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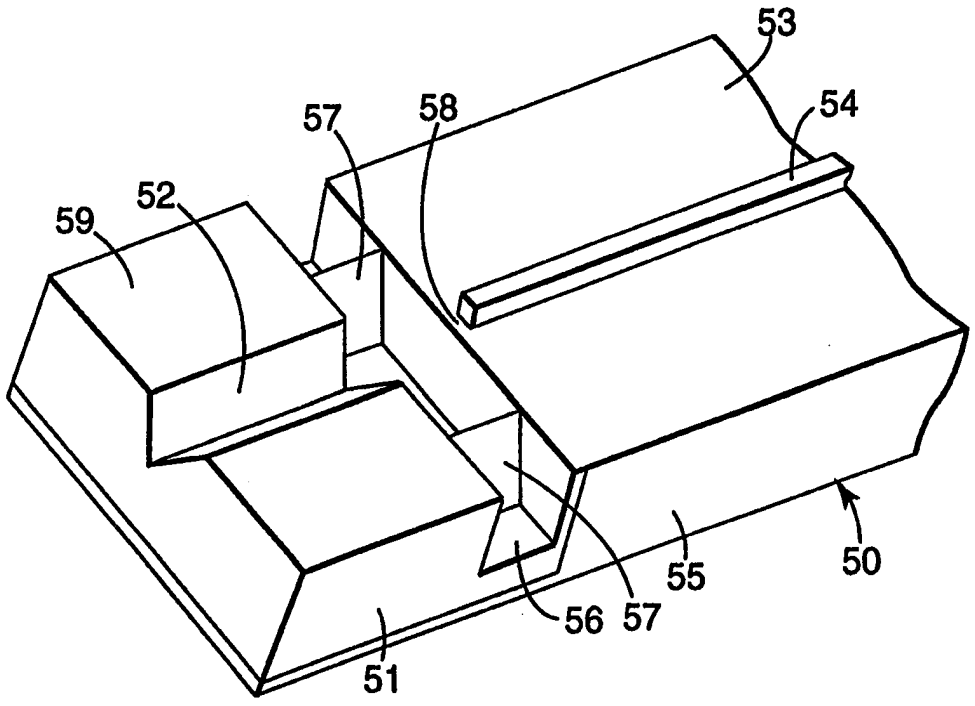

(57) Abstract

An integrated optical coupler connects one or more optical fibers to one or more remote sites by means of a rib, rather than channel, waveguide. Use of the rib design allow for light throughput evaluation prior to permanent fiber insertion, a much simpler covering member (and concomitant simplification of assembly), and a more uniform geometry of the light guiding structure. The rib waveguide structure (54) rises from the surface of the core layer (53) and is made of the same polymeric material. A polymeric cladding layer (55) is formed below the core layer. The optical fibers (64) are aligned and held in V–shaped grooves (52). The optical coupler is formed by molding.

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RIB-TYPE INTEGRATED OPTICAL INTERCONNECT

BACKGROUND INFORMATION

1. Field of the Invention

This invention relates to polymeric optical devices that passively couple optical fibers to one or more remote sites by means of prealigned waveguide ribs and fiber guiding structures.

2. Background of the Invention

Optical couplers, sometimes called interconnects, optically connect one or more optical fibers to one or more remote sites (typically, other optical fibers). For example, where light is carried by input fiber(s), it can be transferred to, split between, or merged into one or more remote sites. Optical couplers play an important role in fiber telecommunication, cable television links, and data communication.

Commonly, couplers are made by fusing glass optical fibers or by attaching fibers to a planar, glass integrated optical device that guides light from the input fiber(s) to output fiber(s) attached at the opposite end of the device. Both of these methods are labor intensive and costly. Also, cost increases proportionately with the number of fibers used because of the amount of effort needed to fuse or attach each individual fiber. Also, these labor intensive processes inhibit mass production of these devices.

Unlike glass optical couplers, polymeric channel waveguides are easily produced. In the past twenty years, numerous methods for producing these waveguides have been developed. For instance, electroplating nickel onto a master to form a channel waveguide mold and using photo-resist techniques to form waveguide channels have been known for a number of years. Cast-and-cure methods have supplemented older injection molding methods of forming polymeric channel waveguides. None of these techniques provide a means for passively aligning optical fibers to such channel waveguides, however.

A. Neyer et al., *Electronics Letters*, **29**, 399 (1993), disclose a method of cheaply reproducing numerous waveguides. This method involves creating a

master mold in photo-resist followed by electroplating in nickel, forming waveguide channels in poly(methyl methacrylate) by injection molding, filling the grooves with a UV-cured resin having a high index of refraction, placing a flat top piece on the resin-substrate article, and curing the whole.

Extension of this technique to the formation of a polymeric passive optical coupler can be found in U.S. Patent Nos. 5,311,604 (Rogner et al.) and 5,343,544 (Boyd et al.). The former makes mention of a coupler that employs a rib-type waveguide wherein the waveguide is formed by "ion implantation" in the top few micrometers of the waveguide preformed rib; the latter does not mention rib-type devices at all.

U. S. Patent Nos. 5,138,687 and 5,511,142 (Horie et al., Omron Corp.) describe polymeric rib-type optical waveguides formed on a polymeric substrate, including an optional cladding layer. No description of a fiber-guiding portion of the waveguide is given.

U. S. Patent No. 5,359,687 (McFarland, AlliedSignal Inc.) describes a polymeric rib-type optical waveguide formed on a polymeric substrate, wherein fiber-guiding channels (elongated ribs) are disposed on the same surface as the waveguide. The disclosure is directed toward fiber-guiding structures other than V-grooves.

A significant disadvantage of presently available channel-type couplers is the fact that light throughput evaluation prior to permanent fiber insertion is not possible.

SUMMARY OF THE INVENTION

Briefly, the present invention provides a device for routing light to or from one or more optical fibers from or to, respectively, at least one site remote from the optical fiber(s). The device includes grooves to guide the optical fiber(s) and, adjacent thereto, a region that includes (a) a polymeric cladding layer and, on a surface thereof, (b) a polymeric core layer which includes a portion that defines at least one rib waveguide structure having the same polymeric composition and essentially same chemical and physical properties rising from the surface of the core layer opposite the cladding layer. The rib waveguide structure(s) provide one

or more light guiding optical paths that optically connect the optical fiber(s) to the remote site(s). The remote site(s) can be one or more other optical fibers. Alternatively, the remote site(s) can be, for example, a light emitting source (e.g., LED or laser diode) or a light detecting device (e.g., a photodiode).

The following definitions apply hereinthroughout unless a contrary intention is explicitly indicated:

(a) "optical coupler" or "interconnect" means a device that joins one or more input optical fibers to one or more output optical fibers and includes devices such as splitters and combiners;

(b) "registry" means precise location of two structures with respect to each other (e.g., axial alignment of the point where the core of an optical fiber, inserted into a fiber guiding structure, will be located with a corresponding rib waveguide);

(c) "(meth)acrylate" means acrylate, methacrylate, acrylamide, and methacrylamide compounds; and

(d) "group" or "compound" or "monomer" or "polymer" or "mer unit" means a chemical species that allows for substitution by conventional substituents that do not interfere with the desired product.

"(e) "fiber" means a single-mode telecommunications fiber such as, for example, Corning SMF-28™, or equivalent fiber with 125 micron outside diameter and mode field diameter between 9 μm and about 10 μm near wavelengths of about 1300 nm or about 1550 nm."

The present invention involves a polymeric housing that passively aligns the cores of optical fibers to waveguide ribs. This housing normally includes two members, namely a substrate and a covering. In one or both of those members are found v-shaped grooves that guide optical fiber(s) inserted into the housing. The grooves have a depth and width such that an optical fiber laid in the groove will be positioned with its core near the surface of the substrate or cover. In the substrate, a polymeric core layer overlays a polymeric cladding layer. Rising from a portion of the core layer is one or more rib waveguide structures that provide light guiding path(s) which optically connect one or more optical fibers to one or more remote sites. Those sites optionally can be one or more other optical fibers.

Both portions of the substrate (i.e., the polymeric core layer and the polymeric cladding layer) can be microreplicated from molds. Each mold, in turn, can be formed by electroplating metal onto a master component and then separating the mold from that master. In one master component (specifically, the master component for the polymeric core layer) are delineated the aforementioned fiber guiding structures and rib waveguides. These fiber guiding structures and rib waveguides are formed to strict tolerances so that the cores of optical fibers inserted in the grooves of polymeric housings derived from this master are precisely aligned with the waveguide ribs.

Non-polymeric (e.g., glass) couplers are manufactured individually which is a labor intensive process. By carefully forming a master from which numerous daughter molds can be made, the polymeric optical coupler of the present invention can be mass produced. Formation of fiber guiding structures that are precisely formed so that fibers inserted therein are passively aligned with corresponding waveguide ribs allows for easy assembly.

When completely assembled, the optical coupler of the present invention includes optical fibers surrounded by polymeric materials. Once one or more optical fibers are secured in the fiber guiding structures of a coupler of the present invention, which precisely align the cores of those fibers with the corresponding waveguide ribs, they are unlikely to become misaligned due to thermal expansion of the surrounding materials.

Where a coupler of the present invention is sufficiently thick, the sandwich construction thereof provides a protective seal. This reduces the chance that the optical characteristics thereof can change due to moisture absorption.

In comparison to waveguide channel-type optical couplers, the rib-type optical couplers of the present invention possess several advantages. Some of these include the possibility of light throughput evaluation prior to permanent fiber insertion, the relative simplicity of the covering member (which simplifies the assembly process), and a more uniform geometry of the light guiding structure.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a greatly enlarged, perspective view, portions broken away, showing one end of one embodiment of a master component from which can be electroplated multiple daughter molds. This master component includes all features that eventually are to be included in the polymeric core layer of the substrate component of the housing of an optical coupler of the present invention.

