A method of coupling a silica fiber and a sapphire fiber includes providing a silica fiber having a doped core and a cladding layer, with the doped core having a prescribed diameter, providing a sapphire fiber having a diameter less than the doped core, placing an end of the sapphire fiber in close proximity to an end of the silica fiber, applying a heat source to the end of silica fiber and introducing the end of sapphire fiber into the heated doped core of the silica fiber to produce a coupling between the silica and sapphire fibers.

32 Claims, 8 Drawing Sheets
A. Wang, S. Gollapudi, R. G. May, K. A. Murphey, and R. O. Claus, 
“Advances in sapphire-fiber-based intrinsic interferometric sensors,” 

* cited by examiner

J. Tapping and M. L. Reilly, “Index of refraction of sapphire between 

OTHER PUBLICATIONS
INPUT LIGHT

FIG. 1

OUTPUT LIGHT

FIG. 2

FIG. 3
(a) ANY FIBER TO BE CONNECTED WITH SAPPHIRE FIBER

(b) SPLICE THE FIBER TO ANOTHER FIBER WITH A LARGE LOW MELTING POINT CORE AND CLEAVE IT TO LEAVE A SHORT LENGTH

(c) SPLICE THE SHORT PIECE TO THE SAPPHIRE FIBER

FIG. 6
FIG. 7

INTENSITY (ARB. UNIT)

WAVELENGTH (nm)

1597 °C

25 °C

FIG. 8

NORMALIZED REFLECTED POWER

ARC NUMBER
FIG. 9

![Graph showing optical thickness versus temperature with a parabolic fit and experiment data. The equation for the parabolic fit is OT = 103.782 + 1.398 \times 10^{-3} T + 3.727 \times 10^{-7} T^2.]

FIG. 10

![Graph showing optical thickness over time with a histogram of counts. The optical thickness values range from 104.653 to 104.6555 μm.]

EXPERIMENT
PARABOLIC FIT
CALCULATION
FIG. 16

\[ T = -3.44 \times 10^4 \times t^4 + 5.373 \times 10^{3} \times t^3 - 35.02 \times 10^2 \times t^2 + 472.7 \times t + 973.3 \]

\[ ot = OT - 105.5 \]
been widely adopted for sensor fabrication owing to their
temperature. Most of the fiber-optic, high-temperaturesen-
tures well above 1000 °C., single-crystal optical fibers have
herein by reference.

radiation, fluorescence lifetime and optical interference.
The targetsurface and transmitting it to the detector. See, for
coupling of elements that allows for proper dispersion and
infrared using the standard two-color approach.

The simplest form of radiation-based sensors are fiber ver-
ions of optical pyrometers, often referred to as lightpipe
eradiation thermometers (LPTs), devices used in the semi-
conductor industry for wafer temperature monitoring during
rapid thermal processing (RTP) by collecting radiation from
the target surface and transmitting it to the detector. See, for
example, M. R. Jones, and D. G. Barker, “Use of optical fiber
thermometers in high temperature environment,” 11th IEEE
international conference on advanced thermal processing of
semiconductors, 2003, pp. 89–100. Temperature can then be
inferred using the standard two-color approach.

Other than merely a light collecting and transmitting pipe,
another type of radiation-based sensor generates its own
radiation signal with a metal-coated sapphire fiber tip which
forms a blackbody cavity. See, for example, R. R. Dils,
54, 1198-1201 (1983). Operation up to 2300 °C. has been
demonstrated using zirconia single-crystal fiber. See, for
example, L. Tong, Y. Shen, L. Ye, and Z. Ding, “A zirconia
single-crystal fiber-optic sensor for contact measurement of
temperatures above 2000 °C.,” Meas. Sci. Technol. 10, 607-
611 (1999).

