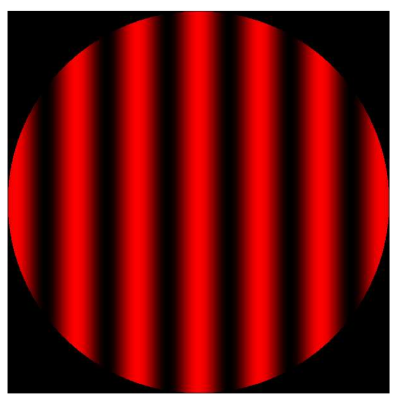
Highly birefringent fiber-based temperature sensor utilizing the wavelength interrogation



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Abstract

Spectral interferometric techniques utilizing the interference of polarization modes in a highly birefringent (HB) elliptical-core fiber to measure temperature are analyzed experimentally and theoretically. First, an experimental setup comprising a white-light source, a polarizer, a sensing birefringent fiber, an analyzer and a spectrometer is considered. Temperature sensing by this method is based on the wavelength interrogation, that is the position of a chosen spectral interference fringe in the channeled spectrum is measured as a function of temperature. Second, a setup with another interferometer (represented by a polarizer, a birefringent quartz crystal and an analyzer) to increase the sensitivity of the temperature sensing is considered. In this setup, the resultant channeled spectrum is with envelope which shifts as temperature increases.

