High-Volume Manufacturing of Photonic Components on Flexible Substrates

The penetration of photonic technologies into the low-cost consumer-electronics marketplace has so far been limited. This article details several flexible-substrate-based manufacturing processes that have been developed for the high-volume low-cost production of optical waveguides – key components of a specific optical touch-screen system.

by Robbie Charters

THE RAPID INCREASE in functionality of handheld electronic devices has put significant pressure on standard keypad interfaces to the point that touch-screen interfaces on mobile devices are now a common feature. In addition, the release of Microsoft Windows 7, with its strong touch-application focus, looks ready to make touch screens pervasive at larger screen sizes.

Attractive features of any touch-screen technology include low power consumption, double-touch-pen and/or gloved-finger operation, and freedom from distortion of the liquid-crystal-display (LCD) optical performance through absorbing overlays or films. One class of technology that exhibits all of these features is optical or infrared (IR) touch.[1] In this approach, a grid of IR light beams is constructed, propagating just above the top surface of the LCD. Any touch event breaks the beams, casting a shadow that can be detected by electronic means. Figure 1 shows the typical configuration for an IR touch screen, in which the beams are set on a Cartesian grid and discrete emitters and receivers are mounted in one-to-one correspondence around the edge of the LCD.

An alternative approach, developed by NextWindow, uses point-source corner-mounted emitters to create a spherical coordinate system for IR light beams and camera-based detection. More recently, RPO, Inc., has introduced Digital Waveguide Touch (DWT), in which a series of densely packed light pipes, or optical waveguides, are employed to route LED-generated IR light from the touch-screen grid on the perimeter of

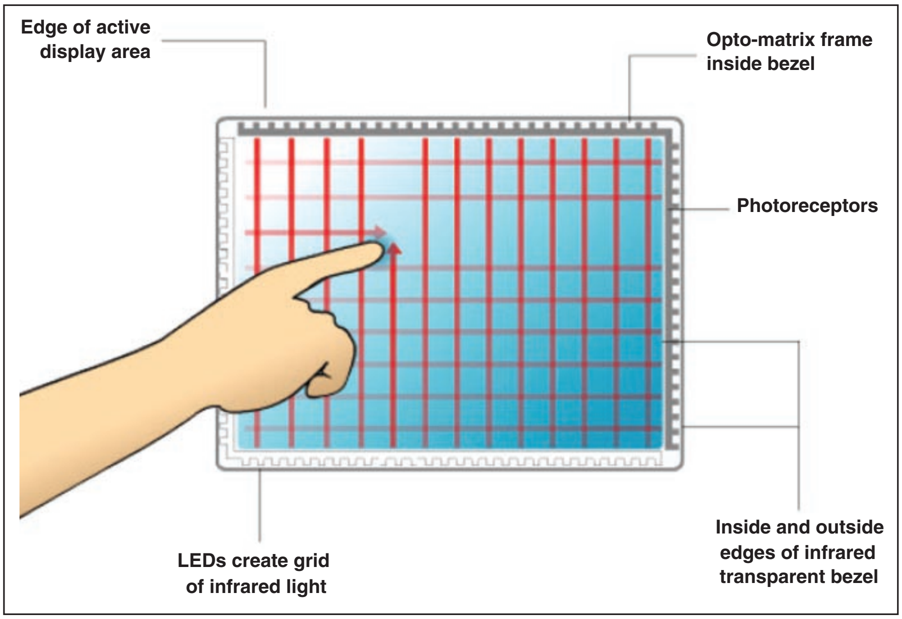

Fig. 1: *In this typical optical-touch-technology configuration, LEDs arranged along two edges create a grid of IR light and discrete receivers (photoreceptors) are mounted in one-to-one correspondence around the opposite edges of the display. Illustration courtesy Elo TouchSystems.*

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the LCD to remotely mounted cameras. The elements of a DWT-based touch screen, shown in Fig. 2, are described below.

The DWT touch-screen module is assembled around a central rectangular LCD panel with the waveguides mounted to the bottom and left edge of the touch-screen assembly. Infrared light is emitted by two LEDs, with each divergent IR light beam striking a parabolic reflector on the opposite side of the assembly. The light beams are collimated by the reflector along the top and left edges of the assembly and reflected back over the top of the LCD panel as a 300-μm thin sheet of IR light projected over the glass surface. The collimated light is captured by the waveguides on the opposite sides of the assembly. Each waveguide channels an independent light path to one or more pixels on an application-specific integrated circuit (ASIC) based light-sensor camera.