In both types, the radiation emitted by the fiber lightpipe
itself adds to the target radiation and thus constitutes an error
source, leaving the measurement sensitive to environmental
temperature changes around the lightpipe. Therefore, in situ
calibration is usually required and brings inconvenience to its
field application. In fluorescence-based sensors, the fiber is
doped and the dopant is excited by laser pulses to generate
fluorescence, whose decay rate is temperature-dependent and

used as the measurand. Operating temperatures of 1600 °C.
have been achieved by a Yb-doped single crystal YAG optical
fiber. See, for example, J. L. Kennedy, and N. Djeu, “Operation
of Yb:YAG fiber-optic temperature sensor up to 1600 °C.,” Sensors
Actuators A 100, 187-191 (2002). The temperature
dependence of the decay rate usually exhibits a vastly
changing profile, increasing slowly at low temperature and
very quickly toward the high temperature end. That will leave
the sensor with quite different sensitivities and performance
at different temperature ranges and therefore may limit its
dynamic range.

As another widely employed technique, fiber-optic interferometric
sensors are known for their large dynamic range, high
resolution and high accuracy. Various principles have
been proposed based on both intrinsic and extrinsic Fabry-
Perot (FP) interferometers. See, for example, A. Wang, S.
Gollapudi, K. A. Murphey, R. C. May, and R. O. Claus,
“Sapphire-fiber-based intrinsic Fabry-Perot interferometer,”
Opt. Lett. 17, 1021-1223 (1992). However, one major con-
cern of these sensors in high-temperature measurements is
the large modal volume of single-crystal sapphire fibers. The
intermodal dispersion makes it difficult to generate good
fringes which are sensitive to the quality and the parallelism
of the interferometer surfaces.

To address that issue, an extrinsic Fabry-Perot inter-
ferometric (EFPI) sensor, using a sapphire wafer as the inter-
ferometer, has been developed. The high quality and parallelism
of the wafer surfaces allow easy generation of good interfer-
ence fringes even for highly-multimode sapphire fiber. As the
measurand, the wafer’s optical thickness is temperature-de-
pendent, as both the refractive index and the physical thick-
ness increase with temperature.

Even so, the coupling of elements raises issues addressed
above, in that dispersion and proper alignment become
greater concerns. There is also a need for simpler and smaller
configurations and achieving compact and durable connections
between the wafer and the fiber.

SUMMARY OF THE INVENTION

It is thus an object of the present invention to provide a
coupling of elements that allows for proper dispersion and
proper alignment. It is also an object to provide such a cou-
pling that can be used in a temperature sensor. It is also an
object to provide simpler and smaller configurations achiev-
ing compact and durable connections between the wafer and the
fiber.

To achieve the above and other objects, the present inven-
tion is directed to a method of coupling a silica fiber and a
sapphire fiber that includes providing a silica fiber having a
diameter less than the doped core, and a cladding layer, with the doped core having a
prescribed diameter, providing a sapphire fiber having a
diameter less than the doped core, placing an end of the
sapphire fiber in close proximity to an end of the silica fiber,
applying a heat source to the end of silica fiber and intrud-
ing the end of the sapphire fiber into the heated doped core of
the silica fiber to produce a coupling between the silica and
sapphire fibers.

The step of providing the silica may also include providing
another optical fiber and coupling a short length of the silica
fiber to the other optical fiber. The step of applying a heat
source to the end of the silica fiber may include applying a
splicing arc to the end of the silica fiber. The coupling
between the silica and sapphire fibers may provide an inser-
tion loss for light passing through the coupling of less than 1
dB. The method may also produce the coupling without the
use of an adhesive interlayer.
The present invention is also directed to a fiber optic coupling between a silica fiber and a sapphire fiber that includes a silica fiber having a doped core and a cladding layer, with the doped core having a prescribed diameter and a sapphire fiber introduced into the doped core through heating of an end of the silica fiber. The diameter of the doped core may be at least 100 μm and a diameter of the sapphire fiber is at least 75 μm. The coupling may also include a short length of the silica fiber coupled to another optical fiber through an adhesive. The coupling between the silica and sapphire fibers provides an insertion loss for light passing through the coupling of less than 1 dB.

