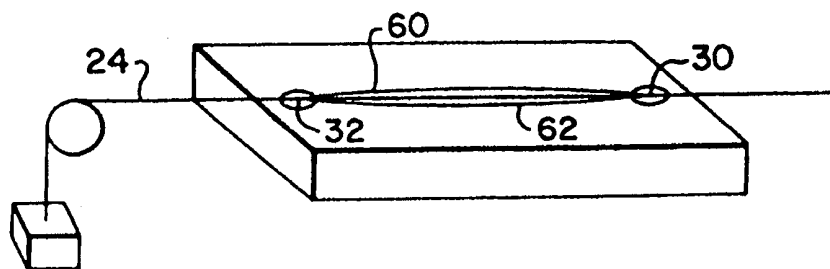




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(54) Title: NEGATIVE THERMAL EXPANSION MATERIALS INCLUDING METHOD OF PREPARATION AND USES THEREFOR



(57) Abstract

Negative thermal expansion materials, methods of preparation and uses therefor are disclosed. The materials are useful for negative thermal expansion substrates, such as those used for optical fiber gratings.

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**NEGATIVE THERMAL EXPANSION MATERIALS INCLUDING METHOD OF
PREPARATION AND USES THEREFOR**

5 This application claims priority to U.S. Application
60/086,053, filed on 5/19/98, the contents of which are
herein incorporated by reference.

FIELD OF THE INVENTION

10 The invention pertains to negative thermal expansion
materials, devices made therefrom, and methods of making
the materials. More particularly, the present invention
concerns compositions including zirconium phosphate
tungstates, which can be used to make substrates for
athermalized optical fiber reflective grating devices.

15

BACKGROUND OF THE INVENTION

 Negative thermal expansion (contraction with
increasing temperature) is an unusual and potentially
useful property for a solid material, and very few
20 crystalline materials possess strongly negative expansions
over an extended temperature range. Materials that
exhibit a negative expansion due to extensive
microcracking, by virtue of a negative coefficient of
thermal expansion ("CTE") along at least one
25 crystallographic axis and a substantially different

CTE along at least one other axis, include some lithium aluminosilicates, "NZPs" (compounds with crystal structures similar to that of $\text{NaZr}_2\text{P}_3\text{O}_{12}$), and $\text{Ta}_2\text{O}_5\text{-WO}_3$ compounds. On the other hand, materials having negative mean lattice expansions that do not require microcracking for negative bulk ceramic CTEs are even more limited, and include certain synthetic alkali-free zeolites having low aluminum contents, ZrW_2O_8 , HfW_2O_8 , $\text{ZrV}_2\text{-xPxO}_7$ (above about 100°C), and $\text{NbZrP}_3\text{O}_{12}$ (an NZP type compound).

Of the compounds that have negative mean lattice expansions, zeolite expansions from 25 to 100°C are in the range $-20 \times 10^{-7}^\circ\text{C}^{-1}$ to $-40 \times 10^{-7}^\circ\text{C}^{-1}$, but have the disadvantages of being dependent upon the amount of adsorbed water in the zeolite, and their CTE curves can exhibit considerable hysteresis. The CTE of $\text{NbZrP}_3\text{O}_{12}$ below 100°C is about $-27 \times 10^{-7}^\circ\text{C}^{-1}$, while that of ZrW_2O_8 and HfW_2O_8 is about $-90 \times 10^{-7}^\circ\text{C}^{-1}$. Thus, ZrW_2O_8 and HfW_2O_8 are presently unique as materials that display a CTE more negative than $-40 \times 10^{-7}^\circ\text{C}^{-1}$ without microcracking.

Martinek and Hummel (1960, *J. Amer. Ceram. Soc.*, 53, 159-161) first reported the existence of $\text{Zr}_2\text{P}_2\text{WO}_{12}$ in their study of the phase relations in the $\text{ZrO}_2\text{-WO}_3\text{-P}_2\text{O}_5$ system at 1125°C . An XRD powder pattern was presented for this new compound, which reportedly has a melting point above 1750°C , although extensive volatilization occurs in air at 1600°C . Synthesis of $\text{Zr}_2\text{P}_2\text{WO}_{12}$ was achieved by calcining a mixture of hydrous zirconium carbonate, tungstic acid, and mono-hydrogen ammonium phosphate.

Tsvigunov and Sirotinkin (1990, *Russ. Jour. of Inorg. Chem.*, 35, 1740) subsequently reported a more complete and precise powder XRD pattern for this compound, which they synthesized from a mixture of ZrO_2 , WO_3 , and $\text{NH}_4\text{H}_2\text{PO}_4$.

Evans et al. (1995, *Jour. Solid State Chem.*, 120, 101-104) have shown that the structure of $\text{Zr}_2\text{P}_2\text{WO}_{12}$ (also referred to as $\text{Zr}_2(\text{WO}_4)(\text{PO}_4)_2$) is comprised of ZrO_6 octahedra sharing corners with WO_4 and PO_4 tetrahedra. Those
5 workers report that dilatometric and variable temperature X-ray diffractometry studies indicate that $\text{Zr}_2\text{P}_2\text{WO}_{12}$ exhibits a negative thermal expansion over a broad temperature range. More recently, Evans et al. (1997, *Journal Solid State Chem.*, 133, 580-83) have reported that
10 $\text{Zr}_2\text{P}_2\text{WO}_{12}$ has a mean lattice CTE of about $-30 \times 10^{-7} \text{ }^\circ\text{C}^{-1}$.

The $\text{Zr}_2\text{P}_2\text{WO}_{12}$ bodies synthesized according to the methods reported in the above literature have porosities greater than about 25%, typically greater than 30%. Such high porosity bodies generally are not useful for
15 industrial applications. Thus, it would be useful to provide a composition having a low, preferably a negative thermal expansion, comprised of $\text{Zr}_2\text{P}_2\text{WO}_{12}$, or analogues thereof in which Hf is fully or partially substituted for Zr, having a porosity less than about 20%, preferably less
20 than about 10%, and more preferably less than about 5%.

Bodies having a highly negative CTE, such as -30 to $-100 \times 10^{-7} \text{ }^\circ\text{C}^{-1}$, can find use as substrates for athermalization of fiber Bragg gratings (FBGs). In the latter application, a FBG is mounted in tension on the
25 negative expansion substrate. Applications of FBGs include passive wavelength division multiplexing and filtering in dense WDM systems, as well as distributed fiber sensors for smart systems to monitor bridges, structures, and highways.

30 For such applications, variation of the center wavelength of fiber Bragg gratings (FBGs) with respect to temperature, due to thermal expansion of the fiber and variation of the refractive index of the glass, must be minimized. For example, at a Bragg wavelength of 1550 nm,

thermal variation of λ_B is expected to be 0.012 nm/°C, whereas a value less than 0.002 nm/°C is desired. Variation in λ_B with temperature can be reduced to well below 0.002 nm/°C by mounting the FBG in tension on a substrate having a negative thermal expansion of about -70 to $-85 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$ within that range also -70 to $-80 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$, -75 to $-82 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$. The reduction in tension with increasing temperature associated with the contraction of the substrate partially or entirely offsets the contribution to increased optical path length resulting from the thermal expansion and change in refractive index of the glass.

β -eucryptite based ceramics formed by controlled devitrification of sintered lithium aluminosilicate glass are being studied as FBG substrates and are disclosed in international patent application no. PCT/US/13062, Beall et al., entitled, "Athermal Optical Device." The attainment of CTEs of -70 to $-85 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$ in β -eucryptite bodies requires extensive microcracking; an unmicrocracked β -eucryptite exhibits a CTE near $-5 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$. This microcracking results from internal stresses associated with the large difference in CTE along the *c* and *a* axes of the crystals (approximately -176 and $+78 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$, respectively), coupled with the coarse grain size of the crystals.

United States patent no. 5,694,503, issued to Fleming et al., discloses using the negative coefficient of thermal expansion material ZrW_2O_8 to form substrates for temperature compensated fiber Bragg gratings. Since the coefficient of thermal expansion of ZrW_2O_8 may be too negative to provide temperature compensation for Bragg gratings, the Fleming et al. patent suggests mixing ZrW_2O_8 with a positive coefficient of thermal expansion material

such as alumina, silica, zirconia, magnesia, calcia, or yttria in an amount to raise the coefficient of thermal expansion.

5 The mixtures of ZrW_2O_8 with positive coefficient of thermal expansion materials suggested in the Fleming et al. patent, however, have several disadvantages. Large relative differences in the thermal expansion coefficients of ZrW_2O_8 and the positive CTE materials can cause microcracking in the composite material upon heating and
10 cooling of the material. Such microcracking can result in hysteresis in the thermal expansion curve or dimensional change of the body with changes in humidity, characteristics that are undesirable in a fiber Bragg grating substrate. Furthermore, many of the positive CTE
15 components recommended in the Fleming et al. patent react with the ZrW_2O_8 during sintering to form copious amounts of liquid. Such reactions and liquid formation tend to cause the body to slump during firing. Alternatively, some of the positive CTE components recommended in the Fleming et
20 al. patent react with the ZrW_2O_8 to form other high CTE crystalline phases so that the ceramic body does not have the desired strongly negative CTE after firing. In addition, ceramics comprised of ZrW_2O_8 and ZrO_2 undergo a length change having an absolute value greater than 500
25 parts per million over 700 hours at 85% relative humidity and 85 °C, which is undesirably large.

The presence of microcracking in a FBG substrate requires that the fiber/substrate package be hermetically sealed to prevent dimensional drift of the substrate due
30 to opening and closing of the microcracks resulting from variations in humidity. Hermetic sealing adds significantly to the cost of the assembly, and the reliability of the device becomes dependent upon long-term reliability of the hermetic seal.

Thus, it would be desirable to provide an unmicrocracked material having a porosity less than about 25%, preferably less than about 10% and more preferably less than about 5%. Further, there is a need for a body having a CTE of about $-70 \times 10^{-7} \text{ }^{\circ}\text{C}^{-1}$ to $-85 \times 10^{-7} \text{ }^{\circ}\text{C}^{-1}$ to provide temperature compensation for the gratings of current interest which could be used to make FBG substrates because hermetic sealing would not be required for long-term stability. In addition, it would be desirable to provide a material that has a length change having an absolute value less than 500 ppm over 700 hours at 85°C and 85% relative humidity.

15 SUMMARY OF INVENTION

The present invention provides a low-porosity body containing at least one phase having a negative thermal expansion, a method of making the phase, and devices made from the phase. In one embodiment, the body is comprised of the compound $\text{Zr}_2\text{P}_2\text{W}_{12}\text{O}_{42}$ which exhibits a room-temperature CTE of about $-40 \times 10^{-7}^\circ\text{C}^{-1}$, and a CTE from about 25 to 800°C of about $-25 \times 10^{-7}^\circ\text{C}^{-1}$. Hafnium may be partially or entirely substituted for zirconium. The body further comprises a crystalline or non-crystalline oxide phase, which may include a glassy phase, which contains a metal selected from the group consisting of alkaline earth metals, alkali metals, manganese, iron, cobalt, copper, zinc, aluminum, gallium, and bismuth. The oxide phase may also contain one or more of the metals selected from the group zirconium, tungsten and phosphorous.

In another embodiment, this invention comprises a ceramic body comprised of two negative CTE phases, preferably wherein at least one of the phases has a room temperature CTE more negative than $-50 \times 10^{-7} \text{C}^{-1}$. In an

exemplary embodiment, one phase has the composition $M_2B_3O_{12}$ where M is selected from the group including aluminum, scandium, indium, yttrium, the lanthanide metals, zirconium, and hafnium, and where B is selected from the group consisting of tungsten, molybdenum, and phosphorus, and where M and B are selected such that the compound $M_2B_3O_{12}$ has a negative CTE, and comprising a second phase of the composition AX_2O_8 , where A is selected from the group consisting of zirconium and hafnium, and X is selected from the group consisting of tungsten and molybdenum.

For example, the ceramic body may comprise a mixture of ZrW_2O_8 and $Zr_2P_2WO_{12}$, wherein hafnium may be partially or fully substituted for zirconium in $Zr_2P_2WO_{12}$ and ZrW_2O_8 . In a preferred embodiment, the ceramic body is unmicrocracked. The ceramic body may further include a crystalline or non-crystalline oxide phase, which may include a glassy phase, which contains a metal selected from the group consisting of alkaline earth metals, alkali metals, lanthanum group metals, niobium, titanium, manganese, iron, cobalt, nickel, copper, zinc, yttrium, scandium, aluminum, gallium, and bismuth. The oxide phase may also contain one or more of the metals selected from the group zirconium, tungsten and phosphorous.

The invention also includes a method of making ceramic bodies of the present invention comprising mixing together powders of $Zr_2P_2WO_{12}$ or precursor powders of $Zr_2P_2WO_{12}$ or analogues of these powders in which Hf is substituted for Zr, or mixtures thereof, and at least one oxide or oxide precursor of metals selected from the group consisting of alkaline earth metals, alkali metals, manganese, iron, cobalt, copper, zinc, aluminum, gallium, and bismuth.

Another embodiment of this invention involves a method of raising and making the negative thermal expansion of a ceramic body less negative comprising a

phase having a room temperature coefficient of thermal expansion more negative than $-50 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$ comprising mixing together the first phase with at least a second phase or precursors of the first phase and at least the second
5 phase, the second phase having a negative thermal expansion less negative than $-50 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$. A body made according to this method preferably will not exhibit microcracking. Alternatively, the method includes forming a ceramic body comprising two negative CTE phases,
10 preferably wherein the room temperature CTE of one of the phases is more negative than $-50 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$ and the other phase is less negative than $-50 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$, to provide a body having a CTE less negative than $-50 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$.

