Printed Polymer Photonic Devices for Optical Interconnect Systems

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ABSTRACT

Polymer photonic device fabrication usually relies on the utilization of clean-room processes, including photolithography, e-beam lithography, reactive ion etching (RIE) and lift-off methods etc, which are expensive and are limited to areas as large as a wafer. Utilizing a novel and a scalable printing process involving ink-jet printing and imprinting, we have fabricated polymer based photonic interconnect components, such as electro-optic polymer based modulators and ring resonator switches, and thermo-optic polymer switch based delay networks and demonstrated their operation. Specifically, a modulator operating at 15MHz and a 2-bit delay network providing up to 35.4ps are presented. In this paper, we also discuss the manufacturing challenges that need to be overcome in order to make roll-to-roll manufacturing practically viable. We discuss a few manufacturing challenges, such as inspection and quality control, registration, and web control, that need to be overcome in order to realize true implementation of roll-to-roll manufacturing of flexible polymer photonic systems. We have overcome these challenges, and currently utilizing our in-house developed hardware and software tools, <10μm alignment accuracy at a 5m/min is demonstrated. Such a scalable roll-to-roll manufacturing scheme will enable the development of unique optoelectronic devices which can be used in a myriad of different applications, including communication, sensing, medicine, security, imaging, energy, lighting etc.

Keywords: Ink-jet printing, Nanoimprinting, Printed optoelectronics, R2R printing

1. INTRODUCTION

Conventional integrated electronic and photonic systems are bulky, heavy and traditionally the more the technologies are needed to support different functionalities including data terminal, solar cells, display, communication system, batteries, sensors etc, the heavier the systems become. It is desirable to have such varied functionalities in an extremely light weight alternative form, for example, on a light weight flexible substrate that can be integrated together with clothing and other non-planar surfaces. Through functional integration of inorganic, organic and bio-inspired materials, several unique flexible integrated electronic and photonic components such as light sources, modulators, phase shifters, organic solar cells, photodetectors, antennae, reconfigurable logic and switches, OLED displays, sensors, memory, batteries etc, can all be fabricated on a low-cost, light weight flexible substrate.

So far, most of the photonics 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, 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 [1-3]. Of these, NIL has shown great promise for low cost and high resolution patterning of sub-100nm patterns on a large area [4-6]. 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 brightness LEDs), biomedical applications etc [5-15, 16-19]. The International Roadmap for Semiconductors (ITRS) placed NIL in

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its 2003 edition and NIL is currently heading for 32-nm node. Although NIL technique has been used to pattern sub-wavelength features on a variety of rigid and flat substrates to demonstrate optical devices such as photonic crystals, high brightness LEDs, etc, the throughput of such systems of ~1-3 minutes per wafer is still low to meet the demands of many practical applications, especially in flat panel displays, photonics, biotechnology, and organic optoelectronics. Only a continuous roll-to-roll process, that can increase the patterning speed, thus reducing cost, can be considered to be a viable manufacturing technology.

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. Utilization of a R2R compatible ink-jet printing system, in conjunction with R2RNIL manufacturing system, can provide excellent flexibility in terms of precise material placement, low material wastage, and full automation capability, thus leading to the development of a low-cost, high rate manufacturing technique for forming flexible photonic and electronic devices. Several other unique materials, such as nanowires, quantum dots, nanotubes, nanoparticles, organics, can be utilized to develop several unique components, such as RFID tags, sensors, batteries, displays, photovoltaic cells, RF amplifiers, switches, antenna elements, etc, that can be integrated together with printed photonic devices to form multifunctional conformal optoelectronic systems, that can easily be attached to any surface.

A viable manufacturing scheme for developing integrated photonic devices is schematically shown in Fig. 1 [20]. R2R fabrication of waveguide patterns on flexible substrates for photonics applications is performed using a R2RNIL process. Utilizing a series of precise ink-jet printers equipped with alignment and quality control tools, all the other materials are precisely deposited. Depending on the specific device structure, NIL and Ink-Jet printing processes can be utilized in an appropriate sequence to develop discrete photonic components or a complete optoelectronic integrated system. For example, Fig. 1 also shows a scheme for forming a flexible EO polymer modulator combining R2R NIL and Ink-Jet printing. To begin, a silver ground electrode is deposited using ink-jet printing on the flexible substrate and cured. Following this, a UV curable polymer such as UV15LV is deposited and patterned using a R2RNIL system. The EO polymer material is then precisely deposited over the patterned area using an ink-jet printer and baked to form a solid layer. In the next two ink-jet printing stages, top cladding polymer, such as UV15LV, and top silver electrodes are printed and cured, respectively, to form a full device. The development of such an affordable high-rate manufacturing process for integrated photonic and electronic systems enables the availability of a whole new suite of cheap, light weight, low-power, and conformal circuits that can be used for military as well as for commercial applications.

