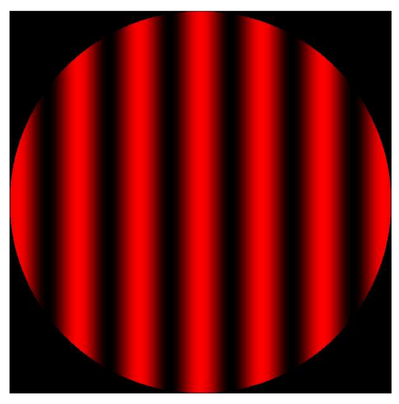
Highly sensitive displacement measurement utilizing the wavelength interrogation



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Abstract

Spectral interferometric methods utilizing the interference of two beams in a Michelson interferometer to measure the displacement are analyzed experimentally. First we consider an experimental setup comprising a white-light source, a dispersion balanced Michelson interferometer and a spectrometer. The position of one of the interferometer mirrors is controlled via a piezo positioning system and the displacement measurement is based on the wavelength interrogation, i.e., the position of a selected interference fringe in the resultant channeled spectrum is measured as a function of the mirror displacement. Second we consider a setup with another interferometer, included in the Michelson interferometer, to increase the sensitivity of the displacement measurement. In this setup, the resultant channeled spectrum is with envelope which shifts with the displacement of the interferometer mirror.

1. Experimental setup

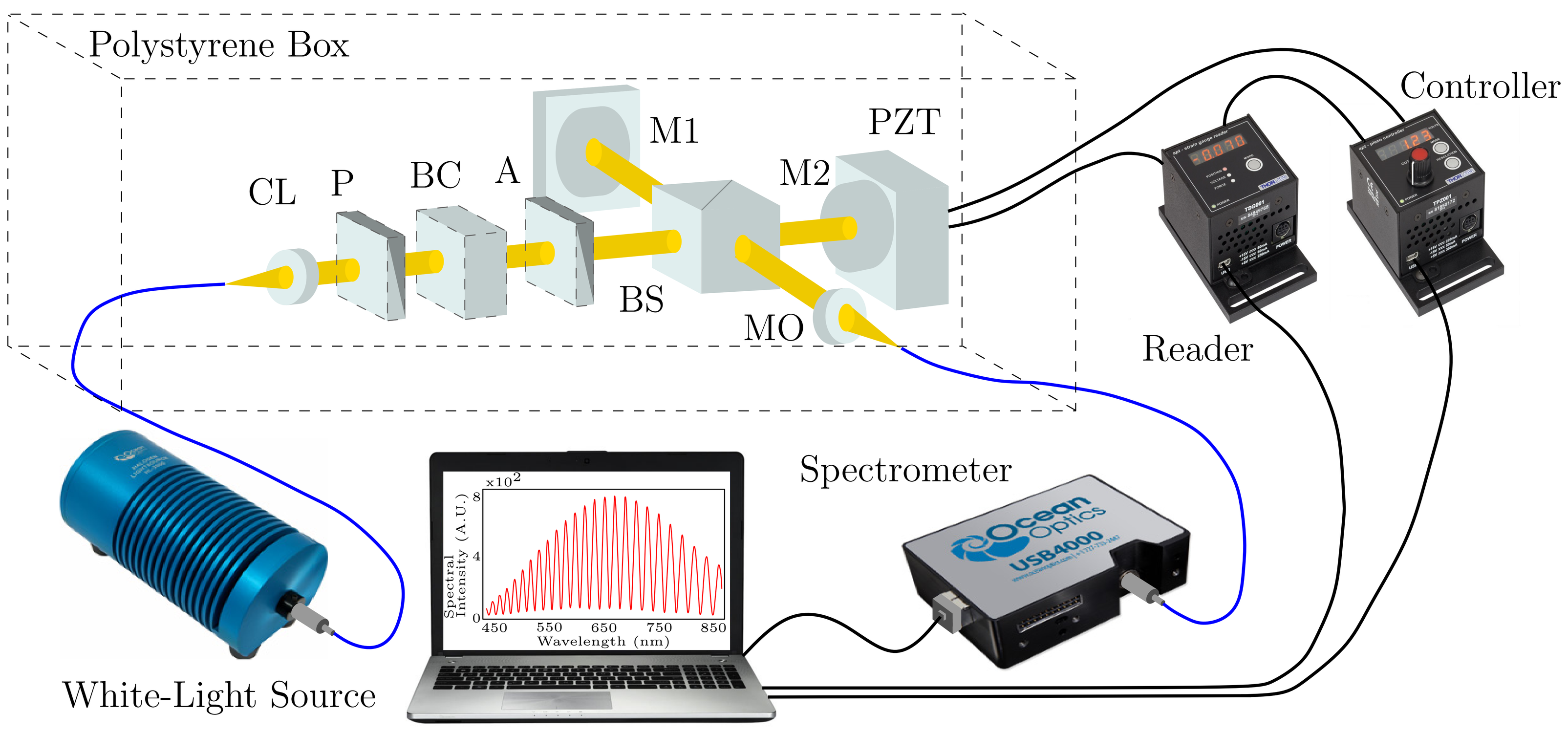

Figure 1: *Experimental setup with a Michelson interferometer to measure mirror displacement; collimating lens (CL), polarizer (P), birefringent crystal (BC), analyzer (A), beam splitter (BS), mirrors (M1, M2), piezo transducer (PZT) and microscope objective (MO).*