15 In an exemplary embodiment, one phase has the composition $\text{M}_2\text{B}_3\text{O}_{12}$ where M is selected from the group including aluminum, scandium, indium, yttrium, the lanthanide metals, zirconium, and hafnium, and where B is selected from the group consisting of tungsten,
20 molybdenum, and phosphorus, and where M and B are selected such that the compound $\text{M}_2\text{B}_3\text{O}_{12}$ has a negative CTE, and comprising a second phase of the composition AX_2O_8 , where A is selected from the group consisting of zirconium and hafnium, and X is selected from the group consisting of
25 tungsten and molybdenum. In another exemplary embodiment, the method comprises mixing ZrW_2O_8 or precursors of ZrW_2O_8 , or analogues of these materials in which Hf is substituted for Zr, with $\text{Zr}_2\text{P}_2\text{WO}_{12}$ or precursor powders of $\text{Zr}_2\text{P}_2\text{WO}_{12}$ or
30 analogues of these powders in which Hf is substituted for Zr. Optionally, these may also be mixed with at least one oxide or oxide precursor of metals selected from the group consisting of alkaline earth metals, alkali metals, manganese, iron, cobalt, copper, zinc, aluminum, gallium, and bismuth. The mixed powders are consolidated together

using a ceramic forming method and heated to sinter the ceramic body. Preferably, the heating occurs at a temperature of about 1050°C to 1300°C, more preferably 1120°C to 1230°C for about 1 minute to 10 hours. When the ZrW₂O₈ phase is desired to be present in the ceramic body, preferably heating occurs at a temperature of about 1150°C to 1230°C.

Another aspect of the invention involves an optical device comprising a negative expansion substrate having a composition comprising two negative CTE phases, preferably wherein at least one of the phases has a room temperature CTE more negative than $-50 \times 10^{-7} \text{°C}^{-1}$, and one of the phases has a thermal expansion less negative than $-50 \times 10^{-7} \text{°C}^{-1}$. For example, the substrate composition may comprise a mixture of ZrW₂O₈ and Zr₂P₂WO₁₂. Hafnium may be partially or fully substituted for zirconium in Zr₂P₂WO₁₂ and ZrW₂O₈. In a preferred embodiment, the substrate is unmicrocracked. The substrate may further include a crystalline or non-crystalline oxide phase, which may include a glassy phase, which contains a metal selected from the group consisting of alkaline earth metals, alkali metals, lanthanum group metals, niobium, titanium, manganese, iron, cobalt, nickel, copper, zinc, yttrium, scandium, aluminum, gallium, and bismuth. The oxide phase may also contain one or more of the metals selected from the group zirconium, tungsten and phosphorous.

The device further comprises a thermally sensitive, positive expansion optical component affixed to the substrate. In one embodiment, the optical component is an optical fiber grating and the substrate has a mean linear coefficient of thermal expansion of about $-40 \times 10^{-7} \text{°C}^{-1}$ to $-85 \times 10^{-7} \text{°C}^{-1}$ over a temperature range of about -40°C to 85°C. Another aspect of the invention relates to a negative

expansion substrate having a composition comprising $Zr_2P_2WO_{12}$ and a crystalline or non-crystalline oxide phase, which may include a glassy phase, which contains a metal selected from the group consisting of alkaline earth
5 metals, alkali metals, manganese, iron, cobalt, copper, zinc, aluminum, gallium, and bismuth. Hafnium may be fully or partially substituted for zirconium. The oxide phase may also contain one or more of the metals selected from the group zirconium, tungsten and phosphorous.

10 Thus the present invention generally provides a novel ceramic body comprised of phase having a negative CTE, such as $Zr_2P_2WO_{12}$ or $Hf_2P_2WO_{12}$ or mixtures thereof, which exhibits a negative coefficient of thermal expansion (CTE) at all temperatures from at least as low as 25 °C to at
15 least as high as 500 °C. The mean CTE near room temperature is about $-40 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$, while the mean CTE from 25 to 800°C is about $-25 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$. The $Zr_2P_2WO_{12}$ or $Hf_2P_2WO_{12}$ phase is stable at all temperatures from at least as low as -50°C to at least as high as 1150°C.

20 Also disclosed is a method for fabricating the sintered ceramic body which, in some embodiments, entails the addition of small amounts of additives which function as sintering aids to powders of $Zr_2P_2WO_{12}$ or $Hf_2P_2WO_{12}$ or mixtures thereof or their precursors. These additives
25 include the compounds of lithium, sodium, potassium, magnesium, calcium, barium, manganese, iron, copper, and zinc. Aluminum compounds may also be used as sintering aids, but are not as effective. Compounds of rubidium, cesium, and strontium would also likely be effective for
30 densification.

The present invention also includes a ceramic body comprised mainly of the phases ZrW_2O_8 and $Zr_2P_2WO_{12}$ and their hafnium analogues and mixtures thereof, having a mean linear coefficient of thermal expansion of about -40

to $-85 \times 10^{-7} \text{ }^{\circ}\text{C}^{-1}$ over the temperature range -40°C to $+85^{\circ}\text{C}$. These bodies also exhibit a negative CTE to higher temperatures as well. Preferred embodiments of the invention have less than 10% total porosity, especially less than 5% porosity. In one embodiment, achievement of low porosity is enhanced by the addition of small amounts (0.01 to 5.0 wt%) of certain sintering additives, such as the oxides or oxide-forming compounds of alkali (group IA) metals, alkaline earth (group IIA) metals, manganese, iron, cobalt, nickel, copper, zinc, yttrium, scandium, lanthanide metals, niobium, titanium, aluminum, gallium, and bismuth. Many of these materials have the desirable properties of having excellent dimensional stability at 85°C and 85% relative humidity and possessing no microcracking, and thus exhibit no hysteresis in their thermal expansion curves. Such ceramics are suitable as athermalizing substrates for fiber Bragg gratings.

Additional features and advantages of the invention will be set forth in the description which follows. It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory and are intended to provide further explanation of the invention as claimed.

The accompanying drawings are included to provide a further understanding of the invention and are incorporated in and constitute a part of this specification, illustrate one embodiment of the invention and together with the description serve to explain the principles of the invention. In the drawings, like reference characters denote similar elements throughout the several views. It is to be understood that various elements of the drawings are not intended to be drawn to scale, but instead are sometimes purposely distorted for the purposes of illustrating the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows the relationship of the dependence of the coefficient of thermal expansion at 25°C on the weight percent of $Zr_2P_2WO_{12}$ in a ceramic body comprised mainly of $Zr_2P_2WO_{12}$ and ZrW_2O_8 ;

FIG. 2 shows the dimensional change of sample bars of ZrW_2O_8 with 15 weight percent ZrO_2 at 85°C and 85% relative humidity compared with the dimensional changes of inventive bodies under the same conditions;

FIG. 3 is a schematic drawing of an embodiment of an athermal optical fiber grating device;

FIG. 4 is a schematic drawing of an embodiment of an athermal optical fiber grating device;

FIG. 5 is a schematic drawing an embodiment of an athermal optical fiber grating device;

FIG. 6 is an enlarged view of the affixing channel shown in FIG. 5;

FIG. 7 is a schematic drawing of an embodiment of an athermal fiber grating device;

FIG. 8 is a schematic drawing of an embodiment of an athermal optical fiber fused coupler device;

FIG. 9 is a schematic drawing of an embodiment of an athermal planar waveguide device; and

FIG. 10 is a plot of center wavelength (nm) versus temperature (°C) of an embodiment of an athermal fiber Bragg grating device.

DETAILED DESCRIPTION

Reference will now be made in detail to the present preferred embodiment of the invention, an example of which is illustrated in the accompanying drawings.

According to one embodiment of the present invention, small amounts of additives, which function as sintering

aids, are mixed with $\text{Zr}_2\text{P}_2\text{WO}_{12}$ powder or to a mixture of precursor compounds that can form $\text{Zr}_2\text{P}_2\text{WO}_{12}$ by reaction. The precursors may include, for example, ZrO_2 , $\text{Zr}(\text{NO}_3)_4 \cdot x\text{H}_2\text{O}$, $\text{ZrOCl}_2 \cdot x\text{H}_2\text{O}$, $\text{Zr}(\text{SO}_4)_2 \cdot x\text{H}_2\text{O}$, WO_3 , $\text{H}_2\text{WO}_4 \cdot x\text{H}_2\text{O}$, P_2O_5 , ZrP_2O_7 , $\text{Zr}_2\text{P}_2\text{O}_9$, $\text{Zr}(\text{HPO}_4)_2 \cdot x\text{H}_2\text{O}$, ZrW_2O_8 , $\text{NH}_4\text{H}_2\text{PO}_4$, $(\text{NH}_4)_2\text{HPO}_4$, $(\text{NH}_4)_3\text{PO}_4 \cdot 3\text{H}_2\text{O}$, phospho-tungstic acid, etc. Hafnium may be partially or fully substituted for zirconium. The mixtures may be dry mixed or blended using an appropriate organic or inorganic liquid medium. Water may be used when the precursors have low aqueous solubility. If mixed in a fluid medium, the precursors may also be milled by any of the methods known to the art (e.g., ball milling, attrition milling, vibratory milling, etc.). When some or all of the precursors are soluble in water, they may be dissolved in water and subsequently coprecipitated to form an even more intimate mixture.

The mixture may optionally be dried and calcined, followed by milling, or may be directly "green" formed into the desired shape. Organic binders such as a polyethylene glycol or methyl cellulose may optionally be added to provide strength to the green body. The body is then raised to and held at a temperature sufficient for densification to take place, such as at 1150°C for 4 hours.

In another aspect of the invention, ceramic bodies are comprised predominately of two materials having a negative CTE, such as ZrW_2O_8 and $\text{Zr}_2\text{P}_2\text{WO}_{12}$ or their hafnium analogues or mixtures thereof, and the bodies exhibit CTEs of -40 to $-85 \times 10^{-7}^\circ\text{C}^{-1}$ between -40°C and $+85^\circ\text{C}$. In one embodiment one of the materials has a room temperature CTE more negative than about $-50 \times 10^{-7}^\circ\text{C}^{-1}$. Depending upon the ratio of the two negative CTE materials, it is possible to achieve these CTEs in the body without microcracking. Ceramic bodies having negative CTEs within this range

without relying upon microcracking have not previously been reported in the literature, and represent a unique invention.

5 In a two-phase ceramic containing ZrW_2O_8 , the second phase must either be in chemical equilibrium with ZrW_2O_8 at the sintering temperature, or else reaction between the second phase and ZrW_2O_8 must be sufficiently slow that most of the second phase is retained through the firing process. Also, to avoid microcracking, the difference
10 between the CTEs of the two phases, ΔCTE , must be minimized (while still being sufficient to achieve the desired bulk CTE of about $-70 \times 10^{-7} \text{ }^\circ\text{C}^{-1}$ to $-85 \times 10^{-7} \text{ }^\circ\text{C}^{-1}$), and the mean grain size of the components must be finer than some critical value which is dictated by the value of
15 ΔCTE . The term "grain size" is meant to include either the size of a primary crystal, or the size of a cluster or aggregate of two or more adjacent crystals of the same phase.

Addition of chemically compatible phases with
20 positive CTEs, such as ZrSiO_4 , ZrO_2 , or WO_3 , to a ZrW_2O_8 -based ceramic could be employed to create materials having expansions less negative than that of pure ZrW_2O_8 , however, the large disparity in CTE between the two components would result in microcracking unless the grains of the two
25 phases were maintained at less than about 1 micron during sintering.

The present invention involves the discovery of an alternative to prevent microcracking. Applicant has discovered that the combination of a material having a
30 strongly negative CTE, for example, a first material such as ZrW_2O_8 having a room temperature CTE more negative than $-50 \times 10^{-7} \text{ }^\circ\text{C}^{-1}$, with a second phase whose CTE is also negative, but not as strongly negative as that of the first material, results in lower stresses from the CTE

mismatch between the phases. Thus, the present invention provides a body that avoids microcracking for grain sizes less than about 15 microns, preferably less than about 10 microns. In an additional alternative embodiment, the grain sizes are greater than 1 micron.

Applicant has recently measured the room temperature CTE of the compound $\text{Zr}_2\text{P}_2\text{WO}_{12}$ to be about $-40 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$. Applicant has discovered that because the CTE of this compound is not extremely different from that of ZrW_2O_8 , a ceramic body containing both phases can exhibit a CTE of intermediate value without undergoing microcracking, provided that the grain size of the two components is less than about 10 microns. This restriction on grain size can easily be met for an appropriate choice of starting materials and sintering conditions.

According to an exemplary embodiment of the present invention, powders of ZrW_2O_8 and $\text{Zr}_2\text{P}_2\text{WO}_{12}$, or precursors that form ZrW_2O_8 and $\text{Zr}_2\text{P}_2\text{WO}_{12}$ by reaction upon firing, or their hafnium analogues or mixtures thereof, are mixed together and formed into the desired shape by ceramic processes known in the art, e.g., dry pressing, injection molding, extrusion, slip casting, etc. Mixing may be performed on the dry powders, or the powders may be mixed with a liquid and may optionally be further reduced in particle size by ball milling, attrition milling, vibratory milling, etc. An organic binder may be added to the powders to increase handling strength in the green (pre-fired) state. Optionally, inorganic or organometallic compounds which serve as densification aids may also be added in small quantities to the mixture of starting materials. It has been found that oxides or oxide-forming compounds of alkali (group IA) metals, alkaline earth (group IIA) metals, manganese, iron, cobalt, nickel, copper, zinc, yttrium, scandium, lanthanide metals, niobium, titanium, aluminum, gallium,

and bismuth are especially effective at reducing porosity of the ceramic body during firing. The quantity of sintering aids is preferably the minimum amount required for densification, as it has been found that larger
5 additions of such additives tend to produce large-scale cracking of the body during firing.

