# A lithium-niobate-based photorefractive novelty filter microscope and its application in micro-fluid flow diagnostics

**Vishnu Vardhan Krishnamachari, Oliver Grothe, Hendrik Deitmar and Cornelia Denz**

*Institut für Angewandte Physik, Westfälische Wilhelms-Universität Münster*
*Corrensstrasse 2/4 48149 Münster, Germany*
*vishnu@uni-muenster.de*

**Abstract:** In this contribution, we present a photorefractive lithium-niobate novelty filter microscope. We derive conditions, based on the photorefractive model by Kukhtarev et al. [1], for simulating the two-beam coupling functionality in a lithium-niobate crystal. We verify them experimentally by measuring phase changes due to the mixing of equally transparent fluids in a micro-channel using this novelty filter microscope.



**OCIS codes:** (190.5330) Photorefractive nonlinear optics; (120.5050) Phase measurement; (180.0180) Microscopy; (100.0100) Image processing

## 1. Introduction

Photorefractive novelty filter is sensitive to amplitude and phase changes. Using the phase sensitivity of the device, phase changes from zero to $\pi$ radians can be measured in real-time without any necessity for complex hardware or software phase-unwrapping solutions [2]. Also the range of phase measurement can be extended to $-\pi$ to $+\pi$ radians using a phase trigger technique [3]. However, for reliable phase measurement the most important condition is that the trail formation, resulting due to the finite time constant of photorefractive grating formation, $\tau_g$, has to be suppressed. This is best achieved by using very small incident intensities as described in the reference [2]. It was shown in barium titanate ($BaTiO_3$) crystals that the time constants as large as 20 s can be achieved based on the intensity dependence [3].

For phase measurements where the dynamics of the processes under investigation are longer than tens of seconds, some other mechanism has to be developed to extend the time constant. In this article, we present a lithium niobate-based novelty filter which possesses $\tau_g$ greater than 90 minutes. It is well known that a lithium niobate ($LiNbO_3$) crystal, due to its small dark conductivity, possesses very large time constants, as large as a few hours to a couple of days. However, it does not exhibit two-beam coupling, an essential feature for the functioning of a novelty filter. The phenomenon of two-beam coupling relies on the existence of a phase shift of $\pi/2$ radians between the incident interference pattern and the recorded refractive index modulation. This, we introduce in a $LiNbO_3$ crystal, after recording the background hologram, by applying an external phase shift to the reference beam during the hologram read-out. Also, to increase $\tau_g$, we reduce the total intensity incident on the crystal during the reconstruction process.

In the following section, we discuss the influence of the grating formation time constant on the phase measurements by presenting the numerical results of photorefractive coupled differential equations. In Section 3, we present our experimental setup and discuss the design and the function of the object under investigation, the micro-channel for fluid mixing. We also derive conditions for which a $LiNbO_3$ crystal can be used for novelty filtering based on the steady-state expressions of photorefractive beam-coupling phenomenon. In Section 4, we describe the experimental procedure and present our results. Finally, in Section 5, we conclude by briefly discussing the advantage of phase measurement using a novelty filter over a real-time holographic interferometer, a device which is also often used for real-time phase measurement.

## 2. Influence of time constant on phase measurement

To study the influence of the grating time constant $\tau_g$ on the signal output, we let the phase of the signal beam vary linearly with time with a slope of $0.1\,\mathrm{s}^{-1}$ and obtained the temporally varying output of the novelty filter by numerically solving the coupled differential equations described in reference [3]. From the phase transfer function [2] of the novelty filter one knows that the output should be a sinusoidal form of intensity curve with maxima at $(2k+1)\pi$ radians (in the above example at $t = 5\,\mathrm{s},\ 15\,\mathrm{s},\ 25\,\mathrm{s},\ \ldots$) and minima at $2k\pi$ radians (at $t = 10\,\mathrm{s},\ 20\,\mathrm{s},\ 30\,\mathrm{s},\ \ldots$) where $k$ is an integer. However from Figure 1 one notices that the output from the filter is different depending on the time constant of the filter. Especially, for smaller $\tau_g = 10\,\mathrm{s}$ and $100\,\mathrm{s}$, one can not reliably use the calibrated phase transfer function of the system to determine the input phase changes. This is only possible for large $\tau_g = 1000\,\mathrm{s}$.

