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Major Goals: Microphotonic devices that consist of micron-sized preformed cavities filled with an active optical material would be useful for important DoD applications. At the forefront of these applications is a thermal imager. In this device a liquid crystal material needs to be aligned along a specified direction in the cavity by an "alignment layer". Previous work has shown that anchoring energies of this order are possible with a class of alignment layer materials based on azo dyes. But azo dye alignment layers have been shown to be unstable, and very little is has been reported concerning the underling physics related to this problem.
This project is to research and improve the properties of azo-dye photoalignment layers for liquid crystal based micro-photonic devices. Key to this understanding will be knowledge about how the azodye materials organize, align and bond to a surface.
An approach to stabilize azodye alignment layers is to use a UV polymerizable liquid crystal (RM) to stabilize the alignment provided by the azodye alignment layer. Therefore, one aspect of the problem to be studied under this project, is to provide greater understanding of the physics of the RM stabilization approach.
Major Goals:
– To understand how to control the strength and stability of azodye photoalignment
– To provide a liquid crystal process and optical system design to maximize signal and minimize noise.
–
The objectives of this project were first set in 2017, but some were modified as the project progressed. Replaced objectives are enclosed in brackets [ ] , and new objectives are underlined. Motivation for the modifications are in italic
Objectives related to the first goal :to understand and control azo-dye alignment layers, are aimed at these questions:
A. How is the order of the dye layer correlated with the anchoring effect of the liquid crystal. And how does its effect compare with our goal and other alignment layers.
• What is the effect of external optical excitation on the order parameter of the dye layer?
• Task 1a: Measure and analyze the effect of exposure wavelength, dose, and intensity on the order parameter of the dye molecules
• What is the effect of the azo dye layer on the liquid crystal?
• Task 2a: Measure the anchoring energy
• Task 2b: Compare azodye alignment with other types of alignment layers.
B. What is the relative importance of inter dye molecule interactions and dye-surface interactions and how to control those interactions?
• The current literature analysis of the ability of dye to photo-orient with low intensity light, emphasizes the aggregation of dye molecules.

- But the literature concerning dye adhesion, emphasizes the surface interaction
- Is dye aggregation or liquid crystalline properties of the dye relevant to photo induced dye order?
- Task 1b: Measure and analyze effect of solvent and dye concentration in the solvent.
- [What is the importance of the surface interaction?
- Task 1d: Measure and analyze the effect of surface properties on the order of azo dye layers.
- Task 1e: Measure and analyze the effect of molecular structure of dye molecules]

It was discovered in the course of the project that if the process related to the deposition of the azodye alignment layer was optimized, that the particular material chosen originally (Brilliant Yellow) worked very well. So more time was spent on understanding the processing of the Brilliant yellow to provide excellent results. And it was then seen that looking in more detail into the interaction of BY with a surface as outlined in the original tasks 1d and 1e is not required.
Related to the above, we have found that the reactive messogen properites are more important than originally planned, so with the decrease in activity in tasks 1d and 1e, we were able to spend more time on task 1c, as reported in the “accomplishments” section.
C. What affects the ordering and effectiveness of the RM stabilization layer?
- We expect that the polymerization of the RM layer will cause the order of the RM to be lower than the Azodye.
- We will want to consider to increase the order of the RM layer by

Thinner RM layers ,Decreasing the cure temperature, and Controlling the polymerization rate
- Task 1c: Develop process for reactive mesogen stabilized azo-dye alignment layer and characterize effect on anchoring energy and lifetime.
-

Objectives related to the second goal : to provide the process and optical system design to maximize signal to noise, are aimed at these questions:
A. Consider various approaches to measuring the order-parameter vs temperature of a liquid crystal to maximize the signal.
- The birefringence of the LC is dependent on the order parameter, So measuring the birefringence of the LC is one way to detect a temperature change. This could be accomplished by measuring the change in the polarization state of light, the change in transmission through an etalon, the change in the elastic constants

A. Task 4a: Design of measurement of birefringence from the polarization state of light
B. Task 4b: Design of measurement of the LC birefringence from the transmission of light through a resonate cavity
C. Task 4c: Design of measurement of the change in LC elastic constants .
D. Task 4d: Provide more detail on above through numerical modeling where needed.

B. Analytical and Numerical modeling of the director fluctuations and the light propagation in a cavity to understand the noise
- The director fluctuations, causing noise, are expected to be affected by the cavity size. They can be modeled using continuum theory, and the light propagation through a LC where the director variations have a short length scale is difficult to calculate analytically, we will use a the FDTD numerical approach (a direct solve of maxwell’s eqns on a grid with sub-wavelength spacing)

A. [Task 3a: Analytical modeling of director fluctuations in a micro cavity]
Provide analytical modeling of the effect of confinement of the 1rst order nature of the isotropic to nematic phase transition.
B. [Task 3b: Analytical modeling of light propagation with results from previous task.]
Experimental consideration of the effect of a polymer fiber network on the 1rst order nature of the isotropic to nematic phase transition, and on the effect of director fluctuations.

C. [Task 3c: Numerical modeling of director fluctuations in a micro cavity]
D. [Task 3d: Numerical modeling of light propagation with results from previous task.]

The objective related to tasks 3a – 3d, was to provide insight into approaches to reduce the noise related to director fluctuations in micro-cavity cells. However, our initial results using a fiber network of aligned polymer material, not only showed that the noise from director fluctuations could be reduced, but also the 1rst order nematic to isotropic transition could be made to look more “2nd order like”. So the work with forming a fiber network not only decreased the noise, but also increased the signal. For this reason, the tasks to find an approach to reduce the noise are not needed (as we have found one) , and more time should be spend on understanding and the effect of a fiber network to reduce noise , and the optimization of the process for the thermal imager application.

C. Optical methods to maximize the signal to noise
• Want optical system that can provide a large change in signal for a small change in birefringence, but also, is insensitive to director fluctuations.
A. Task 5a: Consider best optical set up to maximize S/N using fixed retarders
B. Task 5b: Consider time and spatial averaging of noise in a pixel
C. Task 5c: Consider simultaneous measurements with multiple wavelengths of light

Accomplishments: The major goals and tasks related to them were all completed successfully. We greatly enjoyed our collaboration with the Lincoln Laboratory that resulted in 11 papers and 1 patent. We hope this will be a continuing collaboration related to the thermal imager application. Specifics of the accomplishments are given below by task:

Related to tasks 1a and 1b:We have isolated and quantified the major factors related to the processing of a surface alignment layer (referred to as 'BY') on the ability to photo-align that layer. We have found that the major factor is humidity present at different steps of the process. Specifically, dramatic effects of the humidity during the spin-coating of the BY/Solvent and the solvent removal was quantified. We have found that small differences (10%) in the relative humidity can have drastic effects on the ability to subsequently photo-align the surface layer. Also, we have isolated the cause of this phenomenon to be related to the small amounts of water from the air condensing on the BY material and resulting aggregation of the material to an extent that makes it difficult to re-align.
As we considered that the effect of humidity BEFORE exposure was here causing the BY to have a greater degree of aggregation and therefor making the film more stable and more difficult to photoalign, we also considered to apply humidity AFTER photoexposure . We found that in this case the order of the BY molecules could be significantly increased, and that the order is amazingly high.
Our work in this area has led to greater control of the production of high quality alignment layers, and also has provided data that will be useful in the development of theories of mechanism of photo alignment.
• For more details, please see the interim reports and the two papers that resulted from this work that are included in the products section :
• "The effect of humidity and surface type on the photo-alignability of the azo-dye brilliant yellow",
• "Optimization of azo-dye and infused RM process parameters for stable photo-patterned liquid crystal alignment ."
Results related to task 1c:A key objective to obtain to obtain the major goals of this project is related to the stabilization of the an azo-dye based alignment layer.

We found that when the reactive mesogen (RM) layer was formed and polymerized on the azodye alignment layer, that the alignment of the liquid crystal layer was then primary controlled by the RM layer.. This increased our interest in the structure of the RM layer toward improving the properties of the thermal imager. The work first focused on the use of typical RMs and liquid crystals, and is fully reported in the published paper "Process for a Reactive Monomer Alignment Layer for Liquid Crystals Formed on an Azodye Sublayer"

We have shown that the absorption of the BY layer can be eliminated after the alignment layer is RM stabilized. In our approach, the BY layer is deposited and used to align the RM layer over it , that is then polymerized. After the RM layer is polymerized, the BY is "Bleached" by applying a high intensity of light, removing its ability to absorb light further, and to guarantee the long term stability of the RM alignment layer

The impact of this work is very significant to the development of new types of liquid crystal photonic devices in general, and thermal imagers in particular, as the new method ensures the stability of this very versatile alignment layer. The impact on the wider liquid crystal display community was recognized the acceptance of our work as an oral presentation at the major international information display conference.

