

Capped Optical Polymeric Waveguide

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Abstract

We present here a new type of polymer waveguides (i.e., capped waveguide) fabricated using contact photolithography with considerable performance improvement over the conventional waveguides. We also show that by simultaneous patterning of the core and the top cladding in capped waveguides, we can considerably reduce the effect of fabrication defects and reduce the propagation loss by at least 20% compared to conventional waveguides.

1. Introduction

The widespread use of the advanced package technologies, such as Ball Grid Array (BGA),[1] Chip Scale Packaging (CSP),[2] flip chip, and wafer-level-packaging,[3] has promoted the development of high density substrates and printed circuit boards (PCBs).[1] To realize high speed in these substrates, it is essential to develop processes for the integration of high speed optics. One of the most important components for this integration is the optical polymer waveguide, and there have been extensive efforts on the development of fabrication techniques for waveguides and waveguide-based devices. As an example, integration of optical waveguides and polymer passive devices on high

density substrate/PCB is a major area of research in optoelectronics. During the later 1980's, early attempts were focused on the integration of polymer waveguides on printed circuit boards for interconnection use.[2] Several technologies have been developed such as photolithography, reactive ion etch (RIE), laser ablation molding/embossing, lamination, and monomers diffusion, etc., to define optical waveguides.[3,4,5,6] Among these technologies, photolithography has excellent ability to define smooth and high definition waveguides. However, there are process-related challenges that limit the manufacturability of such waveguide. For example, dust particles, contaminations, scratches, mechanical damages, chemical swells, corrosions, and overetching degrade the performance of a high quality waveguide and other polymer-based devices. In this paper, we introduce a novel cap-clad approach for creating high quality waveguides by minimizing the process-induced defects and improving waveguide definition that result in the improvement of the manufacturability of such waveguides for the integrated optoelectronics.

2. Optical Waveguide Materials

In this study, a pair of optical polymers, LighLinkTM, provided by Rohm & Haas Electronic Materials was used. The LightLinkTM is a negative acting photoimaging polymeric system which is based on an inorganic-organic hybrid platform [7]. It consists of two parts with refractive indices of 1.5196 and 1.4908. The higher index material is used for the waveguide core and the lower one is used for the cladding. Since the materials are in monomer liquid form, they are applied either by spin coating, slot coating, or meniscus coating on a substrate which can be silicon, glass, ceramic, organic package

substrate, or printed circuit board. Both the core and the cladding are photoimaging with high resolution. The photolithography process allows us to define a few micron to a few hundred micron structures with high degree of accuracy so that high performance single mode and multimode waveguides and polymer related passive devices can be made for the integrated optoelectronics. Figure 1 shows an atomic force microscopy (AFM) picture of a 4 micron wide waveguide on an 8 micron pitch multi-channel waveguide with a few nanometer smooth surfaces. This high density polymeric channel waveguides were formed by using the low cost printed circuit board (PCB) facility and process in a class-1000 substrate laboratory at the Packaging Research Center (PRC) at Georgia Institute of Technology.

Propagation loss is one of the most important properties of optical waveguides. Unlike the optical glass fibers, optical polymer waveguides have much higher propagation losses. For example, the loss of a typical optical fiber at 1550nm is about 0.1dB/km, while that of a typical un-fluorinated polymer waveguide is 0.2~0.3dB/cm at 1310nm and 0.5~1.5dB/cm at 1550nm. This loss can be as low as 0.02~0.1dB/cm at 850nm, but it is quite sensitive to the process.[7] Thus, the fabrication of low-loss waveguides is crucial for using polymer waveguides in the practical applications. The propagation loss of a typical waveguide can be divided into intrinsic loss and extrinsic loss. The intrinsic loss is caused by material absorption and compositional inhomogeneity, while the extrinsic loss is mostly caused by the fabrication process. Practically, scattering from defects such as contaminations, bubbles, dimples, bumps, cracks, surface roughness, and also poor definition are responsible for most of the waveguide loss. Optical waveguides with good performance must have clear, defect-free and smooth surfaces. An ultra clean

environment is required for the large area board level optoelectronics integration, which results in high fabrication cost. In this paper, we show a reliable procedure for almost complete elimination of the fabrication-related defects by using capped waveguides without requiring ultra clean fabrication environment to reduce the fabrication cost considerably.