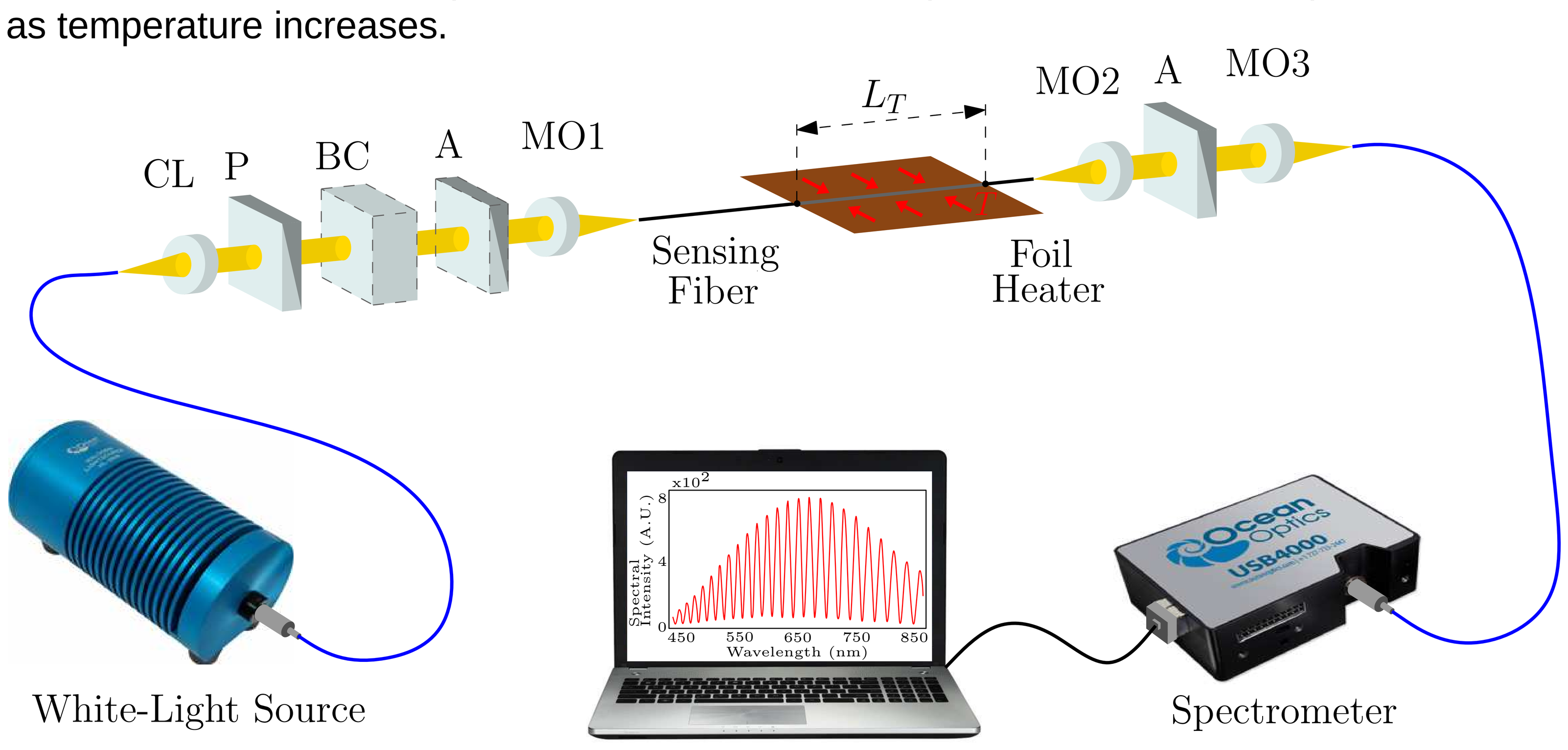

Figure 1: *Experimental setup with HB sensing fiber to measure temperature; collimating lens (CL), polarizer (P), birefringent crystal (BC), analyzer (A) and microscope objectives (MO1 - MO3).*

1. Experimental results and discussion

1.1 Polarimetric sensitivity to temperature

Using the experimental setup shown in Fig. 1, we measured for the HB fiber the spectral dependence of the polarimetric sensitivity to temperature $K_T(\lambda)$. The parameter is defined by the following relation

$$K_T(\lambda) = \frac{1}{L_T}\frac{\mathrm{d}[\phi_x(\lambda) - \phi_y(\lambda)]}{\mathrm{d}T}, \tag{1}$$

and represents an increase in the phase shift between two polarization modes of the HB fiber induced by the unit change of the temperature acting on unit fiber length [1].

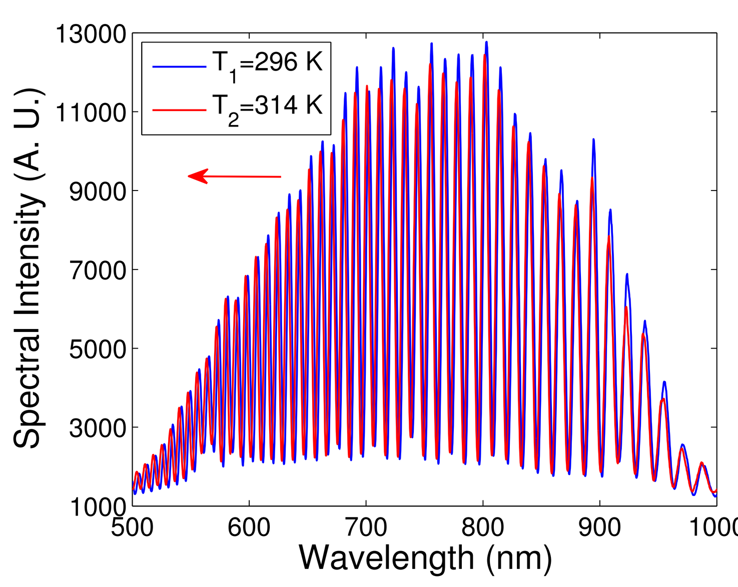

Figure 2: *Two examples of the recorded channeled spectra corresponding to temperatures T_1 and T_2; the overall length of the fiber was $L = 356$ mm.*

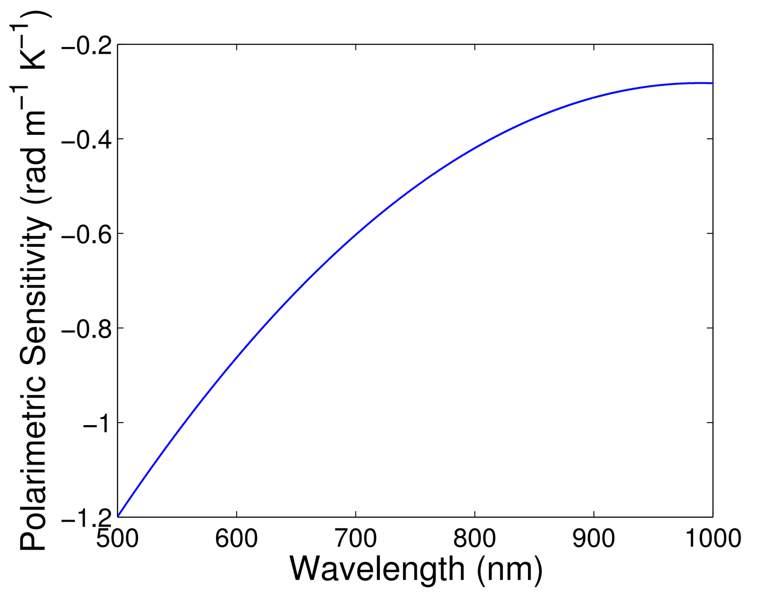

Figure 3: *The spectral dependence of the mean value of the polarimetric sensitivity to temperature retrieved from a series of the recorded channeled spectra.*

