The optical analogue of the Yoneda effect

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Abstract. Issues related to the surface treatment of materials and its quality control remain important to this day. Research on new methods and techniques is mainly related to the rapid development of new technologies in materials science, in particular, nanotechnology. Roughness parameters are still very important measures when working with various materials. The effect of the anomalous reflection of X-rays has played an extremely important role in the historical development of methods regarding in-process quality control when polishing high-strength materials (sapphires, diamonds, etc.). It is, however, important to look for ways to use nanotechnological control of optical materials that are universal, sensible, safe and inexpensive.

1. Introduction
The electromagnetic nature of X-rays is shown by the laws of geometrical optics: sliding beams are fully reflected and split on two Yoneda beams (mirror and anomalous) [1].

In this article the similar behaviour of the electromagnetic waves of the optical range is described. This phenomenon is considered to be the same for both the nuclear scale of beams and for radio waves.

Despite economic and ecological issues in terms of use, anomalous reflection of X-rays seems to be the only method for several strong materials because of its high accuracy, reliability and the localness of measurements.

Research on anomalous full external reflections (FER) of ultrasoft X-ray radiation was first conducted at Saint Petersburg School of Physicists under the guidance of A.P. Lukirskij [2, 3].

In the area of high-radiation, regional works using the classical methods of Mössbauer spectroscopy ($\lambda_{Fe-57} = 0.086$ nanometres) are known [4, 5].

The works of Moscow and St. Petersburg researchers [6] show that the appearance of additional anomalous (more inclined) rays – together with mirror reflection – is associated with the usual scattering of radiation due to blemishes near the surface structures of the material. The term anomalous scattering is not commonly accepted. All previous and subsequent works of X-ray optics [7] may, however, be considered part of a new area of research-based on Yoneda spectroscopy. This method is similar to such methods as the spectroscopic method of broken full internal reflection (BFIR).

A similar phenomenon [8] was discovered more than twenty years ago in the optical range. The essence of the optical analogue of the same phenomenon consists in the identical nature of the interaction of electromagnetic radiation with a substance on borders of its separate phases.

However, optical specificity of the detection of anomalous reflection requires the use of “high specified” interference mechanisms of the polarized coherent radiation near surface structures on phase borders. For these reasons, polarization-optical devices using ellipsometry are used. The sensitivity of polarization-optical methods appears on some orders above usual power ways of the control of materials.
Due to the analysis of amplitudes-phase parameters of the polarized light, it is possible to compete with the methods of X-ray optics.

2. Results and Discussion

The primary aim of nanotechnology is to control the properties of nanoobjects, for example, the formation of films on the substrate. The most acceptable and most sensitive technologies for controlling the optical properties of nanoobjects (layers, films) are polarized-optic technologies, in particular, ellipsometry. Ellipsometry is the study of the polarization characteristics of light after interaction with a substance. This is a unique method for determining the optical parameters of materials \(\lambda = n – ik\): \(n\) – the index of refraction, \(k\) – the index of extinction, \(d\) – the thickness of the films, using the amplitude-phase characteristics of the polarization state of a reflected wave field \((\psi, \Delta)\). The method sensitivity is many times above the energetic method of research. However, this method has a range of internal contradictions connected with the high sensitivity of the solution of the direct task (determining \(\psi, \Delta\)) and the lack of determination of the optical parameters of materials \((n, k)\) (solution of the inverse task).

The research focuses on the system analysis of the decision properties of the main ellipsometry equation (1):

\[
\tan(\psi)\exp(i\Delta) = R_p/R_s = (E_{\text{refl}}(p)/E_{\text{inc}}(p))/ (E_{\text{refl}}(s)/E_{\text{inc}}(s))
\]

\(R_p, R_s\) – the integrated Fresnel's coefficients; \(E_{\text{refl}}(p, s)\), \(E_{\text{inc}}(p, s)\) – reflected and incident components of radiation for \(p\) and \(s\) components, respectively.

The modelling of the inverse task solution of ellipsometry shows angular dependence of the optical parameters \((n, k)\) with incident angles.

