Computer-Controlled Technique for Cutting Curved Grooves in Polished Fiber-Optic Coupler Substrates

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Abstract—**The fabrication of polished fiber-optic couplers requires a substrate or glass block to protect the fiber during grinding and polishing steps. Polished coupler substrates are a major source of process and performance variability, due to mechanical variation of the block and groove. An automated system capable of cutting repeatable grooves in glass blocks has been developed, which greatly improves the quality of the substrates. The fiber groove longitudinal profile (which determines interaction length) and other parameters can be defined and controlled programmatically with this approach. The transverse groove profile exhibits a flat, smooth bottom and minimal width, which allows for flatter polishing of fiber / substrate assemblies.**

I. Introduction

It is often desirable to have access to the evanescent portion of the guided optical energy in single-mode optical fibers. Side-polished optical fibers are one technique for accessing the evanescent field, and this technique has been exploited to make a family of fiber-optic devices, including couplers [1]. In most techniques, the optical fiber is first embedded in a carrier or substrate that supports the fiber during the subsequent grinding and polishing steps.

The earliest-known method for fabricating substrates out of glass used a low-speed wire saw [1] to cut a curved groove in the substrate block. Alternate substrate fabrication techniques have included bonding to a prefabricated curved surface [2], "sandwich" assemblies [3], silicon v-grooves [4], and modified commercial low-speed saws [5]. These techniques all have various disadvantages, such as mehcanical variation, complexity, dissimilar materials, and

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slow process throughput. It is the object of this paper to describe a new technique for reproducibly fabricating substrates for polished fiber-based optical devices.

II. COMPUTER-CONTROLLED GROOVE GENERATOR

Consistent high-quality polishing of the fiber is critical to successful device fabrication, as small imperfections are well known to induce losses and polarization cross coupling. Birefringent fiber devices also suffer from stress relief when the geometry of the stress-applying parts is modified by polishing. A uniformly precise fiber substrate is desirable to reduce perturbations and permit repeatable processing. Fig. 1 illustrates a fiber side-polishing substrate that consists of a glass block with a groove for receiving the bare fiber. The interaction length—an important parameter for several devices—is $\alpha \sqrt{R}$, where R is the radius of curvature of the groove [6]. The wider grooves in the substrate are for the jacketed areas of the fiber, where a low-modulus adhesive provides strain relief. Some of the desirable characteristics of a successful polishing substrate include the following:

1) Groove straightness and registration.
2) Controlled fiber profile, i.e., radius.
3) Repeatable groove depth at center.
4) Controlled width to minimize epoxy.
5) Smooth groove bottom surface.
6) Rapid processing and operator insensitivity.

A great improvement in substrate groove reproducibility can be achieved by adopting techniques developed by the numerically controlled machine tool industry. Fig. 2 is a schematic groove generator, which is not unlike a horizontal milling machine. A cutting wheel is held in a fixed position over a set of precision *xyz* stages, and runs on a precision spindle bearing at a maximum speed of 300 rpm. Movement in the x direction along the groove and the z-motion, which controls the depth of cut, are controlled by a computer. Table I summarizes the characteristics of the stages; the y-axis stage is only adjusted once during setup to manually center the groove on the block. The motorized stages incorporate limit and home sensors that communicate to the computer via the stepper motor controller electronics. The position of the substrate relative to the blade is controlled by a series of motion commands given to the motion controller by the computer.

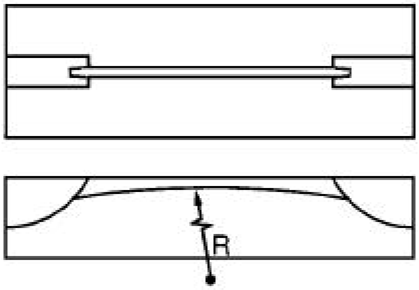

Fig. 1. Glass substrate top and side views.

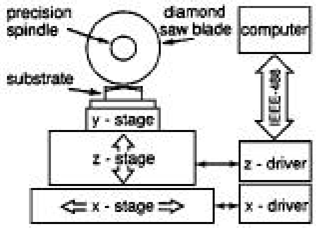

Fig. 2. Numerically controlled groove generator.