Please see the interim reports for more details on this work.
• A paper resulted from this work that is included in the products section: "Stable azodye photo-alignment layer for liquid crystal devices achieved by "turning off" dye photosensitivity".

Work related to Tasks 2a and 2b These two preparational tasks were completed and reported on in the first interim progress report.
Work related to Tasks 3a -3d The thermal imager's operating principle is to optically detect the effect of the change in of the molecular order parameter with temperature. If the 1st order transition could be made to be more 2nd order like by applying confinement effects, we could make a more sensitive thermal imager.
It was demonstrated that for the right combination of surface order and average domain size, that up to a 3.3x

increase in sensitivity could be expected for the Polymer Network Liquid Crystal (PNLC) sample relative to the pure LC. PNLC samples were then fabricated with varying concentration of RM 257 in E7. The temperature dependence of the retardation in the samples was measured. When both the experimental data and calculations were considered the PNLC sample provided 2x the sensitivity of the pure LC sample.

Also, in doing the measurements on these materials, The MIT/LL scientist observed a noticeable decrease in the noise due to director fluctuations. As our final goal is to increase the signal /noise ratio, this finding makes the use of a polymer fiber network in the LC cell even more interesting.
Please see the interim project reports for more details on this work,
• A paper resulting from this work is included in the products section: "Enhancing the Thermo-Optical Response of Nematic Liquid Crystal with a Polymer Network"
Results related to task 4a: Task 4a, " Design of measurement of birefringence from the polarization state of light", has the objective of considering improvements to the current measurement technique to measure the polarization state of light in the thermal imager application. This year we considered the use of a field sequential system where the intensity of light is recorded for to measurement system configurations. We have shown that a factor of 2 increase in sensitivity can result from this technique.

Results related to tasks 4b, 4d and 5c. In order to increase the intensity of the thermal imager device , we considered a design based on the Fabry-Perot interferometer (Etalon) which is known for its sharp spectral peaks. Preliminary results looked encouraging, so detailed numerical calculations for this device were made utilizing the Berreman 4x4 method.

Our results have shown that when a single wavelength measurement is made that a 10x increase in the sensitivity over the senarmont-type device. When a differential measurement is considered using two wavelengths, an even larger increase is demonstrated. We note here that the thickness of the pixel for the Etalon device is also half that of the senarmont, which improves the response time of the device.

This study therefor shows a potential pathway to a very sensitive thermal imager. However, this sensitivity requires measurement with narrow bandwidth light that will have issues with speckle, and be quite difficult to implement in general.

Please see the interim reports for more details.
• A paper with more details on this work is included in the projects section : " Design of a Sensitive Uncooled Thermal Imager Based on a Liquid Crystal Fabry-Perot Interferometer";

Results related to task 4c In task 4c, we consider to apply that fact that not only the birefringence is a function of temperature, but the elastic constants and dielectric constants are as well. We found that while the temperature dependence of the elastic constants was, in fact, useful in improving the device sensitivity, that with this measurement technique, the temperature dependence of the dielectric constants, working against the effect of the temperature dependence of the elastic constants, effectively cancelled this advantage.

Training Opportunities: This project has resulted in students working directly on the goals of this project to be trained in device modeling, materials design, and device fabrication techniques that are valuable for the advancement of new types of photonic devices based on liquid crystals in general, and for the development of thermal imagers in particular.
Also, students working in related areas, have been able to learn from the advancements of this project and make advancements in the area of alignment layers for displays, and electronic lenses. The results of that work is included in the publications listed in the next section, and included in the "products" section.

PhDs that are directly related to the collaboration with MIT/LL were:
- Valerie Finnemeyer PhD, 2016 to MIT/LL
- Colin McGinty, PhD ,2018 to NRL
- Junren Wang PhD, to Facebook Reality Labs

PhDs that greatly benefited from the results of this project are:
- Gun Gao PhD 2017, to Beam Corporation
- Afsoon Jamali 2018, to Facebook Reality Labs
- Comrun Yousefzadeh , nearing completion

Results Dissemination: This project has resulted useful information related to the use of photoalignment layers for photonic devices. The area of focus has been for thermal imaging applications, but the area of displays and electronic lenses has also benefited.
Related to basic information related to stable photoalignment that is applicable to thermal imagers, there were six papers published with authors from Lincoln Laboratory that were directly related to the project goals:

- "Enhancing the Thermo-Optical Response of Nematic Liquid Crystal with a Polymer Network"; Colin McGinty, Robert Reich, Harry Clark, and Philip Bos; Accepted for publication in the Journal of Applied Physics

- "Effects of humidity and surface on photoalignment of brilliant yellow"; J.Wang, C. McGinty, J.West, D.Bryant, V.Finnemeyer, R.Reich, S.Berry, H.Clark, O.Yaroshchuk, P.Bos; Liquid Crystals ,5., 2016; DOI: 10.1080 /02678292.2016.1247479

- "Scalable Fabrication Process for Liquid Crystal-Based Uncooled Thermal Imagers"; Berry, S; Bozler, CO; Reich, RK; Clark, HR; Bos, P; Finnemeyer, V; McGinty, C; JOURNAL OF MICROELECTROMECHANICAL SYSTEMS; JUN PY 2016 VL 25 IS 3 BP 479 EP 488

- "Stable azodye photo-alignment layer for liquid crystal devices achieved by "turning off" dye photosensitivity". ; C.McGinty; V.Finnemeyer; R.Reich, H.Clark, S,Berry, P.Bos; Journal of Applied Physics, 122, 205301 (2017)

- "Process for a Reactive Monomer Alignment Layer for Liquid Crystals Formed on an Azodye Sublayer"; J. Wang, C. McGinty, R. Reich, V. Finnemeyer, H. Clark, S Berry, P.Bos; Materials 2018, 11, 1195

- " Design of a Sensitive Uncooled Thermal Imager Based on a Liquid Crystal Fabry-Perot Interferometer"; C. McGinty, R.Reich, H. Clark, V. Finnemeyer, S.Berry, and P. Bos; Applied Optics 57, p 8264 (2018)

And there were also five papers that resulted from the basic science work accomplished under this project :

- "High-efficiency large-angle Pancharatnam phase deflector based on dual-twist design"
Kun Gao, Colin McGinty, Harold Payson, Shaun Berry, Joseph Vornehm, Valerie Finnemeyer, Brian Roberts , and Philip Bos OPTICS EXPRESS 25,no6, 20 Mar 2017 p6283

- "Achromatic Limits of Pancharatnam Phase lenses" ; C.Yousefzahdeh, A.Jamaili, C.McGinty, P.Bos. ; Applied Optics, 57, no. 7 (2018)

- "A thin film liquid crystal based compensator for the chromatic aberration of optical lenses" ; A. Jamali, P. Bos; Molecular Crystals and Liquid Crystals, 657:1, 46-50 (2017)

- "LC lens systems to solve accommodation/convergence conflict in 3D and Virtual Reality displays" ; A. Jamali, C.Yousefzahdeh, C. McGinty, D.Bryant, P.Bos; (under review)

- A non-mechanical zoom lens fabricated from liquid crystal reactive mesogens; K Gao, A. Bhowmik, C.McGinty, P.Bos; Proc of SPIE volume 9940; Doi: 10.1117/12.2237324

There have also been conference presentations:

- "Enhancing the Thermo-Optical Response of Nematic Liquid Crystals with a Polymer Network"; C. McGinty, R. Reich, H. Clark, P. Bos; Optics of Liquid Crystals 2019; Sept 2, 2019; Quebec, Canada (Invited talk)

• “Simple method to provide exceptionally well stabilized azo-dye photoalignment layers for cavities” C. McGinty, V.Finnemeyer, P.Bos, J.West; presented at the 2016 International Liquid Crystal Conference

? An Invited talk at the Gordon Conference on Liquid Crystals (June 18-23, University of New England, Biddeford, ME)

? A oral presentation at the International Conference of the Society for Information Display : “Strong Effect of Azodye Layer Thickness on RM Stabilized Photoalignment.” C.McGinty, V, Finnemeyer, R.Reich, H.Clark, S Berry, P.Bos; ; Proceedings of the 2017 International Symposium of the Society for Information Display; LosAngeles , May 21-26 , 2017 ; paper 41.1

