

Processing and Characterization of Benzocyclobutene Optical Waveguides

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Abstract—Digital circuits are continuing to see an increase in clock speeds which puts significant demands on the design and packaging of electronic subsystems. One possible solution is to take advantage of the high bandwidth of optics. This has clearly taken place for long-distance telecommunications, but has yet to happen at the board- or chip-level in electronic systems. While there are many reasons for this, one serious issue concerns the materials that are required to achieve optical signal transmission in the electronic system. First and foremost, the material must exhibit low optical loss. The material must also be compatible with the standard processing techniques of printed wiring boards, multichip modules, or integrated circuits. In addition, the materials must be easily processed into the desired optical structures. In this paper, we present our work on using benzocyclobutene as an optical waveguide material. Benzocyclobutene is an advanced organic polymer that is ideally suited as a dielectric layer in high-speed digital circuits. We show that as a waveguide material, single-mode (1300 nm) optical waveguides can be fabricated with losses of 0.81 dB/cm. Detailed processing conditions are discussed.

I. INTRODUCTION

DRIVEN by demands of the marketplace, designers of electronic integrated circuits (IC's) have been constantly forced to produce circuits of increasing speed and greater functionality. Using improvements in device design and material processing, IC designers have had great success in meeting these demands [1]. As IC technology continues to evolve, it has become increasingly important to ensure corresponding advancements in the chip-to-chip interconnection technology associated with these IC's. Improved packaging techniques have allowed a growing number of IC's to be incorporated into electronic systems, resulting in the interconnects between the IC's to increase in length. Increased interconnection length is accompanied by an increase in the signal delay, which if the interconnection is long enough, can be a significant portion of the total signal delay time. Since not all interconnection lengths will be identical, maintaining synchronous clock and data distribution in these multichip high-speed systems is extremely difficult. Using microstrip transmission lines for interconnection allows for the incorporation of delay lines to minimize clock skew and aid in the overall timing of the system. However, impedance matching issues must be given a great deal of attention when incorporating transmission

lines. Serious conflicts can arise between the integrity of the transmission line and reasonable circuit board layouts, which increase with signal frequency and system complexity. This is the major reason that the interconnection of electronic IC's has become one of the most important hardware issues in digital high-speed electronics [2].

While the capabilities of electrical interconnects have not yet been exhausted, it has become increasingly apparent that either new methods of interconnection or packaging techniques are required to support the needs of systems operating at very high frequencies. For this reason, the use of photonics for clock and data distribution in high-speed complex electronic systems has been the subject of intense study in the recent past [2], [3]. The study of photonics is concerned with the use of photons to work with or replace electrons in certain applications traditionally carried out by electronics. Since the bandwidth of an optical channel is over 1 THz in the near infrared, it can easily handle even the fastest electronics, and is the main reason optics has the potential to enhance the performance of systems utilizing only electronics.

One form of optical interconnect that has met with great success is optical fiber. Optical fiber is a very low optical loss, low dispersion medium that has become the dominant technology for long haul data transmission in the telecommunications industry. However, its use in very short distance data communications has been mostly limited to interconnects which span distances on the order of a few meters. The difficulty of fabricating boards which incorporate optical fiber is the major reason fiber is seldom used for chip-to-chip interconnects only a few centimeters long. The routing of fiber is a very time consuming, serial process that is not easily integrated into the manufacturing process. Furthermore, due to its size (125- μ m diameter), the volume of space required for optical fiber interconnects would grow rapidly with more frequent use within the system. These issues have created an interest in using a material system that allows the fabrication of the waveguide structure by embedding them in, or depositing them directly on the circuit board on which the integrated circuits are mounted. The challenge is to develop such a system that still produces sufficiently low optical loss and meets the needs of the electronic environment.

When choosing a material system for board-level optical interconnects, there are several key issues that must be considered. First, since the waveguides are to be fabricated directly on or in the board, the materials used should be compatible with typical electronic processing techniques and

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environments. They should be able to withstand the chemical etches and temperatures encountered in electronics fabrication and adhere to the materials commonly used for substrates. The materials should require only standard fabrication steps such as spin coating, etching, and photolithography. Finally, the material systems used in the fabrication of board level optical interconnects are required to have low optical losses. In this paper, we consider an optical waveguide system fabricated from the organic polymer benzocyclobutene (BCB). It is the purpose of this paper to describe in detail the fabrication of BCB single-mode (at 1300 nm) waveguides, and to present the measured optical losses in these waveguides.

