Measurement of the thermo-optic effect in IBS SiN_x coating

Matteo Bischi[1,2]; Benoît Sassolas[3]; Federica Fabrizi[1,2]; Massimo Granata[3];
Filippo Martelli[1,2]; Matteo Montani[1,2]; Francesco Piergiovanni[1,2]; Gianluca M. Guidi[1,2]
[1]Università di Urbino; [2]INFN Firenze; [3]Laboratoire des Matériaux Avancés, CNRS

Introduction

Thermo-optic noise is one of the possible sources of coating thermal noise that affects precision optical measurements, such as gravitational-wave detectors. A lot of effort is dedicated to identify coatings with low Brownian noise, but also coating thermo-optic noise should be considered as a possible limiting noise source for the next generation of GWDs mirrors. Silicon nitride (SiN_x) is one of the most promising new materials for new mirror coatings and a first measurement of thermo-optic parameters has been performed. This kind of measurement permits to know a linear combination of thermal expansion (α) and thermo-optic (β) coefficients. In the near future an evaluation of the thermal expansion coefficient will be carried out by measuring the curvature variation of a coated cantilever as a function of temperature.

What is thermo-optic noise?

Thermo-optic noise is the coherent sum of thermo-elastic and thermo-refractive noises that are due to thermal fluctuations in the coating.

- Thermo-elastic noise is due to variations of the nominal thickness (D) of the coating material linked to temperature fluctuations.
  The thermal expansion coefficient is defined as: $\alpha = \frac{1}{D}\frac{dD}{dT}$
- Thermo-refractive noise is due to the variation of the refractive index (n) of the coating material linked to temperature fluctuations.
  The thermo-optic coefficient is defined as: $\beta = \frac{dn}{dT}$

Using the thin film interference it is possible to estimate the optical thickness (L) of the coating, that is defined as: $L = nD$.
The optical thickness of the coating can change because both n and D can vary due to thermal fluctuations, so the dependence of L with temperature can be expressed as:

$$\frac{1}{L}\frac{dL}{dT} = \frac{1}{n}\frac{dn}{dT} + \frac{1}{D}\frac{dD}{dT} = \alpha + \frac{\beta}{n}$$

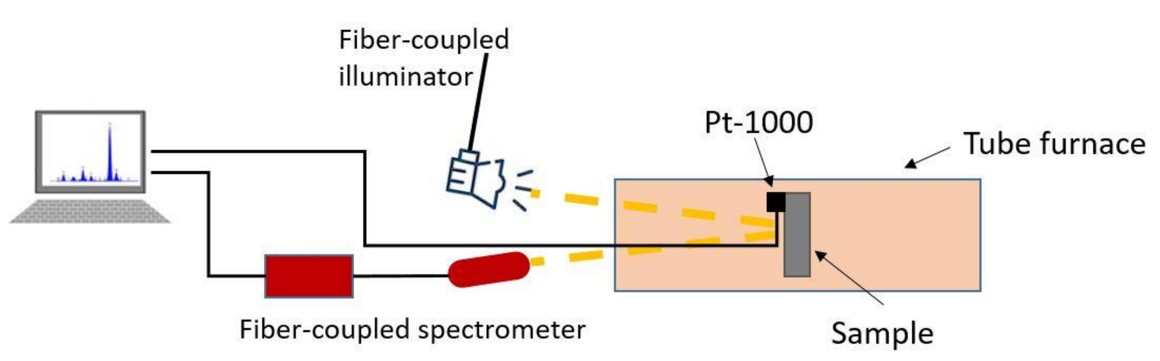
The total thermo-optic noise is given by [1]:

$$S_{TO}^{\Delta z} \cong S_{TO}^{\Delta T}\left(\overline{\alpha_c} d - \overline{\beta}\lambda - \overline{\alpha_s} d \frac{C_c}{C_s}\right)^2$$

Where $\overline{\alpha_c}$ depends on the coating expansion coefficient and $\overline{\beta}$ depends on $\alpha + \beta/n$.
Thermo-optic noise is not a limiting noise for second generation GW detectors, but our current knowledge of the properties of coating materials is inaccurate, so more precise measures are needed.

