The resolution of optical image edge detection based on Brewster effect

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Abstract. In the present work, we study the influence of the Brewster effect on the resolution of optical system for optical edge detection. The estimation of resolution for initial and transformed images of optical objects is performed both theoretically and experimentally. Our research demonstrates that the image edge detection based on the transformation by the Brewster effect improves the resolution of the optical system approximately by the factor of 1.6.

1. Introduction
The cost-effective approaches and methods for ultrafast calculations are highly demanded for image processing. Analog optical image processing is capable of performing ultrafast calculations over entire images. Studies in this field of optics are aimed at finding effective approaches and methods for the image and signal processing using low-cost effective optical elements.

Many theoretical researches of diffractive resonance structures are performed to create and optimize compact systems of ultra-fast analog computing and real-time image processing in medical and geographic information applications, etc.

The efficiency of resonance structures was shown in the implementation of a wide class of mathematical operations over light field, such as the differentiation and integration of optical signals, the calculation of Laplace operator, and the optical solution of differential equations [1-6]. The complexity of manufacturing two- and three-dimensional structures is a challenge for experimental demonstration of the effects under study. Structures based on excitation of surface plasmon-polariton modes were also proposed and investigated for experimental demonstration of the optical image edge detection for polarized monochromatic radiation [7].

The feasibility of spatial differentiation of polarized optical signals by Brewster effect was theoretically investigated in Ref. [8]. In our previous work, we performed an experimental demonstration of the optical differentiation and optical image edge detection by the Brewster effect for both phase and amplitude objects [9]. The Brewster effect is observed as a resonance dip in angular reflectivity spectra of p-polarized plane waves at interfaces between two dielectrics. In the vicinity of the Brewster angle, the field transformation by the Brewster effect is described by the transfer function of the first-order differentiator. In general, the resolution of optical imaging systems can be affected by spatial filtering. In the present work, we study the influence of the Brewster effect on the resolution.
2. Description of the experiment

Assume incidence of a \( p \) polarized plane wave on an interface between two dielectrics with refractive indices \( n_1 \) and \( n_2 \). It is well known that the reflection coefficient tends to zero, and the transmission reaches its maximum value at a certain incidence angle \( \theta_{br} \) to the normal of the interface, which is referred to as Brewster angle, where \( \tan(\theta_{br}) = n_2 / n_1 \).

The scheme of the optical system was built for the experimental research is shown in Figure 1, where ND is a filter of neutral optical density, P is a polarizer, \( L_1 \) and \( L_2 \) are collimator lenses, A is an aperture, O is an object, Pr is a prism, \( L_3 \) is a lens, PD is a photosensitive matrix. The detailed description of this optical system is provided in Ref. [9].

![Figure 1. Optical schema.](image)

The resolution of the optical system is defined as a minimal distance between point sources at the object plane, for which their images at the image plane can be distinguished. The spatial and angular resolutions are determined by the spatial and angular distances between point sources, respectively.

3. Results and discussion

We consider imaging of a slit aperture with adjustable width by the optical system. For the experimental study of the characteristics of the optical transform based on Brewster effect, we study images of a slit aperture in the object plane for different values of the slit width. The spatial distributions of the intensity of the beam passed the slit aperture and the beam reflected from the prism at Brewster angle are shown in Figure 2. The intensity distribution of the beam reflected from the prism exhibits narrow peaks corresponding to the scattering of light at the edges of the aperture, which directly demonstrates the effect of spatial differentiation and image edge detection.

The intensity cross-sections taken in the perpendicular to the slit direction are demonstrated in Figure 3. For ease of comparison, the intensity profiles are centered. Intensity values are normalized to the maximum value in each cross-section. Intensity fluctuations observed near the peaks in Figure 2 and 3 are resulted from light diffraction at the slit edges. Based on the experimental data, the value for the linear resolution is 12 \( \mu \)m as the minimum slit width at which edges are visible [9].

The experimental resolution value is calculated in accordance with the scheme shown in Figure 4. Figure 4 shows the part of the optical scheme used to calculate the resolution, where \( \theta_{ex} \) is an angular distance at which the object O is visible from the lens \( L_3 \), \( l \) is a linear size of the object O, \( a \) is a distance from the object to the lens \( L_3 \). Then the angular resolution value will be calculated as

\[
\theta_{ex} = 2 \arctan \left( \frac{l}{2a} \right).
\]

For \( l = 0.012 \) mm, \( a = 2f = 150 \) mm, the experimentally obtained angular resolution is 0.004584\(^\circ\). The expression for calculating the angular resolution of an optical system is given as
where $\theta_d$ is the angular size of the object, $\lambda$ is the wavelength, $D$ is the aperture diameter of the lens [10]. In our system, the aperture of $L_3$ is $D = 5\text{ mm}$ for $\lambda = 532\mu\text{m}$.

As a result of the calculation according to the formula (2), we obtain a theoretical value of the angular resolution is $0.007437^\circ$. Therefore, the experimentally obtained resolution of the optical system is approximately 38% better as compared to the theoretical one.

**Figure 2.** Optical differentiation of images of amplitude objects: (a-e) the intensity of the beam passing through the slit aperture with a width of 200, 100, 50, 25 and 15 µm, respectively; (f-l) the intensity distribution of the beam reflected from the prism for apertures of the corresponding width.

**Figure 3.** Spatial differentiation for beams passing slit apertures: (a) normalized intensity of the field passing the slit aperture for the values of width 200, 150, 50, 25, 15 µm, respectively; (b) normalized average intensity of the transformed field.
4. Conclusion

Comparison of experimental and theoretical values of angular resolution demonstrates that the image edge detection based on the transformation by the Brewster effect improves the resolution of the optical system approximately by the factor of 1.6. The considered effect can be used in the microscopy of biological and medical applications for processing of images of objects with linear dimensions larger than the wavelength of the light source.

5. References

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