3. Manufacture Challenges and Environment Requirements

A typical optical polymer waveguide is a triple-layer structure: bottom cladding, core, and top cladding. The waveguide is formed layer by layer from the bottom cladding to the top cladding in a sequential process. The process includes coating, soft-baking, and curing. In addition, the core is patterned after soft-baking. For board-level integration, soft-baking usually takes around 10 minutes at low temperatures (for example, 90⁰C) while curing takes about 1 hour to a few hours at a higher temperature (for example, 150⁰C). In the formation of the core, a contact mode UV exposure is used followed by post-baking and development in a chemical solution, and then curing is performed in a convectional oven. In the long-period processes, the top surface of the core layer goes through mechanic contact, chemical solution, and convectional oven resulting in defects and damages (including contamination, dust, scratch, dimple, and bubble) and thus a rough waveguide surface. In addition, very low electrical conductivity of the polymers results in the build up of static charges on the core surface, which can attract dust particles even in very clean environments. The light scattering from such dust particles can be considerable if the particle size is comparable to the optical wavelength (typically in the range of 850nm – 1550nm for most practical applications).

Figure 2(a) shows a particle with 10 μ m diameter attached to the top of a well defined waveguide during the curing process in a convectional oven. Figure 2(b) shows debris of the polymer residue with size of 5 μ m \times 30 μ m attached to the waveguide core during the process of chemical development. Once these particles attach to the waveguide, they can not be removed. Thus, usually for low-loss waveguide processing, ultra-clean fabrication environment, special storage, special handling techniques, and careful precautions, are required.

Another important requirement for fabricating practical optical devices like waveguides is the accuracy of the fabricated structures. This requires very good resolution in forming feature sizes using photolithography. The resolution (or the minimum achievable feature size, b_{\min}) in photolithography with a UV lamp at wavelength λ is represented by [8]

$$b_{\min} = 3/2 \sqrt{\lambda(G + h/2)}, \quad (1)$$

with G being the separation or gap between the lithography mask and the polymer film and h being the thickness of the polymer film. Equation (1) clearly shows that in order to achieve very fine resolutions, the mask needs to be in contact with the polymer.

The gap or the separation of the mask and the polymer layer (i.e., G in Eq.(1)) results in poor resolution and poor definition due to the wave diffraction effect. Thus, contact mode is commonly used for high-definition waveguide formation. However, the physical contact between the mask and the polymer can potentially cause mechanical damages to the core of the waveguide. For example, Figure 3(a) shows a scratch on the waveguide happened because of the handling during lithography, and Figure 3(b) shows a typical surface damage caused by mask contact during waveguide formation.

Dark field photography was used in Figures 3(a) and 3(b) to clearly show the defects. All these defects cause the increasing of scattering loss. So, defect-free or defect-less smooth surface and high definition are required for fabricating low-loss waveguides and other passive devices. In the next section, we describe a new approach to form such low-loss waveguides, without requiring ultra-clean fabrication environment.

4. Fabrication of Capped Waveguides

The key step in the fabrication of capped waveguides developed in this research is the simultaneous photolithographic formation of the core and the top cladding layer of the waveguide. This avoids the formation of defects or attachment of dust particles to the core surface, which is the most sensitive place in the waveguide to defects. The sequential steps in the fabrication of a capped waveguide (also demonstrated graphically in Figure 4) are as follows: 1) Coat the bottom cladding layer on the substrate or the printed circuit board (PCB) and cure it, 2) coat the core layer and soft-bake it, 3) coat the cladding layer on top of the core layer and soft-bake it, 4) expose two layers to an appropriate dose of UV radiation through a mask, 5) develop the pattern using a wet process. The developer used for patterning of LightLinkTM is an aqueous solution (2% Alkaline). Developments are carried out in room temperature for about 3 minutes. Unexposed areas are dissolved and washed away and the exposed areas remain. The cladding layer on top of the core acts as both cap and cladding. We call it cap-clad, and we call the waveguide the capped waveguide. In this structure the surface of the core is protected by the cap-clad during the later processes. 6) Finally, the capped waveguide is

completed by applying a layer of polymer to clad the sides of the core as well as the top of the core.

Since the core and the cap-clad are patterned simultaneously, the problem of the formation of defects on top of the core layer in conventional waveguides does not exist in the capped waveguides. Instead, almost all existing defects occur on the top of the cap-clad layer and have much less effect on light propagation in the waveguide due to lower field intensity in the cladding (the thickness of the cap-clad is much larger than the wavelength of the light guided in the core layer). Furthermore, the side walls of the capped waveguide have similar quality to those of the conventional waveguide due to the similarity of the development process. In both waveguides, the probability of defect formation on the side walls is much less than that on the top surface. There is also no contact damage on side walls, as the mask will only contact the top surface. Similarly, the probability of the attachment of dust particle to the side walls is far less than that for the top surfaces. As a result, capped waveguides can have considerably lower propagation loss than the conventional waveguides fabricated in the same environment.