Overstate values of the material's extinctions are observed for dielectrics. Semi-conductors show appropriate values of \(k\) (extinctions).

The next interpretation of \(k\) by R. W. Pohl is supposed: the index of refraction is the sum of the dispersing absorption and radiation scattering:

\[
k(\phi) = k_{\text{disp}} + k_{\text{scat}}(\phi).
\]

The angle dependence \((\phi)\) and the overstate values of extinction can be directly explained with the aid of such interpretation. Traditionally \(k\) only represents the dispersing absorption. This is the principal error of the ellipsometry method.

A new approach is to take \(k\) as representing the values of two components (dispersing absorption and radiation scattering). The contribution of scattering and the rate of the optical roughness of objects can be estimated using the values of “anomalous reflection” in angle scanning (the technology of spectroellipsometry).

Let us consider the empirical spectra number of the angular distribution indicatrix of the anomalous reflection (AR components of radiation) for typical mirrors from matte up to ideally smooth surfaces.

Figure 1 shows an AR spectra for artificial heavy-duty crystals of NB. The nitride is a pine forest; the opaque one axis is a crystal of opal bone colour as class cleanliness of polishing it is achieved hardly to 6 levels \((R_s = 10\) microns\).

The angular distribution of the maxims indicatrix in dispersion directed to mirror channels of different sides of crystals NB has a typical kind of AR spectra.

The estimation Brewster of refraction parameters for ordinary \((n_o)\) and unusual \((n_e)\) beams NB, which is based on Brewster’s law and uses multangular ellipsometer measurements (Figure 2), allows us to calculate values for \(n_o\) and \(n_e\) for the first time: \(n_o = 1.755 \pm 0.007\) and \(n_e = 1.59 \pm 0.01\).

The peak \(\Psi(\phi)\) function in this interval of corners exhibits abnormal relaxation behaviour (Figure 2) in comparison with a monotonous course.
Figure 1. Spectra of AR (on Yoneda) on crystals NB.

Figure 2. (a) AR in system Sc-Fe-Sc; (b) Behaviour of peak function $\Psi(\varphi)$ of AR from the X-ray’s filter at sliding corners of falling.

The similar extremely anomalous course is shown also with a phase function $\Delta(\varphi)$ of a field of a light wave (Figure 3).

Figure 3. Behaviour of a phase function $\Delta(\varphi)$ of AR from the X-ray’s filter at sliding corners of falling.
Figure 3 shows that the usual recession of this function from 180° up to 0° in zone ambassador Brewster corners of falling also starts relaxation and, moreover, undergoes a break in continuity, passing in the ambassador Brewster zone asymptotic approach from 180° to 360° [9] twice. Similar breaks of phase function are usually caused by air defence in highly absorptive materials. Repeated breaks of this function may be explained by lamination near superficial structures.

The opposite nature of AR phenomena can be seen in Figure 4, in which the spectra of two stages coverings chromic mirrors on a sapphire substrate by a thickness of 3 and 30 nm are represented.

![Figure 4](image)

**Figure 4.** An AR spectrum of abnormal "not repayable" part $U_{\varphi \omega \varphi}$ (φinc/refl) of a light field.

The intensive AR phenomena, a thin covering mean an obvious roughness, and the thick layer, on the contrary, shields a substrate and monolayers of metal which is, naturally, a feebly marked roughness.

3. Conclusion

On the basis of the data considered it is possible to confirm and draw conclusions about the existence of abnormal (on Yoneda) reflections in an optical range. As a spectrum of angular distribution bending around directed to mirror channel, indicatrix depolarized light is allocated from the general light beam in the simple way of clearing its polarized component.

Based on the fundamental nature of optical interaction radiation with substance in γ-, X-rays-, light-optics and radio-optics, it is desirable to unite effects AR in uniform independent class by Yoneda’s reflective spectroscopy as the experimental research tool for real mechanisms scattering light.

Also analysis of angle dependence and overstate values of $k$ with dependence "anomalous reflection" signal occurs using incident angles in common with determination of optical roughness of investigated materials.

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