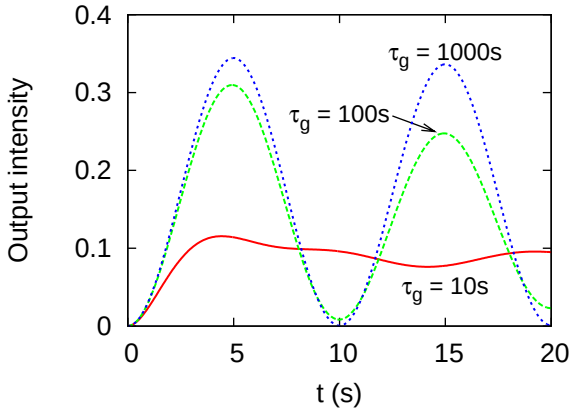


Fig. 1. Numerical simulation result of the novelty filtered output for a linear input phase variation of $0.1t$ plotted for different $\tau_g$. Parameters used: $m = 0.1$, $\Delta n = 5 \cdot 10^{-5}$, $\gamma = 6.3\,\mathrm{cm}^{-1}$ and $\phi = 90^\circ$.

The grating time constant in $BaTiO_3$, the most often used crystal for implementing novelty filter, can be increased by decreasing the total intensity incident on the material [2]. However, if the time constant has to be increased further, the only other alternative is to use a different material. We chose $LiNbO_3$ as the material of our choice due to its availability in good optical quality and its property of large grating diffraction efficiency ($\eta$). But, it does not exhibit beam-coupling large enough to directly implement a novelty filter. This is due to the fact that in $LiNbO_3$ crystals the

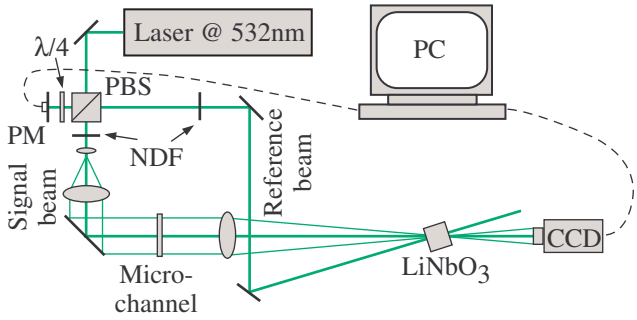


Fig. 2. Sketch of the experimental setup of a $LiNbO_3$-based novelty filter microscope.

photorefractive phase shift $\phi \approx 0$ radians. In the following, we present a technique as to how to simulate a phase shift of $\pi/2$ radians in a $LiNbO_3$ crystal. This technique relies on an interference model [4] which is an improved version of the model presented in reference [5].

## 3. Lithium niobate-based novelty filter microscope

Figure 2 shows a sketch of a $LiNbO_3$-based novelty filter. The laser beam from a frequency-doubled Nd:YAG laser was split into two beams, the signal and the reference, with the help of a polarizing beam-splitter. The signal beam was collimated to illuminate a probe. The probe in our case was a micro-channel used for mixing fluids of different refractive indices. The details about this channel are given below. This probe was imaged with the help of microscope optics on to a progressive-scan CCD camera. This signal beam was made to interfere with the reference (both with e-polarization) in a 0°-cut $LiNbO_3$ crystal (see Figure 2).

The reference beam after getting reflected off the polarizing beam-splitter was incident on a piezo-controlled mirror (PM) after passing through a quarter-wave-plate (QWP). The mirror, used to retro-reflect the incident beam, also served as a phase shifting element for measurements with $LiNbO_3$ crystal and for calibrating the system (details can be found in Section 4). Due to the passage of the light beam twice through QWP, the polarization of the beam that reaches the beam splitter on reflection from the mirror is rotated by 90°. Due to this fact, the light beam gets transmitted rather than reflected (at PBS) back in to the laser. This combination of PBS, QWP and mirror helped us to avoid reflection back into the laser and also helped us to conserve laser energy.

