Complete characterization of multipass gas cell using a high sensitive optical frequency-domain reflectometry

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ABSTRACT

This paper reports on the experimental characterization by means of optical frequency-domain reflectometry of a White-type multipass gas cell used for trace gas spectroscopy. The fractional Lambertian reflections inevitably arising from the three high reflectivity mirrors of this multipass cell is precisely detected due to the high sensitivity of the reflectometer. Each bounce of light on the mirror surface generates backscattered light, which returns to the sensing system. Then, using the measured distribution of multiple back-reflections as a function of distance the position of the 3mm-thick CaF_2 entrance window is clearly identified, thanks to the spatial resolution of 731µm. In addition, the physical distance between mirrors at both sides of the cavity is accurately assessed to be 40.72cm, delivering the exact optical path length of light inside the multipass cell of 30.9853m, which is an important parameter for improving the accuracy of the computation to retrieve the gas concentration from the measured light absorption spectrum.

Keywords: optical frequency-domain reflectometry, frequency-modulated continuous wave, light detection and ranging, trace gas spectroscopy, multipass gas cell, semiconductor lasers, optical sensing

1. INTRODUCTION

Recently, distributed optical sensing systems have attracted a particular attention to the optical sensing society due to their great potential on various applications for monitoring structural health [1] and pipeline Oil&Gas leakage [2], geotechnical detection [3] and gas spectroscopy [4-6], just to mention a few. To date, many different types of distributed sensing systems have been developed, using a variety of physical mechanisms such as Raman, Brillouin and Rayleigh scattering as well as fiber Bragg grating in optical fibers. Compared to other techniques, the Rayleigh backscattering-based optical frequency-domain reflectometry (OFDR) takes advantage of unmatched spatial resolution, readily reaching a few micrometers. Such a high spatial resolution is especially advantageous to accurately characterize the multipass cell (MPC), which is effectively utilized to enhance the performance of the trace gas spectroscopy as it increases the light-gas interaction length. Indeed, it is very important to measure the exact length of the optical path within the MPC since it is an important parameter to precisely retrieve the gas concentration from the measured light absorption spectrum. In this paper, we have experimentally demonstrated the feasibility that an OFDR sensing system consisting of a standard discrete mode semiconductor laser can unambiguously measure both single and total optical path length of the MPC.

2. EXPERIMENTAL SETUP AND RESULTS

Figure 1 depicts the simplified schematic diagram of the OFDR sensing system, consisting of two independent unbalanced Mach-Zehnder interferometers: k-clock interferometer for the linearization of continuously swept-frequency and main interferometer for the measurement on the distributed back-reflection over distance. A single frequency laser diode from Eblana Photonics based on their patented discrete mode (DM) platform operating at the wavelength of 1550nm is employed to generate a frequency-modulated continuous wave (FMCW) light source, simply by directly modulating the injection current applied to the laser. As other types of semiconductor lasers such as distributed-feedback laser (DFB) and vertical-cavity surface-emitting laser (VCSEL), DM lasers suffer from the same trade-off relationship between the coherence length; hence the maximal achievable sensing range and the DC frequency tuning rate; hence the spatial resolution. This tradeoff is in principle attributed to the laser cavity gain and laser cavity volume. It means that when the length of the laser gain chip becomes larger the spectral purity of the emitting light turns to be improved. In order words, the laser coherence length becomes longer, resulting in a larger measurement range. However, it must be noticed that such an improvement is usually obtained at the cost of the reduction of the DC frequency tuning rate, caused by the smaller temperature change in the laser cavity attributed to the relatively larger laser cavity volume. Three lasers from Eblana Photonics, having linewidths of 0.2MHz (EP-1550-NLW-100), 0.5MHz (EP-1550-NLW-400) and 1MHz (EP-1550-DM), owing to the different gain chip lengths of 2500µm, 750µm and 275µm were evaluated in terms of the optical frequency sweep range, showing the DC frequency tuning coefficient of -0.25GHz/mA, -1GHz/mA and -2.75GHz/mA, respectively.

