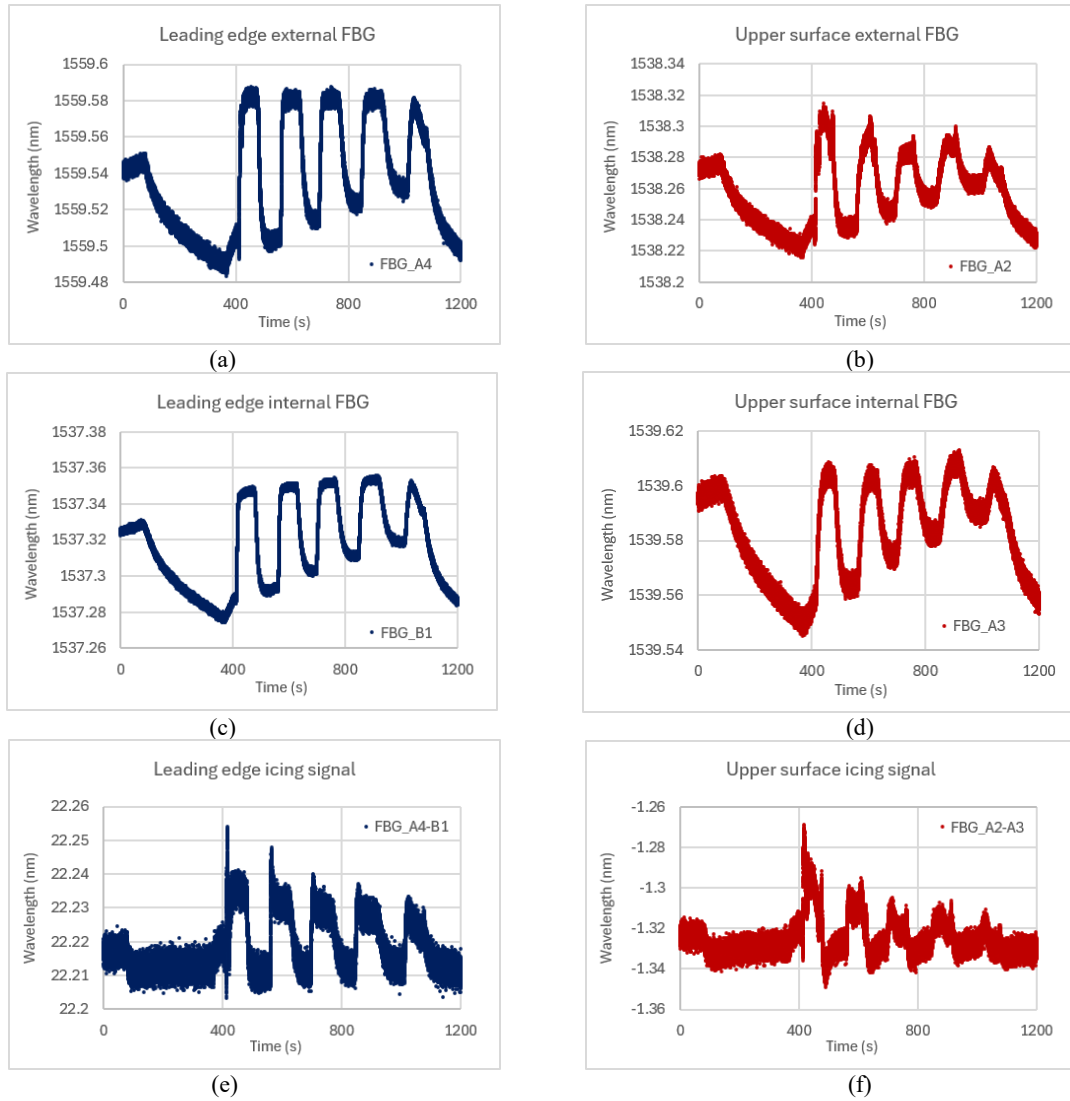


Figure 8. First icing experiment in the IWT. The response of FBGs has been presented in nm. (a) and (b) present the response of sprayed the external sensors; (c) and (d) the response of internal sensors and (e) and (f) the icing signal

The result of the ice accreted during the current experiment can be shown in the Figure 9. The type of ice obtained in this experiment was glaze.

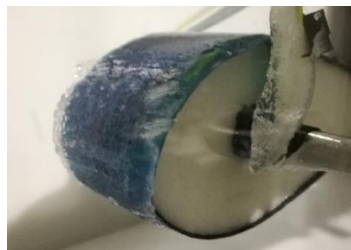


Figure 9. Ice accreted at the end of the experiment 1.

