Modeling of programmable lenses with liquid crystal elastomers

V. van der Doef[1,2], P. Lyu[2,3], M. Spiegelberg[1], E. Weldeghebreal[1], D. Liu[2,3], E. Tangdiongga[1], O. Raz[1]

1Department of Electrical Engineering, Eindhoven Hendrik Casimir Institute, Eindhoven University of Technology, 5600 Eindhoven, The Netherlands

2Laboratory of human interactive Materials and Devices (HIM), Department of Chemical Engineering and Chemistry, Eindhoven University of Technology, Groene Loper 3, 5612 AE Eindhoven, The Netherlands

3Institute for Complex Molecular Systems (ICMS)Eindhoven University of Technology Groene Loper 3, Eindhoven 5612 AE, Netherlands

***Abstract**: Optical-wireless communications (OWC) is a promising alternative to radio frequency communication. A significant challenge with OWC systems is the free space optics. In this paper we propose an alternative solution for optical beam steering using thermally actuating liquid crystal elastomers to deform a soft lens. We devised a model to find an optimal shape of our programmable lens to achieve maximal beam-steering capabilities. The simulated ring actuates in the 45-60 °C range and changes the focal point by 10 mm.*

Introduction

In-door wireless communication systems are facing more stringent requirements, such as higher bandwidth, improved privacy and the need to accommodate more end-users. The radio frequency (RF) spectrum is quickly becoming overcrowded, causing interference for users, limiting the total bandwidth and also having high power requirements [1]. To overcome these challenges alternatives such as optical wireless communications (OWC) are being considered [2]. OWC offers various advantages over radio wave based technologies. It requires end-users to share less resources, requires less power to function and also increases the privacy of the users by being harder to intercept. Most important is the huge and unlicensed bandwidth available for OWC. Yet in order to deploy OWC solutions, bridging the final meters of the OWC link still has considerable challenges. Optical beam steering is essential for controlling the optical beam in order to connect the end-users to the internet. Many approaches have been suggested to solve this problem including diffractive steering, polarization gratings and optical phased arrays [3]–[5]. In this paper we propose solving the problem of optical beam steering by introducing programmable lenses made of liquid crystal elastomers and deformable polymers.

Liquid crystals are a type of material which exhibits a phase in between the crystal and liquid state. This phase shows both crystalline and liquid properties. Liquid crystals have been used initially for their optical properties [6], but recently have seen new use in soft robotics as a soft actuator [7]. A lot of applications supported by liquid crystals (and liquid crystal elastomers) have been made possible using responsive materials and devices fabricated using special 3D printer [8, 9]. These 3D printers are capable of inducing alignment by pushing the molecules through a small nozzle. Thanks to the alignment, the liquid crystal elastomer (LCE) can be thermally actuated in a controllable and reversible manner [10]. Having a good alignment means that the liquid crystal molecules, often with a rod shape, all point in the same direction. When the liquid crystal is heated, the rods get more thermal energy, which makes them move more and they start losing their alignment, so the rods are starting to tilt. Because all the rods are tilting away from the alignment direction the material contracts alongside the alignment while expanding in the perpendicular directions. The material deforms therefore in an anisotropic manner which makes it a good material for designing soft actuators. Previously, a thermally deformable polydimethylsiloxane (PDMS) lens has been demonstrated with the help of a liquid crystal elastomer ring immersed in a polydimethylsiloxane square [11]. However,

the mechanical properties and the adhesion between the PDMS have not been fully studied and may results in material fatigue.

In this paper we report on the modelling and initial fabrication of a programmable lens using LCE for both the lens and the actuator alike. This is proposed in order to insure better chemically adhesion between the active LCE ring and the passive lens. We present the result of our simulation and show some preliminary results from an initial fabrication run demonstrating the ability to deform such a lens by applying a temperature change.

Modeling and simulation

To model the behavior of the LCE a commercially available software, COMSOL Multiphysics, has been used. The model consists of two physics modules. The first one is called solid mechanics which simulates the deformation of the programmable liquid crystal lens. The second module is called ray optics which describes the way the light travel through the lens.