The body may be placed upon a glass or ceramic setter pallet or in a partially enclosed container of a glass or ceramic material and heated to a maximum temperature of
10 between about 1120 and 1230 °C, preferably between about 1150 to 1200 °C, and held for a period of time sufficient for reaction and sintering to take place, such as 1 minute to 10 hours. A glass or ceramic powder or "sand" may be placed between the body and the pallet to reduce drag
15 during shrinkage of the body during firing. Zirconium oxide or zircon powder or silica powder or sand are especially preferred in this role. After holding at peak temperature, the body is rapidly cooled to a temperature below about 500°C in a few minutes to minimize
20 decomposition of the ZrW_2O_8 phase. ZrW_2O_8 is unstable below about 1140°C, but decomposition proceeds only very slowly at temperatures less than about 800°C. The fired body may optionally undergo surface grinding or other machining if desired.

25

The present invention is illustrated by the following non-limiting examples.

EXAMPLES 1 to 18

30

Examples 1-18 were prepared by mixing together powders of zirconium oxide, tungsten oxide, and acid zirconium phosphate, $\text{Zr}(\text{HPO}_4)_2 \cdot 0.93\text{H}_2\text{O}$, in the proportions required to yield the compound $\text{Zr}_2\text{P}_2\text{WO}_{12}$ after firing. Mixtures for Examples 2-18 also contained 1 weight percent

addition of a metal oxide, or metal oxide forming source. Powders were mixed with a sufficient amount of isopropanol to form a slurry, and the slurry was milled in a vibratory mill for approximately sixteen hours using zirconium oxide milling media. The slurry was subsequently dried in a dish at about 85 °C, repulverized, and the powder pressed into 1.2 cm diameter, 0.4 cm thick pills, or 7.6 cm x 1.3 cm x 0.4 cm bars in a steel mold at a pressure of about 70 Mpa (10,000 pounds/inch²). The pills and bars were placed on coarse zirconium oxide sand in covered aluminum oxide setter boxes inside of an electrically heated furnace. Temperature of the furnace was raised at a rate of about 30 °C/hr to 350°C to allow volatilization of the water from the acid zirconium phosphate, then heated at a rate of about 100 to 200°C/hr to a maximum temperature of 1150°C. After holding at 1150°C for 4 hours, power to the furnace was shut off and the samples gradually cooled to room temperature.

The fired bars were cut to a 5 cm length for measurement of thermal expansion. Porosity was measured by the Archimedes method, and phases present after firing were determined by powder x-ray diffractometry (XRD). Coefficients of thermal expansion were measured by dilatometry.

Example 1 shows that, in the absence of a sintering additive, the $\text{Zr}_2\text{P}_2\text{WO}_{12}$ ceramic was poorly densified, containing about 32 percent porosity. The mean coefficient of thermal expansion (CTE) from 25 to 50°C was $-32 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$, and from 25 to 500°C was $-30 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$. This specimen consisted entirely of the desired $\text{Zr}_2\text{P}_2\text{WO}_{12}$ phase.

Examples 2-4 demonstrate that the addition of only 1% of the carbonates of the alkali (Group IA) metals is highly effective in promoting densification of the $\text{Zr}_2\text{P}_2\text{WO}_{12}$ ceramics. Samples contain essentially no open porosity,

and total porosities are reduced to approximately 1-5%. Thermal expansions remain strongly negative at room temperature. XRD showed that these ceramic bodies contain mostly $\text{Zr}_2\text{P}_2\text{WO}_{12}$ with minor amounts of $\text{LiZr}_2\text{P}_3\text{O}_{12}$, $\text{NaZr}_2\text{P}_3\text{O}_{12}$,
5 and $\text{KZr}_2\text{P}_3\text{O}_{12}$, in samples 2-4, respectively. These secondary phases are responsible for the somewhat less negative CTE from 25 to 500 °C for Examples 2 and 3.

Examples 5-7 illustrate that the addition of only 1% of the oxides or carbonates of the alkaline earth (Group
10 IIA) metals is also very effective in reducing the porosity of $\text{Zr}_2\text{P}_2\text{WO}_{12}$ ceramics. Total porosities are less than 3%, and there is virtually no open porosity. Fired bodies contained predominately $\text{Zr}_2\text{P}_2\text{WO}_{12}$. Example 5 contained a very minor amount of MgWO_4 , Example 6 contained
15 very minor amounts of $\text{CaZr}_4\text{P}_6\text{O}_{24}$ and CaWO_4 , and Example 7 had a very small amount of $\text{BaZr}_4\text{P}_6\text{O}_{24}$. CTEs were very negative from 25 to 50°C (-27 to $-35 \times 10^{-7} \text{ }^\circ\text{C}^{-1}$) and 25 to 500°C (-24 to $-26 \times 10^{-7} \text{ }^\circ\text{C}^{-1}$).

Table 1

Experimental data for $Zr_2P_2WO_{12}$ ceramics.

Example Number	Weight % $Zr_2P_2WO_{12}$	Weight % Additive	Measured on pills				Measured on bars				Mean Coefficient of Thermal Expansion ($10^{-6} / ^\circ C$)			
			Bulk Density (g/cm^3)		% Open Porosity		% Total Porosity		Bulk Density (g/cm^3)		% Open Porosity		% Total Porosity	
			100	0	100	0	100	0	100	0	100	0	100	0
1	100	0	2.71	0	28.5	0	30.5	0	2.65	0	31.1	0	32.1	0
2	99	1	3.85	1	0.1	1.3	1.3	0.8	3.87	0.3	0.3	0.8	0.8	-30
3	99	1	3.81	1	0.0	2.3	2.3	1.5	3.84	0.1	1.5	1.5	1.5	-15
4	99	1	3.69	1	0.4	5.4	5.4	5.1	3.70	0.5	5.1	5.1	5.1	-18
5	99	1	3.87	1	0.0	0.8	0.8	0.8	3.87	0.1	0.8	0.8	0.8	-27
6	99	1	3.72	1	0.3	4.6	4.6	2.3	3.81	0.2	2.3	2.3	2.3	-24
7	99	1	3.82	1	0.1	2.1	2.1	2.1	3.82	0.2	2.1	2.1	2.1	-26
8	99	1	3.84	1	0.0	1.5	1.5	1.0	3.86	0.0	1.0	1.0	1.0	-28
9	99	1	3.82	1	0.2	2.1	2.1	2.6	3.80	0.4	2.6	2.6	2.6	-29
10	99	1	3.76	1	0.2	3.6	3.6	3.8	3.75	0.2	3.8	3.8	3.8	-27
11	99	1	3.87	1	0.0	0.8	0.8	0.5	3.88	0.1	0.5	0.5	0.5	-38
12	99	1	3.14	1	16.5	19.5	19.5	0.5						
13	99	1	2.59	1	31.4	33.6	33.6	0.5						
14	99	1	2.47	1	37.1	36.7	36.7	0.5						
15	99	1	2.52	1	32.8	35.4	35.4	0.5						
16	99	1	2.36	1	37.8	39.5	39.5	0.5						
17	99	1	2.66	1	29.6	31.8	31.8	0.5						
18	99	1	2.59	1	33.7	33.6	33.6	0.5						

Examples 8-11 show that the addition of only 1% of the oxides or carbonates of manganese, iron, copper, and zinc is highly effective in densifying $\text{Zr}_2\text{P}_2\text{WO}_{12}$ ceramics to less than 4% total porosity, with essentially no open porosity. Example 8 contained a trace of MnWO_4 , and Example 9 contained a very minor amount of an unidentified phase. Examples 10 and 11 exhibited only $\text{Zr}_2\text{P}_2\text{WO}_{12}$ in their XRD patterns. All samples had highly negative CTEs of -29 to $-38 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$ from 25 to 50°C , and -26 to $-28 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$ from 25 to 500°C .

Example 12 demonstrates that aluminum oxide also serves to lower the porosity of $\text{Zr}_2\text{P}_2\text{WO}_{12}$ ceramics; however, total porosity is still about 20%. XRD indicated the presence only of $\text{Zr}_2\text{P}_2\text{WO}_{12}$. Thermal expansion was not measured.

Examples 13-18 prove that not all oxides are effective as sintering aids for $\text{Zr}_2\text{P}_2\text{WO}_{12}$ ceramics. Thus, the addition of 1% of the oxides of titanium, nickel, yttrium, silicon, tin, and niobium, for example, yield a ceramic body containing greater than 30% porosity.

EXAMPLES 19 to 28

Powder preparation for Examples 19 and 21-28 was conducted in the same manner as Examples 1-18, with the proportions of the starting materials adjusted to yield $\text{Zr}_2\text{P}_2\text{WO}_{12}$ and ZrW_2O_8 in the ratios stated in Table 2. In these examples, the weight percentages of $\text{Zr}_2\text{P}_2\text{WO}_{12}$ and ZrW_2O_8 are relative to the sum of the weights of the $\text{Zr}_2\text{P}_2\text{WO}_{12}$ and ZrW_2O_8 components only. Weight percent of additive is relative to total weight percent of starting material.

Table 2

Experimental data for $\text{Zr}_2\text{P}_2\text{WO}_{12}$ ceramics with various amounts of ZrW_2O_8 .

Example Number	Weight % $\text{Zr}_2\text{P}_2\text{WO}_{12}$	Weight % ZrW_2O_8	Weight % Additive	Additive	Sample Geometry	Heating rate above 900°C (°C/hr)	Soak Temperature	Soak Time
19	100	0	0.00	none	7.6 cm bar	200	1150	4
20	50	50	0.00	none	7.6 cm bar	100	1150	4
21	49	51	0.00	none	7.6 cm bar	200	1150	4
22	32	68	0.00	none	7.6 cm bar	100	1150	4
23	32	68	0.00	none	7.6 cm bar	100	1150	4
24	32	68	0.00	none	7.6 cm bar	25	1150	4
25	24	76	0.00	none	7.6 cm bar	200	1150	4
26	10	91	0.00	none	7.6 cm bar	200	1150	4
27	5	95	0.00	none	7.6 cm bar	200	1150	4
28	0	100	0.00	none	7.6 cm bar	200	1150	4
29	32	68	0.25	AlOOH	7.6 cm bar	100	1150	4
30	32	68	0.25	TiO ₂	7.6 cm bar	100	1150	4
31	32	68	0.25	Nb ₂ O ₅	7.6 cm bar	100	1150	4
32	32	68	0.25	SiO ₂	7.6 cm bar	100	1150	4
33	32	68	0.05	Li ₂ CO ₃	7.6 cm bar	100	1150	4
34	32	68	0.10	Na ₂ CO ₃	7.6 cm bar	100	1150	4
35	32	68	0.05	Na ₂ CO ₃	7.6 cm bar	100	1150	4
36	32	68	0.01	Na ₂ CO ₃	7.6 cm bar	100	1150	4
37	32	68	0.25	K ₂ CO ₃	7.6 cm bar	100	1150	4
38	32	68	0.25	K ₂ CO ₃	7.6 cm bar	25	1150	4
39	32	68	0.05	K ₂ CO ₃	7.6 cm bar	100	1150	4
40	32	68	0.25	CaCO ₃	7.6 cm bar	100	1150	4
41	32	68	0.25	CaCO ₃	7.6 cm bar	25	1150	4
42	32	68	0.05	CaCO ₃	7.6 cm bar	100	1150	4
43	32	68	0.25	BaCO ₃	7.6 cm bar	100	1150	4
44	32	68	0.25	BaCO ₃	7.6 cm bar	25	1150	4
45	32	68	0.10	BaCO ₃	7.6 cm bar	100	1150	4
46	32	68	1.00	MgO	1.3 cm disc	100	1150	4
47	32	68	0.25	MgO	7.6 cm bar	100	1150	4
48	32	68	0.25	MgO	7.6 cm bar	25	1150	4
49	32	68	0.05	MgO	7.6 cm bar	100	1150	4
50	32	68	1.00	CuO	1.3 cm disc	100	1150	4
51	32	68	0.25	CuO	7.6 cm bar	100	1150	4
52	32	68	0.05	CuO	7.6 cm bar	100	1150	4
53	32	68	1.00	ZnO	1.3 cm disc	100	1150	4
54	32	68	1.00	ZnO	7.6 cm bar	100	1150	4
55	32	68	0.25	ZnO	7.6 cm bar	100	1150	4
56	32	68	0.25	ZnO	7.6 cm bar	25	1150	4
57	32	68	0.10	ZnO	7.6 cm bar	100	1150	4
58	32	68	1.00	MnCO ₃	1.3 cm disc	100	1150	4
59	32	68	1.00	MnCO ₃	7.6 cm bar	100	1150	4
60	32	68	0.25	MnCO ₃	7.6 cm bar	100	1150	4
61	32	68	0.25	MnCO ₃	7.6 cm bar	25	1150	4
62	32	68	0.05	MnCO ₃	7.6 cm bar	100	1150	4
63	32	68	1.00	Fe ₂ O ₃	1.3 cm disc	100	1150	4
64	32	68	1.00	Fe ₂ O ₃	7.6 cm bar	100	1150	4
65	32	68	0.25	Fe ₂ O ₃	7.6 cm bar	100	1150	4

Table 2 (continued)
Experimental data for $Zr_2P_2WO_{12}$ ceramics with various amounts of ZrW_2O_8 .