FIG. **2** is a greatly enlarged, perspective view, portions broken away, showing one end of one embodiment of a mold from which can be microreplicated numerous optical couplers of the present invention.

FIG. **3** is a greatly enlarged, perspective view, portions broken away, showing one embodiment of a mold covered with core monomer.

FIG. **4** is a greatly enlarged, perspective view, portions broken away, showing one end of a polymeric cladding layer (of the substrate component) of one embodiment of an optical coupler of the present invention.

FIG. **5** is a greatly enlarged, perspective view, portions broken away, of one end of a substrate member of the housing of one embodiment of an optical coupler of the present invention.

FIG. **6** is a greatly enlarged, exploded, perspective view, portions broken away, of the housing of one embodiment of an optical coupler of the present invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Making a polymeric optical coupler of the present invention begins with the formation of a master, particularly, a master for the polymeric core layer of a substrate component. In FIG. **1**, one end of one piece of a master for the polymeric core layer of a substrate component is shown.

Master component 10 is a unitary structure that includes first portion 11 in which is located fiber guiding v-shaped groove 12, second portion 13 in which is located rib 14, and third portion 19. First portion 11 and second portion 13 are separated by relatively wide trench 16. First portion 11 and third portion 19 are separated by relatively narrow trench 15.

On second portion 13, rib 14 is separated from trench 16 by gap 18, which is an optically insignificant distance. For single mode applications, an optically insignificant distance means no more than about 20 μm; for multi-mode applications, an optically insignificant distance can be up to about 200 μm.

Although various fiber guiding structures are possible (e.g., raised rails such as those described in U.S. Patent No. 5,359,687 (McFarland et al.), the disclosure of which is incorporated herein by reference), v-shaped grooves are preferred, and the following disclosure focuses on them.

In master component 10, only a single groove (i.e., fiber guiding v-shaped groove 12) and a single rib (i.e., rib 14) are shown. Of course, multiple grooves and/or ribs can be formed on a single master component. Also, any given rib can divide one or more times such that a single fiber guiding structure is "connected" to numerous remote sites. Those remote sites can be other fiber guiding structures.

From master component 10 can be made one or more daughter molds from which polymeric optical couplers can be produced. The optical coupler of the present invention is made directly from a daughter mold which, in turn, is made by electroplating on a master (such as master component 10). Therefore, master component 10 has substantially the same features as the desired coupler, and a mold made from master component 10 has a reverse pattern, i.e., the mold has channels where raised ribs are desired on the optical coupler.

Because daughter molds made from master component 10 have dimensional tolerances that are complementary thereto, care must be taken in forming master component 10. Particularly, rib 14 and v-shaped fiber groove 12 must be delineated in master component 10 to precise tolerances. For example, where single mode operation is desired, rib 14 with a 4 to 100 μm^2 cross section must be aligned to submicron precision with that portion of v-shaped fiber groove 12 where the optical core of a fiber having a relatively large cladding radius (e.g., 62.5 μm) would be located.

In choosing materials from which to make master component 10, the primary consideration is to find a material capable of being patterned to provide rib 14 that can range in width and height from approximately 2 to approximately 10 μm, preferably from about 4 to about 8 μm, as well as v-shaped fiber groove 12

that can hold an optical fiber. A variety of materials including polymer films, silicon oxide, and silicon nitride can be used to form master component 10, depending on the method chosen to form rib 14 and v-shaped fiber groove 12. Because photolithography in silicon using anisotropic etching has proven to be a preferred method of forming v-shaped groove 12, a particularly preferred material is silicon coated with a photo-resist material.

Potential methods for forming v-shaped groove 12 include diamond turning, laser ablation, and photolithographic techniques. The usefulness of the first of these techniques is limited by the difficulty involved in forming v-shaped groove 12 with an abrupt end. Because the present invention involves the formation of fiber alignment v-shaped groove 12 that can end abruptly at the beginning of rib 14, diamond turning as a groove-forming method is less preferred.

Although laser ablation can be used, it is not as routinely used in the microelectronics industry. Thus it is not as fully developed, and is not as preferred as, photolithography.

Preferably, photolithographic techniques are used to form v-shaped groove 12 and rib 14. In practice, v-shaped groove 12 is formed first; however, for the sake of convenience of discussion, formation of rib 14 will be described first.

Positive photo-resist can be used to mask second portion 13 so as to define the desired waveguide pattern. On second portion 13 is deposited a photo-resist layer, optionally after the application of an adhesion promoter. This layer can be applied to a thickness of up to 200 μm, preferably up to 100 μm. The process of developing this photo-resist is the same as that for the formation of groove 12, discussed *infra*, only a positive photo-resist is used in place of a negative photo-resist. Thus, the photo-resist that gets rinsed away is everything but the desired rib pattern.

Controlling the dimensions of rib 14 is of great importance since the dimensions thereof preferably essentially match the dimensions of the core of an optical fiber. Widths and heights of rib 14 are carefully controlled by precisely designing the mask pattern, monitoring the time the photo-resist is exposed to a light source, adjusting the amount of time the developer is allowed to etch the photo-resist, or a combination of these variables. Widths and heights range from 1

to 200 μm, preferably from 5 to 100 μm, even more preferably from about 5 to 8 μm.

Because the process for cutting trench 16 (discussed *infra*) can damage finely formed rib 14, gap 18 can be built in to second portion 13 of master component 10. In other words, rib 14 can be designed such that its length is slightly shorter than necessary to allow for cross trench 16 so that the cutting process (discussed *infra*) does not damage rib 14. The length of gap 18 (i.e., the distance from end of rib 14 to cross trench 16) can be fine tuned so that it is an optically insignificant distance. Preferably, the length of gap 18 is kept as small as possible (e.g. preferably no more than about 5 μm for single mode operation).

Fiber groove 12 can be formed in Si crystal wafers by photolithographic patterning followed by anisotropic etching in a basic solution, e.g., a KOH solution. Because silicon has been found to be particularly amenable to the following etching process and is therefore a preferred material, it has been used for the purposes of the following discussion. Silicon crystal <100> wafers are a particularly preferred base material for master component 10. However, those skilled in the art can recognize that the following method can be adapted for use with a variety of base materials.

In order that any input and/or output optical fiber(s) be securely held and precisely aligned with the rib(s) of the molded article that ultimately results from master component 10, groove 12 must be formed near the end portions of the silicon crystal wafer. (Using a simple 1 × 2 splitter as an example, one end of the wafer has a single groove whereas the other end has two grooves.) A preferred method for forming groove 12 can be found in a number of sources including Tsang et al., *Applied Optics*, **14**, 1200 (1975). A brief summary is given for convenience.

On a clean silicon wafer is deposited a masking layer such as silicon nitride or silicon oxide. This layer can range in thickness from 50 to 200 nm, although 100 nm has been found to work particularly well. This layer is then patterned by means of conventional photolithography. For instance, a photo-resist material can be spin coated onto the surface of the substrate, optionally after the application of an adhesion promoter such as hexamethyldisilazane. After heating to remove

photo-resist solvent, the fiber groove pattern is created by exposing the photo-resist to a light source, preferably a source of ultraviolet light such as a mercury lamp, through a mask aligned in the <110> crystal direction. Once patterned, the photo-resist is developed according to processes well known in the art.

The patterned, exposed masking layer is then etched by one of a number of well known means, although reactive ion etching (e.g., CF_4 and oxygen) has been found to be a preferred etching means. By carefully controlling the etching time and rate, the desired amount of patterned masking layer is etched to expose the substrate material (e.g., silicon wafer). Once this is completed, remaining photo-resist is removed by rinsing with an organic solvent in which the remaining photo-resist is soluble. A common solvent for this purpose is an acetone/isopropanol solution. Remnants of photo-resist can be removed by rinsing in an acidic liquid.

Once the masking layer has been etched, the silicon crystal wafer can be anisotropically etched with a strongly basic solution. A particularly preferred etching solution is an aqueous 30% (by weight) KOH solution. Etching of the wafer can be performed at an elevated temperature (e.g., 80°C) to decrease the amount of time necessary to complete formation of groove 12.

Etching depth can be controlled by adjusting the etching solution concentration, the temperature at which the etching is carried out, the amount of time the etching solution is allowed to contact the substrate, or a combination of these factors. Controlling the depth of groove 12 is important to ensure alignment of an optical fiber inserted therein to waveguide rib 14. Using a single mode fiber as an example, a width (at the upper surface of the substrate) of groove 12 in the range of 140 to 160 μm is desirable to ensure that the core of an inserted fiber (approximately 62.5 μm from the surface of the fiber) is at the same height as corresponding waveguide rib 14. (This width can be somewhat greater than might appear optimal to account for possible dimensional changes inherent in the polymeric housing forming process discussed below.) The depth of groove 12 can range from about 50 to 500 μm, preferably from about 60 to 200 μm, depending on the type of fiber to be used. Groove 12 preferably is of such a length that a fiber inserted in the corresponding groove of a molded housing is secure and supported.

Lengths as short as 1 mm can be effective for this purpose, although lengths of at least about 8 mm are preferred.

For some applications, tapering groove 12 may be desired, for example, to aid in the insertion of fibers. For instance, a groove that (horizontally) narrows from the outside edge toward the waveguide channel and (vertically) tapers in the same direction can potentially make easier the fiber insertion process.

