Towards Roll-to-Roll Manufacturing of Polymer Photonic Devices

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ABSTRACT

Traditionally, polymer photonic devices are fabricated using clean-room processes such as photolithography, e-beam lithography, reactive ion etching (RIE) and lift-off methods etc, which leads to long fabrication time, low throughput and high cost. We have utilized a novel process for fabricating polymer photonic devices using a combination of imprinting and ink jet printing methods, which provides high throughput on a variety of rigid and flexible substrates with low cost. We discuss the manufacturing challenges that need to be overcome in order to realize true implementation of roll-to-roll manufacturing of flexible polymer photonic systems. Several metrology and instrumentation challenges involved such as availability of particulate-free high quality substrate, development and implementation of high-speed in-line and off-line inspection and diagnostic tools with adaptive control for patterned and unpatterned material films, development of reliable hardware, etc need to be addressed and overcome in order to realize a successful manufacturing process. Due to extreme resolution requirements compared to print media, the burden of software and hardware tools on the throughput also needs to be carefully determined. Moreover, the effect of web wander and variations in web speed need to accurately be determined in the design of the system hardware and software. In this paper, we show the realization of solutions for few challenges, and utilizing these solutions for developing a high-rate R2R dual stage ink-jet printer that can provide alignment accuracy of <10μm at a web speed of 5m/min. The development of a roll-to-roll manufacturing system for polymer photonic systems opens limitless possibilities for the deployment of high performance components in a variety of applications including communication, sensing, medicine, agriculture, energy, lighting etc.

Keywords: imprint lithography, ink jet printing, polymer photonics, roll-to-roll, high-rate

1. INTRODUCTION

Polymer based devices provides an excellent platform for demonstrating various kinds of active and passive devices, including optical bus waveguides [1], optical switches [2, 3], optical modulators [4-6], etc. Most of the fabrication has relied extensively on conventional microelectronic fabrication processes including electron-beam and ion-beam writing. The use of electron or ion-beam writing has made possible the patterning of sub-100nm features on a variety of substrates, leading to the demonstration of a large variety of interesting and useful phenomena in both the electronics and photonics domains, which are unthinkable using conventional photolithography. Although such tools have tremendously helped researchers and scientists explore interesting areas of physics and engineering, they are inherently restricted for use over small areas, up to the size of a full wafer. Moreover, the throughput using such high-resolution tools is prohibitive for use in the commercial market. Since the cost of the fabrication system has been increasing rapidly with diminishing feature size, and the cost of an extreme UV (EUV) wafer fabrication system for sub 35nm features is likely to exceed $1Billion, other low cost alternatives need to be explored in order to make the technology commercially viable.

To counter this problem, over the last decade, there has been an escalating progress in several patterning technologies such as optical soft lithography (OSL), nanoimprint lithography (NIL), edge lithography, solid-state superionic stamping etc [7-9]. Of these, NIL has shown great promise for low cost and high resolution patterning of sub-100nm patterns on a large area [10-12]. The use of NIL has found tremendous market in the areas of semiconductor devices (CMOS integrated circuits, transistors), nanotechnology (Hard Disk Drives etc), sensors (CMOS image sensors), optics (high

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brightness LEDs), biomedical applications etc [11-14]. The International Roadmap for Semiconductors (ITRS) placed NIL in its 2003 edition and NIL is currently heading for 32-nm node.

Although R2RNIL has shown tremendous promise for developing ultra-small nanoscale optical structures with high throughput and at a fraction of the cost of conventional lithography tools on a large area substrate, it does not provide the capability of controlled placement of materials at desired locations on the substrate, which is a crucial requirement for developing integrated photonic components. Ink-jet printing, used in conjunction with R2RNIL manufacturing system, can provide excellent flexibility in terms of precise material placement, low material wastage, and full automation capability. Another advantage is that several flexible electronic components such as RFID tags, sensors, batteries, displays, photovoltaic cells, RF amplifiers, switches, antenna elements, driving electronics etc, can also be fully printed along with R2RNIL developed photonic nanostructures for developing fully printed, multi-functional conformal optoelectronic systems that can easily be attached to any surface.