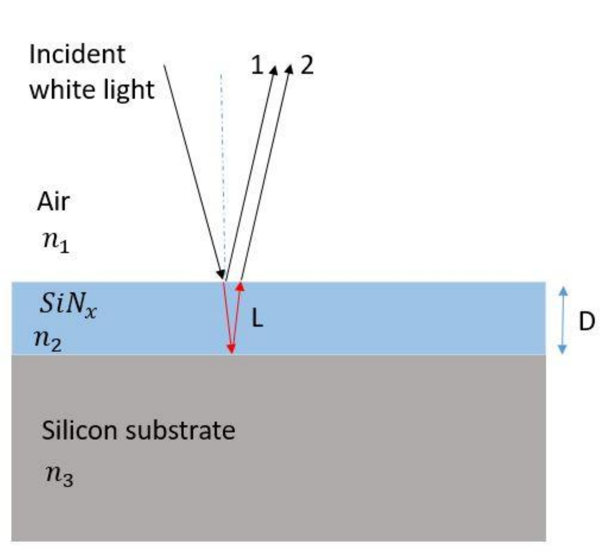
Experimental setup

In the Urbino Laboratory we have an experimental facility similar to the one developed by Gretarsson[2] at the Embry-Riddle Aeronautical University.



The sample is kept in vertical position inside a tube furnace. A collimated broadband white light (halogen lamp) is reflected (or transmitted) by the sample and focused on a fiber-coupled spectrometer (with a wavelength range 350-700 nm). The temperature is measured using a thermometer attached on the surface of the sample. The sample is heated up to 300°C and then spectra are acquired during the cooling process every 10°C.

It is possible to measure L using the thin film interference phenomenon in which broadband light waves are reflected or transmitted by the upper and lower boundaries of the coating and interfere with one another, either enhancing or reducing the reflected light, producing a pattern of maxima and minima. This kind of experiment can be performed in two configurations: in reflection using a silicon substrate or in transmission using a silica substrate.



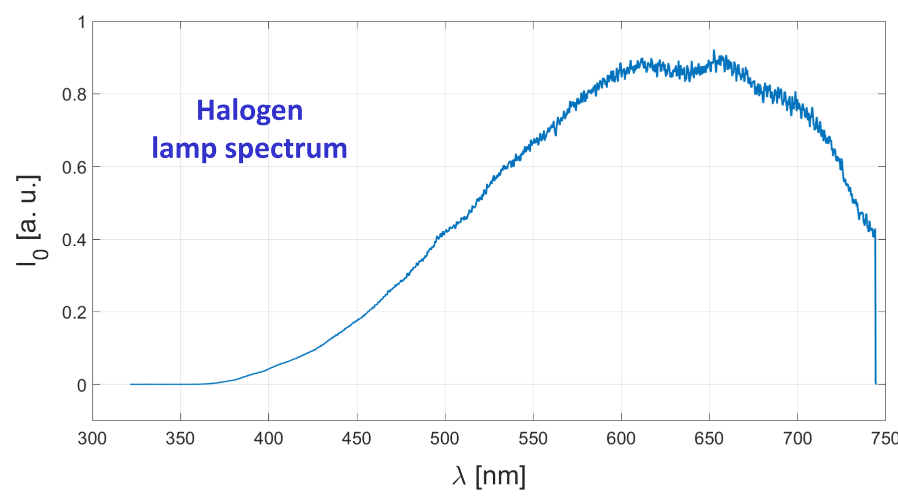
As can be seen in the scheme, the difference in the path followed by two reflected beams is 2L. If 2L is equal to an even multiple of λ/2 the two beams will be in phase and we observe constructive interference; if 2L is equal to an odd multiple of λ/2 we observe destructive interference. Using a broadband light on a thin film with an optical length L we will observe extrema located at:

