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Novelty filtering with a photorefractive lithium–niobate crystal

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In this letter we present a technique which employs a photorefractive lithium–niobate crystal for novelty filtering. Due to the minimal trail formation exhibited by this novelty filter, it can be used for reliable quantitative phase measurement for time intervals of the order of a few hours. We present a simplified theoretical description of this filter based on a coupled wave theory [N. V. Kukhtarev, V. B. Markov, S. G. Odulov, M. S. Soskin, and V. L. Vinetskii, Ferroelectrics **22**, 949 (1979); **22**, 961 (1979)]. We also demonstrate the first experimental results of employing this device in the field of microfluid dynamics for measuring the concentration changes produced due to the mixing of two transparent liquids in a microchannel. © *2005 American Institute of Physics*.
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The photorefractive-based optical novelty filter[1] has been known for almost two decades. It is a temporal high pass filter[2] which detects only the dynamic portions in the field of view while suppressing the stationary background. The photorefractive barium titanate ($BaTiO_3$) crystals are often employed to implement this filter. The most important highlight of this optical filter is that it is sensitive not only to amplitude changes but also to phase changes.[3] We demonstrated that the phase sensitivity of the device can be used to detect and measure in real time the phase changes introduced by moving phase objects.[4] In combination with a phase triggering technique,[5] it is even possible to extend the phase measurement range to 2π radians. To perform reliable phase measurement, one of the important conditions is that the trail formation,[6] has to be suppressed. This can be achieved only if the photorefractive grating formation time constant (τ) is made much larger than the slowest dynamic process under observation.[4] Though τ can be varied by utilizing its intensity dependence from a few hundred milliseconds to a few tens of seconds, for longer duration of measurement of the order of hours new methods have to be investigated.

In this letter, we present a lithium–niobate-based photorefractive novelty filter. Due to its small dark conductivity, the lithium–niobate ($LiNbO_3$) crystal has large τ of the order of hours. However, the $LiNbO_3$ crystal, unlike $BaTiO_3$, is not a diffusion-dominated crystal and hence does not exhibit two-beam coupling. For the novelty filter function, the phenomenon of two beam coupling, resulting due to the the phase shift between the incident intensity pattern and the generated refractive index grating, is necessary. To induce the grating phase shift in $LiNbO_3$ crystal, we introduce an additional phase to the reference beam after writing the initial grating in the crystal. Moreover, to achieve large time constants, we reduce the total intensity of the beams during the readout process.

In this contribution, we provide a simplified but universal theoretical description of this novelty filter by recasting the solution, based on the photorefractive model of Kukhtarev *et al.*,[7,8] of two-beam coupling coupled differential equations, in the form of interference between the transmitted (through the grating in the crystal) portion of one beam and the diffracted (at the grating in the crystal) portion of the other beam. The validity of the resulting expressions is only limited by the validity of the assumptions made in the steady-state Kukhtarev model and thus they can be used to analyze the wave mixing in any photorefractive crystal. We also present the first experimental results of the application of this novelty filter for measuring the phase changes due to the mixing of two transparent fluids, water and 1% isopropanol, in a microchannel.

Though Guest, Mirsalehi, and Gaylord,[9] demonstrated the utility of a similar $LiNbO_3$-based wave mixing setup for performing exclusive-OR (XOR) operation between two input images, their theoretical treatment of the device was limited. On the other hand, Vahey in his landmark article[10] provided a rigorous theoretical analysis of this device, however only for the particular case of unit input beam ratio. Though he discussed briefly the potential application of this device for detecting small phase changes, to the best of our knowledge, this is the first time that this novelty filter is being used to measure phase changes in fluid flows.

The novelty filtering function with a photorefractive $LiNbO_3$ crystal can be realized in three steps: (a) recording the initial stationary background, (b) nullifying the output signal beam, and (c) observing the dynamic processes in the signal beam. The three steps can be explained by using the coupled wave theory for photorefractive wave mixing developed by Kukhtarev *et al.* and by invoking the interference nature of the two-beam coupling output. The expressions for the intensities of the beams (for convenience let us define beam 1 to be the signal beam and beam 2 the reference beam) after undergoing beam coupling in a photorefractive material are given by the coupled wave theory as[11]

$$I_{1,2}(\ell) = I_{1,2}(0)\left(\frac{1+m^{\mp 1}}{1+m^{\mp 1}e^{\pm\gamma\ell}}\right), \tag{1}$$

where $m = I_1(0)/I_2(0)$ is the input beam intensity ratio, $\gamma = 2\pi\Delta n \sin\phi/\lambda\cos\theta$ is the energy coupling constant, Δn is the peak-to-peak change in the refractive index, λ is the wavelength of light in the medium, and ϕ is the phase shift between the incident interference pattern and the refractive

