Characterization of periodically poled structures using digital holography

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Abstract

In this work we present a measurement system for nondestructive testing periodically poled structures formed in lithium niobate (PPLN) which is based on digital holography (DH) technique. A performance of the measurement system is theoretically and experimentally studied. Optimal parameters of DH system are found. As a result the best combination of spatial resolution (0.3 μm) and field of view (130 μm) which are sufficient for characterization of PPLN structures with spatial period down to 6.8 μm is achieved.

Keywords: Digital holography, PPLN, non-destructive testing

1. Introduction

Periodically poled structure formed in LiNbO₃ is known to be one of the most promising candidates for wavelength conversion applications [1]. For example, PPLN structures are used for development of very compact and powerful lasers [2]. In order to achieve high wavelength conversion efficiency, PPLN spatial period of high accuracy and good uniformity must be provided. That is why a structure characterization problem is very important. Since a PPLN sample is a uniformly transparent object, usual technique for it’s period measurement is based on an investigation of preliminary etched PPLN structure [3]. However the etching process destructs PPLN sample, making it unworthiness in the sequel.

In this work we present a measurement system based on digital holography optimized for non-destructive characterization of periodically poled structures formed in non-linear optical crystals.

2. Digital holography measurement system

Figure 1 shows the scheme of the measurement system which base is the Mach-Zehnder interferometer. Light from DPSS laser (λ = 532 nm, output power of 15 mW) is divided by beam splitter (BS) into two beams. One of them represents the object beam which passes trough the sample under the testing and is combined with second (reference) beam by means of second BS. Resulting interference pattern is captured by 1024×1024 CCD camera (pixel size Δx = 4.7 μm) and processed in a computer. The reference wave is a plane wave with Gaussian intensity distribution which cross-section diameter was preliminary extended up to 20 mm by means of beam expander. Neutral density filter (NDF) was used for matching intensities of object and reference beams in order to obtain interference fringes with high contrast.

Since the measurement system is intended for characterization of PPLN structures which spatial period can be as low as...
5 μm the lateral resolution of 0.5 μm or better should be provided. In order to achieve such high resolution the light passed through the sample was collected by the microscope objective (MO) to produce a magnified image. In our system we used 50x objective, however the real magnification can be adjusted by adjusting a distance $c$ between sample and microscope objective’s plane.

The magnification $M$ as well as a distance $d$ between the image plane and CCD camera is not fixed, but they determine the measurement system performance. The search of these parameters is a subject of the system optimization.

3. Optimization of the measurement system

Two main output parameters define a performance of any imaging system. These are lateral resolution and field of view. In case of system based on digital holography we need to take into account the third one – open area of the reconstructed image. In this section we present results of theoretical analysis devoted to optimization of the DH measurement system performance from viewpoint of reaching best combination of mentioned parameters.

Lateral Resolution. We introduce a numerical lateral resolution as a real linear size of the sample per one pixel in a plane of image reconstructed from a digital hologram. One can show that lateral resolution depends on neither image nor sample size but depends on both distance $d$ and magnification $M$ simultaneously:

$$
\rho = \frac{\lambda}{X M}
$$

where $X$ is lateral size of the CCD, $\lambda$ is a light wavelength. For further analysis we introduce a normalized distance $d_M = d/M$. Linear dependency $\rho(d_M)$ for given CCD (i.e. fixed $X$) can be controlled only by changing $\lambda$. Generally the resolution can be enhanced by reduction of $d_M$. At the same time it is well known that there is diffraction limit of lateral resolution for optics which is given by Abbe’s formula: $\delta = \lambda / 2NA$ (NA is an input numerical aperture of a microscope objective). Therefore by setting $\rho$ equal to $\delta$, we can find the optimal value of the normalized distance from image plane to CCD camera:

$$
d_M^0 = \frac{X}{2NA}.
$$

Note that $d_M^0$ does not depend on a wavelength. For the CCD camera used in our setup ($X = 4.8$ mm) and the microscope objective ($NA = 0.75$), the optimal normalized distance $d_M^0 = 3.2$ mm. However absolute distance $d$ and magnification $M$ are still not defined. From viewpoint of numerical resolution these parameters can possess any value while keeping the ratio $d/M$ equal to or less than $d_M^0$. At the same time the distance $d$ and magnification $M$ affect on field of view which is considered below.

Field of view. The field of view (FOV) defines visible area of a sample. In conventional microscopy FOV is mostly determined by microscope objective. In our case we use additional image processing steps – recording and reconstruction hologram, which also affect on FOV due to limited size of CCD. Figure 2 shows beams propagation diagram in DH imaging system. As one can see the part of the sample captured by CCD is determined by MO power and CCD size. Using geometrical optics principle one can show that field of view can be calculated as:
\[ \text{FOV} = S_t \approx f_M X / (M f_M + d), \]

where \( S_t \) is a sample size captures by CCD, \( f_M \) is a MO’s focal length.