II. MATERIAL PROPERTIES OF BCB

Benzocyclobutenes are a relatively new class of thermally produced polymers possessing characteristics desirable for board-level optical interconnects. Designed originally for use as a thin-film dielectric in applications such as MCM's, GaAs IC's, magnetic media, and flat panel displays, BCB possesses the necessary properties required for materials used in most electronic systems [4]. Important properties include a low dielectric constant (2.7, 10 kHz–10 GHz), excellent planarization (>90%), low moisture uptake (<0.23 wt. % after 24 h in boiling water), good adhesion to various substrates and itself, thermal stability in excess of 350°C, and good mechanical properties [5]. A recent work has reported the optical loss of this material to be low (0.04 dB/cm at a wavelength of 1300 nm) [6]. While these properties are required for any optical waveguide material, the emergence of a photodefinable version of BCB has made this material system very attractive for use as board-level optical interconnects. This negative working system allows the waveguides to be fabricated following steps similar to photoresist processing without the need for any plasma etching.

Two formulations of BCB are currently available based on the monomer, 1,3 bis(2-bicyclo[4.2.0]octa-1,3,5-trien-3-ythenyl)-1,1,3,3-tetramethyl disiloxane. They are supplied as partially polymerized solids dissolved in mesitylene. The first version is a nonphotodefinable formulation and is currently marketed under the name Cyclotene [7]. Solutions containing 35–62% solids are available with viscosities suitable for spin coating and are able to produce uniform films of thicknesses from 300 Å to 25 µm. Upon completion of the polymerization, this material has an index of refraction of 1.559 at a wavelength of 589 nm and is used as the cladding layer in our waveguides. The second formulation of BCB is a proprietary material currently under development at Dow Chemical. This material is a photodefinable version of BCB based upon the above monomer and contains the photocrosslinking agent 2,6-bis(4 azidobenzylidene)-4-methylcyclohexanone, BAC-M. After this material is polymerized, it has an index of refraction of 1.562 at 589 nm and is used for the core material in the waveguides. The small index difference of 0.003 between the core and cladding materials results in this material system being capable of producing single-mode waveguides at 1300 nm with dimensions suitable for coupling to optical fiber, as will be shown below.

The polymerization of BCB is a purely thermal process requiring no catalyst and produces no volatile by-products. During polymerization, a three-dimensional, highly crosslinked network is formed that is unaffected by most chemicals. The cure time can range from days at 170°C to minutes at 300°C and should be carried out in an oxygen free atmosphere (<100 ppm O₂) to avoid oxidation of the polymer. Oxidized films reveal a degradation in the electrical and physical properties, including a rise of approximately 0.025 in the index of refraction and a darkening of the film.

III. EXPERIMENT

The starting materials are pale yellow liquids with the cladding material containing 56% solids and the core material containing 46% solids that are kept refrigerated and brought to room temperature before processing. When these materials were spun at speeds required to achieve the desired thicknesses, strings with the consistency of cotton candy were formed by the ejected material that often redeposited on the surface creating defects. To combat this problem, the percentage of solids was decreased by adding mesitylene to the solutions and spinning the substrates slower. The final solutions used for the core and cladding layers contained approximately 38% and 46% solids respectively. Silicon wafers were used as the substrate material. The substrates were prepared by washing them with soap and DI water, and then soaking them in trichloroethylene for 15 min, rinsing them with acetone and then methanol, and finally blowing them dry with nitrogen.

