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A FIBER-COUPLED GAS CELL FOR SPACE APPLICATION

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I. INTRODUCTION

An increasing number of space-borne optical instruments now include fiber components. Telecom-type components have proved their reliability and versatility for space missions. Fibered lasers are now used for various purposes, such as remote IR-sounding missions, metrology, scientific missions and optical links (satellite-to-satellite, Earth-to-satellite).

Some of those applications require a stable and accurate wavelength reference, which, in some cases, can be achieved with molecular species. For example, acetylene or hydrogen cyanide are well-known references in the telecom optical C-band (1530 – 1565nm).

COTS Acetylene Gas Cell Wavelength Calibrators exist but they are not qualified for space environment like launching shock and vibrations. Sodern has developed and is now manufacturing a 1.5µm metrology laser system for the Meteosat - Third Generation (MTG) satellites. This laser system [1] will provide a signal with wavelength stability better than 10^{-6} over the mission lifetime (8.5 Years) and better than 10^{-7} over a duration of 24 hours. The laser's frequency is locked on the P(16) (ν1+ν3) transition of acetylene 13C2H2 (at 1542.4 nm) [2]. It corresponds to a reference wavelength which has been well characterized in terms of sensitivity to its environments (pressure and temperature) [3]-[4], and for which reliable telecommunications optical components are commercially available. The first point was the main driver to choose this particular frequency as compared to other ones, mainly P8 at 1537.7 nm.

In this paper, we present the fiber-coupled gas cell providing this frequency reference. The first part is the description of the sub-assembly and the second part is a summary of the main tests results available so far.

II. DESCRIPTION OF THE GAS-CELL SUBASSEMBLY

The Gas-Cell Subassembly (GCS) is used in the MTG Laser unit as a frequency discriminator. It has been mainly specified in terms of absolute transmission of the laser signal out of and in the vicinity of the absorption line. A sufficient relative absorption depth (> 50 %), a linewidth of less than 700 MHz and transmission stability while operating in its nominal thermal range are also required. Fig. 1 is a sketch of the GCS.

A. Optical design

The product designed by Sodern is a compact two-connector fibered sub-assembly containing a sealed-glass acetylene gas cell. Free-space laser propagation inside the GCS is necessary since no space-qualified fibered acetylene reference was found. Sodern has had some experience with gas cells since they have already been used on the optical bench of PHARAO's Laser Source [5].

The length of the gas cell and the gas pressure inside the cell were chosen taking into account various criteria like availability of COTS parts, low mass and dimensions constraints, minimum relative absorption of the laser beam inside the gas, worst case gas pressure drop in case of a cell leak, or FWHM (Full Width at Half Maximum) and line shift in the operational temperature range.

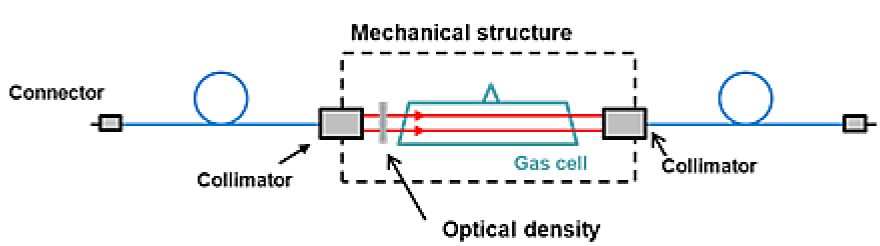

Fig. 1: Sketch of the GCS

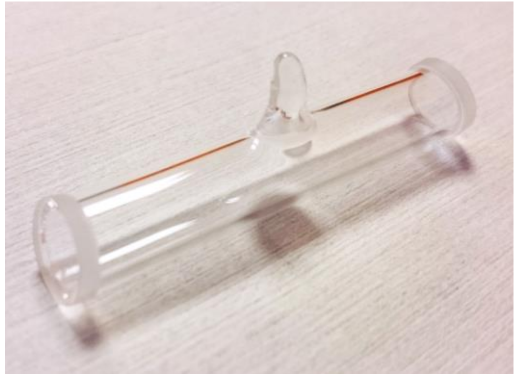

Fig. 2 : Acetylene gas cell

In our case, the gas cell is made of a 50 mm long 10 mm diameter quartz tube to which 2 fused silica windows are sealed. The flat windows, to better than λ/4, are angled to compensate for beam offset. The cell is filled with 99% pure C2H2 and the gas pressure at 20°C is in the 25-27.6 mbar range. The stability of this pressure, for a given temperature, throughout the lifetime of the GCS is of paramount importance in order to reach the above-mentioned specified requirements. Thus the gas pressure shall not vary by more than 4 mbar over a total duration of 17 years through a leak in the cell, be it on Earth where air would enter into the cell and react with acetylene, or in orbit where the gas would leak out of the cell. Gas filling is made through a small pipe which is then cut to form a sealed exhaust tip. The windows are anti-reflective coated to reduce the reflectivity at 1542 nm. Fig. 2 is a picture of the gas cell.