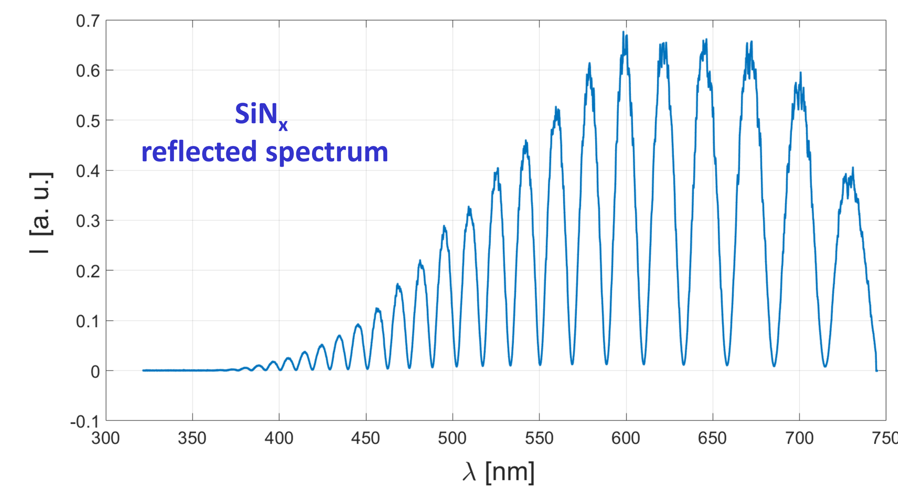
$$\lambda_j = \frac{4L}{N} \Longrightarrow \begin{cases} max & \text{for even N} \\ min & \text{for odd N} \end{cases}$$

The goal is to measure the optical length of the coating (from the location of the spectrum extrema) for different temperatures.
According to the last equation, the relative variation of the optical length with temperature is equal to the combination of thermo-optic parameters α and β.

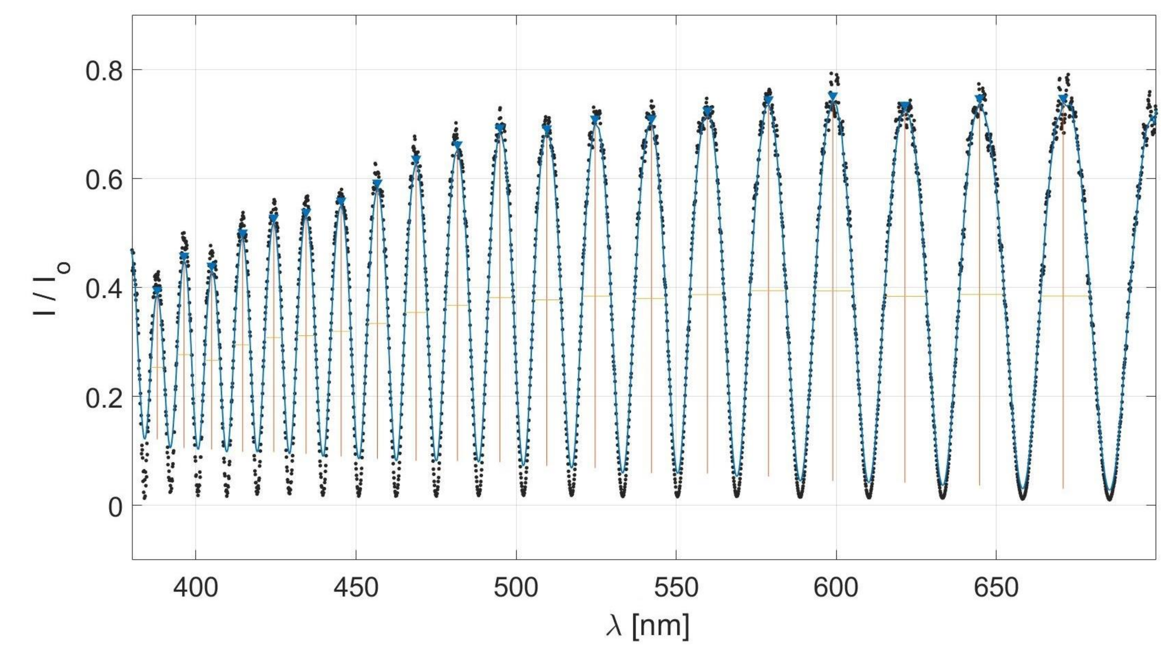
Acquired data and analysis

Lamp spectrum and reflected spectrum are acquired at room temperature. The thin film interference appear in the reflected spectrum.