To determine the polarimetric sensitivity to temperature $K_T(\lambda)$, we recorded a series of spectral interferograms for increasing temperature T with a step small enough to assure unambiguity in retrieving the temperature-induced phase changes $\Delta[\phi_x(\lambda) - \phi_y(\lambda)]$. To measure $K_T(\lambda)$, the fiber of length $L_T = 76.2$ mm was in contact with a resistive foil heater (HT10K, Thorlabs) and its temperature was increased up to 373 K. Figure 2 shows two examples of the recorded spectra. Using a windowed Fourier transform [2], we retrieved from the spectral interferograms the phase functions that are needed in the evaluation of the phase difference $\phi_x(\lambda) - \phi_y(\lambda)$. It is wavelength dependent and provides the spectral dependence of the polarimetric sensitivity to temperature $K_T(\lambda)$ according to Eq. (1); see Fig. 3.

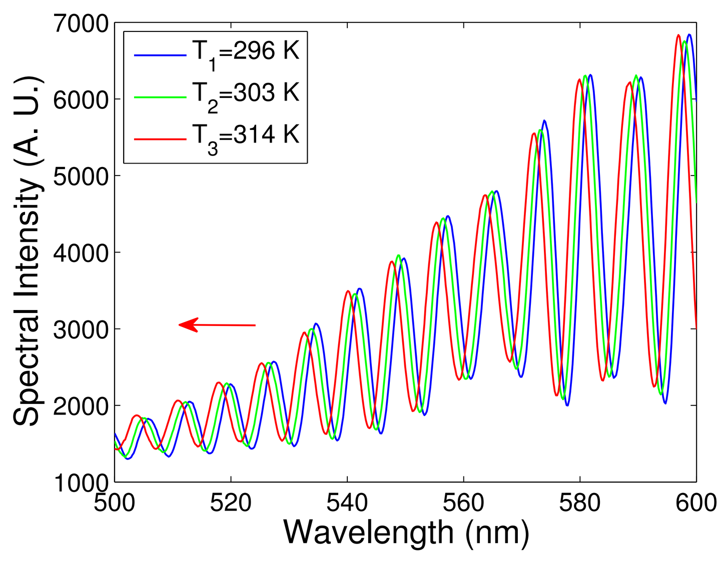

Figure 4: *Three examples of the recorded channeled spectra corresponding to temperatures T_1, T_2 and T_3 (the wavelength range from 500 to 600 nm).*

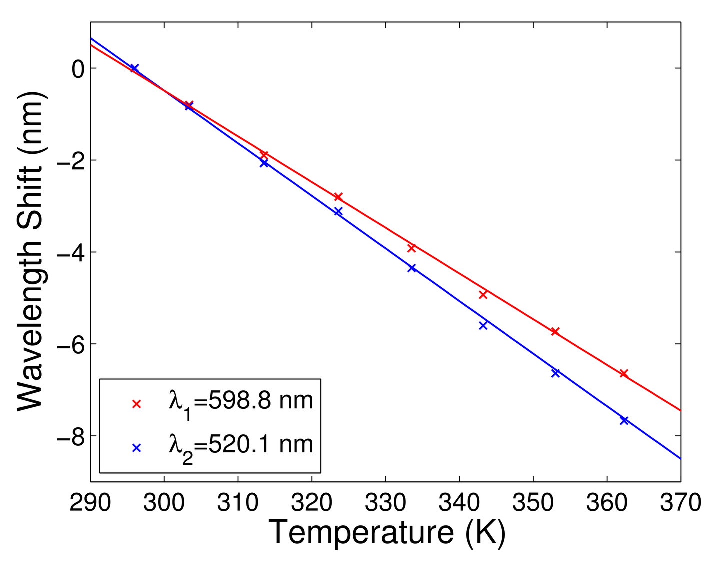

Figure 5: *The wavelength shift of interference maximum as a function of temperature corresponding to different initial positions λ_1 and λ_2 (solid lines are fits).*

The interference of polarization modes of the investigated HB fiber shows up as a channeled spectrum and a wavelength shift of a selected spectral interference maximum is temperature dependent; see Fig. 4. The wavelength shifts of selected maxima in the channeled spectra for increasing temperature T are shown in Fig. 5 by crosses. To the lower dependence corresponds the temperature sensitivity -0.11 nm/K and to the upper one corresponds the temperature sensitivity -0.10 nm/K so that it is higher at shorter wavelengths.