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index grating. The beams get diffracted at the grating with an intensity diffraction efficiency of[8]

$$\eta = \frac{2me^{-\gamma\ell/2}}{1+m}\left[\frac{\cosh\frac{\gamma\ell}{2} - \cos\beta\ell}{1+me^{-\gamma\ell}}\right], \tag{2}$$

where $\beta=\pi\Delta n\cos\phi/\lambda\cos\theta$ is the phase coupling constant. The above expressions can be written conveniently in a form which brings forth the inherent interference between the transmitted portion of one beam and the diffracted portion of the other beam. If the incident amplitudes of the beams are $\sqrt{I_{10}}e^{-i\psi_{10}}$ and $\sqrt{I_{20}}e^{-i\psi_{20}}$, respectively, then the output intensities in Eqs. (1) take the form

$$I_{1,2}(\ell) = (1-\eta)I_{10,20} + \eta I_{20,10} + 2\sqrt{\eta(1-\eta)I_{10}I_{20}}\cos\left(\Delta\psi_0 + \chi(\ell) \pm \frac{\pi}{2}\right), \tag{3}$$

where $\Delta\psi_0=\psi_2(0)-\psi_1(0)$, $\chi(\ell)=\tilde{\chi}(\ell)-\Delta\psi_0$ is the photorefractive phase coupling angle due to diffraction with

$$\tilde{\chi}(z) = \arcsin\left[\frac{\sinh\alpha\cos\beta z - \sinh\delta}{\sqrt{\sinh^2\alpha + \sinh^2\delta + \sin^2\beta z - 2\sinh\alpha\sinh\delta\cos\beta z}}\right], \tag{4}$$

$\alpha=\log\sqrt{m}$, and $\delta=\alpha-\gamma\ell/2$.

In Eqs. (3), $\pi/2$ in the argument of the cosine function corresponds to the phase shift in the diffracted beam due the diffraction at the grating. It is important to note that $\tilde{\chi}(\ell)=\phi$ only for the case when $m=1$ and the coupling is small, unlike what is assumed in the interference model introduced in Ref. 3.

The advantage of writing the output intensity expressions as in Eqs. (3) is that the grating parameters (lumped in η and χ) and the input beam amplitudes are well separated. Now, for the case where the input changes rapidly in comparison to the photorefractive time constant, one can substitute the new input amplitudes in Eqs. (3) and study the effects of diffraction at the grating recorded in the crystal.

Nullifying the output signal beam is equivalent to suppressing the stationary background. This is achieved by changing the signal and reference beam amplitudes. If the modified beam amplitudes are $\sqrt{I'_{10}}e^{-i(\psi_{10}+\varphi)}$ and $\sqrt{I'_{20}}e^{-i(\psi_{20}+\xi)}$, respectively, then the output intensities are

$$I'_{1,2}(\ell) = (1-\eta)I'_{10,20} + \eta I'_{20,10} \mp 2\sqrt{\eta(1-\eta)I'_{10}I'_{20}}\sin(\xi - \varphi + \tilde{\chi}(\ell)), \tag{5}$$

where ξ is a known phase change applied to the reference beam and φ is the phase change in the signal beam which has to be determined. Equations (5) are general expressions for the intensities of two beams diffracting from a photorefractive grating at the Bragg angle of incidence. For the special case of $I'_{10}/I'_{20}=1$, the expressions agree with the results obtained by Vahey.[10]

To derive the condition(s) for nullifying the signal beam, before observing any dynamic processes (i.e., $\varphi=0$), we require that the left hand side of the first equality in Eq. (5) vanish for the new beam amplitudes. This leads to the following conditions which have to be satisfied simultaneously:

$$m' = \frac{I'_1(0)}{I'_2(0)} = \frac{\eta}{1-\eta}, \tag{6}$$

$$\xi = \frac{\pi}{2} + 2k\pi - \tilde{\chi}(\ell), \tag{7}$$

where k is an integer.

The intensity ratio condition (6) implies that at the output signal port the transmitted portion of the signal beam and the diffracted portion of the reference beam should be of equal intensity. Since the restriction is only on the intensity ratio and not on the total intensity, one can use much lower total intensity (a factor of 1/10 in our case) compared to that used in the first step. The advantage is that because of lower intensity, the background grating recorded in the crystal does not get erased as fast as it was written, thus enhancing τ.

The phase condition (7) gives the expression for the phase shift to be applied to the reference beam to achieve the destructive interference. The amount of phase shift ξ is dependent on the type of grating written in the crystal.

