Prism-based Broadband Optical Cavity (400 – 1600 nm) for High-Sensitivity Trace Gas Sensing by Cavity Enhanced Absorption Spectroscopy

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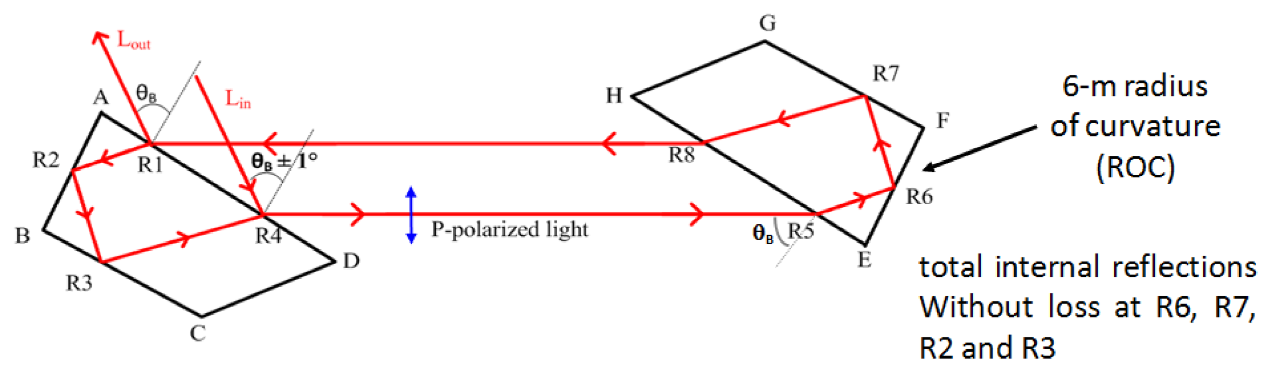
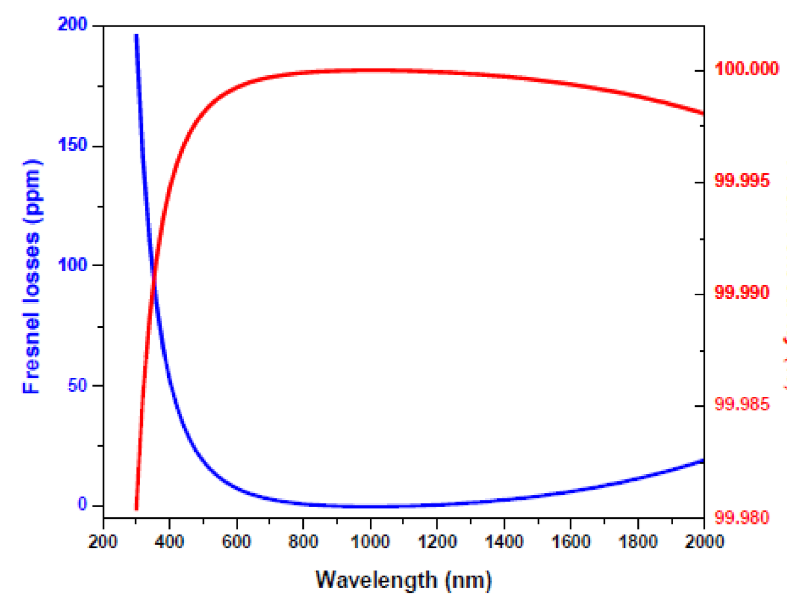
Introduction The use of high-reflectivity dielectric mirrors to form an optical cavity allows one to achieve effective optical path lengths of up to several kilometres for high-sensitivity spectroscopy applications [1,2]. However, the high reflectivity of a dielectric mirror is obtained via constructive interference of the Fresnel reflection at the interfaces produced by multilayer coatings of alternate high and low refractive index materials. This wavelength-dependent coating limits the bandwidth of the mirror's high reflectivity to only a few percent of the designed central wavelength [3]. In this work, we report the development of a novel optical cavity based on prism in CaF_2 used as cavity reflector through total internal reflection combined with Brewster angle incidence [4,5], which offers a high-finesse optical cavity operating in a broadband spectral region from 400 to 1600 nm. Cavity Enhanced Absorption Spectroscopy (CEAS) of NO_2 and H_2O vapour was applied to determine the prism reflectivity and to validate its broadband spectral capability.

