NIOBAT LITIY KRISTALINING OPTIK XOSSALARI VA ULARNING GOLOGRAFIK INTERFEROMETRIADA QO'LLANILISHI

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Annotation: From the presented curves, it is evident that the concentration coefficient has a significant impact on the short-circuit current value and, consequently, on the output power generated by the solar cell. However, as the concentration coefficient of solar radiation increases, the absolute rise in short-circuit current is accompanied by a decrease in the fill factor of the current–voltage characteristic due to the enhanced recombination of minority charge carriers.

As shown in Figure 2, the output electrical power exhibits a substantial increase up to a concentration factor of $\mathbf{K_s = 80}$, after which saturation occurs, and further increases in the concentration coefficient result in only a minimal rise in generated power. A similar trend is observed in the dependence of the short-circuit current on $\mathbf{K_s}$ (Figure 1). Here as well, starting from $\mathbf{K_s = 80}$, a decrease in the growth rate of $\mathbf{I_{k.x.}}$ is observed; however, this change is less pronounced compared to the effect on output power.

Keywords: Lithium niobate crystal; $LiNbO_3$; nonlinear optics; photorefractive effect; electro-optic properties; holography; holographic interferometry; diffraction efficiency; optical grating; phase modulation; optical metrology; interference; deformation measurement; non-contact diagnostics.

Introduction.

The photorefractive lithium niobate crystal is currently one of the most unique and widely used ferroelectric materials in piezotechnology, quantum electronics, optoelectronics, and acousto-electronics, as discussed in detail above. The optical properties of such materials — including linear optical coefficients, holographic recording sensitivity, and the ability to generate second harmonics, which enables radiation in the laser wavelength range — demonstrate how exceptional the $LiNbO_3$ crystal is as a material.

One of the reasons for the universality of the lithium niobate crystal is the ability to control its physical properties over a wide range by modifying its composition. This feature is especially important in integrated optical devices, where $LiNbO_3$ is extensively used.

Main part.

In lithium niobate crystals, the photorefractive effect is a threshold phenomenon that occurs even at low light intensities ($I \approx 10$ mW/cm^2). Another characteristic feature of the photorefractive effect is that, even after the laser illumination is stopped, the change in the refractive index (Δn) of the crystal remains for a long time. In ferroelectric crystals, the photorefractive effect is based on the presence of charged particles that are more weakly bound compared to the electrons within the structure. Under laser irradiation, electrons associated with impurity atoms or defect-related localized states transition from the forbidden band into the conduction band. These electrons then drift into regions outside the illuminated area and become trapped in deep-level centers. As a result, the refractive index of the crystal changes, and a sufficiently strong internal electric field is generated.

The change in refractive index occurs locally in the region through which the light passes and in its surrounding area. After the laser illumination ends, a region with a modified refractive index (a “track”) usually remains in the crystal and may persist for a long time. Lithium niobate ($LiNbO_3$) is a uniaxial negative crystal ($n_0 > n_e$, where n_0 and n_e are the ordinary and extraordinary refractive indices, respectively). This means it has a single optical axis along which no birefringence occurs, since in this direction the crystal’s optical and polar axes coincide.

If the laser beam propagates perpendicular to the polar axis, its initially circular cross-section gradually transforms into asymmetrical lemniscate (figure-eight) shapes over time, as the major axis of the pattern aligns with the positive direction of the polar axis. This phenomenon is caused by the transfer of energy from the ordinary beam to the extraordinary beam. If the laser beam is directed into the lithium niobate crystal such that the electric field vector of the light lies in the plane of the polar axis (Figure 1), then due to optical inhomogeneities, both ordinary and extraordinary beams scatter at different angles.