In our previous work, Using a combination of imprinting and ink-jet printing, for the first time, a 2x2 TO polymer switch was developed and high speed switching at 1kHz, with a rise/fall time of less than 0.5ms, was demonstrated [15]. We also developed an EO polymer modulator using the printing method, and demonstrated operation up to 15MHz [16] for the first time.

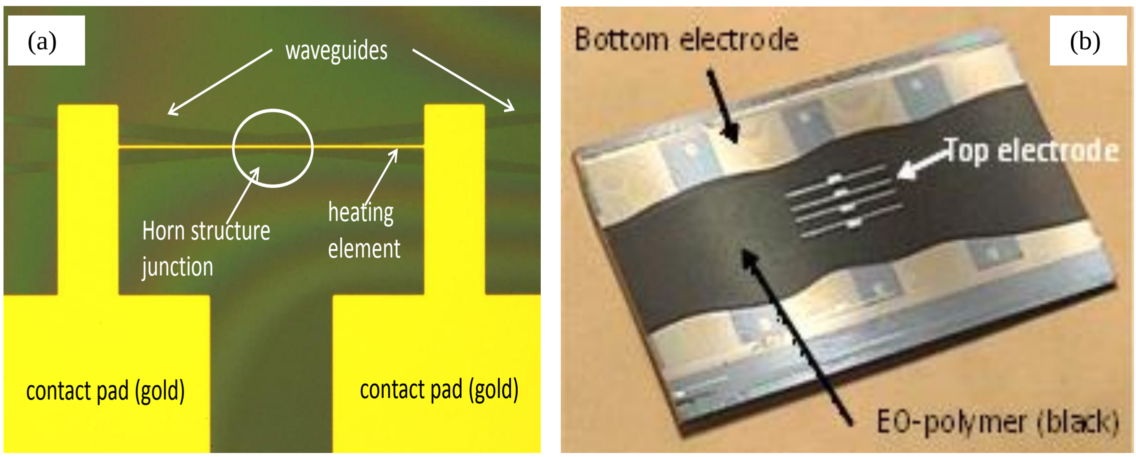

Fig. 1 microscope images of (a) printed thermo-optic (TO) polymer switch [15] and (b) electro-optic (EO) polymer modulator [16]

For both these devices, a soft SSQ mold was prepared from a silicon master mold, and the core layer pattern was imprinted in a polymer bottom cladding. Then, ink-jet printing was utilized to precisely align and print the other layers to complete device fabrication. Accurate alignment was achieved via utilization of alignment marks. Microscope images of the fabricated devices are shown in Figs. 1(a) and (b). Fig. 2 shows SEM images of the cross sections, together with device characterization results for the printed EO polymer modulator [Figs. 2(a-b)] and TO polymer switch [Fig. 2(c-d)]. The performance metrics are comparable with those fabricated using traditional fabrication processes.

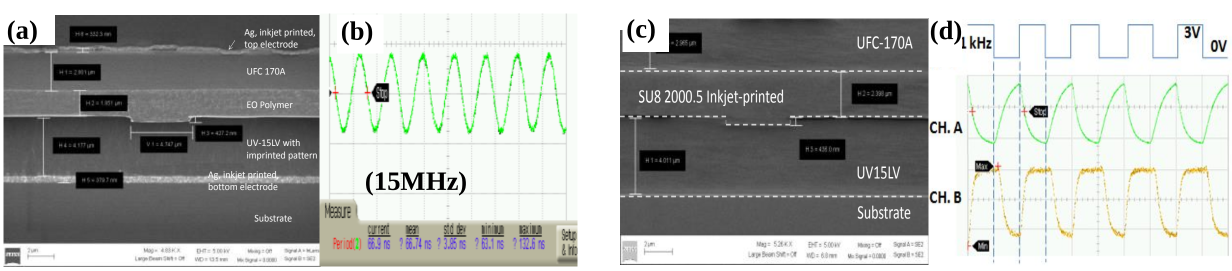

Fig. 2 (a) SEM cross section of fabricated EO polymer modulator. (b) Characterization result at a frequency of 15MHz is shown [16]. (c) SEM cross section of fabricated TO polymer switch. (d) Characterization result at a switching speed of 1kHz is shown [15]

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In this paper, we will discuss some of the metrology and instrumentation challenges that need to be overcome in order to enable R2R manufacturing of printed photonic devices. We have successfully addressed several of the challenges and developed complete R2R printing systems that can be utilized for manufacturing, which will be able to provide a great potential solution for the development of flexible and low cost integrated photonic devices with high yield.