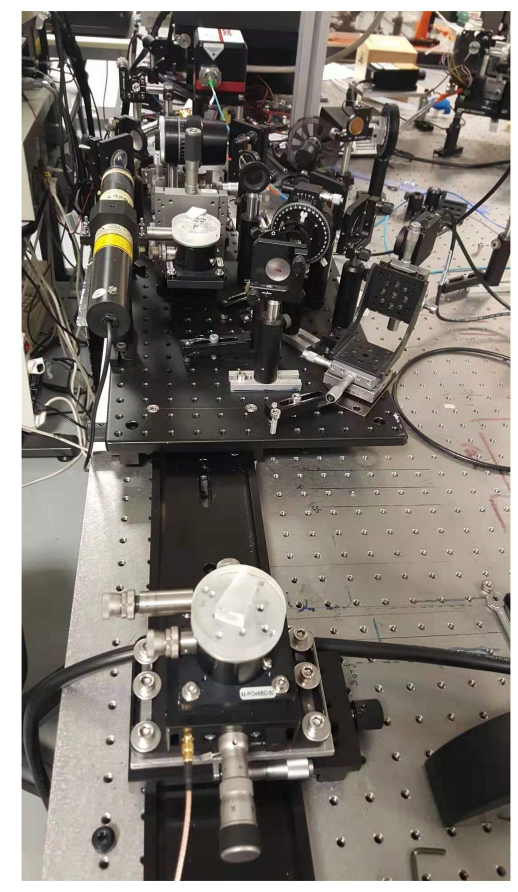
Prism-cavity based on total internal reflection : material losses limited reflectivity



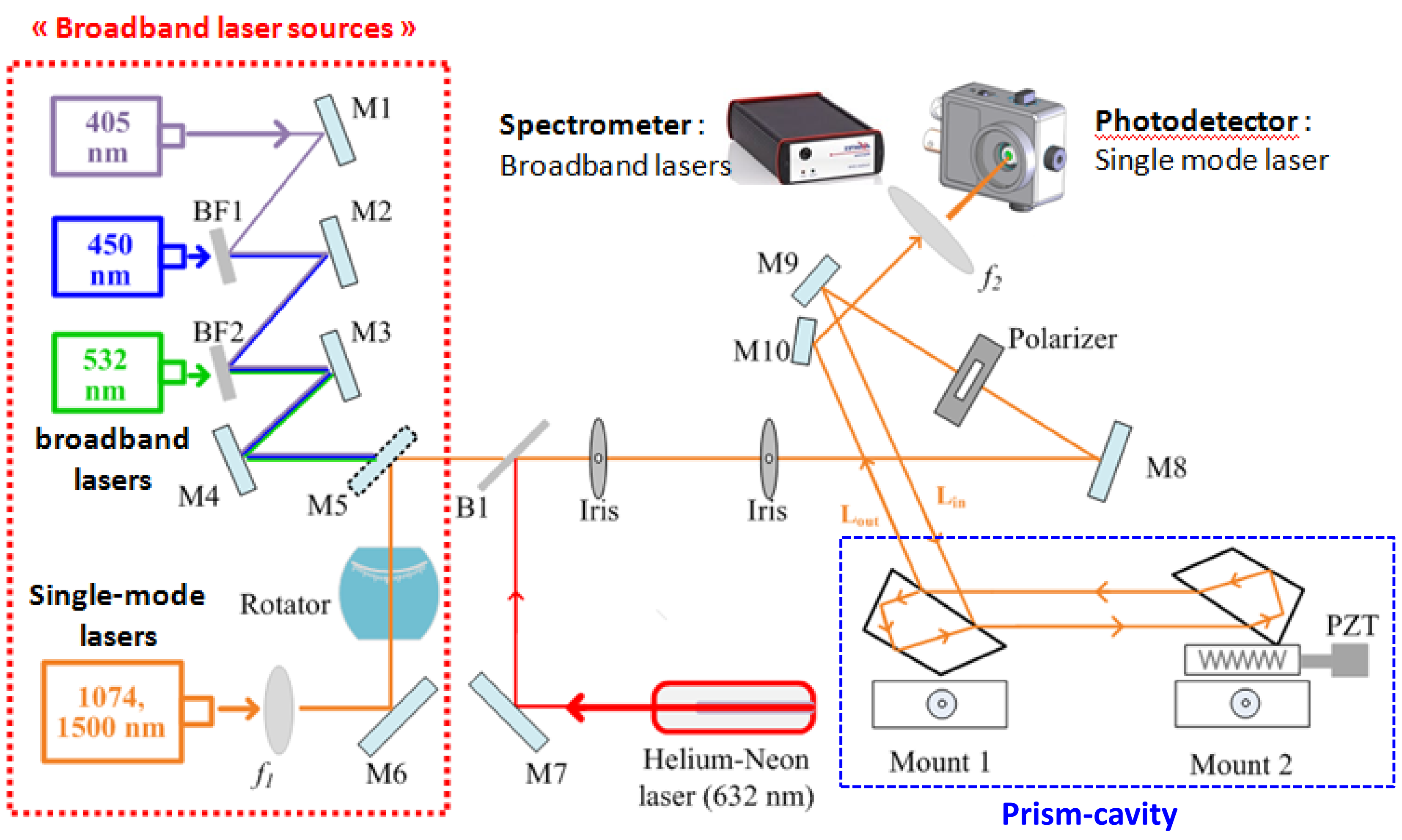
Prism-based cavity consists of two prism reflectors, which rely on total internal reflection of light beam at near the Brewster angle incidence. Light L_{in} is coupled into the cavity at R_4 and coupled out (L_{out}) at R_1. All surfaces are flat with exception to EF, which has a 6 m convex curve [5]. **Effective prism reflectivity is controllable** by tuning the beam incident angel around the Brewster angle (θ_B), within ~ 1°.



