

Controlling resonance peak shifts of a LiNbO₃ Fabry-Perot etalon via dielectric coatings

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Abstract

The Vigil mission requires continuous solar monitoring for improved space-weather forecasting. Its solar polarimeter uses a filtergraph with a single tuneable LiNbO₃ Fabry-Perot etalon operating near the Fe I 617.334 nm line. To reach the target finesse of 30, both etalon surfaces require a high-reflective dielectric coating. This paper presents the coating concept, deposition and characterisation for a SiO₂/Ta₂O₅ multilayer stack deposited by magnetron sputtering. An indium tin oxide top layer is integrated as a transparent electrode for fine tuning of the resonance peaks through the piezoelectric response of LiNbO₃. Because of polishing tolerances that can shift the resonance peak significantly away from the science wavelength, the paper describes how targeted thickness adjustment within the dielectric stack can tune the effective optical response and realise controlled peak shifts between 80 pm and 168 pm, with the potential to cover more than a full free spectral range with more than 300 pm.

Keywords: Fabry-Perot etalon; LiNbO₃; dielectric coating; magnetron sputtering; high reflectance; resonance peak shift; ITO electrode; solar polarimetry

1. INTRODUCTION

The Vigil mission will provide solar observations for space-weather forecasting. The filtergraph in its solar polarimeter uses a combination of two pre-filters and a single tuneable LiNbO₃ Fabry-Perot etalon near the Fe I 617.334 nm line, referred to as science wavelength, to monitor the solar magnetic field signatures [1]. The present paper focuses on the optical coating of this etalon, and covers coating design, sputter deposition, characterisation and qualification.

A Fabry-Perot etalon requires defined reflectance at two parallel surfaces to build the desired cavity that reaches its final finesse. In this case, the target finesse is around 30. A high-reflective dielectric coating is therefore required on both sides of the etalon. The coating must preserve the polished LiNbO₃ surface quality, and needs to be compatible with a transparent electrode, because resonance fine tuning shall also be realised by changing the effective cavity spacing through the piezoelectric response of LiNbO₃.

However, the fine tuning range is limited, and in particular much smaller compared to the free spectral range, separating two adjacent resonant peaks. Thus, also the absolute resonant peak position needs to match the science wavelength. The necessary spectral ranges and accuracies are motivated in the following, before the interference coating design, fabrication and verification measurements are presented.

At normal incidence, the resonance condition is

$$2 n d_{\text{eff}} = m \lambda,$$

where n is the refractive index of LiNbO₃, d_{eff} is the effective cavity thickness, m is the interference order and λ is the resonance wavelength. The dielectric coatings modify the reflection phase at both cavity boundaries. Their contribution must therefore be included when the resonance lines of the etalon are aligned with the science wavelength. The free spectral range, i.e. the spectral difference between two resonance peaks, may be estimated as [2]

$$FSR(\lambda) \approx \lambda^2 / (2 n_g d_{\text{eff}}).$$

With an etalon thickness around 250 µm, and $n_g \approx 2.471$ as the group index of LiNbO₃ (see Tab. 1), a FSR of about 308 pm at the science wavelength 617.334 nm is found. In the final instrument, a voltage-driven fine tuning range of up to 30 pm is foreseen. Thus, it becomes clear how important the correct absolute positioning of the cavity resonance peaks is for the instrument performance.

2. OPTICAL COATING DESIGN

2.1 Optical and functional targets

The measurement cavity is designed for operation near the Fe I 617.334 nm line. The coating's primary optical function is to provide approximately 93% reflectance on each etalon surface to reach a target finesse of 30. The reflectance goal value is considered as an internal value, given for the interface between LiNbO₃ etalon and the coating. The baseline high-reflective dielectric design is a quarter-wave SiO₂/Ta₂O₅ multilayer stack with 5 layer pairs. The coating is applied

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symmetrically to both substrate sides with the same layer sequence and nominal thicknesses. The primary coating function is to provide an internal reflectance of approximately 93% at the science wavelength at each LiNbO₃-coating interface. This value supports the target finesse of approximately 30. The baseline dielectric system contains five SiO₂/Ta₂O₅ layer pairs and an additional high-index termination layer. Identical designs are deposited on both etalon surfaces.