This waveguide-based light-distribution circuit offers a distinct advantage over existing optical touch systems by reducing the number of emitters and receivers, thereby dramatically reducing costs and power consumption. In addition, the miniaturization of the optical components afforded by the waveguide-based approach results in narrower, more aesthetically pleasing borders (bezels) around the LCD. However, the key advantage of DWT lies in its ability to accurately pattern waveguide and micro-optic lens components in a single photolithographic step. This simple mask-based process completely defines the touch-screen resolution, ambient light rejection, and sunlight operation of the system. A change in touch-screen performance or screen size is simply a matter of changing the mask design layout, a routine CAD operation. A description follows of how the DWT waveguide components can be manufactured in high volume on flexible substrates and of how different techniques have been applied for the automated handling of these substrates.

Waveguide Manufacturing

The basic processing steps for manufacturing waveguides for DWT are shown in Fig. 3.

In the first step, a planarization layer of low-refractive-index waveguide buffer material is applied with high uniformity to a flexible substrate. This layer is flood-exposed under UV light to form both a mechanically flat surface for subsequent coatings and also the base section of low-refractive-index material that forms the waveguide cladding. In a second step, a high-refractive-index waveguide material is coated directly onto the buffer and is selectively exposed to UV light through a photomask. The unexposed material is then removed through a simple wet-develop process.

As mentioned above, the waveguides and microlens components formed in this single photopatterning step completely define the DWT touch-screen performance. The resulting photopatterned waveguide core features enable the guiding of light in the same manner as the familiar optical fiber through total internal reflection of light at the interface between the core and cladding materials.

In a final step, another low-refractive-index cladding material is overcoated, which planarizes and encapsulates the core features. For DWT, this third layer is also aligned and photopatterned with large-area features that open air gaps over core-patterned microlens surfaces. In a final processing step, individual waveguide die are singulated from the substrate using a dicing process, at which point they are ready for assembly into DWT touch-screen modules. By design, the waveguide manufacturing process itself is similar to a photoresist photolithography line.

Polymer Waveguides

Polymer waveguides have been an active area of research for many years. The pioneering work of a group at Allied Signal laid the

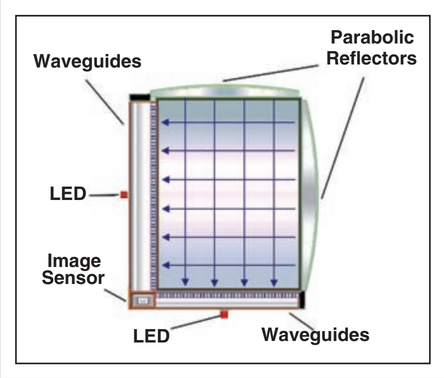

Fig. 2: An optical waveguide approach to touch uses just two LEDs (bottom and left) for IR light. (Drawing components are not to scale.)

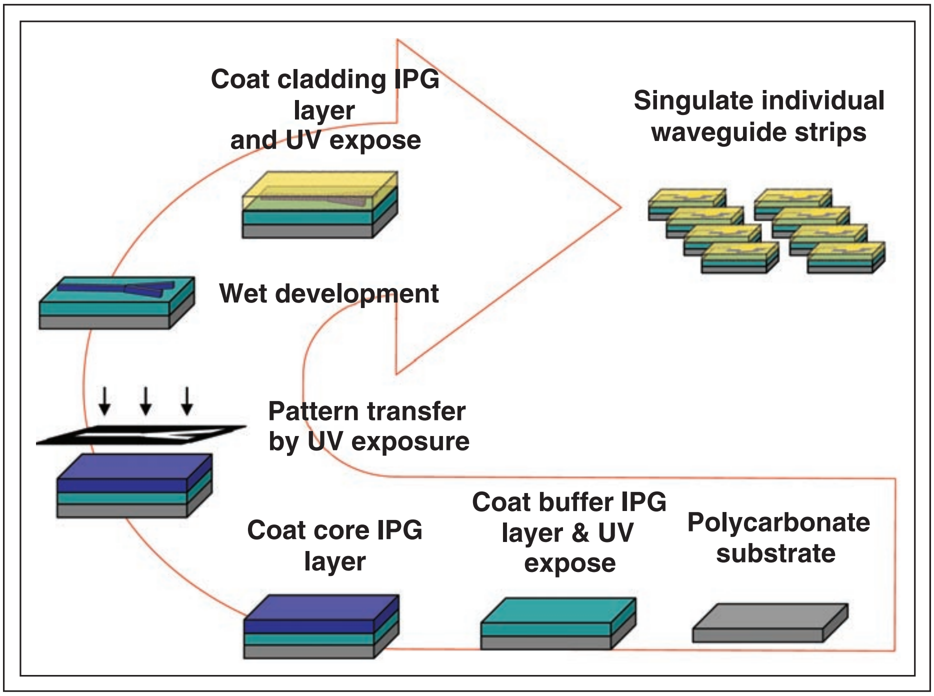

Fig. 3: A polycarbonate substrate (lower right) is the foundation for the waveguide manufacturing process, which ends with individual waveguide strips (upper right). IPG stands for RPO's Inorganic Polymer Glass.