Where desired, arbitrarily shaped fiber grooves also can be made. For example, more rounded fiber groove profiles can reduce stresses around the fiber and increase the surface contact area between the resultant housing and fibers inserted therein for better bonding and improved pull strength. Where master component 10 is made of a photosensitive material such as a thick photo-resist, a gradient mask can be used to obtain the desired groove profile. Another means for making rounded grooves is to create V-shaped grooves in master component 10, electroplate a mold (as described below), replicate the V-groove in a polymer (also described below), then post process the polymer replica and electroplate this processed polymer part to create a new mold. Post processing can include pressing a glass fiber into the polymer V-groove as the polymer part is heated to a temperature above the glass transition point of the polymer. This results in a hemispherical cross section. Alternative post processing techniques include simple heat treatment or xenon flash exposure.

Once groove 12 is etched, the remainder of the silicon nitride masking layer is removed. This is accomplished by the same type of masking layer etching as described above.

In some applications, the groove-forming process described previously can leave a beveled portion of silicon crystal wafer between rib 14 and the bottom of groove 12. This can be corrected by cutting across the groove/rib interface so as to form wide cross trench 16 between the fiber-holding groove 12 and rib 14. A diamond-edged saw can be used to effect this cut.

In a similar fashion (i.e., cutting with a diamond-edged saw), narrow trench 15 can be formed at the terminus of groove 12. Narrow trench 15 can assist in cleanly breaking the ultimate polymeric optical coupler from the mold produced from master component 10. Narrow trench 15 is optional and, if it is not present,

groove 12 preferably extends through third region 19 to the edge of master component 10.

Once master component 10 is formed, one or more daughter molds may be produced. Once these molds are made, they can be used to mass produce the optical coupler of the present invention. This is in contrast to the manner of producing non-polymeric optical couplers which involves the labor intensive step of fusing optical fibers to one another or attaching them to a planar glass integrated optical device.

Molds can be made from the master components described above by an electroplating process. This produces a durable metal mold with the reverse of the desired groove and rib patterns. An example of one end of one such mold (for a polymeric core layer) is shown in FIG. 2.

A silicon/photo-resist master (such as master component 10) first is coated (by means of, for example, a plasma sputtering process known to those skilled in the art) with a film of a metal such as nickel, copper, zinc, silver, or an alloy of a metal, to provide a conductive seed layer. This seed layer preferably is about 10 to 30 nm thick. The coated master is electroplated with about 0.6 to about 0.7 mm of a metal such as nickel, copper, zinc, or silver, although nickel is particularly preferred. A particularly preferred mold is nickel electroplated on a nickel seed layer.

Mold 20 then is separated from the master. This can be done by a variety of physical means including manually prying apart the pieces. If desired, a silicon oxide coating (normally about 80-120 nm thick) can be deposited by, e.g., plasma enhanced chemical vapor deposition, on the surface of the master prior to deposition of photo-resist.

The outer dimensions of mold 20 can be defined by placing a plating mask over the master before electroplating. The mask can be adhered by epoxy against the master before or after a seed layer is deposited or after a small amount of the electroplated metal has already been deposited. The mask typically is an electrical insulator, such as nylon or polytetrafluoroethylene (PTFE), with a hole shaped as the desired outer perimeter. For example, a rectangular hole can be milled in a PTFE slab to give a rectangular mold, and plating occurs only through the hole.

As can be seen in FIG. **2**, mold 20 contains features that are essentially complementary to those of master component 10 from FIG. **1**. Specifically, instead of a groove, mold 20 includes prismatic structure 22 in first portion 21; instead of a rib, mold 20 includes channel 24 in second portion 23; instead of a trench, mold 20 includes raised portion 26; etc. Also included in mold 20 is wall 25 which assists in abruptly and cleanly terminating prismatic structure 22 (as well as any groove in a polymer substrate microreplicated from mold 20). As in master component 10 of FIG. 1, mold 20 includes gap 28 that separates channel 24 from raised portion 26.

Raised portion 26 contains troughs 27 which can assist in allowing excess core monomer applied to mold 20 (see discussion *infra*) to flow away from and off of second portion 23. Troughs 27 can be formed by mechanical stamping, direct milling, etc., of raised portion 26. Although troughs 27 are shown in FIG. **2** as V-shaped, they need not have such a precise shape.

From mold 20 can be produced numerous polymeric core layers on substrate components for polymeric optical couplers. A housing of the present invention includes a substrate and a covering. Both substrates and coverings can be formed by casting, embossing, or injection molding techniques, although the following discussion concentrates on a cast-and-cure technique.

FIG. **3** shows core monomer-covered mold 30, which can be formed simply by pouring core monomer 39 onto mold 35 (similar to mold 20 from FIG. **2**). Features of mold 35 (e.g., wall 31, prismatic structure 32, channel 34, raised portion 36, troughs 37, and gap 38) can be seen through core monomer layer 39.

The amount of monomer (or monomer mixture) 39 poured onto mold 35 is sufficient to at least cover the face of mold 35, including prismatic structure 32 and channel 34. Desirably, a fluorocarbon or silicone release agent can be applied to mold 35 prior to application of monomer(s) 39 to facilitate separation of the polymeric core layer of the substrate (i.e., cured monomer 39) from mold 35.

Once core monomer (or mixture of monomers) 39 has been poured on mold 35, a stiff polymeric backing, made from a cladding monomer (or mixture of monomers), can be pressed against monomer 39. A typical cladding backing can be seen in FIG. **4**. Cladding layer 40, which can cover a core monomer-covered

mold (such as that shown in FIG. 3), can be formed by many techniques such as compression molding, injection molding, reaction molding, and cast-and-cure. Especially with the cast-and-cure technique, the fact that cladding monomers shrink 1-2% when polymerizing needs to be accounted for in designing the mold for cladding layer 40.

In cladding layer 40, shallow region 42 fits over the portion of a mold in which input/output fiber groove(s) is/are located, while plateau 48 fits over the portion of a mold in which the rib(s) is/are located. The height of plateau 48 is such that very little core monomer remains on the mold in the portion of the mold where the rib(s) is/are located. In all areas of that region other than the rib(s), this layer of core monomer ranges in thickness from more than zero to about 2 μm.

Cladding layer 40 can include flow channels 44. These can assist in allowing core monomer in the region of a mold where the rib(s) is/are located to flow off of and away from the mold when cladding layer 40 is pressed into place. Core monomer can flow out directly through egresses 46 or flow through egresses 45, through troughs 37 (from FIG. 3), into depressions 33 (from FIG. 3), and off of the mold.

Some techniques used to form grooves 44 in cladding layer 40 can leave obstructions in egresses 45. To assist in opening egresses 45, a cut similar to that described previously with respect to trench 16 (from FIG. 1) can be effected with, for example, a diamond-edged saw. Because the depth of this cut rarely will be the same as the height of plateau 48, the cutting process can result in a raised lip or gutter between shallow region 42 and plateau 48. (In FIG. 4, this remnant of the cutting process takes the form of lip 43.) Regardless of whether the cutting process results in a raised lip or a gutter, both shallow region 42 and the lip/gutter need to be sufficiently different in height from plateau 48. The lesser (in depth) of shallow region 42 and lip 43 is deeper than the greatest (in height) of wall 31, prismatic structure 32, and raised portion 36 (all of mold 30) to allow plateau 48 to press intimately against the upper surface of mold 35 on either side of channel 34.

To facilitate alignment of polymeric cladding layer 40 with core monomer-covered mold 30 (from FIG. 3), the pieces can be adapted to include conventional fastening means. For instance, mold 35 can be modified to include one or more

small protuberances, while cladding layer 40 can be modified to include complementary small recesses that fit over the protuberances. These protuberances can take the form of ridges or pegs while the recesses can take the form of troughs or holes, respectively. One of the pieces might also be formed with an encircling ridge which fits into a complementary encircling trough in the other piece. Alignment features also can take the form of 1 to 10 mm troughs and ridges that extend to the end of the housing, which also can act as excess monomer flow channels. By having several of these in directions parallel and perpendicular to the primary direction of the waveguide ribs, their height need only be, for example, 200 μm (although about 300 μm is preferred) to achieve good alignment of the two polymer components. Such a design simplifies the core replication processes. Tolerances for these features need only be on order of about 10 to about 20 μm.

If desired, a backing, preferably a polymeric backing, can be adhered to cladding layer 40 prior to or after cladding layer 40 is separated from its mold. Cladding layer 40 can be oxygen plasma treated to enhance its adhesion to the polymeric backing. This involves placing the backing in a reactive ion etching chamber, having an oxygen atmosphere (approximately 26.7 Pa), for approximately ten minutes. Alternatively, a monolithic component can be prepared by placing a plate with a rectangular hole over the mold (i.e., so that the mold features to be replicated are exposed). When cladding monomer is poured over the mold, it fills the rectangular hole. Polymerization of the cladding monomer creates a unitary component with substantial physical integrity.

Both the core monomer(s) and the monomer(s) from which cladding layer 40 is/are formed preferably polymerize to form polymers that have indices of refraction that are quite similar to that of an optical fiber cladding, preferably within 1×10^{-4}, so as to minimize back reflection. Although few compounds have such a refractive index, mixtures of monomers (or monomer precursors) with higher and lower refractive indices can be combined to provide a monomer mixture which, upon polymerization, provides a polymer that has the desired index of refraction. In addition, the index of refraction of cladding layer 40 preferably is about 0.006 less than the index of refraction of cured core monomer(s) so as to

achieve single modes that are similar in dimension in the waveguide and optical fiber.

The refractive index of polymer cladding and the cladding of the optical fiber can differ by as much as up to 0.2, but preferably no more than about 0.1, if optical fibers to be inserted are cleaved at an angle of more than 0 to about 10°, preferably at least 2°, more preferably at least 5°, most preferably about 8°, prior to insertion. This techniques aids in lessening back reflection.