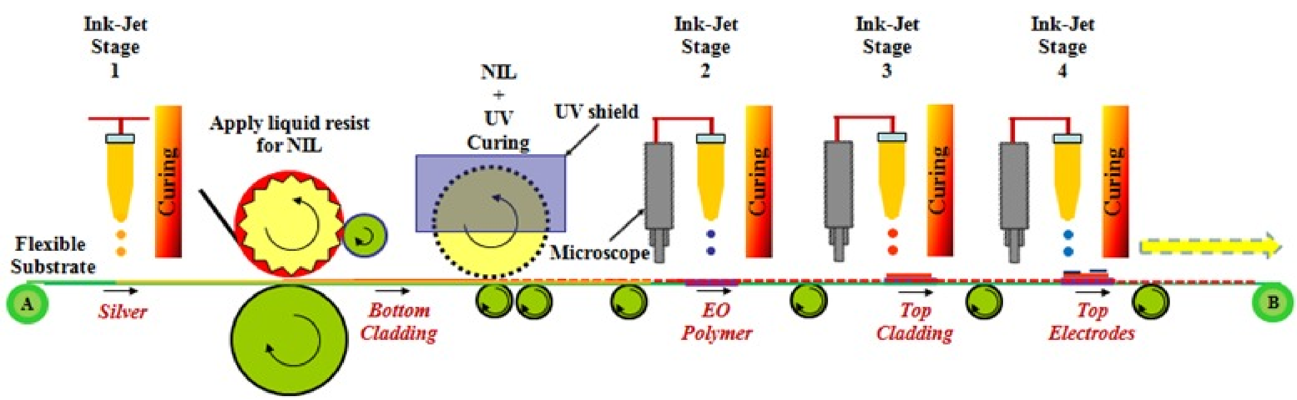

Fig. 1 A schematic of high rate, large area roll-to-roll (R2R) manufacturing of integrated photonic devices using a combination of nanoimprint lithography (NIL) and ink-jet printing processes on a flexible substrate. NIL forms sub-100nm patterns on polymer film. Ink-Jet enables precise placement of materials to form full device [20].

In this paper, we present several printed photonic devices, such as modulators, switches, and delay lines that can be utilized for optical interconnect applications. The paper is outlined as follows: In section 2, the fabrication procedure and characterization results for electro-optic polymer based modulators and switches and thermo-optic polymer switch based delay lines are presented. In section 3, aspects of roll-to-roll processing are covered and some of the challenges for R2R printing of photonic devices, such as quality control, misalignment correction, etc are discussed. Concluding remarks are provided in section 4.

2. PRINTED OPTICAL INTERCONNECT COMPONENTS

2.1 Electro-Optic (EO) Polymer based Mach-Zehnder Modulator

An EO modulator can be used in several applications such as high speed communication networks, radar systems, high frequency optical chopping, RF wave sensing, etc. We developed a modulator structure using the fabrication process flow shown in Fig. 2 [21]. First, a flexible mold is fabricated using a silicon hard mold. The flexible mold is then used to define the core region in a UV15LV (from MasterBond) bottom cladding layer, which is coated on a rigid/flexible substrate which has an ink-jet printed silver bottom electrode layer [**Error! Reference source not found.**(b)]. Following this step, an ink-jet printer is used to print a layer of EO polymer (SEO125 from Soluxra, LLC), which not only fills the core trench, but also forms a planar top surface for further processing [Fig. 2(c)]. Upon curing, a layer of UFC-170A (from Raychem) is ink-jet printed on top to form the top cladding layer. Finally, the top silver electrode is printed on top to complete the device fabrication.

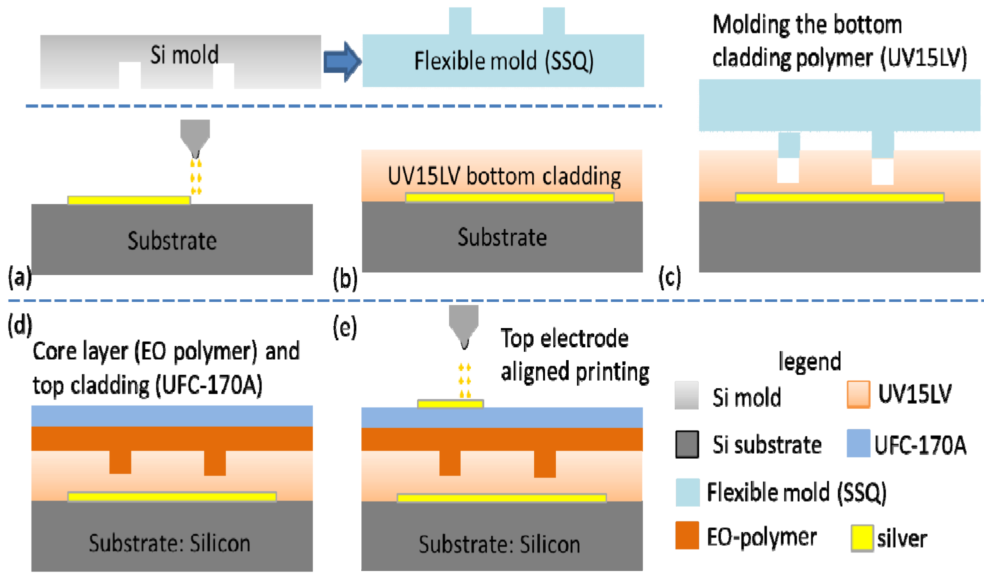

Fig. 2 Process flow for fabrication an electro-optic polymer based device with top and bottom electrodes [21].

