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Spatio-spectral Characterization of Acousto-optical Imagers

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Abstract: We address the problem of hyperspectral data correction necessary for acousto-optical imagers. We demonstrate theoretically and experimentally that inevitable spectral inhomogeneity across the field of view may be eliminated by post-processing of the acquired images.

1. Introduction

The acousto-optical (AO) spectral imagers are usually characterized by the dependency of the central wavelength λ_0 of transmission window on the applied ultrasonic frequency f measured for paraxial light beam [1]. However, λ_0 varies with the angle of incident light, which limits the use of AO tunable filters for wide-aperture input beams in telescopic scheme [2]. We propose to overcome this limitation by means of the spatio-spectral calibration of AO imager and post-processing of acquired images.

2. Theoretical considerations and computer simulation

The equation describing AO phase matching condition may be derived from the momentum conservation law:

$$\mathbf{k}_\mathrm{d} = \mathbf{k}_\mathrm{i} \pm \mathbf{q} \quad \Longleftrightarrow \quad [n_\mathrm{d}(\lambda_{\mathrm{d}0}, \mathbf{e}_\mathrm{kd})/\lambda_{\mathrm{d}0}]\,\mathbf{e}_\mathrm{kd} = [n_\mathrm{i}(\lambda_{\mathrm{i}0}, \mathbf{e}_\mathrm{ki})/\lambda_{\mathrm{i}0}]\,\mathbf{e}_\mathrm{ki} \pm [f/V(\mathbf{e}_\mathrm{q})]\,\mathbf{e}_\mathrm{q}, \tag{1}$$

where $\mathbf{e}_\mathrm{q}$, $\mathbf{e}_\mathrm{ki}$ and $\mathbf{e}_\mathrm{kd}$ are the unit vectors indicating directions of wave vectors $\mathbf{q}, \mathbf{k}_\mathrm{i}$ and $\mathbf{k}_\mathrm{d}$ for sound, incident and diffracted light; $\lambda_{\mathrm{i}0} \approx \lambda_{\mathrm{d}0} = \lambda_0$ are the light wavelengths in vacuum; V is the sound velocity; n_i and n_d are the refractive indices. We consider non-collinear anisotropic ($e \to o$) AO interaction in tetragonal uniaxial crystal where $n_\mathrm{i} = n_\mathrm{e}$, $n_\mathrm{d} = n_\mathrm{o}$ and $\mathbf{e}_\mathrm{q}$ is defined by the cut angle γ (see Fig. 1a). For wide-aperture input beam, Eq. (1) may be represented either as the dependency of λ_0 on incident light direction $\mathbf{e}_\mathrm{ki}$ for given f or as the dependency of f on $\mathbf{e}_\mathrm{ki}$ for given λ_0. Calculation of the dependency $f(\mathbf{e}_\mathrm{kd}, \lambda_0)$ for the output beam direction $\mathbf{e}_\mathrm{kd}$ allows to transform the acquired image stack $I(\mathbf{e}_\mathrm{kd}, f)$ to the stack of corrected spectral images $I(\mathbf{e}_\mathrm{kd}, \lambda_0)$ by varying the sound frequency f as shown in Fig. 1b.

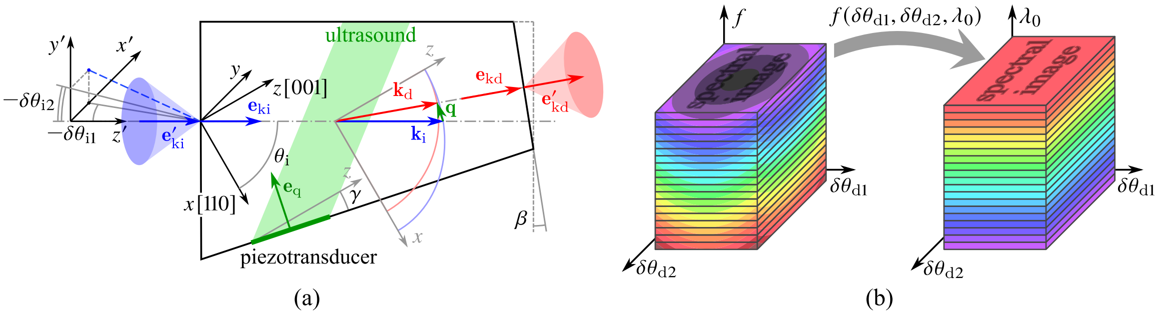

Fig. 1. (a) AO cell configuration and wave vector diagram. (b) Transformation of acquired images $I(\mathbf{e}_\mathrm{kd}, f)$ to corrected spectral images $I(\mathbf{e}_\mathrm{kd}, \lambda_0)$.

We have studied wide-aperture non-collinear diffraction in paratellurite (TeO_2) crystal ($\theta_\mathrm{i} = 73.85°$, $\gamma = 7°$, facet angle $\beta = 2.2°$, AO interaction length $L = 1$ cm, see Fig. 1a) and applied computer simulation to trace the rays $\mathbf{e}'_\mathrm{ki}(\delta\theta_{\mathrm{i}1}, \delta\theta_{\mathrm{i}2}) \to \mathbf{e}'_\mathrm{kd}(\delta\theta_{\mathrm{d}1}, \delta\theta_{\mathrm{d}2})$ through AO cell including the refraction at input and output facets in the range 500...750 nm (109...65 MHz). According to the results of simulation, the dependency $f(\delta\theta_{\mathrm{d}1}, \delta\theta_{\mathrm{d}2})$

for given λ_0 may be approximated by a polynomial with 12 coefficients up to fifth degree with root-mean-square error (RMSE) less than 2 kHz if the field of view is $\pm 6°$.