The first step in designing the model is describing the geometry and boundary conditions. The ring has a diameter of 6 mm, a thickness of 0.15 mm and a height of 0.875 mm. The passive lens has a room temperature curvature of 200 m^{-1}. The geometry of the lens is shown in figure 1a. Rigid motion suppression is set as a boundary condition on the liquid crystal ring which will ensure the average centroid remains the same during the actuation of the lens.

The module solid mechanics relates to the physics of thermal expansion, deformation and elasticity, including anisotropic linear elastic materials. To be able to calculate the deformation of an anisotropic material, the elasticity matrix of the material is required. Since the liquid crystal ring has three planes of symmetry along the three axes the material can is considered to be orthoptic instead. Therefore the Poisson's ratio, Young's modulus, density and the shear modulus will be sufficient to calculate the deformation behavior. For isotropic materials, such as the unaligned liquid crystal the Young's modulus and density is enough. The alignment of the liquid crystal is a challenge when designing the COMSOL model. The axis coordinates are translated along the crystal orientation. The x- and y-coordinates are transformed to- sin(atan2(y,x)) and cos(atan2(y,x)) while z remains the same giving a circular coordinates system.

Finally the ray optics was modeled. COMSOL calculates the position and wave vector of various rays. The ray optics module can also calculate the behavior of the rays when travelling through different mediums. The program uses Snell's law and the Fresnel equations to achieve this goal, as well as the refractive index. The refractive index is in the range of 1.4-1.7. We use a refractive index of 1.5 for the lens material and allow 11 rays (spanning in total +/- 1 mm from the center of the lens) at a wavelength of 1558 nm to be traced.

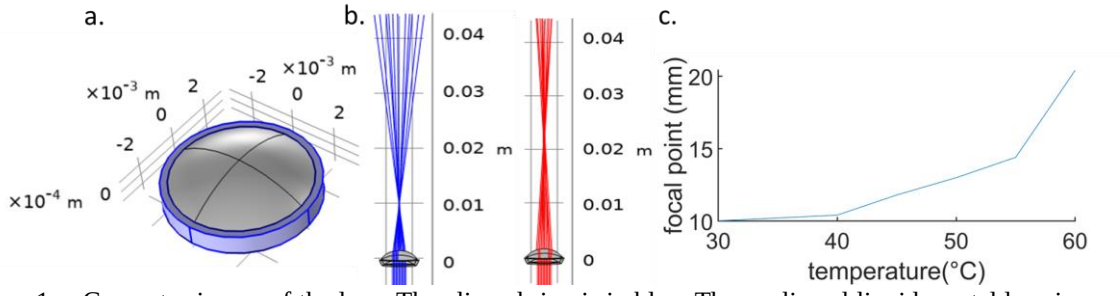

Figure 1 a. Geometry image of the lens. The aligned ring is in blue. The unaligned liquid crystal lens is grey. b. Ray optics of the programmable lens system. Blue is the rays at 30 °C . Red is at 60 °C. c. Shows the change of the focal point at different temperatures.

In figure 1b the results of the COMSOL model are shown. Two light rays are presented, one in blue for a temperature of 30 °C and the other in red for 60 °C. For the lower temperature, the light converges at a distance of 10 mm and for the higher temperature, the focal point is at 20 mm. In figure 1c the change of focal point has been plotted over the temperature of the lens. A difference of 10 mm can be achieved.