The fabrication of the waveguides begins with forming the cladding layer. As mentioned above, the nonphotodefinable formulation is used for this purpose. To avoid coupling the light in the core into the silicon, a sufficiently thick cladding layer is required. To make a layer approximately 8-µm thick, the diluted material was spun on a clean silicon wafer at 700 rpm for 25 s with an acceleration time of 15 s. The next step in the process is the polymerization of the film by a thermal cure. The goal of this step is to produce a film that is resistant to solvents, but will adhere to the next layer of BCB. To achieve this, the film must only be partially polymerized. Curing the film so that all of the monomer units have been polymerized results in very poor adhesion between the core and the cladding layers. However, if the cladding has not been cured enough, the mesitylene in the core material, as well as the developing solvents, will penetrate into the cladding layer, also resulting in poor adhesion. The following schedule was found to produce the desired results: ramp up the temperature from 25°C to 100°C over 1 h, hold at 100°C for 15 min, ramp up to 200°C over 1.3 h, hold at 200°C for 15 min, ramp up to 250°C over 30 min, hold the temperature at 250°C for 30 min, and then ramp the temperature down to 25°C over 2 h. It should be noted that partially curing the cladding layers at 240°C for 30 min resulted in under-cured films that were partially attacked by the solvents used in subsequent processing steps. Curing the film at 260°C for 30 min resulted in over-curing the cladding layer, resulting in poor adhesion between the core and the cladding. Therefore, a small temperature window was

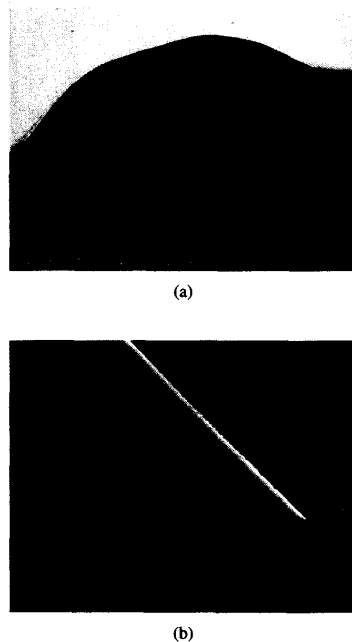


Fig. 2. Scanning electron micrographs of BCB waveguides processed using different developers. (a) Butyl butyrate produced waveguides with smooth surfaces, but very poor resolution; the waveguide was exposed through a 10- μm opening, but was measured to be approximately 20- μm wide. (b) Diglyme shows much better resolution as compared to butyl butyrate, but the rough interface between the core and the cladding could be a source of optical loss in the waveguide. An image of a waveguide developed using Stoddard solvent is shown in Fig. 1(b). This developer produces waveguides with very smooth surfaces and good resolution and is the developer currently in use.

without its drawbacks. Since typical developing times are on the order of 10 s, over-development of the waveguides is common. Over-development often resulted in waveguides that did not adhere and were several microns shorter in height than intended. Another drawback of this developer is the very rough core/cladding interface remaining after polymerization. The roughness is probably due to swelling of the polymer at that point as a result of developer penetration into the material, and could be a potential source of loss in the waveguides.

The third developer, and currently the one in use, is Stoddard solvent.¹ Fig. 1(b) is an SEM micrograph of a waveguide developed with Stoddard solvent. Stoddard solvent is a commercially available solvent commonly used as a negative photoresist developer. With developing times of approximately 80 to 90 s, over-development is less likely to occur with Stoddard solvent. From the SEM micrograph, no roughness at the interface of the core and cladding is evident. This developer has been used to produce waveguides with very smooth surfaces and good resolution. The processing characteristics to be discussed below will only consider waveguides processed with this developer.

¹ Stoddard solvent supplied by OCG Microelectronics Materials, Inc., West Patterson, NJ.

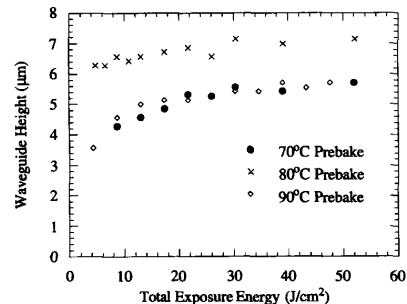


Fig. 3. A graph of the waveguide height versus the exposure energy for various prebake temperatures. The graph demonstrates that the waveguide height is a sensitive function of prebake temperature with a 10°C swing around 80°C producing approximately a 20% decrease in waveguide height.

B. Prebake Characteristics

In order to determine the effect of the prebake temperature on the waveguide dimensions, photodefinable BCB films were spun onto the cladded wafers at a speed of 900 rpm and prebaked at temperatures of 70°C, 80°C, and 90°C for 20 min. These films were then exposed through 7.5- μm wide openings with a power density of 188 mW/cm^2 for times ranging from 10 s to 5 min, and developed with Stoddard solvent. The required developing times were 50, 90, and 120 s for the 70°C, 80°C, and 90°C prebakes, respectively. The films were cured at 250°C for 1 h in nitrogen.