The present invention is also directed to a temperature sensor for use in high-temperature environments that includes a silica fiber having a doped core and a cladding layer, with the doped core having a prescribed diameter and being configured to be connected to a light source and a spectrometer, a sapphire fiber, having a first end introduced into the doped core through heating of an end of the silica fiber and a sapphire wafer coupled to a second end of the sapphire fiber through an adhesive.

The present invention is further directed to a method of forming a temperature sensor for use in high-temperature environments that includes providing a silica fiber having a doped core and a cladding layer, with the doped core having a prescribed diameter and being configured to be connected to a light source and a spectrometer through a second end, heating a first end of the silica fiber, introducing a first end of a sapphire fiber into the doped core of the first end of the silica fiber and coupling a sapphire wafer to a second end of the sapphire fiber through an adhesive.

BRIEF DESCRIPTION OF THE DRAWINGS

A preferred embodiment of the present invention will be set forth in detail with reference to the drawings, in which:

FIG. 1 is a schematic drawing illustrating the principles of a Fabry-Perot interferometer;

FIG. 2 is a drawing which illustrates a bonding connection between a fiber and a wafer, according to at least one embodiment of the present invention;

FIG. 3 is a schematic drawing which illustrates a system for a sensor, according to at least one embodiment of the present invention;

FIG. 4 is a drawing which illustrates the process of splicing an optical fiber with a sapphire fiber, with FIG. 4(a) illustrating the fibers before they are joined and FIG. 4(b) illustrating the fibers after they have been joined, according to at least one embodiment of the present invention;

FIG. 5 is a photograph illustrating the splicing together of a silica fiber with a sapphire fiber, according to at least one embodiment of the present invention;

FIG. 6 is a drawing which illustrates an alternate process of splicing an optical fiber with a sapphire fiber, with FIG. 6(a) illustrating the fiber, FIG. 6(b) illustrating the attachment of a doped fiber section and FIG. 6(c) illustrating the splicing of the sapphire fiber with the co-joined optical fibers, according to at least one embodiment of the present invention;

FIG. 7 illustrates a graph of the sensor spectrum of intensity versus wavelength, according to at least one embodiment of the present invention;

FIG. 8 presents a graph of reflected power versus arc number, according to at least one embodiment of the present invention;

FIG. 9 presents a graph of the change in optical thickness as a function of temperature, according to at least one embodiment of the present invention;

FIG. 10 presents graphs showing the sensor resolution at room temperature, according to at least one embodiment of the present invention;

FIG. 11 is a drawing which illustrates embodiments of bonding between the fiber and the wafer, with FIGS. 11(a), (c) and (e) presenting the embodiments in cross-section and FIGS. 11(b), (d) and (f) presenting the embodiments in plan view; according to at least one embodiment of the present invention;

FIG. 12 is a drawing which illustrates alternative embodiments of bonding between the fiber and the wafer, with FIG. 12(a) presenting the embodiments in cross-section and FIGS. 12(b) and (c) presenting the embodiments in plan view; according to at least one embodiment of the present invention;

FIG. 13 is a drawing which illustrates the need for angle-polishing of the fiber end, according to at least one embodiment of the present invention;

FIG. 14 is a drawing which illustrates the leakage of water into the sensor, according to at least one embodiment of the present invention;

FIG. 15 is a drawing which illustrates the creation of space around the sensing area to accommodate excess water, with FIG. 15(a) providing for the bore to be enlarged in a notched fashion and FIG. 15(b) providing for the bore to be enlarged in a conical fashion, according to at least one embodiment of the present invention;

FIG. 16 presents a graph illustrating the change in the optical thickness with respect to temperature, according to at least one embodiment of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

A preferred embodiment of the present invention will be set forth in detail with reference to the drawings, in which like reference numerals refer to like elements or operational steps throughout.

The present invention is directed to the design and detailed fabrication process of fiber-optic temperature sensors. When properly fabricated, the sensors have been demonstrated to be well-suited for reliable temperature monitoring even in the harshest environments.