2. CHALLENGES FOR HIGH-RATE R2R PHOTONIC DEVICE MANUFACTURING

A schematic of our proposed R2R manufacturing process is shown in Fig. 3. R2RNIL defines the structural patterns, while ink-jet printing is utilized to print all layers and complete device fabrication. There are several challenges that need to be overcome in order to enable high-rate R2R manufacturing of flexible photonic systems. A few key challenges are described below.

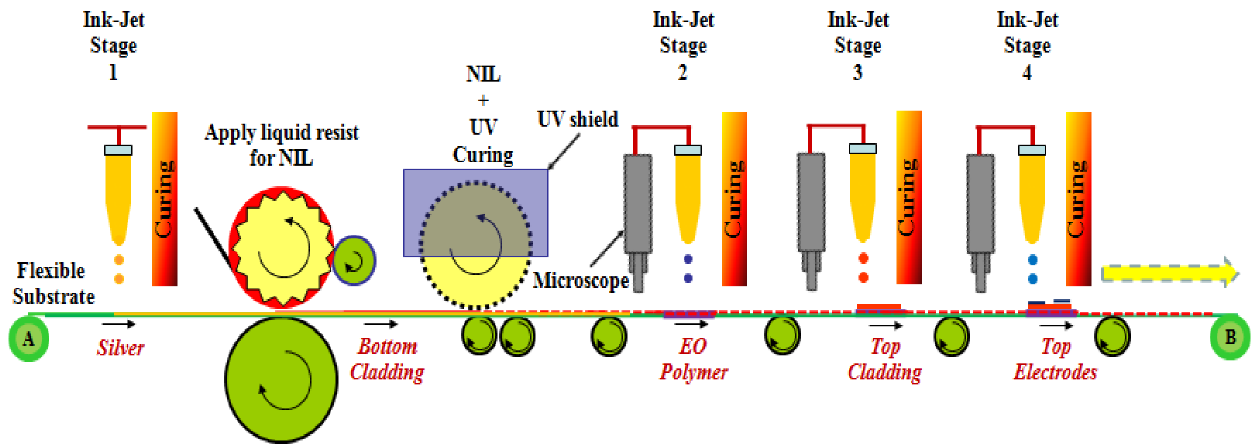

Fig. 3 A schematic for R2R manufacturing of polymer photonic devices utilizing a combination of ink-jet printing and nanoimprinting. An example for fabricating an EO polymer modulator is shown.

i. Defects

Defects such as cracks and breaks in the printed film layer are the biggest concern for printed photonic devices since they can completely destroy the performance of the devices. There are several factors that cause defects such as missing nozzles in the print head, particles on the substrate, particles on the screen/stamp, web wander, non-uniform web tension, mis-registration etc. A few examples of defects are shown in Fig. 4. Fig. 4(a) is the intended pattern, while Figs. 4(b), (c) and (d) show different kinds of defects that can be produced due to various reasons.

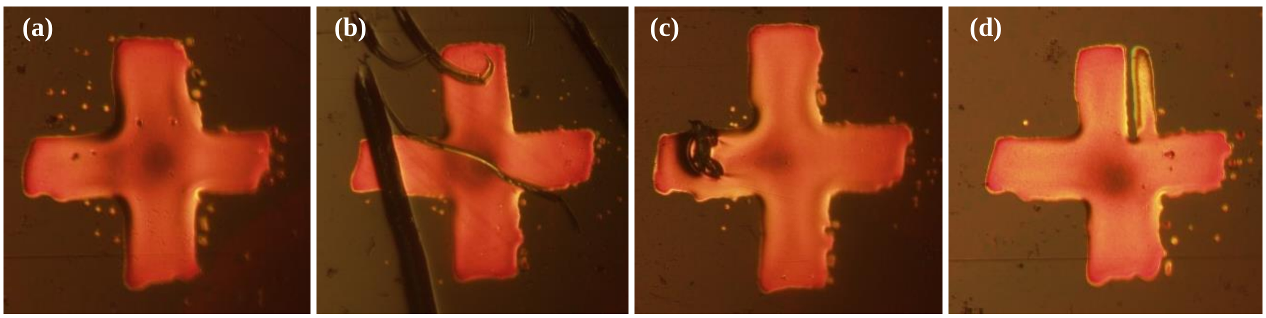

Fig. 4. Optical microscope images of (a) an intended pattern, and (b-d) show defects in the pattern

