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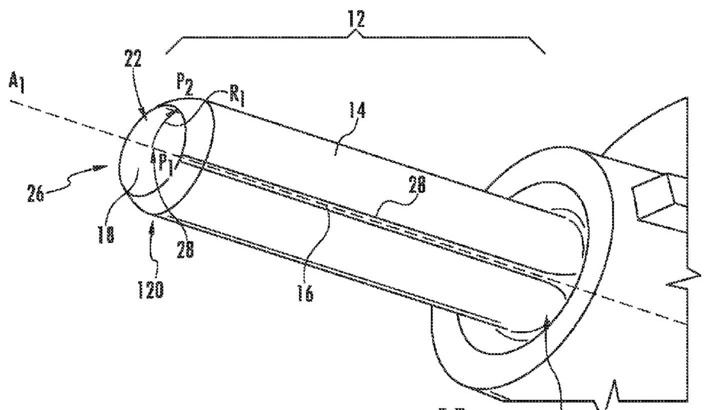



FIG. 1B

**(57) Abstract**: Simultaneous thermal forming of a ferrule (14) and optical fiber (16) as part of a ferrule assembly (12) to thermally form an optical surface (18) in the ferrule assembly. Related fiber optic components, connectors, assemblies, and methods are disclosed. In certain embodiments, the ferrule assembly is comprised of a ferrule (14) and an optical fiber (16) having an end portion (22) extending from an end face (26) of the ferrule. The ferrule (14) may be made from a material or material composition having the same or similar thermal energy absorption characteristics as the optical fiber disposed in the ferrule. Thus, when the end face (26) of the ferrule and the end portion (22) of the optical fiber are simultaneously exposed to a wavelength(s) of a laser beam emitted by a laser, at least a portion of the end face of the ferrule and end portion of the optical fiber are both thermally formed together to form an optical surface.

WO 2013/192122 A1

# Simultaneous Thermal Forming Of Ferrule And Optical Fiber In A Ferrule Assembly To Thermally Form An Optical Surface In The Ferrule Assembly, and Related Fiber Optic Components, Fiber Connectors, Assemblies, and Methods

## RELATED APPLICATIONS

**[0001]** This application claims the benefit of priority under 35 U.S.C. § 120 of U.S. Application Serial No. 13/769,541 filed on February 18, 2013 and U.S. Application No. 61/662,040 filed on June 20, 2012, the content of which is relied upon and incorporated herein by reference in its entirety.

## Background

### *Field of the Disclosure*

**[0002]** The technology of the disclosure relates to creating optical surfaces at the end portions of optical fibers disposed in ferrules as part of fiber optic connector assemblies to establish fiber optic connections.

### *Technical Background*

**[0003]** Benefits of utilizing optical fiber include extremely wide bandwidth and low noise operation. Because of these advantages, optical fiber is increasingly being used for a variety of applications, including but not limited to broadband voice, video, and data transmission in communications networks. As a result, communications networks include a number of optical interconnection points in fiber optic equipment and between fiber optic cables in which optical fibers must be interconnected via fiber optic connections. To conveniently provide these fiber optic connections, fiber optic connectors are provided. A fiber optic connector includes a housing that provides internal components for receiving, supporting, protecting, and aligning one or more end portions of optical fibers exposed from a fiber optic cable(s) when mated with other fiber optic connectors or adapters provided in fiber optic equipment or fiber optic cables. Fiber optic connectors may be installed on fiber optic cables in the field. Alternatively, fiber optic cables may be "pre-connectorized" during the manufacturing of the fiber optic cables.

[0004] To receive, support, and position an optical fiber in a fiber optic connector, a ferrule is typically provided in the fiber optic connector. A ferrule is a component that receives, supports, and positions an optical fiber(s) in a known location with respect to a housing of a fiber optic connector. Thus, when the housing of the fiber optic connector is mated with another fiber optic connector or adapter, the optical fiber(s) in the ferrule is positioned in a known, fixed location about the housing of the fiber optic connector. Thus, the optical fiber(s) are aligned with other optical fiber(s) provided in the mated fiber optic connector or adapter to establish an optical connection(s). In some fiber optic connectors, a “blind hole” ferrule is provided that includes an opening to receive an optical fiber and align the optical fiber with a lens disposed in the ferrule. In other fiber optic connectors, a “pass-through” ferrule is provided that includes a front opening and a rear opening on each end of a bore that allows an optical fiber to pass through the bore and through the front opening to extend past the front end face of the ferrule.

