Injection molded low-thermal-expansion multi-fiber ferrule

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ABSTRACT

Hybrid injection-molded ferrules are presented which consist of a polymer body and an over-molded glass insert. The average coefficient of thermal expansion observed at the front face of the ferrules is 8 ppm/C from room temperature to 100 C. This design could be applicable for direct heterogeneous re-matable connections between fiber ribbons and photonic integrated circuits which exhibit low thermal expansion and operate at elevated temperatures.

Keywords: fiber ferrule, injection molding, low thermal expansion

1. INTRODUCTION

Recently, co-packaging of transceivers and switch ASICs in data-center applications has been proposed and become a major topic at technical conferences[1]. Predictions for the first implementation have been changing to ever later switch generations, and current discussions mention future 51.2 or 102.4-Tbps switches as candidates for co-packaging. From a packaging point of view, it would be advantageous if the optical fiber-ribbons leading to the transceiver chips could be terminated in a dematable connector right at the transceiver. With such a connectorized solution, the switch ASIC and surrounding transceiver chips could be mounted to their common daughterboard without many attached fibers of considerable length complicating the assembly process. A dematable connector would also enable solder-reflow processes of the chip subassembly without exposing fiber ribbons to the required temperature profiles. Standard fiber coatings suffer significant damage at peak temperatures typical for solder reflow of about 260 C.

One design option that minimizes the number of optical interfaces is to directly attach the ferrule to the edge of a photonic integrated circuit where the polished fibers in the ferrule are aligned with corresponding waveguides in the PIC. In contrast to homogenous ferrule-to-ferrule connections, for such a heterogeneous interface with many waveguides and fibers in a row, matching of thermal-expansion becomes a critical parameter. Let us assume typical dimensions (several millimeters), a temperature swing of 100 C, and a thermal expansion difference of 14 ppm/C (coefficient of thermal-expansion [CTE] difference between standard MT ferrule [~17 ppm/C] and silicon [2.6 ppm/C]). In this case, the temperature-induced relative motion (misalignment) would be on the order of several micrometers. That would result in an insertion loss on the order of 1 dB for the case of single-mode fibers and waveguides (if the initial alignment was perfect).

Below, we present a ferrule design with an over-molded glass insert. Related work was previously presented with metal inserts aimed at improving ferrule durability for use in reference connectors[2]. Here, the glass is designed to constrain the thermal expansion of the polymer matrix at the front of the ferrule[3], reducing the CTE to single-digit values (in units of ppm/C) at the optical interface. The observed CTE would reduce thermal misalignment between fibers and waveguides under the assumptions listed above to sub-micrometer values.

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2. METHODOLOGY

2.1 Glass inserts

The glass inserts shown in Figure 1 were manufactured by a process consisting of femtosecond laser exposure and subsequent wet etching. Exposed glass volumes exhibit a much higher etch rate than the unexposed glass matrix which enables the accurate shaping of voids in the glass. The design includes two larger cylindrical holes for the 700 µm-diameter alignment pins. These holes were fabricated with a small oversize of less than 20 µm (diameter). That ensures that the large pins hold the inserts in the correct place in the mold with an uncertainty of less than ±10 µm.

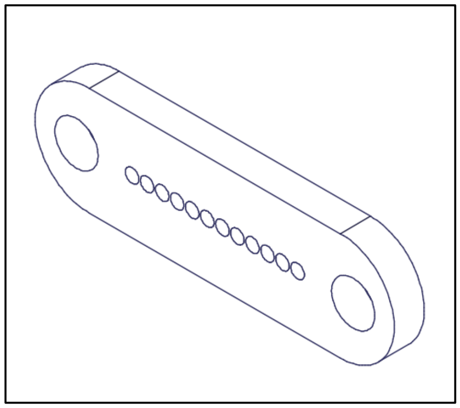

Figure 1. Schematic of the glass inserts. The glass thickness is 0.5 mm, outside dimensions are 6 mm x 1.8 mm.