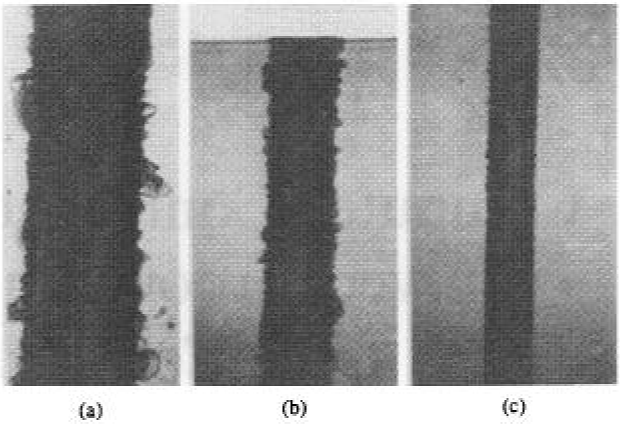
(a) (b) (c)

Fig. 3. Groove top views: (a) 200-grit; (b) 600-grit; (c) IC dicing blade.

TABLE I
TRANSLATION STAGE CHARACTERISTICS

	Travel	Resolution	Tilt/Travel
x	400 mm	1 μm	200 μrad
y	25 mm	< 10 μm (manual)	100 μrad
z	4.2 mm	0.1 μm	200 μrad

TABLE II
BLADE AND TYPICAL GROOVE CHARACTERISTICS

Type/ Diameter	Nominal Width	Groove Width	Kerf Loss
600-grit 3 in	0.006 in	375 μm (a)	220 μm
200-grit 3 in	0.006 in	225 μm (b)	73 μm
IC Dicing 2.188 in	0.0045 in	165 μm (c)	50 μm

The equation used to generate the circular groove of radius R as a function of x is

$$z(x) = z_o + R - \sqrt{R^2 - x^2}$$

where z_o is the depth of the groove at $x = 0$. A personal computer with an interface card controls the position, velocity, and acceleration of the two stages, and prompts the operator running the system. A program written in Pascal iterates through a series of straight cuts, each removing 10 μm at a feed rate of 0.3 mm/s. The curved cuts are then made, and the final curved cut is made in the ductile-mode grinding regime [7] to reduce the roughness of the groove surface. The stages are moved back to the blade loading position, the operator is then asked to change the cutting wheel to the thick blade, and proceeds to cut the wide grooves. The radius of curvature of the

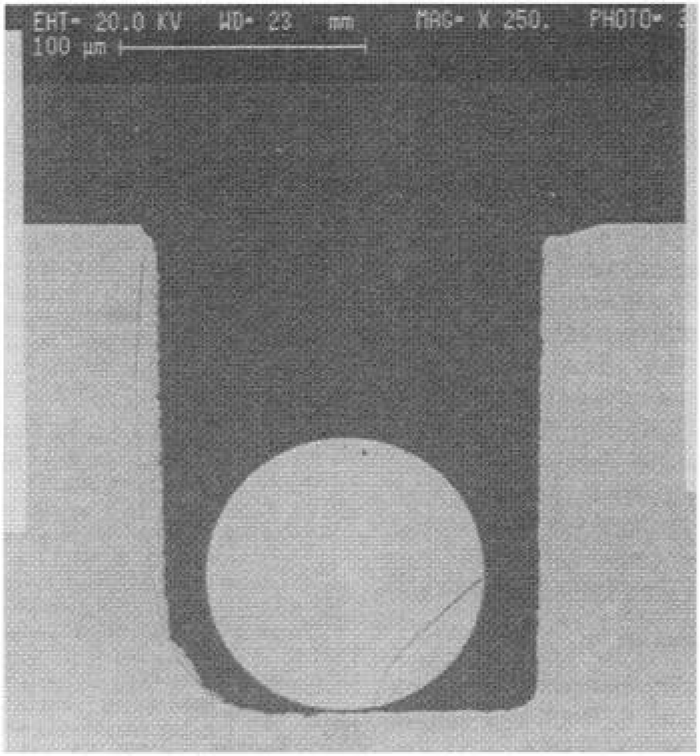

Fig. 4. Cross section of groove and side-polished PM fiber.

groove and other parameters may be easily changed in the software to facilitate cutting a number of groove styles.