? The thermal imager group at Lincoln Laboratory did a collaborative paper with us: “Liquid Crystal Uncooled Thermal Imager Development” Clark, H. R., Jr.; Bozler, C. O.; Berry, S. R.; et al Edited by: LeVan, PD; Sood, AK; Wijewarnasuriya, P; et al. Conference: Conference on Infrared Sensors, Devices, and Applications VI Location: San Diego, CA Date: AUG 31-SEP 01, 2016
Sponsor(s): SPIE INFRARED SENSORS, DEVICES, AND APPLICATIONS VI Book Series: Proceedings of SPIE Volume: 9974 Article Number: UNSP 99740E Published: 2016

• “A continuous variable lens system to address the accommodation problem in VR and 3D displays”; A. Jamali; oral presentation 3Tu2G.5; OSA Imaging and Applied Optics Congress; Orlando, Florida, 25-28 June 2018

• “Highly Versatile and Stable Photoalignment Process for AMLCDs”; C. McGinty, J.Wang, V. Finnemeyer, R. Reich, H.Clark, S. Berry, P. Bos; oral presentation 29-3 , International Symposium of the Society for Information Display, Los Angeles Convention Center, Los Angeles, CA, May 22-25, 2018

• “A continuous variable lens system to address the accommodation problem in VR and 3D displays”; A. Jamali, C. Yousefzahdeh, C. McGinty, D.Bryant, P. Bos; P-148, International Symposium of the Society for Information Display, Los Angeles Convention Center, Los Angeles, CA, May 22-25, 2018

• “Large Aperture Liquid Crystal based lenses and wavefront control devices” Philip Bos, Kun Gao, Colin McGinty , Harold Payson, Shaun Berry,Joseph Vornehm, Valerie Finnemeyer, Brian Roberts, Liwei Li, HsienHui Cheng, Doug Bryant, Afsoon Jamali ; Invited talk, international conference Optics of Liquid Crystals 2017, Guaruja, San Paulo, BRAZIL, 24 -29 September 2017

Also, we wrote a patent disclosure that has been filed with the US patent office:

• Photostable Alignment Layer via Bleaching ; C. McGinty. P.Bos, V.Finnemeyer, R.Reich, C.Clark, S.Berry

Honors and Awards: I was invited to provide talks at the: Optics of Liquid Crystals Conference 2017, 24-29 September, in Guaruja , Brazil; at the Optics of Liquid Crystals Conference 2019, Quebec, Canada, and at the: 7th International Symposium on Liquid Crystal Photonics and Workshop on Liquid Crystals for Sustainable Development, April 13-16, 2018, Nanjing, China.

Protocol Activity Status:

Technology Transfer: Collaboration with Lincoln Laboratory on Development of Uncooled Thermal Imager

All of the work presented in this report has been done collaboratively with MIT Lincoln Laboratory (LL). In particular, we have collaborated with Robert Reich, Harry Clark, and Valerie Finnemeyer from group 87 on the thermal imager project. This collaboration takes place in the form of bi-weekly conference calls during which the main results from the previous weeks are discussed as well as the plans for the coming weeks. As part of these conference calls reports, usually in the form of slides, are sent to the group at LL for discussion during the conference call. Each report that we have sent over the past year has been included in the attached .zip.

The main exchange of materials that takes place between LL and Kent State University (KSU) involves micro cavity samples which are fabricated at LL. These samples which are arrays of 1-2 um thick and 20 um wide micro cavities are the structures which serve as the pixels in the uncooled liquid crystal thermal imager. The main goal of this exchange of materials is developing processes at KSU that will be beneficial to the development of the thermal imager. One example of this work is the development of a process to 'cap' the cavity samples after filling to prevent LC from escaping. We explored the possibility of using the RM already present in the sample to cap the cavities. In addition we did work on the use of SiO2 deposition to prevent LC from escaping which showed promising results. Some detials on these experiments can be seen in 'LCTP 5-12-2016' in the attached .zip. In addition, as reported in the planning section, much of the work planned for the coming year revolves around optimizing the process for producing RM stabilized photoalignment films in the micro-cavities. We have already begun some of the preliminary work on this buy examining the effect of RM concentration on the photostability of cavity samples. Some detials on this work can be seen in 'LCTP 8-2-2017' in the .zip.

In addition to processing, we have also used cavity samples received from LL to look at the effect of confinement on the nematic-isotropic phase transition. An LC which is sufficiently confined will have a second-order phase transititon; if the phase transition is second order then the temperature sensitivity of the order parameter in the 'transition region' will be quite high and increase the sensitivity of the thermal imager. Details on the confinement work can be seen in 'LCTP 4-2-2017'. We predicted theoretically that the LC would need to be confined to a ~20nm thickness in order for the phase transition to become second order. We tried to verify this experimentally not only by making thin cells but also by looking at the phase transition in cavity samples. This work can be seen in 'LCTP 3-2-2017'. Overall, the goal of the transfer of cavity samples to KSU has been to return processes back to LL which will be useful for the fabrication as well as obtaining an increase in sensitivity of the thermal imager.

Collaboration with Lincoln Laboratory for the Fabrication of Pancharatnam Phase Devices

In addition to the work done with group 87 at Lincoln Laboratory, we also collaborated with group 38 and in particular Joe Vornehm to help fabricate pancharatnam phase devices (PPDs). PPDs involve a spiraling director pattern in the plane of the substrate and are typically used for large-angle high-efficiency beam steering. Because of the complicated nature of the alignment pattern, PPDs can only be made by utilizing photoalignment materials. After the film is aligned, successive layers of RM are spin-coated and polymerized until the retardation of the device is a half wave for the design wavelength. The main goal of this collaboration was to demonstrate a high-efficiency beam steering device capable of steering to ~25°. We considred two approaches to accomplishing this. The first utilized three deflectors with steering angles of 3, 6, and 12 degrees respectively to reach 20°. The second involves making a single 25° deflector.

In September of 2016, LL sent substrates with BY films deposited on them which were exposed to give steering angles of 6 and 12°. However, when the samples arrived at KSU, the environmental conditions during transportation had damaged the alignment film. For this reason fabrication of 3,6, and 12° deflectors were exposed and coated with a few layers of RM at KSU and showed positive results. Detials on these samples can be seen in 'PPD Samples Recieved from LL'.

After relaying the results described above to LL, more samples for 6 and 12° were exposed at LL and sent to KSU. Two samples for each steering angle were sent and made it to KSU without damage. One sample for each steering angle was coated with RM until it was a half wave retarder for 1064 nm light – these samples were made as a proof of concept for the application LL was pursuing. Additionally, one sample was coated to a half wave for 543 nm light – these samples were made so that a demonstration of the device capabilities could be made for visible light. In addition to the samples exposed at LL, two 3° deflectors were made completely in house at KSU. These samples were all sent to LL for characterization and use in demonstration on 10-6-2016. Details on these samples can be seen in '10-6-2016 PPD Samples to Lincoln'.

Once the samples described above were sent to LL, their efficiency for 1064 nm light was evaluated (since KSU does not have IR laser) and was found to be >90%. With this knowledge, a 25 degree deflector at 1064 nm was produced completely in house at KSU and sent to LL on 4-7-2017. This sample was used to provide data for a presentation given at the 2017 AIAA Defense and Security Forum. Details on this sample can be seen in Details on this device can be seen in 'PPD Device(4-7-2017)'.

One of the primary reasons for this collaboration has been that LL has had a difficulty with the RM processing steps in their facility. We have not only helped with this problem by performing the RM processing at KSU but have also tried to troubleshoot the fabrication process and carefully note procesing steps that we use. One example of this can be seen in 'PPD Intensity' which shows that a large exposure dose for the BY film can damage the performance of the final device. Besides this document, lines of communication between Joe and KSU are always open and we are always trying to communicate helpful results.