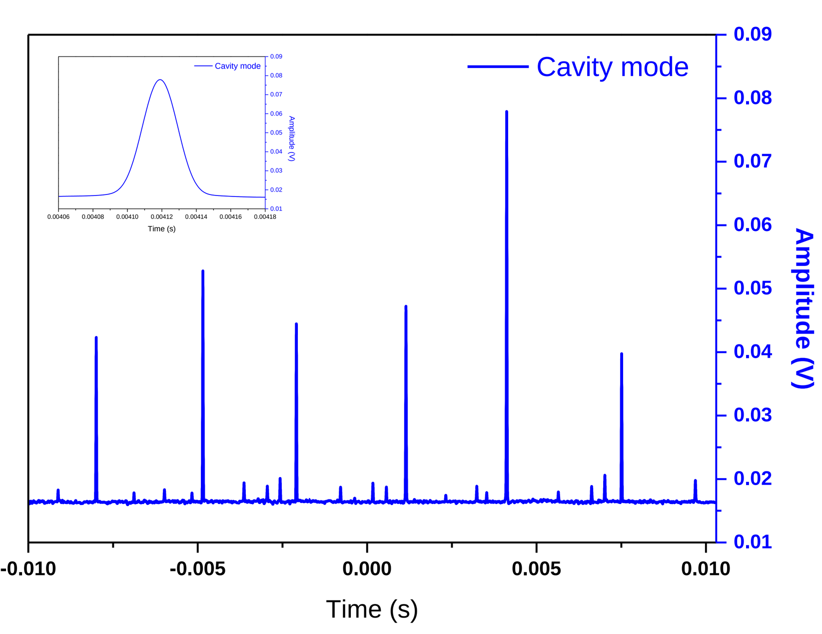
Modeled braodband high-reflectivity with a Brewster angle optimized for λ=1000 nm