Two collimators terminated with space-grade connectors provide a mode coupling between the input and output single-mode fibers. The optical design was optimized according to an analytical model of gaussian beams derived from [6] which takes into account fiber mode mismatch, longitudinal shift between the 2 fiber waists (z_0), lateral offset (x_1) and tilt between the two fibers (θ).

If w_1 and w_2 are the waists of the input and output fibers and if λ is the wavelength, it can be shown that the coupling efficiency (CE) between both collimators can be written as the product of four terms:

$$CE = \frac{1}{\rho^2} \cdot \frac{1}{1+\delta^2} \cdot \exp\left(-\frac{\varepsilon^2}{1+\delta^2}\right) \cdot \exp\left(-\frac{\Theta^2}{\rho^2}\right) \tag{1}$$

where :

$$\rho = \frac{1}{2} \cdot \left(\frac{w_2}{w_1} + \frac{w_1}{w_2}\right), \tag{2}$$

$$w^2 = \frac{1}{2} \cdot \left(w_1^2 + w_2^2\right), \tag{3}$$

$$\delta = \frac{z_0 \cdot \lambda}{2 \cdot \pi \cdot w^2}, \tag{4}$$

$$\varepsilon = \frac{x_1}{w}, \tag{5}$$

$$\Theta = \frac{\sin(\theta) \cdot \pi \cdot w}{\lambda}. \tag{6}$$

In equation (1), $\frac{1}{\rho^2}$ is the coupling term for the mode mismatch between the two modes, $\frac{1}{1+\delta^2}$ is the coupling term for the longitudinal shift between the 2 fiber waists, the first exponential term is the coupling term for transverse misalignment, taking into account the longitudinal shift between the 2 fiber waists, and the second exponential term is the coupling term for tilt errors, taking into account the mode mismatch.

Using this analytical model, it can be shown that the two modes have to be superimposed (z_0=0) to reduce the sensitivity to tilts. This gives a symmetric system, where the two waists are located in the middle of the gas cell. As a consequence, the two collimators are identical (same waist position and dimensions).

It can also be shown, through the analytical model, that there is an optimal value for the common waist $w=w_1=w_2$. Assuming a 35mm distance between the lens and the image waist (half the distance between fibers ends), this optimal value is 131µm. This in turn drives the choice of the Selfoc lens at the end of the fibers and of the glue thickness to try and approach this calculated configuration. Fig. 3 is a drawing of the collimators.

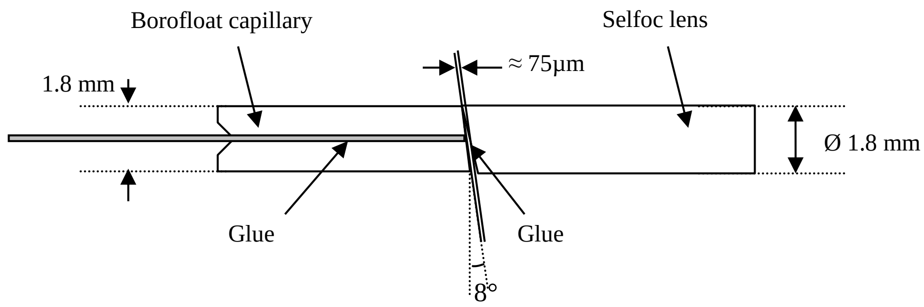

Fig. 3 : Collimator design

Finally, an optical density between one of the collimators and the gas cell to attenuate the power at the output of the cell completes the optical design of the GCS. The density material and thickness were first chosen according to an average system transmission budget and suppliers datasheets. However, values given in datasheets are not always guaranteed, therefore the intrinsic absorption of the chosen material plate was measured on 2 samples. Also, four different thicknesses were considered, giving a transmission span of +/- 20% in order to adapt the final transmission of the GCS to a specified value in case of collimators adjustment difficulties.

B. Mechanical design

The mechanical design is that of a sturdy, compact and light assembly. It was primarily optimized to guarantee the best coupling stability between both collimators.

The gas cell sits inside a rigid aluminum cradle and is glued to it in 4 points. The positions, dimensions and elasticity of these points were optimized so that the mechanical stress due to the coefficient of thermal expansion mismatch between aluminum and quartz is not detrimental to the integrity of the assembling, and also to have a good position stability of the cell after the launch vibrations.

The collimators are precisely adjusted thanks to a wedge shim on one side and a diasporameter on the other side so that the optical axes of both collimators and the cell are superimposed. Once adjusted, the shims are screwed to the cradle.