Thus FOV can be extended by decrease of magnification \( M \) and distance \( d \). However the first of these parameters can not be reduced significantly because the magnification is important in our system. In its turn a reduction of \( d \) increases not only FOV but also enhances the resolution [see Eq.(1)]. However, as we’ll show in the proceeding sub-section, \( d \) also has lower limit which value is typically \( \sim 100 \text{ mm} \). Hence taking into account that in our case \( X = 4.8 \text{ mm} \) while \( f_M \) is order of 10 mm, we can find that for reasonable range of magnification from 10 to 100 the field of view is varied from 230 to 40 \( \mu \text{m} \). One can see that for fixed \( M \) FOV can be extended if the microscope objective has longer focal length, which is typical for objectives with lower magnification. Increase of distance \( d \) leads to less pronounced reduction of FOV, but nevertheless it defines a preference to use as short distance \( d \) as possible.

**Open area.** It is well known that reconstruction from a hologram produces three images – object, twin and zero-order image. All these waves, if overlapping in reconstruction plane (see Fig. 3), interact each other due to interference, which makes impossible a use of full reconstructed object wave image for measurement. Therefore we must to take for consideration only open area (OA) of that image which is not overlapped by others. In digital holography (in contrast to optical one) zero-order-image related with transmitted reference wave can be numerically suppressed [4], while in order to suppress twin image first we need to separate it from object image in space [5]. One can show that open area can be well approximated by using following equation:

\[ \text{OA} = m d \tan \theta / X, \]

where \( m = 2 \) if zero-order image is suppressed, and \( m = 1 \), if not; \( \theta \) is angle between reference and object beams during recording the hologram.

Therefore in order to increase the open area, we must increase \( d \) or \( \theta \). However in digital holography maximal \( \theta \) is limited by few degrees due to finite resolution of CCD which pixel size \( \Delta x \) is typically 5-10 \( \mu \text{m} \): \( \theta_{\text{max}} = \lambda / 4 \Delta x \). Hence only one parameter, distance \( d \), can be used to expand OA. Considering the case when zero-order image is suppressed (\( m = 2 \)), let’s find a minimal distance \( d^0 \) between CCD and reconstruction plane (and as sequence, minimal distance between image plane and CCD; see Fig.2) when reconstructed object image is fully open (\( \text{OA} = 1 \)):

\[ d^0 = X / 2 \tan \theta. \]

**Optimization.** Equation (5) is start point for calculating the measuring system parameters. By using it, we can find the minimal distance \( d^0 \) for every particular CCD. In our case (\( X = 4.8 \text{ mm}, \Delta x = 4.7 \mu \text{m} \)) we have \( d^0 = 86 \text{ mm} \). Then, taking to into account that magnification is related with distance \( d \) via normalized distance \( d_M \) and using for the last one an optimized value which is given by Eq.(2) one can find the maximal magnification for the measurement system \( M^0 = d^0 / d_M^0 \approx 27 \). These values of magnification and distance are optimal because decreasing \( d \) (shorter than \( d^0 \)) will lead to reduction the open area, while increasing \( d \) (longer than \( d^0 \)) – to worsening a numerical resolution. Similar situation with magnification: for \( M < M^0 \) we’re loosing resolution, while for \( M > M^0 \) we reduce FOV. So, for aforementioned optimal value of \( M \) and \( d \) we have \( \text{FOV} = 130 \mu \text{m} \) and numerical resolution \( \Re = 0.36 \mu \text{m/pix} \) (at \( \lambda = 532 \text{ nm} \)). At the same time, by reducing the wavelength, we can enhance the resolution
without affecting FOV or OA. Thus for violet light ($\lambda = 405$ nm) we can reach the resolution $\rho = 0.27 \mu m/pix$.

4. Characterization of periodical phase structure

After the poling procedure which is based on application of a strong electric field to a sample of lithium niobate, the last one gets a periodical structure of oppositely polarized domains – A and B. Before to be annealed PPLN sample has a residual electric field with opposite directions in adjacent areas. As a result a non-annealed PPLN sample could have variation of refractive index with magnitude $\Delta n = 10^{-5} - 10^{-4}$ due to electro-optical effect and/or thickness variation with magnitude $\Delta w = 5-15$ nm due to piezo-electrical effect. Both of these parameters affect on light phase passed through the sample, which is being reconstructed from DH allows one to reconstruct PPLN’s structure.