Defects become even more critical for nanomanufacturing. Since the defect dimensions are on the same order or larger that the structural dimensions (usually in the sub-micron range), their control becomes extremely critical. Since the dimensions are small, any small defect in these structures such as cracks, missing lines, collapsed lines etc can entirely deteriorate the device performance. Several factors, including unequal stress, imprint resist properties, surface energy issues, defect in the mold etc can cause defects in the nanoimprinting process. Due to the nature of the small dimensions, their detection becomes even more challenging at high-rate R2R nanoimprint processes [17]. Alternative solutions based

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on R2R optical lithography can be exploited for such applications as well for higher throughput and potentially reduced defect density [18].

ii. Static:

An important contributing factor to defects is the presence of large amounts of static charges on the fabricated substrate surfaces. These static charges on substrates are produced due to the nature of the fabrication process itself, as well as during to their handling. The static charge attracts dust and other particles from the floor or from the air, which can cause unwanted defects on the printed layers [19]. A particle few microns big can either cause a defect. Static also greatly influences the material deposition accuracy, as the charged ink can be pulled or pushed, causing ghost tracks, overspray, misregistration etc, which are detrimental to the overall quality of the printed layer. Especially for small feature manufacturing at high rates, mis-registration can produce disastrous results. Manufacturing lines occasionally use static rods or special coatings to alleviate this problem [19], however, with increasing complexity in manufacturing processes, their control also becomes tricky. Special techniques, including in-line web cleaning systems with static control need to be incorporated, thus adding to the overall cost of the system.

iii. Missing or disconnected patterns:

Missing or disconnected patterns constitute another kind of defects. For printed media, this does not cause appreciable change in the aesthetic appeal due to the inherent limitation of human eye. However, for photonic devices, they can be disastrous. There can be several causes for such missing patterns – a missing nozzle, a deviating nozzle, web wander. For example, as the web moves sideways, some regions get printed with excess ink and the others miss some ink. Apart from web wander, defects /particles on the stamp or screen can also cause such defects. Timely inspection of hardware is necessary in order to minimize this effect. Web guiding systems need to be employed in order to ensure accurate web movement.

iv. Substrate

Another challenge for high rate R2R manufacturing is the unavailability of good quality substrates. The type of substrate used also greatly impacts defect generation in a R2R process. Several substrate parameters such as transparency, surface roughness, surface energy, high temperature operability, chemical and moisture resistance etc are critical for various applications. An important factor affecting device quality is surface roughness. Current substrate surface roughness is five to ten times worse than that of glass [20]. Controllability of roughness to within a few nanometers is crucial for achieving high quality thin uniform printed films. Although suppliers can produce very smooth surfaces, the material cost is prohibitively high for printed photonics applications [21]. If dealing with rough surfaces, effect of such non-uniformities in the printed layer on the device performance has to be extensively modeled. Thresholds determining decent performance criteria should be set for the operator.

v. Registration

A third challenge is accurate registration control. For printed photonics, it is extremely crucial to have good registration between different printed layers in order to avoid defects and sacrifice performance. Existing tools used in printed media are inadequate to account for tight registration requirements. Therefore, new hardware and software tools need to be developed, which involves high cost. Registration accuracy is impacted by several factors, for example, drop velocity. If two droplets are fired from the print

