A low-temperature lamination technique for assembling polymer-base thermo-capillary optical switch

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1. Introduction

The optical cross-connect switch is a key devise in optical communication systems. Recently, an optical switch based on thermo-capillarity has been proposed for silica base single-mode waveguides [1]. This switch has some attractive optical properties, such as low insertion loss, a high extinction ratio and insensitivity to wavelength and polarization. Moreover, it is self-latching and expected to be integrated into a small waveguide substrate. However, to reduce costs, the switch should be fabricated with a polymer-base waveguide which is easily prepared by expanding and curing a resin on a flat substrate. Moreover polymer-base waveguides are easily formed with conventional reactive ion etching technique.

Figure 1 shows the structure of the thermo-capillary optical switch and its cross section. This switch has a slit that encapsulates oil with a refractive index equal to that of the waveguide core. According to the movement of the oil in the slit, this cross-waveguide structure acts as an optical switch. The slit should be hermetically sealed with a glass lid. However, the width of slit is as narrow as about 10µm so that the slit is easily filled with adhesives. Thus the glass lid should be bonded onto the polymer film without adhesives. Thermal lamination is one of the candidates for the direct bonding. This method strongly bonds a glass plate to a polymer film, but is the conventionally carried out at a temperature higher than the polymer's glass transition temperature \( T_g \). Thermal treatment above \( T_g \) could degrade the optical properties of the waveguides [2]. A lamination technique at a temperature lower than \( T_g \) must therefore be developed for our switch assembly.

In the following paper, we will report that optimizing the curing temperature of the polymer film can provide the required bonding strength at a low bonding temperature. Finally, a demonstration of encapsulating oil in a slit, which was sealed with a glass lid, will be reported.

Fig. 1. Structure of thermo-capillary optical switch and its cross section.
2. Sample preparation

Thermal lamination is thought to require a temperature higher than \( T_g \) to obtain an adequate bonding strength [3]. However, when the curing temperature \( T_c \) of the polymer film is low, bonding could be achieved with a bonding temperature \( T_b \) lower than \( T_g \) because of a residual non-polymerized component.

To investigate the influence of \( T_c \) to the bonding strength of the laminated glass-film interface, we prepared rectangular pieces of Pyrex glass and Si with 50-µm thick polymer film. The UV-curable epoxy resin with a \( T_g \) of 225°C was cured by UV radiation at room temperature after being expanded on Si substrates, and then baked at three different temperatures, 80°C, 140°C, and 200°C for an hour. These temperatures are curing temperatures. We also prepared non-baked samples.

We bonded the glass piece to the polymer film coating on the Si piece in a cross configuration (Fig. 2(a)) on a heating plate. Bonding was carried out at several temperatures with varying durations and pressures.

![Fig. 2. Set-up for measuring bonding strength.](image)

![Graph](image)

Fig. 3. Relationship between the bonding strengths and each \( T_b \) for the four different \( T_c \). The bonding pressure is 0.1 MPa and the bonding duration is 60 min. The cooling rate is below 5°C/min.
3. Bonding strength

Figure 2(c) shows our set-up for measuring bonding strength. To apply the pulling force perpendicular to the bonded interface, a sample piece was bonded on Al fittings with epoxy adhesive (Fig. 2(b)) and was set into a pulling test machine (Fig. 2(c)). The maximum pulling force, that is the breakage force, was measured with a load-cell. The bonding strength is defined as the pressure which is obtained as a maximum pulling force per unit bonded area.

Figure 3 shows the bonding strengths achieved for the different Tcs. The bonding duration was one hour and the pressure on glass plate was 0.1 MPa. The cooling rate after bonding was slower than 5°C/min. In this figure circles indicate the bonding strength of the glass-film interface, and triangles show the breakage strength of the Pyrex glass or the film-Si substrate interface. In the later cases of the triangles, thus the bonding strength of glass-film interface could be higher than the measured values. As seen in Fig. 3 there are samples which show a lower strength values than those of other samples under the same conditions. This may be because of film-edge deformation caused during the dicing process.

The glass pieces were not bond to the polymer films at a temperature lower than Tc, and the bonding strength increased as the temperature difference of Tb and Tc increased. The bonding strength for the non-baked samples, in particular, that bonded at 225°C was larger than the glass breakage strength. However the adhesive strength of Si-interface of the film which was baked at a lower temperature decreased after being heat treatment at 250°C. This is due to film shrinkage caused by heat treatment. These phenomenon were not observed in the films baked at 140°C and 200°C.

Figures 4 and 5 show the bonding strengths achieved for bonding durations and pressures respectively. The samples were cured at R.T. by the UV radiation. The bonding strengths of samples bonded at 80°C, did not seem to be depend on the bonding duration. The strengths of samples bonded at 200°C increased as the duration exceeded 60 min. However, the decrease of the adhesive strength of film-Si interface was observed after 180 min. bonding duration. This is also understood as the effect of the film shrinkage. On the other hand no clear dependence of the bonding strengths could not be observed on pressure.

4. Demonstration of oil encapsulation

To confirm that the low-temperature lamination technique is useful for bonding a glass lid on a real-sized slit, we demonstrated oil encapsulation in the slit in a polymer film. The curing
temperature of the film was 150°C. A 10µm-wide and 18µm-deep slit was formed in the film by RIE. The bonding temperature was 200°C. The glass lid had a narrow channel for oil injection which was also etched by RIE.

Figure 6 shows the top view of the slit. The U-shaped structure in the glass lid is a bypass slit which connects the ends of the slit in the polymer layer and forms a closed loop structure needed for switching operation. We injected oil through the injection channel, which can not be seen clearly in Fig. 6, and sealed the entrance of the channel with epoxy resin. The bright portion in the slit is the oil-filled region. Since the oil was successfully encapsulated in the slit, low-temperature lamination is effective for hermetic bonding for glass-film interface.

5. Conclusion
A sufficiently high bonding strength was obtained with the thermal lamination technique at a bonding temperature lower than \( T_g \). We successfully encapsulated oil in the glass-lid sealed slit using our low-temperature lamination technique. This lamination technique is effective in the direct bonding of a lid onto a polymer base thermo-capillary optical switch.

References