A picture of a fully fabricated modulator device is shown in Fig. 3(a). An SEM image of the cross-section showing the different layers is presented in Fig. 3(b). After fabricating the device, the EO polymer is poled in order to activate the EO effect. The top and the bottom electrodes serve as the poling electrodes. Poling electric field of about 80V/μm is applied vertically across the polymer waveguide. During the poling process, the temperature is controlled to increase from room temperature to a peak poling temperature of 140°C, which is 5°C above the glass transition temperature T_g of the EO polymer, and then quickly decreased back to room temperature. The leakage current is monitored using a picoammeter.

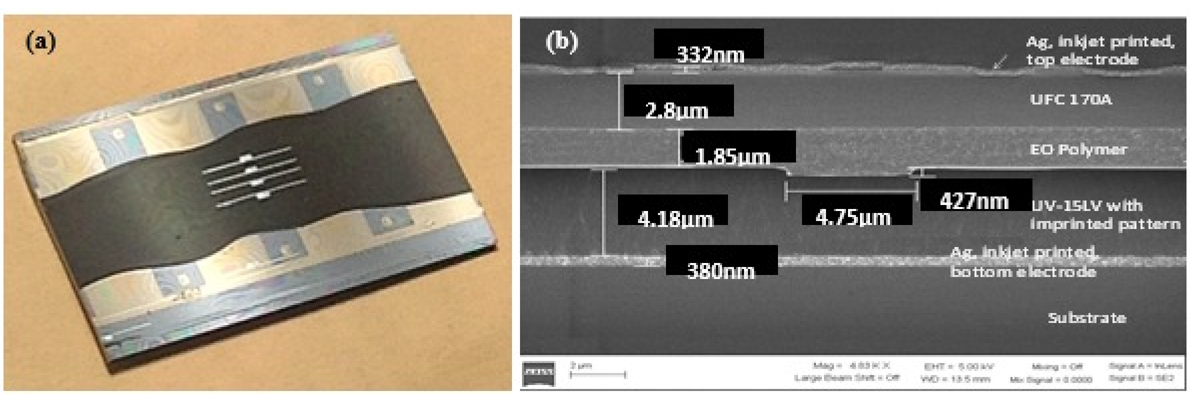

Fig. 3 (a) Picture of a fully fabricated EO modulator device, (b) SEM cross-section image showing the different layers [21].

Upon completing the poling process, TM polarized light at 1550nm wavelength from a tunable laser is launched into the device using a lensed fiber and the output light is collected by a single mode lensed fiber. Output response of a 15MHz sinusoidal input [Fig. 4(a)] applied to the modulator as measured on a digital oscilloscope is shown in Fig. 4(b). The speed limitation is due to the limit on our signal source rather than on the device since EO polymers intrinsically have a very fast response time.

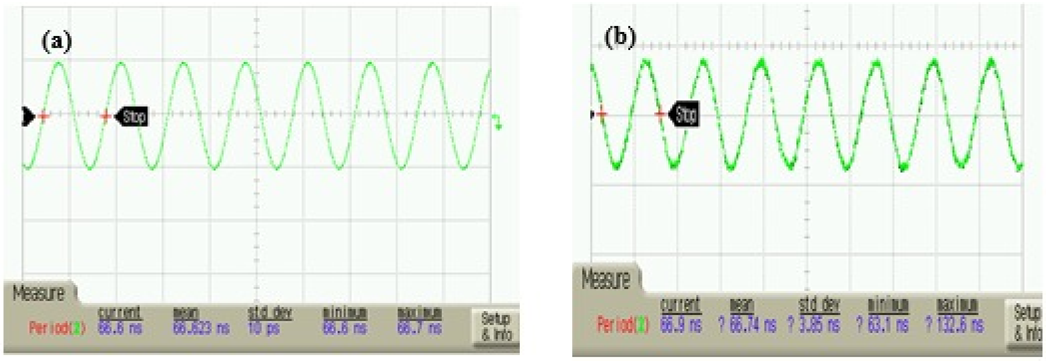

Fig. 4 (a) Input 15MHz electrical signal, (b) Output 15MHz optical signal [21]

2.2 Electro-Optic (EO) Polymer based Ring Resonator Switches

We also developed EO polymer based ring resonators that can be used as switches in optical networks. The fabrication flow is similar to that shown in Fig. 2. Microscope images showing the fabricated results after different steps are shown in Fig. 5.

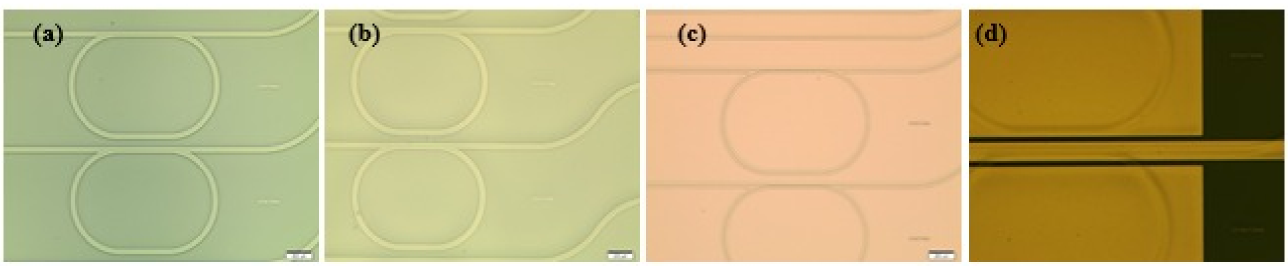

Fig. 5 Microscope images of the device after (a) imprinting in the UV15LV bottom cladding, (b) EO polymer printing, (c) UFC-170A top cladding deposition, and (d) electrode deposition.