[0005] Whether a fiber optic connector includes a “blind hole” or “pass-through” ferrule, the end portion of the optical fiber may be polished during the connectorization process. Polishing the end portion of an optical fiber can reduce or eliminate scratches, cracks, or other blemishes that could otherwise cause optical attenuation. Polishing the end portion of the optical fiber prepares an optical surface on an end face of the optical fiber for low attenuation optical signal transfer. In fiber optic connectors employing “pass-through” ferrules, the height of the optical surface from the rear end face of the ferrule may also need to be precisely controlled as part of polishing to minimize an air gap between mated optical fibers and/or to meet fiber optic connector industry standards (e.g., consistent with International Standard CEI/IEC 61755-3-2).

[0006] Mechanical polishing processes can be employed, but are labor-intensive. For example, in a mechanical polishing process, optical fibers are manually routed through and secured within a ferrule such that an end portion of the optical fiber extends past a front end face of the ferrule at an initial height. The end portion of the optical fiber is then mechanically polished to create an optical surface at the desired height from the front end face of the ferrule. Mechanical polishing equipment can be expensive and not have the desired manufacturing throughput. For example, mechanical polishing equipment may include a fixture that is configured to support multiple ferrule assemblies

2013277364 15 Dec 2014

for polishing as part of a batch process. At various stages of polishing, the ferrules and respective optical fibers may be removed, cleaned, and inspected. Also, this human involvement can lead to optical surface variations in mechanical polishing processes.

**[0007]** To minimize defects in prepared optical surfaces of optical fibers and improve manufacturing productivity, laser polishing may be employed. Laser polishing involves exposing the end portion of the optical fiber extending from the end face of a ferrule to a laser beam. This exposure can be controlled to create an optical surface in the end portion of the optical fiber. However, it may be difficult or not possible to control a laser beam envelope to create a desired optical surface in the end portion of the optical fiber at the desired height from the end face of the ferrule without also exposing the ferrule to the laser beam. Exposing the ferrule to the laser beam can damage the ferrule. Thus, if laser polishing processes are employed, so as to not expose the ferrule to the laser beam, the laser beam is controlled to create an optical surface in the end portion of the optical fiber at a larger distance from the end face of the ferrule. Then, a separate mechanical polishing process can be employed to reduce the height of the optical surface from the end face of the ferrule to create the desired height of the optical surface. Mechanical polishing of optical fibers involves human processing and associated labor costs. Mechanical polishing also introduces variances between prepared optical surfaces in ferrule assemblies.

**[0007a]** The discussion of the background to the invention included herein including reference to documents, acts, materials, devices, articles and the like is included to explain the context of the present invention. This is not to be taken as an admission or a suggestion that any of the material referred to was published, known or part of the common general knowledge in Australia or in any other country as at the priority date of any of the claims.

## SUMMARY OF THE DETAILED DESCRIPTION

**[0008]** Embodiments disclosed herein include simultaneous thermal forming of a ferrule and an optical fiber as part of a ferrule assembly to thermally form an optical surface in the ferrule assembly. Related fiber optic components, connectors, assemblies, and methods are also disclosed. In certain embodiments disclosed herein, the ferrule assembly is comprised of a ferrule and optical fiber. The ferrule has a ferrule bore. The optical fiber is disposed in the ferrule bore, wherein an end portion of the optical fiber extends from an end face of the ferrule. The ferrule may be made from a material or material composition that has the same or similar thermal energy absorption characteristics (e.g., melting and/or ablation) as the optical fiber disposed in the ferrule. Thus, when the end face of the ferrule and an end portion of an optical fiber extending from the end face of the ferrule are simultaneously exposed to one or more wavelengths of a laser beam emitted by a laser, at least a portion of the end face of the ferrule and end portion of the optical fiber are both thermally formed to form an optical surface at the end face of the ferrule. This is opposed to having to control the laser to only create an optical surface in the end portion of the optical fiber at greater distances from the end face of the ferrule to avoid exposing the ferrule to the laser beam to avoid damaging the ferrule. As a result, a separate mechanical polishing process may not be needed to finalize the creation of the optical surface in the ferrule assembly.

**[0009]** In this regard, in one aspect of the present invention a ferrule assembly for a fiber optic connector is provided. The ferrule assembly comprises a ferrule comprising a first end, a second end opposite the first end along an optical axis, a ferrule bore extending between a first opening of the first end and a second opening of the second end, and an end face disposed at the second end. The ferrule assembly also comprises an optical fiber absorptive to the at least one wavelength. The optical fiber is disposed in the ferrule bore of the ferrule, wherein at least a portion of the end face of the ferrule is absorptive to at least one wavelength such that the ferrule is made from a material or material composition that has the same or similar thermal energy absorption characteristics as the optical fiber. The ferrule assembly also comprises an optical surface. The optical surface is formed by thermally forming both at least a portion of the end face of the ferrule and the end portion of the optical fiber by simultaneously exposing the end face of the ferrule and the end portion of the optical fiber to a laser beam of the at least one wavelength emitted by a laser; wherein the ferrule comprises an absorption gradient of ferrule material at the at least one wavelength disposed along a radial axis of the ferrule between an outer perimeter of the ferrule and an inner portion of the ferrule.