Polymers that are potentially useful as core and/or cladding include epoxies, poly(meth)acrylates, poly(vinyl azlactones), poly(urethanes), poly(styrenes), poly(imides), poly(esters), and poly(ureas). These polymers can optionally be substituted with, for example, halogens and/or deuterium to alter their refractive indices and/or to reduce absorptive losses in near infrared wavelengths. Particularly preferred among the halogens are fluorine, chlorine, and bromine. (Where halogenated polymers are used, they can also be silane modified.) Additionally, colloidal silica, such as that described in U.S. Patent No. 4,885,332, can be added to the monomer mixture from which the above polymers are formed to provide lower refractive indices and reduced thermal expansion coefficients.

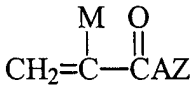
An example of a suitable monomeric combination is a mixture comprising approximately 67% by weight perfluorophenyl acrylate (PFPA, Polysciences, Inc., Warrington, PA), approximately 10% by weight trimethylolpropane triacrylate (TMPTA, Scientific Polymer Products, Inc., Ontario, NY), approximately 23% by weight perfluorocyclohexyl acrylate (PcHA, prepared according to U. S. Patent No. 4,968,116, col. 11) and approximately 0.2% by weight 2,2-diethoxyacetophenone (DEAP, Aldrich Chemical Co., Milwaukee, WI) PHOTOMER™ 4127 propoxylated neopentyl glycol diacrylate (Henkel Corp.; Morristown, NJ) or ethylene glycol dimethacrylate (Aldrich Chem. Co.; Milwaukee, WI) mixed in a ratio such as 89:11 (by weight) with perfluorocyclohexyl methacrylate (PcHMA), as described in U.S. Patent No. 4,968,116 (col. 11), with approximately 1% (by weight) of a photoinitiator such as 2,2-dimethoxy-2-phenylacetophenone (Aldrich). Crosslinking agents, e.g., multifunctional acrylates such as trimethylol propane triacrylate (TMPTA) (Scientific Polymer Products, Inc.; Ontario, NY), can also be

added to reduce solubility and to raise the glass transition temperature of the polymer.

Silane-modified fluoropolymers also are potentially useful. These can be made by copolymerizing fluorinated vinyl monomers with vinyl monomers comprising silane moieties.

A particularly useful class of materials is a combination of highly halogenated acrylates. Highly fluorinated materials have relatively low indices of refraction whereas highly chlorinated (or brominated) materials have relatively high indices of refraction. A class of particularly useful highly halogenated acrylates is disclosed in U.S. Patent Application No. 08/872,235, filed June 10, 1997. Those halogenated acrylates have relatively few C-H bonds, usually no more than three (i.e., those around the acrylate unsaturation) or no more than five (around methacrylate unsaturation). This dearth of hydrogens means that these compounds have very little absorption in the infrared wavelengths of interest, i.e., 1260-1360 nm and 1480-1580 nm, minimizing loss of signal due to absorption by the material of which the device is made.

Those halogenated acrylates have the general formula



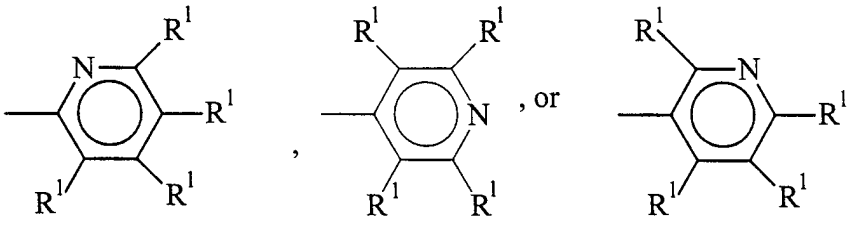
where

M is H, CH_3, F, Cl, Br, I, or CF_3,

A is oxygen or sulfur, and

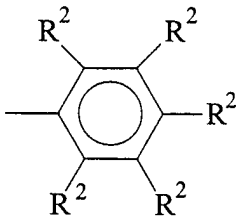
Z is

(1)



in which each R^1 independently is F, Cl, or Br;

(2)



in which each R^2 independently can be

(a) a perfluorinated, perchlorinated, or per(chlorofluoro)

(i) C_1-C_{20} aliphatic group,

(ii) C_3-C_{20} cycloaliphatic group,

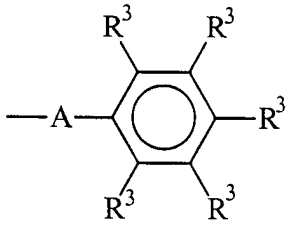
(iii) C_6-C_{20} aryl groups,

(iv) C_7-C_{20} aralkyl groups, and

(v) C_7-C_{20} alkaryl groups,

(b) F, Cl, Br, I, Q (defined below), R^4COO-, R^4O-, -$COOR^4$, -OSO_2R^4, or -SO_2OR^4, wherein R^4 is any group from (a)(i), (a)(ii), (a)(iii), (a)(iv), and (a)(v), or any two adjacent R^2 groups together can form a perfluorinated, perchlorinated, or per(chlorofluoro) cycloaliphatic or aromatic ring moiety in which n fluoro or chloro groups optionally can be replaced by R^2 groups where n is a whole number in the range of 0 to 25, and R^2 is as defined above,

wherein Q is



in which A is as defined above and R^3 has the same definition as R^2, above,

with the proviso that, all R^2 groups in the molecule can be the same only when R^2 is not Cl, F, Br, or I; or

(3) —$C(R_f)_2E$ in which

both R_f groups together can be part of a perfluorinated, perchlorinated, or per(chlorofluoro) cycloaliphatic ring group or each independently can be a perfluorinated, perchlorinated, or per(chlorofluoro)

(a) C_1-C_{20} aliphatic groups

(b) C_3-C_{20} cycloaliphatic groups,

(c) C_6-C_{20} aryl groups,

(d) C_7-C_{20} aralkyl groups,

(e) C_7-C_{20} alkaryl groups,

wherein the heteroatoms can be

(f) C_4-C_{20} heteroaryl groups,

(g) C_4-C_{20} heteroaralkyl groups, or

(h) C_4-C_{20} heteroalkaryl groups,

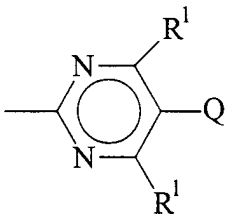
wherein the heteroatoms can be one or more of O, N, and S atoms, with the proviso that at least one R_f group includes one or more of the following:

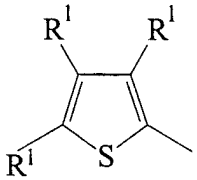
(1) at least one straight-chain C_4-C_{20} aliphatic or C_4-C_{20} cycloaliphatic group,

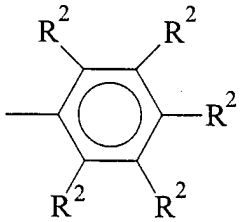
(2) at least one ether oxygen, and

(3) at least one branched C_3 - C_{20} aliphatic group, and

E can be R_f,



,


, or


wherein R^1, R^2, R_f, and Q are defined as above; and

(4) —$CR_f(E)_2$,

wherein each E independently is as defined above, and R_f is as defined above.

The proportion of such materials can be adjusted as necessary to create the proper difference between the index of refraction of the waveguide rib and the index of refraction of the cladding and to match the index of refraction of the glass fiber(s) inserted into the housing (so as to minimize loss and back reflection). Because copolymers made from the previously described highly halogenated acrylates have few residual C-H bonds, they have little absorbance in the critical 1260-1360 nm and 1480-1580 nm wavelength regions and generally are non-hygroscopic, thus reducing the sensitivity of the microreplicated polymeric device to humidity.

Multifunctional monomers can be added to the monomer mixture. This allows a crosslinked polymer to form during cure. Crosslinking reduces creep and the temperature sensitivity of the index of refraction of the housing polymer. The degree of crosslinking can be controlled by the concentration of and/or the functionalities on the crosslinking agent. The degree of crosslinking in the housing polymer controls swelling of the cladding portion by core monomer and limits the amount of core monomer(s) that can diffuse into the clad portion. Accordingly, the refractive index profile of the waveguide can be tailored to adjust the size of the optical mode(s), to reduce optical loss, and to minimize back reflection.

Core monomer can be polymerized by any of a variety of photo or thermal means (or some combination thereof) known in the art. Where photopolymerization is used, core monomer can be cured directly through polymeric cladding layer 40 as long as the cladding polymer can transmit light. Where core monomer is polymerized under pressure (e.g., by placing a core monomer-covered mold in the center of an O-ring, sandwiching this construction between two solid surfaces, and applying pressure), shrinkage of the polymer occurs primarily in the direction of compression, improving fidelity of molded features to those of the mold.

The cured core-cladding substrate then can be physically separated from the mold. To assist in assuring that the core portion of the substrate adheres preferentially to the cladding layer, one of at least two techniques can be used. First, one can use a cladding layer that is not fully polymerized. Second, one can allow a cladding layer to rest on a core monomer-covered mold for a period of time

(e.g., about 30 minutes) prior to polymerizing the core monomer. The efficacy of both of these techniques is believed to be due to the ability of the core monomer to slightly swell and penetrate the cladding polymer.

Where the waveguide portion of the coupler splits or converges (i.e., comes to a point), an advantage of the rib design relative to the previously available trough-type couplers becomes apparent. Specifically, as the substrate is removed from the mold, no portion of the substrate is smaller than the smallest portion of the rib (normally about 5-10 μm); in contrast, in trough-type couplers, forks in the trough come to a very narrow (e.g., less than 1 μm) point which can be extremely difficult to separate intact from a mold.

