Compensation of spectral image shift in AOTF-based system

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Abstract. Recently, it was shown that the use of a tandem acousto-optic tunable filter (TAOTF) in combination with a camera allows one to measure the temperature distribution at the focus of a laser beam on an object's surface. The TAOTF advantage is a reduction of aberrations and spatial distortions. Unfortunately, a TAOTF significantly reduces the intensity of the transmitted light beam, requires longer exposure time and often hampers temperature measurements below 1200 K. A single-crystal AOTF is free from this drawback and allows increasing the intensity of the incident radiation to the camera sensor. The paper presents experimental data for comparing measurements of the temperature distribution at the laser focus, obtained using single-crystal AOTF and TAOTF. A strong chromatic drift caused by AOTF-based system was compensated using the digital processing of the spectral images.

1. Introduction
Measurement of the temperature distribution on the surface of laser heated solids is an important task of geophysics and materials science [1]. In earlier studies [2], it was shown that the use of a tandem acousto-optic filter (TAOTF) in combination with a camera allows measuring the temperature distribution in focused high power laser beam. Temperature measurement is carried out by recording the spectrum of thermal radiation of object and further comparing the theoretical Planck curve with experimental data [3]. The TAOTF was used to avoid strong chromatic drift of the AO spectroscopic image in AOTF imaging system. Unfortunately, a TAOTF significantly reduces the intensity of the transmitted light beam, which makes it impossible to measure temperatures below 1200 K and also with a low intensity of the object's radiation, a long exposure time of the camera is required.

The goal of this work is to demonstrate that the use of AOTF results in a twofold increase in the intensity of multispectral images as compared to a TAOTF. A strong chromatic drift of the AO spectroscopic imaging system was compensated by the use of developed software allowing the alignment of all the images recorded at different wavelength. As a result, the threshold for measuring the minimum temperature is reduced, and the exposure time is also reduced, which allows several times to increase the speed of shooting hyperspectral images. The paper presents experimental data for comparing measurements of temperature distribution in ribbon filament lamp heated by current, obtained using AOTF and TAOTF.

2. Experimental Method
The use of acousto-optic filtering makes it possible to investigate the spectral images of the object under study in a fairly wide range of wavelengths in a certain part of the optical spectrum. The main advantage of acousto-optic tunable filters in the field of optical studies is their high speed and arbitrary positioning of the filter transmission line, compactness, simplicity of design, the absence of moving parts, and characteristic small control voltages. The optical scheme of an AOTF is shown in figure 1. The principle
of operation of an AOTF is based on the effect of light diffraction in an optically anisotropic crystal on traveling acoustic waves excited by a piezoelectric transducer [4]. A crystal of paratellurite is usually used as a transparent optical medium. A feature of AOTFs is a specific transmission function, which, in addition to the main line, has a set of low intensity side lobes described as sinc²-function.

Figure 1. Image shift (Δ) on interval from $\lambda_1 = 640$ nm to $\lambda_2 = 740$ nm in AOTF. P1, P2 – crossed polarizes; L1 – lens; AO cell – tuneable AO crystal; Obj – objective; Cam – video camera with CCD;.

The main problem of using AOTF for imaging is the transverse chromatic aberration (figure 1) [5-7]. These aberrations lead to a transverse displacement of the image occurring in the diffraction plane. To reduce the effect of transverse chromatic aberrations in the manufacture of AOTFs, the output face of the filter is tilted at a certain angle, and the input face is orthogonal to the transmitted beam to reduce reflection losses.

Figure 2. The image shows the displacement on 55 pixels (189 μm) of transmitted radiation in wavelength diapason from 640 nm to 740 nm.

Series of images was taken (figure 2) to evaluate the displacement of the image on AOTF filter. Images taken at 640 nm and 740 nm are shown in figure 2. The relative shift from the image taken at 640 nm to that taken at 740 nm found to be 189 μm or 55 pixels on the camera sensor. There was used an Imaging Source camera with pixel size of 3.75 μm. Resolution test target was used to measure the shift (figure 2). Figure 3 shows the results of the measurements of the transverse shift of TAOTF and AOTF. They show a linear dependence on the wavelength. The displacement of the image is small for TAOTF and is only 7.5 μm for the wavelength range from 640-740 nm. The dependence of the transverse
displacement on the wavelength position can be considered as linear:

\[ z(\lambda) = 2.53(0.89) + 0.572(0.014) \cdot \lambda \]

Figure 3. Dependence of image displacement on wavelength for TAOTF and AOTF. Linear least square fits are shown as red lines.

3. Results

To compare results obtained by the TAOTF and AOTF and resistivity methods were used to conduct an experiment similar to that described in [3, 8] in a current configuration (figure 4). A tungsten lamp was heated by an electric current (10A) and the temperature of the heated tungsten plate was measured using AOTF and TAONF. A lamp with a flat uniformly heated tungsten tape was used as a radiating heated object. The temperature of lamp was determined by fitting [3] the actual signal to Planck’s equation at each point of the specimen’s surface (figure 4):

\[ I(\lambda, \varepsilon, T) = \varepsilon g(\lambda, T), \quad g(\lambda, T) = \frac{c_1}{\lambda^5 \left( \exp\left( \frac{c_2}{\lambda T} \right) - 1 \right)} \]

where \( I \) is the spectral intensity, \( \varepsilon \) is the sample emissivity, \( \lambda \) is wavelength, \( T \) is the temperature, and \( c_1 \) and \( c_2 \) are physical constants \( (c_1 = 2\pi c^2, \ c_2 = \frac{hc}{k} = 0.01432 \ \text{mK}) \). Because the temperature of the heated body should be uniform over the surface the variation of the temperature (~40 K) over the surface is related to the error of the AOTF method.
When the current was 10 A, the temperature measured by AOTF was appeared to be 1969(60) K, and that obtained by TAOTF was 2012(81) K. The number in the brackets are 95% confidence interval described in [3]. The temperature of the lamp measured by TAOTF and AOTF are in an agreement within experimental errors. We also mention that the confidence interval determined AOTF is 30% less than that determined by TAOTF. It might be related to the fact that time of the exposure for the AOTF system is nearly three times as low as that for TAOTF system. It was established experimentally that the transmittance of AOTF is 2.8 times higher than that of TAOTF. This allows reducing the exposure time on the camera while shooting a series of images and as a result data collection speeds up.

4. Conclusions

The paper demonstrates the use of two types of acousto-optical spectral filters with respect to the problem of measuring the temperature of a heated object. A lamp with a flat uniformly heated tungsten tape was used as a radiating heated object. It was established experimentally that the transmittance of AOTF is 2.8 times higher than that of TAOTF. This allows reducing the exposure time on the camera while shooting a series of images and as a result data collection speeds up. We demonstrate that using AOTF also as a TAOTF allows measuring temperature of heated objects. The temperature of lamp was determined by fitting [6] the actual signal to Planck’s equation at each point of the specimen’s surface.

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