Distributed Alarm System Based on OTDR Interrogation of Side Air-Hole Fibers

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Abstract: A distributed sensor for multi-event alarm triggering is demonstrated by measuring the loss change induced by the liquefaction of pressured CO_2 trapped along a side air-hole fiber.

1. Introduction

Several monitoring situations require to detect the presence of localized spots where the temperature goes above or below a preset value. This would be the case to detect overheating along a power cable or icing along a road, among others. In several instances a distributed temperature measurement would be overqualified for this purpose and a simpler cost-effective solution would be more attractive.

Along this line we propose here a fully distributed alarm system interrogated by an ordinary OTDR instrument. It is based on the significant change of propagation loss induced by a gas experiencing a vapor-to-liquid phase transition at a given temperature. For this purpose, the very minor evanescent field in a side air-holes fiber (SAHF), which is specially designed for pressure sensing [1,2], is sufficient to observe the loss change when the gas liquefies in the air holes. This is demonstrated by filling the air holes with carbon dioxide (CO_2) at a well-defined pressure, selected to make the gas liquefy under the target temperature.

2. Principle

A SEM picture of the SAHF under test and the evanescent field in the air-hole region obtained by COMSOL simulation are shown in Fig. 1. During the vapor-to-liquid phase transition, the optical properties in the air-hole volume changes according to the state of the medium. Compared with gaseous CO_2, liquid CO_2 shows a higher refractive index which increases the relative importance of the evanescent field in the holes by about 39%. Just like in its gas vapor, liquid CO_2 shows an absorption band centered at 1572 nm as, but much broader, widely covering the conventional wavelengths of 1550 nm and 1310 nm, far beyond the absorption band of gaseous CO_2. Thus, the transition to liquid CO_2 results in coupling more light into the more strongly absorbing volume, making the attenuation significantly higher. For CO_2, a higher boiling temperature is observed at higher pressure. When the temperature at certain positions is below a preset value, the CO_2 is locally in liquid state and the cold spots can be detected as more lossy segments and interrogated by an OTDR instrument as distributed losses.

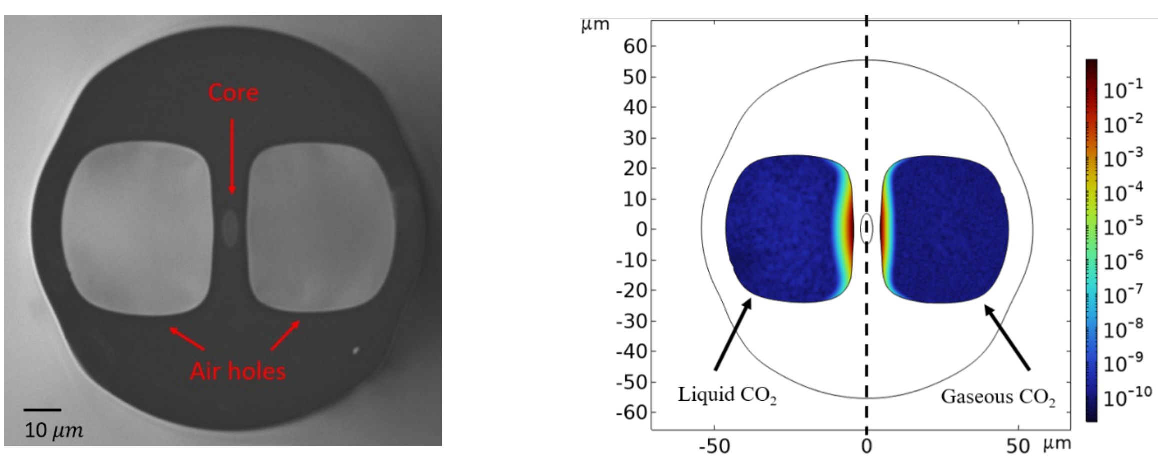

Fig. 1. Left: SEM picture of the side air-holes fiber (SAHF) cross-section. Right: Simulation results of the normalized evanescent field distribution for liquid (left) and gaseous (right) CO_2.

3. Experimental Demonstration

3.1. Measurement Set Up

A commercial OTDR instrument is here used to interrogate the SAHF, which is at one end spliced to a standard single mode fiber for connection and secure a gastight implementation. The target spatial resolution for the measurement is reached by using 3 ns incoherent pulsed light, corresponding to a roughly 0.3 m spatial resolution in the silica core. The backscattered signal is detected by the built-in photoreceiver and acquired with a fixed spatial sampling of 0.05 m. The signal is then smoothed over the neighboring 6 points to benefit from the oversampling over the spatial resolution. The measuring wavelength is first set at 1550 nm. The other end of the SAHF is connected to the gas supply via a tube, purposedly to inject CO_2 at different gas pressure. In a real-world sensor, this end must also be gastight after filling at the target pressure. A precision manometer is set along the gas tube to monitor the gas pressure, which roughly represents the gas pressure along the fiber, neglecting a possible pressure gradient along the system. A water bath is used for precisely thermalizing distinct fiber sections, with an accuracy of 1°C. The whole set-up is sketched in Fig. 2.