The second function is electrical, for which an ITO top layer is included as a transparent electrode. It enables tuning of the resonance peaks in the assembled filtergraph by applying a voltage. For this purpose, a target sheet resistance well below 100 Ω/sq is needed, which implies a nominal ITO layer thickness around 30 nm.

The third function is compensation of the resonance peak position. The polishing process fixes the substrate thickness before coating. The accuracy of the process, however, is limited. Using the resonance condition and values from above, a spectral shift of $\Delta\lambda \approx 2.4$ pm in resonance wavelength per nanometre etalon thickness can be estimated. Thus, a thickness deviation of only 10 nm would already account to about 24 pm of shift in the resonance wavelength of the etalon. This approximation shows how sensitive the instrument's cavity reacts to polishing deviations and the corresponding resonance shifts.

If the resonance peaks of the polished etalon show an offset from the desired spectral position, the coating design can be adapted slightly to compensate this offset. The adjustment changes the coating-induced reflection phase and therefore the effective cavity thickness. In the following, the details of the adaption process are motivated and described.

2.2 Baseline high-reflective multilayer structure

The dielectric system consists of alternating Ta₂O₅ high-index layers (H) and SiO₂ low-index layers (L), with the baseline sequence (HL)⁵H + ITO. The inner quarter-wave stack provides the required reflectance. The two terminating H layers provide an additional degree of freedom for phase and reflectance adjustment to the ITO top layer. Their thickness can be varied independently of the intermediate quarter-wave layers.

The multilayer calculations use the ordinary refractive index of c-plane LiNbO₃ at normal incidence. The value is obtained from the Sellmeier equation reported by Zelmon et al. [3]. The dielectric and ITO dispersions are based on in-house data, where SiO₂ and Ta₂O₅ are treated as non-absorbing in this spectral range. Table 1 lists the optical constants near the science wavelength. OptiLayer is used for the optical design and the calculation of reflectance, transmittance and coating-induced resonance shift. Since the target is not to maximize reflectance, but to reach a defined reflectance value, the HR coating is designed for 640 nm, such that the maximum reflectance is slightly offset against the science wavelength. This makes the target reflectance easier assessable in the design, but shifts the nominal quarter-wave layer thicknesses. These are approximately 75 nm for Ta₂O₅ (H), and 108 nm for SiO₂ (L). The baseline HR coating stack induces already a theoretical shift in resonance wavelength of approximately +35 pm.

Table 1: Optical constants used for the coating design near 617 nm. The ordinary refractive index n_o used for c-plane LiNbO₃ is taken from Ref. [3], and the ordinary group refractive index $n_{g,o}$ is calculated according to $n_{g,o} = n_o - \lambda \, d n_o / d \lambda$.

Material	Refractive index, n	Extinction coefficient, k
SiO ₂	1.477	--
Ta ₂ O ₅	2.148	--
ITO	1.772	0.0056
LiNbO ₃	2.291 (n_o)	--
LiNbO ₃	2.471 ($n_{g,o}$)	--

2.3 Technique for tuning the resonance position

The tuning procedure starts with a high-resolution spectral measurement of the polished, uncoated etalon. The measured resonance position is converted to the specified operating condition and compared with the target wavelength. The required correction and the target reflectance then define the input for the coating optimization.

To adapt the resonance peak position, the optical thickness of selected layers is changed. Each layer thickness adaption, however, changes the reflectance together with the position of resonance wavelengths. The design task is therefore to obtain the required peak shift while maintaining the desired reflectance.