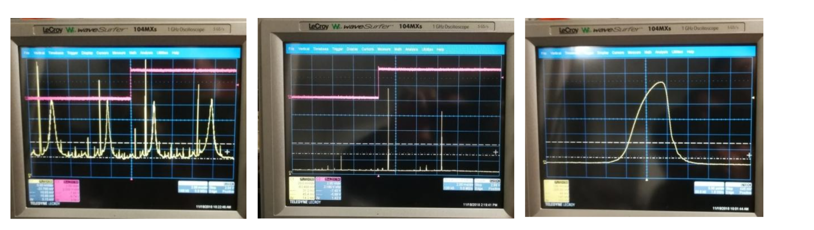


Experimental demonstration of broadband cavity performance

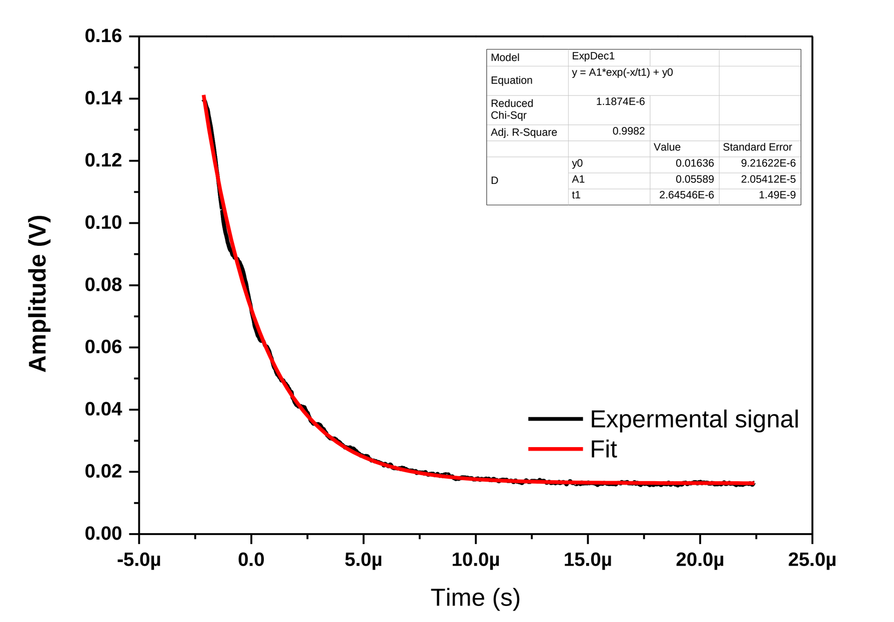


Prism-cavity mode



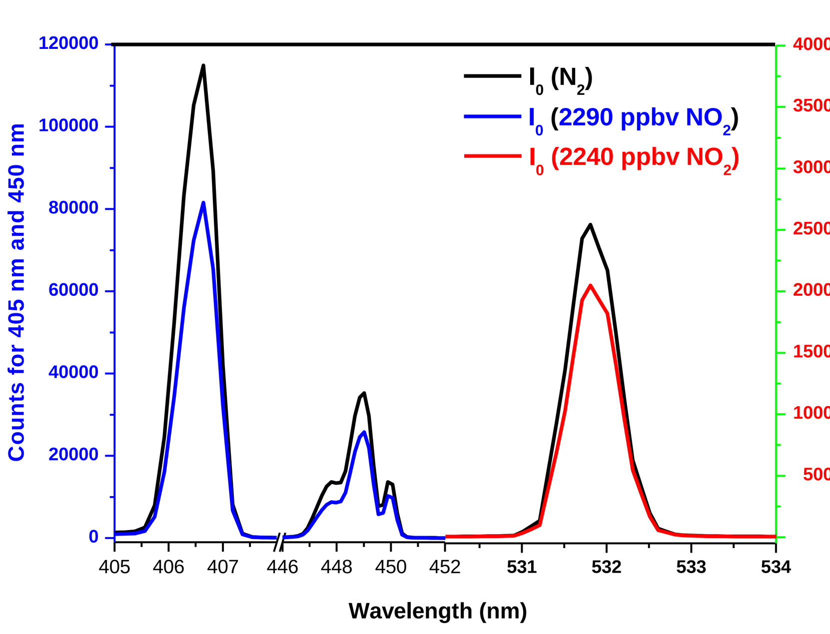


Ring-down time to determine R_{prism}

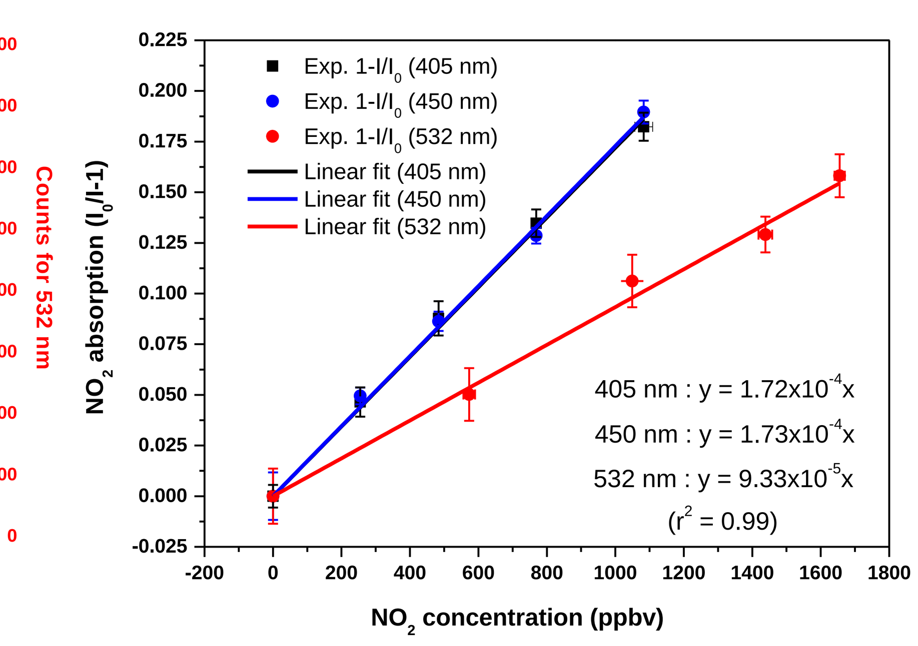


- ✓ Laser @ 1074.6 nm with 1.2 mW P component light power at the prism-cavity entrance
- ✓ d (cavity length) = 60 cm
- ✓ CRD decay time : 2.65 µs => R = 99.925% (by CRD)

BBCEAS measurement of NO_2 absorption using diode lasers at 405, 450, 532 nm