Example Number	Weight % $Zr_2P_2WO_{12}$	Weight % ZrW_2O_8	Weight % Additive	Additive	Sample Geometry	Heating rate above 900°C (°C/hr)	Soak Temperature	Soak Time
66	32	68	0.50	Y_2O_3	11.4 cm bar	100	1150	4
67	32	68	0.25	Y_2O_3	7.6 cm bar	100	1150	4
68	32	68	0.25	Y_2O_3	11.4 cm bar	100	1150	4
69	32	68	0.25	Y_2O_3	11.4 cm bar	100	1150	4
70	32	68	0.12	Y_2O_3	11.4 cm bar	100	1150	4
71	32	68	0.05	Y_2O_3	11.4 cm bar	100	1150	4
72	32	68	0.05	Y_2O_3	11.4 cm bar	100	1150	4
73	32	68	0.05	Y_2O_3	11.4 cm bar	100	1150	4
74	25	75	0.05	Y_2O_3	11.4 cm bar	100	1150	4
75	25	75	0.05	Y_2O_3	11.4 cm bar	450	1175	4
76	25	75	0.05	Y_2O_3	11.4 cm bar	450	1175	8
77	15	85	0.05	Y_2O_3	11.4 cm bar	450	1175	8
78	10	88*	0.05	Y_2O_3	11.4 cm bar	450	1175	6
79	32	68	0.25	La_2O_3	7.6 cm bar	100	1160	4
80	32	68	0.25	CeO_2	7.6 cm bar	100	1160	4
81	32	68	0.25	MoO_3	7.6 cm bar	100	1160	4
82	32	68	0.25	Bi_2O_3	7.6 cm bar	100	1160	4
83	32	68	0.25	B_2O_3	7.6 cm bar	100	1160	4
84	32	68	0.25	Ga_2O_3	7.6 cm bar	100	1160	4
85	32	68	0.25	In_2O_3	7.6 cm bar	100	1160	4
86	32	68	0.25	SnO	7.6 cm bar	100	1160	4
87	32	68	0.25	Cr_2O_3	7.6 cm bar	100	1160	4
88	32	68	0.25	NiO	7.6 cm bar	100	1160	4

*Example 78 also contains 2% tungsten oxide as an additional phase.

Example 20 was prepared by precipitation from aqueous solutions of $ZrOCl_2 \cdot 8H_2O$, $NH_4H_2PO_4$, and H_2WO_4 . According to this method, 79.18 grams of zirconyl chloride (previously assayed to be 2.739×10^{-3} moles Zr per gram of salt) was dissolved in 161 grams of water to form the first solution. A second solution was formed by dissolving 16.63 grams of ammonium dihydrogen phosphate in 73 grams of water. A third solution was made by dissolving 54.19 grams of tungstic acid in 152 grams of water and 54 grams of 14.8 N ammonium hydroxide solution, and heating to 95 °C. The tungsten and phosphate solutions were mixed together and then added to the zirconium solution. More ammonium hydroxide was added to the

mixture to deflocculate the suspension. The slurry was stirred and heated to 85°C until dry. The solid was then calcined at 900°C for 4 hours and subsequently crushed and vibratory milled in isopropanol for 14 hours with zirconia media.

Mixed powders for Examples 19-28 were pressed into 7.6 cm long bars at 70 Mpa. Samples were set on zirconia sand in covered alumina boxes and fired at about 30 °C/hr to 350 °C, then heated at rate ranging from 25 °C/hr to 200 °C/hr to 1150°C and held at that temperature for 4 hours. After 4 hours, the alumina boxes were removed from the furnace and the samples immediately taken from the boxes and transferred to a zirconia sand-covered alumina pallet which was at room temperature. The rapid cooling of the samples prevented the decomposition of the metastable ZrW_2O_8 phase into $\text{ZrO}_2 + \text{WO}_3$ below about 1140 °C.

After firing, samples were inspected for appearance and, in some cases, further characterized for porosity, phase assemblage, and CTE. Properties of fired samples are reported in Table 3.

Table 3

Experimental data for $\text{Zr}_2\text{P}_2\text{WO}_{12}$ ceramics with various amounts of ZrW_2O_8 .

Example Number	Appearance	Bulk Density (g/cm ³)	Theoretical Density	% Total Porosity	Mean Coefficient of Thermal Expansion (10 ⁻⁶ °C ⁻¹) -40 to +85°C	
19	no cracks	2.47	3.90	36.7	-40	
20	no cracks				-61	*
21	no cracks	3.24	4.43	26.8	-66	*
22	no cracks				-72	
23	no cracks	3.12	4.63	32.5	-72	
24	no cracks					
25	no cracks	3.66	4.74	22.7	-76	
26	no cracks	4.03	4.94	18.4	-83	
27	no cracks	4.27	5.01	14.7	-85	
28	no cracks	4.43	5.08	12.8	-90	
29	no cracks	4.42	4.63	4.6	-71	*
30	no cracks	4.06	4.63	12.3	-73	*
31	no cracks	3.97	4.63	14.3	-80	
32	no cracks	3.52	4.63	24.0	-79	
33	scattered cracks	4.07	4.63	12.1		
34	no cracks	4.35	4.63	6.0		
35	no cracks	3.81	4.63	17.8		
36	no cracks	3.16	4.63	31.8		
37	extremely cracked	4.38	4.63	5.4		
38	highly cracked					
39	no cracks	3.81	4.63	17.7		
40	extremely cracked	4.49	4.63	3.1		
41	extremely cracked					
42	no cracks	4.30	4.63	7.1		
43	very few cracks	4.54	4.63	2.0	-70	
44	scattered cracks					
45	no cracks	4.45	4.63	3.9	-72	
46	slumped	4.35	4.63	6.1		
47	extremely cracked	4.56	4.63	1.5		
48	scattered cracks					
49	no cracks	4.51	4.63	2.6		
50	no cracks	4.46	4.63	3.7		
51	scattered cracks	4.58	4.63	1.1		
52	no cracks	4.20	4.63	9.4		
53	open cracks	4.43	4.63	4.4		
54	crazed					
55	extremely cracked	4.55	4.63	1.8		
56	no cracks				-71	*
57	no cracks	4.51	4.63	2.6	-70	
58	open cracks	4.47	4.63	3.5		
59	open cracks					
60	highly cracked	4.54	4.63	2.0		
61	highly cracked					
62	no cracks	4.15	4.63	10.4		

* mean CTE from -40° to +40°C

Table 3 (continued)

Experimental data for $\text{Zr}_2\text{P}_2\text{WO}_{12}$ ceramics with various amounts of ZrW_2O_8 .

Example Number	Appearance	Bulk Density (g/cm^3)	Theoretical Density (g/cm^3)	% Total Porosity	Mean Coefficient of Thermal Expansion (10^{-7}C^{-1}) -40 to +85°C
63	open cracks	4.46	4.63	3.7	
64	open cracks				
65	no cracks	4.51	4.63	2.6	-75
66	moderately cracked				
67	no cracks	4.38	4.63	5.4	-77
68	no cracks				-67
69	no cracks				-70
70	no cracks	4.27	4.63	7.8	-66
71	no cracks	3.79	4.63	18.1	-68
72	no cracks	4.44	4.63	4.1	-68
73	no cracks				-69
74	no cracks				-68
75	no cracks				-70
76	no cracks				-74
77	no cracks				-79
78	no cracks	4.79	4.96	3.6	-84
79	scattered cracks	4.51	4.63	2.6	
80	very few cracks	4.52	4.63	2.3	
81	no cracks	3.01	4.63	35.0	
82	no cracks	4.52	4.63	2.4	
83	no cracks	3.22	4.63	30.4	
84	very few cracks	4.51	4.63	2.7	
85	no cracks	3.14	4.63	32.3	
86	no cracks	3.19	4.63	31.1	
87	no cracks	3.32	4.63	28.3	
88	extremely cracked	4.54	4.63	2.0	

* mean CTE from -40° to +40°C

With increasing addition of ZrW_2O_8 to $\text{Zr}_2\text{P}_2\text{WO}_{12}$, the amount of porosity in the ceramic body decreases, and the thermal expansion becomes progressively more negative, reaching $-90 \times 10^{-7} \text{C}^{-1}$ for 100% ZrW_2O_8 as shown in Figure 1. For the preferred range of CTE between -70 and $-85 \times 10^{-7} \text{C}^{-1}$ desired for athermalization of fiber Bragg gratings, the amount of $\text{Zr}_2\text{P}_2\text{WO}_{12}$ is between about 5% and 40%, and the amount of ZrW_2O_8 is between about 60% and 95%. For the preferred range of CTE between -65 and $-80 \times 10^{-7} \text{C}^{-1}$ desired for athermalization of fiber Bragg gratings, the amount of $\text{Zr}_2\text{P}_2\text{WO}_{12}$ is between about 10% and 50%, and the amount of ZrW_2O_8 is between about 50% and 90%.

EXAMPLES 29 to 88

Powder preparation for Examples 29 to 88 was conducted in the same manner as Examples 1-18, with the proportions of the starting materials adjusted to yield $\text{Zr}_2\text{P}_2\text{WO}_{12}$ and ZrW_2O_8 in the ratios stated in Table 2, with the following exceptions: Example 68 was prepared using ZrO_2 , WO_3 , and a ZrP_2O_7 powder prepared by calcination of acid zirconium phosphate at 1050°C for 4 hours, and Examples 69 and 73-78 were prepared from ZrO_2 , WO_3 , and pre-reacted $\text{Zr}_2\text{P}_2\text{WO}_{12}$. The pre-reacted $\text{Zr}_2\text{P}_2\text{WO}_{12}$ was formed by dry ball milling a mixture of ZrO_2 , WO_3 and acid zirconium phosphate in the appropriate ratios and calcining the mixture at 1050°C for 4 hours. Also, the powders for Examples 72 to 78 were milled in water instead of isopropanol. Examples 29 to 88 were formulated to yield ceramics with coefficients of thermal expansion between -65 and $-85 \times 10^{-7}^\circ\text{C}^{-1}$.

In these examples, the weight percentages of $\text{Zr}_2\text{P}_2\text{WO}_{12}$ and ZrW_2O_8 are relative to the sum of the weights of the $\text{Zr}_2\text{P}_2\text{WO}_{12}$ and ZrW_2O_8 components only. Weight percent of additive is relative to total weight percent of starting material.

Example 29 shows that 0.25% aluminum monohydrate is an effective sintering aid in reducing the porosity of a 68% ZrW_2O_8 -32% $\text{Zr}_2\text{P}_2\text{WO}_{12}$ ceramic to 4.6%. The fired sample exhibited good integrity, with no cracking.

Example 30 shows that 0.25% addition of titania reduces porosity of a 68% ZrW_2O_8 -32% $\text{Zr}_2\text{P}_2\text{WO}_{12}$ ceramic to about 12% with no cracking.

Example 31 illustrates that 0.25% addition of niobium oxide reduces the porosity of a 68% ZrW_2O_8 -32% $\text{Zr}_2\text{P}_2\text{WO}_{12}$ ceramic to about 14% with no cracking.

Example 32 demonstrates that 0.25% silica addition is not effective as a sintering aid for 68% ZrW_2O_8 -32% $\text{Zr}_2\text{P}_2\text{WO}_{12}$ ceramics.

Example 33 shows that although 0.05% lithium carbonate (equivalent to 0.02% Li_2O) reduces porosity of a 68% ZrW_2O_8 -32% $\text{Zr}_2\text{P}_2\text{WO}_{12}$ ceramic, this amount of additive results in scattered cracks.

5 Example 34 illustrates that 0.10% sodium carbonate (equivalent to 0.06% Na_2O) reduces the porosity of the 68% ZrW_2O_8 -32% $\text{Zr}_2\text{P}_2\text{WO}_{12}$ composition to only 6%, without cracking. Example 35 shows that the amount of Na_2CO_3 can be reduced to 0.05% (0.03% Na_2O) and still reduce porosity
10 to 17.8%. However, Example 36 shows that 0.01% sodium carbonate (0.006% Na_2O) is not sufficient to reduce the porosity of this ceramic composition.

Example 37 illustrates that although 0.25% potassium carbonate (equivalent to 0.17% K_2O) is a very effective
15 sintering aid for the 68% ZrW_2O_8 -32% $\text{Zr}_2\text{P}_2\text{WO}_{12}$ composition, reducing porosity to 5.4%, the ceramic body exhibits extreme cracking after firing. Example 38 shows that slowing the heating rate to 25 °C/hour above 1100°C does not eliminate the cracking of this composition. Thus, the
20 amount of K_2O present in a 68% ZrW_2O_8 -32% $\text{Zr}_2\text{P}_2\text{WO}_{12}$ ceramic must be less than 0.17% to avoid cracking. Example 39 demonstrates that even 0.05% K_2CO_3 (0.034% K_2O) is effective as a densification aid for these ceramics.

Examples 40 and 41 demonstrate that addition of 0.25%
25 calcium carbonate (0.14% CaO) is also very effective in reducing porosity; however, samples are extremely cracked after firing. Thus, the amount of CaO in a 68% ZrW_2O_8 -32% $\text{Zr}_2\text{P}_2\text{WO}_{12}$ ceramic must be less than 0.14% to avoid cracking. Example 42 shows that even only 0.05% CaCO_3
30 (0.03% CaO) is sufficient to substantially reduce the porosity in these ceramics.

Examples 43 and 44 show that the addition of 0.25% barium carbonate (0.19% BaO) is effective in reducing porosity to 2.0%; however, the sintered body exhibits a
35 small amount of cracking. Example 45 shows that reduction

of the amount of barium carbonate to 0.1% (0.08% BaO) is still effective in lowering porosity to less than 4%, and results in a crack-free body. Thus, the amount of BaO should be less than about 0.19% to avoid cracking.

