# Leveraging the Photoelastic Effect for the Evaluation of Strain in Tensioned Substrates for Roll-to-Roll Nanomanufacturing

**Groh, Barbara; Connolly, Liam G.; Cullinan, Michael**

[1]University of Texas at Austin, Walker Department of Mechanical Engineering, Austin, TX, USA

## ABSTRACT

**As critical dimensions for roll-to-roll (R2R) nanofabrication shrink, exceptionally precise metrology is required to resolve individual features and make informed process control decisions. This level of measurement certainty, particularly for in-line sampling, is a scale of precision which is not often met in current-art process lines. Reducing measurement uncertainty is a necessary advancement to R2R manufacturing technology if this method is to usurp more traditional silicon wafer, glass, or silicon-on-insulator processes and introduce with better economies of scale.**

**One challenge is that the necessary tension in the web, often a flexible polymer substrate, results in deformation which can vary due to a variety of process effects such as thickness nonuniformity, process temperature, and jitter in the applied tensioning torque. This, in turn, leads to deformation of the fabricated structures along with the substrate. Without postprocessing, any in-line measurement aiming to resolve critical dimensions on the order of $10^{-7}$ m will inherently lose precision to this deformation.**

**This research serves to explore the unique optical properties of many of the flexible substrates used in R2R manufacturing and propose a measurement system for analyzing and modeling in-line web deformation in real time. Specifically, most R2R substrates are transparent polymers which experience the photoelastic effect while under tension, and the change in polarization due to this effect at the microscale is used to characterize deformation across the web. This data will enable the creation of models to correct for errors due to pattern deformation for a variety of in-line measurement tools such as scatterometry, diffractometry, and tip-based measurement.**

## 1. INTRODUCTION

In R2R additive manufacturing, a flexible substrate is tightly stretched between two primary rollers – unwind and rewind – with any processing steps or additional web regulation taking place between the two. Consequently, the material undergoes stress across the stretched-out substrate, otherwise known as the web, which causes strain in the material. For most macro-scale features, this is not a problem because the deformations are typically on the order of hundreds of nanometers. However, as critical dimensions continue to shrink, the deformations cannot be ignored. This becomes particularly problematic when the fabrication process requires more than one patterned layer. It is imperative that all layers align as any error between layers of features, or overlay error, may significantly effect manufacturing yield. Figure 1 shows how registration error can cause misalignment which changes the function of an example device[1], [2].

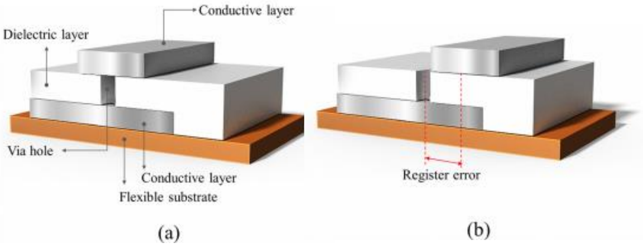

Figure 1 a) A nanoscale feature with multiple layers. b) features are misaligned due to registration error [1]

## 2. PHOTOELASTIC EFFECT

As discussed previously, the tensioning of the substrate introduces deformation to the web and puts it under stress that affects feature location. However, the transparent polymers often used in R2R manufacturing generally experience a unique optical phenomenon known as the photoelastic effect when under tension.

The photoelastic effect occurs when polarized light passes through a transparent, often mostly amorphous material, particularly one that is optically isotropic under no stress, but optically anisotropic under stress [3]. This material, under stress, then has the ability to refract light similar to a crystalline material, such that the index of refraction throughout the material is related to its internal stress state. This results in polarization changes that can make images like the one seen in Figure 2.

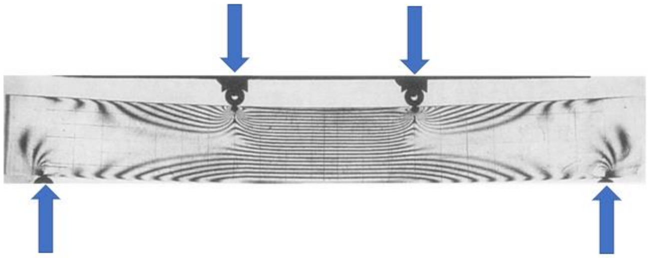

Figure 2 Stress lines in a thin film under a bending load [4]

Therefore, by measuring the change in polarization of light through the stressed substrate, and comparing it to the original polarization of the incoming light, it is possible to create a map of the local strain and account for the deformation when adding features to the material or measuring fabricated patterns. This is done by building a plane polariscope, which is made using a polarizer to polarize the light source, followed by the material to be analyzed, and then a second polarizer at 90 degrees to the original for analyzing the change in polarization after the light has passed through the material. This basic setup can be seen if Figure 3.