Mechanical damping of the GCS is necessary in order to avoid any failure of the cell during the pyrotechnic shock in orbit which is specified at 10000 m/s^{-2} at 1000 Hz. Hence, each of the four feet of the GCS is equipped with a small metal/elastomer damper that lowers the acceleration of the cell down to 2000 m/s^{-2}. Yet the dampers have low eigenfrequencies and they tend to increase the acceleration of the GCS for frequencies in the 300-875 Hz range.

The total mass of the GCS without the dampers is about 85 grams with half of this for the cradle that holds the cell. The first vibration eigenmode of the GCS is well over 1500 Hz. The total length of the GCS except the fibers radii is less than 110 mm and its width is less than 50 mm dampers included.

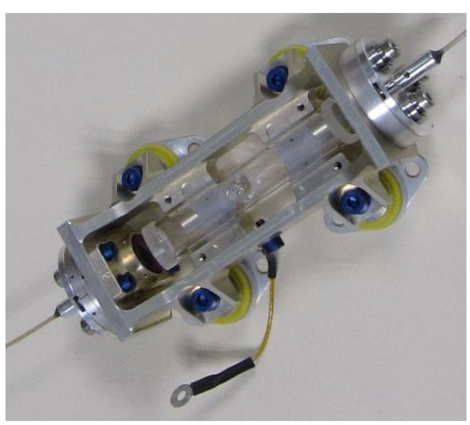

Fig. 4 : Gas-Cell Subassembly

III. GCS PERFORMANCES AND FIRST TEST RESULTS

The main optical performances of the GCS were evaluated using either suppliers' values or measurement made on the first available components (collimators, cells, densities).

The complete transmission budget takes into account contributions from the collimators (coupling efficiency and beam properties), the density (uncertainty of intrinsic absorption value, thickness tolerance and anti-reflective coating transmission) and the gas cell (gas absorption and transmission of the AR coating of both sides of both windows).

We calculated the minimum and maximum values for each term of the coupling efficiency equation (1), based either on specified values or on measured performances of the first batch of collimators.

Acetylene cells for all models have been provided. They were Helium-leak tested before filling and the leak rate was less than 10^{-9} atm.cc.s^{-1}. A screening procedure, consisting in 8 thermal cycles between -25°C and +60°C, was applied to demonstrate that the manufacturing process has been correctly implemented and that it does not lead to unacceptable defects. Full Width at Half Maximum (FWHM) of the absorption line and relative absorption depth must not vary in order for the cell to be retained. These parameters were measured at delivery and three months afterwards on a few cells: no evolution was found.

A first assembled prototype model of the GCS has given most promising results. After the alignment process and a thermal setting, we obtained a coupling ratio greater than 85%, before and after random vibrations up to 15 gRMS. Coupling drifts after thermal cycling and vibration tests were a few percent only, which is comparable to our measurement uncertainty. This validated the mechanical strength of the GCS, especially the stability of the collimators assembly and the cell glass-to-metal bonding.

Two Breadboards of the whole laser system (fig. 5) were fabricated using two of the first assembled GCS. They were used to show the compliance of the electronic definition with the expected spectral stability performances [1]. The mean frequency of a beat note signal between the two breadboards was monitored over a large time scale to deduce an average stability of each Laser. Fig. 6 illustrates the results of the measurements.