As illustrated in FIG. 1, the sensing mechanism is based on a wafer 102 whose surfaces create a Fabry-Perot interferometer. A fiber 101 can be used to deliver light to the wafer 102 and receive the reflected signal from which the wafer’s optical thickness (OT), product of physical thickness, d, and refractive index n) can be obtained by white-light interferometry. Since both d and n have thermal dependences, OT can serve as an excellent indicator of environmental temperature. The sensor can be made of a variety of optical materials, e.g. fused silica, quartz, other types of glass, silicon, polymer, sapphire, zirconia, and many more.

The connections between the fiber and the wafer can be made through various configurations. FIG. 2 illustrates one of these where both the wafer 207 and the fiber 201 are bonded to a supporting tube 203. That bonding can be achieved through a number of methods, e.g., adhesive bonding, direct bonding and fusion bonding.

FIG. 3 illustrates a schematic of the white-light interferometric system, according to one embodiment of the present invention. Broadband light from an 850 nm light-emitting diode (LED) 301 travels to the sensor through a 100/140 μm multimode (MM) fiber 3 dB-coupler 303. The reflected signal carries the wafer’s interference spectrum to be detected by an OceanOptics USB2000 miniature spectrometer 302, in this
embodiment. In the sensing arm, a 59 μm-thick C-plane sapphire wafer 316 of 1 mm×1 mm size is placed in front of a 15 cm-long 75 μm-thick sapphire fiber 314 (MicroMaterials Inc.) by a 99.8% alumina tube 317 (OD: 0.71 mm) and high-temperature adhesive 315. The sapphire fiber 314 also has the C-axis along its length. The other end of the sapphire fiber is spliced 313 to the 100/140 μm silica fiber 312. Sub-millimeter size is achievable if the wafer is machine-diced. It should be noted that the specific equipment and sizes illustrate the use of the sensor in this embodiment, but other equivalent equipment and sizes may be employed to achieve the same or similar sensor.

The present invention is also directed to a coupling method between sapphire fiber and silica fiber. Sapphire fiber has excellent optical, mechanical and thermal properties, and therefore is used in many applications for light transmission. However, sapphire fiber is expensive and hard to couple with conventional silica fibers. Many applications thus require that the sapphire fiber to be coupled with conventional silica fibers to not only extend the length of light transmission, but also make the many silica-fiber-based optical devices available to the system. This invention provides a simple way to join sapphire and silica fibers without the use of any adhesive interlayer. The coupling is strong with low insertion loss.

The coupling may be made through arc fusion splicing. FIG. 4 shows a schematic of the process. The silica fiber 401 has a doped core 403 and an undoped fused silica cladding 402. The sapphire fiber 405 has a diameter no larger than the core. The coupling is based on the fact that the doped core of the silica fiber softens at a much lower temperature than the undoped cladding. As shown in FIG. 4(a), under properly controlled (usually reduced) arc duration and power 404, the core will be softened while the cladding, as well as the sapphire fiber, will remain almost intact. Prior to the arc, the sapphire fiber is brought to the close proximity of the silica fiber. It is then heated by the arc and expands, protruding into the melted core of the silica fiber to make the connection, as illustrated in FIG. 4(b). Multiple arcs may be necessary, depending on the power and duration.

FIG. 5 shows a photo of such a coupling between a core-doped 100/140 μm silica fiber and a 75 μm sapphire fiber with an insertion loss as low as 0.8 dB. This method is suitable for joining all types of silica fibers with sapphire fiber. For those fibers whose structure meets the requirements (low melting point core, core size no less than sapphire fiber diameter), they can be directly spliced to the sapphire fiber. For those fibers that do not meet the requirements, they can be first spliced to a very short piece of large doped core fiber (by splicing and cleaving) which can then be spliced to the sapphire fiber. For those fibers which meet the requirements, the power tends to first decrease and then stabilize with the number of arcs. In FIG. 8, a total of 5 dB loss was recorded from the first arc to the last. However, much of that loss is attributed to the decrease of r_{couple} because of the incomplete contact at the silica-sapphire interface which may leave small high-reflecting air voids during the first several arcs, as a result of low arc power and duration. As more arcs are applied, the two fibers come to full physical contact to eliminate the high-reflecting air voids and the optical power is reduced. Since r_{couple} can be removed in signal processing, its value is not critical to the application. The loss of r_{signal} is however of more importance because it will determine the signal intensity. r_{signal} is measured by immersing the sapphire fiber end from air into an index matching oil (n = 1.522) and recording the intensity change which is proportional to r_{signal}. By comparing r_{signal} before and after the splice, power loss as low as 0.8 dB has
been measured, possibly due to the deformation of the 100/140 μm fiber which may scatter the light out of the coupling point. This method avoids any adhesive, producing a simple and robust joint. It is also successful in splicing 100-μm diameter sapphire fibers but fails for larger ones due to the apparent silica fiber core size limitation.