2. Theoretical results

To increase the sensitivity of temperature measurements with a given HB fiber, we consider an extended setup including a birefringent quartz crystal of a suitable thickness (see Fig. 1). The superposition of both channeled spectra, corresponding to the initial temperature $T = 293$ K of the fiber, is shown in Fig. 6. If we consider that the fiber of length $L_T = 76.2$ mm is subjected to the temperature changes and that the polarimetric sensitivity of the fiber to temperature is the same as that shown in Fig. 3, we can model the spectrum corresponding to temperature $T = 313$ K. It is shown in Fig. 7 and the fringes are slightly shifted to shorter wavelengths, but the envelope is shifted apparently to longer wavelengths.

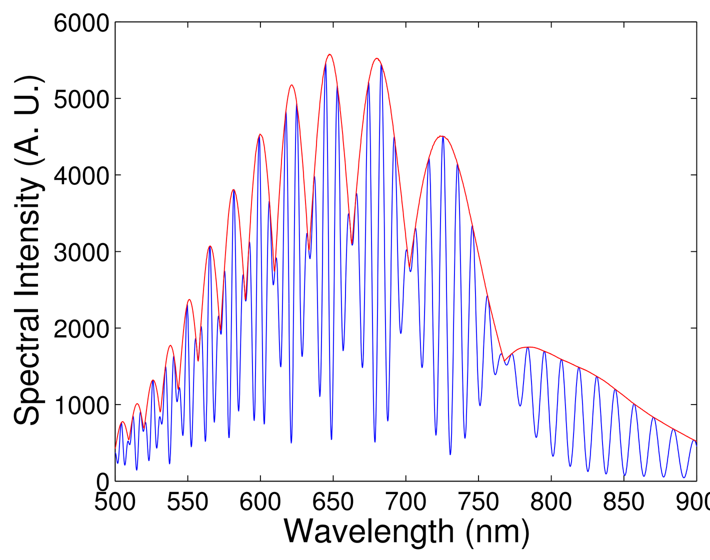

Figure 6: *Theoretical resultant spectrum with the envelope corresponding to temperature $T = 293$ K.*

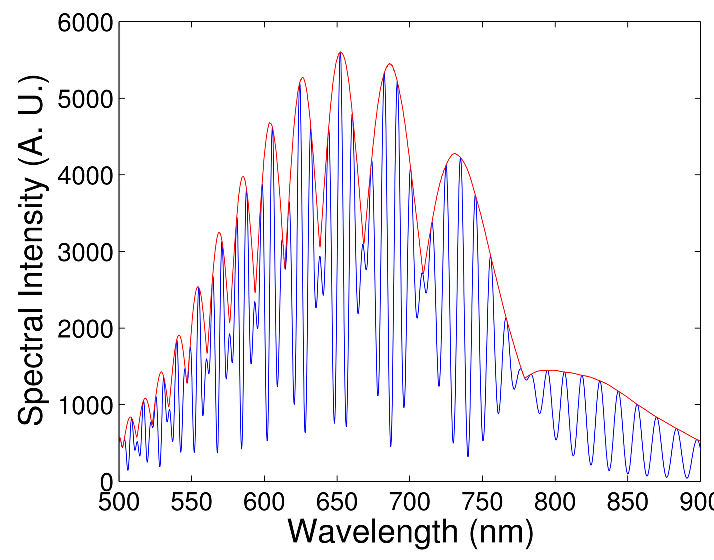

Figure 7: *Theoretical resultant spectrum with the envelope corresponding to temperature $T = 313$ K.*