BBCEAS spectra $I_0(\lambda)$ and $I(\lambda)$ of N_2 and NO_2



Linear dependence of $(I_0-I)/I$ vs. NO_2 concentration

In Broadband CEAS (BBCEAS), gas absorption coefficient is expressed :

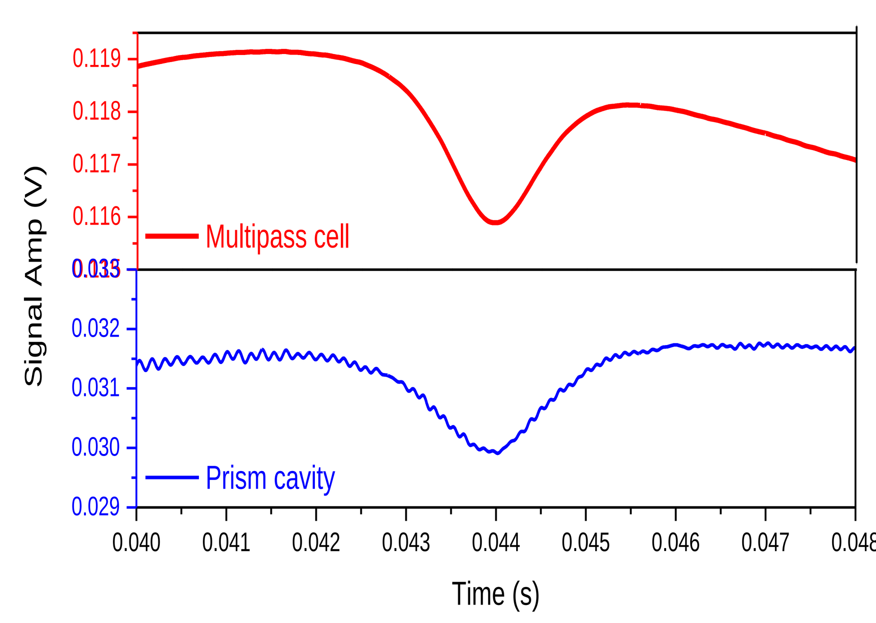
$$\alpha = \left(\frac{I_0}{I}-1\right)\times\left(\frac{1-R}{d}+\alpha_{Ray,N2}\right) = \sum_i \sigma_i(\lambda)\times N_i$$

where d is the cavity length; R the prism reflectivity; $\alpha_{Ray,N2}$ the gas Rayleigh scattering; $\sigma_i(\lambda)$ and N_i are the reference absorption cross section and number density of i species.