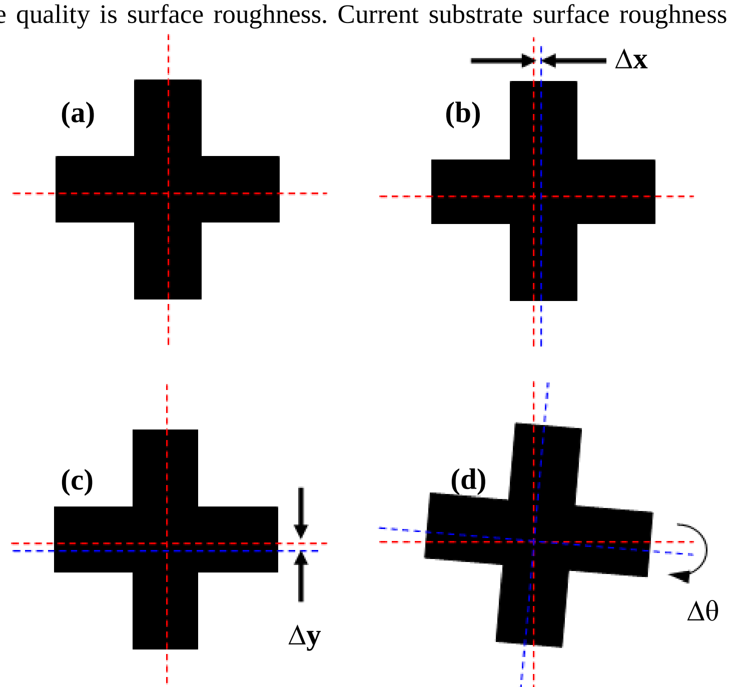

Fig. 5. Copies of patterns with error coordinates of (a) x=0, y=0, $\theta=0^o$ (Intended Pattern), (b) x=Δx, y=0, $\theta=0^o$, (c) x=0, y=Δy, $\theta=0^o$, (d) x=0, y=0, $\theta=\Delta\theta^o$

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head at the same velocity, they will land at the same place on the substrate. However, if the velocities are slightly different, and the web is moving at high rate, then the separation becomes large, thus causing mis-registration. Accuracy also depends on web transport stability, type of hardware or software used etc. Very good software tools need to be developed that can detect misalignments and enable automatic correction. We have developed a tool that looks at the alignment mark at high rate and provides error in position information.

Consider an alignment mark, such as a cross mark, printed along with each layer as shown in Fig. 5(a). Figs. 5(b), (c) and (d) denote various lateral, longitudinal and angular offsets. A high speed camera looks at specific alignment marks that are printed along with the electronic circuits. The imaged alignment marks are compared against a set of standard patterns preloaded in the computer software, and the misalignment coordinates in terms of x, y and rotation (theta) are calculated and displayed. This error information needs to be fed back to the controller in order to correct for the deviation in-line. We have developed the hardware and software tools to achieve accurate alignment between successive printed layers. A picture of our hardware setup consisting of a high speed camera, objective lens, illumination system and an encoder is shown in Fig. 6.

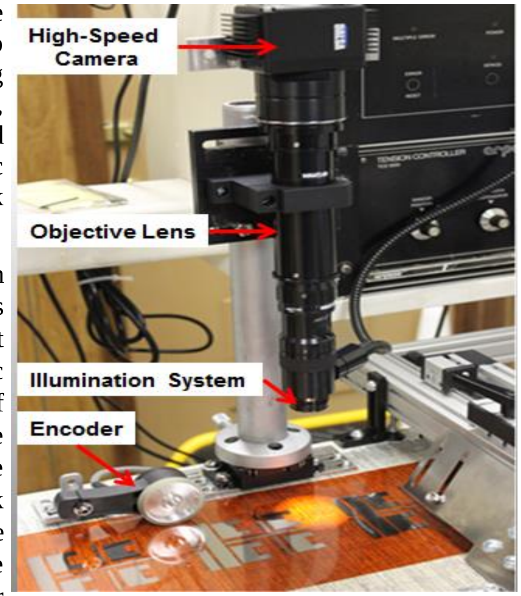

Fig. 6. Picture of hardware toolset developed by us for achieving accurate registration.

The software tool we developed in order to measure mis-registration parameters is shown in Fig. 7. Whenever an alignment mark enters the field of view, it will be captured. The processed result is then used to select the corresponding pre-offset image and send out the print command immediately. The screenshot of the software in operation is shown in Fig. 7 (a). Fig. 7 (b) shows an offset testing result with 20 consecutive alignment marks captured by the camera. A non-flat behavior is typically expected due to sideways wander of the web. From the graph, the maximum sideways wander range of the web is calculated to be about 4mm. We achieved <10μm alignment accuracy using our hardware and software control toolset. This can be further improved with design and architecture modifications.