ground rules for the design of polymer materials for optical applications, with a strong focus on long-haul telecommunications.[2] In that case, highly fluorinated acrylate-based materials were used with silicon-wafer substrates and standard semiconductor processing tools to manufacture high-performance waveguide components. In addition, the large thermo-optic coefficient of these materials allowed highly efficient, electrically tunable devices such as space switches and variable optical attenuators to be demonstrated. Today, polysiloxane-based material systems are also recognized as well-suited to optical waveguide and thermo-optic tuning applications, due to their low optical loss and high environmental stability.[3]

Designed and manufactured by RPO, Inorganic Polymer Glass (IPG) coat materials are polysiloxane-based systems, originally developed with long-haul telecommunications applications in mind. These materials exhibit, among other desirable features, low optical loss at telecommunications wavelengths, an accurately tunable refractive index over a wide range, matched thermo-optic coefficients, and low glass-transition temperature (T_g). Of these, a low T_g outside the operating temperature range of the waveguide component is vitally important to negate the buildup of internal stresses and possible micro-cracking within the materials during any thermal cycling in product use. Indeed, IPG materials are designed to have no material phase transitions within the DWT operating and storage temperature ranges. The IPG materials are therefore always in a rubbery state, also a very important feature for waveguides manufactured on flexible substrates.

IPG materials are manufactured as an oligomeric mixture such that the materials can be coated as films from a viscous, solvent-free resin. By controlling the IPG synthesis process and molecular design, the molecular-weight distribution of the resin can be tuned to combine effective coating properties and high environmental stability with low-volatile outgassing. The solvent-free nature of the coat fluids is a key feature for use with plastic flexible substrates – swelling of the substrate due to the presence of a carrier solvent, even for short periods of time, is never encountered. Indeed, since there is no solvent to bake out, a soft bake step is completely unnecessary. In addition, since there is no solvent evaporation during coating, very high-quality optical films with low surface roughness can be easily formed through techniques such as extrusion coating, spin coating, or extrude-and-spin. On the flipside of these positive features, IPG materials remain a viscous liquid even in film form until exposed to UV light, which presents challenges from a substrate-handling perspective, particularly for fully automated production lines.

Flexible Substrate Requirements

The application of optical waveguides and photonics to consumer-electronics products, such as DWT, requires careful consideration of manufacturing costs, certainly compared to the typical telecommunications products that polymer waveguides have historically targeted. DWT waveguide chips are generally large, rectangular die, a couple of millimeters wide and many tens of millimeters long, dependent on LCD screen size. The packing density of DWT die onto round wafers, whether they are silicon or a cheaper alternative, is severely limited both by geometry and overall substrate size. The use of the rectangular, large-area substrate sizes commonly found in the LCD industry are far better suited to DWT waveguide production, as a significantly higher volume throughput is achievable for the same processing time as a wafer-based process. The current RPO waveguide production process uses 400 × 500-mm-sized substrates (Gen 2.5).

The choice of substrate material is unusual in the flexible substrate world in that the substrate itself has no obvious functionality other than as a carrier, and, in fact, DWT does not use the flexible nature of the substrate at all. The sole reason that RPO chose flexible plastic substrates was to keep product costs low. In addition, the substrate and waveguides only reside in the bezel of the LCD, with no requirement for substrate optical clarity or quality.

The obvious requirements of DWT waveguide substrates are that they are flat enough to enable high-resolution photolithographic printing, have sufficient surface quality to allow a planarizing layer to be coated onto one surface, and, most importantly, are inexpensive. The very-high-performance flexible substrates, such as PEN, developed specifically for flexible-display applications, are unnecessary for DWT; low-cost standard substrate film materials such as PET, polyimide (PI), or polycarbonate (PC) are sufficient.

