Precision measurements for propagation properties of high-definition polymer waveguides by imaging of scattered light

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Abstract. We present a reliable, nondestructive, and real-time technique for characterization of propagation properties of planar optical waveguides based on accurately imaging the scattered light from the optical waveguide using a sensitive charge-coupled device (CCD) camera with built-in integration functionality. This technique can be used for real-time investigation of the propagation properties (loss, mode profile, bending properties, etc.) as well as the fabrication quality of planar optical waveguides. With this technique, we evaluate high-definition polymer optical waveguides on printed circuit board (PCB) substrates with a very low loss of 0.065 dB/cm at a wavelength of 850 nm, and measurement accuracy is less than 0.01 dB/cm. We expect this technique with the given CCD camera to be suitable for reliably measuring loss coefficients well below 0.1 dB/cm.
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The ever-increasing need for higher bandwidth is one of the motivations for extensive research on planar optoelectronic structures.[1] Among many applications, optical interconnects[2] have received considerable attention in the last decade. In all planar optoelectronic systems, optical waveguides are crucial elements that facilitate signal rooting. The development of optical structures like waveguides on high-density organic printed circuit boards (PCBs) has been a major focus of research on board-level interconnection. Low propagation loss, high optical quality, the possibility of bending without excessive loss, and manufacturability are among the requirements of polymer optical waveguides on PCB substrates for practical applications.

Besides fabrication requirements, reliable characterization tools are needed for the accurate and nondestructive measurement of important guiding properties like propagation loss in such waveguides. Several techniques, such as the cutback method,[3] sliding prism technique,[4,5] multiple reflections method,[6] and photographic approach,[7–9] have been studied and used to measure the propagation loss of planar waveguides. The widely used cutback method requires the long waveguide sample, especially for low-loss (i.e., less than 0.1 dB/cm) waveguides. Furthermore, the technique is destructive, time consuming, and hard to implement for waveguides integrated on PCB substrates, which are difficult to cleave. The sliding prism method, in which a prism is moving along the light propagation direction, is also widely employed, but it is hard to maintain the coupling efficiency constant, especially for the polymer waveguides on PCB substrates. The multiple reflection method provides a nondestructive means for loss measurement; however, it involves a complicated reflectometer alignment and it is not suitable for studying the local propagation properties in details.

The photographic method is a simple and accurate way to characterize the properties of planar waveguides, such as waveguide propagation loss, bending behavior, and cross talk among adjacent waveguide channels. In this technique, a video camera is used to record the entire streak of light scattered from the waveguide, and then a computer was employed to analyze the power of the scattered light. However, this method is hard to use for the loss measurement in a waveguide with small scattering, due to the low sensitivity of the video camera.[7] The method was improved later by coating the waveguide with a fluorescent layer to enhance the detection of the scattered light.[8] Strasser and Gupta[9] used photographic films with high sensitivity to record the image of the low-intensity scattered light. Although this method has high sensitivity, it is not a real-time measurement.

We recently demonstrated a new fabrication technique for forming low-loss capped polymer waveguides using contact photolithography.[10] In this work, we present a simple, real-time, accurate, and nondestructive technique for the characterization of loss in optical waveguides that have low scattering losses, such that the application of other loss measurement techniques for the study of these waveguides is not possible.

Polymer waveguide circuits investigated in this work are fabricated and integrated on a PCB substrate using the standard low-cost PCB facilities and processes in the Georgia Institute of Technology Packaging Research Center's Next-Generation Substrate Laboratory. High density interconnects with multiple wire layers are fabricated, and then

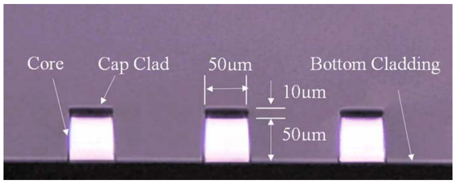

Fig. 1 Microscope image of a polymer-capped waveguide with core and top cladding simultaneously formed. The multimode waveguide has a 50×50 (μm)^2 core covered by a 10-μm cap cladding.

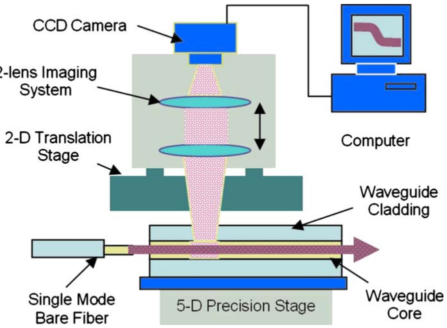

Fig. 2 The experimental setup used to characterize the propagation of the polymer waveguides. A single-mode bare fiber is used as the facet coupler to excite the waveguide modes. The polymer waveguide is mounted on a five-axis precision stage. The adjustable two-lens imaging system with numerical aperture of 0.15 along with the CCD camera is mounted on a 2-D large-range translation stage.