Once the signal beam is nullified, the phase transfer function (PTF) of the system can be experimentally determined and a look-up table can be created for real-time phase measurement in the range of 0–π radians. Also the phase-triggering method can be employed to extend the phase measurement range to 2π radians. The PTF of this novelty filter, calculated by substituting conditions (6) and (7) in the signal expression of Eqs. (5), has a $\sin^2\varphi/2$ dependence which is same as that of a $BaTiO_3$-based novelty filter.[5]

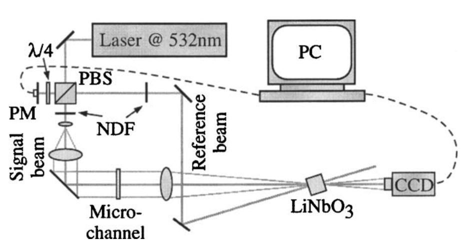

FIG. 1. Experimental setup of $LiNbO_3$ novelty filter.

Figure 1 shows the experimental sketch of the implementation of the novelty filter based on $LiNbO_3$ crystal. The laser beam from a frequency-doubled Nd:yttrium–aluminum–garnet laser is split into two beams: signal beam and reference beam. The signal beam, with p polarization, after beam cleanup and collimation illuminates a microchannel which is imaged on to a 1/3 in. progressive-scan charge coupled device (CCD) camera. The reference beam, on the other hand, is reflected off a computer-controlled piezo mirror (PM). In combination with a quarter-wave plate (labeled

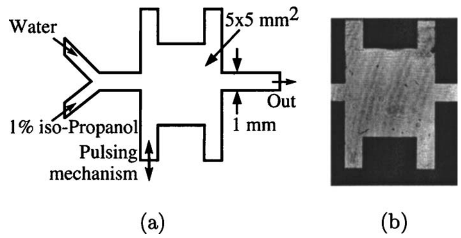

FIG. 2. (a) Sketch of the microchannel (depth=500 μm) and the fluid flow configuration. (b) Non-novelty filtered image of fluid flow.

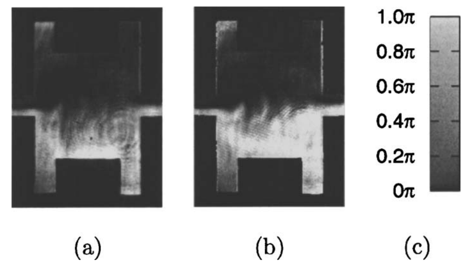

FIG. 3. (a) Novelty filtered image. (b) Phase change map calculated from the PTF. (c) The color mapping for phase shift in terms of π.

as $\lambda/4$) and a polarizing beam splitter (PBS) to achieve the right polarization, the reference beam is made to interfere with the nearly focused signal beam in a photorefractive 0°-cut $LiNbO_3$ crystal. The neutral density filters (indicated as NDF) in the beam paths are used to adjust the beam intensity ratios for nullifying the signal beam once the stationary background is recorded.

In this letter, the object under investigation is a microchannel [Fig. 2(a)], with a typical channel structure reported in the literature (see, for example, Ref. 12). This microchannel is used for studying the mixing of miscible liquids, in our case, water and 1% iso-propanol. These two liquids, barely distinguishable in color and transparency [see Fig. 2(b)], have a density difference of about 2.2×10^{-3} g/cm^3 and show an optical phase difference of π radians. To study their mixing properties, the liquids were pumped into the channel with an average flow rate 1.8 ml/h, corresponding to a fluid flow velocity of 2 mm/s, with the help of a syringe pump. Due to the laminar nature of the flow (Reynold's number =1), as suggested by Oddy, Santiago, and Mikkelsen,[12] to speed up the mixing process we introduced a pulsing mechanism by periodically pumping water at a frequency of 1 Hz from the lower left corner of the channel [Fig. 2(a)].

Initially, we stored the background hologram consisting of the fluid mixing chamber with only water present in it using a total laser power of 2.5 mW with an exposure time of 15 s. In the next step, we set $m'=5\cdot10^{-4}$ with total power of 170 μW and introduced a phase shift to the reference to nullify the signal beam. We calibrated the system, whose $\tau \gg 90$ min, to determine its PTF at every pixel of the CCD camera. Then, we let the iso-propanol flow into the channel and switched on the pulsing mechanism to let the liquids mix. Figure 3(a) shows a novelty filtered image and Fig. 3(b) shows its corresponding phase change map calculated using the PTF. The minimum concentration change that could be detected with our system, limited only by the dynamic range of the CCD camera used, is 2.2×10^{-4} g/cm^3 for a channel thickness of 500 μm.

Summarizing our article, we demonstrated, both theoretically and experimentally, a novelty filter based on photorefractive $LiNbO_3$. We showed that, using this novelty filter, time constants of the order of a few hours can be achieved. We also demonstrated the applicability of this novelty filter in the field of fluid dynamics to detect and measure the mixing of two equally transparent fluids without any requirement for coloring or seeding the liquids.

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