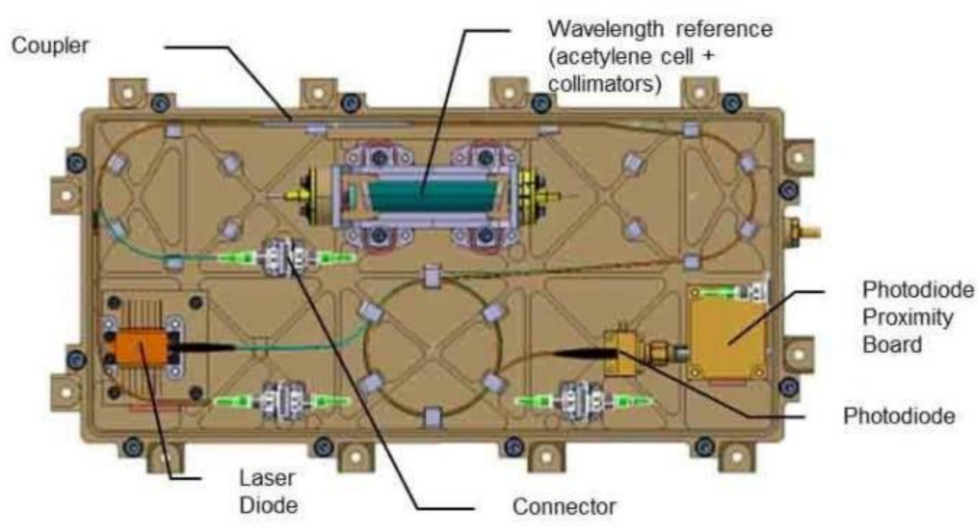

Fig. 5 : Fiber Optical Bench of the MTG Laser

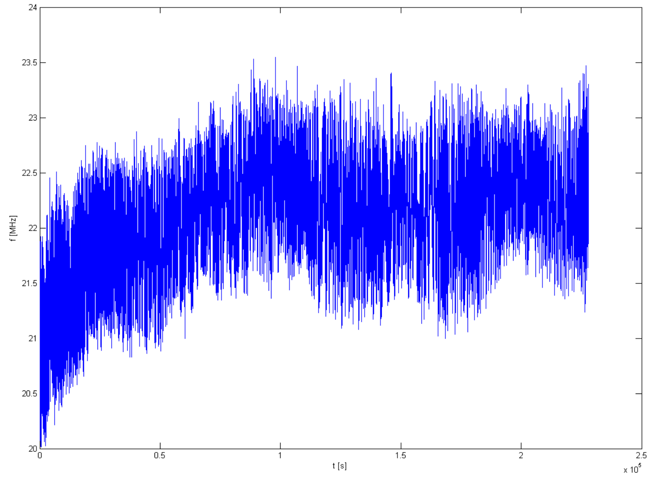

Fig. 6 : Frequency stability of the beat signal over 63 hours

The peak-to-peak shift is 3.5 MHz on the beat frequency which is the difference between two uncorrelated random variables. As a consequence, the stability of one EBB Laser is computed as follows:

$$\Delta\nu_{EBB} = \frac{\Delta f_{beatsignal}}{\sqrt{2}} = 2.5 \text{ MHz} \tag{7}$$

The relative stability over 63 hours is then: 1.3 x 10^{-8} to be compared to the specified value of 1 x 10^{-6}. Even if thermal sensitivity has not been tested at this time, this measurement gives promising results regarding the long-term frequency stability of the MTG Laser Flight Model.

Another model of GCS was fully manufactured and adjusted according to the future flight model manufacturing procedure. A thermal setting with a decreasing thermal span was applied in order to stabilize the adjusted collimators. The transmission of the GCS is around 20% once the optical density was integrated and it changed by less than 1% after thermal setting. The relative absorption depth and the FWHM of the cell were measured as shown on figure 7. The FWHM was 656 MHz and the relative absorption depth was 0,484 which correspond to an acetylene pressure of 19.1 Torr. These values all comply with internal specifications.

The Qualification Model is now being assembled. A complete qualification campaign will take place by the end of 2016, including shock tests, in-line radiation tests and a measurement of the Temperature Dependent Loss in vacuum. Integration of flight models GCS will begin by the end of 2016. Lot Validation Tests will be performed on one of the assembled GCS comprising thermal cycling (8 cycles -30°C/+65°C), damp heat test (45°C-95%RH for 48 hours), random vibrations (up to 15 gRMS) and shock (half sine 500 g for 1 ms, 5 times in 3 orthogonal axes).

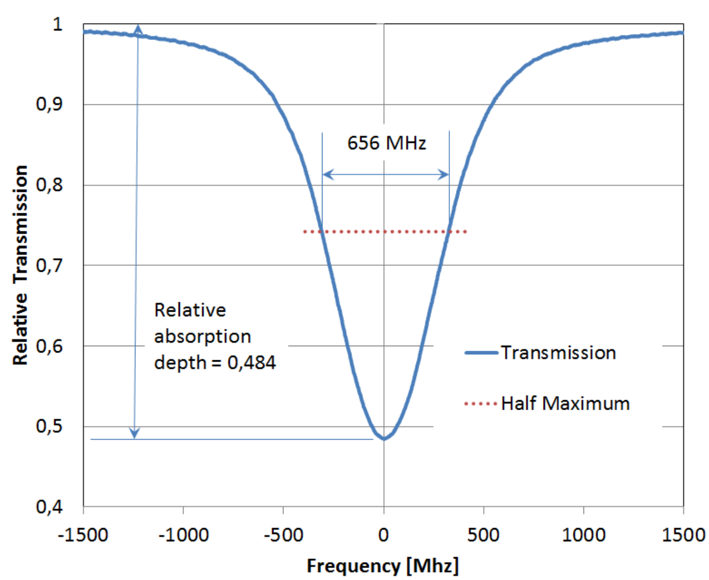

Fig. 7 : FWHM and relative transmission of a fully-integrated GCS

IV. CONCLUSION

A compact, stable and accurate 1542 nm fibered wavelength reference has been designed by Sodern. First results on prototype and breadboards show very good compliance of the Gas Cell Subassembly with the MTG Laser specification requirements. Full assessment of the Qualification Model performances is the next step before the manufacturing of the Flight Models.

Moreover, this design could be used with another gas in the cell for another wavelength reference.

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