After fabricating the device and poling the polymer, we measured the optical spectrum on an optical spectrum analyzer at different voltages (-1V, 0V,+1V) applied across the electrodes. A superimposed spectrum for the three bias voltages is shown in Fig. 6(a), and a zoomed-in view showing the resonance feature details around 1565nm is shown in Fig. 6(b).

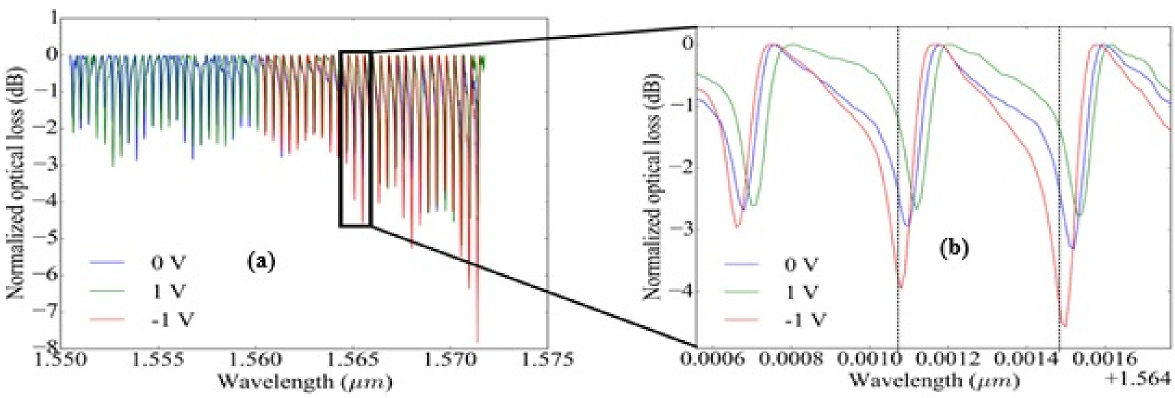

Fig. 6 (a) Measured optical spectra at different bias voltages applied across the device. (b) a zoomed-in section of the spectra showing the detailed shifts in the resonance wavelengths as a function of the applied voltage.

It can clearly be seen from the figure that there is a shift in the resonance when the bias voltage is varied. At a fixed wavelength, indicated by vertical solid lines in Fig. 6(b), a change in output intensity is observed as the bias voltage is varied, thus changing the state of the switch from an OFF to an ON state.

2.3 Reconfigurable delay network comprising of thermo-optic polymer switches

Reconfigurable delay networks are very useful in optical, communication and radar networks. Among various optical switches, polymer-based thermo-optic (TO) switches have been found very attractive, owing to the advantages of 1) high thermo-optic coefficient (-1~3 x10^{-4} K^{-1}), 2) high transparency in the telecommunication wavelength window, and 3) fabrication feasibility over large areas on PCBs and other kinds of substrates. A schematic of an n-bit delay network is shown in Fig. 7(a).

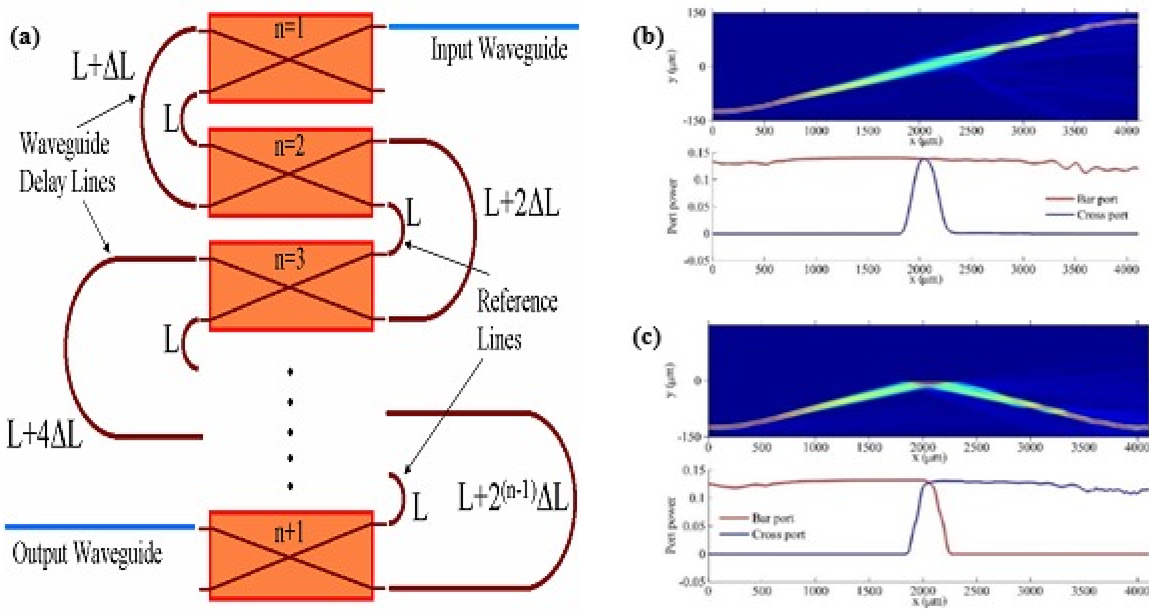

Fig. 7(a) Schematic of an n-bit delay module. It comprises of (n+1) TO polymer switches and judiciously chosen lengths of interconnecting polymer waveguides. (b-c) RSoft BeamPROP simulations showing the switch performance in the absence and in the presence of heater power.