FIG. **5** shows a polymeric substrate 50 made up of cladding layer 55 with core layer 51 located thereupon and intimately joined therewith. The polymers that make up cladding layer 55 and core layer 51 preferably are very close compositionally and have indices of refraction that are approximately in the range of 0.004 to 0.010, preferably approximately 0.006 apart; accordingly, cladding layer 55 and core layer 51 adhere to one another without the need for an intermediate adhesive layer.

Cladding layer 55 can be as thick or as thin as desired, although thicknesses in the range of about 100 to about 5000 μm generally are preferred. The primary purpose of cladding layer 55 is to form a light-guiding boundary underneath waveguide rib 54, so its exact form or shape is relatively unimportant.

Core layer 51 includes two primary regions: flash layer 53 and groove region 59, which are separated by cross trench 56. Flash layer 53 is very thin except where it includes waveguide rib 54. Specifically, the majority of flash layer 53 can range from more than zero to about 2 μm in thickness. Preferably, the thickness of the majority of flash layer 53 is kept as thin as possible so as to minimize leakage of light from waveguide rib 54 (once light is launched therethrough). Waveguide rib 54, however, can have a height of from 2 to 10 μm and a width of from 2 to 10 μm. Preferably, both the height and width of waveguide rib 54 are between about 4 and 8 μm, especially where the optical coupler is intended for single mode operation.

Waveguide rib 54 is separated from cross trench 56 by gap 58. When an optical fiber is inserted into groove 52, it can be pushed forward until its end abuts the wall of cross trench 56 adjacent to flash layer 53. Although the end of such a fiber is separated from the end of waveguide rib 54 by gap 58, light launched from the fiber can be coupled to waveguide rib 54 because gap 58 is an optically insignificant distance, e.g., between 0 and 50 μm, preferably less than 25 μm. (See discussion *supra*.)

In cross trench 56 are located prismatic structures 57. These are the complements of troughs 27 (from FIG. **2**). Prismatic structures 57 serve no essential purpose in the final optical coupler and can be, if desired, removed (by a diamond-edged saw cut, for example).

Although polymeric substrate 50 has features that replicate those of the grandparent master (e.g., master component 10 from FIG. **1**) and are complementary to those of the parent mold (e.g., mold 20 from FIG. **2**), polymeric substrate 50 may be a bit (i.e., a few percent) smaller than the ancestor pieces. This is due to the tendency of most monomers useful as core monomers to shrink during polymerization. This shrinkage of core monomer can be accounted for (e.g., enable proper alignment of fibers to rib 54) by adjusting the size of the master from which the cladding layer is ultimately formed.

Once polymeric substrate 50 has been prepared, its light guiding efficiency can be tested and optimized. A cleaved or polished optical fiber can be inserted into groove 52 and pushed forward so as to at least partially bridge cross trench 56. Light can be launched through the fiber and, by measuring the intensity of light exiting rib waveguide 54 at the end opposite gap 58 (not shown in FIG. **5**), coupling efficiency can be measured and maximized before the optical fiber is permanently adhered into place or merely for quality control purposes.

Once all optical fibers have been temporarily secured into place by means of, for example, one or more external clamps (for example, after the testing just described has been completed), more cladding monomer(s) is/are poured on the top surface (i.e., the core polymer side) of polymeric substrate 50. Sufficient cladding monomer(s) is/are used so as to cover all features of polymeric substrate 50 and any optical fiber(s) inserted therein. Advantageously, the cladding monomer(s)

can act as an adhesive (upon polymerization) to permanently secure the optical fiber(s) inserted into polymeric substrate 50. Bonding between the optical fiber(s) and the cladding monomer(s) can be enhanced by treating the fibers with or adding to the cladding monomer mixture a silane coupling agent.

FIG. **6** shows one end of a complete optical coupler 60 in an exploded form. Optical coupler 60 includes substrate member 61 overlaid with cladding overlayer 63, cover member 62, and optical fiber 64. Substrate member 61, which includes the same features as polymeric substrate 50 from FIG. **5**, can be prepared as described above.

Cover member 62 can be prepared from any material that is or that can be made to be substantially planar such as, for example, ceramics, polymer, glass, metal, etc. Where cladding overlayer 63 is to be photopolymerized, cover member 62 is made from a material that can transmit light. Cover member 62 can be made in the same manner as cladding layer 40 (from FIG. **4**), discussed *supra*.

After insertion of fiber 64 into groove 65, cover member 62 can be placed on substrate member 61 and adhered thereto by polymerization of the monomers from which is formed cladding overlayer 63. This additional cladding monomer is polymerized by any available means (e.g., photopolymerization through cover member 62). By polymerizing the additional cladding monomer at an elevated temperature (i.e., a temperature exceeding any temperature at which the coupler will be used), a compressive force on the fibers can be created. In other words, the resulting point of "zero stress" will be above the curing temperature. This creation of a compressive force on the fiber aids in preventing delamination of the polymer from the fiber throughout the operating temperature range up to the curing temperature.

Because of the unique design of the polymeric substrate, assembly of the rib-type optical coupler of the present invention is surprisingly simple and easy. Once core monomer is poured on a mold (such as mold 20 from FIG. **2**), a polymeric cladding backing (such as cladding backing 40 from FIG. **4**) is placed on the core monomer-covered mold and the whole is irradiated, normally through the polymeric cladding backing, or heated (depending on whether photo or thermal initiation is to be used). The resulting polymerized layered structure is separated

(e.g., manually pried apart) from the mold to provide a light guiding device precursor. On this precursor is poured cladding monomer and optical fibers are inserted into the fiber guiding structures. The precursor is then polymerized (e.g., by UV irradiation) to provide a light guiding device.

At this point, the device can be used to optically connect the optical fibers to one or more remote sites which themselves can be other optical fibers. However, commonly, a cover piece (such as cover member 62 from FIG. 6) is desired to protect the device and the fibers it contains. Accordingly, prior to polymerizing the cladding monomer, a cover can be placed on the precursor. Then, as cladding monomer polymerizes, the cover piece becomes adhered to the precursor so as to form a unified optical coupler. Preferably, the cover piece is made from a material that allows UV radiation to reach the cladding monomer thereunder so that the cladding monomer can be photopolymerized. In general, the shape of any cover piece used is unimportant as long as it allows a compressive force to be applied to the optical fibers contained within the optical coupler.

After the coupler is assembled, it can be placed in a protective jacket made of, for example, a polymer, a metal, an alloy, a ceramic, or a composite. Alternatively, the coupler can be adhered to backing made of a polymer, metal, ceramic, etc.

When assembled, the optical coupler of the present invention is up to a few centimeters in length and has a thickness of up to a few millimeters, although couplers which are as small as possible normally are desired. The width of the coupler depends on the number of input and/or output fibers to be inserted. For instance, simple 1 × 1 or 1 × 2 couplers can be made quite narrow (i.e., approximately the width of two optical fibers) whereas couplers with 20 or more input or output fibers would be significantly wider.

Objects and advantages of this invention are further illustrated by the following examples. The particular materials and amounts thereof, as well as other conditions and details, recited in these examples should not be construed to unduly limit this invention.

EXAMPLES

Example 1. Formation of Rib Waveguide Master Mold

A silicon wafer having V-shaped grooves was prepared as described in U. S. Patent No. 5,343,544, Example 1. The wafer was spin-coated with an excess of Shipley Microposit™ primer (Shipley Co., Marlborough, MA) which was dried briefly at 21° C. Next, the coated wafer was spin-coated with an excess of Shipley STR 1045™ photoresist (previously diluted with 1 part Shipley Photoresist thinner to 4.5 parts STR1045™) at 9500 rpm for about 60 seconds, followed by heating at 95° C for 30 minutes. Finally, the coated wafer was spin-coated with an excess of Shipley STR1075™ photoresist at 9500 rpm for about 60 seconds, to a total thickness of approximately 7.5 μm. This thickness controls the height of the resulting rib waveguide. The wafer was dried at 95° C for approximately 30 minutes.

A photomask with a 1X1 opaque pattern positioned so as to connect the two V-grooves was placed on the coated substrate and the wafer was exposed to a mercury lamp (λ=405 nm) at 5.5 mW/cm^2 for about 80 seconds. The mask was removed and the resist was developed with Shipley 319™ developer for about 180 seconds, then with water, and dried. Beveled ends of the V-shaped fiber-guiding grooves were removed by dicing a 75 μm-wide trench across the ends of the grooves adjacent to the rib waveguide with a diamond-edged saw. The wafer was vacuum baked for one hour at 70° C.

Example 2. Making A Mold

A thin seed coating of nickel was deposited on the wafer of Example 1 using a DC sputtering method as follows: The wafer was placed in a vacuum chamber equipped with a rotary pump, a turbo pump and a liquid nitrogen cold trap evacuated to a base pressure of from 10^{-6} to 10^{-7} torr. The chamber was equipped with a nickel target in the cathode cell such that the target is more negatively biased than the sample (wafer). About 100 sccm of argon gas was fed into the evacuated chamber, and plasma was generated by applying a current of about 0.53 amps at 192 volts to the electrodes. The chamber was further equipped with a shutter between the Ni target and the sample. The sample was mounted to a

rotatable metal (*e.g.*, stainless steel or aluminum) plate that is mounted on a rotatable turntable capable of holding six such plates. During deposition, the plates were spun while the turntable was rotated, in order to assure even deposition on all surfaces of the target.

In order to avoid heat damage to delicate resist patterns, an interrupted sputtering regime was used. While the turntable holding samples was rotated, a sputtering sequence of 3 sessions comprising 20 seconds of sputtering each followed by a three-minute pause; 2 sessions of 30 seconds of sputtering each followed by a three-minute pause, and 3 sessions of one minute of sputtering each followed by a three-minute pause deposited approximately 130 Å of nickel on the wafer.