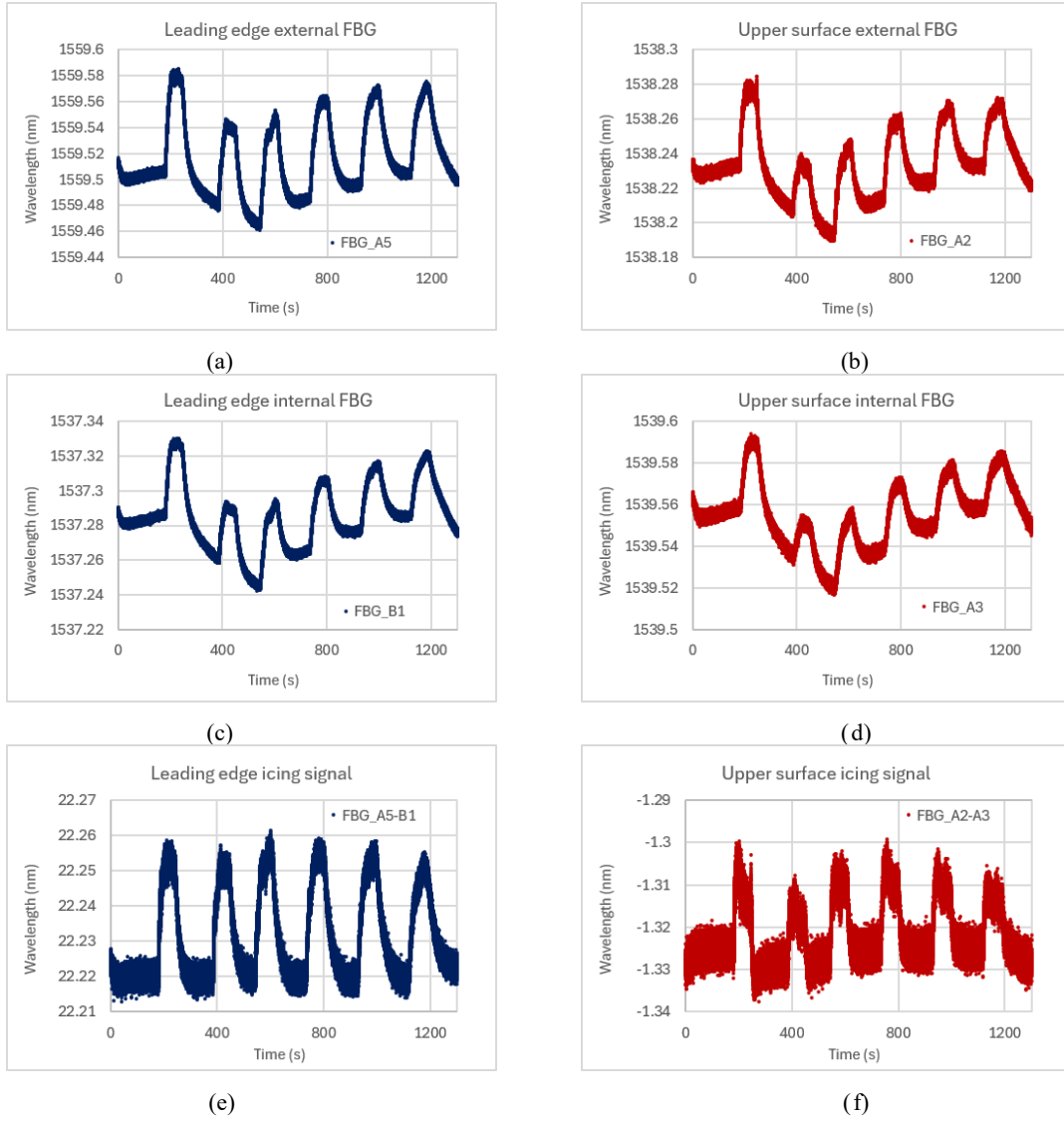


Figure 10. Second icing experiment in the IWT. The response of FBGs has been presented in nm. (a) and (b) present the response of sprayed the external sensors; (c) and (d) the response of internal sensors and (e) and (f) the icing signal

Wind speed was increased to 70 m/s (252 km/h) for Experiment 2 (Figure 10). The droplet size was slightly greater than 20 micrometres, resulting in an increase of liquid water content. The initial temperature of the cold chamber was -13 °C. Under these conditions, rime ice is formed, as can be seen in the image in Figure 11.

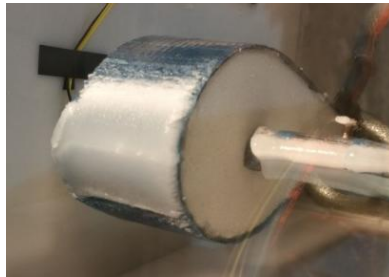


Figure 11. Ice accreted at the end of the experiment 2.

The results of experiment 3 are presented in Figure 12. The initial temperature of the cold chamber was -13°C and the wind speed was 50 m/s . In this case the liquid water content was of 1.63 g/cm^3 and the droplet size was of $20\text{ }\mu\text{m}$.