The openings for the 12 fibers (and their corresponding pins in the mold) are individual holes with a diameter of 225 µm. This design leaves a circular gap of about 50 µm width around each pin in the mold which is filled with polymer during the mold injection. A borosilicate glass wafer with multiple of the hole pattern shown in Fig. 1 for an individual insert was prepared by Optoscribe** using the expose-and-etch process. Individual inserts were cut out of the wafer in a race-track shape by laser cutting. The samples were then treated with an adhesion promoter to improve adhesion of the glass to the polymer.

2.2 Overmolding

The glass inserts were preheated and then placed manually into an MT-ferrule mold of standard 12-fiber design with a non-angled front face. Then, the inserts were over-molded with filled polyphenylene sulfide polymer (PPS), the same material as used for production MT ferrules. In a last step, the manufactured ferrules were populated with single-mode 12-fiber ribbons as shown in Figure 2 and the front faces were polished.

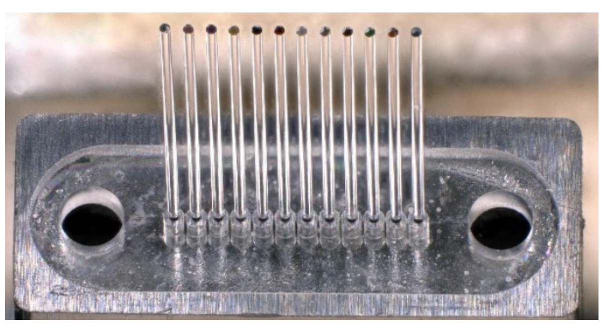

Figure 2. Front face of a ferrule with glass insert and fibers before cutting off excess fiber length and polishing.

** Optoscribe LTD., Livingston, United Kingdom

2.3 CTE measurements

Prepared hybrid ferrules were placed into a temperature-controlled fixture which was designed to enclose the ferrule under test from all sides except small access slots at the back (for fiber ribbon access) and the front (for pick-up fiber access). All fibers were illuminated at the far end with laser light at 1310 nm. Light exiting the fiber tips at the front of the ferrule was picked up by a single-mode fiber mounted on a high-accuracy 6-axis manipulator. The position of the light mode exiting each fiber was determined by lateral scanning of a single-mode pick-up fiber close to the ferrule surface. As the thermally induced length change of the sample is small, most measurements were done on the outside fiber positions which exhibit the largest change. The average CTE was determined by fitting a straight line to the fiber #1-to-#12 distance-versus-temperature data.

2.4 Modeling

A three-dimensional finite element model was built to predict the temperature-dependent fiber displacements of the outermost fibers. The model components and corresponding finite element mesh are presented in Figure 3. The time history of the prescribed temperature from the experiments is given in Figure 4. There are six set temperatures at which experimental measurements were carried out: 25 C, 40 C, 55 C, 70 C, 85 C and 100 C. The transition time from one temperature to the next was 10 minutes with 20 minutes used for temperature stabilization. The problem was solved using a coupled thermo-mechanical procedure. The transient heat transfer analysis used the boundary conditions described in Figure 4 (heating element is located below the ferrule) while the static mechanical solution assumed a thermo-elastic response of the system components. Three points were constrained at the bottom back of the ferrule as boundary conditions to avoid rigid body motions. The interfaces between the components were assumed to be bonded (no thermal resistance).

