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Speckle contrast reduction of laser light using a chiral nematic liquid crystal diffuser

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High coherence in laser light causes spatially distributed interference called speckle. In applications such as holographic projection, this undesirable side effect degrades image clarity. The current methods of speckle reduction, such as a rotating ground-glass diffuser, require additional bulky moving parts. Here, we present an alternative technology based upon a compact, electrohydrodynamic chiral nematic liquid crystal device. A spatially random phase modulation of the incident light is achieved through the electrohydrodynamic instabilities that are induced by an alternating electric field. Using a chiral nematic liquid crystal device that is doped with an ionic compound, we find that the speckle contrast can be reduced by as much as 80%.

Speckle is a well-known phenomenon that occurs when coherent laser light is reflected diffusely from an optically rough surface and imaged by an intensity detector with finite aperture, such as the eye. Any point in the observation plane may be subject to incident light from numerous spatially separated positions on the surface. The incident wavefronts have a fixed phase relationship as a result of their coherence, which causes constructive and destructive interference. A stationary detector will observe a time invariant, high contrast, high spatial frequency speckle pattern superimposed upon the intended image. This phenomenon is often unwanted, particularly when laser sources are used in projection displays since important information in the intended image is often obscured. Furthermore, lasers are a necessary requirement in applications such as holography, which is fundamentally a coherent imaging technique. Consequently, there has been a considerable body of research dedicated to finding new techniques with which to reduce speckle.

In order to quantify the degree of speckle within an image of uniform intensity, the speckle contrast parameter is typically used, which is defined as

\[ C = \frac{\sigma_I}{I} = \sqrt{\frac{\langle I^2 \rangle - \langle I \rangle^2}{I}} , \quad (1) \]

where \( \sigma_I \) is the standard deviation of the intensities, \( I \) is the intensity of an individual pixel, \( \langle ... \rangle \) represents a spatial average over the image. The speckle parameter \( C \) can take any value between 0 and 1, with 1 corresponding to fully developed speckle where intensity fluctuations are of the same order as the average intensity. A perfectly monochromatic laser with linear polarization that is scattered from a depolarizing white field. Using a chiral nematic liquid crystal device that is doped with an ionic compound, we find that the speckle contrast can be reduced by as much as 80%.

Ultimately, the phenomenon of speckle cannot be eliminated per se without destroying the coherence of the beam upon which many applications rely. Instead, the most commonly used methods of speckle reduction take advantage of the finite temporal response and spatial resolution of the detector to reduce observable speckle. The traditional approach to speckle reduction is the time averaging of \( N \) statistically independent speckle patterns, implying that the patterns have to be both non-interfering and uncorrelated. In the ideal case of \( N \) independent patterns, the speckle contrast can be reduced by a factor of \( 1/\sqrt{N} \). Creating independent patterns can be achieved through the diversification of properties such as incident angle, time, frequency, and polarization. One example is to use a rotating ground glass diffuser (RGGD) that creates a time-varying speckle pattern, which when averaged over a sum of \( N \) independent patterns results in the smearing out of the effects of speckle. Other techniques for reducing the speckle contrast parameter include the use of a rotating rectangular light pipe, a vibrating diffractive beam shaper and fast scanning micromirrors. These methods all achieve a reduction in speckle contrast to \( C = 0.04 - 0.075 \), but typically at the cost of additional bulky mechanical parts or expensive components, making them unsuitable or undesirable for applications that require a compact and vibration-free solution such as laser-based pico-projectors, for example.

An alternative approach that utilises the electro-optical properties of certain liquid crystal (LC) phases has recently been reported. For example, Furue et al. achieved 40% speckle reduction by applying an alternating square-wave electric field to a ferroelectric LC, combined with a wedge cell and polarizer. They later reported 25% speckle reduction with an electrically addressed polymer-dispersed nematic LC device. Similarly, Andreev et al. have reported 50% speckle reduction with the application of more complicated waveforms to a ferroelectric LC. The practicality of these devices is limited by their use of a polarizer and complicated waveforms. In addition, the speckle reduction is limited by the response time of the LC mixtures to the applied alternating field and the low number of distinct

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speckle patterns that can be produced. Unfortunately, no values of $C$ were quoted in these reports to allow direct comparison with other techniques. Nevertheless, these devices are a potentially attractive alternative as they do not require bulky, moving parts which is a significant advantage; however, the amount of speckle reduction must be significantly improved in order to make speckle unperceivable.