The seed-coated wafer was mounted onto a stainless steel plate and the assembly was immersed in a 50° C nickel sulfamate solution containing a nickel counterelectrode. A current density of 0.022 A/cm^2 (20 A/ft^2) was applied so as to plate 25.4 μm (1 mil) of nickel per hour. After 0.51 mm (20mil) of nickel had been deposited, the assembly was removed and rinsed thoroughly with water. The nickel mold was carefully pried away from the silicon/photoresist master.

Example 3. Forming a Cladding Master Mold

A cladding master mold (corresponding to Fig. 4, *supra*) was prepared essentially as described in U. S. Patent No. 5,343,544, col. 9, lines 11-22, which is incorporated herein by reference. As shown in FIG. 4, above, silicon substrate was etched to form two V-grooves **46** adjacent to and parallel to the central longitudinal axis. A portion of the silicon substrate was then masked as described above and the unmasked area was etched to form plateau **42**.

In preparing the cladding master mold, care was taken to consider the volume shrinkage of the cladding polymer during the curing thereof. Since the cladding substrate prepared from the mold (*e.g.*, substrate **55**, Fig. 5) was to fit precisely with, *e.g.*, nickel mold **35** (Fig. 3), consideration of shrinkage of the cladding substrate was important.

All outer dimensions of the cladding master mold were increased by 2% over those of nickel mold **35**, and the size of grooves **46** and shelf **42** were

similarly increased over those described for covering 44 of U. S. Patent No. 5,343,544. Once the cladding master was formed, it was plated with nickel as described in Example 2 to form the cladding master mold, except that nickel sputtering to form a 130 Å seed layer was carried out in a single 5-minute step rather than the interrupted sequence described in Example 2.

Example 4. Forming a Waveguide

To form a cladding substrate, a mixture comprising approximately 67% by weight perfluorophenyl acrylate (PFPA, Polysciences, Inc., Warrington, PA), approximately 10% by weight trimethylolpropane triacrylate (TMPTA, Scientific Polymer Products, Inc., Ontario, NY), approximately 23% by weight perfluorocyclohexyl acrylate (PcHA, prepared according to U. S. Patent No. 4,968,116, col. 11) and approximately 0.2% by weight 2,2-diethoxyacetophenone (DEAP, Aldrich Chemical Co., Milwaukee, WI) was prepared and cast onto the mold of Example 3. Curing of the monomer mixture took place in a nitrogen atmosphere using from about 2 to about 5 mW/cm^2 of UV light, measured at 365 nm, for from about 5 to about 30 minutes. Preferably, cure was effected by using 4 mW/cm^2 of UV light for 10 minutes.

The molded cladding substrate was removed from the mold and placed face down on the nickel waveguide mold of Example 1 and carefully aligned so that only the flat region of the cladding, the region lying between the V-grooves, was directly over the trough of the waveguide master mold. An opaque silicone rubber pad was placed under the rib waveguide mold as a cushion. In addition, a clear transparent pad of poly(vinyl chloride) was used on top of the substrate-plus-waveguide mold when pressing them together. When alignment was satisfactory, the cladding substrate was lifted off the waveguide mold without disturbing its registration with the mold by mechanical means, such as an optical manipulator available commercially from Newport Corp., Irvine, CA., and one drop of waveguide core prepolymer formulation was placed on the waveguide mold (Example 1), the formulation comprising a mixture of about 78 weight % PFPA, 10 weight % TMPTA, 12 weight % PcHA, and 0.2 weight % DEAP. The cladding substrate was then repositioned on the waveguide mold and clamped in place with

a pressure of from about 1 to about 10 kg/cm^2, preferably about 5 kg/cm^2. The liquid core monomer was cured by irradiation through the clad substrate using a UV light (Ultracure 100SS™, Efos, Inc., Mississauga, Ontario, Canada) of from about 2 mW/cm^2 to about 50 mW/cm^2, preferably about 4 mW/cm^2, for about 10 minutes, under a nitrogen gas blanket. After curing, the cladding substrate, to which was attached a molded rib waveguide of the invention, was peeled from the mold.

The waveguide-containing substrate was prepared for optical loss measurement by polishing the end facets by hand to 1μm final grit. The length of the waveguide was between 8 and 9 mm. The substrate was mounted under a microscope on a vibration-isolating table.

The loss was measured by illuminating one end of the waveguide using an AT&T single-mode communications fiber with core size of 9μm. The fiber was, in turn, illuminated by focusing the light of an LED-pumped Nd:Yag laser (Amoco Laser Co., Naperville, IL) into the far end. The wavelength of the light was 1318 nm. Optical power in the fiber was approximately 1 mW. The light was chopped with a mechanical chopper at 1 kHz. A second fiber of the same type was positioned at the other end of the waveguide; its far end was positioned within about 1 mm of a 5-mm diameter Ge photodiode (EG&G Judson, Montgomeryville, PA) connected to the input of a transimpedance amplifier (EG&G Judson). The amplifier output fed the input of a lock-in amplifier (Ithaco, Inc., Ithica, NY) synchronized to the output of the mechanical chopper. Both fibers were held in three-axis "Ultralign" micropositioners (Newport Corp., Irvine, CA). The positions of the fibers were separately adjusted for maximum light throughput. A drop of glycerin surrounded the tip of each fiber to reduce Fresnel reflections. The optical power was proportional to the voltage reading on the lock-in. After maximizing this reading, the voltage was recorded. The fibers were immediately backed away from the substrate, the substrate and its holder were removed, and the two fibers were brought together. The reference power transmitted from one fiber to the other was maximized as before by adjusting the position of one fiber. The loss was expressed as the ratio of the fiber-to-fiber reference power divided by the

waveguide-transmitted power. Ten times the base-ten logarithm of this ratio is the loss, in decibels. The loss was 4.9dB, or approximately 5.4 - 6.1 dB/cm.

An optical fiber-rib waveguide assembly was prepared by clamping the rib waveguide of Example 4 to a rigid surface with the rib facing up. Single-mode optical fibers (e.g., SMF-28, available from Corning, Inc., Corning, NY) having a 250 μm diameter coating were prepared by stripping a suitable length of the coating and cleaving the ends at an angle of about 8°, using, *e.g.*, a cleaver available from Fujikura America, Inc., Atlanta, GA, in order to minimize back reflection. Fibers were positioned in the fiber grooves, butted against the trench adjacent to the rib ends, and held in place mechanically while the fiber-rib-fiber assembly was flooded with the cladding formulation described above. Curing of the cladding by UV radiation locked the fibers in place and provided an upper cladding layer. Alternatively, an upper molded substrate can be prepared and used to press the fibers in place after introduction of the cladding formulation, followed by UV cure. Preferably, UV cure included irradiation at about 4 mW/cm^2 for 30 minutes at about 21° C, followed by heating in an oven for one hour at about 70° C.

Various modification and alterations that do not depart from the scope and spirit of this invention will become apparent to those skilled in the art. This invention is not to be unduly limited to the illustrative embodiments set forth herein.

We claim:

1. A device for routing light to or from one or more optical fibers from or to, respectively, at least one site remote from said one or more optical fibers, said device comprising:

a) one or more v-shaped grooves to guide said one or more optical fibers,

b) a region adjacent to said fiber guiding structures, said region comprising

1) a polymeric cladding layer and, on one surface thereof,

2) a polymeric core layer, said core layer comprising a portion that defines at least one rib waveguide structure rising from the surface of said core layer opposite said cladding layer,

said at least one rib waveguide structure providing one or more light guiding optical paths that optically connect said one or more optical fibers to said at least one remote site, and

said one or more v-shaped grooves having a depth and width suitable to hold an optical fiber core at a predetermined location in registry with said at least one rib waveguide, and

said at least one rib waveguide having chemical and physical properties essentially identical to those of said core layer.

2. The device according to claim 1 wherein said rib waveguide structure is of approximately square cross section.

3. The device of claim 1 wherein said rib waveguide structure has a height to width ratio of between about 1:2 and about 2:1.

4. The device according to any of claims 1 - 3, wherein said cladding layer has a refractive index that is in the range of 0.004 to 0.010 less than the refractive index of said core layer.

5. The device according to any of claims 1 - 4, wherein said rib waveguide structure of said core layer terminates an optically insignificant distance from a cross trench, the cross trench being located between said rib waveguide structure and at least one of said v-shaped grooves.

6. The device according to any of claims 1 - 5, further comprising a second polymeric cladding layer that overlays said polymeric core layer wherein said second cladding layer has a refractive index that is in the range of 0.004 to 0.010 less than the refractive index of said core layer.

7. The device of claim 6 further comprising a cover piece overlaying and adhered to said second polymeric cladding layer.

8. The device according to any of claims 1 - 7, wherein said one or more optical fibers route light into said at least one waveguide structure.

9. The device of claim 8 wherein said at least one remote site comprises one or more output optical fibers secured in structures to guide said output optical fibers, said output optical fibers being optically connected with said at least one rib waveguide structure.

10. A process for making a device for routing light to or from one or more optical fibers from or to, respectively, at least one site remote from said one or more optical fibers, comprising the steps:

a) providing a layered structure that comprises a polymeric cladding layer on a core monomer-covered mold, said mold comprising

1) a first portion that includes structures that form one or more fiber guiding structures in said core monomer, when polymerized, and

2) a second portion that includes one or more troughs from which are formed at least one rib waveguide structure in said core monomer, when polymerized,

said at least one rib waveguide structure being in registry with the core of said one or more optical fibers when said fibers are inserted in said one or more fiber guiding structures;

b) polymerizing said core monomer so as to form a polymerized layered structure and then separating said polymerized layered structure from said mold to provide a light guiding device;

c) optionally, pouring cladding monomer on and inserting optical fibers into the fiber guiding structures of said device; and

d) optionally, polymerizing said cladding monomer.