A key element of the module is a printed thermo-optic polymer based 2x2 switch [22]. The thermo-optic polymer switch is a total internal reflection (TIR) based switch. It consists of a heater located at the X-junction of the switch. In the normal case when no heat is applied, light from input port is directed to the bar port [Fig. 7(b)]. When the heater is turned on, the refractive index of the polymer underneath the heater increases compared to the surrounding, thereby causing light to be reflected into the cross port [Fig. 7(c)]. The simulations were performed using RSoft BeamPROP software. Therefore, depending on the ON and OFF states of the n+1 switches, light from the input waveguide is routed to the output waveguide with different delays, through judiciously chosen lengths of polymer waveguides. The minimum length delay step (ΔL) determines the minimum achievable time delay step ($\Delta\tau$) according to $\Delta\tau = n_{eff} \cdot (\Delta L/c)$, where n_{eff} is the effective index of the mode in the waveguide and c is the speed of light in vacuum. At the first switch (n=1), the optical signal is delivered to either the reference waveguide (length L) or the delay line (length $L+\Delta L$), depending on the chosen ON or OFF state of TO polymer switch. Then, the second switch (n=2) couples the optical signal into two more waveguides with lengths L and $L+2\cdot\Delta L$. This sequence is continued until the last switch delivers the optical signal to two waveguides The last switch (n+1) of the n-bit delay TTD line is used to control the optical signal to couple into the output waveguide.

Hard mold imprinting gives satisfactory results for small-area devices, but lacks the capability to provide uniform imprinting over a large area, with de-molding constituting the greatest challenge. In comparison, soft mold gives better uniformity over a large area and an easier the de-molding process however, a suitable material system needs to be selected in order to provide a reliable mold that can repeatedly be utilized. In this work, PDMS was chosen as the imprinting soft mold material. First, a 4-inch Si mold was fabricated using conventional RIE method, and it was then thoroughly cleaned and coated with a surfactant to lower its surface energy. Then, PDMS was used to duplicate the TTD patterns from a 4-inch Si mold. Pictures of a successfully developed large-area PDMS flexible mold are shown in Fig. 8(a-b). The mold showed no defects when inspected under a microscope over the entire area. Next, the PDMS mold was used to imprint the pattern in the UV15DC80LV bottom cladding layer [Fig. 8(c)]. Next, SU-8 was deposited to cover the imprinted trenches to form the core layer of the waveguide. Following this, UFC-170A was deposited on top to form the top cladding [Fig. 8(d)]. The heater was formed using gold evaporation. Note that a metal transfer technique can be used for this purpose. A picture of a fully fabricated delay networ is shown in Fig. 8(e). A zoomed-in area of the heater is also shown.

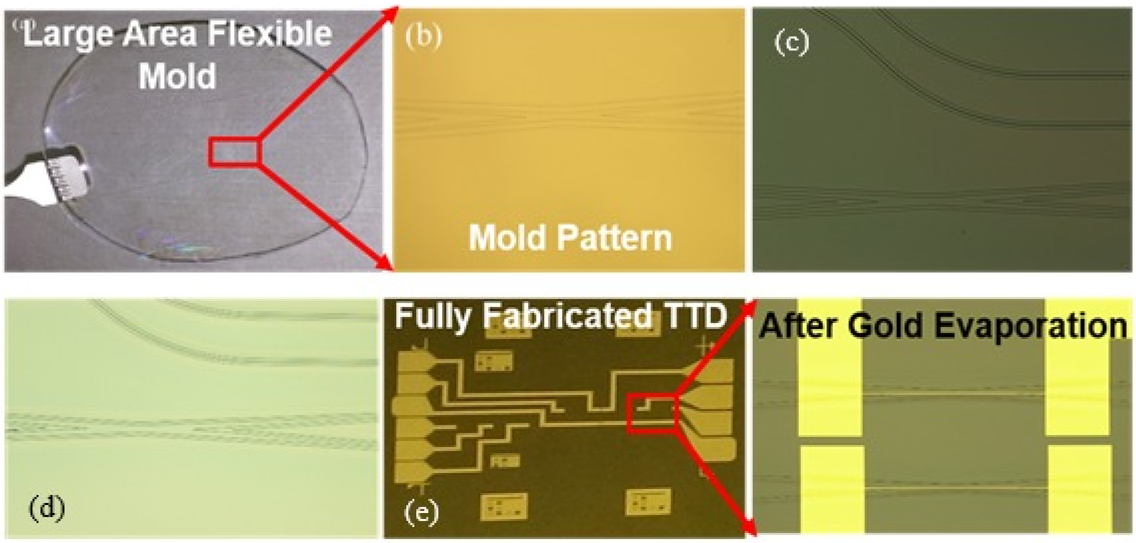

Fig. 8. Pictures of (a-b) large are flexible mold and mold patterns, (c) successful transfer of pattern into a bottom cladding layer, (d) device after top cladding deposition, (e) picture of fully fabricated 2-bit and 4-bit delay networks. A zoomed in view of the heater is shown

We characterized the performance of single switches, and demonstrated over 30dB extinction ratio, as shown in Fig. 9(a). By controlling the ON and OFF states of the different switches in the TTD network, we have demonstrated true-time-delay operation. A phase versus frequency plot for different switch configurations is shown. The slope of the phase versus frequency line gives the time delay. As can be seen, a time delay of 35.39ps is achieved from a 2-bit device.