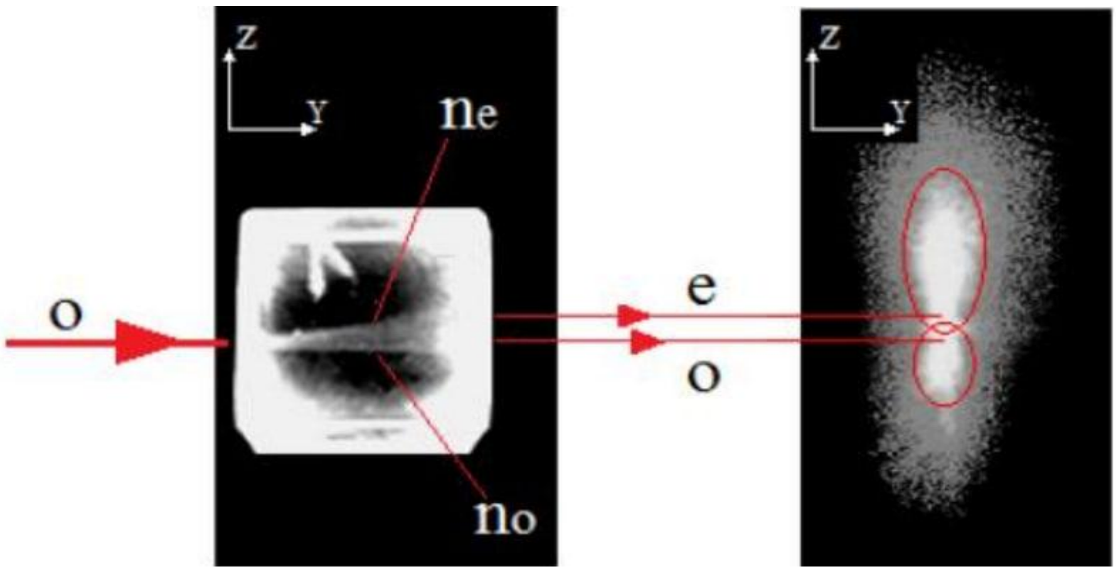

Figure 1. Formation of the ordinary and extraordinary refractive indices in a $LiNbO_3$

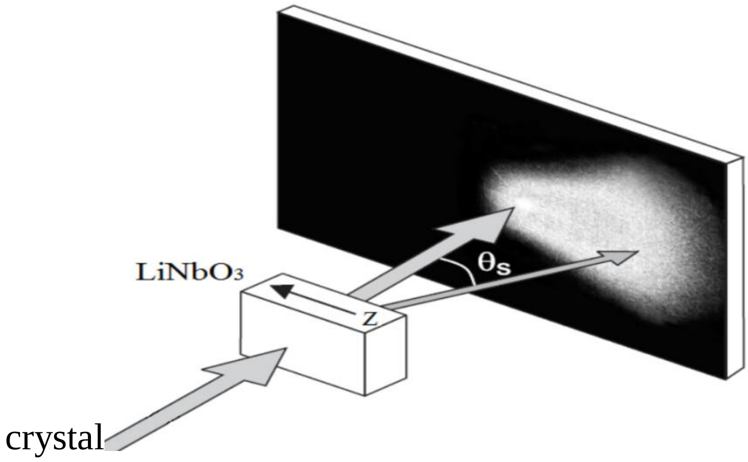

Figure 2. Scattered pattern on the screen of light transmitted through a stoichiometric $LiNbO_3$ crystal

The electric field generated in the crystal modifies its refractive index through the electro-optic effect, resulting in a speckle pattern of scattered laser light on the screen (Fig. 2). Holographic techniques make it possible to record, store, reconstruct information, shape optical fields, and obtain three-dimensional images. The performance of optical information-processing systems largely depends on the physicochemical properties of the recording medium. Although photographic emulsions offer high sensitivity and resolution, they are unsuitable for real-time or repetitive recording because the medium cannot be reused.

For optical data-processing systems, the recording material must ensure high-density data storage, nondestructive readout, sufficient diffraction efficiency, and easy rewriting (10^7–10^8 cycles). Based on these requirements, the key advantages of holographic memory can be highlighted:

1. **High read/write speed:**

Because holographic memory is page-oriented, an entire page containing more than 10^6 bits can be written or read simultaneously, enabling data-transfer rates up to 1 Gbit/s—much faster than sequential (bit-by-bit) methods.

2. **Fast access time:**

Improved holographic systems rely on optical deflectors or galvanometers to steer the reference beam, offering extremely short access times (10 μs to 1 ms). In contrast, conventional systems suffer from mechanical inertia due to physical head movement.

3. **High storage density:**

Up to 10,000 pages can be stored in the same volume, with each page exceeding 10^6 bits. The volumetric storage density may reach 100 bits/μm², far surpassing conventional media such as DVDs (≈2.5 bits/μm²).

4. **Noise resistance:**

Traditional media store each bit in a unique surface location, making them vulnerable to local defects. In holographic storage, information is distributed throughout the volume of the medium; thus, local damage only reduces signal-to-noise ratio rather than causing complete data loss.

5. **Associative search capability:**

Holographic memory enables optical correlation-based searching. When multiple holograms (N) are multiplexed, the efficiency of a reconstructed hologram depends on the similarity between the readout beam and the original reference beam. A partial input pattern can retrieve the matching stored image rapidly through fully parallel optical processing—a capability unmatched by conventional memory systems.

A typical electronic computer (EHM) holographic memory device (Fig. 3) consists of a laser, beam-steering device, optical storage medium (photographic plate or other recording material), and a photodetector matrix. After optical processing, the retrieved information is converted into electronic data. Such systems can achieve total capacities of 10^{10} bits or more. For example, IBM developed a 36 cm optical disk with a capacity of 1.8×10^{10} bits. In 2001, Lucent Technologies (USA) introduced a low-cost holographic disk system offering 100 GB storage and 20 MB/s data-transfer speed. Figure 4 shows an experimental setup for obtaining dense (multiplexed) holograms.