### *3.1. Description of the micro-channel*

Of late, there has been growing interest to apply the technique of particle image velocimetry to study the flow properties in micro-channels and micro-fluidic devices which have an enormous application potential in the field of biology, medicine and robotics. The aim of this work is to use the technique of novelty filtering to visualize and measure density changes in microscopic flows without using tracer particles which may eventually disturb the flow properties. Toward this end, we realized a micro-channel based on the design published by Oddy et al. [6].

Figure 3(a) and (b) show a sketch and a photograph of the channel respectively. The channel was eroded in a thin (500 $\mu$m) aluminum metal plate. This metal plate was sandwiched between a plane glass substrate and a plane plexiglas. The channel connections were bored into the plexiglas. Due

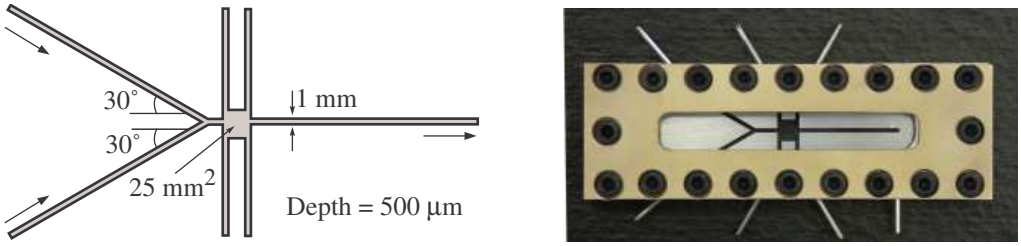


Fig. 3. (a) Sketch of the micro-channel (b) Photograph of the channel.

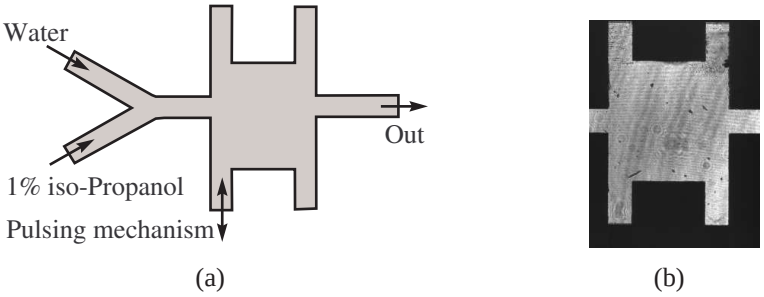


Fig. 4. (a) Fluid flow configuration in the channel (b) Non-novelty filtered image of the channel with both the liquids: water and 1% iso-propanol.

to the excellent surface quality of the metal used and the soft nature of the plexiglas, the channel set in well between the substrates. As a result of which, this channel was completely air-tight.

To study the mixing of two different liquids in the channel, we chose the mixing liquids to be water and 1% iso-propanol. The flow configuration is sketched in Figure 4(a). The fluids were pumped into the channels using a syringe pump at the rate of 1.8 ml/h with an average fluid flow velocity of 2 mm/s. This corresponds to a Reynolds number of 1. We chose this combination of fluids because when observed with a typical imaging system, both the liquids due to their equal transparency are hardly separable (Figure 4(b)). But they show an optical path difference of approximately $\pi$ radians (equivalent to 532 nm) due to their minimal difference in their densities (approximately $2.2{\cdot}10^{-3}$ g/cm$^3$). The aim is to detect the variation in the fluid density due to the mixing of the two fluids using the $LiNbO_3$-based novelty filter.

### *3.2. Strategy of novelty filtering using a $LiNbO_3$ crystal*

The implementation a $LiNbO_3$-based novelty filter is done in three steps. In the first step the hologram of the initial state of the probe is stored. In our case, the initial state corresponds to the channel with only water present in it. The steady-state output from the crystal after the hologram is stored in the crystal can be written as [4]

$$\frac{I_s(z)}{I_s(0)} = (1-\eta)+\frac{\eta}{m}-2\sqrt{\frac{\eta(1-\eta)}{m}}\,\sin(\Delta\psi(0)+\chi) \quad (1)$$

$$\frac{I_r(z)}{I_r(0)} = \eta m+(1-\eta)+2\sqrt{\eta(1-\eta)m}\,\sin(\Delta\psi(0)+\chi) \quad (2)$$

where $\eta(z)$ and $\chi(z)$ are the intensity diffraction efficiency and the grating-induced phase shift of the photorefractive hologram respectively and are given by