multimode polymeric waveguides are formed on the wire layers. The polysiloxane-based material LightLink,[11] developed by Rohm and Haas Electronic Materials, is employed in this research. This is a negative acting photoimaging polymeric system based on an inorganic-organic hybrid platform. This material has the advantages of excellent manufacturability, high-definition photoimaging properties, and excellent optical quality. The LightLink consists of two different (but similar) materials with $\Delta n = 0.03$ difference in the refractive index that can be used as the waveguide cladding and core separately. The waveguides were formed using spin coating of the polymers. To improve the surface quality of these waveguides, we used a new technique in which the core and top cladding layer of the waveguide are patterned together. The details of fabrication were already reported[10] and are not repeated here. Figure 1 shows the microscope image of a high-definition and defect-free polymer capped waveguide with a core 50 μm wide and 50 μm thick and a 10-μm-thick top cladding on an organic package substrate. In the remainder of this work, we show that this waveguide has very low propagation loss in the wavelength range of 850 to 1000 nm, which is rather difficult to measure by using the cutback method as explained earlier.

Propagation loss in optical waveguides is primarily due to material absorption, scattering, and radiation. The scattered and radiated light can be observed from the top as a streak of light in the waveguide. The intensity of the observed light above the waveguide is directly proportional to the intensity of the guided light inside the waveguide. Therefore, the propagation loss of the optical waveguide can be nondestructively measured by monitoring the intensity of the scattered light I along the propagation direction and fitting this variation with a monoexponential formula:

$$I = I_o \exp(-\alpha x), \tag{1}$$

with I_o being the incident intensity at the waveguide input at $x=0$, x being the coordinate along the propagation direction, and α being the loss coefficient.

Equation (1) can be rewritten (by taking the logarithm of both sides) as:

$$\ln I = \ln I_o - \alpha x. \tag{2}$$

The loss coefficient α of the waveguide is then calculated as the slope of the linear function of $\ln I$, which can be obtained by simply fitting the data with a linear function.

Figure 2 shows the experimental setup used to characterize the propagation properties of our polymer waveguides. A single-mode bare fiber is used as the facet coupler to excite the waveguide modes (a prism-film coupler can also be used to couple light into the waveguide; however, an extra stop must be used to block the scattered light from the edge of the input prism). The polymer waveguide is mounted on a five-axis precision stage. A highly sensitive commercial charge-coupled device (CCD) camera (model SBIG ST-7XME) with a built-in integration function is utilized to observe the light streak in two dimensions through a two-lens imaging system with a numerical aperture of 0.15. By changing the magnification ratio of the imaging system, we can study the scattered light to obtain detailed information about waveguide propagation properties such as guided mode profiles, defect distributions, bending behavior, etc. The imaging system along with the CCD camera is mounted on a 2-D large-range translation stage, which enables the investigation of different locations of the waveguide structure. The output data of the CCD camera are sent to a computer through an analog-to-digital converter to characterize the propagation properties of the waveguide structure. The high sensitivity and built-in integration function of the CCD camera with a dark current of 1 e/pixel/sec, 765×560 pixel array (with 9×9-μm pixel size), and a 6×10^4 dynamic range enables the system to detect low-intensity scattering light, and thus to measure the low-loss coefficients. This technique has the advantages of being nondestructive, requiring low guided power, being readily automated, independent of the coupling efficiency and facet reflectivity, and being applicable to complex waveguide circuits.

By adjusting the imaging system, a clear image, as shown in Fig. 3(a), of the light from the waveguide is captured by the CCD camera with 10-sec integration time. The length of the measured waveguide is 1.7 cm. The variations of the scattered light with propagation length detected by the camera at two different wavelengths (850 and 980 nm) are illustrated in Fig. 3(b).

The loss analysis is performed by sampling the light intensity in 2-D (both longitudinal and transverse) along the propagation direction. The relative intensity at each position along the propagation direction is then obtained by the integration of the light intensity perpendicular to the propagation direction within the width of the waveguide. The logarithm of the relative scattered power versus the propagation position is then plotted. A linear least-square fit of

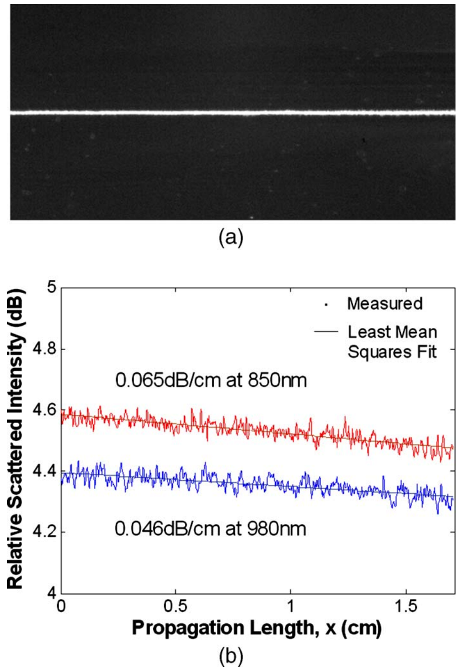

Fig. 3 (a) The image captured by the CCD camera of the scattered intensity of the multimode waveguide shown in Fig. 1. The propagation length of the waveguide is L=1.7 cm, and the integration time of the CCD camera is 10 sec. The wavelength of the coupled light is 850 nm. (b) Relative scattered intensity versus the propagation length at two different wavelengths (850 and 980 nm) for the waveguide shown in Fig. 1. The lines are the least-square fits of the measured relative scattered intensity with a monoexponential function.

this plot gives the propagation loss coefficient for the waveguide under test. Note that this technique is quite general and can be used for any waveguide geometry (straight, bent, etc.).