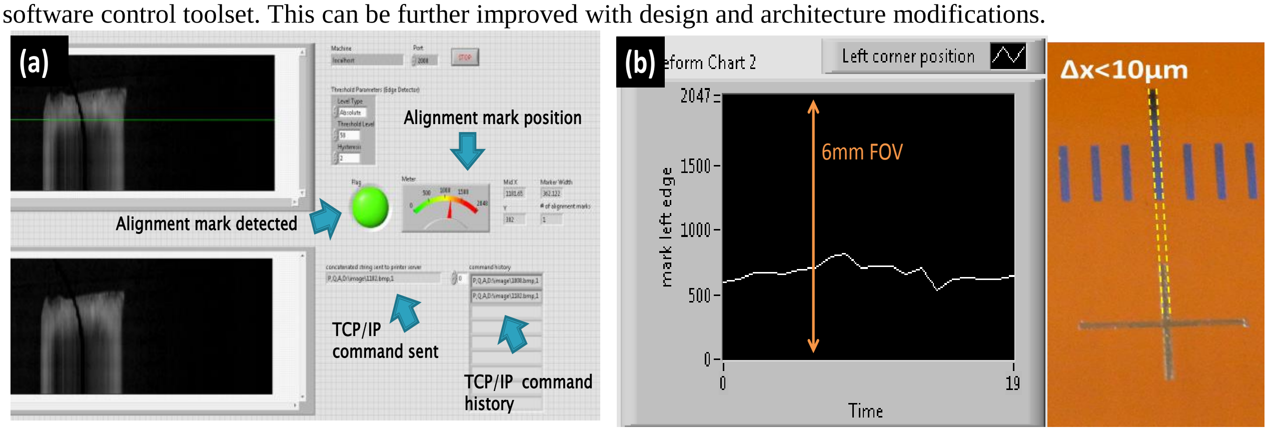

Fig. 7(a) screenshot of the software showing position of alignment mark; (b) detected positions of 20 consecutive alignment marks, indicating the web sideway wander of around 1.5-2mm for this pass. Alignment accuracy <10um can be achieved

vi. In-line/off-line optical inspection and quality control

A critical challenge is in-line optical inspection and quality control. Since the performance of the fabricated device depends strongly on the quality of the printed layers, there is a need to measure the uniformity, surface roughness, dimensions, registration error etc [22]. The defects not only need to be identified at high rate, but they also need to be able to mark of flag bad devices so that it becomes easy to identify waste. If the defect can be corrected, suitable corrective options should be provided. Such correction will tremendously improve throughput and yield. Overall, such tools help in achieving low wastage, high productivity, high quality and customer satisfaction [22, 23].

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We have developed a solution utilizing a high-speed camera, together with associated software that can highlight the image and displays it on the user's panel, as shown in Fig. 8.

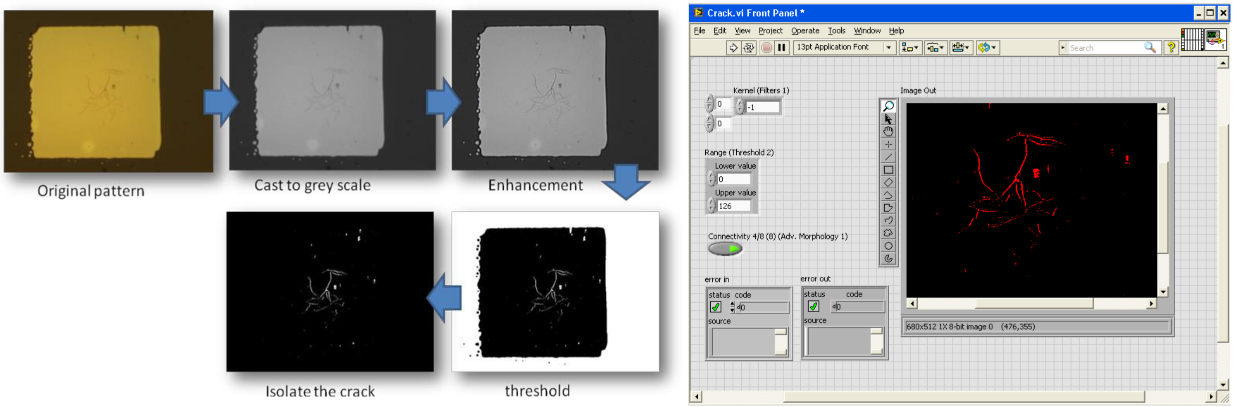

Fig. 8 (left) LabVIEW software developed by Omega Optics and UT Austin to high light defects in a printed layer, (right) highlighted defect is displayed to the user

Utilizing the above identified solutions to some of the challenges, we have developed a high-rate dual stage R2R ink-jet printing system, as shown in Fig. 9. Utilizing this system, together with R2RNIL system, we have started working on developing polymer photonic devices, the results of which will be shared in a future publication.