The dependence of waveguide height on prebake temperature is shown in Fig. 3. In this figure, a 10°C swing around 80°C is shown to reduce the waveguide height by approximately 20% as compared to the 80°C prebaked film. The short developing time of the 70°C film is indicative of excess residual solvent in the film allowing the developer to penetrate quickly, and dissolve the top portion of the waveguide. The reduced height and long developing time of the 90°C prebaked film may result from this film being overbaked. This temperature appears to have been high enough to drive out a greater portion of the mesitylene from the spun-on film, as compared to the 80°C prebaked film, making it more difficult for the Stoddard solvent to penetrate and dissolve it. The reduction in height could be the result of the photocrosslinking agent being negatively affected by the increased temperature or due to the developer washing away a portion of the waveguide during the lengthy development.

C. Film Retention

After depositing a thin film of photodefinable material to be used in optical applications, it is generally desired that the film retain as much of its original film thickness as possible during processing. Excessive film loss leads to the need for the application of thicker films to achieve the desired final thickness. However, thick films of photodefinable material are more likely to exhibit the negative effects of diffraction than thin films of the material. Since diffraction can lead to a loss of resolution in the material, it is desired to apply as thin a layer as possible.

found to exist for this processing step to achieve the desired results. The cure was carried out in a nitrogen ambient to avoid oxidation of the polymer.

Immediately after the cladding layer is cured, the core layer is spun on the cladded wafers. In anticipation of coupling light from a single-mode fiber into the waveguide, it was desired to produce waveguides with a cross-sectional area approximately equal to that of the fiber's 8- μm diameter core. To achieve this, the core material was spun onto the cladded wafers at 900 rpm for 25 s after an acceleration time of 20 s. After spinning, the wafer was then pre-baked at 80°C for 20 min in air to remove any residual solvents. After pre-baking, the BCB is not tacky and is suitable for use in a contact printing system. However, an edge bead is formed along the wafer edge during spinning that was cleaved off in order to obtain the maximum resolution possible. The waveguides were patterned by placing the prepared substrates in contact with a chrome mask and exposing the BCB using a 1000 W Hg-Xe lamp with 200–450 nm light through various openings. With a measured power density of 188 mW/cm², typical exposure times are approximately 30–60 s. After exposure, the waveguides can be developed by immersion in butyl butyrate, diglyme, or Stoddard solvent for 20, 10, or 90 s, respectively. The unexposed regions are washed away leaving photopatterned waveguides. To complete the processing, the waveguides are then cured in a similar manner to the cladding layer, but with the time at 250°C extended to 1 h. Fig. 1(a) and 1(b) are scanning electron micrographs of BCB optical ridge waveguides exposed through a 7.5- μm opening. The photopatterned waveguides in Fig. 1 exhibit smooth surfaces and good resolution. Also note that the shape of the waveguides are not perfectly rectangular due to the diffraction effects associated with the mask opening and the spin-on film thickness.

IV. DISCUSSION

When fabricating the BCB waveguides, it was desired to produce waveguides of rectangular cross-section that would be single-mode at 1300 nm, and also have dimensions suitable for coupling to single-mode optical fiber. Since the photodefinable BCB is a material currently under development, experimentation with the various fabrication steps was required to determine the proper processing conditions that would produce these waveguides. The topics examined below include developer selection, affect of prebake temperature on waveguide dimensions, film retention, and photosensitivity. When investigating these topics, the waveguide characteristics of most interest are the surface quality and resolution of the waveguides. A very smooth surface is required of optical waveguides to minimize optical losses that could result from scattering due to surface roughness. Resolution refers to how closely the waveguide width matches that of the opening through which it was exposed. Although resolution may have no effect on the optical losses, if other devices such as optical switches and couplers are to be fabricated with the material, high resolution is desired since these devices require spacing on the order of a few microns [8].