2. Experimental results and discussion

Consider a Michelson interferometer (see Fig. 1) with the optical path difference (OPD) Δ_M adjusted between its beams $\Delta_M = 2(L - l)$, where l and L are the optical path lengths of the beam in the air in the first and in the second arm of the interferometer, respectively. The interference of the beams at the output of the interferometer shows up as a channeled spectrum with the period

$$\Lambda(\lambda) = \frac{\lambda^2}{|\,\Delta_M\,|}. \tag{1}$$

To demonstrate the generation of the channeled spectrum at the output of the Michelson interferometer, we consider an experimental setup comprising a white-light source, a dispersion balanced interferometer and a spectrometer (see Fig. 1). The position of mirror 2 is controlled via a piezo positioning system and we recorded a series of channeled spectra for increasing displacement Δl with a step of approximately 25 nm.

Figure 2 shows two examples of the recorded spectra for selected mirror displacements. It is clearly seen from the figure that the two-beam interference shows up as a channeled spectrum and that the spectral interference extremes are shifting toward shorter wavelengths as the mirror displacement increases and the shift is smaller for shorter wavelengths.

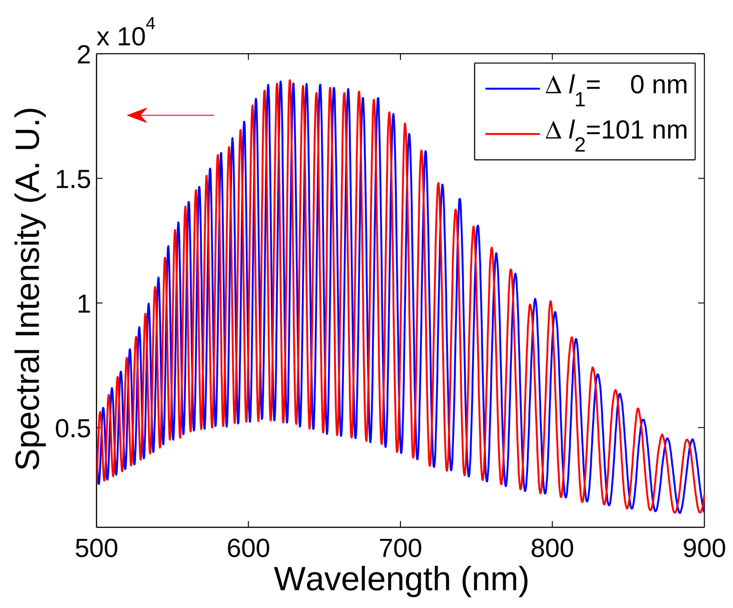

Figure 2: *Two examples of the recorded channeled spectra corresponding to mirror displacements Δl_1 and Δl_2.*

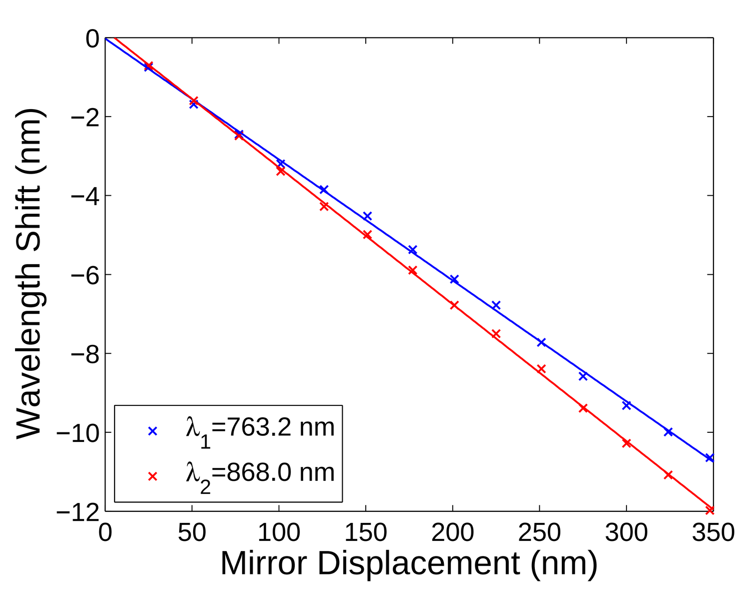

Figure 3: *The wavelength shift of interference extremes as a function of mirror displacement corresponding to different initial positions λ_1 and λ_2 (solid lines are fits).*

The wavelength shifts of two selected maxima in the channeled spectra for increasing mirror displacement are shown in Fig. 3. From the linear fits of the measured dependencies, the displacement sensitivities can be obtained. To the lower dependence corresponds the displacement sensitivity -35 nm/μm and to the upper one corresponds the displacement sensitivity -31 nm/μm so that it is higher at longer wavelengths.