5 Example 46 demonstrates that the addition of 1.0% magnesium oxide, MgO, to the 68%ZrW₂O₈-32%Zr₂P₂WO₁₂ composition results in the formation of excessive liquid, so that the body underwent considerable slumping. Examples 47 and 48 show that reduction in the MgO
10 concentration to 0.25% yielded a cracked body that was otherwise well densified. Example 49 demonstrates that addition of only 0.05% MgO still yields a low-porosity body which is also free of cracks. Thus, the amount of MgO must be less than 0.25% to avoid cracking.

15 Examples 50 and 51 show that 1.0% or 0.25% cupric oxide, CuO, is effective in lowering porosity of the 68%ZrW₂O₈-32%Zr₂P₂WO₁₂ composition. However, XRD revealed considerable amounts of zirconium oxide and tungsten oxide in the fired body which are undesirable for strongly
20 negative CTE. However, 0.05% CuO addition (Example 52) still yields a low-porosity ceramic, while maintaining the ZrW₂O₈ and Zr₂P₂WO₁₂ phases with essentially no secondary zirconium or tungsten oxides. Thus, the amount of CuO
25 should be less than about 0.25% to prevent the formation of excessive amounts of ZrO₂ and WO₃ in the fired ceramic.

 Examples 53 and 54 illustrate that addition of 1.0% zinc oxide, ZnO, to the 68%ZrW₂O₈-32%Zr₂P₂WO₁₂ composition is effective in reducing porosity, but results in cracking of the body. Examples 55 and 56 show that reduction of
30 the amount of ZnO to 0.25% is still useful in densifying the ceramic, and can result in a crack-free body when the heating rate above 1100°C is less than 100 °C/hour. Further lowering of the amount of ZnO to 0.1% results in a dense, crack-free body even for heating rates of 100
35 °C/hour (Example 57).

Examples 58 and 59 demonstrate that 1.0% manganese carbonate (yielding 0.62% MnO) is effective in densifying 68%ZrW₂O₈-32%Zr₂P₂WO₁₂ ceramics, but produces cracking in the fired body. Examples 60 and 61 show that 0.25% MnCO₃ (0.15% MnO) still reduces porosity to low levels, but cracking is present. Example 62 shows that 0.05% MnCO₃ (0.03% MnO) is still effective as a sintering aid, and does not produce cracking. Thus, the amount of MnO in the %ZrW₂O₈-32%Zr₂P₂WO₁₂ ceramic must be less than about 0.15% to prevent crack formation during sintering.

Examples 63 and 64 illustrate that 1.0% ferric oxide, Fe₂O₃, is effective as a sintering aid for %ZrW₂O₈-32%Zr₂P₂WO₁₂ ceramics, but results in cracking. Example 65 shows that 0.25% Fe₂O₃ yields a low-porosity, uncracked body. Thus, the amount of Fe₂O₃ to be used as a sintering aid for the 68%ZrW₂O₈-32%Zr₂P₂WO₁₂ composition is preferably less than 1.0% to avoid cracking.

Example 66 shows that addition of 0.50% yttrium oxide, Y₂O₃, yields a cracked body of 68%ZrW₂O₈-32%Zr₂P₂WO₁₂ composition. Example 67 shows that reducing the yttria to 0.25% eliminates cracking and still reduces porosity to 5.4%. Example 68 demonstrates that the phosphorus can be supplied as ZrP₂O₇ powder. Example 69 shows that the phosphorus can be supplied as pre-reacted Zr₂P₂WO₁₂ powder. Example 70 illustrates that the amount of yttria can be reduced to 0.12% and still yield a 68%ZrW₂O₈-32%Zr₂P₂WO₁₂ ceramic with low porosity without cracking. Example 71 shows that reduction of the amount of yttria to only 0.05% results in an increase in porosity to 18.1% when the powders are milled in isopropanol. However, Example 72 demonstrates that 0.05% yttria is sufficient to serve as an effective densification aid when the powders are milled in water. Example 73 shows that phosphorus may be supplied as pre-reacted Zr₂P₂WO₁₂ powder to the raw material mixture.

Example 74 demonstrates that a ceramic comprised of 75% ZrW_2O_8 and 25% $\text{Zr}_2\text{P}_2\text{WO}_{12}$ with 0.05% yttria additive is uncracked and possesses a CTE of $-68 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$. Examples 75 and 76 show that this composition may be fired at 1175°C for 4 to 8 hours.

Example 77 shows that the amount of ZrW_2O_8 can be increased to 85 weight % with 0.05% yttria as a sintering aid to yield a crack-free sample with a CTE of $-79 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$.

Example 78 shows that the amount of ZrW_2O_8 can be further increased to 88 weight % with 0.05% yttria as a sintering aid to yield a crack-free, low-porosity ceramic with a CTE of $-84 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$. Example 78 also contains an addition of about 2 weight % excess tungsten oxide as a separate phase, in addition to the 10 weight % $\text{Zr}_2\text{P}_2\text{WO}_{12}$.

Examples 79 and 80 show that addition of 0.25% of the oxides of the rare earth metals lanthanum and cerium are very effective at reducing the porosity of 68% ZrW_2O_8 and 32% $\text{Zr}_2\text{P}_2\text{WO}_{12}$ bodies to less than 3%. Slight cracking of these compositions shows that the amount of La_2O_3 or CeO_2 additive is preferably less than 0.25%.

Example 81 demonstrates that the addition of 0.25% MoO_3 is not effective as a sintering aid for 68% ZrW_2O_8 and 32% $\text{Zr}_2\text{P}_2\text{WO}_{12}$ ceramics.

Example 82 illustrates that 0.25% bismuth oxide greatly lowers the porosity of 68% ZrW_2O_8 and 32% $\text{Zr}_2\text{P}_2\text{WO}_{12}$ bodies, and that no cracking is present.

Example 83 shows that addition of 0.25% B_2O_3 to a 68% ZrW_2O_8 and 32% $\text{Zr}_2\text{P}_2\text{WO}_{12}$ body does not significantly reduce porosity.

Example 84 demonstrates that 0.25% gallium oxide is highly effective in lowering the porosity of 68% ZrW_2O_8 and 32% $\text{Zr}_2\text{P}_2\text{WO}_{12}$ ceramics. However, amounts less than 0.25 weight % are preferred to avoid cracking.

Examples 85, 86, and 87 illustrate that 0.25% addition of the oxides of indium, or tin, or chromium is not greatly effective in reducing the porosity of 68% ZrW_2O_8 and 32% $\text{Zr}_2\text{P}_2\text{WO}_{12}$ bodies.

Example 88 shows that addition of 0.25% nickel oxide to the 68% ZrW_2O_8 and 32% $\text{Zr}_2\text{P}_2\text{WO}_{12}$ composition reduces porosity to very low levels; however, the amount of NiO is preferably less than 0.25% to prevent cracking of the ceramic.

COMPARATIVE EXAMPLES

Although the thermal expansion coefficient of zirconium tungstate is more strongly negative than that which is required for athermalization of a fiber Bragg grating, ceramic bodies having the desired thermal expansion can be prepared from mixtures of ZrW_2O_8 with one or more additional phases whose CTEs are either positive or less negative than that of zirconium tungstate. The amount of additional phases that would be required to yield a ceramic having a specific CTE can be estimated from the relation

$$\text{(Equation 1)} \quad \alpha_m = V_1\alpha_1 + V_2\alpha_2 + V_3\alpha_3 + \dots + V_n\alpha_n$$

in which α_m is the coefficient of thermal expansion of the mixture, α_1 is the CTE of component 1, chosen to be ZrW_2O_8 , α_2 is the CTE of component 2, etc. for n phases, and V_1, V_2, \dots, V_n are the volume fractions of components 1 (ZrW_2O_8), 2, etc. Equation 1 is only approximate, because it does not take into account the effect of the different elastic moduli of the various phases, or the possibility of microcracking.

The terms in Equation 1 refer to the actual volume fractions of the phases that are present in the fired

ceramic. For a given mixture of starting materials, one must understand the phase relations for that system at the temperature to which the body is fired. Addition of a metal oxide to the ZrW_2O_8 precursor (such as $\text{ZrO}_2 + \text{WO}_3$) does not ensure that the fired ceramic will consist only of ZrW_2O_8 plus that metal oxide. In many instances, the metal oxide additive will react with the zirconium tungstate to form two or more new phases. In order to achieve the desired CTE in the fired ceramic, it is necessary to know the phases that will form, the volume fractions of those phases, and their CTEs, so that the amount of metal oxide additive(s) can be judiciously selected.

In the comparative examples described below, oxide compounds having positive coefficients of thermal expansion were added to zirconium and tungsten oxides in amounts that nominally would yield ZrW_2O_8 -based ceramics having mean CTEs of about $-75 \times 10^{-7} \text{ }^\circ\text{C}^{-1}$ if the oxide additives remained unreacted during firing of the ceramic. The amount of metal oxide second phase that would be required to yield a ceramic having this CTE was computed from the relation

$$\text{(Equation 2)} \quad \alpha_m = -75 \times 10^{-7} \text{ }^\circ\text{C}^{-1} = V_{zw}\alpha_{zw} + V_{mo}\alpha_{mo}$$

in which α_m is the mean coefficient of thermal expansion of the mixture near 25°C , chosen to be $-75 \times 10^{-7} \text{ }^\circ\text{C}^{-1}$, α_{zw} is the mean CTE of ZrW_2O_8 near 25°C , which is about $-90 \times 10^{-7} \text{ }^\circ\text{C}^{-1}$, α_{mo} is the mean CTE of the metal oxide added as the oxide or added as its precursor, and V_{zw} and V_{mo} are the volume fractions of ZrW_2O_8 and metal oxide, respectively.

The compositions of the examples are provided in Table 4. Table 5 lists the appearances of the samples and their phase compositions after firing as determined by X-ray diffractometry. CTE was measured by dilatometry.

Table 4
Experimental data for ZrW₂O₈ ceramics with various amounts of second phase additives

Example Number	Weight % ZrW ₂ O ₈	Volume % ZrW ₂ O ₈	Additive	Weight % Additive	Volume % Additive as Oxide	Nominal CTE of Oxide (25-100°C)	Sample Geometry	Heating rate above 1100°C (°C/hr)	Soak Temperature (°C)	Soak Time (hours)
C1	90.4	88	Al ₂ O ₃	9.6	12	70	11.4 cm bar	100	1150	4
C2	90.4	88	Al ₂ O ₃	9.6	12	70	11.4 cm bar	450	1200	8
C3	93.5	91	MgO	6.5	9	120	11.4 cm bar	100	1150	4
C4	89.7	91	CaCO ₃	10.3	9	130	11.4 cm bar	100	1150	4
C5	88.1	88	Y ₂ O ₃	11.9	12	70	11.4 cm bar	100	1150	4
C6	88.1	88	Y ₂ O ₃	11.9	12	70	11.4 cm bar	450	1200	8
C7	86.3	88	ZrO ₂	13.7	12	70	11.4 cm bar	100	1150	4
C8	86.3	88	ZrO ₂	13.7	12	70	11.4 cm bar	450	1200	8
C9	90.8	81	Fused SiO ₂	9.2	19	5	11.4 cm bar	100	1150	4
C10	90.8	81	Fused SiO ₂	9.2	19	5	11.4 cm bar	450	1200	8
C11	95.1	91	Quartz SiO ₂	4.9	9	120	11.4 cm bar	100	1150	4
C12	95.1	91	Quartz SiO ₂	4.9	9	120	11.4 cm bar	450	1200	8
C13	85.0	83.6	ZrSiO ₄	15	16.4	40	7.6 cm bar	100	1175	8.5

Table 5
Experimental data for ZrW_2O_8 ceramics with various amounts of second phase additives

Example Number	Appearance	Crystalline Phases (Powder XRD)	Mean Coefficient of Thermal Expansion ($10^{-6}C^{-1}$) -40 to +85°C	CTE predicted by weighted average of starting oxides ($10^{-6}C^{-1}$)
C1	Sintered bar	$Al_2(WO_4)_3$, ZrO_2	+100	-75
C2	Severely slumped bar; severe sticking	$Al_2(WO_4)_3$, ZrO_2 , Al_2O_3	**	-75
C3	Slumped bar; severe sticking	$MgWO_4$, ZrO_2 , unidentified phase(s)	**	-76
C4	Severely slumped bar; severe sticking	$CaWO_4$, ZrO_2 , unidentified phase(s)	**	-75
C5	Concave surfaces; severe sticking	ZrO_2 , unidentified phase(s)	+101	-75
C6	Deformed, tapered bar; sticking	ZrO_2 , unidentified phase(s)		-75
C7	Chalky surface	ZrW_2O_8 , ZrO_2		-75
C8	Chalky surface	ZrW_2O_8 , ZrO_2	-68	-75
C9	Sintered bar, slightly chalky surface	$ZrSiO_4$, WO_3 , cristobalite, ZrO_2		-76
C10	Sintered bar, slightly chalky surface	$ZrSiO_4$, WO_3 , cristobalite	+64	-76
C11	Sintered bar, slightly chalky surface	ZrW_2O_8 , $ZrSiO_4$, WO_3 , cristobalite, ZrO_2		-76
C12	Sintered bar, hard surface	ZrW_2O_8 , $ZrSiO_4$, WO_3	-61	-76
C13	Sintered bar, hard surface	ZrW_2O_8 , $ZrSiO_4$, trace WO_3	-51	-69

**Too deformed for CTE measurement

Samples were prepared by vibratory milling the powders in water for 16 hours, adding a polyethylene glycol binder, drying the slurry, granulating the dried cake, and uniaxially pressing bars of 11.4 cm length, except for Example C13, which was pressed into a bar of 7.6 cm length. Bars were set on zirconium oxide "sand" in an alumina box and fired at 1150°C or 1175°C, or were set on zircon "sand" on an aluminosilicate pallet and fired at 1200°C (Table 4).