The innermost H layer, adjacent to the LiNbO₃ substrate, is used primarily to change the coating-induced reflection phase. Increasing the thickness of this layer red-shifts the calculated resonance while leaving the rest of the periodic stack unchanged. The outermost H layer, adjacent to the ITO top layer, is adjusted to recover the required reflectance, and has only minor influence on the peak shift. Both thicknesses are varied iteratively until the targeted values for spectral shift and reflectance are obtained. This method separates the main phase correction from the reflectance adjustment and limits changes to the established quarter-wave stack.

For the exemplary etalon discussed in the following, the intended peak shift amounts to 168 pm. The adapted design increases the innermost Ta_2O_5 layer by 30 nm (from ~ 75 nm to ~ 105 nm), while reducing the outermost Ta_2O_5 layer from ~ 18 nm to ~ 12 nm. All intermediate layers remain unchanged. The calculation predicts a red-shift of +168 pm, while retaining the internal reflectance of $\sim 93\%$ at 617.3 nm.

The coating therefore provides a coarse, pre-deposition correction of the peak frequency. In the final instrument, the LiNbO_3 voltage tuning then provides fine adjustment during operation.

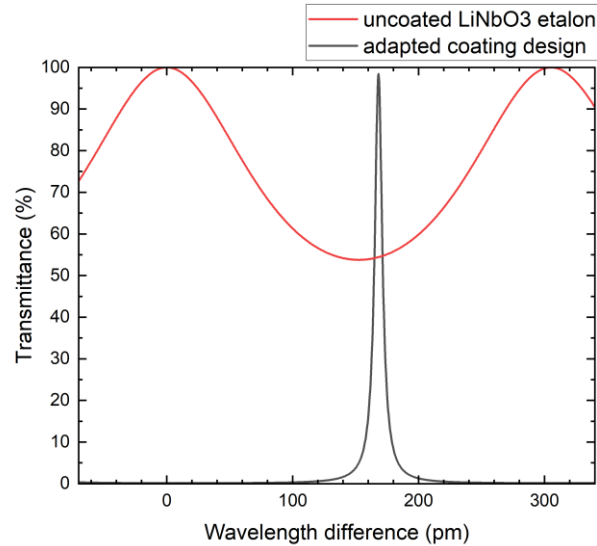


Figure 1: Calculated transmission peaks of the uncoated LiNbO_3 etalon and the adapted coating design for SN503. The coating design reveals a calculated redshift of +168 pm, displayed relative to the uncoated etalon.

The same optimisation strategy has been applied to several etalons with different measured offsets. Fig. 2 shows the reflectance and transmittance curves for the adapted design described above, together with the measurements that are discussed in the following sections.

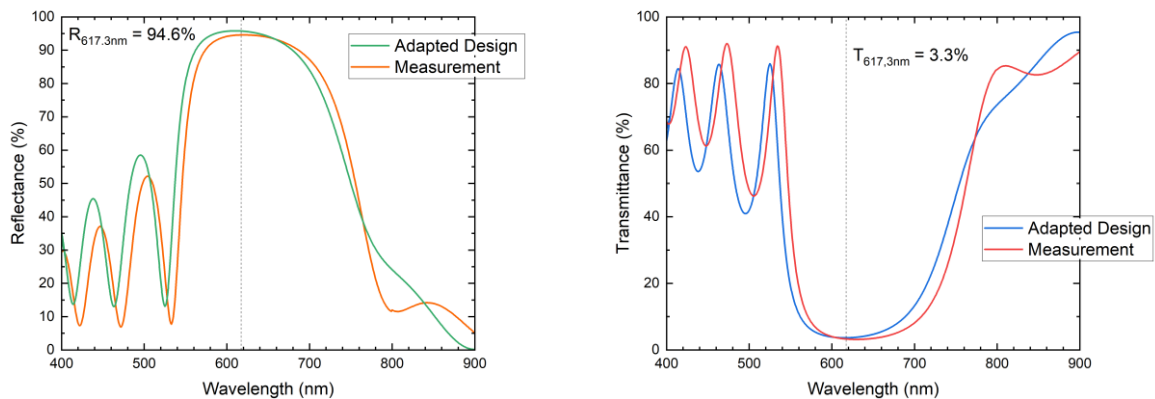


Figure 2: Calculated and measured broadband optical response of the fully coated exemplary etalon (SN503): External reflectance measured at 8° angle of incidence (left), transmittance measured at normal incidence (right). The vertical line indicates the science wavelength at 617.3 nm.