Stabilized Photoalignment in Microcavities

After establishing a reliable method for obtaining a stable surface-localized reactive mesogen alignment layer through phase separation, attention was turned towards achieving a similar result in microcavity structures. Samples for this purpose were provided to the LCI by Dr. Robert Reich and Harry Clark from MIT Lincoln Laboratory; the thickness of the microcavity samples provided was 1 ?m. Work on this portion of the project can be seen in the reports sent to MIT-LL between 8-17-2017 and 11-16-2017. From previous work done with the 5 ?m thick bulk samples we found that the necessary concentration of RM 257 in the LC host, E7, was 1.5% by weight. However, in these thinner cells it was anticipated that a higher concentration of RM would be needed. We then investigated utilizing larger concentrations of RM 257. Concentrations of 3,6,9, and 12% RM 257 in E7 were tested and only 12% exhibited stable photoalignment in the cavities. This experiment was then repeated for a larger batch of samples and the results were verified.
Also, related to technology transfer was a talk given at LL: “Very large angle optical beam deflectors using Pancharatnam” Phase, Philip Bos, Kun Gao, Colin McGinty , Harold Payson, Shaun Berry,Joseph Vornehm, Valerie Finnemeyer, Brian Roberts, Liwei Li, HsienHui Cheng, Doug Bryant, Afsoon Jamali; MIT Lincoln Laboratory, 18 July 2

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Participant: Philip Bos
Person Months Worked: 5.00 **Funding Support:**
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Participant Type: Graduate Student (research assistant)
Participant: Junren Wang
Person Months Worked: 7.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Comrun Yousefzadeh
Person Months Worked: 5.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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ARTICLES:

Publication Type: Journal Article   Peer Reviewed: Y   **Publication Status:** 1-Published
Journal: Applied Optics
Publication Identifier Type: Other   Publication Identifier: 11111
Volume: 57   Issue: na   First Page #: 8264
Date Submitted: 8/21/18 12:00AM   Date Published: 12/31/18 3:00PM
Publication Location:
Article Title: Design of a Sensitive Uncooled Thermal Imager Based on a Liquid Crystal Fabry-Perot Interferometer
Authors: C. McGinty, R.Reich, H. Clark, V. Finnemeyer, S.Berry, and P. Bos
Keywords: liquid crystals, thermal imager, alignment layer
Abstract: Microbolometers are the dominant technology for uncooled thermal imaging, however, devices based on a direct retardation measurement of a liquid crystal (LC) transducer pixel have been shown to have comparable sensitivity. In this paper, an approach for increasing LC transducer sensitivity utilizing an etalon structure is considered. A detailed design for an LC resonant cavity between dielectric mirrors is proposed and the performance is evaluated numerically. The measured quantity is the transmission of a visible wavelength through the etalon which requires no thermal contact with the IR sensor. Numerical and analytical calculations which consider a 470 nm-thick LC pixel demonstrate that the change in transmitted intensity with temperature is 26 times greater in the device based on a resonant structure than in a device based on a direct retardation measurement.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article   Peer Reviewed: Y   **Publication Status:** 1-Published
Journal: JOURNAL OF MICROELECTROMECHANICAL SYSTEMS
Publication Identifier Type: Other   Publication Identifier: 1111
Volume: 25   Issue: 3   First Page #: 479
Date Submitted: 12/30/19 12:00AM   Date Published: 6/30/16 4:00AM
Publication Location:
Article Title: Scalable Fabrication Process for Liquid Crystal-Based Uncooled Thermal Imagers
Authors: Shawn Berry,Carl Bozler, Robert Reich, Harry Clark, Philip Bos, Valerie Finnemeyer, Colin McGinty,
Keywords: Thermal Imager
Abstract: —A novel sensor is being developed for a new uncooled imager technology that is scalable to large formats (tens of megapixels), which is greater than what is achieved by commercial microbolometer arrays. In this novel sensor, a liquid-crystal transducer is used to change a long-wavelength infrared scene into a visible image that can be detected using a conventional visible imager. This approach has the potential for making a more flexible thermal sensor that can be optimized for a variety of applications. In this paper, we describe the microfabrication processes required to create an array of sealed thermally isolated micro-cavities filled with liquid crystals to be used for an uncooled thermal imager. Experimental results from the fabricated arrays will also be discussed.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

CONFERENCE PAPERS:

Publication Type: Conference Paper or Presentation   **Publication Status:** 0-Other
Conference Name: 2016 International Liquid Crystal Conference
Date Received: 23-Aug-2016   Conference Date: 02-Aug-2016   Date Published: 02-Aug-2016
Conference Location: Kent , Ohio
Paper Title: Simple method to provide exceptionally well stabilized azosye photoalignent layers for cavities
Authors: Colin McGinty, Valerie Finnemeyer, Philip Bos, John West
Acknowledged Federal Support: **Y**

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Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: International Symposium of the Society for Information Display
Date Received: 11-Aug-2017 Conference Date: 23-May-2017 Date Published: 23-May-2017
Conference Location: Los Angeles, CA
Paper Title: Strong Effect of Azodye Layer Thickness on RM-Stabilized Photoalignment
Authors: Colin McGinty, Valerie Finnemeyer, Robert Reich, Harry Clark, Shaun Berry, Philip Bos
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: OSA Imaging and Applied Optics Congress
Date Received: 22-Aug-2018 Conference Date: 25-Jun-2018 Date Published:
Conference Location: Orlando, FL
Paper Title: A continuous variable lens system to address the accommodation problem in VR and 3D displays
Authors: A. Jamali;
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: International Symposium of the Society for Information Display,
Date Received: 22-Aug-2018 Conference Date: 22-May-2018 Date Published:
Conference Location: Los Angeles, CA
Paper Title: Highly Versatile and Stable Photoalignment Process for AMLCDs
Authors: C. McGinty, J.Wang, V. Finnemeyer, R.Reich, H.Clark, S. Berry, P. Bos
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 0-Other
Conference Name: International Symposium of the Society for Information Display
Date Received: 22-Aug-2018 Conference Date: 22-May-2018 Date Published:
Conference Location: Los Angeles, CA
Paper Title: A continuous variable lens system to address the accommodation problem in VR and 3D displays
Authors: A. Jamali, C. Yousefzahdeh, C. McGinty, D.Bryant, P. Bos; P
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 0-Other
Conference Name: International conference on optics of liquid crystals
Date Received: 22-Aug-2018 Conference Date: 25-Sep-2017 Date Published:
Conference Location: San Paulo, Brazil
Paper Title: Large Aperture Liquid Crystal based lenses and wavefront control devices
Authors: Bos Philip, Gao Kun, McGinty Colin ,Payson Harold , Berry Shaun, Vornehm Joseph ,Finnemeyer Va
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 0-Other
Conference Name: Optics of Liquid Crystals
Date Received: Conference Date: 08-Sep-2019 Date Published: 08-Sep-2019
Conference Location: Quebec, Canada
Paper Title: Enhancing the Thermo-Optical Response of Nematic Liquid Crystals with a Polymer Network
Authors: C. McGinty, R. Reich, H. Clark, P. Bos
Acknowledged Federal Support: **Y**

DISSERTATIONS:

Publication Type: Thesis or Dissertation
Institution: Kent State University
Date Received: Completion Date: 12/31/18 7:35PM
Title: Enhancing the thermal optical response of nematic liquid crystals
Authors: Colin McGinty
Acknowledged Federal Support: **Y**

Publication Type: Thesis or Dissertation
Institution: Kent State University
Date Received: Completion Date: 12/31/18 7:35PM
Title: Enhancing the thermal optical response of nematic liquid crystals
Authors: Colin McGinty
Acknowledged Federal Support: **Y**

PATENTS:

Intellectual Property Type: Patent Date Received:
Patent Title: Photostable Alignment layer via Bleaching
Patent Abstract: [0012] The present disclosure relates to methods for “locking in” desired alignment in
Patent Number: 5555
Patent Country: USA
Application Date: 19-May-2017 Application Status: 1
Date Issued:

Major Goals (7411 characters/8000)

Microphotonic devices that consist of micron-sized preformed cavities filled with an active optical material would be useful for important DoD applications. At the forefront of these applications is a thermal imager. In this device a liquid crystal material needs to be aligned along a specified direction in the cavity by an "alignment layer". This alignment layer not only needs to define the direction of the average long axis of the liquid crystal material, but needs to have sufficient strength to suppress thermal fluctuations of the liquid crystal that can cause noise in the thermal measurement. We have estimated that a value of the anchoring energy of greater than 10^{-4} J/m^2 would minimize the problematic liquid crystal fluctuations for cavity thicknesses of about 1 micron. Previous work has shown that anchoring energies of this order are possible with a class of alignment layer materials based on azo dyes. But azo dye alignment layers have been shown to be unstable, and very little is has been reported concerning the underling physics related to this problem.

This project is to research and improve the properties of azo-dye photoalignment layers for liquid crystal based micro-photonic devices. Key to this understanding will be knowledge about how the azodye materials organize, align and bond to a surface.