To demonstrate the increase of the sensitivity of displacement measurements in the setup shown in Fig. 1, we consider the birefringent quartz crystal of thickness $d = 6.4$ mm. The position of mirror 2 is controlled via a piezo positioning system as well as in the case with the Michelson interferometer alone and we recorded a series of modulated channeled spectral for increasing displacement Δl with a step of approximately 25 nm.

Figures 4 and 5 show two examples of the recorded normalized spectra for selected mirror displacements. It is clearly seen from the figures that the envelope of the modulated normalized channeled spectrum shifts toward longer wavelengths as displacement increases. To obtain the envelope from the channeled spectrum, first the spectral signal [1] defined as $S(\lambda) = I_r(\lambda)/I_0(\lambda) - 1$ needs to be obtained and then a Hilbert transform [2] needs to be applied. Unfortunately, the reference unmodulated spectrum of the resultant spectrum and the spectral signal as well cannot be obtained and thus a Hilbert transform cannot be used to obtain the envelope of the recorded normalized spectrum. Fortunately, the position of the envelope minimum can be obtained through the use of a trick. It is based on the fact that the envelope near zero is well approximated by a linear function. Consequently, the crossing of the decreasing and increasing linear functions gives the right position of the envelope minimum as is demonstrated in Fig. 6.

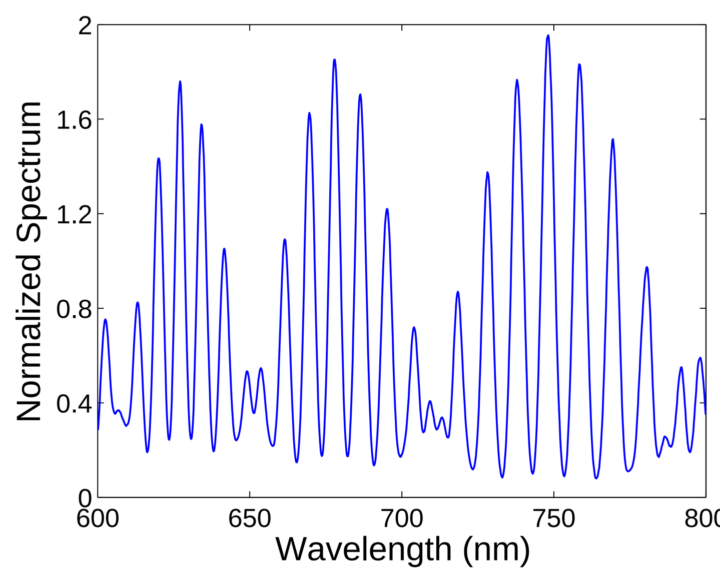

Figure 4: *Recorded normalized spectrum corresponding to mirror displacement $\Delta l_1 = 0$ nm.*

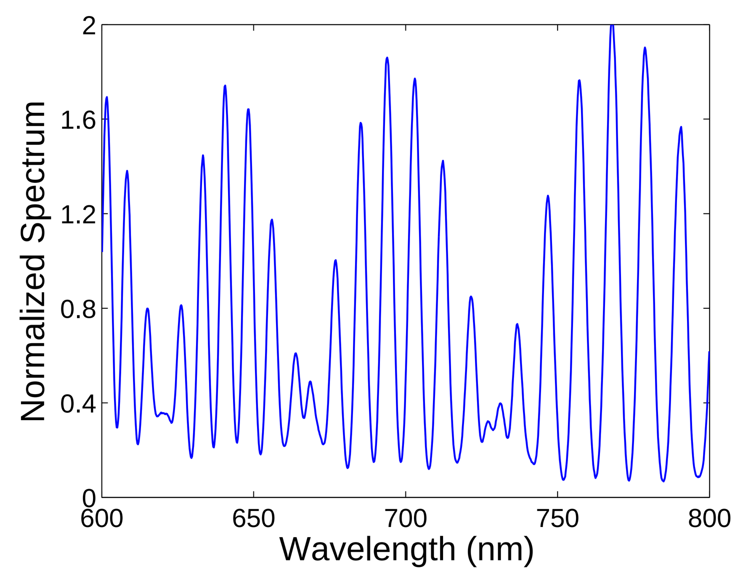

Figure 5: *Recorded normalized spectrum corresponding to mirror displacement $\Delta l_2 = 101$ nm.*