The sensor’s temperature response was tested in a furnace (DelTech, Inc.) from 230°C to 1600°C. A B-type thermocouple was used for temperature reference. FIG. 9 plots the change of optical thickness (open circles) with respect to temperature measured by the S-type thermocouple. The data is fitted by a parabola as the following:

\[ OT = n(T) \cdot d(T) \]
\[ = 103.782 + 1.398 \times 10^{-3} T + 3.727 \times 10^{-7} T^2 \] (μm)

and shown in FIG. 11 (solid curve). Also plotted is the calculated temperature response (dotted line) from published data of sapphire’s thermal expansion and its refractive index. The recommended values of C-axis thermal expansion of sapphire can be written as:

\[ d(T) = \left( 1 - 1.192 \times 5.927 \times 10^{-3} T + 2.142 \times 10^{-7} T^2 - 2.207 \times 10^{-11} T^3 \right) d_0 \] (3)

where \( T \) is the absolute temperature in Kelvin, \( d(T) \) is the thickness at \( T \) and \( d_0 \) is the initial thickness at 293 K (20°C).

For the temperature dependence of the refractive index of the ordinary ray in sapphire, \( n(T) \), the authors of J. Tapping and M. L. Reilly, “Index of refraction of sapphire between 24 and 1060°C for wavelengths of 633 and 799 nm,” J. Opt. Soc. Am. A 3, 610-616 (1986), have measured this value from 24°C to 1060°C for wavelengths of 633 nm and 799 nm, as given by:

\[ n(T)_{633nm} = 1.75656 + 1.258 \times 10^{-3} T + 4.06 \times 10^{-7} T^2 \] (4)

\[ n(T)_{799nm} = 1.75691 + 1.229 \times 10^{-3} T + 3.10 \times 10^{-7} T^2 \] (5)

where \( T \) is temperature in degree Celsius. By linear extrapolation from these two equations, a good estimation of \( n(T) \) for 850 nm can be obtained as the following:

\[ n(T)_{850nm} = 1.75815 + 1.220 \times 10^{-3} T + 2.81 \times 10^{-7} T^2 \] (6)

Based on Eqs. (3) and (6), a theoretical prediction of the optical thickness is given as the dotted line in FIG. 9. The calculation shows a reasonable match to the experimental data.

Eq. (2) indicates that the optical thickness increases with temperature in the form of a convex function. Therefore the sensitivity of the sensor, defined as the slope of the temperature response curve, increases with temperature as well. From Eq. (2) the sensitivity \( S \) can be obtained as:

\[ S = \frac{d}{dT}[n(T) \cdot d(T)] = 1.398 \times 10^{-3} + 7.454 \times 10^{-7} T \text{ (nm/°C.)} \] (7)

Therefore, \( S \) increases with temperature from 1.42 nm/°C. at 24°C to 2.59 nm/°C. at 1600°C. Unlike the fluorescence-type sensor whose sensitivities can vary by orders of magnitude over a large temperature range, the sensitivities of this sensor remain at a similar level. Hence, one can expect similar performance throughout the entire temperature range.