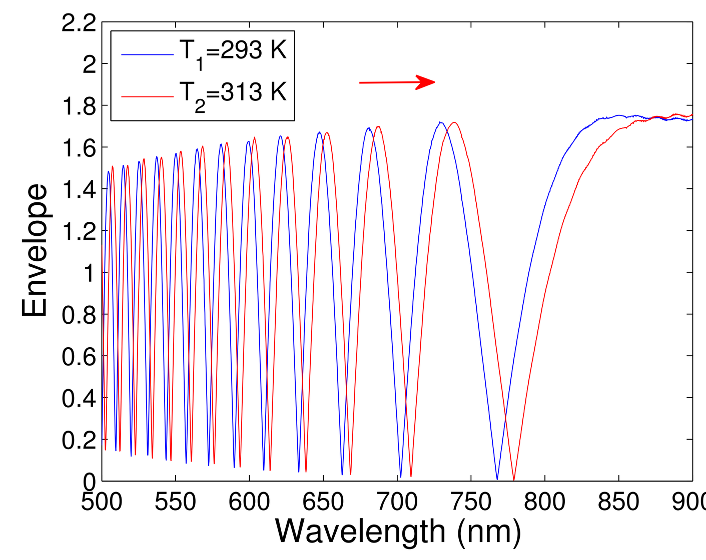

Figure 8: *The spectral dependence of the envelope corresponding to temperatures T_1 and T_2.*

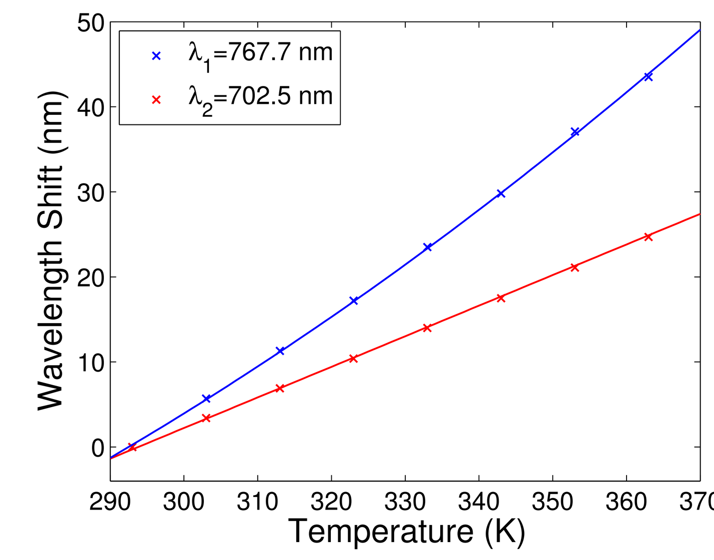

Figure 9: *The wavelength shift of the envelope minimum as a function of temperature corresponding to different initial positions λ_1 and λ_2.*

The envelope was obtained from the spectral signal [2] defined as $S(\lambda) = I_r(\lambda)/I_0(\lambda) - 1$ using a Hilbert transform [3]. The envelopes of the spectral signal $S(\lambda)$ corresponding to both temperatures are shown in Fig. 8 and they include both maxima and minima which are shifted with increased temperature toward longer wavelengths. The wavelength shifts of the selected minima in the envelope spectra for increasing temperature are shown in Fig. 9 by crosses. From the fits of the modelled dependencies, the temperature sensitivities can be obtained. To the lower linear dependence corresponds the temperature sensitivity 0.36 nm/K and to the upper quadratic dependence corresponds the temperature sensitivity 0.68 nm/K so that it is higher at longer wavelengths.

3. Conclusions

Spectral interferometric techniques utilizing the interference of polarization modes in a highly birefringent fiber to measure temperature are analyzed experimentally and theoretically.
First, employing an experimental setup comprising a white-light source, a polarizer, a sensing birefringent fiber, an analyzer and a spectrometer, we carried out temperature sensing in the range from 300 to 370 K. The measured temperature sensitivity reaches -0.11 nm/K.
Second, we consider a setup with another interferometer (represented by a polarizer, a birefringent quartz crystal and an analyzer) to increase the sensitivity of the temperature sensing. The temperature sensitivity to be reached is 0.68 nm/K.
The results obtained are important from the point of view of implementation of new sensor configurations employing HB fibers and utilizing the interference of polarization modes.

Acknowledgments

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References

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[2] Hlubina, P. *et al*, *Opt. Commun.* **281**, 2349–2354 (2008).
[3] Pavlicek, P. *et al*, *Opt. Lasers Eng.* **50**, 1063–1068 (2012).