In this paper, we present an approach based upon volume scattering that uses the turbulent dynamic scattering state of a chiral nematic LC to generate a continuous series of independent speckle patterns that are then observed within a finite integration time. Using the turbulence of a birefringent material instead of switching between set states allows us to achieve greater variation in spatial phase modulation of the incident light. In doing so, the speckle contrast is found to be reduced to $C = 0.22$ for a simple applied square wave E-field of $E = 12 \, \text{V/um}$ and $f = 160 \, \text{Hz}$ at $T = 25 \, \text{°C}$. In this case, the scattering states are caused by electrohydrodynamic instabilities (EHDI) that arise when the chiral nematic LC is subjected to a low frequency applied E-field. The change in the refractive indices over small length scales results in the multiple scattering of light. Here, we demonstrate an analog control of the speckle contrast that appears to show very little in the way of hysteresis upon increasing and decreasing the amplitude of the applied E-field.

The chiral nematic LC mixture (Merck) consisted of the wide temperature range nematic LC, BL006, and the high-twisting power chiral dopant, R5011. This mixture formed a chiral nematic LC phase at room temperature with a right-handed helical structure, which was confirmed using optical polarizing microscopy. (As the Bragg reflection condition does not coincide with the wavelength of our input beam, we would expect the same behavior from a similar, but left-handed chiral nematic LC.) At a temperature of 25 °C, the pitch was found to be 250 nm. To enhance the conductivity properties of the mixture, an ionic species in the form of cetyltrimethylammonium bromide (CTAB) was added to selected cells at a concentration of 0.1 wt. %. To first approximation, the conductivity of an isotropic liquid is determined by the ionic charge, the ionic concentration, and the mobility. By dispersing CTAB into the host mixture, we are effectively increasing both the ionic charge and the concentration, which serves to reduce the electric field amplitude required for EHDI. The glass cells used in this study consisted of two indium tin oxide-coated glass substrates with anti-parallel rubbed polyimide alignment layers. In all cases, the cell thickness was defined by the 20 µm diameter spacer beads that were dispersed throughout the cell. After the mixtures had been prepared, each cell was filled by capillary action at a temperature of $T = 80 \, \text{°C}$, before allowing them to cool to room temperature.

To measure the speckle contrast, $C$, a Helium-Neon (He-Ne) LASER (JDS Uniphase 1122P, $\lambda = 633 \, \text{nm}$, linearly polarized) was used as the coherent light source, as shown in a diagram of the experimental apparatus in Fig. 1. The effect of different wavelengths is not investigated in this report, but we expect a limited change in the performance of our device, as the birefringence of the LC does not change significantly across the visible wavelength regime. The microscope objective (Olympus UPLFLN10XP, strain-free for polarization independence) collects light transmitted through the cell and the charge-coupled device (CCD) camera operating in the linear regime then captures an image of the resulting spot that is projected onto the white screen. In the captured image, a selection of $200 \times 200$ pixels from the center of the beam are then analyzed to calculate $C$. A combination of signal generator and amplifier was used to apply a square wave ac electric field across the cell electrodes. A frequency of $f = 160 \, \text{Hz}$ was used in all experiments reported here. The CCD and signal generator were both computer controlled to ensure accurate timing of the electric field condition and image acquisition.

A range of neutral density filters (NDFs) were used to maintain a near-constant mean intensity in each image. Histograms for every image recorded were checked to ensure no over- or under-exposure of the light occurred. The hot-stage was used to ensure a constant operating temperature of $T = 25 \, \text{°C}$ for the LC cell throughout each measurement reported here. Normal white printing paper was used as a projection screen, and the CCD was placed at a distance of 160 mm from the screen at an angle of 25°.

Finally, a monochrome CCD was selected to maximize resolution as the Bayer filter layout used in color CCDs renders up to 75% of the sensors obsolete when imaging monochromatic light.