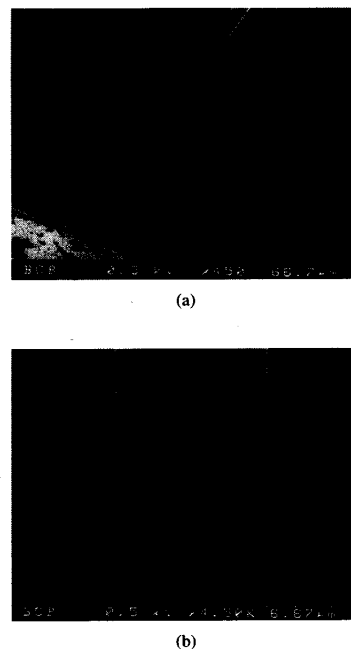


Fig. 1. Scanning electron micrographs of benzocyclobutene (BCB) optical waveguides. The substrate material is oxidized silicon. The cladding layer is a nonphotodefinable version of BCB ($n = 1.559$) while the core layer is a photodefinable version ($n = 1.562$). (a) Overview and (b) high resolution cross section indicating the smooth surface and well-defined walls.

A. Developer Selection

Butyl butyrate was the first developer studied for use in the fabrication of BCB waveguides. The cross section of a waveguide developed with butyl butyrate after exposure through a 10- μm opening is pictured in Fig. 2(a). This developer produced waveguides with smooth surfaces but very long, sloped sidewalls. This results in the waveguides having dimensions much larger than the mask dimension through which it was exposed, leading to poor resolution. For the waveguide shown, the full width measured at one-half its full height was found to be approximately 2 times larger than the mask opening. It is believed that this problem comes from the developer's poor selectivity with respect to the exposed/unexposed regions of the BCB. It should be noted that although there appears to be four layers to this structure, it possesses only three. The line that appears about 4 μm from the top of the guide is an artifact resulting from the cleave, and not an indication of separate layers.

The second developer used in the fabrication of the waveguides was diglyme (diethylene glycol dimethyl ether). A typical waveguide fabricated with diglyme is shown in Fig. 2(b). The selectivity of this developer is much better than that of butyl butyrate as evident from the sidewalls being much closer to vertical. This waveguide was exposed through a 10- μm opening and was measured to be 12- μm wide and has a very smooth surface. This developer, however, is not

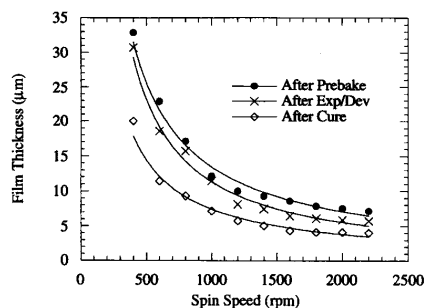


Fig. 4. A graph of the film thickness versus the spin speed at various stages in the processing of the photodefinable BCB. A significant portion of the original film thickness is lost during processing due to dissolution during development and film shrinkage during final cure.

Fig. 4 shows the relation of film thickness versus spin speed at various steps in the processing. Specifically, the film thickness was measured after prebake, after exposure and development, and after the final cure. All of the films were prebaked at 80°C for 20 min and exposed with a total energy of 9.4 J/cm². From these curves, it is evident that approximately 20% of the film is lost during development and another 20% is lost during the cure. The change in film thickness for each step occurs as the result of two factors. During development, the film thickness decreases as a result of a portion of the film being removed by the developer. However, the actual material removed may not be readily apparent due to swelling of the film caused by developer penetration into the film. During the cure, the film thickness changes due to reduction of the swelling as the developer evaporates at high temperatures, and due to the shrinkage of the film as it polymerizes. Overall, approximately 40% of the initial film thickness is lost during the entire processing sequence. This is undesirable because diffraction during the exposure step occurs on a film that is considerably thicker than the final film thus limiting resolution. As evident in the above SEM's, the waveguide width is consistently larger than the mask opening through which it was exposed. While the loss in film thickness due to shrinkage cannot be avoided, the loss due to developing may be reduced by using a more selective developer. However, at this time we are unaware of such a developer.

D. Photosensitivity

To characterize this photodefinable system, a study was made of the effect that the exposure energy and the width of the mask opening had on the waveguide dimensions. Films of BCB were exposed through mask openings of widths 5, 10, 25, and 50 μm with a power density of 188 mW/cm² after a prebake of 80°C for 20 min. After exposure, the samples were developed in Stoddard solvent for 1.5 min and then cured in nitrogen for 1 h at 250°C.