To test the DH measurement system performance we applied it for characterization of a test periodical structure TPS (Fig. 4) formed by deposition SiO$_2$ step layer (thickness $\Delta w = 30 \pm 3$ nm) on glass substrate (thickness $w = 1$ mm). Taking into account refractive index of glass/SiO$_2$ $n_g = 1.46$, a phase variation amplitude to be detected at wavelength $\lambda = 532$ nm can be estimated as 0.5 rad. Such a phase difference corresponds to variation of refractive index $\Delta n \approx 1 \times 10^{-4}$ (for sample with thickness $w = 400 \mu m$) which is expected for real PPLN.

The final target of TPS characterization (and PPLN as well) is to measure $A$ and $B$, and also parameters derived from $A$ and $B$: such as spatial period $T = A + B$, duty cycle $D = A/(A + B)$ (or $B/(A+B)$) etc. Therefore we must find boundary between domains A and B and measure their dimensions. However it is quite difficult to do using data obtained after reconstruction and phase unwrapping presented in Fig.5, a due to high level of noise. This noise is caused by a number of reasons, such as interference of light waves multiply reflected from sample’s sides, diffraction, beams imperfections etc. Since the noise has higher spatial frequencies than characteristic frequency of periodical pattern to be reconstructed a low-pass spatial frequency filter can be used for removing the noise. We found that better result is achieved in case of using Gaussian pass 2D filter with half-width at level $1/e$ equal to 0.3 of maximal spatial frequency. The filtered distribution of phase difference is shown in Fig.5, b.

The next step of data processing is a determination of $A/B$ domains boundary and measurement dimensions A and B. This procedure was done on the base of data thresholding. Threshold level $Th$ was selected as polynomial averaging of data in the line perpendicular to domain structures:

$$Th(x) = \gamma a_0 + a_1 x + a_2 x^2,$$

Fig. 4. Structure of the test phase sample.

Fig. 5. Phase map of TPS sample at different steps of data processing: a – reconstructed from DH; b – after spatial spectra filtering; c – after thresholding.
where $a_i$ – polynomial coefficients; $\gamma$ – correction coefficient ($\gamma \approx 1$). Use of the 2nd order polynomial has allowed one to compensate “slow” variation of the sample thickness.

Using the thresholded phase distribution (Fig. 5, c) we calculated $A$ and $B$ size through the whole captured part of the TPS sample. Obtained average values of $A$ and $B$ as well as the total period $T$ and the duty cycle $D$ calculated from $A$ and $B$ are presented in Table 1 in comparison with data obtained after manual processing of optical microscopy image.

Table 1. Parameters of TPS obtained by two techniques.

<table>
<thead>
<tr>
<th></th>
<th>Digital Holography</th>
<th>Optical Microscopy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$, $\mu m$</td>
<td>$2.81 \pm 0.11$</td>
<td>$2.82 \pm 0.07$</td>
</tr>
<tr>
<td>$B$, $\mu m$</td>
<td>$3.17 \pm 0.12$</td>
<td>$3.17 \pm 0.07$</td>
</tr>
<tr>
<td>$T$, $\mu m$</td>
<td>$5.98 \pm 0.10$</td>
<td>$5.99 \pm 0.07$</td>
</tr>
<tr>
<td>$D$, %</td>
<td>$47.0 \pm 1.7$</td>
<td>$47.0 \pm 1.1$</td>
</tr>
</tbody>
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As one can see from Table 1 there is good agreement between data obtained by means of digital holography and optical microscopy. Smaller values for standard deviation in case of optical microscopy are resulting from lower number of data (below 10) taken from OM image for statistical processing, while all data (~300) are taken from whole image in case of DH. Note that results presented in Table 1 are obtained for TPS sample with thickness variation of 30 nm. At the same time we checked experimentally that DH system allows one to characterize TPS even if its thickness variation is much smaller – down to 10 nm, which belongs to expected range for non-annealed PPLN sample. Hence the digital holography system developed provides sufficient accuracy of non-destructive measurement of phase object parameters and can be successfully used for PPLN characterization.

5. Conclusion

In this work we studied performance of the measurement system based on digital holography which is designed for characterization of periodically poled structures formed in LiNbO$_3$. Relations which allow us to find optimal values for both magnification and distance from image plane to CCD for given parameters of CCD and required numerical resolution are derived. It is shown that resolution required for characterization of PPLN structures (<0.5 $\mu m$) can be achieved with sufficient field of view (>100 $\mu m$) which is completely free from overlapping by other images produced during a digital hologram reconstruction. It is shown that measurement system is capable to detect a variation of refractive index of sample with amplitude as low as $10^{-4}$ or thickness variation with amplitude as low as 10 nm, which is expected in real PPLN structure.

References