3. DEPOSITION AND CHARACTERISATION

3.1 Magnetron sputtering process

The dielectric coatings are deposited by magnetron sputtering on the EOSS[®] production platform [4-7]. EOSS[®] uses a rotating substrate holder and rotatable cylindrical cathodes. Mixed metal/metal-oxide targets provide a stable deposition regime without reactive process gas. The process therefore avoids variations associated with reactive-gas control and supports reproducible optical constants and deposition rates. The process reaches coating uniformities typically above 99.8% on substrates with 200 mm diameter. The upward-facing coating geometry also reduces particle contamination of the optical surface. This way, a uniform reflectance distribution across the 50 mm clear aperture of the etalon is assured.

The Ta₂O₅ and SiO₂ layer thicknesses are controlled by in-situ optical monitoring. Both HR coatings are deposited sequentially with the same adapted design. The substrate is turned between the two coating runs.

The ITO electrodes are deposited subsequently in a Leybold A700V in-line coater. A separate coating plant is used because the ITO coating requires different thermal conditions from the dielectric stack. ITO is deposited on both sides with a nominal thickness of 40 nm to ensure the necessary conductivity. The electrical and optical properties are verified on associated witness samples and partly on the coated etalon.

3.2 Broadband optical and electrical characterisation

Broadband reflectance and transmittance are measured after deposition of the dielectric and ITO coatings on the etalon surfaces. A Cary 5000 spectrophotometer is used under standard laboratory conditions. The wavelength range extended from 400 to 900 nm. External reflectance was measured at an incidence angle of 8°, whereas transmittance was measured at normal incidence. The spectra are compared with the calculated curves for the final coating design (Fig. 2). At 617.3 nm, the measured external reflectance of the exemplary etalon is 94.6%, compared with a calculated value of 95.8%. The measured transmittance is 3.3%, whereas the design predicts 3.7%. The measured spectra reproduce the calculated high-reflectance band in general, but a slight red-shift is found together with a reflectance reduced by about 1%, which is discussed in Section 4. The internal reflectance at the LiNbO₃-coating interface is not directly accessible after coating. Compliance with the internal target was therefore assessed by comparison of the external spectra with the multilayer model.

Electrical characterisation was performed on ITO-coated witness samples from the front-side and back-side coating runs. The measured sheet resistances are 38 and 40 Ω/sq, respectively. Both values remain below the specified limit of 100 Ω/sq and confirm the electrical function of the transparent electrodes.

3.3 High-resolution resonance measurement

For the high-resolution measurement, a broadband LED emitting around 617 nm is connected to a transceiver optic used to illuminate the etalon at an angle of 0°. The exact position of the etalon inside the illumination beam is controlled by a hexapod. A receiver optic feeds the transmitted light into a hyperfine-spectrometer, with appropriate resolution for the measurement of the resonance peaks. As the finesse is not measurable directly, further data processing is required. By means of different receiving optics, either the full clear aperture of 50 mm or smaller spots with a size of 10 mm diameter can be measured. The spot measurement is important to learn about the homogeneity of the substrate and possible local variations of the optical properties.

Fig. 3 shows such high-resolution transmission spectra for the uncoated and coated etalon over the full 50 mm clear aperture. The measurement therefore represents the aperture-integrated etalon response. The uncoated measurement is performed at room temperature. The target wavelength refers to an operating temperature of 40°C, and the measured peak position is converted using an empirical thermal correction.