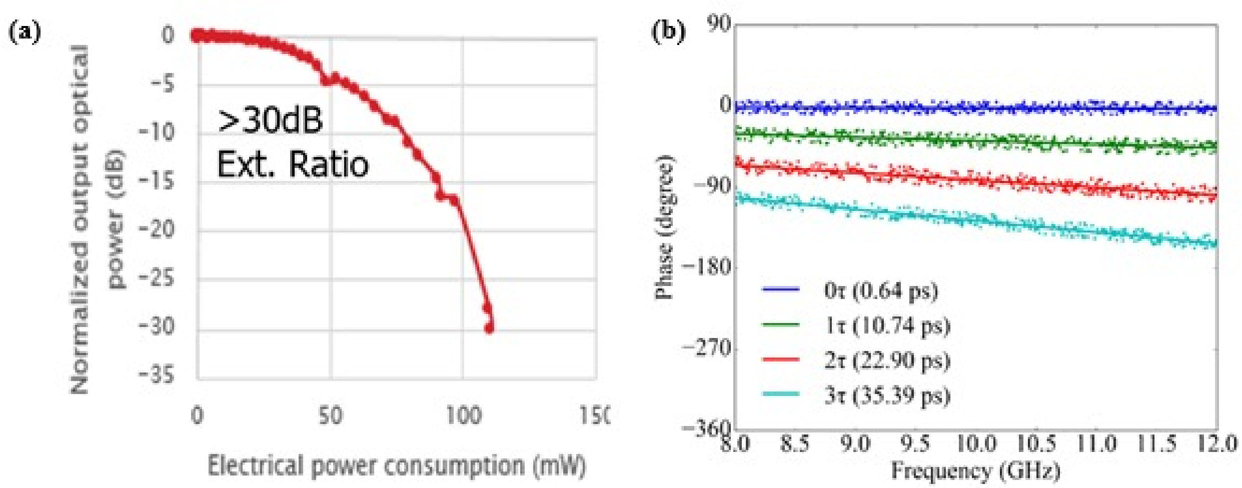

Fig. 9 (a) DC testing of a TO polymer switch. Over 30dB extinction ratio is achieved. (b) Linear Phase vs. Frequency relationship confirming true-time-delay behavior. A time delay of 35.39ps is achieved from the 2-bit device

3. TOWARDS ROLL-TO-ROLL PRINTED PHOTONIC DEVICES

The combination of R2R nanoimprint lithography and R2R ink-jet printing [Fig. 1] forms a very strong manufacturing option for developing printed integrated photonic components requiring sub-wavelength features and integration of several functional materials. In Fig. 1, the flexible substrate is rolled on a web transport system from a source roller A to a collector roller B. After pattern definition utilizing R2RNIL, the materials forming the different layers of the devices are printed using ink-jet printing. For the development of photonic systems requiring ink-jet printing of N materials, in general, a serial array of N print engines is required in order to maximize the throughput. However, for achieving a successful production line, several challenges in the context of photonic device printing must be overcome. A brief discussion of some of the important challenges is provided below:

a. 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. The defects not only need to be identified at high rate, but they also need to be displayed to the operator so that timely action can be taken to correct these defects. The inspection tool should also 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. We have developed a software algorithm that identifies non-uniformities and defects in the print layer at high speed, as shown in Fig. 10(a). The algorithm can also automatically detect defects, as shown in Fig. 10(b) and flag the bad devices for the operator of the machine to see [20, 23].