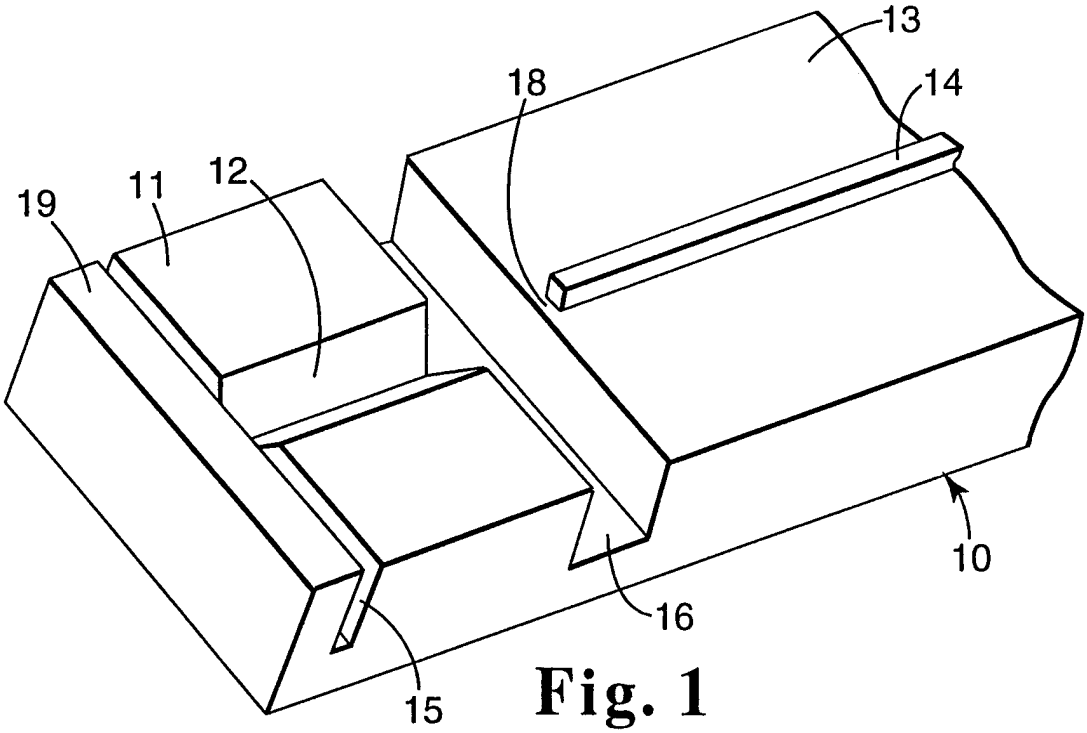


Fig. 1

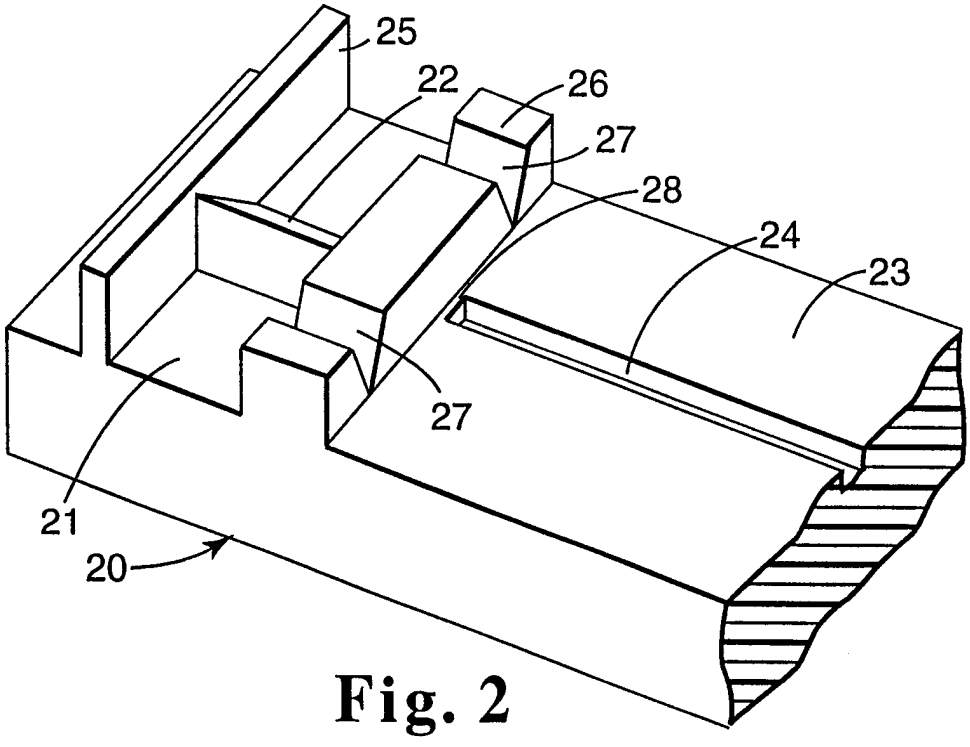


Fig. 2

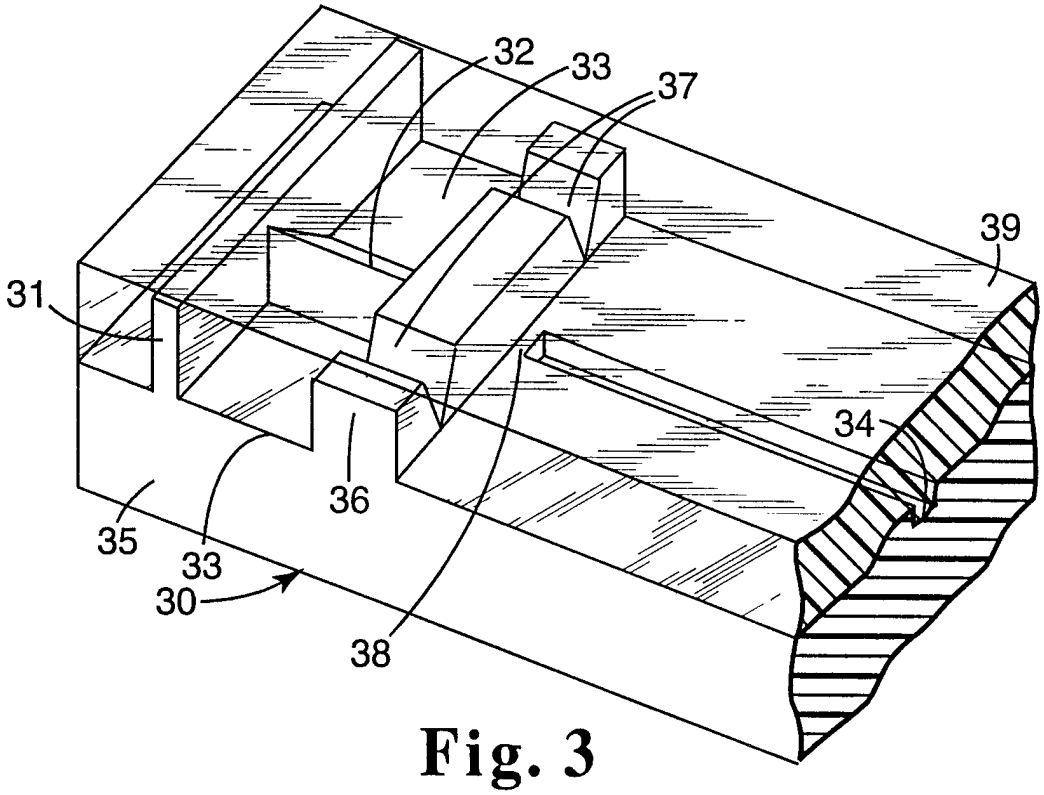


Fig. 3

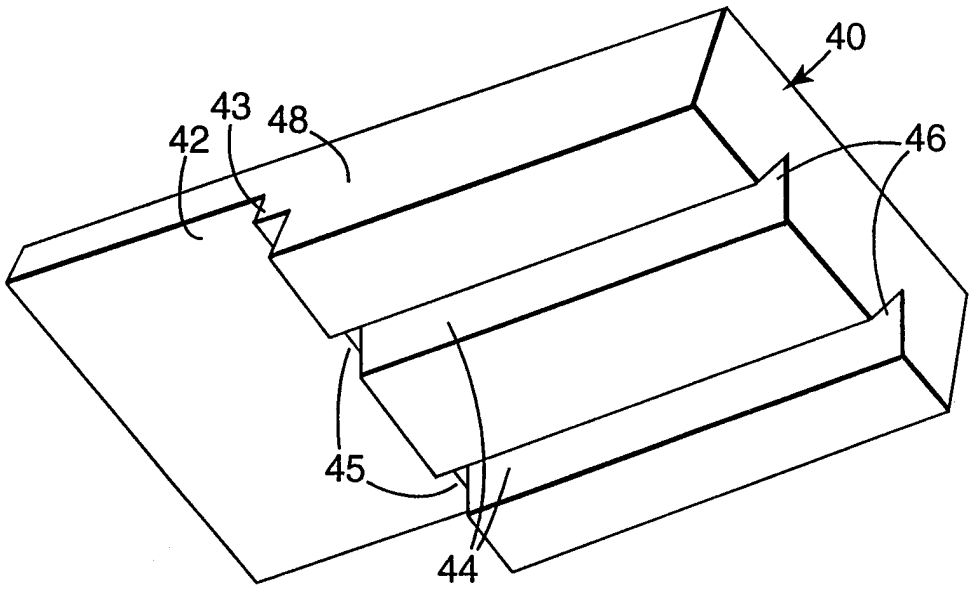


Fig. 4

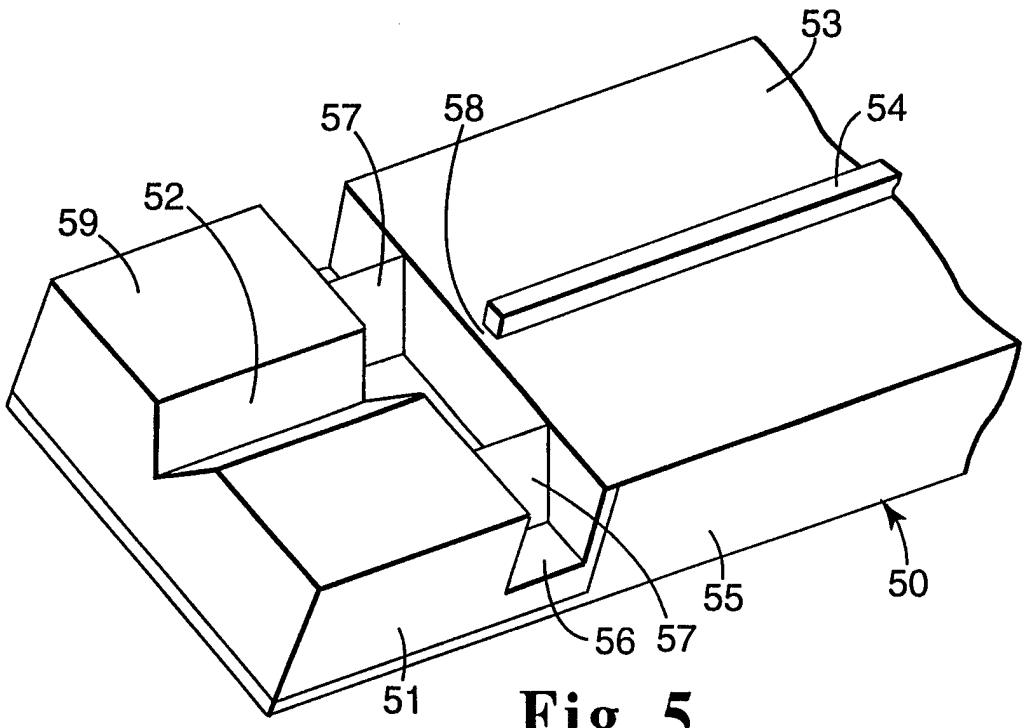


Fig. 5

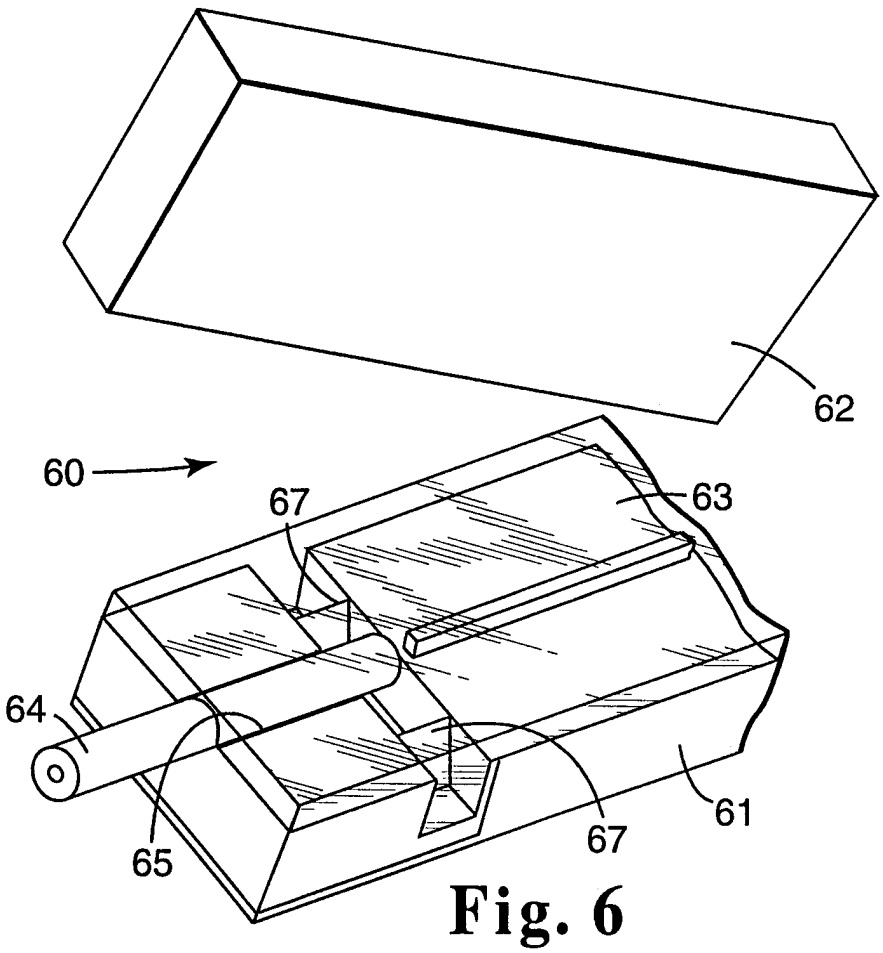


Fig. 6

INTERNATIONAL SEARCH REPORT

Inte: ›nal Application No
PCT/US 98/10915

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G02B6/30 G02B6/12

According to International Patent Classification(IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	PATENT ABSTRACTS OF JAPAN vol. 016, no. 159 (P-1339), 17 April 1992 -& JP 04 009808 A (OMRON CORP), 14 January 1992,	1-3,8-10
Y	see abstract; figures 2,3 ---	4-7
Y	US 5 343 544 A (BOYD GARY T ET AL) 30 August 1994 cited in the application see column 8, line 30 - line 36; figure 6 see column 9, line 67 - column 12, line 10	4-7
A	--- -/--	10

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
21 August 1998	31/08/1998

Name and mailing address of the ISA	Authorized officer
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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 511 142 A (KIYOMOTO HIRONOBU ET AL) 23 April 1996 cited in the application see abstract; figure 1 see column 23, line 46 - line 59; figure 3 see column 24, line 29 - column 25, line 6; figure 6 see column 29, line 18 - line 56; figure 32 see column 35, line 64 - column 36, line 36; figure 59	1-4,6,10
A	EP 0 608 566 A (MATSUSHITA ELECTRIC IND CO LTD) 3 August 1994 see page 4, line 54 - last line; figure 1 see page 5, line 43 - line 45	1
A	PATENT ABSTRACTS OF JAPAN vol. 009, no. 224 (P-387), 10 September 1985 & JP 60 083006 A (HITACHI SEISAKUSHO KK), 11 May 1985, see abstract	1
A	US 4 929 302 A (VALETTE SERGE) 29 May 1990 see column 3, line 51 - column 4, line 43; figures 5,6	1