Examples C1 and C2 were prepared to yield a ceramic with a nominal composition of 88 volume% ZrW_2O_8 + 12 volume% (9.6 weight%) Al_2O_3 . However, the results in Table 5 demonstrate that ZrW_2O_8 is unstable when fired with alumina, and reacts to form $\text{Al}_2(\text{WO}_4)_3$ + ZrO_2 . This results in a positive CTE for this material of $+100 \times 10^{-7} \text{ }^\circ\text{C}^{-1}$. Thus, the concept of forming a ZrW_2O_8 + Al_2O_3 ceramic is untenable, because no such ceramic can be produced due to reaction of alumina with zirconium tungstate. However, it is contemplated that a ceramic article consisting of ZrW_2O_8 with small amounts of $\text{Al}_2(\text{WO}_4)_3$ could be fabricated by addition of aluminum and tungsten oxides to the ZrW_2O_8 precursor powders, and the amount of $\text{Al}_2(\text{WO}_4)_3$ in such a ceramic could be selected so as to yield a body with a CTE that is less negative than $-90 \times 10^{-7} \text{ }^\circ\text{C}^{-1}$. Also, it is contemplated that a body comprised of $\text{ZrW}_2\text{O}_8 + \text{Al}_2(\text{WO}_4)_3 + \text{ZrO}_2$ having a CTE less negative than $-90 \times 10^{-7} \text{ }^\circ\text{C}^{-1}$ could be prepared by adding only alumina, provided that the alumina addition is much less than 9.6 weight%.

Example C3 was prepared to yield a ceramic with a nominal composition of 91 volume% ZrW_2O_8 + 9 volume% (6.5 weight%) MgO . However, as seen in Table 5, this composition, even when fired at only 1150°C (just above the lower thermal stability limit of ZrW_2O_8), undergoes reaction between ZrW_2O_8 and MgO to form MgWO_4 + ZrO_2 +

unidentified phases. No ZrW_2O_8 remains in the body, and the remaining phases all have large positive CTEs, making this ceramic inappropriate for use as a substrate for a fiber Bragg grating. Furthermore, the ceramic body
5 underwent slumping and sticking to the zirconia sand due to extensive formation of liquid during firing. Thus, the formation of a $\text{ZrW}_2\text{O}_8 + \text{MgO}$ ceramic is not feasible, because no such ceramic can be produced. Instead, MgO reacts with ZrW_2O_8 to form phases other than MgO . Addition
10 of MgO to ZrW_2O_8 in amounts of more than a few weight percent is undesirable.

Example C4 was prepared to yield a ceramic with a nominal composition of 91 volume% $\text{ZrW}_2\text{O}_8 + 9$ volume% CaO , in which the CaO was provided as 10.3 weight% CaCO_3 .
15 However, as seen in Table 5, this composition, even when fired at only 1150 °C, undergoes reaction between ZrW_2O_8 and CaO to form $\text{CaWO}_4 + \text{ZrO}_2 +$ unidentified phases. No ZrW_2O_8 remains in the body, and the remaining phases all have large positive CTEs (the CTE of CaWO_4 is about
20 $100 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$), making this ceramic inappropriate for use as a substrate for a fiber Bragg grating. Furthermore, the ceramic body underwent severe slumping and sticking to the zirconia sand due to extensive formation of liquid during firing. Thus, the formation of a $\text{ZrW}_2\text{O}_8 + \text{CaO}$ ceramic is
25 not feasible, because no such ceramic can be produced. Instead, CaO reacts with ZrW_2O_8 to form phases other than CaO . Addition of CaO , or a CaO source such as CaCO_3 , to ZrW_2O_8 in amounts of more than a few weight percent is undesirable.

30 Examples C5 and C6 were formulated to yield a ceramic with a nominal composition of 88 volume% $\text{ZrW}_2\text{O}_8 + 12$ volume% (11.9 weight%) Y_2O_3 . However, Table 5 shows that, after firing, the ceramic contained no ZrW_2O_8 . Instead, reaction of the starting materials yielded ZrO_2 , and
35 several unidentified phases. The high CTE resulting from

this reaction, $+101 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$, demonstrates that the amount of yttria in a zirconium tungstate ceramic should be kept to less than a few percent.

5 Examples C7 and C8 were prepared to yield a ceramic
with a nominal composition of 88 volume% ZrW_2O_8 + 12
volume% (13.7 weight%) ZrO_2 . X-ray diffractometry of the
fired samples (Table 5) shows that these two phases do, in
fact, coexist. The fired bar possessed a very powdery
surface after firing, which was found to consist almost
10 entirely of zirconium oxide. Such a surface would be
unsuitable for direct attachment of a fiber grating, and
would require machining to expose the low-porosity
interior of the sample. The CTE of the sample, after
removal of the surface layer, was measured to be -68×10^{-7}
15 $^\circ\text{C}^{-1}$, only slightly less negative than the predicted value
of $-75 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$. The dimensional stability of a similar
ceramic of ZrW_2O_8 with 15 weight% ZrO_2 was determined by
monitoring the lengths of two sintered bars as a function
of time in an 85 $^\circ\text{C}$, 85% relative humidity environment.
20 The dimensional changes of these bars is provided in Table
6 (examples D4 and D5) and depicted in Figure 2.

Table 6

Change in length expressed as $\Delta L/L$, in parts per million,
of ceramic bars exposed to 85°C, 85% relative humidity, for indicated durations.

Example D1		Example D2		Example D3		Example D4	Example D5
68% ZrW ₂ O ₈ 32% Zr ₂ P ₂ WO ₁₂		68% ZrW ₂ O ₈ 32% Zr ₂ P ₂ WO ₁₂		68% ZrW ₂ O ₈ 32% Zr ₂ P ₂ WO ₁₂		85% ZrW ₂ O ₈ 15% ZrO ₂	85% ZrW ₂ O ₈ 15% ZrO ₂
Time (hours)	0.25% Y ₂ O ₃	0.25% Y ₂ O ₃	Time (hours)	0.10% BaCO ₃	Time (hours)		
0	0	0	0	0	0	0	0
160	-15	-5	178	-13	162	-222	-191
322	0	10	338	-15	301	-476	-458
482	-13	-2	498	-10	462	-1044	-1123
642	-10	7	658	-13	623	-2279	-2800
802	-10	7	800	-13	783	-4376	-5441

The severe shrinkage of these ceramics over a relatively short span of time renders them inappropriate for use as a fiber grating substrate. For comparison, bars of the inventive compositions 68%ZrW₂O₈ +32% Zr₂P₂WO₁₂ + 0.25% Y₂O₃ (Examples D1 and D2) and the inventive composition 68%ZrW₂O₈ +32% Zr₂P₂WO₁₂ + 0.10% BaCO₃ (Example D3) undergo negligible dimensional change with time under the same conditions of temperature and humidity.

Examples C9 and C10 were prepared to yield a ceramic with a nominal composition of 81 volume% ZrW₂O₈ + 19 volume% (9.2 weight%) SiO₂ in which the SiO₂ is added as fused silica. Table 5 shows that this combination results in reaction of the ZrW₂O₈ with SiO₂ to form zircon (ZrSiO₄) + tungsten oxide, which have CTEs at 25°C of about 40x10⁻⁷°C⁻¹ and 160x10⁻⁷°C⁻¹, respectively. Consequently, the CTE of this ceramic body is highly positive, 64x10⁻⁷°C⁻¹. The presence of a small amount of cristobalite, a crystalline form of silica, indicates that the reaction did not proceed to completion during the time allowed. Thus, the formation of a ZrW₂O₈ + fused SiO₂ ceramic is not possible, because no such ceramic can be produced due to reaction of silica with the ZrW₂O₈.

Examples C11 and C12 were formulated to yield a ceramic having a nominal composition of 91 volume% ZrW₂O₈ + 9 volume% (4.9 weight%) SiO₂ in which the SiO₂ is added as quartz, a crystalline form of silica. Less volume percent of this form of silica was added than for the case where the SiO₂ was added as fused silica because quartz has a much higher thermal expansion than fused silica, so less is required to compensate the CTE of the mixture by Equation 2. As seen in Table 5, the quartz also reacts with ZrW₂O₈ to form zircon and tungsten oxide, although in these two examples the lower amount of silica allows for some ZrW₂O₈ to remain in the body after firing. However,

the CTE of this mixed phase ceramic is only $-61 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$, less negative than desired, and less negative than predicted from Equation 2 because of the reaction of silica with ZrW_2O_8 .

5 Example C13 was formulated to yield a ceramic consisting of 85 weight% (83.6 volume%) ZrW_2O_8 + 15 weight% (16.5 volume%) ZrSiO_4 , in which the silicate was added as a very fine zircon powder. After firing, the ceramic consisted of ZrW_2O_8 + ZrSiO_4 , with only trace amounts of
10 residual ZrO_2 and WO_3 . The nominal CTE predicted for this composition is $-69 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$; however, the measured expansion from -40° to $+40^\circ\text{C}$ was $-51 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$. Furthermore, the dilatometric CTE curve exhibited a hysteresis upon heating to $+90^\circ\text{C}$ and cooling back to 20°C , with an increase in
15 sample length corresponding to a $\Delta\text{L}/\text{L}$ of over 400 parts per million. Examination of the sample by scanning electron microscopy showed that the sample had pervasive microcracking throughout the ZrW_2O_8 matrix. The dimensional instability of the sample with thermal cycling
20 above room temperature renders this composition inappropriate for application as a fiber grating substrate.

The materials and methods of the present invention can be utilized for a variety of applications requiring
25 negative thermal expansion materials, such as providing temperature compensation for optical devices such as gratings. The materials of the present invention could be used to make support members for such devices.

For example, referring to Figure 3, there is
30 illustrated a first exemplary embodiment of the invention. The optical fiber reflective grating device 20 has a substrate 22 formed from a flat block of a negative expansion material, such as the materials of the present invention. An optical fiber 24 having at least one

UV-induced reflective grating 26 written therein is mounted on the surface 28 and attached at either end of the surface at points 30 and 32. It is important that the fiber is straight and not subject to compression as a result of the negative expansion and thus the fiber is usually mounted under tension. Before attachment the fiber is placed under a controlled tension, as shown schematically by the use of a weight 34. The proper choice of tension assures that the fiber is not under compression at all anticipated use temperatures. However, the fiber can be under tension at all anticipated use temperatures. The required degree of tension to compensate for the negative expansion in a particular application can readily be calculated by those with skill in this art.

The attachment material could be an organic polymer, for example an epoxy cement, an inorganic frit, for example ground glass, ceramic or glass-ceramic material, or a metal. In one embodiment the fiber is tacked to the substrate with a UV-cured epoxy adhesive. Mechanical means for attaching the fiber can also be used.

Generally the optical fiber reflective grating is supplied with a coating material surrounding the fiber. In the preferred packaging approach the coating in the grating region of the fiber is left intact while it is removed in the substrate attachment region at each end of the grating. However, the device can have the coating completely removed between the attachment locations. Removal of the coating can be accomplished by one of two methods : a non-contact, non-chemical stripping mechanism or by conventional chemical stripping.

In another embodiment shown in Figure 4, the fiber is not attached directly to the substrate. Bonding pads 40, 42 made from a material differing from the substrate, for example a glass or a ceramic, are attached to the substrate at either end. The fiber 26 is mounted to the

5 pads at points 44, 46. These pads afford better attachment properties of the pad to the fiber than could be achieved from the substrate directly to the fiber because of the large thermal expansion mismatch. Suitable pad materials have a coefficient of thermal expansion intermediate between that of the fiber and the substrate, for example, between -50 and $+5 \times 10^{-7}$, preferably about -20×10^{-7} . Alternatively the pad could be a fused silica with a coefficient of expansion closely matching that of the fiber. The pad allows the stress of this joint induced by both the thermal mismatch and the tension of the fiber, to be spread out over a wider area, lessening the chances of cracking and detachment. The attachment materials for the fiber and pad connections are similar to those used for mounting the fiber directly to the substrate, for example, an epoxy cement, an inorganic frit, for example ground glass, ceramic or glass-ceramic material, or a metal.

20 In another embodiment shown in Figure 5, the negative expansion of the substrate material 22 is used to create a clamping force on the fiber. The attachment feature, which might be a hole or channel 50, 52 in a raised portion 54, 56 of the substrate, is formed in the substrate at room temperature with a gap that is very slightly smaller than the fiber. Referring to Figure 6, by lowering the temperature to a point lower than any anticipated use temperature, the substrate expands and allows the insertion of the fiber 24 into the channel 50. Warming of the substrate then causes substrate contraction and creates a clamping force for holding the fiber in the channel.

30 In another embodiment, Figure 7, the fiber 24 is attached to the substrate at points 30, 32 and the intermediate fiber length 60 is cushioned by a low modulus damping material 62. This low-modulus material, for example a silicone rubber coating surrounding the fiber or

a pad of a silicone rubber, a natural or synthetic rubber or mixtures thereof, between the fiber and the substrate protects the fiber reflective grating against external perturbations such as mechanical shock or vibration.

5 Bowing of the fiber is also minimized. In one embodiment the low modulus material is adhesively attached to the fiber and the substrate.

Mounting the fiber under tension will alter the optical properties of the device (for example, the center
10 wavelength of a grating). This can be addressed by biasing the device with a reflective grating written therein to account for the tension, or it can be done by mounting a fiber, for example a germania doped silica fiber, without a reflective grating written therein under tension and
15 then exposing the fiber to UV light in order to fabricate the grating in the device *in situ*.