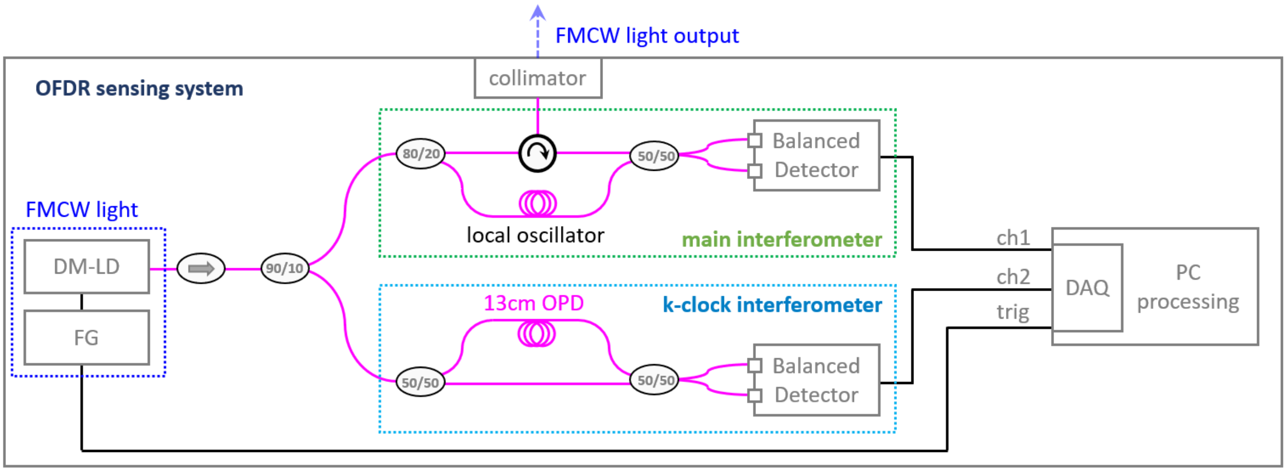

Figure 1: Simplified schematic diagram of optical frequency-domain reflectometry

However, we figured out that the frequency tuning coefficient has a strong dependence on the frequency sweep speed, as shown in Figure 2. The frequency sweep range of the laser having the largest DC tuning coefficient was evaluated for different sweep speeds while the laser temperature was stabilized at 11°C, revealing the maximum frequency tuning coefficient of -4.77GHz/mA at 10Hz. As expected, the amount of the frequency sweep range shows a perfect linear response to the current modulation depth and is reduced as the sweep speed increases due to the slow thermal response time of the laser cavity.

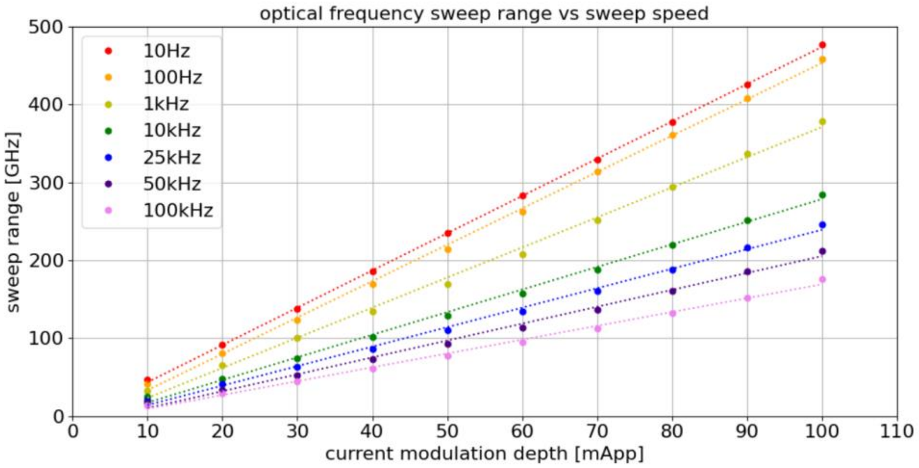

Figure 2: Optical frequency sweeping range as a function of current modulation depth at different sweep speed. The measured points are line-fitted.