**[0010]** In another aspect of the present invention, a method of thermally forming ferrule assembly is provided. The method comprises providing a ferrule having a first end, a second end opposite the first end along an optical axis, a ferrule bore extending between a first opening of the first end and a second opening of the second end, and an end face disposed at the second end. The method also comprises disposing an optical fiber through the ferrule bore and extending an end portion of the optical fiber through the end face of the ferrule. The method also comprises simultaneously exposing the end face of the ferrule and the end portion of the optical fiber to a laser beam of at least one wavelength emitted by a laser to thermally form at least a portion of the end face of the ferrule and the end portion of the optical fiber to thermally form an optical surface.

**[0011]** Also described is an apparatus for thermally forming an optical surface of an optical fiber in a ferrule assembly is provided. The apparatus comprises a fixture. The fixture is configured to support a ferrule comprising a ferrule bore and an optical fiber disposed in the ferrule bore, wherein an end portion of the optical fiber extends from an end face of the ferrule, at least a portion of the end face of the ferrule and the optical fiber are both absorptive to at least one wavelength. The apparatus also comprises a laser. The laser is configured to emit a laser beam having the at least one wavelength to simultaneously expose the end face of the ferrule and the end portion of the optical fiber to the laser beam to thermally form an optical surface in at least a portion of the end face of the ferrule and the end portion of the optical fiber.

**[0012]** Additional features and advantages will be set forth in the detailed description which follows, and in part will be readily apparent to those skilled in the art from that description or recognized by practicing the embodiments as described herein, including the detailed description that follows, the claims, as well as the appended drawings.

**[0013]** It is to be understood that both the foregoing general description and the following detailed description present embodiments, and are intended to provide an overview or framework for understanding the nature and character of the disclosure. The accompanying drawings are included to provide a further understanding, and are incorporated into and constitute a part of this specification. The drawings illustrate various embodiments, and together with the description serve to explain the principles and operation of the concepts disclosed.

one wavelength, wherein the ferrule end face and the optical fiber end portion were simultaneously exposed to a laser beam to thermally form at least a portion of the ferrule end face and the optical fiber end portion into an optical surface in the ferrule assembly;

**[0016]** **FIG. 2** is a chart of a percent absorption of a laser beam through a one-hundred micron thick sample of silica (i.e., silicon dioxide ($SiO_2$)) versus a wavelength of a laser beam;

**[0017]** **FIG. 3** is a flowchart diagram of an exemplary process of simultaneously exposing the ferrule end face and the optical fiber end portion in the ferrule assembly in **FIG. 1** to a laser beam having at least one wavelength to thermally form at least a portion of the ferrule end face and the optical fiber end portion into an optical surface in the ferrule assembly, wherein the ferrule and optical fiber have the same or similar thermal energy absorption characteristics for the at least one wavelength;

**[0018]** **FIG. 4A** is a top view of one embodiment of an exemplary laser processing apparatus including a laser configured to emit a laser beam having at least one wavelength to simultaneously expose the ferrule end face and the optical fiber end portion of the ferrule assembly in **FIG. 1A** to the laser beam to thermally form at least a portion of the ferrule end face and the optical fiber end portion into an optical surface in the ferrule assembly in **FIG. 1B**;

**[0019]** **FIG. 4B** is a close-up side view of providing a ferrule and optical fiber disposed therein as part of a ferrule assembly in **FIG. 1A** exposed to a laser beam of a laser to thermally form at least a portion of the ferrule end face and the optical fiber end portion into an optical surface in the ferrule assembly;

**[0020]** **FIG. 5** is an exemplary cross-sectional energy distribution of an exemplary diffractive optic that can be employed in the laser processing apparatus of **FIGS. 4A** and **4B** to control the energy distribution of the laser beam to thermally form an optical surface in the ferrule assembly of **FIG. 1**;

**[0021]** **FIG. 6A** is an exemplary Cartesian plot of an exemplary height and curvature of an optical surface formed in a ferrule assembly according to the process in **FIG. 3**;

**[0022]** **FIG. 6B** is an exemplary three-dimensional (3-D) interferometric plot of height and curvature of an optical surface formed in a ferrule assembly according to the process in **FIG. 3**;

**[0023]** **FIG. 7A** is a perspective view of an exemplary gradient ferrule having an absorption gradient of ferrule material for the at least one wavelength disposed along a radial axis of the ferrule between an outer perimeter of the ferrule and an inner portion of the ferrule;

**[0024]** **FIG. 7B** is an end view of the gradient ferrule in **FIG. 7A** having a step-wise absorption gradient of ferrule material;

**[0025]** **FIG. 7C** is an end view of an exemplary gradient ferrule having a continuous absorption gradient of ferrule material for the at least one wavelength disposed along a radial axis of the ferrule between an outer perimeter of the gradient ferrule and an inner portion of the ferrule; and

**[0026]** **FIG. 8** is an exemplary plot of a ferrule comprised of a zirconia-silica gradient material to provide a zirconia-silica absorption gradient.