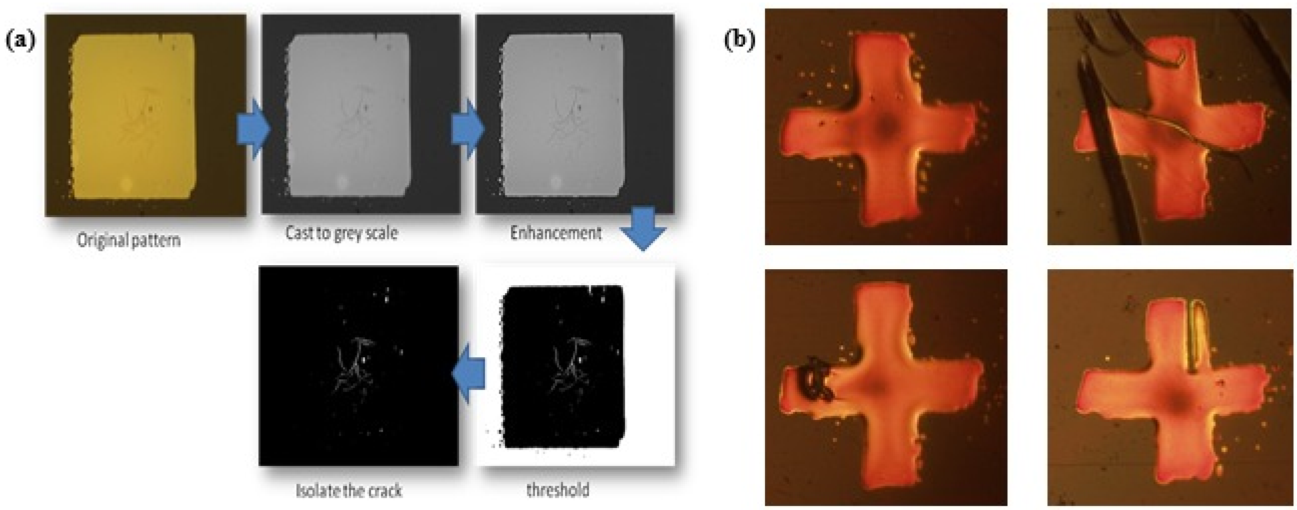

Fig. 10. (a) A defect detection algorithm developed by us that identifies non-uniformities and defects in the printed layer, (b) examples of different defects that can appear on the printed layer that are detrimental to the device performance [20, 23].

b. Registration: In order to ensure good device performance, it is important to make sure all the desired patterns are present at intended locations. There are no existing tools that can provide good registration at high speeds. Most solutions focus on printed electronics applications whose features are in the 10-100μm range. For printed photonics applications, <10μm alignment accuracy is desired. While the alignment accuracy is impacted by a few factors, including print head nozzle firing inconsistencies, these can be minimized by a suitable choice of high performance heads. Web wander is another factor that contributes to misalignment. Efficient software and hardware tools are required that can read an alignment mark at high speed, process it, and correct the print to minimize misalignment. We have developed a toolset, as shown in Fig. 11(a), that can automatically read an alignment mark, calculate the misalignment, and print a corrected pattern. An example of the capability is shown in Fig. 11(b-c). A test pattern comprising of a cross mark is desired to be printed. The print result at a print speed of 5m/min is shown in Fig. 11(c) [24]. We measured the misalignment to be between 10-100microns. By utilizing advanced hardware, it will be possible to consistently achieve <10 microns accuracy. Such a toolset will significantly reduce errors due to misalignment and enable a higher yield of photonic devices.

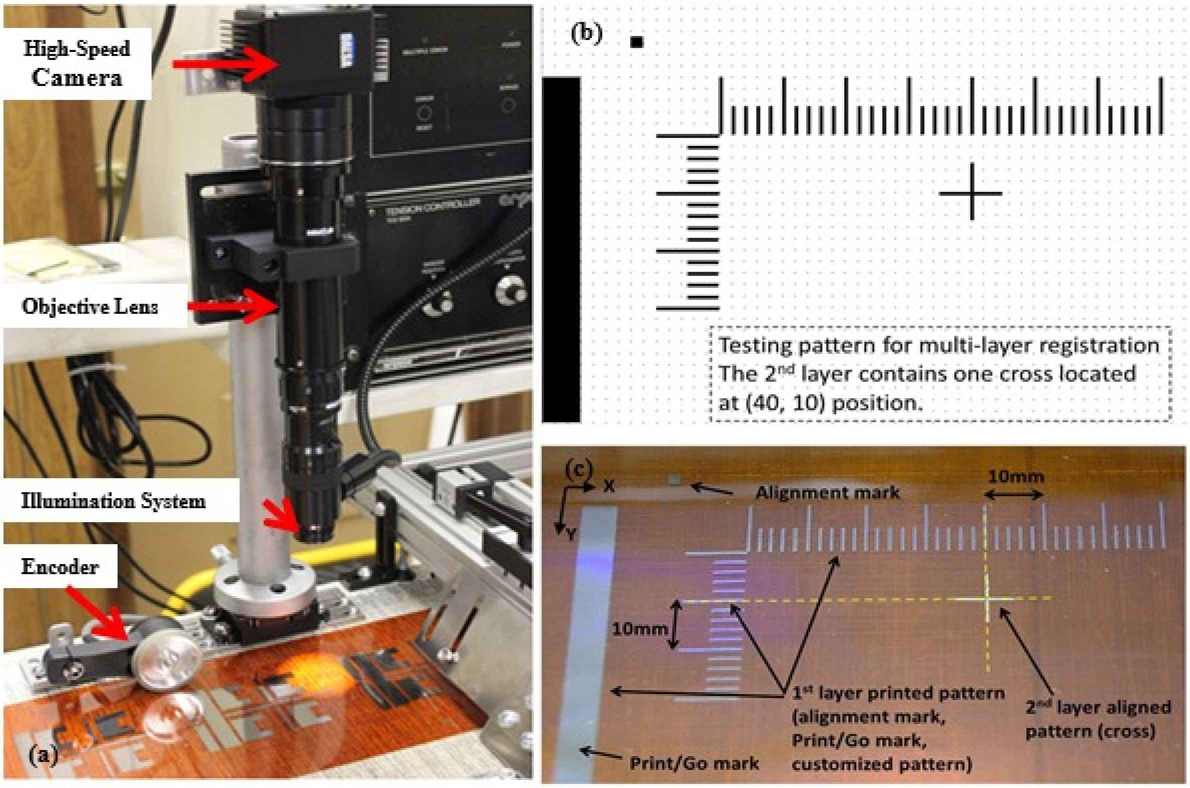

Fig. 11. (a) picture of the hardware toolset used for achieving misalignment correction. (b) an example print design comprising of a cross mark to prove the feasibility. (c) print result at a speed of 5m/min. Misalignment error less in the range of 10-100μm is achieved [24].