To accurately characterize the MPC structure made by Senseair AB within the framework of EU project TRIAGE [7], a current modulation depth of 60mA at 1kHz was applied to this laser, providing a frequency sweep range of 205GHz, corresponding to a spatial resolution of 731µm in air. Then, the generated FMCW light exiting from an FC/APC connector was collimated using a reflective collimator (RC02APC-P01, Thorlabs), and the collimated beam was focused on the wedged 3mm-thick CaF_2 entrance window of the MPC using an off-axis parabolic (OAP) mirror with a reflected focal length of 50.8mm (MPD129-M03, Thorlabs). Figure 3(left) shows the reflection profile before the FMCW light enters the

MPC. The strong Fresnel reflection generated from the FC/APC connector at the collimator was set to 0m of the reflectometer and the measured distribution of the reflection profile over distance is referenced by the reflectance at this position. Notice the reflection peak observed at 95mm, which corresponds to the OAP mirror position, with a reflectance of -18dB lower than the reflectance from the fiber connector. Note also that the back-reflections from the 0.5° wedged front surface and flat rear surface of the window were obviously measured with a good signal-to-noise ratio, showing the distance interval of 3.08mm, matching well the thickness of the window (3mm±0.1mm in datasheet). Even, the distance between the OAP mirror and the front facet of the CaF$_2$window is 50.9mm, proving the correct alignment of optical components since the MPC is designed to have light focused on the entrance window to secure the number of traversals and beam quality inside the multipass cell. Furthermore, the measurement precision was measured to be 54µm, which was statistically evaluated by the standard deviation out of 1000 consecutive measured reflection position at the OAP mirror.

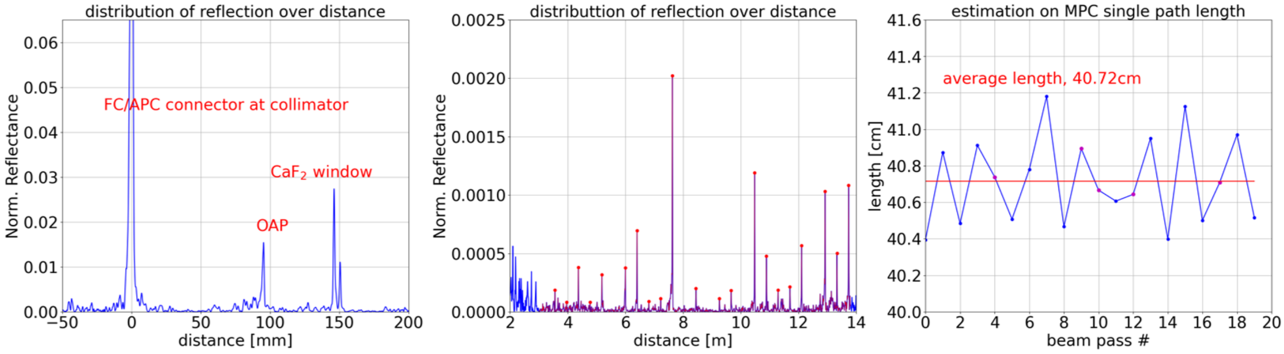

Figure 3: (left) Clear reflection peaks from the collimator, OAP and CaF$_2$ entrance window. (middle) Measured distribution of reflection over distance. (right) Measured beam path length, showing the average single path length of 40.72cm.