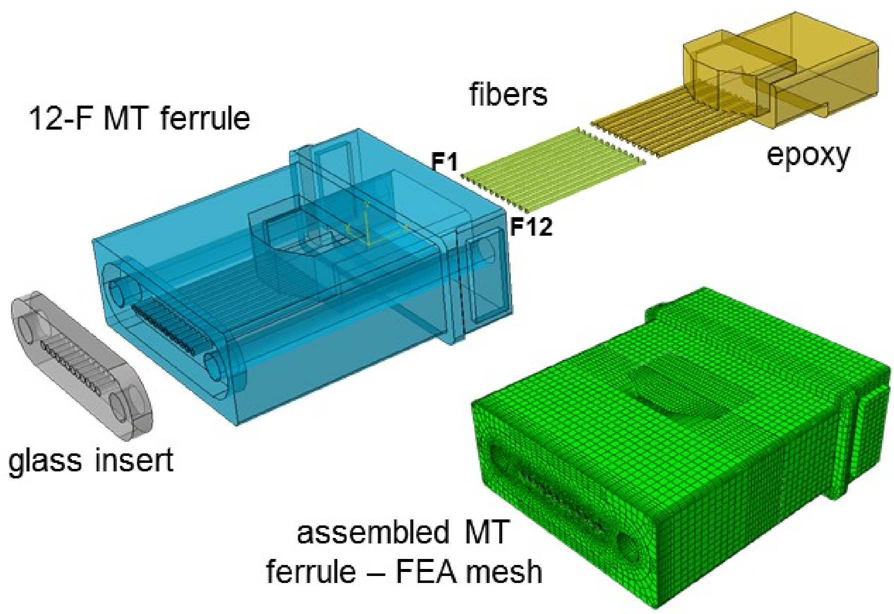

Figure 3. Model components for coupled thermo-mechanical numerical analysis.

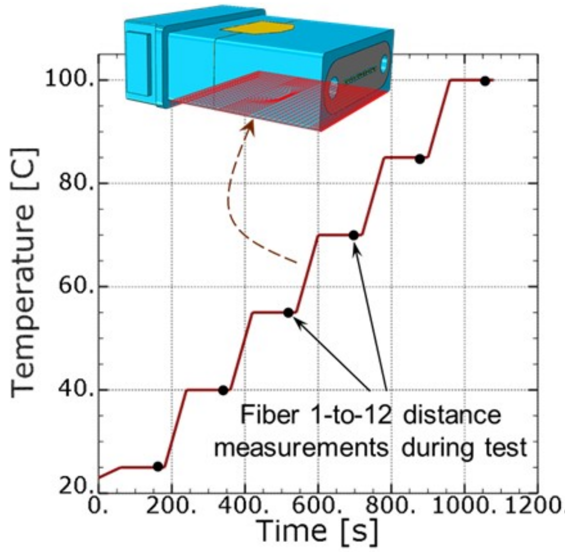

Figure 4. Prescribed temperature at the bottom of the ferrule while other surfaces are heated by convection from the environment with the same temperature history.

The mechanical and thermal material properties at room temperature used in the analysis are given in Table 1. Although not presented here, the temperature dependence of some properties (CTE of the adhesive and MT ferrule) was also included in the simulations. However, no data on the temperature dependence of Young's modulus for filled PPS were available at the time of analysis, so that property was assumed to be independent on temperature.

Table 1. Isotropic Mechanical and Thermal Material Properties (23 C). The PPS is glass filled as used for MT ferrules.

Material	Young's modulus, E [GPa]	Poisson's ratio, ν	Coeff. thermal expansion, CTE [μm/(m C)]	Density, ρ [Kg/m^3]	Thermal conductivity, κ [W/(m C)]	Specific heat capacity, C_p [J/(Kg C)]
Silica	73	0.19	0.55	2200	1.38	740
Epoxy 353	2.47	0.34	55	1200	0.25	1000
PPS	3.45	0.35	16.3	1350	0.288	1290
Borofloat 33	64	0.2	3.25	2200	1.2	830

3. RESULTS

3.1 Experimental results

Figure 5 shows the distance between fibers #1 and #12 for two different samples measured as a function of ferrule temperature. Note that the absolute distance at room temperature is about 16 μm larger than the 2.75 mm (11 x 250 μm) nominal distance in a standard 12-fiber MT ferrule. The slopes of the linear fits to the data in the figure correspond to CTEs of 6.8 ppm/C (top curve, dashed line) and 7.3 ppm/C (lower curve, solid line), respectively. Across several samples, observed CTE values varied between 6.2 and 10.5 ppm/C with an average of 8.0 ppm/C.