$$\eta = \frac{1}{2}\left(\frac{\cosh(\delta-\alpha)-\cos\beta z}{\cosh\alpha\cosh\delta}\right) \tag{3}$$

$$\chi(z) = \sin^{-1}\left(\frac{\sinh\alpha\cos\beta z-\sinh\delta}{\sqrt{\sinh^2\alpha+\sinh^2\delta+\sin^2\beta z-2\sinh\alpha\sinh\delta\cos\beta z}}\right)-\Delta\psi(0) \tag{4}$$

where $m$ is the incident beam intensity ratio $I_s(0)/I_r(0)$, $\Delta\psi(0)=\psi_r(0)-\psi_s(0)$ is the phase difference between the incident beams (at $z=0$) and the variables $\alpha$ and $\delta$ are defined as

$$\alpha = \ln\sqrt{m} \quad \text{and} \quad \delta = \alpha - \frac{\gamma z}{2} \tag{5}$$

respectively with $\gamma$ and $\beta$ being the photorefractive amplitude and phase coupling constants. It can be verified that the above expressions for the output intensities are equivalent to the results presented in reference [7].

The advantage of writing the output beam intensities in this form is that the grating parameters $\eta$ and $\chi$ are well separated from the incident beam amplitudes and phases. Thus, for a grating with a long time constant $\tau_g$, the immediate effect of the input phase or amplitude changes in the beams can be easily obtained by simply substituting their values in Eqs. (1) and (2).

In the second step, the intensity ratio between the beams and the phase of the reference beam are varied in such a way that the output signal beam is nullified. This is equivalent to the suppression of the stationary background in a conventional $BaTiO_3$-based novelty filter (here, the background corresponds to the initial state where only the water is present in the channel). The conditions for the new beam ratio $m'$ and the phase shift $\xi$ to the reference beam can be obtained by substituting these new input conditions in Eq. (1) and letting the left-hand side of the equation to zero.

$$0 = (1-\eta)+\frac{\eta}{m'}-2\sqrt{\frac{\eta(1-\eta)}{m'}}\,\sin(\psi_r(0)+\xi-\psi_s(0)+\chi) \tag{6}$$

This equation leads to the following two conditions which have to be satisfied simultaneously:

$$m' = \frac{\eta}{1-\eta} \tag{7}$$

$$\xi = \frac{\pi}{2}+2k\pi-\chi-\Delta\psi(0) \tag{8}$$

Equation (7) gives the condition for the new input beam ratio for which the background is nullified. Since the condition is specified only for the input ratio and not the total intensity, one can use lower intensity during the read out process to reduce the speed of decay of the background hologram. Equation (8) corresponds to the phase condition and it specifies the amount of phase shift that needs to be applied to the reference beam so that the background is nullified. This parameter depends strongly on the properties of the grating written in the crystal. Only for the case when $\gamma=0$ and $m=1$, $\xi$ is $\pi/2$. For the rest of the cases, the external phase shift to the reference beam has to be other than $\pi/2$.

The final step, in realizing the novelty filtering functionality with a $LiNbO_3$ crystal, involves calibrating the novelty filter to determine its phase transfer function (PTF). This is done in our setup by giving known phase shifts to the reference beam (using the piezo-mirror) and detecting the corresponding output signal intensities. The resulting plot of the input phase changes versus the output intensity is the PTF of the system which also serves as the calibration curve of the device.

## 4. Application in fluid flow diagnostics

In this section, we present our experimental results of measurement of phase changes introduced by two mixing liquids, with a density difference of $2.2 \cdot 10^{-3}$ g/cm$^3$ in the channel. Before the $LiNbO_3$ novelty filter was used for measurement, the three important steps, as described in the previous section, were performed. The background image stored in the crystal consisted of the channel with only water present in it. A total laser power of 2.5 mW was used to store the background hologram with an exposure time of 15 s and with an intensity beam ratio of approximately 1.7. In the next step, we changed the intensity ratio of the beams to $m' = 4 \cdot 10^{-3}$ with the total power of 170 $\mu$W and introduced a phase shift to the reference beam to nullify the signal beam. Because of the reduced total intensity during the readout process, the time constant $\tau_g$ was extended to more than 90 minutes. We calibrated the system by determining its PTF at every pixel of the CCD camera to reduce the artifacts arising out of inhomogeneous illumination.