Figure 3(middle) shows the measured multiple reflections, generated by the FMCW light while propagating back and forth inside the MPC. Each time the light hits a mirror, fractional back-reflection is generated, indicating the exact position of the three mirrors. The distance interval between two adjacent reflections was then averaged to properly estimate the mirror cavity length inside the gas cell, resulting in the single path length of 40.72cm, as shown in Figure 3(right). However, we found that the inherent laser linewidth of 1MHz was not sufficient to measure the distribution of reflection profile over the 30m path length within the MPC since the dynamic linewidth of the laser tends to be degraded when its frequency is swept by means of the direct current modulation [8,9]. To unambiguously measure the total optical path length of the MPC, a higher coherent laser was required for >30 m distance ranging purpose; hence, requiring a laser having >60 m coherence length considering the round-trip feature. So, another DM laser with 0.2MHz linewidth was used, and its optical frequency was swept by 17 GHz, corresponding to the spatial resolution of 8.8mm. Because of the high reflection loss from the finite mirror reflectivity of 98.25%, an extra flat mirror (PF10-03-M02, Thorlabs) was placed at 2 cm position after the MPC exit to generate a strong reflection, which makes it possible to clearly present the gas cell exit, as shown in Figure 4.

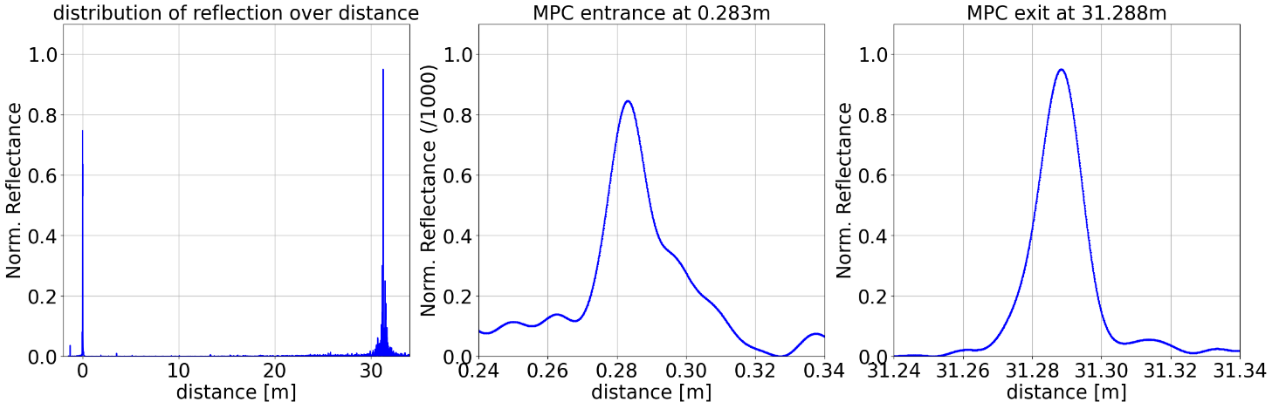

Figure 4: (left) Measured distribution of reflection over distance. (middle) Reflection from the CaF$_2$ window at the MPC entrance. (right) Reflection from the mirror right after the MPC output, showing the total optical path length of 30.9853m.

According to the measured positions of the entrance and exit of the MPC, the total optical path length was estimated to be 30.9853 m. Therefore, the total number of travels inside the gas cell is logically deduced to be 76 since the total number of reflections is a multiples of four due to the unique feature of the MPC. Then, the single optical path length, representing the distance between front and rear mirrors would be estimated to be 40.77cm, showing a good agreement to the measured single path length of 40.72cm, because the distance mismatching of 0.05 cm is within the measurement accuracy of ±0.073cm, equivalent to the spatial resolution of the reflectometer.

3. CONCLUSIONS

We have successfully demonstrated the complete characterization of the MPC in terms of optical path length, using a coherent OFDR reflectometer. For such application, we need to appropriately select a laser diode to optimize the trade-off relation between the ambiguity measurement range and the spatial resolution, because a longer ambiguity measurement range can be achieved by a higher coherent laser, which has a lower DC tuning rate as discussed. According to these results, we believe that the OFDR sensing system can be a promising scientific tool to completely characterize reflection properties of multipass cells.

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