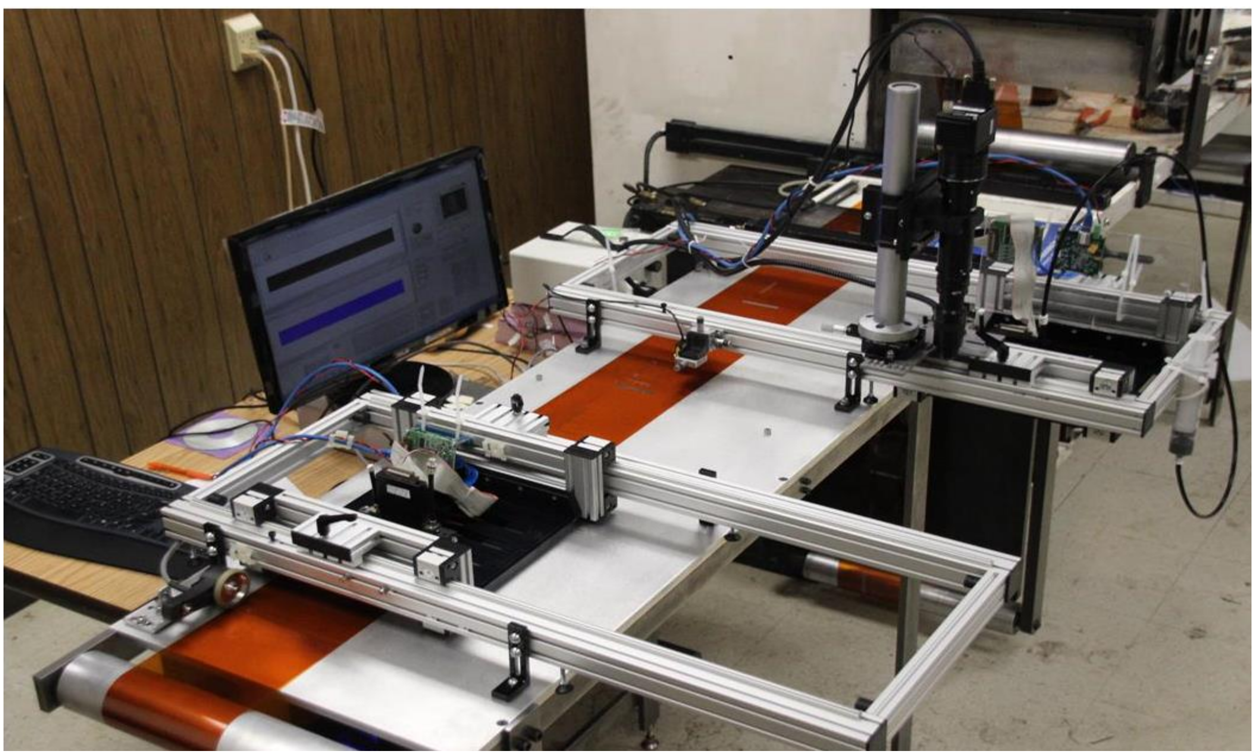

Fig. 9. Dual stage R2R ink-jet printer with integrated hardware and software alignment and quality control tools

3. CONCLUSION AND FUTURE WORK

In conclusion, R2R printing of photonic devices will enable the development of low-cost, conformal, and light weight devices, not achievable utilizing conventional fabrication techniques. In order to achieve such manufacturing, several challenges need to be overcome. We have identified solutions to several of these issues, and developed a dual-stage R2R

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ink-jet printer with integrated alignment and quality control hardware and software toolset. Future work will include utilization of R2R processes for device development, and optimizing parameters for achieving high throughput and yield.

4. ACKNOWLEDGEMENTS

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