It is important to note that speckle measurements vary considerably with different experimental set-ups, making it somewhat difficult to compare directly the reported speckle contrast values. Nevertheless, there are a number of factors that should always be taken into consideration. These include (1) ensuring ambient lighting is less than the least significant bit of the dynamic range; (2) a minimal camera bit-depth of 6; (3) a ratio of pixel area to minimum speckle grain area of at least 3.5; and (4) a ratio of maximum speckle intensity to camera saturation of 0.3–1.0. All of these conditions were satisfied in our experimental set-up.

With applications such as imaging and holographic projection in mind, conditions were chosen to observe speckle in a way that closely matches human perception. Therefore, a 3.2 mm iris in front of the CCD sensor was inserted to match the average pupil size under similar lighting conditions. The integration time of the camera was set to 50 ms (although a range of exposure times are also reported in Fig. 4 for completeness), which corresponds to the temporal integration time of the eye. The focusing lens used with the camera (f = 33 mm) was selected to spatially sample incoming light with a camera pixel density equal to the
density of cones in the eye, which corresponds to a pixel-speckle ratio of 3.5 as required above.

Fig. 2 presents the results of the speckle contrast, C, as a function of the applied electric field amplitude for cells consisting of the chiral nematic LC mixture with and without CTAB. For the range of field amplitudes considered here, no dynamic scattering and consequently no reduction in C were observed using the cell without CTAB, as shown in Fig. 2. The absence of a dynamic scattering state was also confirmed by observing the sample on a polarizing optical microscope. In contrast, for the LC device with the addition of the ionic dopant, CTAB, a dynamic scattering state was observed above an electric field threshold of $E = 4 \, \text{V/\mu m}$. A further increase in the E-field strength then resulted in an increase in the turbulence of the scattering state, which in turn served to reduce the magnitude of C to a value of 0.22 for $E = 12 \, \text{V/\mu m}$. For comparison, the speckle contrast parameter for the He-Ne alone was found to be $0.611 \pm 0.008$, close to the theoretical value of $1/\sqrt{2}$ reported above and is shown as the straight solid line in Fig. 2. As a result, we calculate the speckle reduction to be 64% in this case.

For this device, we believe that the dynamic scattering state is governed by a Carr-Helfrich-type mechanism, where EHDl arises as a result of a spatial distribution in the charge, which in turn is driven by an anisotropy in the conductivity of the LC mixture. Without the addition of the CTAB, the voltage range considered in this study is too small to induce a sufficient spatial distribution of the charge and so no scattering is observed. To some extent, this is consistent with the very early work of Heilmeier and co-workers who observed a scattering state using low frequency ac electric fields, but with very large amplitudes. However, by adding the CTAB compound, the ionic concentration and mobility increases and therefore the conductivities become large enough to reduce the driving voltage required to trigger dynamic scattering. Therefore, at relatively low ac frequencies (i.e., $f = 160 \, \text{Hz}$) and using moderately low electric field amplitudes ($E = 4 \, \text{V/\mu m}$), the flow becomes sufficiently turbulent so that the local director becomes randomly aligned resulting in the multiple scattering of light. Consequently, this then applies a time varying, spatially random phase delay to any light transmitted through the device.

In order to benchmark our measurements against existing, well-known technologies, Fig. 2 also shows the speckle contrast ratio when an RGGD (tested at 40–200 rpm) was placed in the diffuser plane (see Fig. 1). We found that, in this case, $C = 0.04$ and is in good agreement with previously published results for similar devices. Evidently, our LC device does not quite reach the low value obtained by the RGGD, but it does have the benefit of being more compact and free of mechanically rotating parts. Furthermore, by altering the E-field amplitude, it is possible to control the magnitude of C should an application require a moderate amount of speckle.