Before coating, the selected resonance peak is measured at 617.1008 nm with a full width at half maximum of 123 pm. After coating with the compensating layer stack, the corresponding peak is measured at 617.285 nm with a full width at half maximum of 15.0 pm. The measured redshift is therefore +184 pm and slightly larger than intended (+16 pm). Still, the peak after coating will be close to the science wavelength of 617.334 nm at the elevated operating temperature of 40°C and can therefore be addressed by the available fine-tuning range, as demonstrated in Fig. 4. Furthermore, the finesse of the coated etalon can be estimated within 10 mm spots across the clear aperture, reaching values between 26.9 and 30.1, which is in good agreement with the expectations.

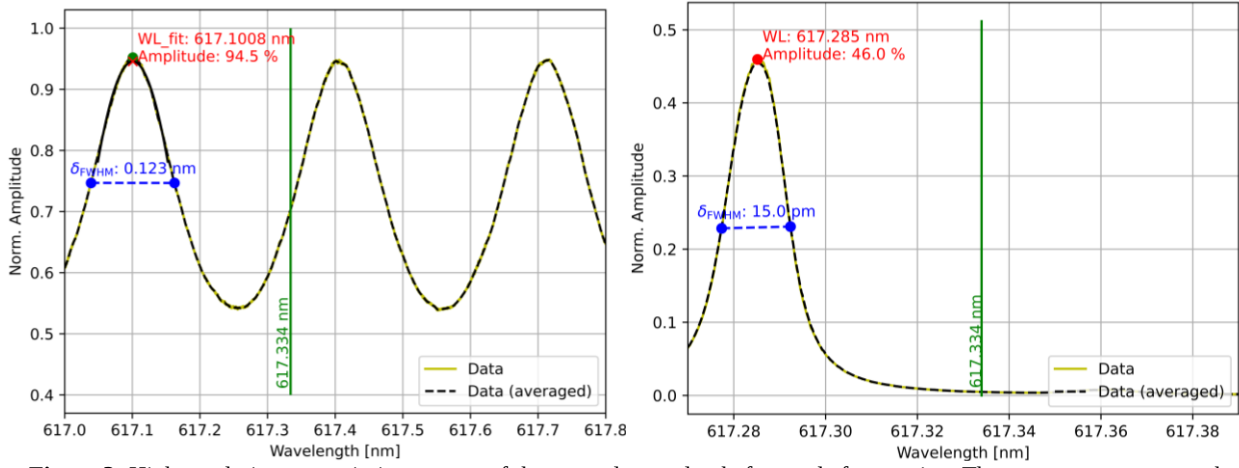


Figure 3: High-resolution transmission spectra of the exemplary etalon before and after coating. The measurements cover the full 50 mm clear aperture. The measured coating-induced redshift is +184 pm, compared with the target value of +168 pm. Note that the corrected resonance peak does not align with the science wavelength, as the measurements were performed at room temperature and not at 40°C operating temperature.

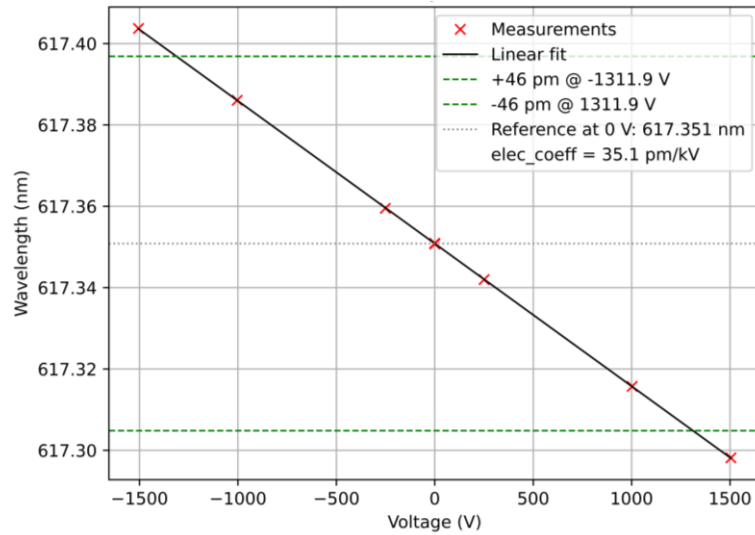


Figure 4: Shifting of the resonance peak wavelength with applied fine-tuning voltage. The measurement is performed at 40°C operating temperature and covers the intended science wavelength of 617.334 nm.