Another advantage of the capped waveguide technology is the possibility of forming high definition passive devices such as Y-splitter, H-tree, and multimode interference (MMI) that require good definition and accurate structures or require square (or rectangular) shapes with sharp edges. Using conventional waveguides, it is difficult to form such devices accurately, as the top surface of the core tend to have a round shape instead of a square or a rectangle due to overetching of the sharp edges in wet etching processes. However, this problem can occur only for the cladding surface in a capped waveguide, as the core is buried under the cladding during the etching process. Figure 5 shows the

microscope image of a fabricated capped waveguide with a $50\mu\text{m} \times 50\mu\text{m}$ core and a cap-clad with thickness of $10\mu\text{m}$. As seen in Figure 5, the core has a well-defined square shape while minor rounding at the cladding surface is visible. Since most of the guided light energy is concentrated in the core of the waveguide, moving non-ideal features like round surface, from the core to the cladding results in improved performance of the optical devices fabricated using capped waveguide technology.

5. Characterization of propagation loss in capped waveguides

Several techniques such as cutback method,[9] sliding prism technique,[10] and photographic approach,[11] etc., have been used for loss measurement in optical waveguides. In this paper, we use a non-destructive technique based on the scattering loss measurement along the propagation direction of the waveguide under investigation.[12] Light is coupled to the waveguide using free-space optics and the scattering pattern on top of the waveguide is monitored by a fast, high precision, and sensitive integrated CCD camera through a two-lens imaging system. Since the scattered intensity from the waveguide is a function of light intensity inside the waveguide, the variation of the scattered intensity with propagation length can be used for the measurement of the propagation loss coefficient. The details of this technique have been described in Ref [ref] and will not be repeated here.

Figure 6(a) shows the CCD image of the scattered light on top of a capped waveguide with a $50\mu\text{m} \times 50\mu\text{m}$ core area and a $10\mu\text{m}$ thick cap-clad. Figure 6(b) shows the variation of the relative scattered intensity from the capped waveguide with propagation length for the capped waveguide at two different wavelengths (850nm and 980nm).

Using a linear curve fitting, we measure the loss coefficients of $\alpha_1 = 0.064 \text{ dB/cm}$ at $\lambda = 850 \text{ nm}$ and $\alpha_2 = 0.045 \text{ dB/cm}$ at $\lambda = 980 \text{ nm}$ for the capped waveguide. To compare the propagation loss of the capped waveguide with that of a conventional one, we fabricated the latter using a layer-by-layer process with a $50 \mu\text{m} \times 50 \mu\text{m}$ core and a $10 \mu\text{m}$ thick top cladding. The variation of the relative scattered intensity with propagation length at 850 nm for the conventional waveguide is also shown as in Figure 6(b). The local scattering peak for this case corresponds to a local defect formed during fabrication. We use linear curve fitting on both sides of this defect and then average the slope of the fitting lines in these two curves to find a propagation loss coefficient of $\alpha_3 = 0.085 \text{ dB/cm}$.

We repeated the experiments for several waveguides and found similar loss coefficients. Our results suggest that under the same fabrication environment, the capped waveguide has at least 20% less propagation loss compared to the conventional waveguide. Furthermore, the effect of local defects in the capped waveguide is highly suppressed as they moved from the core (as in the conventional waveguide case) to the cladding. Thus, our results suggest that the capped waveguide technology proposed in the paper is a much better candidate for the formation of passive optical devices using simple photolithography.

6. Conclusion

We presented here a new type of waveguide (i.e., capped waveguide) with improved manufacturability for integrated optoelectronics. The key feature in these waveguides is the simultaneous fabrication of the core and the cap-clad layers. This results in almost no

defect on the core surface. Instead, the defects appear only on the cap-clad surface, which has much less effect on the light propagation. Furthermore, the capped waveguide technology is suitable for the formation of high definition optical devices due to the possibility of defining sharp feature on the waveguide core. Finally, we showed that the capped waveguide has at least 20% less propagation loss compared to the conventional waveguide fabricated in the same environment. We conclude that the proposed capped waveguide will have a big impact on the improvement of manufacturability of optical waveguide and related passive devices for the optoelectronics integration on the system packages. This new capped waveguide technology can be extended to almost all other fabrication methods, such as RIE, molding/embossing, direct writing etc., for waveguides and waveguide-based devices which need low loss and high definition.

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Figure 3. Microscope pictures (dark field) of Surface damages on a $50\mu\text{m} \times 50\mu\text{m}$ waveguide core: a) a scratch caused by handling, and b) damage caused by contacting with the photomask.