On closer inspection, however, there are additional features that need to be added to the substrate to allow successful production processing and also provide high-performance DWT operation. First, the photolithographic processing of IPG waveguides for high-volume production requires high-intensity UV light of a specific wavelength spectrum, to achieve high throughput but also to counteract detrimental oxygen-inhibition processes within the IPG photochemistry. RPO has worked directly with a photolithography-tool manufacturer to develop a customized projection scanning tool for DWT waveguide component manufacture. These production systems operate at high UV intensities, and under these conditions, the photosensitivity of the substrate as well as that of the IPG materials must be taken into account. By correct specification of the substrate material properties, it is possible to control the substrate photosensitivity. Figure 4 shows the large improve-

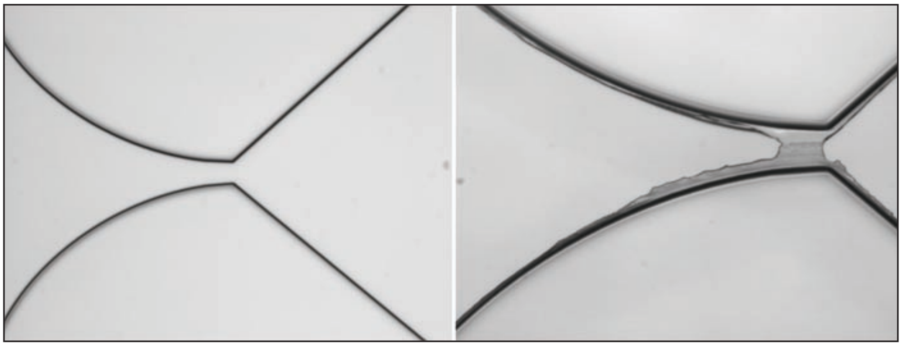

Fig. 4: *At left is shown photopatterning of IPG materials coated onto a substrate with correctly specified properties, and, at right, with a poor substrate choice.*

ment in photolithographic resolution of IPG photopatterned features that can be achieved with a correctly specified substrate.

Secondly, the sunlight performance of the DWT system as a whole is dictated by the amount of stray light that can reach the camera. This light is non-directional and therefore acts as a large background noise signal. The main source of this noise is ambient light that can travel through the substrate material to the camera rather than *via* the waveguide-defined path. Again, correct specification of the flexible substrate material properties allows control of stray light and can improve system performance markedly.

For DWT waveguides, however, the choice of base-substrate material is ultimately driven by the cutting process in which individual optical chips are singulated from the Gen 2.5 substrate, as shown earlier in Fig. 3. Unlike microelectronics components, in which surface contacts and pads located on the top surface of the die are usual, the most efficient use of photonic chips generally requires light to be injected or captured from the edges of the die. For polymer waveguides to be viable for consumer-electronics products, the singulation process must therefore provide an optical-quality chip endface in a single step – additional post-processes such as polishing are not viable.

Through judicious choice of substrate material, RPO has developed a single-step dicing process using high-speed diamond-impregnated blades similar to those used for dicing silicon wafers. When employed with a polycarbonate substrate material, very high-quality optical endfaces are achievable on waveguides with acceptably fast throughputs for volume production. This is in contrast to PET-type materials, in which the semi-crystalline nature of the substrate leads to high internal stress build-up and shattering/delamination of the waveguide layers during cutting. While PC is not as robust an industrial plastic as either PET or PEN, for example, the low temperatures involved in DWT waveguide processing, and the solvent-free nature of the IPG coat fluids, mean that PC is sufficiently well specified for the DWT application.

Automated Flexible Substrate Handling for DWT

While the manufacture of waveguides on flexible substrates is simple to achieve in a pilot-line process, the scale-up to fully automated production is dictated by cost requirements. Specifically, product cost structures dictate that it is not possible to handle the flexible substrates by the more usual approach of laminating to a rigid carrier such as FPD motherglass,[5] or by using rigid perimeter frames – rather, the flexible substrates need to be robotically handled as-is. Combined with the wet nature of some of the in-process IPG-coated substrates, this places restrictions on the type of robotic handling schemes that can be employed, and also on the design of the process-tool vacuum chucks that hold the substrate in place during processing. Of importance here is the choice of substrate thickness – the thicker the substrate, the less it will flex. However, it should be borne in mind that DWT waveguides occupy a space inside the LCD bezel, and with current LCD trends pushing to narrower and thinner bezels, keeping substrate volume to a minimum is important. Balancing these two counteracting effects leads to an optimum polycarbonate substrate thickness that is readily available in roll form.