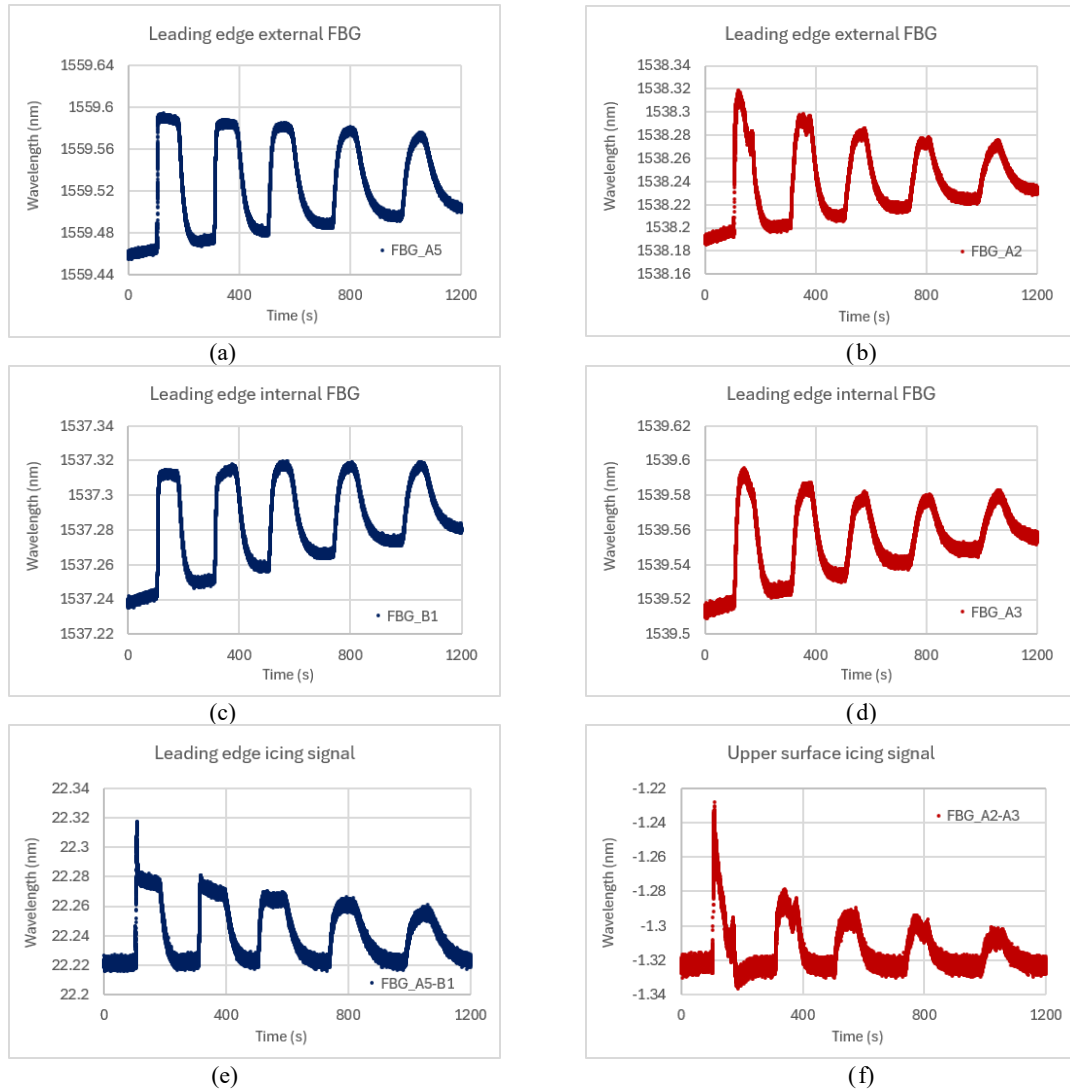


Figure 12. Third icing experiment in the IWT. The response of FBGs has been presented in nm. (a) and (b) present the response of sprayed the external sensors; (c) and (d) the response of internal sensors and (e) and (f) the icing signal



Figure 13. Ice accreted at the end of the experiment 3.

The ice layer accreted on the wing profile after the experiment consists of rime ice.

4. CONCLUSIONS

This paper has presented an icing sensor that could be useful for detecting supercooled water in planetary exploration. The sensor consists of two FBG sensors, one positioned on the outer surface of a composite skin and the second positioned on the inside of the skin. Preliminary tests of the sensor have been carried out in an icing wind tunnel, and it has been confirmed that it can detect the freezing of super-cooled water for WLC of 0.63 g/cm^3 and 1.63 g/cm^3 ; wind speeds of 180 km/h and 250 km/h and droplet sizes of $20 \text{ }\mu\text{m}$.

For the optimum performance of the system, it is recommendable to implement a system in which the icing sensor detects the accretion of ice on the surfaces of scientific instruments, and an anti-icing system that melts the ice layer to restore the functionalities of scientific instruments.

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