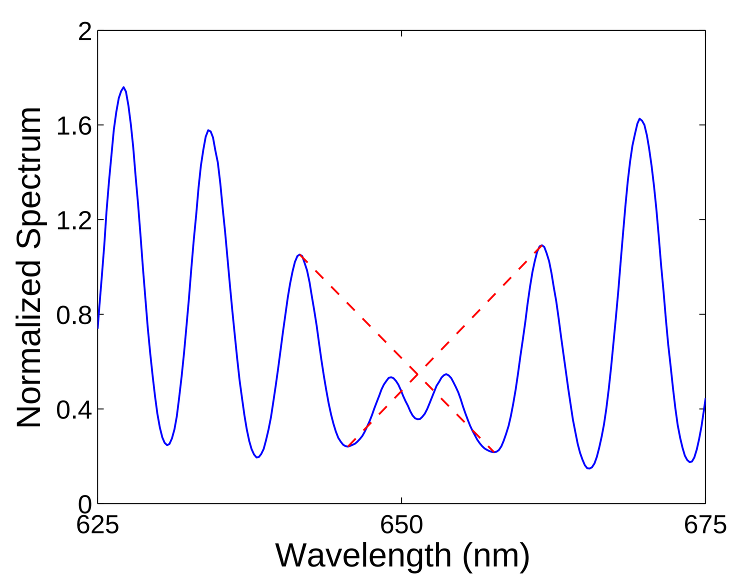

Figure 6: *Recorded normalized spectrum with lines enabling determination of the wavelength of the envelope minimum.*

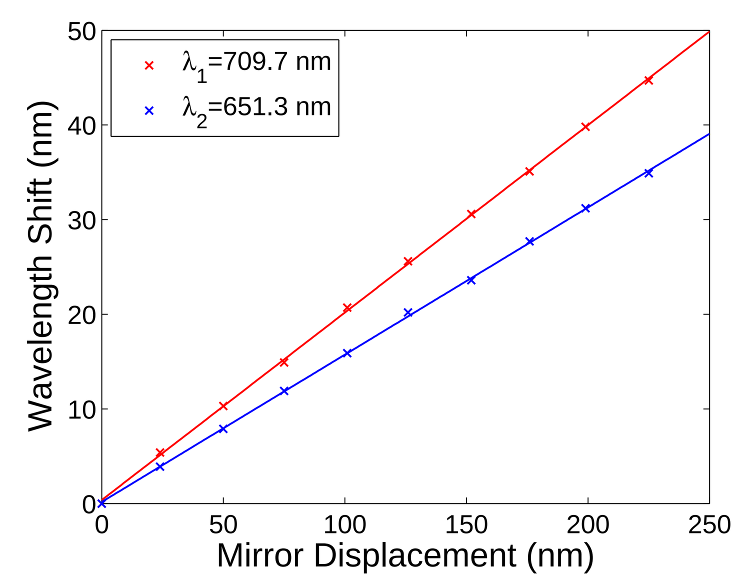

Figure 7: *The wavelength shift of the envelope minimum as a function of temperature corresponding to different initial positions λ_1 and λ_2.*

The wavelength shifts of two selected minima of the envelope for increasing displacement are shown in Fig. 7 by crosses. From the fits of the resultant linear dependencies, the displacement sensitivities can be obtained. To the lower linear dependence corresponds the displacement sensitivity 156 nm/μm and to the upper one corresponds the displacement sensitivity 198 nm/μm so that it is higher at longer wavelengths. The displacement sensitivities are in this case more than five times higher than for the case of the Michelson interferometer alone.

3. Conclusions

Spectral interferometric methods utilizing the interference of two beams in a Michelson interferometer to measure the displacement have been analyzed experimentally. First, we considered an experimental setup comprising a white-light source, a dispersion balanced Michelson interferometer and a spectrometer. As an example, the measured sensitivity of the displacement measurement reaches -35 nm/μm.

Second, we considered a setup with another interferometer, represented by a polarizer, a birefringent quartz crystal and an analyzer, to increase the sensitivity of the displacement measurement. The sensitivity of the displacement measurement reaches 198 nm/μm.

The results obtained are important from the point of view of implementation of new sensor configurations employing two-beam interference. In addition, the shift of the envelope of the channeled spectrum can be simply utilized to increase the sensitivity of the displacement measurement.

Acknowledgments

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References

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[2] Pavlicek, P. *et al*, *Opt. Lasers Eng.* **50**, 1063–1068 (2012).