From Fig. 3, we measured loss coefficients of $\alpha_1 = 0.065$ dB/cm at $\lambda = 850$ nm and $\alpha_2 = 0.046$ dB/cm at $\lambda = 980$ nm for the capped waveguide described in Fig. 1. To examine the repeatability of these results, we repeated the experiment with different waveguides (with the same feature size) under different input coupling conditions, and we obtained less than 10% variation in all our measurements. The accuracy of the measurement can be obtained by analyzing the deviation of the linear fitting. The standard deviation of the linear fitting shown in Fig. 3(b) is less than ± 0.004 dB/cm. We believe this technique with the given CCD camera has accuracy better than 0.01 dB/cm, and therefore is suitable for reliably measuring loss coefficients well below 0.1 dB/cm.

Compared with reported results for similar waveguides,[12] we believe that the losses reported here are among the smallest values reported for polymer waveguides fabricated using the basic contact photolithography on a PCB substrate. We think that the lower loss obtained at 980 nm is primarily due to the lower material absorption at 980 nm. This small loss makes the presented waveguides excellent candidates for the implementation of optical interconnects on PCB boards.

While the main focus of this work is the loss measurement, the characterization setup described in Fig. 2 can be used to investigate several other properties of the planar waveguides. As an example, Fig. 4 shows the 2-D scattered light intensity from a traditional multimode polymer waveguide when an air bubble exists in the waveguide core. This waveguide is fabricated layer by layer, not with the capped waveguide technique,[10] and it has the same core and cladding dimensions as the waveguide shown in Fig. 1. As shown in Fig. 4, the air bubble causes a local peak in the scattered intensity. The spatial extent of the peak is directly related to the size of the air bubble. Thus, the experimental setup presented can be used to investigate the fabrication quality of the waveguides as well.

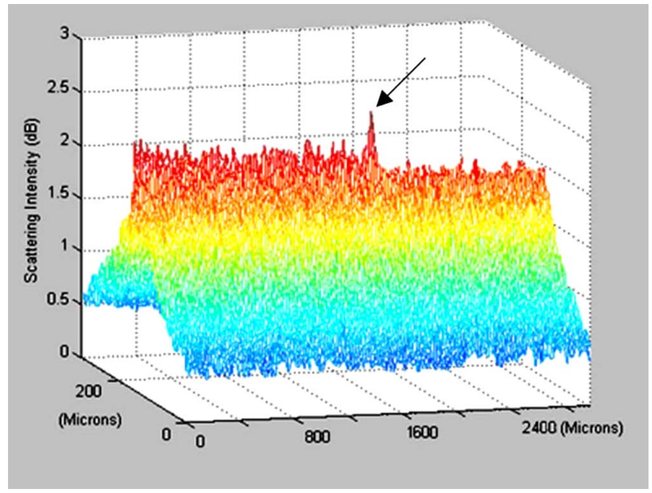

Fig. 4 The 2-D scattered light intensity from a traditional multimode polymer waveguide when an air bubble exists in the waveguide core. This waveguide was fabricated layer by layer (not with the capped waveguide technique), and has the same core and cladding dimensions as the capped waveguide in Fig. 1. The air bubble causes a local peak in the scattered intensity.

In summary, we presented a reliable, nondestructive, and real-time technique for characterization of propagation properties of planar optical waveguides based on accurately imaging the scattered light from the waveguide using a sensitive CCD camera with built-in integration functionality. This technique can be used for real-time investigation of the propagation properties (loss, mode profile, bending properties, etc.), as well as the fabrication quality of planar waveguides with better sensitivity compared to other techniques. Using this characterization tool, we measured capped waveguides with loss coefficients of $\alpha_1 = 0.065$ dB/cm at $\lambda = 850$ nm, and $\alpha_2 = 0.046$ dB/cm at $\lambda = 980$ nm with accuracy of 0.008 dB/cm. To the best of our knowledge, these data are among the lowest loss coefficients reported for polymer waveguides on PCB substrates to date. This makes our capped waveguides excellent candidates for board-level optical interconnects.

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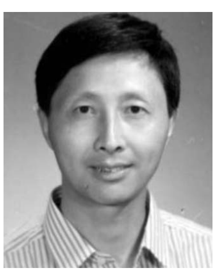

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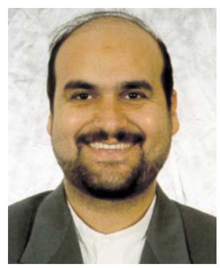

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