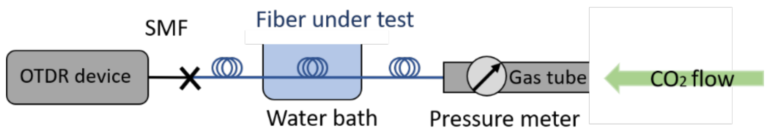

Fig. 2. Experimental validation setup. One end of the SAHF is spliced to a standard single mode fiber for interrogation using a commercial OTDR instrument, the other end is connected to a tube loaded with CO_2 at different gas pressures. The temperature of the optical fiber under test is controlled by a water bath.

3.2. Temperature and Pressure Change Measurements

Measurements are first performed at room temperature along the fiber, to evaluate the possible impact on the loss of gaseous CO_2 filling the side air-hole at different pressures, as shown in Fig. 3. When using a 1550 nm light source, there is no significant induced loss along the fiber over a CO_2 pressure range from 0 bar to 40 bar, as a result of the combined effect of a negligible molecular absorption and a minor fraction of the evanescent field in the air holes.

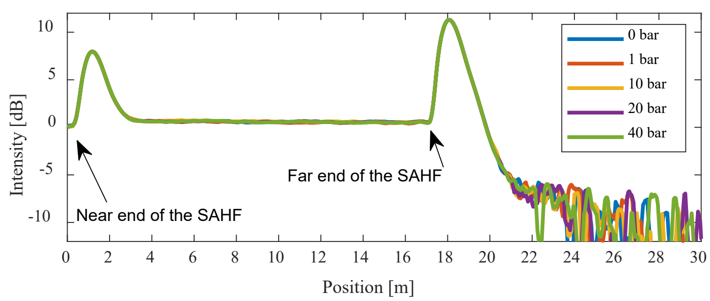

Fig. 3. Room temperature measurements of the SAHF backscattering signal at different CO_2 pressures, where the CO_2 always keeps in a gaseous state. No significant induced losses are observable.

Measurements are then performed when the whole fiber is filled with CO_2 at a constant pressure of 37 bar while a fiber section is cooled at varying temperature (position from 8 to 10 m). The phase change temperature for CO_2 gas at a pressure of 37 bar is about 2.4°C and keeps liquid for all lower temperatures. The section is cooled from room temperature (RT) to 0°C, sweeping over the phase change point of CO_2. The potential loss should be due to the presence of liquid CO_2 and not to any pressure change during the phase transition, as validated before.

As shown in Fig. 4, when the temperature of the fiber is above the critical temperature of the CO_2 phase transition, the loss along the fiber is uniform. When the section of the fiber is just below the critical temperature of the phase transition, the CO_2 in the side air-holes partially turns into liquid, showing higher losses. When the temperature is a bit lower, the gas completely liquefies and stabilizes, resulting in a consistently higher loss over the cooled section.

The slight discrepancy between the transition temperature in the measurement and the theoretical phase transition temperature of CO_2 (2.4°C) may be caused by some inhomogeneities of both gas pressure and temperature.

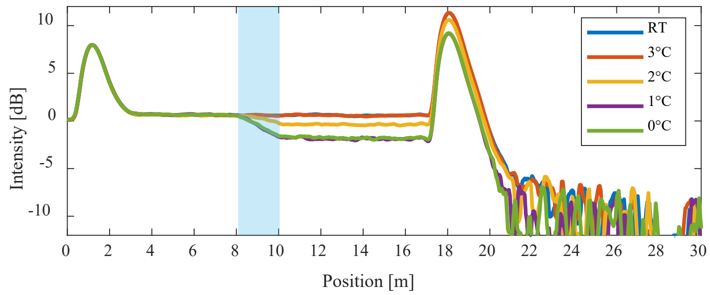

Fig. 4. Measurements of the SAHF backscattering signal at a constant pressure of 37 bar. A fiber section, marked by the light blue shading, is cooled from room temperature down to 0°C. Induced losses are clearly observable for all temperatures below 3°C and remain steady below 1°C.

We repeated the measurements sweeping over the CO_2 phase change point, by fixing the temperature of the fiber cooled section at 1°C and varying the pressure of the CO_2 filled in the side air-hole from 1 bar to 40 bar. Similar results were obtained, as shown in Fig. 5, proving that the additional losses are due to the phase change of the CO_2 gas into liquid.

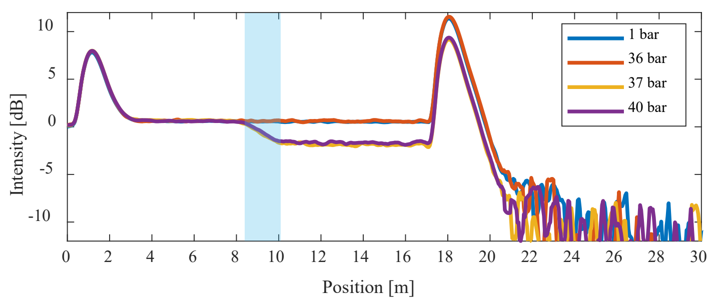

Fig. 5. Measurements of the SAHF backscattering signal at different pressures from 1 bar to 40 bar. The light blue shading indicates the optical fiber segment placed at a constant temperature of 1°C. The extra loss appears in the region where the pressure is not below 37 bar.