An approach to stabilize azodye alignment layers that has been demonstrated by others, and in our work with Lincoln Laboratories, is to use a UV polymerizable liquid crystal to stabilize the alignment provided by the azodye alignment layer. Polymerizeable liquid crystals are materials whose monomers possess the liquid crystalline phase of matter, but also contain UV cross linkable groups so they can form polymers. The importance is that monomers can be aligned in the liquid crystalline phase, and then polymerized through the action of UV light. These materials are commercially available and have been given the name of reactive mesogens, which is abbreviated as RM materials. What has not been demonstrated, is that these layers can be applied to the stabilization of azodye alignment layers through infusion into cavities , and to offer sufficient stability under subsequent photo exposure. Therefore, one aspect of the problem to be studied under this project, is to provide greater understanding of the physics of the RM stabilization approach.

Major Goals:

- To understand how to control the strength and stability of azodye photoalignment
- To provide a liquid crystal process and optical system design to maximize signal and minimize noise.

The objectives of this project were first set in 2017, but some were modified as the project progressed. Replaced objectives are enclosed in brackets [ ] , and new objectives are underlined. Motivation for the modifications are in italic

Objectives related to the first goal :to understand and control azo-dye alignment layers, are aimed at these questions:

A. How is the order of the dye layer correlated with the anchoring effect of the liquid crystal. And how does its effect compare with our goal and other alignment layers.

- What is the effect of external optical excitation on the order parameter of the dye layer?
    - Task 1a: Measure and analyze the effect of exposure wavelength, dose, and intensity on the order parameter of the dye molecules
- What is the effect of the azo dye layer on the liquid crystal?
    - Task 2a: Measure the anchoring energy
    - Task 2b: Compare azodye alignment with other types of alignment layers.

B. What is the relative importance of inter dye molecule interactions and dye-surface interactions and how to control those interactions?
- The current literature analysis of the ability of dye to photo-orient with low intensity light, emphasizes the aggregation of dye molecules.
- But the literature concerning dye adhesion, emphasizes the surface interaction
- Is dye aggregation or liquid crystalline properties of the dye relevant to photo induced dye order?
    - Task 1b: Measure and analyze effect of solvent and dye concentration in the solvent.
- [What is the importance of the surface interaction?
    - Task 1d: Measure and analyze the effect of surface properties on the order of azo dye layers.
    - Task 1e: Measure and analyze the effect of molecular structure of dye molecules]

It was discovered in the course of the project that if the process related to the deposition of the azodye alignment layer was optimized, that the particular material chosen originally (Brilliant Yellow) worked very well. So more time was spent on understanding the processing of the Brilliant yellow to provide excellent results. And it was then seen that looking in more detail into the interaction of BY with a surface as outlined in the original tasks 1d and 1e is not required.

Related to the above, we have found that the reactive messogen properites are more important than originally planned, so with the decrease in activity in tasks 1d and 1e, we were able to spend more time on task 1c, as reported in the "accomplishments" section.

C. What affects the ordering and effectiveness of the RM stabilization layer?
- We expect that the polymerization of the RM layer will cause the order of the RM to be lower than the Azodye.
- We will want to consider to increase the order of the RM layer by
  Thinner RM layers ,Decreasing the cure temperature, and Controlling the polymerization rate
    - Task 1c: Develop process for reactive mesogen stabilized azo-dye alignment layer and characterize effect on anchoring energy and lifetime.

Objectives related to the second goal : to provide the process and optical system design to maximize signal to noise, are aimed at these questions:

A. Consider various approaches to measuring the order-parameter vs temperature of a liquid crystal to maximize the signal.
   - The birefringence of the LC is dependent on the order parameter, So measuring the birefringence of the LC is one way to detect a temperature change. This could be accomplished by measuring the change in the polarization state of light, the change in transmission through an etalon, the change in the elastic constants
      A. Task 4a: Design of measurement of birefringence from the polarization state of light
      B. Task 4b: Design of measurement of the LC birefringence from the transmission of light through a resonate cavity
      C. Task 4c: Design of measurement of the change in LC elastic constants .
      D. Task 4d: Provide more detail on above through numerical modeling where needed.

B. Analytical and Numerical modeling of the director fluctuations and the light propagation in a cavity to understand the noise
   - The director fluctuations, causing noise, are expected to be affected by the cavity size. They can be modeled using continuum theory, and the light propagation through a LC where the director variations have a short length scale is difficult to calculate analytically, we will use a the FDTD numerical approach (a direct solve of maxwell's eqns on a grid with sub-wavelength spacing)
      A. [Task 3a: Analytical modeling of director fluctuations in a micro cavity] <u>Provide analytical modeling of the effect of confinement of the 1rst order nature of the isotropic to nematic phase transition.</u>
      B. [Task 3b: Analytical modeling of light propagation with results from previous task.]
<u>Experimental consideration of the effect of a polymer fiber network on the 1rst order nature of the isotropic to nematic phase transition, and on the effect of director fluctuations.</u>

      C. [Task 3c: Numerical modeling of director fluctuations in a micro cavity]
      D. [Task 3d: Numerical modeling of light propagation with results from previous task.]

The objective related to tasks 3a – 3d, was to provide insight into approaches to reduce the noise related to director fluctuations in micro-cavity cells.   However, our initial results using a fiber network of aligned polymer material, not only showed that the noise from director fluctuations could be reduced, but also the 1rst order nematic to isotropic transition could be made to look more "2nd order like". So the work with forming a fiber network not only decreased the noise, but also increased the signal.   For this reason, the tasks <u>to find</u> an approach to reduce the noise are not needed (as we have found one) , and more time should be spend on understanding and the effect of a fiber network to reduce noise , and the optimization of the process for the thermal imager application.

C. Optical methods to maximize the signal to noise

- Want optical system that can provide a large change in signal for a small change in birefringence, but also, is insensitive to director fluctuations.
    A. Task 5a: Consider best optical set up to maximize S/N using fixed retarders
    B. Task 5b: Consider time and spatial averaging of noise in a pixel
    C. Task 5c: Consider simultaneous measurements with multiple wavelengths of light.

Accomplishments (7560/8000)

The major goals and tasks related to them were all completed successfully. We greatly enjoyed our collaboration with the Lincoln Laboratory that resulted in 11 papers and 1 patent. We hope this will be a continuing collaboration related to the thermal imager application. Specifics of the accomplishments are given below by task:

Related to tasks 1a and 1b:

Related to those tasks, over the last year we have isolated and quantified the major factors related to the processing of a surface alignment layer (referred to as 'BY') that affect the ability to photo-align that layer. We have found that the major factor is humidity present at different steps of the process. Specifically, dramatic effects of the humidity during the spin-coating of the BY/Solvent and the solvent removal was quantified. We have found that small differences (10%) in the relative humidity can have drastic effects on the ability to subsequently photo-align the surface layer. Also, we have isolated the cause of this phenomenon to be related to the small amounts of water from the air condensing on the BY material and resulting aggregation of the material to an extent that makes it difficult to re-align.

As we considered that the effect of humidity BEFORE exposure was here causing the BY to have a greater degree of aggregation and therefor making the film more stable and more difficult to photoalign, we also considered to apply humidity AFTER photoexposure . We found that in this case the order of the BY molecules could be significantly increased, and that the order is amazingly high.

Our work in this area has led to greater control of the production of high quality alignment layers, and also has provided data that will be useful in the development of theories of mechanism of photo alignment.

- For more details, please see the interim reports and the two papers that resulted from this work that are included in the products section :
    - "The effect of humidity and surface type on the photo-alignability of the azo-dye brilliant yellow",
    - "Optimization of azo-dye and infused RM process parameters for stable photo-patterned liquid crystal alignment ."

Results related to task 1c:

A key objective to obtain to obtain the major goals of this project is related to the stabilization of the an azo-dye based alignment layer.

We found that when the reactive mesogen (RM) layer was formed and polymerized on the azodye alignment layer, that the alignment of the liquid crystal layer was then primary controlled by the RM layer.. This increased our interest in the structure of the RM layer toward improving the properties of the thermal imager. In this regard we did study of the effect of different combinations of RM materials and LCs. The work first focused on the use of typical RMs and liquid crystals, and is fully reported in the published paper "Process for a Reactive Monomer Alignment Layer for Liquid Crystals Formed on an Azodye Sublayer"

We had shown that the resulting liquid crystal devices fabricated with this method were stable over the time intervals tested, but there were two remaining issues. One is that it was not clear that the device would remain stable over times longer than were tested, and also that alignment layer absorbed light and could limit applications of this method.