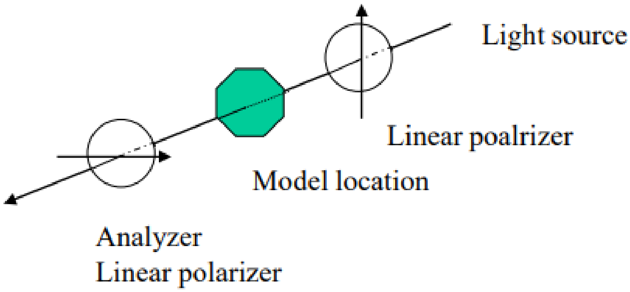

Figure 3 Progression of light through a plane polariscope [3]

The original polarizer sets the original polarization of the light from the light source, so that it may pass through the tensioned substrate and have its polarization angle changed by the photoelastic effect. Then, a polarizer oriented perpendicular to the first polarizer analyzes the light that passed through the substrate by cancelling out all light except for that which had its polarization changed by the photoelastic effect. A proposed experimental setup is pictured in Figure 4 and depicts the flow of light through the system and includes the locations of the proposed image capturing device.

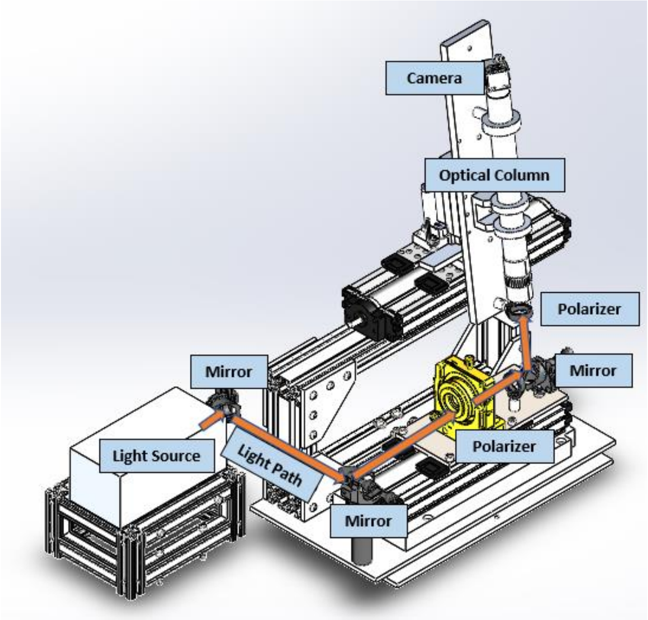

Figure 4 Full Polariscope Tool Design

## 3. METHODS AND ANALYSIS

The images captured by the setup will be visual representations of the stress across the web. These will be generally composed of fringes of varying intensity of light that can be counted and analyzed to determine the amount of strain that the web undergoes during R2R-typical tension. In order to capture usable data as quickly as possible, with as few images as possible, the light source must be white light. The resulting fringes will include the full spectrum of light, and bands of each color can be analyzed separately to produce the most accurate results. Otherwise, monochromatic analysis would require taking multiple images of each section of the web at various polarization angles to produce similar results [5].

The proposed method of image analysis is a computer-vision-based approach that will employ image segmentation to identify and count fringes in each image.

Upon the completion and optimization of the tool construction and the necessary image analysis methods, the setup will be able to output reliable deformation measurements of the web on the R2R system. With these measurements, it will be necessary to model and predict web deformation under tension, and begin working on a reliable method of adjusting manufacturing parameters in order to correct for the measured displacement and begin manufacturing multilayer devices with minimal register error.

## ACKNOWLEDGMENTS

This research is based upon work supported primarily by the National Science Foundation under Cooperative Agreement No. EEC-1160494 and Graduate Research Fellowship Program Grant No. 2017251210.

## REFERENCES

[1] J. Lee, S. Park, K. H. Shin, and H. Jung, “Smearing defects: a root cause of register measurement error in roll-to-roll additive manufacturing system,” *Int. J. Adv. Manuf. Technol.*, vol. 98, no. 9–12, pp. 3155–3165, 2018, doi: 10.1007/s00170-018-2465-0.

[2] J. Lee, P. Isto, H. Jeong, J. Park, D. Lee, and K. H. Shin, “Register mark measurement errors in high-precision roll-to-roll continuous systems: The effect of register mark geometry on measurement error,” *Appl. Phys. Lett.*, vol. 109, no. 14, 2016, doi: 10.1063/1.4964262.

[3] W.-C. Wang, “Photoelasticity,” p. 66.

[4] G. Cloud, *Optical Methods of Engineering Analysis*, vol. 34. Cambridge University Press, 1995. Accessed: Jul. 26, 2021. [Online]. Available: http://doi.wiley.com/10.1111/j.1747-1567.2009.00611.x

[5] M. Ramji and K. Ramesh, “Whole field evaluation of stress components in digital photoelasticity—Issues, implementation and application,” *Opt. Lasers Eng.*, vol. 46, no. 3, pp. 257–271, Mar. 2008, doi: 10.1016/j.optlaseng.2007.09.006.