4. DISCUSSION

The adapted coating design produced the intended resonance shift while retaining an optical response close to the calculated performance. However, the measured external reflectance and the absolute peak shift showed small deviations from the predicted values.

At 617.3 nm, the measured external reflectance was 94.6%, compared with the calculated value of 95.8%. The internal reflectance at the LiNbO₃-coating interface is not directly accessible after coating. The coating performance can therefore be assessed only indirectly from the broadband spectra, coating uniformity and process-control data. The layer-thickness inhomogeneity measured immediately before deposition was below 0.2%. Simulations indicate that this variation changes the broadband reflectance by less than 0.1% and is thus negligible. The monitored layer thicknesses also agreed with the process targets. Coating non-uniformity or a systematic thickness error is therefore unlikely to explain the reflectance deviation.

The measured transmittance was 3.3%, compared with the calculated value of 3.7%. The lower reflectance is thus not compensated by increased transmittance, as the influence of the small difference in angle of incidence between the reflectance (8°) and transmittance measurements (0°) can be neglected. Additional optical loss therefore provides a plausible explanation. The ITO termination layer is a potential source because it has a finite extinction coefficient. An inaccurate dispersion could affect the calculated optical behaviour. Furthermore, in an ideal system, the finesse is only

depending on the cavity reflectance or losses, whereas in the real etalon further losses and spectral broadening can be introduced by the etalon's thickness homogeneity or surface roughness. The measured finesse nevertheless remained close to the expected value. This indicates that the internal reflectance seems not substantially reduced and that the deviation may predominantly originate from the outer part of the coating stack.

The adapted design predicted a resonance redshift of +168 pm. The measured shift was +184 pm, corresponding to an excess shift of 16 pm. Errors in the absolute LiNbO₃ thickness or refractive index affect the resonance position and free spectral range. However, their influence should largely cancel when comparing the uncoated and coated states of the same etalon. The residual deviation may instead originate from the high-resolution measurement itself, where the coated front and back sides were not electrically short-circuited during the measurement. Residual charge could therefore generate an electric field across the piezoelectric LiNbO₃ substrate and modify the effective cavity thickness. Thus, measurements with an assembled etalon, or evaluations on instrument level, could be required to clarify this point. Furthermore, from the comparison of all the measurements carried out so far, the residual thickness homogeneity after polishing is strongly correlated with the performance inhomogeneity after coating. This proves that the coating, and in particular its homogeneity, has negligible impact on local optical performance deviations.

5. CONCLUSIONS

This paper demonstrates a coating-based method for controlling the resonance position of a ~250 µm thick LiNbO₃ Fabry-Perot etalon. The sputtered SiO₂/Ta₂O₅ multilayer provides the required reflectance of ~93% to form an optical cavity with the target finesse around 30, while an ITO top layer forms a transparent electrode needed for voltage-based fine-tuning. Targeted adjustment of the terminating high-index layers modifies the coating-induced reflection phase without changing the established quarter-wave stack.

For the exemplary etalon presented here, the adapted design predicted a redshift of +168 pm, compared to a measured shift was +184 pm. Although the origin of the deviation could not be fully evaluated, yet, the influence of electrical charges on the high-resolution measurement itself could be possible. The realised coating designs for further etalons not presented here cover calculated peak shifts from approximately +80 to +168 pm. Furthermore, design variants that provide calculated peak shifts from approximately -68 to +271 pm were investigated as well and seem realistic. Therefore, more than one full spectral range can be covered, opening new design possibilities. The investigated approach compensates substrate-thickness deviations by the required coating step and avoids further mechanical processing of the polished LiNbO₃ substrate. It therefore provides a practical method for setting the absolute resonance position of future instruments with high-finesse etalons.

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