Fig. 5 illustrates the effect that the total exposure energy has on the width of the waveguides. The shaded region to the left represents the energy doses that resulted in underexposed waveguides. Exposures with these energy doses resulted in waveguides that were not sufficiently crosslinked to avoid

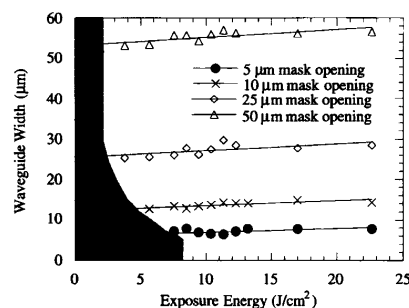


Fig. 5. A graph of the waveguide width versus the exposure energy. As desired, the waveguide width remains relatively constant over a wide range of exposure energies, allowing for a great deal of latitude in the exposure step. The shaded region represents underexposed waveguides. In these waveguides, the exposure energy was too low to produce well-defined waveguides primarily due to the severely reduced height (see Fig. 3).

partial dissolution during the development step. An important characteristic of this photodefinable system is the latitude in the allowable exposure energy doses with respect to the waveguide width. The small slope of the curves in Fig. 5 indicates that the waveguide width remains relatively constant over a wide range of exposure energies.

The dependence of the waveguide height on the width of the mask opening is illustrated in Fig. 6. Inspection of this figure indicates that the wider the mask opening through which the waveguides were exposed, the taller the resulting waveguide. The reason for this dependence is not entirely clear. It would appear that the wider openings may allow for a higher degree of crosslinking during exposure, rendering the exposed material less soluble in the developer as compared to a waveguide exposed through a more narrow opening. In any case, this dependence puts an upper limit on the waveguide height as the width of the opening decreases. It has not been found possible to produce waveguides that are taller than they are wide.

E. Loss Measurement

To evaluate the optical losses in BCB ridge waveguides, a cutback measurement technique was used. In this measurement, light is coupled into the cleaved end of a waveguide from a single-mode optical fiber. The alignment of the fiber to the waveguide is adjusted until the output of waveguide is maximized, and then measured. A measured length of the waveguide is then cleaved from the output end of the guide and the process repeated. This continues until only a few millimeters of the waveguide remain. The length of the waveguide is then plotted against the insertion loss. The insertion loss, calculated in dB as $10 \log(P_{\text{out}}/P_{\text{in}})$, where P_{out} is the power detected at the output end of the waveguide, and P_{in} is the power output from the optical fiber, includes both the waveguide losses and the coupling losses. By plotting the insertion loss as a function of the waveguide length, the optical loss in the waveguides, measured in dB/cm, is found to be equal to the slope of the line and the y -intercept is equal to the coupling loss. For this work, we were not interested in

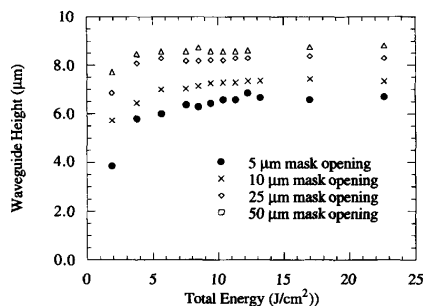


Fig. 6. A graph of the waveguide height versus the exposure energy. Wider mask openings produced taller waveguides. The mechanism behind this is not understood at this time.

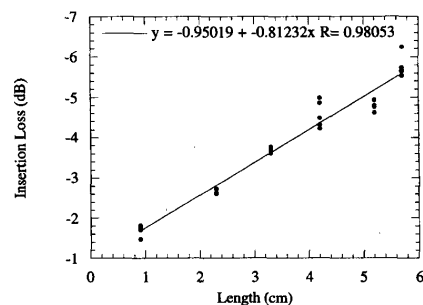
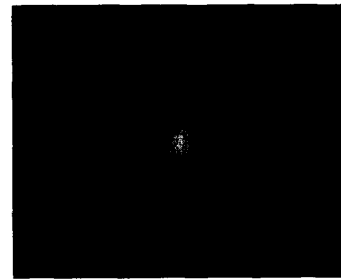


Fig. 7. Results of a cutback loss measurement on BCB channel waveguides. The slope of the line indicates a waveguide loss of 0.81 dB/cm while the coupling loss is approximately 0.9 dB. These measurements were done at 1300 nm.