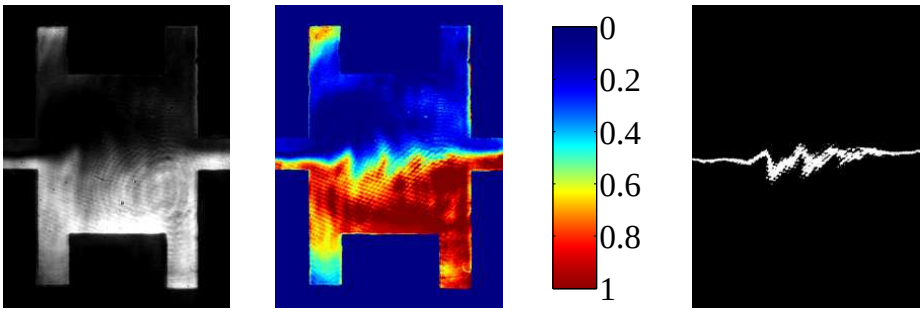


Fig. 5. Mixing of water and iso-propanol in the channel (a) As captured with the camera (b) Calculated phase changes based on the PTF (c) Colorbar representing the phase changes in (b) in multiples of $\pi$ (d) A binary image highlighting the region of mixing.

Now, we let iso-propanol flow into the channel. Both the liquids are clearly distinguishable as shown in Figure 5(a) (water is dark and alcohol is bright). Due to the laminar nature of the flow, the two liquids do not mix with each other. In the literature, to speedup the process of mixing the liquids, often a pulsing mechanism is used [6]. We introduced this pulsing mechanism to the flowing fluids with a frequency of 1 Hz with the help of a piezo-based compressor. As indicated in Figure 4(a), iso-propanol was pumped from the bottom left corner of the chamber. One can clearly visualize the flow of liquids in the presence of the pulses as seen in Figure 5(a). To understand how the liquids mix with each other and how the concentration of the liquids change at the borders, we calculated the phase changes based upon the calibration that we had performed earlier. Figure 5(b) shows the result after the calibration has been applied to the images. Figure 5(c) is the color-bar

used in mapping different phase differences to different colors in Figure 5(b). The minimum density change that we can currently detect with our system is $2.2{\cdot}10^{-4}$ g/cm$^3$ for a channel thickness of 500 $\mu$m and this is limited only by the dynamic range of the camera being used.

Figure 5(d), obtained from Figure 5(b) by setting a lower and an upper gray value (phase-change) threshold of 40 ($0.3\pi$) and 180 ($0.7\pi$) respectively, clearly highlights the strength of the novelty filter. It is evident that in the regions where there is no pulse (viz. the left (entry point) and the right (exit point) regions), the width of the highlighted region is narrow, about 9 pixels. Whereas in the regions where the flow is perturbed by the pulses, the highlighted region is broad (about 18 to 24 pixels) suggesting that the pulsing mechanism helps in mixing the fluids better.

## 5. Discussion and Conclusion

Seen from the perspective of holographic interferometry, a novelty filter is a special form of real-time holographic interferometer (RTHI) [8] with two important differences: namely, finite hologram time constant and a different operating point. Due to the dynamic nature of the photorefractive grating, the hologram recorded gets gradually erased. The operating point of the novelty filter for phase measurements is $\varphi = 0$ radians. This is evident when one looks at the form of the PTF of the novelty filter which has a $\sin^2 \varphi/2$ dependence, where $\varphi$ is the input phase change. On the other hand, the PTF of a RTHI using a photographic emulsion as the hologram recording medium is of the form $\cos^2 \varphi/2$. The advantage of the novelty filter system is that when there is no variation in the input phase of either beams, the output is zero and hence, the background is suppressed highlighting only the dynamic portions.

In conclusion, we have presented a novelty filter microscope system based on a $LiNbO_3$ crystal which can be used for measuring the optical phase changes due to dynamic processes occurring over a period of time of a few hours. We derived conditions based on the photorefractive model to simulate the novelty filter functioning using a $LiNbO_3$ crystal. We applied this filter in studying the mixing processes of two liquids with a density difference of $2.2 \cdot 10^{-3}$ g/cm$^3$.

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