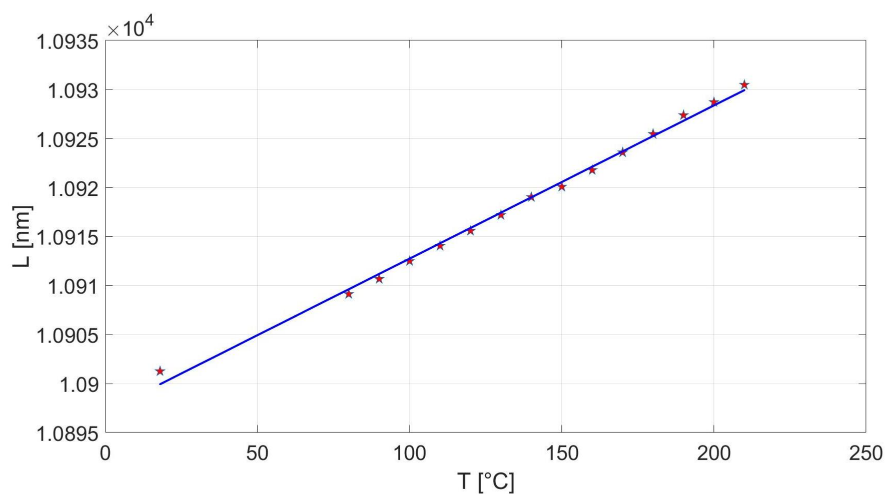


First of all the raw reflected spectrum is normalized with the lamp spectrum, then positions of maxima and minima are identified performing a parabolic fit. From their location we estimate the coating's optical thickness (L).

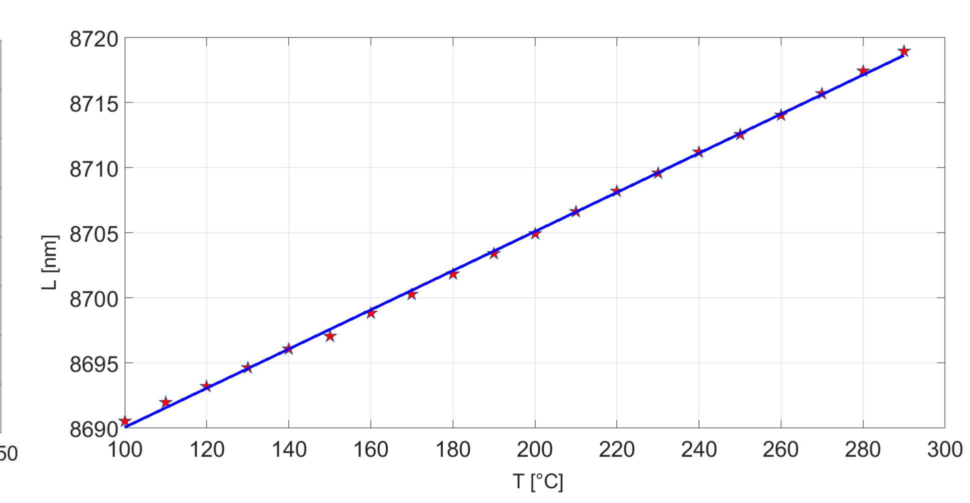


The reflected spectrum is acquired every 10°C and the coating's optical length dependence with temperature for SiN_x and tantala are reported below:

Ta_2O_5 coating



SiN_x coating



From the slope of the linear fit we have:

$\frac{1}{L}\frac{dL}{dT} = \alpha + \frac{\beta}{n} = (1.43 \pm 0.05) \times 10^{-5}\ K^{-1}$ for the tantala coating

$\frac{1}{L}\frac{dL}{dT} = \alpha + \frac{\beta}{n} = (1.64 \pm 0.02) \times 10^{-5}\ K^{-1}$ for the silicon nitride coating

The tantala sample is the same measured by Gretarsson in [2] and is used to validate our experimental setup and data analysis method. The result is compatible to the one reported in [2].

From the value of the coating's nominal thickness (D) provided by the developer (estimated from the deposition time) and the value of the coating's optical thickness (L) measured at room temperature, the refractive index of SiN_x coating results to be: $n = (2.06 \pm 0.07)$

Future work

We are developing a facility to measure the variation of the curvature of a coated silicon cantilever as reported in [3]. In this way we can have an evaluation of the thermal expansion coefficient (α) of the coating and obtain the value of the thermo-optic coefficient (β) separately.

Conclusions

We measured a combination of thermo-optic parameters of SiN_x for the first time and result to be:

$$\alpha + \frac{\beta}{n} = (1.64 \pm 0.02) \times 10^{-5}\ K^{-1}$$

In the near future we will measure the two parameters separately, in order to have a better estimation of the total thermo-optic noise that arise from silicon nitride coatings.

References

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3. Abernathy, Matthew R., et al. "Investigation of the Young's modulus and thermal expansion of amorphous titania-doped tantala films." Applied Optics 53.15 (2014): 3196-3202.