III. Experiments and Results

Initial testing of this concept with 3-in-diameter 200-grit cutting blades produced grooves with unacceptable roughness, kerf loss, and edge chipping; a finer, 600-grit abrasive blade was an improvement. Both of these general-purpose blades had a poor thickness tolerance, and more importantly, were unavailable in a thickness less than 0.006 in. Table II summarizes some of the characteristics of the different blades used in these experiments, and lists typical groove widths and estimated kerf losses for each type. Subsequently, diamond-impregnated nickel blades commonly used for IC wafer dicing [8] were employed for this application. These blades were approximately 2-in diameter and had a thick backing plate, which greatly reduced wobble, runout, and kerf loss. These blades were available in 0.0005 increments down to 0.004-in thick, and had a very fine grit size, which permitted control of groove width and roughness. Fig. 3 is a photograph of grooves made with the three types of cutting blades and shows the 4 × reduction in kerf loss and a decrease in chipping. Fig. 4 is a cross section photograph of a single-mode optical fiber epoxied in a substrate groove made with the IC dicing wheel. Note the flat, smooth groove bottom surface and the narrow gaps between the fiber and walls of the groove. It is important to minimize the amount of high-CTE polymetric materials such as epoxies in the fiber/substrate structure. This will produce a more environmentally stable assembly, and also enable flatter polishing of the fiber and substrate because of the relatively low Young's modulus and hardness of the adhesive.

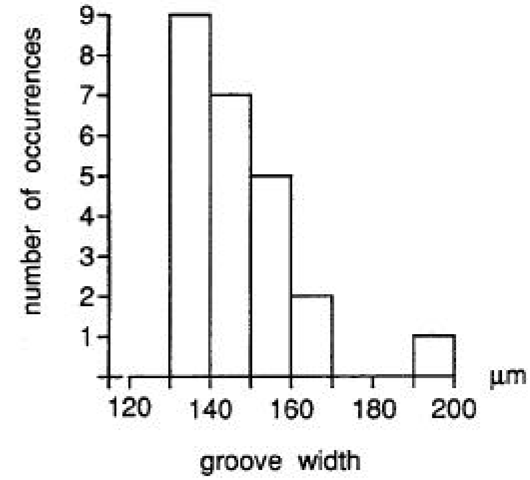

Fig. 5. Histogram of 24 consecutive groove widths.

There is a block-to-block thickness variation, so z_o was set using an accelerometer to acoustically sense blade contact when jogging the z stage, or alternately, a piece of plastic thin shim stock on the block surface was used to calibrate the z axis. The groove-to-block registration, groove radius, and groove width can also be made very consistent with this machine. For the latter characteristic, Fig. 5 plots a histogram of the groove widths of 24 consecutive substrates made for 125-μm diameter cladding fiber cut with a 0.0045-in IC dicing blade. Methods [1]–[5] are usable for adjustable devices and the occasional optically-contacted bonded (OCB) coupler. However, to have a repeatable OCB process, the surface across the polished fiber and substrate must be flatter than $\lambda/15$ [9]. By controlling the groove width and minimizing the volume of epoxy, the above flatness specification can be routinely met.

IV. CONCLUSION

In conclusion, a new technique has been demonstrated for the fabrication of polished coupler substrates that produces superior groove repeatability. Before this method was fully implemented, it was rare to achieve a stable OCB. Consistent groove cutting and subsequent polishing of half-couplers with flatness $< \lambda/15$ have been achieved with this method. This technique has made routine OCB coupler and resonator assembly possible, achieving high performance [10], [11]. Goals 1) through 5) have been met by this fixture, and throughput could be improved in future versions with upgrades to the fixture and software.

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