Experimental results

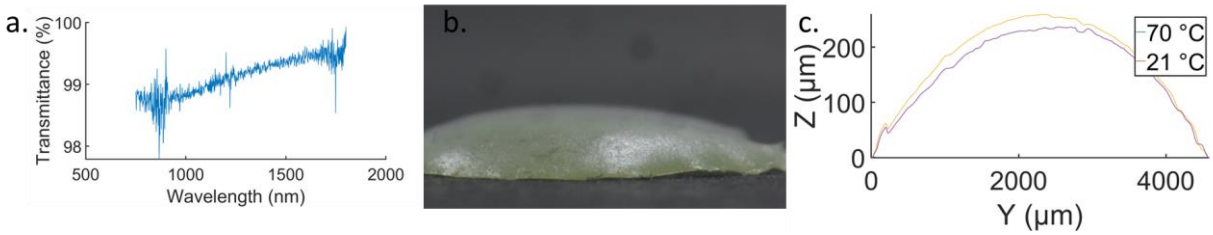

Figure 2 a. Transmittance of the thin film liquid crstal elastomer at various wavelengths. b. Sideview of the printed programmable lens c. Cross section of the middle of the liquid crystal ring measured at room temperature and 70 °C.

Based on our modelling we proceeded to fabricate a prototype of the LCE lens. We made the liquid crystal elastomer with the Michael addition reaction by adding 1 mol liquid crystal to 0.9 mol chain extender DODT (2,2'-(ethylenedioxy) diethanethiol). We use two different liquid crystal molecules, C6BAPE (4- (6-(acryloyloxy)hexyloxy)phenyl-4-(6-(acryloyloxy)hexyloxy) benzoate) and RM257 (2-Methyl-1,4-phenylene bis(4-(3-(acryloyloxy)propoxy)benzoate)) with a 0.8:0.2 mol ratio respectively. Together they will form a liquid crystal polymer to be used in the 3D printer. Also added are the catalyst DBU(1,8-Diazabicyclo(5.4.0)undec-7-ene), photo initiator Irgacure 819 (Phenylbis(2,4,6-trimethylbenzoyl)phosphine oxide) and photo inhibitor BHT (butylated hydroxytoluene). With a weight percentage of 0,001%, 1.5% and 1% respectively. The mixture was dissolved in dichloromethane (DCM), stirred for 15 minutes and left at room temperature for 6 hours. The DCM was then removed in a vacuum oven overnight.

Firstly some material analysis on the liquid crystal material have been made to ensure that it could be used for OWC. Therefore the transmission of the material has been measured. A thin film of the liquid crystal elastomer has been spin coated and the transmittance of the material has been measured for the IR wavelength with the LAMBDA™ 750 UV/Vis/NIR spectrophotometer (PerkinElmer). The transmittance is 99% at 1558 nm wavelength (see figure 2a), making it suitable to function as a lens. Secondly the deformability of the material has been measured. A layer of 40x24 mm was printed with a commercial 3d printer from Hyrel 3D using a 0.5 mm nozzle at 400 mm min^{-1}. Afterwards it has been photo crosslinked for 15 minutes. DMA Q800 was used to measure the Youngs modules and the thermal expansion of the material [12]. This gives a young's modulus along the aligned axis of 7.0 MPa, and the perpendicular axis has a modulus of 1.7 MPa. Subsequently the liquid crystal lens has been printed with the Hyrel printer using 300 mm min^{-1}. The ring has a diameter of 6 mm and is 4 layers thick. It has been cured by photo crosslinking. The inner lens is then printed with 5 layers, and put in the vacuum oven for 1 hour at 40 °C, before being crosslinked. A photo is shown at figure 2b. The cross section (figure 2c) across the middle of the lens was measured with the profilometer (DektakXT) at room temperature as well as at 70 °C. We have measured a radius of curvature of 0.000033 μm^{-1} at room temperature and 0.000041 μm^{-1} at 70 °C confirming that the combined structure does deform when heated. Furthermore, when exposing the lens to repeated

heat cycles we saw that no delamination of the LPE ring from the LPE lens occurred confirming good adhesion between the two.