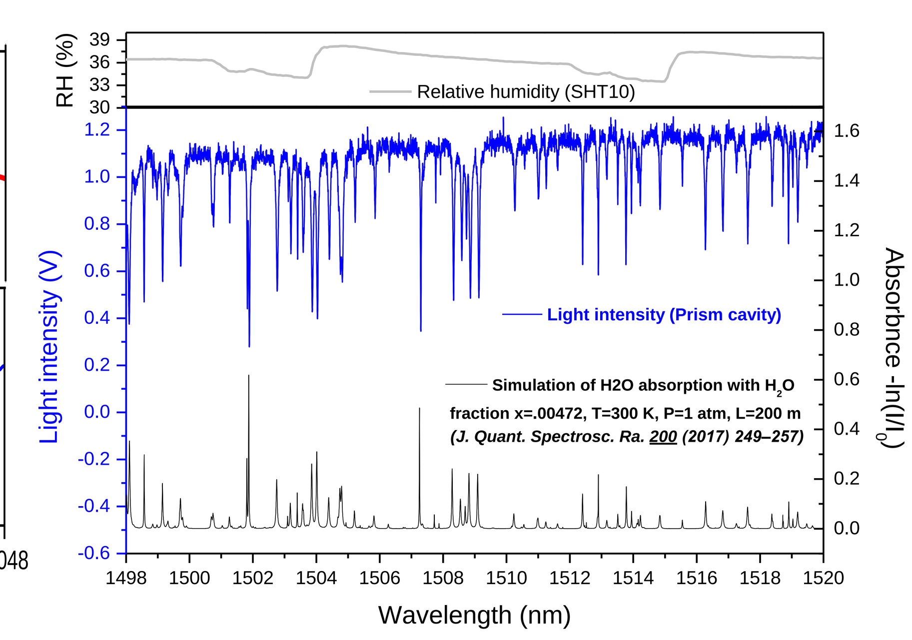
Using known concentration N of calibration gas, prism reflectivities were deduced :

405 nm : **99.48±0.01%**
450 nm : **99.58±0.01%**
532 nm : **99.77±0.02%**

CEAS measurement of H_2O at 1074.6 nm & 1500 – 1520 nm



H_2O vapour absorption spectra at 1074.6 nm in a multipass cell (L_{eff}=152 m) and the prism cavity



H_2O absorption simulation vs. experimental spectrum in the prism cavity over 1500 - 1520 nm

- **CaF_2 prism reflectivity** : **99.917±0.004%** (vs. **99.925%** from CDR) @ 1074.6 nm deduced from the H_2O vapour absorption spectrum whose concentration was determined by direct absorption spectroscopy in a multipass cell (L_{eff}=152 m).
- **CaF_2 prism reflectivity** : **99.972±0.001%** at 1507.25 nm determined from the measured high-resolution H_2O absorption spectra over 1500-1520 nm.
- **Prism offering material losses α limited reflectivities (R_{ideal}=1-α)** : CaF_2 prism losses of ~500 ppm at 500 nm [5] ➡

R_{ideal} ~ 99.95% (@ 500 nm) vs. **R_{exp} ~ 99.77%** (@ 532 nm)

Summary

Measured CEAS spectra of NO_2 in the visible and of H_2O vapour in the near-infared (NIR) using the developed CaF_2 prism-cavity demonstrated its broadband capability and allowed for determination of its reflectivities : **99.48%** (405 nm), **99.58%** (450 nm), **99.77%** (532 nm), **99.917%** (1074.6 nm) and **99.972%** (1507.25 nm).

The prism reflectivity is mainly limited by its optical losses including bulk absorption & scattering, surface scattering, residual birefringence induced losses (converting P to S polarization) due to either strain or misalignment of the optic axis of the prism substrate material, and fraction loss related to incident angle's deviation from the Brewster's angle.

Further improvement using lower losses SiO_2 prism : ~50 ppm @ 1570 nm in the NIR.

References

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