Development projects between RPO and individual tool suppliers have resulted in a cohesive set of solutions for the handling of RPO flexible substrates. For all tools, the design of any substrate vacuum hold-down system requires that vacuum holes to the rear of the flexible substrate do not cause an appreciable distortion. This is particularly important for lithography tools where distortion of the substrate out of the focal plane can result in a reduction in resolution or changes in critical dimension of the waveguides. In addition, any through-holes in the substrate chuck that allow access for lift pins or pads must be carefully designed to avoid any resonant oscillation of the flexible substrate during processing.

Based on detailed finite-element analysis simulations, robot end effectors, cassettes, and spin-coat/develop chucks with integrated lift pads have been successfully designed, manufactured, and tested under continuous production conditions. Figure 5 shows a spin chuck with integrated lift pads in the raised position, allowing access for a robot end effector.

Extrusion coating is well established as the coating method of choice for large-area LCD screen manufacturing and is a key part of RPO's manufacturing strategy to minimize IPG material consumption. However, it presents further challenges for IPG coating of

***Fig. 5:** Above is an example of a flexible-substrate transfer paddle and spin chuck with integrated lift pads*

flexible substrates. During the IPG extrusion coating process, there is a measurable force from the fluid exiting the extrusion die down onto the flexible substrate; indeed, the proximity of the substrate itself causes a back pressure into the die cavity.

Additionally, the polysiloxane nature of the IPG materials necessitates a high-precision extrusion-coating process with accurately designed wetting surfaces and gaps. The flexible substrate must therefore be held flat with respect to the extrusion die with tight tolerances. These tight tolerances, and the potential of the fluid force to distort the flexible substrate over lift pad or vacuum holes, negates the ability to use the integrated handling solutions used for the spin tools. As a solution to this problem, a flexible substrate load station has been designed, using air to levitate the substrate and float it onto an interdigitated station where the end effector can raise the substrate and move it to the next process module. An image of the load station is shown in Fig. 6.

Summary

The high-volume manufacture of polymer waveguides on flexible substrates for DWT touch-screen applications is already under way. In particular, the choice of flexible substrate material allows for integration into a complete high-volume production solution for optical waveguides and planar photonic components for consumer electronics. Although pilot-production development work has been based on Gen 2.5 substrate sizes, all the techniques developed scale readily to larger substrate sizes and therefore greatly increased volumes. With minor detail modification to some of the process steps, this manufacturing process should be eminently suitable for scaling to roll-to-roll production.

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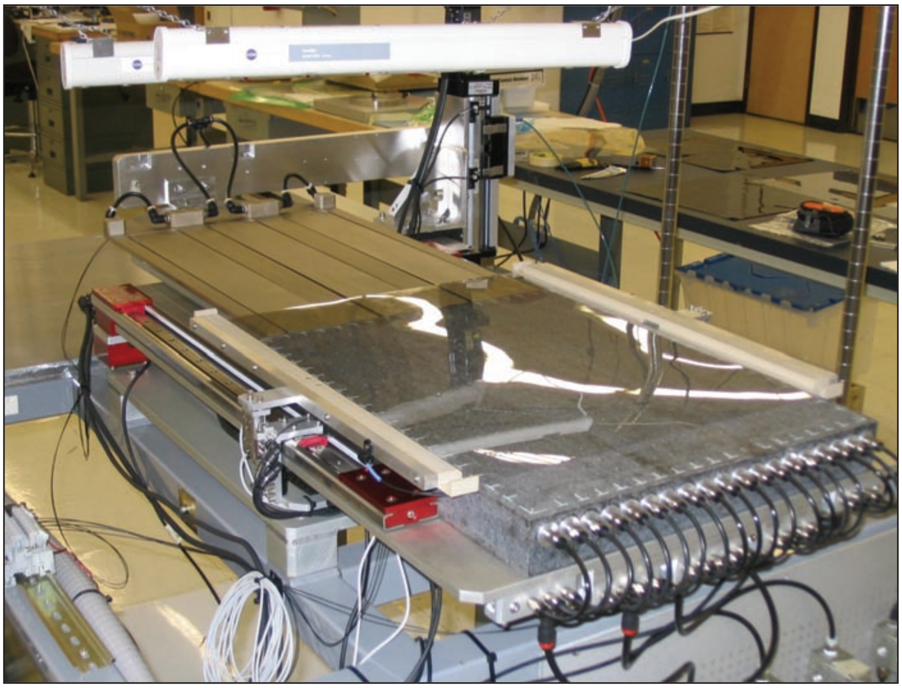

Fig. 6: This extrusion-coater flexible-substrate load station uses air to levitate the substrate.