The resolution of the sensor is the smallest temperature change the sensor could resolve. Even under the same temperature, the sensor output (optical thickness) would statistically fluctuate due to system noises. A temperature change is discernible only when it is larger than this fluctuation, to determine which, the sensor’s optical thickness was recorded for 15 minutes at room temperature (24°C). FIG. 12 shows the result and the statistical distribution. It is then determined that the standard deviation \( \delta \) of these data is about 0.3 nm. Therefore the resolution of the sensor at room temperature is:

\[ \frac{2\delta}{S} = \frac{2 \times 0.3 \text{ nm}}{1.42 \text{ nm/°C.}} = 0.4° \text{ C.} \] (8)

Other configurations eliminate the supporting tube and bond the wafer directly on the fiber, making possible ultraminiature sensors having a size of only a few hundred microns. FIG. 13 illustrates some such structures, with Figs. 13(a), (c) and (e) illustrating side views and Figs. 13(b), (d) and (f) illustrating plan views of the embodiments. Each has a partially recessed fiber end-face, with the recessed part for sensing and the non-recessed part for supporting and bonding. FIGS. 13(a) and (b) illustrate a fiber having a centered, cylindrical recess, FIGS. 13(c) and (d) illustrate the recess being a notch in the fiber end and having two portions supporting the wafer and FIGS. 13(e) and (f) illustrate a similar notch that is non-symmetric.

It is also possible to have the recess in the wafer, instead of the fiber, as illustrated in FIG. 14. FIG. 14(a) illustrates a cross-section of such an embodiment. FIG. 14(b) illustrates a groove etched on the wafer and FIG. 14(c) illustrates a pit etched on the wafer.

With respect to fabrication, many of the discussed embodiments use sapphire fibers and wafers, but the fabrication processes can be used with other materials with little or no modification. For effective light transmission, the sapphire fiber end-face needs to be well polished. If such a high-quality surface is parallel to the wafer, it can form a Fabry-Perot interferometer with the first surface of the wafer. This second interferometer, in addition to the one formed by the wafer, will distort sensor signals and cause errors.

To avoid such errors, the fiber needs to be angle-polished to suppress this extra interface, as illustrated in FIG. 15. For 75 μm-thick sapphire fiber, experiments show that an angle of 1° is adequate to eliminate the distortion. Larger angles will reduce the coupling efficiency of reflected light and the signal amplitude. The angle requires that the fiber and the tube cannot be bonded and polished together before putting the wafer on. Otherwise, all surfaces would be parallel. Hence, the tube should be bonded first to the wafer and then to the fiber, in most embodiments.

In the application of adhesives, most adhesives are liquid or liquid-containing. The liquid may cause contamination if not handled properly. One example involves the use of a high-temperature adhesive for a sapphire-fiber sensor that is paste-
like with a prescribed water content. Water can seep in between the wafer and the tube. Even though both are well polished, there may be a micro-sized or smaller gap therebetween. If too much adhesive was applied at the same time, water would carry contaminants all the way to the sensing area through the center and could flow into the bore, as illustrated in FIG. 16. Even after the water is dried out, the contaminants will remain on the optical surfaces. This may also occur when applying adhesive to bond the fiber and the tube.

To avoid contamination, the water content can be reduced by avoiding the use of excessive adhesive. Thus, only a small amount need be applied at a time over multiple applications, allowing time for the water to evaporate and the adhesive to dry before each application. Given the millimeter scale of the tube and the wafer, millimeter-sized adhesive is considered to be a large amount. A regular, bare silica fiber may be used to pick up and apply such a small amount of adhesive. Also, a microscope may be used for precise operation, which can be used manually or with translation stages. Another solution is to enlarge the bore to create more space around the sensing area to accommodate excess water, as shown in FIG. 17. In the two illustrated embodiments, the fiber 1703 makes contact with the wafer 1707 through a tube 1705. FIG. 17(a) provides for the bore 1702 to be enlarged in a notched fashion and FIG. 17(b) provides for the bore 1704 to be enlarged in a conical fashion.