c. Web control: A good web transport module is crucial in achieving high yield of the devices. As the web is transported using the computer controlled motor drive system, the substrate passes underneath the print head module. Depending on the individual material characterization results and curing time, the speed of the web drive system needs be controlled in order to achieve successful printing and curing of each material to form the full photonic device. Several factors related to the web such as tension, sudden movement, non-synchronized web parts, web wander etc, can all cause a poor print. Fortunately, precise web control tools are available in the market which can be further customized to suit photonic device development needs.

d. Static: Another contributing factor to defects is the presence of large amounts of static charges on the fabricated substrate surfaces. The static charges attract dust and other particles from the environment, which can jeopardize the photonic device operation. For example, a particle stuck in a critical area of large area flexible mold will render the entire imprinted device useless since it will destroy the waveguide structure. We utilized appropriate static control schemes, such as utilization of static rods, air ionizers, etc to overcome this issue.

We have carefully addressed the above challenges (and a few others not discussed above), and we have customized R2R nanoimprinting and ink-jet printing systems, as shown in Fig. 12. Currently, the R2R NIL system can imprint at a speed of 1m/min [25, 26], while the ink-jet printer can print two materials with good alignment at speeds exceeding 15m/min. We are working on developing and demonstrating photonic devices using our customized systems. The development of such a scalable and affordable high-rate manufacturing system for integrated photonic and electronic systems enables the availability of a whole new suite of cheap, light weight, low-power, and conformal circuits that can be used for several applications.

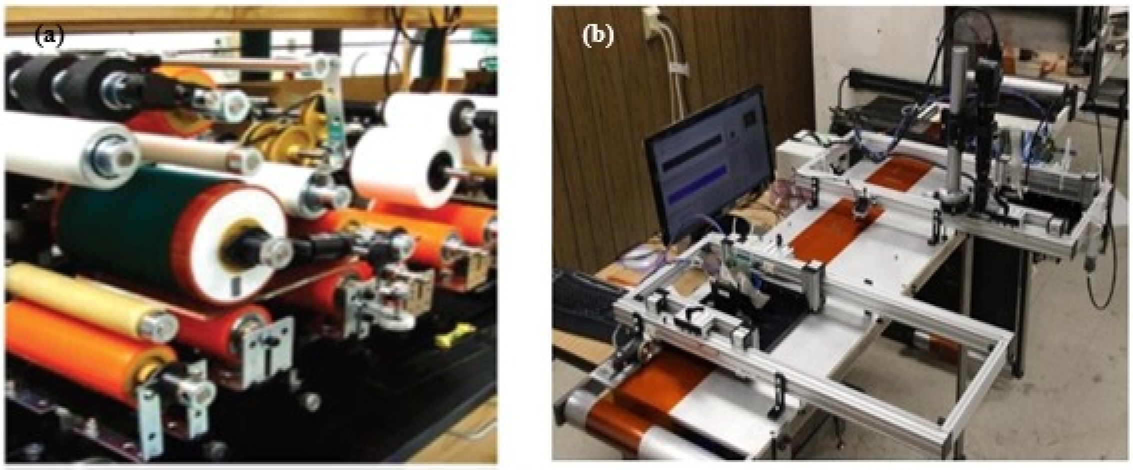

Fig. 12 Pictures of a (a) R2R Nanoimprint (R2RNIL) system [25, 26], and (b) R2R ink-jet printing system that can be scaled for large area and high-throughput development of flexible optoelectronic devices and systems

CONCLUSIONS

Conventional fabrication processes are expensive and as the feature size decreases, the cost increases. Additionally, these methods are not well suited for flexible and conformal device fabrication. In order to enable high throughput and low cost manufacturing of photonic devices, alternative processes are required. We proposed and utilized a combination process comprising of nanoimprinting and ink-jet printing for fabricating photonic devices. In order to prove the feasibility, the fabrication and working of key optical interconnect components such as modulators, switches, delay lines are demonstrated. In our method, nanoimprinting is used to define the waveguide patterns in a bottom cladding polymer such as UV15LV, while ink-jet printing is utilized to deposit the remaining material layers, such as EO polymer and TO polymer core layers, UFC-170A top cladding layer, and silver electrodes. Specifically, an electro-optic polymer based Mach-Zehnder modulator operating at 15MHz, a EO polymer microring switch operating around telecommunication wavelength, and a TO polymer switch based delay line network providing up to 35.4ps in a 2-bit configuration are demonstrated. R2R printing will enable fabrication of optoelectronic devices at high throughput and over large areas on rigid/flexible substrates. We discussed several challenges related to R2R implementation, and we have successfully identified several solutions. Utilizing our customized R2R NIL and ink-jet printing systems, high-rate and low-cost development of optoelectronic devices and systems is achievable.

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