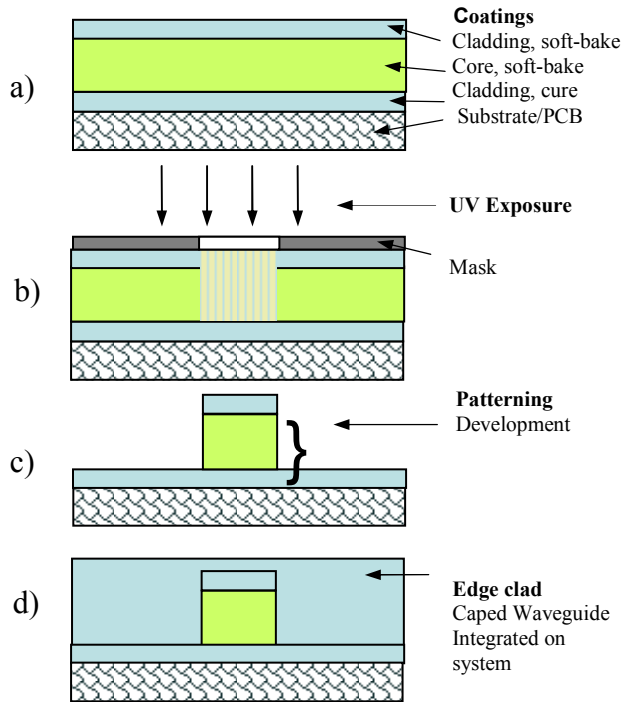


Figure 4. Capped waveguide fabrication process flow: a) coat and cure the bottom cladding layer, coat and soft-bake the core layer, and then coat and soft-bake the top cladding layer, b) expose two top layers to an appropriate dose of UV radiation through a mask, c) develop the pattern using a wet process, and d) finally, apply a layer of polymer to clad the sides of the core as well as the top of the core.

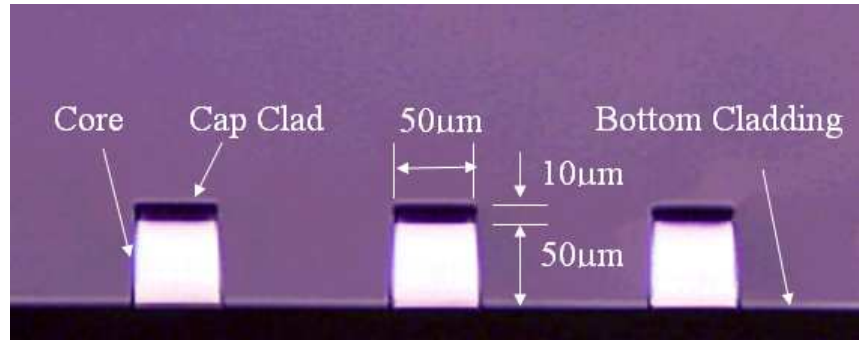


Figure 5. Microscope image of a capped polymeric waveguide with a $50\mu\text{m} \times 50\mu\text{m}$ core and a $10\mu\text{m}$ cap-clad.

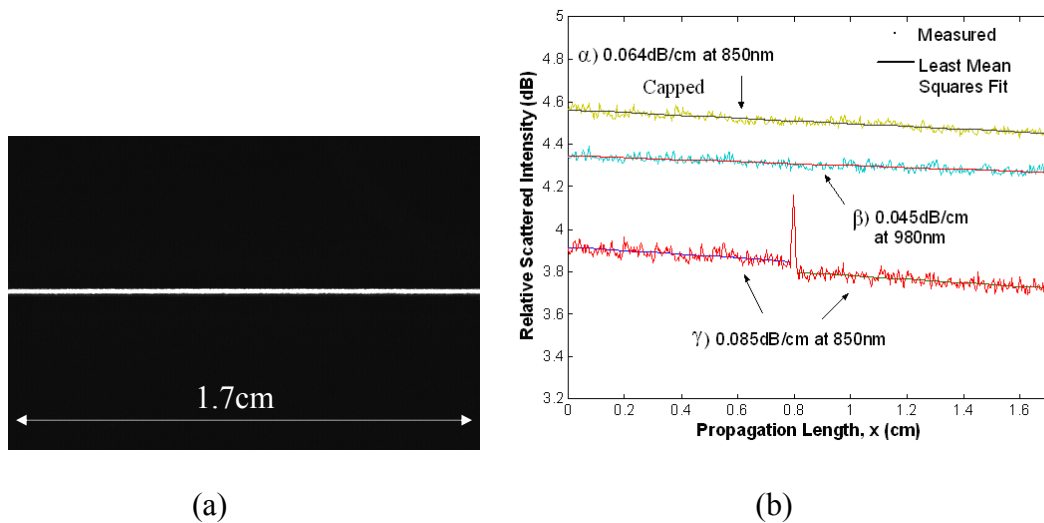


Figure 6. a) The image captured by the CCD camera of the scattered intensity of capped waveguide shown in Figure 5. The propagation length of the waveguide is 1.7cm and the exposure time of the CCD camera is 12 seconds. The wavelength of the coupled light is 850nm. b) Relative scattered intensity versus the propagation length a) at 850nm and b) at 980nm for the capped waveguide, and c) at 980nm for a conventional waveguide with the same feature size on the capped waveguide. The lines are the least-mean-squares fits of the measured data to a monoexponential function of x .