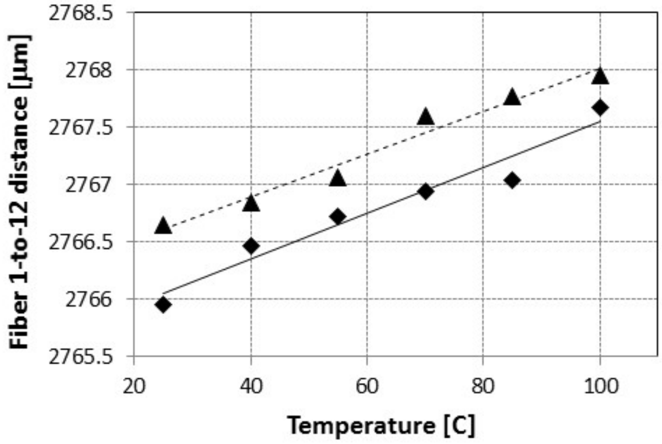

Figure 5. Distance between first and last fibers in two different composite ferrules as a function of temperature.

3.2 Modeling results

The computed time-temperature curves at the tips of fibers #1 and #12 are presented in Figure 6a. Clearly, these temperatures follow closely the prescribed temperature profile at the bottom of the ferrule. Figure 6b displays a contour plot of the x-displacement component (in mm) at 100 C. It is noted that large x-displacements exist at the back of the MT ferrule due mainly to the expansion of the large volume of epoxy adhesive that fills up the ferrule cavity (see figure 3). As expected, the thermal expansion decreases closer to the front of the ferrule.

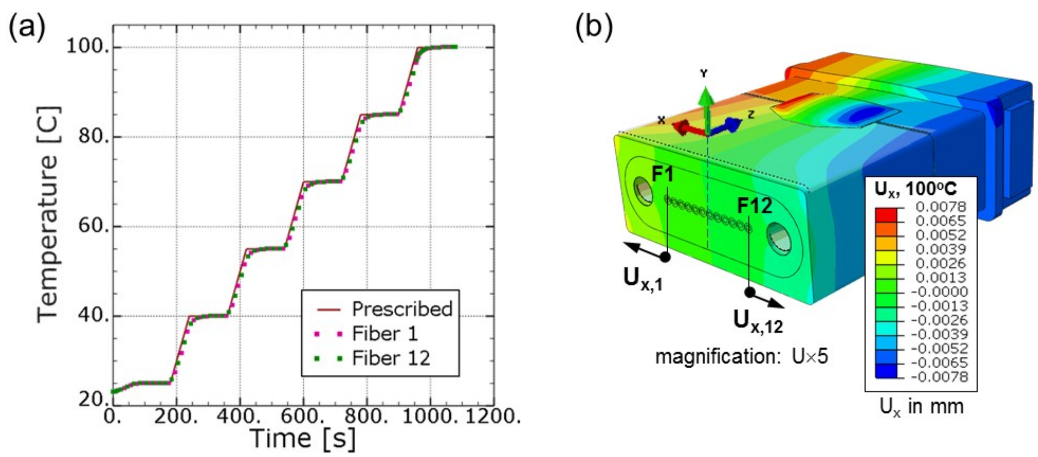

Figure 6. (a) Computed temperature at Fibers #1 and #12; (b) Contour plots of displacement U_x.

Figure 7 compares the calculated displacement difference (blue dots) between fiber #1 and #12 with the bottom one of the experimental data sets from figure 5. The sudden increase observed in the range 50 C to 60 C is induced by the temperature-dependent CTE of the epoxy and MT ferrule.