In temperature tests, the furnace was run from 230°C to 1600°C at 3°C/min three times. The change in the optical thickness with respect to temperature by the B-type thermo-rials are the same. Thus, one curve may be used for all similar sensors and there is no need to calibrate each individual sensor. Only an initial thickness is necessary for each sensor, its calibration curve can be readily obtained as the product of this initial thickness and the universal normalization curve.

This can be understood through the following equation:

\[ OT = n(T)d(T) \]

\[ = n_0d_0F(T)G(T) \]

\[ = OT_0F(T)G(T) \]

where \( OT \) is the optical thickness, \( n \) is the refractive index, \( d \) is the wafer thickness, \( T \) is temperature, \( n_0 \) and \( d_0 \) are \( n \) and \( d \) at a certain temperature. \( G(T) \) is a function of temperature only and determines the thermal expansion of the material. Similarly, \( F(T) \) controls the thermal changes of refractive index. Therefore, when normalized to \( OT_0 \), this becomes:

\[ \frac{OPD}{OPD_0} = F(T)G(T) \]

Thus, a sapphire-fiber-based extrinsic Fabry-Perot interferometric sensor has been demonstrated for high temperature measurement. The adhesive-free coupling of the silica and sapphire fibers is made possible through fusion splicing by the low-melting point of the doped silica fiber core and a loss as low as 0.8 dB has been measured. Also studied is the dependence of the sensor signal on the alignment angle, showing that a relatively large angle range can be tolerated for high fringe intensity. The prototype sensor was tested from 230°C to about 1600°C with a resolution of 0.4°C C. and the sensor response is in good agreement with the theoretical prediction.

Additionally, while the present invention has been discussed with respect to sapphire fibers and wafers, the present invention is not so limited. For example, the silica-sapphire fiber coupling and sensor head may be made from other types of “single-crystal” fibers and wafers. Possible examples include lithium niobate, silver bromide, barium metaborate, etc. The coupling may be accomplished as long as the inserted fiber has a smaller diameter that the core of the fiber into which it is inserted.

While a preferred embodiment has been set forth in detail above, those skilled in the art will readily appreciate that other embodiments can be realized within the scope of the invention. For example, numerical values are illustrative rather than limiting, as is the order in which steps are carried out. Therefore, the present invention should be construed as limited only by the appended claims.

What is claimed is:

1. A method of coupling a silica fiber and a sapphire fiber, comprising the steps of:
   - providing a silica fiber having a doped core and a cladding layer, with the doped core having a prescribed diameter;
   - applying a heat source to the end of the silica fiber;
   - introducing the end of the sapphire fiber into the heated doped core of the silica fiber to produce a coupling between the silica fiber and sapphire fiber.

2. The method according to claim 1, wherein the diameter of the doped core is at least 100 μm and the diameter of the sapphire fiber is at least 75 μm.

3. The method according to claim 1, wherein the step of providing the silica fiber further comprises:
   - providing another optical fiber, and
   - coupling a short length of the silica fiber to the other optical fiber.

4. The method according to claim 1, wherein the step of applying a heat source to the end of the silica fiber comprises applying a splicing arc to the end of the silica fiber.

5. The method according to claim 1, wherein the coupling between the silica and sapphire fibers provides an insertion loss for light passing through the coupling of less than 1 dB.

6. The method according to claim 5, wherein the method produces coupling without the use of an adhesive interlayer.

7. A fiber optic coupling between a silica fiber and a sapphire fiber, comprising:
   - a silica fiber having a doped core and a cladding layer, with the doped core having a prescribed diameter; and
   - a sapphire fiber introduced into the doped core through heating of an end of the sapphire fiber.

8. The coupling according to claim 7, wherein the diameter of the doped core is at least 100 μm and a diameter of the sapphire fiber is at least 75 μm.

9. The coupling according to claim 7, further comprising a short length of the silica fiber coupled to another optical fiber.
A temperature sensor for use in high-temperature environments, comprising:

10. The coupling according to claim 7, wherein the short length of the silica fiber is coupled to the other optical fiber through an adhesive.

11. The coupling according to claim 7, wherein the coupling between the silica and sapphire fibers provides an insertion loss for light passing through the coupling of less than 1 dB.