In a typical embodiment of the invention, the temperature sensitivity of the center wavelength is about 0.0125 nm/°C for the uncompensated grating, the stress
20 sensitivity of the center wavelength is 0.125 nm shift for 9g of tension, the bare fiber has a diameter of 125 microns, a coated fiber has a diameter of 250 microns. The strength of the fiber is greater than 200 kpsi, and therefore has a very high reliability.

25 Although this invention has been described for UV photo induced gratings it can also be applied to the packaging of other thermally sensitive devices. For instance, optical fiber couplers and optical waveguides could be athermalized by attachment to a negative
30 expansion substrate.

An optical fiber fused coupler has two or more fibers fused together at one or more points along their length and is mounted on a substrate. Such couplers are thermally sensitive which results in a certain amount of thermal
35 instability. Especially sensitive are biconically tapered

couplers in which interferometric effects are used, for example a Mach-Zehnder interferometer. Such couplers can be athermalized by mounting the coupler to a negative expansion substrate. Figure 8 illustrates a fused biconical coupler device 70 which includes a negative expansion substrate 72 to which are mounted two fibers 74, 76. The fibers are fused together at regions 78, 80. The fibers are attached to the substrate near the ends at locations 82, 84 in the same manner as described above for the optical fiber reflective grating.

Waveguides can be defined, for example, in optical fibers or planar substrates. Such waveguides are thermally sensitive which results in a certain amount of thermal instability. Such waveguides can be athermalized by mounting the waveguide to a negative expansion substrate. Figure 9 illustrates a planar waveguide device 90 which includes a negative expansion substrate 92 on which is adhesively mounted a layer of material 94 in which a planar waveguide 96 is fabricated by methods well known to those skilled in this art. The waveguide material can be, for example, a doped silica such as a germania silicate, other suitable glass compositions, polymers and semiconductors, including semiconductors with gain, such as laser diodes.

A fiber Bragg grating device with greatly reduced temperature dependence was fabricated by attaching a fiber Bragg grating under tension to a substrate of Example 78 of Tables 2 and 3 using a tin zinc phosphate glass frit containing 45 weight % of a magnesium cobalt pyrophosphate filler. FIG. 10 shows the beneficial athermalization properties of the invention with the center wavelength of this fiber Bragg grating device plotted against temperature of the device. At -5°C the center wavelength of the grating was 1531.353 nm, and at 75°C the center

wavelength was 1531.277 nm. Thus, over this range in temperature, the device exhibited a variation in wavelength versus temperature of $-0.00095 \text{ nm/}^{\circ}\text{C}$, compared with $+0.012 \text{ nm/}^{\circ}\text{C}$ for an unattached grating. In a preferred embodiment, the device includes a negative expansion substrate having a composition comprising two phases having negative coefficients of thermal expansion, one of the phases having a room temperature coefficient of thermal expansion more negative than $-50 \times 10^{-7} \text{ }^{\circ}\text{C}^{-1}$ and a fiber Bragg grating affixed to the substrate, wherein the absolute value of the average temperature dependence of the Bragg wavelength between 0°C and 70°C is not more than about $0.0025 \text{ nm/}^{\circ}\text{C}$. In a further embodiment, the device includes a negative expansion substrate having a composition comprising two phases having negative coefficients of thermal expansion, one of the phases having a room temperature coefficient of thermal expansion more negative than $-50 \times 10^{-7} \text{ }^{\circ}\text{C}^{-1}$ and a fiber Bragg grating affixed to the substrate, wherein the absolute value of the average temperature dependence of the Bragg wavelength between 0°C and 70°C is not more than about $0.001 \text{ nm/}^{\circ}\text{C}$.

It will be understood that while the exemplary device embodiments included flat substrates, this invention is not limited to a particularly shaped substrate. For example, it is contemplated that the ceramic bodies of the present invention could be utilized to make tubular and cylindrical substrates, or substrates that contain a V-shaped, U-shaped, or rectangular trough or groove.

The device of this invention is a completely passive system and mechanically simple, and demonstrates athermalization. The method of producing the device is advantageous because it provides temperature compensated optical devices which tolerate shock and vibration and are thermally stable.

It will be apparent to those skilled in the art that various modifications and variations can be made in the of the present invention without departing from the spirit or scope of the invention. Thus, it is intended that the
5 present invention cover the modifications and variations of this invention provided they come within the scope of the appended claims and their equivalents.

CLAIMS

What is claimed is:

1. A ceramic body comprising $A_2P_2WO_{12}$, and a crystalline
5 or non-crystalline oxide phase, including a glassy phase,
which contains a metal selected from the group consisting
of alkaline earth metals, alkali metals, manganese, iron,
cobalt, copper, zinc, aluminum, gallium, and bismuth,
wherein A is selected from the group consisting of Zr and
10 Hf.
2. The ceramic body of claim 1, wherein the $A_2P_2WO_{12}$ is
present in amount greater than about 95 weight percent and
the body has a porosity less than about 5%.
- 15 3. The ceramic body of claim 1, further comprising AW_2O_8 ,
and wherein the metal of the oxide phase further may be
selected from the group yttrium, lanthanide metals,
scandium, niobium, titanium, and nickel.
- 20 4. The ceramic body of claim 3, wherein, on a weight
percent basis, the AW_2O_8 is present in an amount ranging
from about 1% to 95%, the $A_2P_2WO_{12}$ is present in amount of
about 5% to 99%, and the metal oxide is present in amount
25 of about 0.01% to 7%.
5. The ceramic body of claim 3, wherein, on a weight
percent basis, the AW_2O_8 is present in an amount ranging
from about 50% to 90%, the AP_2WO_{12} is present in amount of
30 about 10% to 50%, and the metal oxide is present in amount
of about 0.01% to 3%.
6. The ceramic body of claim 3, wherein, on a weight
percent basis, the AW_2O_8 is present in an amount ranging
35 from about 65% to 90%, the $A_2P_2WO_{12}$ is present in amount of

about 10% to 35%, and the metal oxide is present in amount of about 0.01% to 1%.

5 7. The ceramic body of claim 6, wherein the AW_2O_8 is present in an amount ranging from about 80% to 88%, the $A_2P_2WO_{12}$ is present in an amount of about 12% to 20%, and the metal oxide is present in an amount of about 0.01% to 0.50%.

10 8. The ceramic body of claim 6, wherein the ceramic body has a tungsten oxide phase amount less than about 4 weight % and a zirconium oxide phase amount less than about 5 weight %.

15 9. The ceramic body of claim 7, wherein the ceramic body has a tungsten oxide phase amount less than about 3 weight % and a zirconium oxide phase amount less than about 4 weight %.

20 10. The ceramic body of claim 4, wherein the body has a total porosity of less than about 10%.

25 11. The ceramic body of claim 4, wherein the body has a total porosity less than about 5%.

12. The ceramic body of claim 4, wherein the body has a coefficient of thermal expansion over a temperature range of about -50°C to about 100°C in the range of about $-50 \times 10^{-7}^{\circ}\text{C}^{-1}$ to about $-88 \times 10^{-7}^{\circ}\text{C}^{-1}$.

30 13. The ceramic body of claim 4, wherein the body exhibits a length change having an absolute value less than 150 ppm over 700 hours at 85°C and 85% relative humidity.

14. The ceramic body of claim 4, wherein the body exhibits a length change having an absolute value less than 35 ppm over 700 hours at 85°C and 85% relative humidity.

15. The ceramic body of claim 4, wherein the body exhibits a length change having an absolute value less than 20 ppm over 700 hours at 85°C and 85% relative humidity.

16. A ceramic body comprising two phases having negative coefficients of thermal expansion, wherein one of the phases has a room temperature coefficient of thermal expansion more negative than $-50 \times 10^{-7} \text{°C}^{-1}$.

17. The ceramic body of claim 16, wherein the body does not exhibit microcracking.

18. The ceramic body of claim 16, wherein one phase has the composition $M_2B_3O_{12}$ where M is selected from the group including aluminum, scandium, indium, yttrium, the lanthanide metals, zirconium, and hafnium, and where B is selected from the group consisting of tungsten, molybdenum, and phosphorus, and where M and B are selected such that the compound $M_2B_3O_{12}$ has a negative CTE, and comprising a second phase of the composition AX_2O_8 , where A is selected from the group consisting of zirconium and hafnium, and X is selected from the group consisting of tungsten and molybdenum.

19. The ceramic body of claim 17, wherein the first phase is $A_2P_2WO_{12}$ and the second phase is AW_2O_8 , wherein A is selected from the group consisting of Zr and Hf, and

wherein the body exhibits a length change having an absolute value less than 150 ppm over 700 hours at 85°C and 85% relative humidity.

5 20. The ceramic body of claim 17, wherein the first phase is $A_2P_2WO_{12}$ and the second phase is AW_2O_8 , wherein A is selected from the group consisting of Zr and Hf, and wherein the body exhibits a length change having an absolute value less than 35 ppm over 700 hours at 85°C and
10 85% relative humidity.

21. The ceramic body of claim 17, wherein the first phase is $A_2P_2WO_{12}$ and the second phase is AW_2O_8 , wherein A is selected from the group consisting of Zr and Hf, and
15 wherein the body exhibits a length change having an absolute value less than 20 ppm over 700 hours at 85°C and 85% relative humidity.

22. A method of making a ceramic body having a porosity
20 less than 10% comprising:

 mixing together powders of $A_2P_2WO_{12}$ or precursor
 powders of $A_2P_2WO_{12}$, and at least one oxide or oxide
 precursor of metals selected from the group consisting of
 alkaline earth metals, alkali metals, manganese, iron,
25 cobalt, copper, zinc, aluminum, gallium, and bismuth
 wherein A is selected from the group consisting of Zr and
 Hf;

 consolidating the powders together using a ceramic
 forming method; and

30 heating the consolidated powders at a temperature of
 about 1050°C to 1300°C for about 1 minute to 10 hours.

23. The method of claim 22, wherein the mixing step further comprises mixing together powders of AW_2O_8 or

precursor powders of AW_2O_8 , and wherein the metal of the oxide phase further may be selected from the group yttrium, lanthanide metals, scandium, niobium, titanium, and nickel.

5

24. The method of claim 22, wherein the metal oxide or metal oxide precursor is present in an amount of less than 2 weight percent.

10

25. The method of claim 23, wherein the metal oxide or metal oxide precursor is present in an amount of less than 2 weight percent.

15

26. The method of claim 23, wherein the powder of AW_2O_8 or precursor powder of AW_2O_8 is present in amount ranging from about 50 weight percent and 95 weight percent and the powder of AP_2WO_{12} or precursor powder of AP_2WO_{12} is present in an amount of about 5 weight percent to 50 weight percent.

20

27. The method of claim 23, wherein the heating step is performed at a temperature of about 1150°C to 1220°C for about 1 minute to 10 hours.

25

28. A method of raising the negative thermal expansion (i.e. making the thermal expansion less negative) of a ceramic body comprising a phase having a room temperature coefficient of thermal expansion more negative than $-50 \times 10^{-7}^{\circ}\text{C}^{-1}$ comprising mixing together the first phase with at least a second phase or precursors of the first phase and at least the second phase, the second phase having a negative thermal expansion less negative than $-50 \times 10^{-7}^{\circ}\text{C}^{-1}$.

30

29. The method of claim 28, wherein the material does not exhibit microcracking.

30. The method of claim 28, wherein one phase has the composition AX_2O_8 , where A is selected from the group consisting of zirconium and hafnium, and X is selected from the group consisting of tungsten and molybdenum, and wherein the second phase has the composition $M_2B_3O_{12}$ where M is selected from the group including aluminum, scandium, indium, yttrium, the lanthanide metals, zirconium, and hafnium, and where B is selected from the group consisting of tungsten, molybdenum, and phosphorus, and where M and B are selected such that the compound $M_2B_3O_{12}$ has a negative CTE.

15

31. An optical device comprising:

a negative expansion substrate having a composition comprising two phases having negative coefficients of thermal expansion, one of the phases having a room temperature coefficient of thermal expansion more negative than $-50 \times 10^{-7} ^\circ C^{-1}$; and

a thermally sensitive, positive expansion optical component affixed to the substrate.

32. The optical device of claim 31, wherein one phase has the composition $M_2B_3O_{12}$ where M is selected from the group including aluminum, scandium, indium, yttrium, the lanthanide metals, zirconium, and hafnium, and where B is selected from the group consisting of tungsten, molybdenum, and phosphorus, and where M and B are selected such that the compound $M_2B_3O_{12}$ has a negative CTE, and wherein the second phase has the composition AX_2O_8 , where A is selected from the group consisting of zirconium and hafnium, and X is selected from the group consisting of tungsten and molybdenum.

33. The optical device of claim 31, wherein the first material is AW_2O_8 and the second material is $A_2P_2WO_{12}$, wherein A is selected from the group consisting of Zr and Hf.

34. The optical device of claim 33, wherein the substrate does not exhibit microcracking.

35. The optical device of claim 33, wherein the substrate further includes a crystalline or non-crystalline oxide phase, including a glassy phase, which contains a metal selected from the group consisting of alkaline earth metals, alkali metals, manganese, iron, cobalt, copper, zinc, aluminum, gallium, bismuth, yttrium, lanthanide metals, scandium, niobium, titanium and nickel.

36. The optical device of claim 34, wherein, on a weight percent basis, the AW_2O_8 is present in an amount ranging from about 50% to 95%, $A_2P_2WO_{12}$ is present in amount of about 5% to 50%.

37. The optical device of claim 31, wherein the optical component is a an optical fiber grating.

38. The optical device of claim 34, wherein the substrate has a mean linear coefficient of thermal expansion of about $-40 \times 10^{-7} ^\circ C^{-1}$ to $-88 \times 10^{-7} ^\circ C^{-1}$ over a temperature range of about $-40^\circ C$ to $85^\circ C$.