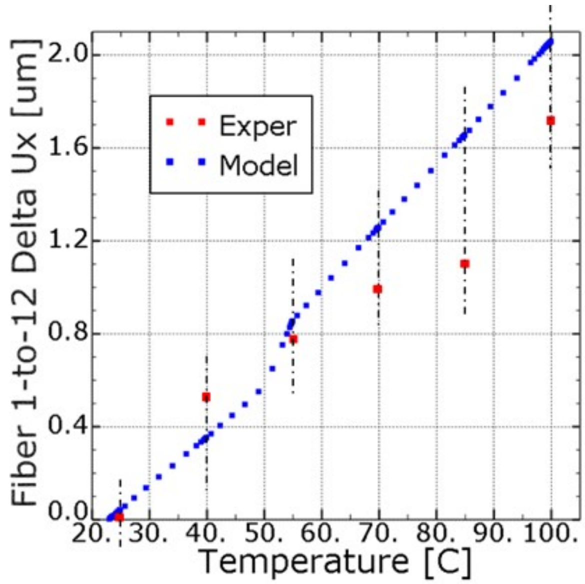

Figure 7. Predicted displacement difference ΔU_x between outermost fibers versus experimental values.

3.3 Discussion

The standard MT mold used here is designed with a finely tuned fiber pitch which is a little larger than the targeted 250 µm. After ejection from the mold, standard ferrules shrink to almost exactly the 250 µm pitch as they cool down from molding temperatures to room temperature (RT). The hybrid ferrule has less shrinkage out of the mold than the standard PPS ferrule and therefore the fiber pitch on the hybrid ferrules is larger than 250 µm (see figure 5). A custom-designed mold for our hybrid design would be required in order to mold hybrid ferrules with a 250 µm fiber pitch.

Unlike in polymer ferrules, as the front face of the hybrid ferrule consists mostly of glass, the fiber ends do not protrude significantly after standard polishing. However, fiber protrusion is a significant factor (of many) in achieving physical contact between the connected waveguides at the optical interface. Therefore, a connection using the hybrid ferrule as it stands today, would likely require an index-matching medium at the optical interface.

The effective CTE values (assuming a constant CTE over the full temperature range) we observed range from 6.2 to 10.5 ppm/C with an average of 8.0 ppm/C. Repeat measurements show that the observed sample-to-sample variation can largely be explained by the error of the CTE measurement.

The modeled thermal expansion at the fiber tips agrees well with the measurements as the calculated CTE of 9.7 ppm/C falls into the top range of the experimental values. Thus, the difference to the measured average CTE of 8 ppm/C is barely significant given the observed variability of the experimental data. Fundamentally, the effective CTE at the front face lies in between the CTE of the glass insert and that of the polymer components. The exact value is driven by the geometry, the CTE and Young's moduli of the different materials. For lack of reliable data, the model presently does not contain the decrease of moduli of the PPS and the adhesive with increasing temperature. That omission leads to an overestimation of the stiffness of the high-CTE polymer/adhesive at elevates temperatures, which in turn leads to an increase of the effective CTE in the model.

With the observed average CTE of the hybrid ferrules, the mismatch to silicon would drop from 14 (PPS ferrule as reference) to about 5 ppm/C. While we expect that the thermal expansion could be further reduced by adjustments to the design, that reduction is already significant. In a symmetric layout of 12 fibers on a pitch of 250 µm, the maximum thermally-induced misalignment of the outermost fibers would amount to only 0.7 µm for a temperature excursion of 100 C. Such a misalignment would lead to an additional insertion loss of only 0.1 dB for single-mode fibers, if initial alignment was ideal. Also, optimization of the insert geometry and choice of the glass-insert material can be leveraged to tune the ferrule CTE to different values that might be required by different applications.

REFERENCES

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[3] Neukirch, U. and Yates, W.: "Optical fiber ferrules incorporating glass faceplate and methods of fabricating the same." International Patent application WO2018/164954, September 2018.