12. A temperature sensor for use in high-temperature environments, comprising:

- a silica fiber having a doped core and a cladding layer, with the core having a prescribed diameter and being configured to be connected to a light source and a spectrometer;
- a sapphire fiber, having a first end introduced into the doped core through heating of an end of the silica fiber; and
- a sapphire wafer coupled to a second end of the sapphire fiber through an adhesive.

13. The temperature sensor according to claim 12, wherein the second end of the sapphire fiber has a region removed from a center of the sapphire fiber.

14. The temperature sensor according to claim 13, wherein the second end of the sapphire fiber has a region removed from the silica fiber to form a notch in the second end of the sapphire fiber.

15. The temperature sensor according to claim 12, wherein the sapphire wafer has a region removed from a coupling surface of the sapphire wafer to facilitate the coupling of the sapphire wafer and fiber.

16. The temperature sensor according to claim 15, wherein the region removed from a coupling surface of the sapphire wafer is circular.

17. The temperature sensor according to claim 15, wherein the region removed from a coupling surface of the sapphire wafer forms a slot on the coupling surface of the sapphire wafer.

18. The temperature sensor according to claim 12, further comprising a tube surrounding the sapphire fiber at the second end of the sapphire fiber and adhesive which is applied between a second end of the tube and the sapphire wafer.

19. The temperature sensor according to claim 18, wherein further adhesive bonds the sapphire fiber to a first end of the tube.

20. The temperature sensor according to claim 18, wherein the second end of the sapphire fiber is polished to approximately a 1° angle with respect to a centerline of the sapphire fiber.

21. The temperature sensor according to claim 18, wherein the second end of the tube is recessed to accommodate excess water.

22. A method of forming a temperature sensor for use in high-temperature environments, comprising the steps of:

- providing the silica fiber having a doped core and a cladding layer, with the doped core having a prescribed diameter and being configured to be connected to a light source and a spectrometer through a second end; and
- heating a first end of the silica fiber.

23. The method according to claim 22, wherein the step of providing a sapphire wafer to a second end of the sapphire fiber through an adhesive comprises adding small amounts of adhesive to the sapphire wafer.

24. The method according to claim 22, further comprising:

- providing a tube over the sapphire fiber such that the tube surrounds the sapphire fiber at the second end of the sapphire fiber; and
- applying an adhesive between a second end of the tube and the sapphire wafer.

25. The method according to claim 24, further comprising applying adhesive bonds from the sapphire fiber to a first end of the tube.

26. The method according to claim 24, further comprising:

- providing an optical fiber having a core and a cladding layer, with the core having a prescribed diameter;
- providing a single-crystal fiber having a diameter less than the core;
- placing an end of the single-crystal in close proximity to an end of the optical fiber; and
- introducing the end of the single-crystal fiber into the heated core of the optical fiber to produce a coupling between the optical and single-crystal fibers.

27. A method of coupling an optical fiber and a single-crystal fiber, comprising the steps of:

- providing an optical fiber having a core and a cladding layer, with the core having a prescribed diameter;
- providing a single-crystal fiber having a diameter less than the core;
- placing an end of the single-crystal in close proximity to an end of the optical fiber; and
- introducing the end of the single-crystal fiber into the heated core of the optical fiber to produce a coupling between the optical and single-crystal fibers.

28. The method according to claim 27, wherein the diameter of the core is at least 100 μm and the diameter of the single-crystal fiber is at least 75 μm.

29. The method according to claim 27, wherein the step of providing the optical fiber further comprises:

- providing another optical fiber; and
- coupling a short length of the optical fiber to the other optical fiber.

30. The method according to claim 27, wherein the step of applying a heat source to the end of the optical fiber comprises applying a splicing arc to the end of the optical fiber.

31. The method according to claim 27, wherein the coupling between the optical fiber and the single-crystal fiber provides an insertion loss for light passing through the coupling of less than 1 dB.

32. The method according to claim 31, wherein the method produces coupling without the use of an adhesive interlayer.