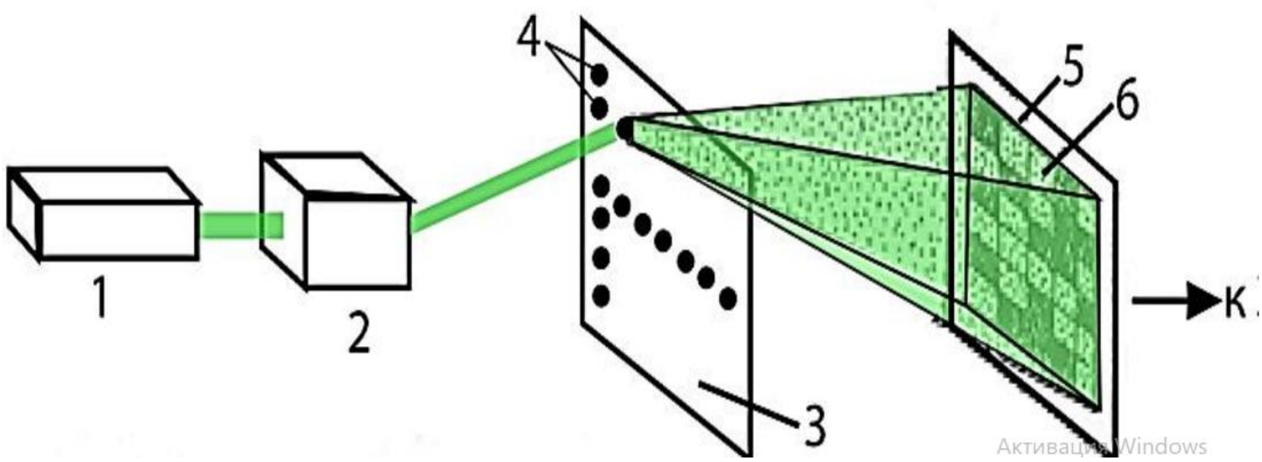

Figure 3. Simplified schematic diagram of a holographic memory system for computers: 1 – laser; 2 – deflector;
3 – recording element; 4 – hologram array with a capacity of 10^4 bits; 5 – photodetector array; 6 – reconstructed image.

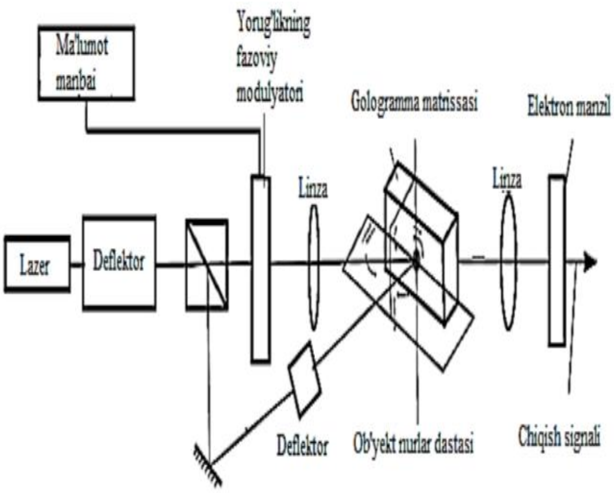

Figure 4. Experimental setup for holographic recording.

Holographic interferometry is a form of the holographic method and represents a physical measurement technique based on comparing wavefronts recorded at different moments in time. Initially, this method was used for measuring deformations and displacements of objects, and the holograms themselves were recorded on photoplates or photo-thermo-plastic materials. The reconstruction of recorded holograms and the detection of deformations and displacements were carried out by illuminating the photoplate with laser light. The principle of interferometry relies on the interference of two light waves. Typically, a light beam (in general, an electromagnetic wave) is split into two or more phase-coherent beams. The resulting interference pattern makes it possible to determine the phase shift between these beams. The optical path difference caused by surface irregularities of the object under study enables the extraction of physical quantities from the observed phase shifts.