39. The optical device of claim 33, wherein the device is not hermetically sealed.

40. An optical device comprising:

a negative expansion substrate having a composition comprising two phases having negative coefficients of thermal expansion, one of the phases having a room temperature coefficient of thermal expansion more negative than $-50 \times 10^{-7} \text{ } ^\circ\text{C}^{-1}$; and

a fiber Bragg grating having a Bragg wavelength affixed to the substrate, wherein the absolute value of the average temperature dependence of the Bragg wavelength between 0°C and 70°C is not more than about $0.0025 \text{ nm}/^\circ\text{C}$.

41. The optical device of claim 40, wherein one phase has the composition $\text{M}_2\text{B}_3\text{O}_{12}$ where M is selected from the group including aluminum, scandium, indium, yttrium, the lanthanide metals, zirconium, and hafnium, and where B is selected from the group consisting of tungsten, molybdenum, and phosphorus, and where M and B are selected such that the compound $\text{M}_2\text{B}_3\text{O}_{12}$ has a negative CTE, and wherein the second phase has the composition AX_2O_8 , where A is selected from the group consisting of zirconium and hafnium, and X is selected from the group consisting of tungsten and molybdenum.

42. The optical device of claim 40, wherein the first material is AW_2O_8 and the second material is $\text{A}_2\text{P}_2\text{WO}_{12}$, wherein A is selected from the group consisting of Zr and Hf.

43. The optical device of claim 42, wherein the substrate does not exhibit microcracking.

FIG.1

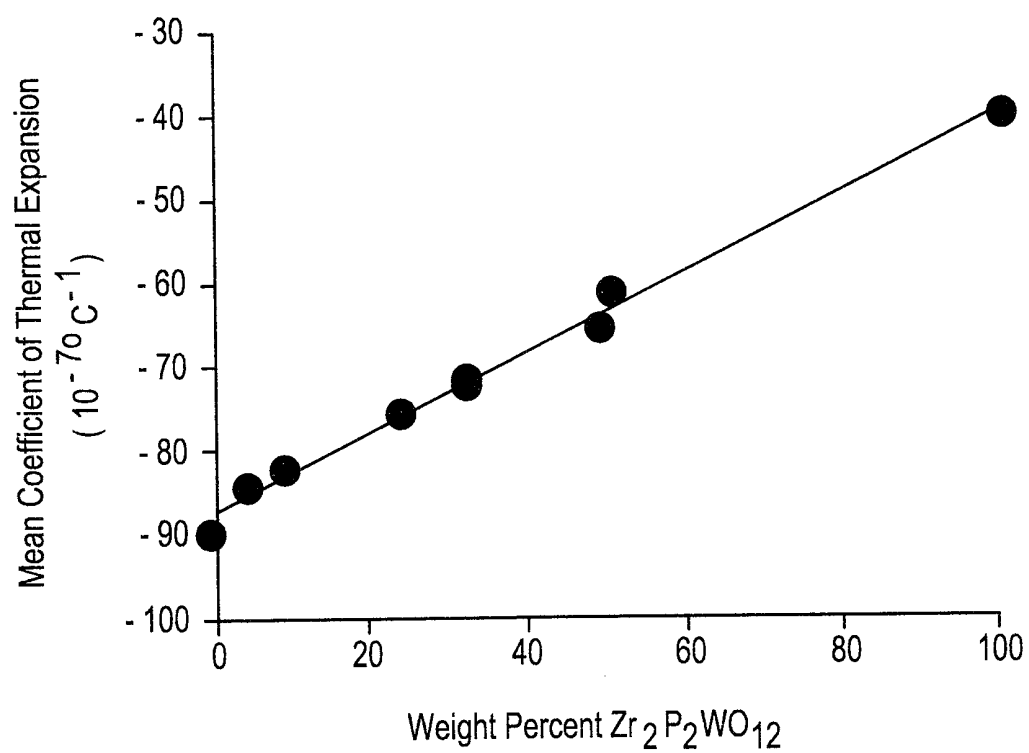


FIG.2

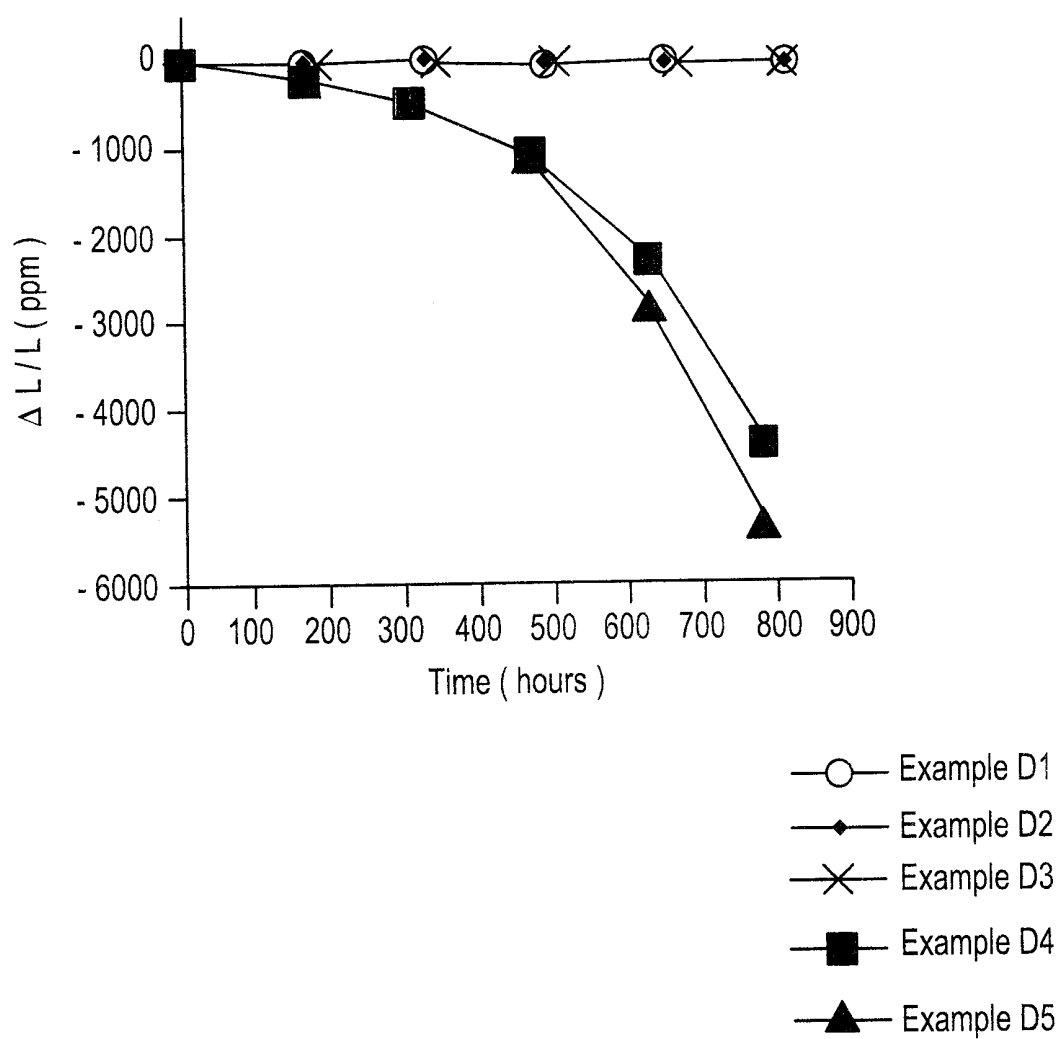


FIG. 3

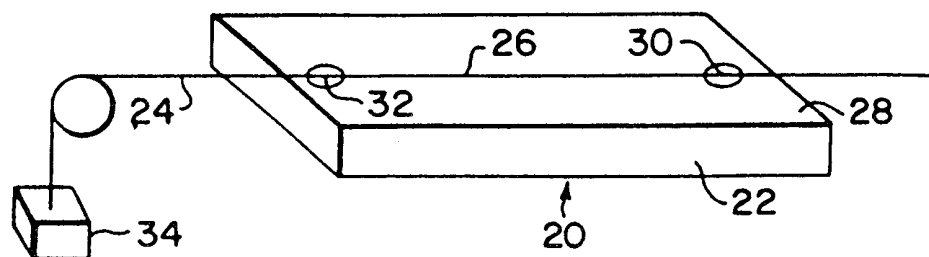


FIG. 4

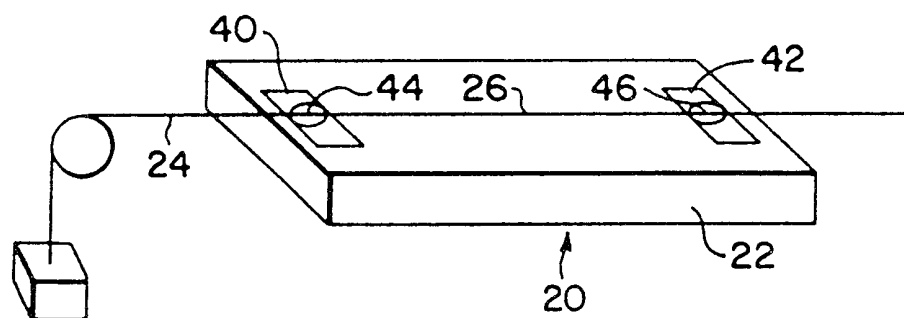


FIG. 5

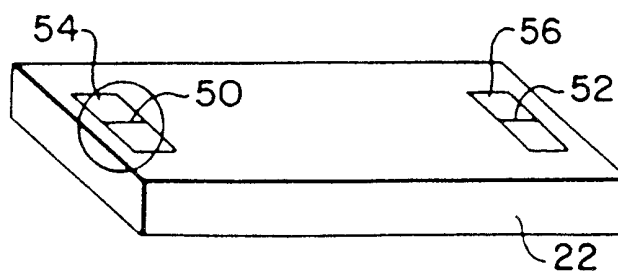


FIG. 6

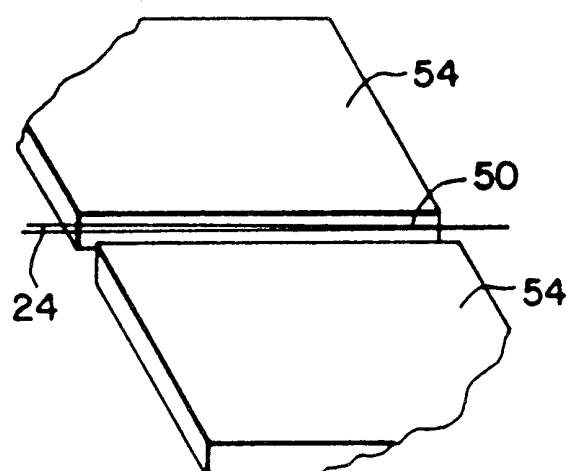


FIG. 7

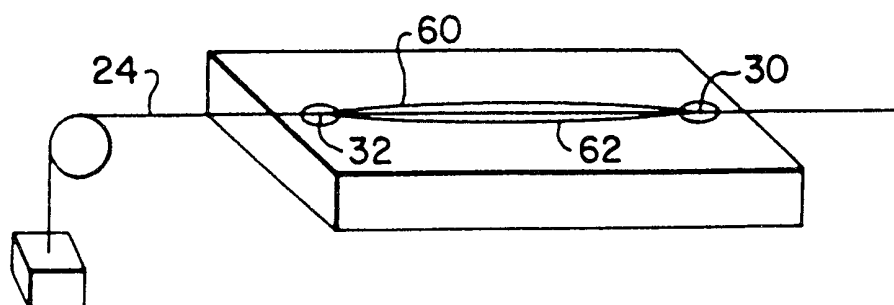


FIG. 8

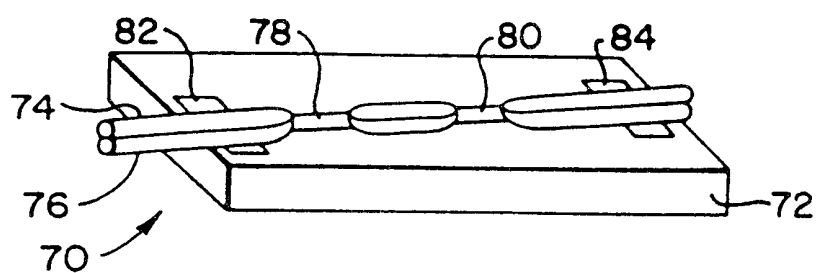


FIG. 9

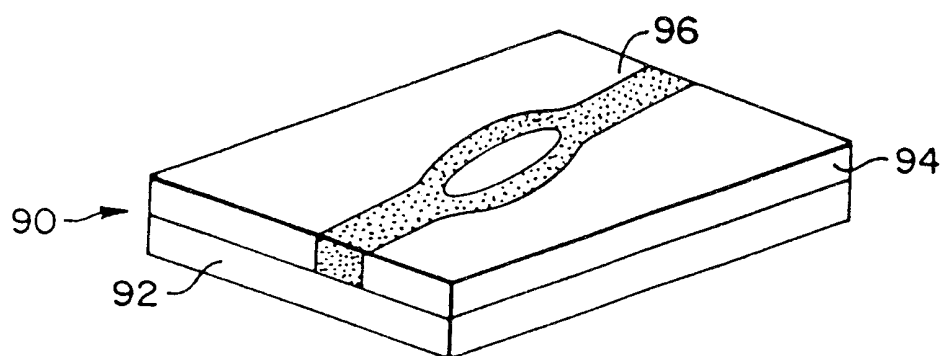


FIG. 10