3.3. Multi Cold Spots Measurement

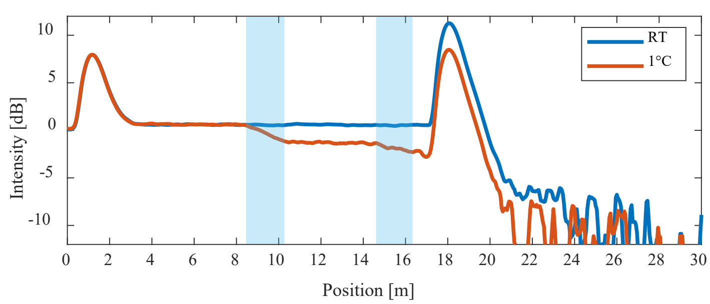

Fig. 6. Measurements of the SAHF backscattering signal at constant pressure of 37 bar in presence of distinct multiple cooled spots. Two fiber sections, indicated by the light blue shading, are cooled from room temperature to 1°C. The successive induced losses along the two sections validates the potential for distributed sensing.

This scheme shows all its potentiality for distributed sensing because the gaseous CO_2 can flow along the fibers, giving all points an equal chance of being liquefied. To validate it, the pressure of CO_2 is set at 37 bar and two distinct fiber sections are cooled at 1°C: the 8 to 10 m and 14 to 16 m sections, respectively. Fig. 6 shows the distributed signal along the fiber. The additional loss coefficient at the first location is 0.90 dB/m while the coefficient at second location is around 0.55 dB/m. The different additional loss coefficients may be caused by the inhomogeneous liquefaction of CO_2 in the symmetrical side air holes due to a loss of uniformity of the gas pressure.

3.4. Loss Comparison at Different Wavelengths

Significant loss signals appear during the measurement using a 1550 nm light source. Measurements are sensitive, but at the same time facing the issue of a rapid signal attenuation due to excessive loss. To achieve distributed measurements over longer distances, it is possible to vary the wavelength of the light source to be more spectrally distant from the absorption line of CO_2 at 1572 nm, thus potentially experiencing a lower loss.

In our experiment, we compared measurement results at 1550 nm and 1310 nm under the exact same conditions, as shown in Fig. 7, and found that the corresponding position of the lossy segment is fully matching, though with an additional loss coefficient about 3.5 times larger at 1550 nm than at 1310 nm, demonstrating the flexibility to adapt the loss coefficient to the operating conditions.

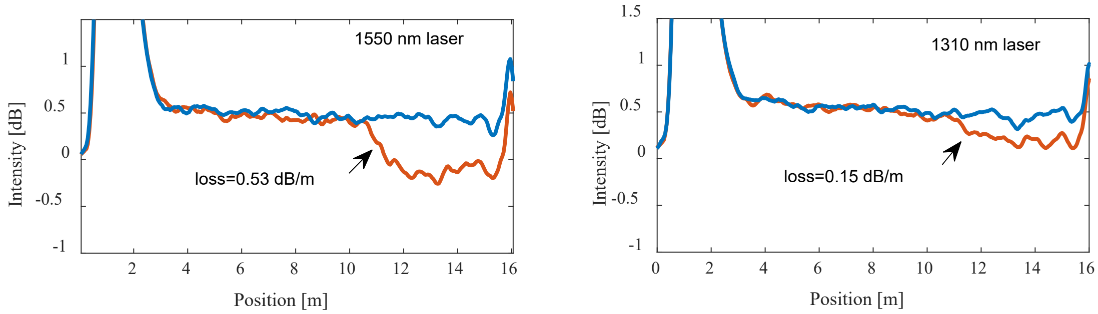

Fig. 7. Additional loss coefficients are measured when using laser sources with wavelengths of 1550 nm (left) and 1310 nm (right). The coefficient using 1550 nm laser source is 3.5 times higher than the 1310 nm one.

4. Discussion and Conclusions

By comparing sets of measurements performed along a simple SAHF, we validated that CO_2-filled SAHF can be used as a temperature alarm distributed system at its boiling temperature and can be interrogated using a standard OTDR instrument by interpreting the distributed losses. The alarm temperature can be customized by loading CO_2 at a defined pressure in the air-hole region. For a given experimental setup, the accuracy required on the loss measurement limits the spatial resolution of the cooled section, as a classical tradeoff. Light sources with wavelengths resulting in different attenuation factors can therefore be assigned for different purposes. For more accurate measurements, a 1550 nm source is better suited because it shows a higher loss contrast between gas and liquid. For long distance monitoring, a 1310 nm light source is a better choice since it can deliver relevant measurements over longer cooled sections.

However, it is important to mention that the predicted numerical results of the attenuation coefficients are not completely consistent with the measurements, probably due to an incomplete liquefaction of the CO_2 in the cooled sections, which still needs to be studied in the next stages of this work.

5. References

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