We have shown that the absorption of the BY layer can be eliminated after the alignment layer is RM stabilized. This result solved a major problem for this project, but also for much more general applications. In our approach, the BY layer is deposited and used to align the RM layer over it , that is then polymerized. After the RM layer is polymerized, the BY is "Bleached" by applying a high intensity of light, removing its ability to absorb light further, and to guarantee the long term stability of the RM alignment layer. In this effort we uncovered the surprising result that thinner BY layers are much more affective in this process than thicker ones that are typically used.

The impact of this work is very significant to the development of new types of liquid crystal photonic devices in general, and thermal imagers in particular, as the new method ensures the stability of this very versatile alignment layer. The impact on the wider liquid crystal display community was recognized the acceptance of our work as an oral presentation at the major international information display conference.

Please see the interim reports for more details on this work.

- A paper resulted from this work that is included in the products section: "Stable azodye photo-alignment layer for liquid crystal devices achieved by "turning off" dye photosensitivity".

Work related to Tasks 2a and 2b

These two preparational tasks were completed and reported on in the first interim progress report.

Work related to Tasks 3a -3d

The thermal imager's operating principle is to optically detect the effect of the change in of the molecular order parameter with temperature. The change in the order parameter with temperature is the greatest near the first order (discontinuous) thermal phase transition from the isotropic to ordered nematic phase. Obviously, if the 1st order transition could be made to be more 2nd order like, we could make a more sensitive thermal imager.

It was demonstrated that for the right combination of surface order and average domain size, that up to a 3.3x increase in sensitivity could be expected for the Polymer Network Liquid Crystal (PNLC) sample relative to the pure LC. PNLC samples were then fabricated with varying concentration of RM 257 in E7. The temperature dependence of the retardation in the samples was measured. When both the experimental data and calculations were considered the PNLC sample provided 2x the sensitivity of the pure LC sample.

Also, in doing the measurements on these materials, The MIT/LL scientist observed a noticeable decrease in the noise due to director fluctuations. As our final goal is to increase the signal /noise ratio, this finding makes the use of a polymer fiber network in the LC cell even more interesting.

Please see the interim project reports for more details on this work,

- A paper resulting from this work is included in the products section: “Enhancing the Thermo-Optical Response of Nematic Liquid Crystal with a Polymer Network”

Results related to task 4a:

Task 4a, “ Design of measurement of birefringence from the polarization state of light”, has the objective of considering improvements to the current measurement technique to measure the polarization state of light in the thermal imager application. This year we considered the use of a field sequential system where the intensity of light is recorded for to measurement system configurations. We have shown that a factor of 2 increase in sensitivity can result from this technique.

Results related to tasks 4b, 4d and 5c.

In order to increase the intensity of the thermal imager device , we considered a design based on the Fabry-Perot interferometer (Etalon) which is known for its sharp spectral peaks. Preliminary results looked encouraging, so detailed numerical calculations for this device were made utilizing the Berreman 4x4 method.

Our results have shown that when a single wavelength measurement is made that a 10x increase in the sensitivity over the senarmont-type device. When a differential measurement is considered using two wavelengths, an even larger increase is demonstrated. We note here that the thickness of the pixel for the Etalon device is also half that of the senarmont, which improves the response time of the device.

This study therefor shows a potential pathway to a very sensitive thermal imager. However, this sensitivity requires measurement with narrow bandwidth light that will have issues with speckle, and be quite difficult to implement in general.

Please see the interim reports for more details.

- A paper with more details on this work is included in the projects section : “ Design of a Sensitive Uncooled Thermal Imager Based on a Liquid Crystal Fabry-Perot Interferometer”;

Results related to task 4c

In task 4c, we consider to apply that fact that not only the birefringence is a function of temperature, but the elastic constants and dielectric constants are as well. So the option of using the temperature dependence of these additional factors was explored for their use in a thermal imager.

In this year we modeled the effect of the optical change in cell transmission as a function of temperature when a voltage was applied to the LC material. In this geometry the orientation of the LC is function of the temperature dependent electric torque, and the temperature dependent elastic energy that are working against each other. We found that while the temperature dependence of the elastic constants was, in fact, useful in improving the device sensitivity, that with this measurement technique, the temperature dependence of the dielectric constants, working against the effect of the temperature dependence of the elastic constants, effectively cancelled this advantage.

Training

This project has resulted in students working directly on the goals of this project to be trained in device modeling, materials design, and device fabrication techniques that are valuable for the advancement of new types of photonic devices based on liquid crystals in general, and for the development of thermal imagers in particular.

Also, students working in related areas, have been able to learn from the advancements of this project and make advancements in the area of alignment layers for displays, and electronic lenses. The results of that work is included in the publications listed in the next section, and included in the "products" section.

PhDs that are directly related to the collaboration with MIT/LL were:

- Valerie Finnemeyer PhD, 2016 to MIT/LL
- Colin McGinty, PhD ,2018 to NRL
- Junren Wang PhD, to Facebook Reality Labs

PhDs that greatly benefited from the results of this project are:

- Gun Gao PhD 2017, to Beam Corporation
- Afsoon Jamali 2018, to Facebook Reality Labs
- Comrun Yousefzadeh , nearing completion

Dissemination. (4279 /8000)

This project has resulted useful information related to the use of photoalignment layers for photonic devices. The area of focus has been for thermal imaging applications, but the area of displays and electronic lenses has also benefited.

Related to basic information related to stable photoalignment that is applicable to thermal imagers, there were six papers published with authors from Lincoln Laboratory that were directly related to the project goals:

- "Enhancing the Thermo-Optical Response of Nematic Liquid Crystal with a Polymer Network"; Colin McGinty, Robert Reich, Harry Clark, and Philip Bos; Accepted for publication in the Journal of Applied Physics

- "Effects of humidity and surface on photoalignment of brilliant yellow"; J.Wang, C. McGinty, J.West, D.Bryant, V.Finnemeyer, R.Reich, S.Berry, H.Clark, O.Yaroshchuk, P.Bos; Liquid Crystals ,5., 2016; DOI: 10.1080/02678292.2016.1247479

- "Scalable Fabrication Process for Liquid Crystal-Based Uncooled Thermal Imagers"; Berry, S; Bozler, CO; Reich, RK; Clark, HR; Bos, P; Finnemeyer, V; McGinty, C; JOURNAL OF MICROELECTROMECHANICAL SYSTEMS; JUN PY 2016 VL 25 IS 3 BP 479 EP 488

- “Stable azodye photo-alignment layer for liquid crystal devices achieved by “turning off” dye photosensitivity”. ; C.McGinty; V.Finnemeyer; R.Reich, H.Clark, S,Berry, P.Bos; Journal of Applied Physics, **122**, 205301 (2017)

- “Process for a Reactive Monomer Alignment Layer for Liquid Crystals Formed on an Azodye Sublayer”; J.Wang, C. McGinty, R. Reich, V. Finnemeyer, H. Clark, S Berry, P.Bos; Materials 2018, 11, 1195

- “ Design of a Sensitive Uncooled Thermal Imager Based on a Liquid Crystal Fabry-Perot Interferometer”; C. McGinty, R.Reich, H. Clark, V. Finnemeyer, S.Berry, and P. Bos; Applied Optics **57**, p 8264 (2018)

And there were also five papers that resulted from the basic science work accomplished under this project :

- “High-efficiency large-angle Pancharatnam phase deflector based on dual-twist design” Kun Gao, Colin McGinty, Harold Payson, Shaun Berry, Joseph Vornehm, Valerie Finnemeyer, Brian Roberts , and Philip Bos OPTICS EXPRESS 25,no6, 20 Mar 2017 p6283

- “Achromatic Limits of Pancharatnam Phase lenses” ; C.Yousefzahdeh, A.Jamaili, C.McGinty, P.Bos. ; Applied Optics, 57, no. 7 (2018)

- “A thin film liquid crystal based compensator for the chromatic aberration of optical lenses” ; A. Jamali, P. Bos; Molecular Crystals and Liquid Crystals, 657:1, 46-50 (2017)

- “LC lens systems to solve accommodation/convergence conflict in 3D and Virtual Reality displays” ; A. Jamali, C.Yousefzahdeh, C. McGinty, D.Bryant, P.Bos; (under review)

- A non-mechanical zoom lens fabricated from liquid crystal reactive mesogens; K Gao, A. Bhowmik, C.McGinty, P.Bos; Proc of SPIE volume 9940; Doi: 10.1117/12.2237324

There have also been conference presentations:

- "Enhancing the Thermo-Optical Response of Nematic Liquid Crystals with a Polymer Network"; C. McGinty, R. Reich, H. Clark, P. Bos; Optics of Liquid Crystals 2019; Sept 2, 2019; Quebec, Canada (Invited talk)

- "Simple method to provide exceptionally well stabilized azo-dye photoalignment layers for cavities" C. McGinty, V.Finnemeyer, P.Bos, J.West; presented at the 2016 International Liquid Crystal Conference

- An Invited talk at the Gordon Conference on Liquid Crystals (June 18-23, University of New England, Biddeford, ME)

- A oral presentation at the International Conference of the Society for Information Display : "Strong Effect of Azodye Layer Thickness on RM Stabilized Photoalignment." C.McGinty, V, Finnemeyer, R.Reich, H.Clark, S Berry, P.Bos; ; Proceedings of the 2017 International Symposium of the Society for Information Display; LosAngeles , May 21-26 , 2017 ; paper 41.1

- The thermal imager group at Lincoln Laboratory did a collaborative paper with us: "Liquid Crystal Uncooled Thermal Imager Development" Clark, H. R., Jr.; Bozler, C. O.; Berry, S. R.; et al Edited by: LeVan, PD; Sood, AK; Wijewarnasuriya, P; et al. Conference: Conference on Infrared Sensors, Devices, and Applications VI Location: San Diego, CA Date: AUG 31-SEP 01, 2016 Sponsor(s): SPIE INFRARED SENSORS, DEVICES, AND APPLICATIONS VI Book Series: Proceedings of SPIE Volume: 9974 Article Number: UNSP 99740E Published: 2016

- "A continuous variable lens system to address the accommodation problem in VR and 3D displays"; A. Jamali; oral presentation 3Tu2G.5; OSA Imaging and Applied Optics Congress; Orlando, Florida, 25-28 June 2018

- "Highly Versatile and Stable Photoalignment Process for AMLCDs"; C. McGinty, J.Wang, V. Finnemeyer, R.Reich, H.Clark, S. Berry, P. Bos; oral presentation 29-3 , International Symposium of the Society for Information Display, Los Angeles Convention Center, Los Angeles, CA, May 22-25, 2018

- "A continuous variable lens system to address the accommodation problem in VR and 3D displays"; A. Jamali, C. Yousefzahdeh, C. McGinty, D.Bryant, P. Bos; P-148, International Symposium of the Society for Information Display, Los Angeles Convention Center, Los Angeles, CA, May 22-25, 2018

- “Large Aperture Liquid Crystal based lenses and wavefront control devices” Philip Bos, Kun Gao, Colin McGinty , Harold Payson, Shaun Berry,Joseph Vornehm, Valerie Finnemeyer, Brian Roberts, Liwei Li, HsienHui Cheng, Doug Bryant, Afsoon Jamali ; Invited talk, international conference Optics of Liquid Crystals 2017, Guaruja, San Paulo, BRAZIL, 24 -29 September 2017

Also, we wrote a patent disclosure that has been filed with the US patent office:

- Photostable Alignment Layer via Bleaching ; C. McGinty. P.Bos, V.Finnemeyer, R.Reich, C.Clark, S.Berry

Honors and Awards

I was invited to provide talks at the: Optics of Liquid Crystals Conference 2017, 24-29 September, in Guaruja , Brazil; at the Optics of Liquid Crystals Conference 2019, Quebec, Canada, and at the: 7th International Symposium on Liquid Crystal Photonics and Workshop on Liquid Crystals for Sustainable Development, April 13-16, 2018, Nanjing, China.

Technology Transfer (5398/8000)

Collaboration with Lincoln Laboratory on Development of Uncooled Thermal Imager

All of the work presented in this report has been done collaboratively with MIT Lincoln Laboratory (LL). In particular, we have collaborated with Robert Reich, Harry Clark, and Valerie Finnemeyer from group 87 on the thermal imager project. This collaboration takes place in the form of bi-weekly conference calls during which the main results from the previous weeks are discussed as well as the plans for the coming weeks. As part of these conference calls reports, usually in the form of slides, are sent to the group at LL for discussion during the conference call. Each report that we have sent over the past year has been included in the attached .zip.

The main exchange of materials that takes place between LL and Kent State University (KSU) involves micro cavity samples which are fabricated at LL. These samples which are arrays of 1-2 um thick and 20 um wide micro cavities are the structures which serve as the pixels in the uncooled liquid crystal thermal imager. The main goal of this exchange of materials is developing processes at KSU that will be beneficial to the development of the thermal imager. One example of this work is the development of a process to 'cap' the cavity samples after filling to prevent LC from escaping. We explored the possibility of using the RM already present in the sample to cap the cavities. In addition we did work on the use of SiO_2 deposition to prevent LC from escaping which showed promising results. Some detials on these experiments can be seen in 'LCTP 5-12-2016' in the attached .zip. In addition, as reported in the planning section, much of the work planned for the coming year revolves around optimizing the process for producing RM stabilized photoalignment films in the micro-cavities. We have already begun some of the preliminary work on this buy examining the effect of RM concentration on the photostability of cavity samples. Some detials on this work can be seen in 'LCTP 8-2-2017' in the .zip.

In addition to processing, we have also used cavity samples received from LL to look at the effect of confinement on the nematic-isotropic phase transition. An LC which is sufficiently confined will have a second-order phase transititon; if the phase transition is second order then the temperature sensitivity of the order parameter in the 'transition region' will be quite high and increase the sensitivity of the thermal imager. Details on the confinement work can be seen in 'LCTP 4-2-2017'. We predicted theoretically that the LC would need to be confined to a ~20nm thickness in order for the phase transition to become second order. We tried to verify this experimentally not only by making thin cells but also by looking at the phase transition in cavity samples. This work can be seen in 'LCTP 3-2-2017'. Overall, the goal of the transfer of cavity samples to KSU has been to return processes back to LL which will be useful for the fabrication as well as obtaining an increase in sensitivity of the thermal imager.

Collaboration with Lincoln Laboratory for the Fabrication of Pancharatnam Phase Devices

In addition to the work done with group 87 at Lincoln Laboratory, we also collaborated with group 38 and in particular Joe Vornehm to help fabricate pancharatnam phase devices

(PPDs). PPDs involve a spiraling director pattern in the plane of the substrate and are typically used for large-angle high-efficiency beam steering. Because of the complicated nature of the alignment pattern, PPDs can only be made by utilizing photoalignment materials. After the film is aligned, successive layers of RM are spin-coated and polymerized until the retardation of the device is a half wave for the design wavelength. The main goal of this collaboration was to demonstrate a high-efficiency beam steering device capable of steering to ~25°. We considred two approaches to accomplishing this. The first utilized three deflectors with steering angles of 3, 6, and 12 degrees respectively to reach 20°. The second involves making a single 25° deflector.

In September of 2016, LL sent substrates with BY films deposited on them which were exposed to give steering angles of 6 and 12°. However, when the samples arrived at KSU, the environmental conditions during transportation had damaged the alignment film. For this reason fabrication of 3,6, and 12° deflectors were exposed and coated with a few layers of RM at KSU and showed positive results. Detials on these samples can be seen in 'PPD Samples Recieved from LL'.

After relaying the results described above to LL, more samples for 6 and 12° were exposed at LL and sent to KSU. Two samples for each steering angle were sent and made it to KSU without damage. One sample for each steering angle was coated with RM until it was a half wave retarder for 1064 nm light – these samples were made as a proof of concept for the application LL was pursuing. Additionally, one sample was coated to a half wave for 543 nm light – these samples were made so that a demonstration of the device capabilities could be made for visible light. In addition to the samples exposed at LL, two 3° deflectors were made completely in house at KSU. These samples were all sent to LL for characterization and use in demonstration on 10-6-2016. Details on these samples can be seen in '10-6-2016 PPD Samples to Lincoln'.

Once the samples described above were sent to LL, their efficiency for 1064 nm light was evaluated (since KSU does not have IR laser) and was found to be >90%. With this knowledge, a 25 degree deflector at 1064 nm was produced completely in house at KSU and sent to LL on 4-7-2017. This sample was used to provide data for a presentation given at the 2017 AIAA Defense and Security Forum. Details on this sample can be seen in Details on this device can be seen in 'PPD Device(4-7-2017)'.