Discussion & Conclusion

In this paper we have explored an alternative method of beam steering method by using heat sensitive liquid crystal elastomers. Using modeling software it has been shown that the focal distance of the lens is dependent on the temperature. The focal point range can be adjusted by designing the initial curvature of the programmable lens to the desired range. Also by moving the light source of-center the resulting focal point will also move off-center. This focal plane array concept for steering [13] can be used not only to change the size of the spot but also its eventual position in 3D space. Finally our preliminary fabricated lenses show actuation when changing the temperature, in good agreement with our model. Based on our robust COMSOL model combined with the preliminary experimental results, optical beam steering using liquid crystal lenses is a promising technology for solving the last-meter indoor wireless communication systems

References

[1] R. Maaloul, R. Taktak, L. Chaari, and B. Cousin, "Energy-Aware Routing in Carrier-Grade Ethernet Using SDN Approach," *IEEE Transactions on Green Communications and Networking*, vol. 2, no. 3, pp. 844–858, Sep. 2018, doi: 10.1109/TGCN.2018.2832658.

[2] T. Koonen, "Indoor Optical Wireless Systems: Technology, Trends, and Applications," *Journal of Lightwave Technology*, vol. 36, no. 8, pp. 1459–1467, Apr. 2018, doi: 10.1109/JLT.2017.2787614.

[3] C. W. Oh, Z. Cao, E. Tangdiongga, and T. Koonen, "Free-space transmission with passive 2D beam steering for multi-gigabit-per-second per-beam indoor optical wireless networks," *Opt Express*, vol. 24, no. 17, p. 19211, Aug. 2016, doi: 10.1364/oe.24.019211.

[4] C. Hoy, J. Stockley, J. Shane, K. Kluttz, D. McKnight, and S. Serati, "Non-mechanical beam steering with polarization gratings: A review," *Crystals (Basel)*, vol. 11, no. 4, Apr. 2021, doi: 10.3390/cryst11040361.

[5] R. Fatemi, A. Khachaturian, and A. Hajimiri, "A Nonuniform Sparse 2-D Large-FOV Optical Phased Array With a Low-Power PWM Drive," *IEEE J Solid-State Circuits*, vol. 54, no. 5, pp. 1200–1215, May 2019, doi: 10.1109/JSSC.2019.2896767.

[6] J. F. Lindner *et al.*, "NATURE · VOL 3 78 · 30 NOVEMBER."

[7] M. O. Astam, Y. Zhan, T. K. Slot, and D. Liu, "Active Surfaces Formed in Liquid Crystal Polymer Networks," *ACS Applied Materials and Interfaces*, vol. 14, no. 20. American Chemical Society, pp. 22697–22705, May 25, 2022. doi: 10.1021/acsami.1c21024.

[8] M. del Pozo, J. A. H. P. Sol, A. P. H. J. Schenning, and M. G. Debije, "4D Printing of Liquid Crystals: What's Right for Me?," *Advanced Materials*, vol. 34, no. 3. John Wiley and Sons Inc, Jan. 01, 2022. doi: 10.1002/adma.202104390.

[9] C. P. Ambulo, J. J. Burroughs, J. M. Boothby, H. Kim, M. R. Shankar, and T. H. Ware, "Four-dimensional Printing of Liquid Crystal Elastomers," *ACS Appl Mater Interfaces*, vol. 9, no. 42, pp. 37332–37339, Oct. 2017, doi: 10.1021/acsami.7b11851.

[10] T. J. White and D. J. Broer, "Programmable and adaptive mechanics with liquid crystal polymer networks and elastomers," *Nature Materials*, vol. 14, no. 11. Nature Publishing Group, pp. 1087–1098, Oct. 22, 2015. doi: 10.1038/nmat4433.

[11] M. López-Valdeolivas, D. Liu, D. J. Broer, and C. Sánchez-Somolinos, "4D Printed Actuators with Soft-Robotic Functions," *Macromol Rapid Commun*, vol. 39, no. 5, Mar. 2018, doi: 10.1002/marc.201700710.

[12] PerkinElmer and Inc, "Expansion Coefficient of Polymeric Materials using DMA 8000", Accessed: Nov. 07, 2023. [Online]. Available: www.perkinelmer.com

[13] X. Zhang, K. Kwon, J. Henriksson, J. Luo, and M. C. Wu, "Large-scale Silicon Photonics Focal Plane Switch Array for Optical Beam Steering," 2021.