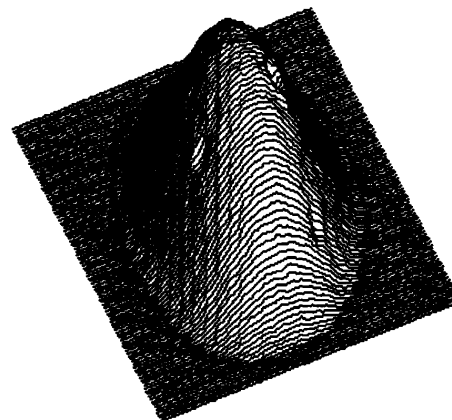
coupling losses but rather the waveguide losses. Therefore, no special procedures were involved in coupling the single-mode fiber to the BCB waveguide. Coupling was accomplished by butt coupling the single-mode fiber to the cleaved endface of the BCB waveguide. No index matching fluids were used.

The results of a cutback loss measurement performed on BCB optical waveguides are shown in Fig. 7. In this measurement, 1300-nm light was coupled from a single-mode fiber (8.3- μm core diameter; cleaved and polished) into the core of waveguides 8.7- μm wide, 6.8- μm tall. The slope of the line indicates that the optical losses in the waveguide are 0.81 dB/cm. When examined through an infrared viewer, the waveguides appear to be of good quality due to the absence of defects and scattering centers. However, a loss of 0.81 dB/cm is large compared to the published absorption data for a slab of nonphotodefinable BCB of 0.04 dB/cm. The additional loss could be due to the addition of the photocrosslinking agent. Determining the source of the additional losses is one area for future research, however, with the losses equal to 0.81 dB/cm these waveguides are suitable for use in relatively short (several centimeters) optical interconnect situations, characteristic of many MCM's.

To determine the number of modes supported by these waveguides, an infrared imaging system was used to examine the mode structure at the output of the waveguides. Fig. 8(a) is



(a)



(b)

Fig. 8. (a) An image of the output light ($\lambda = 1300$ nm) from a BCB channel waveguide measuring 6.8- μm tall and 8.7- μm wide. (b) A surface plot of the output light intensity. The single lobe of light in the core indicates that the waveguide supports a single mode at this wavelength.

an image of the waveguide output with 1.3- μm light coupled in at the input, while Fig. 8(b) is a surface plot of this image. The single lobe of light evident in these figures is a clear indication that these waveguides support only one mode at this wavelength. Inspection of Fig. 8(a) and 8(b) reveals that the intensity distribution across the output of the waveguide is not perfectly symmetric. The asymmetry of the distribution can be attributed to the asymmetry of the waveguide structure. The waveguide has a BCB cladding only on one side, air on the others, and is not perfectly square. Therefore, it is reasonable to expect a certain degree of asymmetry in the intensity distribution.

V. SUMMARY

Benzocyclobutene is an advanced organic polymer that has several desirable properties for use as a dielectric layer in high-speed electronic systems. It is characterized by a low dielectric constant (2.7, 10 kHz–10 GHz), excellent planarization (>90%), low moisture uptake (<0.23 wt.% after 24 h in boiling water), good adhesion to various substrates and itself, thermal stability in excess of 350°C, and good mechanical properties. These properties make it ideal for use

as a dielectric layer in MCM's, GaAs IC's, magnetic media, and flat panel displays. In this paper, we have demonstrated that this material can also be used as an optical waveguide medium. In particular, we have demonstrated single-mode optical waveguides at 1300 nm with waveguide losses of 0.81 dB/cm. The dimensions of the core of these waveguides are approximately equal to the dimensions of the core of a single-mode fiber within the constraint that the waveguides are rectangular and the fiber is cylindrical. This close matching of the core dimensions is critical for achieving high coupling efficiency between fiber and waveguides without using mode transformers. Therefore, this material system is ideally suited for applications that will require interfacing board or chip level optical processing with optical fiber. The low water absorption and high glass transition temperature of BCB should insure long-term stability of the optical waveguides. The detailed processing conditions were presented. The photo-definable version of BCB has a very narrow process window in which one can fabricate the structures described in this paper. However, recent work has shown that process latitude is increased for optical waveguide structures that require smaller cross-sectional dimensions, i.e., for waveguides that are not intended to couple to single-mode optical fiber.

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