X	US 5 311 604 A (ROGNER ARND ET AL) 10 May 1994 cited in the application	10
A	see column 3, line 47 - column 4, line 64 see column 7, line 59 - column 8, line 12	1
A	DE 23 22 012 A (WESTERN ELECTRIC CO) 15 November 1973 see page 4, paragraph 2 see page 9 - page 16; figures 2A-D	10

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

Inte onal Application No
PCT/US 98/10915

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5343544 A	30-08-1994	AU 680519 B	31-07-1997
		AU 7048994 A	24-01-1995
		CA 2164108 A	12-01-1995
		CN 1128066 A	31-07-1996
		EP 0706670 A	17-04-1996
		JP 8512143 T	17-12-1996
		MX 9404683 A	31-01-1995
		PL 312259 A	15-04-1996
		WO 9501580 A	12-01-1995
US 5511142 A	23-04-1996	JP 3110505 A	10-05-1991
		JP 3168718 A	22-07-1991
		JP 3168703 A	22-07-1991
		JP 3168704 A	22-07-1991
		JP 3168705 A	22-07-1991
		JP 3185405 A	13-08-1991
		JP 3200104 A	02-09-1991
		JP 3200106 A	02-09-1991
		JP 3248104 A	06-11-1991
		JP 4022904 A	27-01-1992
		JP 4070801 A	05-03-1992
		JP 4076505 A	11-03-1992
		JP 4083204 A	17-03-1992
		JP 4083208 A	17-03-1992
		JP 4097101 A	30-03-1992
		JP 4102807 A	03-04-1992
		EP 0420173 A	03-04-1991
		US 5138687 A	11-08-1992
EP 0608566 A	03-08-1994	JP 6201936 A	22-07-1994
		US 5425118 A	13-06-1995
US 4929302 A	29-05-1990	FR 2625333 A	30-06-1989
		DE 3873300 A	03-09-1992
		EP 0323317 A	05-07-1989
		FI 885972 A,B,	25-06-1989
		JP 1196005 A	07-08-1989
		JP 2065378 C	24-06-1996
		JP 7082133 B	06-09-1995

INTERNATIONAL SEARCH REPORT

Information on patent family members

Inte onal Application No
PCT/US 98/10915

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5311604 A	10-05-1994	DE 4207207 A	09-09-1993
		DE 4217526 A	02-12-1993
		DE 59306756 D	24-07-1997
		EP 0560043 A	15-09-1993
		FI 930989 A	08-09-1993
		JP 6003545 A	14-01-1994
DE 2322012 A	15-11-1973	FR 2187518 A	18-01-1974
		JP 49062151 A	17-06-1974