One of the primary reasons for this collaboration has been that LL has had a difficulty with the RM processing steps in their facility. We have not only helped with this problem by performing the RM processing at KSU but have also tried to troubleshoot the fabrication process and carefully note procesing steps that we use. One example of this can be seen in 'PPD Intensity' which shows that a large exposure dose for the BY film can damage the performance of the final device. Besides this document, lines of communication between Joe and KSU are always open and we are always trying to communicate helpful results.

Stabilized Photoalignment in Microcavities

After establishing a reliable method for obtaining a stable surface-localized reactive mesogen alignment layer through phase separation, attention was turned towards achieving a similar result in microcavity structures. Samples for this purpose were provided to the LCI by Dr. Robert Reich and Harry Clark from MIT Lincoln Laboratory; the thickness of the microcavity samples provided was 1 μm. Work on this portion of the project can be seen in the reports sent to MIT-LL between 8-17-2017 and 11-16-2017. From previous work done with the 5 μm thick bulk samples we found that the necessary concentration of RM 257 in the LC host, E7, was 1.5% by weight. However, in these thinner cells it was anticipated that a higher concentration of RM would be needed. We then investigated utilizing larger concentrations of RM 257. Concentrations of 3,6,9, and 12% RM 257 in E7 were tested and only 12% exhibited stable photoalignment in the cavities. This experiment was then repeated for a larger batch of samples and the results were verified.

Also, related to technology transfer was a talk given at LL: **"Very large angle optical beam deflectors using Pancharatnam"** Phase, Philip Bos, Kun Gao, Colin McGinty , Harold Payson, Shaun Berry,Joseph Vornehm, Valerie Finnemeyer, Brian Roberts, Liwei Li, HsienHui Cheng, Doug Bryant, Afsoon Jamali; MIT Lincoln Laboratory, 18 July 2017

Participants

Philip Bos (Professor and PI)

- 10% 10/1/2014 –7/31/16
- 12% 8/1/16 -7/31/17
- 15% 8/01/17 – 6/30/18

John West (Professor) :

- 10% 6/1/16 – 7/31/16,

Colin McGinty (Graduate Student)

- 100% 5/1/2015 – 5/31/16
- 100%, 8/1/16 – 6/30/18

Junren Wang, (Graduate Student)

- 100% 6/1/15- 7/31/16
  18% 7/01/17 – 6/30/18

Comrun Yousefzadeh, (Graduate Student)

- 50% 1/1/17- 7/31/17
- 16% 8/01/17 – 6/30/18

Products:

- Interim reports that have included more details on the work done
- Bi weekly reports provided to MIT/LL over the duration of the project that are included in the interim reports.
- Journal articles
  - J1: "Stable azodye photo-alignment layer for liquid crystal devices achieved by "turning off" dye photosensitivity". ; C.McGinty; V.Finnemeyer; R.Reich, H.Clark, S,Berry, P.Bos; Journal of Applied Physics, **122**, 205301 (2017)
  - J2: "Process for a Reactive Monomer Alignment Layer for Liquid Crystals Formed on an Azodye Sublayer"; J.Wang, C. McGinty, R. Reich, V. Finnemeyer, H. Clark, S Berry, P.Bos; Materials 2018, 11, 1195
  - J3: " Design of a Sensitive Uncooled Thermal Imager Based on a Liquid Crystal Fabry-Perot Interferometer"; C. McGinty, R.Reich, H. Clark, V. Finnemeyer, S.Berry, and P. Bos, Applied Optics **57**, p 8264 (2018)
  - J4: "Achromatic Limits of Pancharatnam Phase lenses" ; C.Yousefzahdeh, A.Jamaili, C.McGinty, P.Bos. ; Applied Optics, 57, no. 7 (2018)
  - J5: "A thin film liquid crystal based compensator for the chromatic aberration of optical lenses" ; A. Jamali, P. Bos; Molecular Crystals and Liquid Crystals, 657:1, 46-50 (2017)

- J6: “LC lens systems to solve accommodation/convergence conflict in 3D and Virtual Reality displays” ; A. Jamali, C.Yousefzahdeh, C. McGinty, D.Bryant, P.Bos; (under review)

- J7: “Enhancing the Thermo-Optical Response of Nematic Liquid Crystal with a Polymer Network”; Colin McGinty, Robert Reich, Harry Clark, and Philip Bos; Accepted for publication in the Journal of Applied Physics
- J8: “Effects of humidity and surface on photoalignment of brilliant yellow”; J.Wang, C. McGinty, J.West, D.Bryant, V.Finnemeyer, R.Reich, S.Berry, H.Clark, O.Yaroshchuk, P.Bos; Liquid Crystals ,5., 2016; DOI: 10.1080/02678292.2016.1247479
- J9: “Scalable Fabrication Process for Liquid Crystal-Based Uncooled Thermal Imagers”; Berry, S; Bozler, CO; Reich, RK; Clark, HR; Bos, P; Finnemeyer, V; McGinty, C; JOURNAL OF MICROELECTROMECHANICAL SYSTEMS; JUN PY 2016 VL 25 IS 3 BP 479 EP 488
- J10: “High-efficiency large-angle Pancharatnam phase deflector based on dual-twist design”
Kun Gao, Colin McGinty, Harold Payson, Shaun Berry, Joseph Vornehm, Valerie Finnemeyer, Brian Roberts , and Philip Bos OPTICS EXPRESS 25,no6, 20 Mar 2017 p6283
- J11: A non-mechanical zoom lens fabricated from liquid crystal reactive mesogens; K Gao, A. Bhowmik, C.McGinty, P.Bos; Proc of SPIE volume 9940; Doi: 10.1117/12.2237324

Conference presentations:

- C1: “A continuous variable lens system to address the accommodation problem in VR and 3D displays”; A. Jamali; oral presentation 3Tu2G.5; OSA Imaging and Applied Optics Congress; Orlando, Florida, 25-28 June 2018

- C2: “Highly Versatile and Stable Photoalignment Process for AMLCDs”; C. McGinty, J.Wang, V. Finnemeyer, R.Reich, H.Clark, S. Berry, P. Bos; oral presentation 29-3 , International Symposium of the Society for Information Display, Los Angeles Convention Center, Los Angeles, CA, May 22-25, 2018

- C3: “A continuous variable lens system to address the accommodation problem in VR and 3D displays”; A. Jamali, C. Yousefzahdeh, C. McGinty, D.Bryant, P. Bos; P-148, International Symposium of the Society for Information Display, Los Angeles Convention Center, Los Angeles, CA, May 22-25, 2018

- C4: “Large Aperture Liquid Crystal based lenses and wavefront control devices”
Philip Bos, Kun Gao, Colin McGinty , Harold Payson, Shaun Berry,Joseph Vornehm, Valerie Finnemeyer, Brian Roberts, Liwei Li, HsienHui Cheng, Doug

Bryant, Afsoon Jamali ; Invited talk, international conference Optics of Liquid Crystals 2017, Guaruja, San Paulo, BRAZIL, 24 -29 September 2017

- C5: “Enhancing the Thermo-Optical Response of Nematic Liquid Crystals with a Polymer Network”; C. McGinty, R. Reich, H. Clark, P. Bos; Optics of Liquid Crystals 2019; Sept 2, 2019; Quebec, Canada (Invited talk)
- C6: “Simple method to provide exceptionally well stabilized azo-dye photoalignment layers for cavities” C. McGinty, V.Finnemeyer, P.Bos, J.West; presented at the 2016 International Liquid Crystal Conference
- C7: An Invited talk at the Gordon Conference on Liquid Crystals (June 18-23, University of New England, Biddeford, ME)
- C8: A oral presentation at the International Conference of the Society for Information Display : “Strong Effect of Azodye Layer Thickness on RM Stabilized Photoalignment.” C.McGinty, V, Finnemeyer, R.Reich, H.Clark, S Berry, P.Bos; ; Proceedings of the 2017 International Symposium of the Society for Information Display; LosAngeles , May 21-26 , 2017 ; paper 41.1
- C9: The thermal imager group at Lincoln Laboratory did a collaborative paper with us: “Liquid Crystal Uncooled Thermal Imager Development” Clark, H. R., Jr.; Bozler, C. O.; Berry, S. R.; et al Edited by: LeVan, PD; Sood, AK; Wijewarnasuriya, P; et al. Conference: Conference on Infrared Sensors, Devices, and Applications VI Location: San Diego, CA Date: AUG 31-SEP 01, 2016 Sponsor(s): SPIE INFRARED SENSORS, DEVICES, AND APPLICATIONS VI Book Series: Proceedings of SPIE Volume: 9974 Article Number: UNSP 99740E Published: 2016