Fig. 3(a) shows microscope images of the CTAB-doped chiral nematic LC cell taken between uncrossed polarizers. At $E = 0 \, \text{V/\mu m}$, there is no observable turbulence in the cell, but above $E = 4 \, \text{V/\mu m}$ EHDl are observed, which increases with the electric field. This results in a marked drop in transmission to almost 13% at $E = 12 \, \text{V/\mu m}$. (In comparison, the RGGD was found to have a transmission of 33%.) Three 20 \, \mu m spacer beads are also present in each image. Fig. 3(b) shows the $200 \times 200$ pixel, monochrome images of the speckle pattern that were recorded for three different magnitudes of the applied electric field. The mean intensity of each image has been normalized in order to allow for a direct comparison. A plot of pixel intensities through the central line of the image (shown in red) is provided in Fig. 3(c), where it can be seen that the contrast between the light and dark regions in the granular pattern has been significantly reduced.

The speckle contrast observed for the CTAB-doped cell was also recorded as a function of camera exposure time, as
shown in Fig. 4. It is noted that increasing exposure time serves to further reduce speckle contrast as more independent speckle patterns are averaged during the integration time. These results suggest that further speckle reduction could be achieved through a faster response of the dynamic scattering process.

We tested for hysteresis effects by applying an E-field that increased and decreased in amplitude for 5 consecutive cycles, with the electric field being held constant for 2 s at each level. Specifically, the electric field was increased from $E = 0 \text{ V/µm}$ to $E = 12 \text{ V/µm}$ and subsequently decreased back to $E = 0 \text{ V/µm}$ in increments of 0.1 V/µm. We compared the measured speckle contrast at matching electric fields for each cycle and found a maximum difference of <2%, as shown in Fig. 5. Clearly, there is little in the way of hysteresis throughout the cycles.

In addition, we have also carried out a study of the speckle contrast dependency on frequency of the applied electric field, where it was found that $C$ varies very little over a range of $f = 150–450 \text{ Hz}$, irrespective of E-field amplitude. A speckle contrast as low as $C = 0.214$ was achieved with $E = 12 \text{ V/µm}$ and $f = 275 \text{ Hz}$. With a sufficiently high frequency (approximately >20 kHz at $E = 12 \text{ V/µm}, T = 25 ^\circ \text{C}$), EHDI disappears at the transition from the “conductive” to the “dielectric” regime. At frequencies below 150 Hz, speckle contrast is again increased. This is believed to be due to the ion transport time being shorter than the time period between the reversals in the polarity of the E-field, leading to a build-up of ions at the substrates.

Both the repeatability and stability of a device are important parameters and, towards this end, we have examined how the speckle contrast varied over a period of several hours. In particular, the device was tested by applying a constant E-field amplitude to a CTAB-doped chiral nematic LC cell for two-hour periods and a measurement of $C$ was then taken every 1 s. We report that the speckle contrast was constant ($\pm 1\%$ from the mean) over 2 h for electric field amplitudes up to $E = 12 \text{ V/µm}$, as shown in Fig. 6. Cells were tested above $E = 12 \text{ V/µm}$, but the results were found to be inconsistent. Incidentally, a speckle contrast as low as $C = 0.12$ (speckle reduction of over 80%) was recorded, but the cells appeared to degrade when subjected to larger E-field amplitudes for extended periods of time.

In summary, we have demonstrated that a chiral nematic LC device doped with an ionic compound can be used to reduce the speckle contrast. The application of a simple, low frequency (150–450 Hz) square-wave electric field causes microscopic turbulence in the LC device above a threshold of $E = 4 \text{ V/µm}$. This turbulence, coupled with the birefringent nature of the LC, applies a spatially random phase modulation to light that is transmitted through the device. The results show that the reduction in speckle is constant over prolonged periods of time and is free from hysteresis when cycling through the E-field amplitudes. Subsequently, this compact device shows great potential in applications requiring speckle reduction. Moreover, we anticipate that further reduction in the speckle contrast can be achieved through an optimization of the macroscopic properties of the LC in the form of the birefringence, the pitch as well as the conductive and dielectric anisotropies. Further studies are currently under way to better understand the correlation between these physical properties and the magnitude of the speckle reduction that is observed so that optimized mixtures can be prepared. It is also expected that the speckle contrast can be reduced further through the addition of high refractive index
scattering particulates such as titanium dioxide nanoparticles.

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