3. Experimental results

The experimental setup (Fig. 2a) includes the light source with monochromator (MC), diffuser plate (D), lenses (L1, L2, L3), polarizers (P1, P2), AO cell installed in telescopic scheme and a camera (C). First, we captured image stacks $I(u,v,f)$ ($f = 60...115$ MHz, step 0.1 MHz) for several central wavelengths λ_{MC} of the monochromator ($\lambda_{MC} = 500...750$ nm, step 25 nm) with slit width 1 nm using monochrome and color cameras. For each λ_{MC}, the set was processed to extract the dependency $f(u,v)$ corresponding to maximal values of $I(u,v,f)$ and match it with modeled $f(\delta\theta_{d1}, \delta\theta_{d2})$ by least-squares fitting of pinhole camera transformation $(u,v) \rightarrow (\delta\theta_{d1}, \delta\theta_{d2})$ and with polynomial approximation of $f(\delta\theta_{d1}, \delta\theta_{d2})$ by fitting also polynomial coefficients. The results indicate good coincidence of experimental and modeled $f(u,v)$ (see example in Fig. 2b), RMSE does not exceed 0.02 MHz. Second, we acquired sets $I(u,v,f)$ with slit width 6.5 nm using color camera and transformed them to spectral images $I(u,v,\lambda_0)$ using the dependencies $f(u,v,\lambda_0)$ obtained on the previous step. As shown in Fig. 2c, the proposed technique allows to correct spectral inhomogeneity across the field of view.

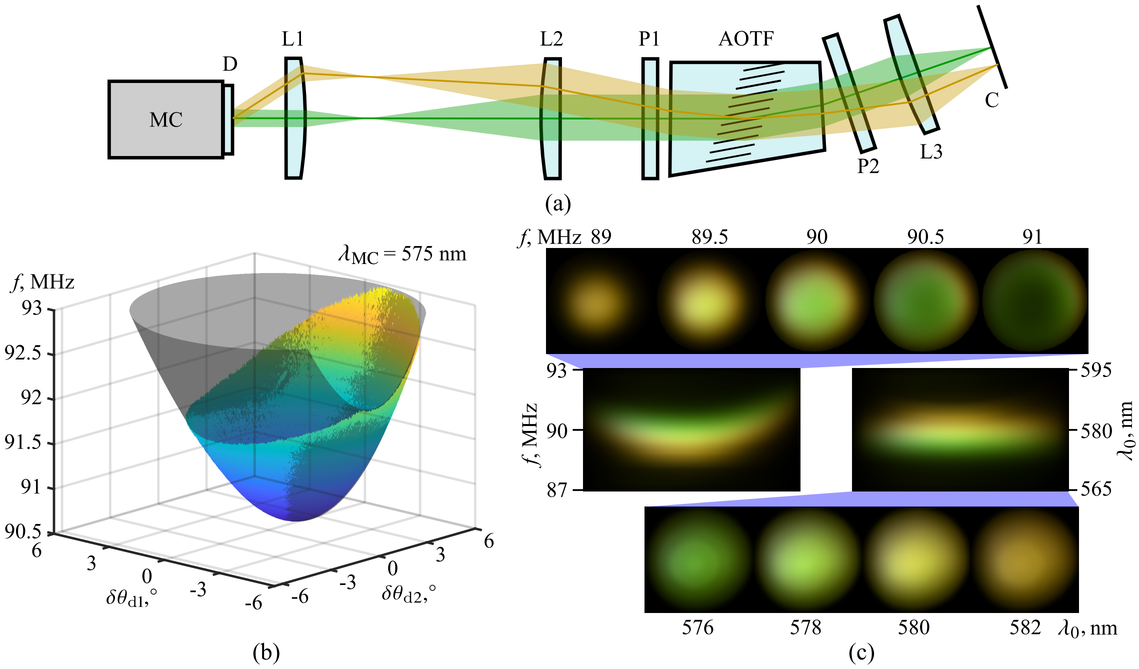

Fig. 2. (a) Experimental setup. (b) Experimental (color) and modeled (gray) dependencies $f(\delta\theta_{d1}, \delta\theta_{d2})$ for $\lambda_{MC} = 575$ nm. (c) Examples of acquired images $I(u,v,f)$ and corrected spectral images $I(u,v,\lambda_0)$ and their central sections $I(u,f)$, $I(u,\lambda_0)$ for $\lambda_{MC} = 580$ nm.

4. Conclusion

We have demonstrated that the variation of the central wavelength of transmission window with the incident light angle in AO spectral imager may be corrected by means of its calibration and post-processing of obtained image stack. Theoretical consideration is confirmed by experimental study of non-collinear AO diffraction in paratellurite crystal. Proposed approach paves the way to accurate characterization and multiple metrological applications of AO imagers.

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References

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2. A. Machikhin, A. Gorevoy, G. Martynov, and V. Pozhar, “Spatio-spectral transformation of non-collimated lightbeam diffracted by,” Phot. Res **9**, 1–6 (2021).