Classical interferometry works with transparent or well-reflecting (mirror-like) surfaces. Interferometric diagnostic methods can also be applied to transparent objects, provided that the maximum refraction within the object does not exceed 0.1 mrad; in such cases, absorption can be neglected. These transparent objects are referred to as *phase objects*, meaning that they affect only the phase of the probing radiation. With the advent of holography, interferometric measurements could now be performed not only on transparent objects but also in diffusely reflecting media. Holography is a method that enables the recording of any oscillatory process by capturing both the amplitude and phase of vibrations, and reproducing them at any desired moment in time. Complete information about the object's shape is preserved in the scattered optical field during illumination, allowing the shape to be recorded in an unknown manner and later reconstructed as a reference. The further development of digital optical-recording techniques gave a new impetus to diagnostic methods. In **digital holographic interferometry**, matrix detectors began to replace photoplates

(Fig. 5). Although digital matrices have significantly lower spatial resolution than holographic photoplates, new methods of analyzing digital holographic interferograms were developed to compensate for resolution differences. Today, several techniques exist for analyzing digital holographic interferograms; however, many of them still have limitations that hinder their widespread implementation in practical measurement systems.

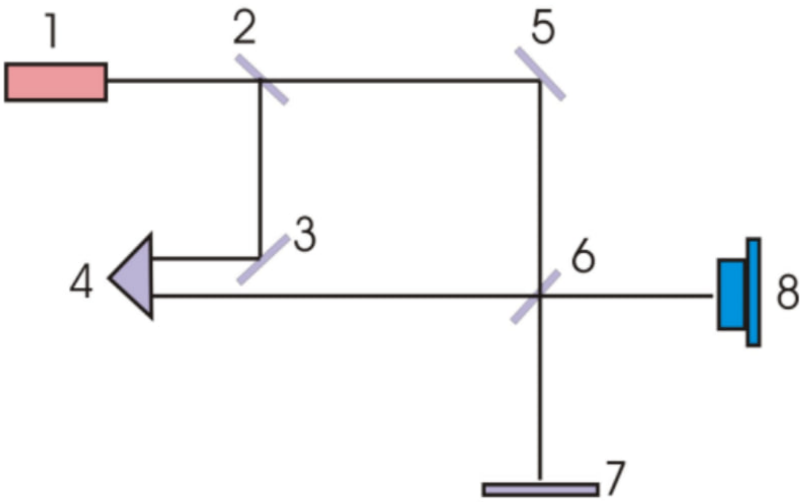

Figure 5. Schematic diagram of digital hologram recording: 1 – laser; 2, 6 – beam-splitting plates;
3, 5 – mirrors; 4 – delay line; 7 – sample; 8 – sensor matrix.

Holographic and speckle interferometry methods are widely used for measuring parametric changes in objects under various external influences. Several types of holographic interferometry exist, including the double-exposure method, real-time method, time-averaging method, and stroboscopic holography. Among them, the double-exposure technique is one of the most commonly applied approaches. In this method, a hologram of the sample under investigation is first recorded. Then, an external influence (mechanical, optical, or thermal) is applied to the sample, and a second hologram of its altered state is recorded. When the hologram is reconstructed, interference fringes appear on the screen, revealing the surface changes that occurred in the sample. Holographic interferometry is applicable for studying both transparent and reflective objects. The difference between examining these two object types—although the analysis of transparent, phase-inhomogeneous media is treated as a separate direction—does not have a fundamental nature. Instead, it is explained by the specific features of the optical schemes used and the methods of analyzing the obtained results, which are in turn determined by the particular type of phase distortions introduced by each kind of object.

Conclusion:

The analyses indicate that lithium niobate ($LiNbO_3$) is one of the most efficient and promising materials for modern optical technologies, particularly for holographic interferometry systems. Its strong nonlinear optical response, pronounced photorefractive effect, high electro-optic coefficients, and pyroelectric sensitivity enable highly effective interaction with optical radiation. In particular, the material's ability to exhibit intensity-dependent refractive-index changes and to maintain stable phase modulation makes $LiNbO_3$ ideally suited for recording, storing, and updating holographic gratings in real time. The study shows that holographic interferometers based on $LiNbO_3$ can measure mechanical deformations with nanometer precision, detect vibrations with high sensitivity, and identify extremely small temperature variations. This broadens the material's applicability in optical metrology, structural diagnostics, laser engineering, materials science, microelectronics, and the aerospace industry. Its contactless operating principle further ensures precise analysis without disturbing the physical state of the object under investigation. Moreover, the real-time photorefractive response of $LiNbO_3$ makes it suitable for monitoring dynamic processes. The crystal's stability under laser illumination, resistance to optical noise, and long-term durability establish it as a universal platform for scientific and industrial applications. In conclusion, the unique optical properties of $LiNbO_3$ elevate holographic interferometry technologies to a new level. Devices developed on the basis of this crystal can efficiently address tasks requiring high accuracy, reliability, and sensitivity, and are expected to play a significant role in holographic diagnostics, sensor systems, and optical information technologies. Therefore, further research on the physical properties of lithium niobate—including the introduction of new dopants, the development of modified crystal structures, and the enhancement of its optical response—remains an important direction for future scientific and practical advancements.

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