## DETAILED DESCRIPTION

**[0027]** Reference will now be made in detail to the embodiments, examples of which are illustrated in the accompanying drawings, in which some, but not all embodiments are shown. Indeed, the concepts may be embodied in many different forms and should not be construed as limiting herein; rather, these embodiments are provided so that this disclosure will satisfy applicable legal requirements. Whenever possible, like reference numbers will be used to refer to like components or parts.

**[0028]** Embodiments disclosed herein include simultaneous thermal forming of a ferrule and an optical fiber as part of a ferrule assembly to thermally form an optical surface in the ferrule assembly. Related fiber optic components, connectors, assemblies, and methods are also disclosed. In certain embodiments disclosed herein, the ferrule assembly is comprised of a ferrule and optical fiber. The ferrule has a ferrule bore. The optical fiber is disposed in the ferrule bore, wherein an end portion of the optical fiber extends from an end face of the ferrule. The ferrule may be made from a material or material composition that has the same or similar thermal energy absorption characteristics (e.g., melting and/or ablation) as the optical fiber disposed in the ferrule. Thus, when the end face of the ferrule and an end portion of an optical fiber extending from the end face of the ferrule are simultaneously exposed to one or more wavelengths of a laser beam emitted by a laser, at least a portion of the end face of the ferrule and end portion of the optical fiber are both thermally formed to form an optical surface at the end face of the ferrule. This is opposed to having to control the laser to only create an optical surface in the end portion of the optical fiber at greater distances from the end face of the ferrule to avoid exposing the ferrule to the laser beam to avoid damaging the ferrule. As a result, a separate mechanical polishing process may not be needed to finalize the creation of the optical surface in the ferrule assembly.

**[0029]** In this regard, **FIG. 1A** is a side cross-sectional view of an exemplary fiber optic connector sub-assembly **10**. The fiber optic connector sub-assembly **10** includes a ferrule assembly **12** having an exemplary ferrule **14** and optical fiber **16** having the same or similar thermal energy absorption characteristics for at least one wavelength. **FIG. 1B** is a close-up, perspective view of the ferrule assembly **12** in **FIG. 1A** after an optical surface **18** has been thermally formed in the ferrule **14**. The optical surface **18** is formed in the ferrule **14**, as illustrated in **FIG. 1B**, to facilitate optical transfer with another optical fiber in another fiber optic connector. As will be described in more detail below, at least an end face **20** of the ferrule **14** and an end portion **22** of the optical fiber **16** were simultaneously exposed to a laser beam to thermally form the end face **20** of the ferrule **14** and the end portion **22** of the optical fiber **16** into the optical surface **18**. The end face **20** of the ferrule **14** and an end portion **22** of the optical fiber **16** are thermally formed simultaneously and together to form the optical surface **18**. By simultaneously, it is meant that the end face **20** of the ferrule **14** and an end portion **22** of the optical fiber **16** are both exposed to a laser beam together, not that only either end face **20** of the ferrule **14** or the end portion **22** of the optical fiber **16** being exposed to the laser beam. Because the ferrule **14** includes a material having the same or similar thermal energy absorption characteristics for at least one wavelength as the optical fiber **16** in this example, the end face **20** of the ferrule **14** and end portion **22** of the optical fiber **16** can be thermally formed together into a substantially planar end optical surface **18**.

**[0030]** The thermal forming discussed herein can also be performed in one laser processing step, if desired, that is geometrically compliant with desired design parameters or standards. The thermal forming process can cut the end portion **22** of the optical fiber **16** and polish the optical surface **18** thermally formed as a result of thermally forming both the end face **20** of the ferrule **14** and the end portion **22** of the optical fiber **16** simultaneously. This is opposed to having to control a laser to only create an optical surface in the end portion of an optical fiber at greater distances from an end face of a ferrule to avoid exposing the ferrule to the laser beam to avoid damaging the ferrule. Mechanical steps, including polishing the end portion **22** of the optical fiber **16** through a mechanical grinding process can result in process variations, increased labor time, and defect and scrap, may be avoided.

**[0031]** As will also be discussed in more detail below, only a portion of the end face **20** of the ferrule **14** need be manufactured from a material that has the same or similar thermal energy absorption characteristics of the optical fiber **16**. The portion of the end face **20** of the ferrule **14** proximate to the second opening **23** where the end portion **22** of the optical fiber **16** extends from, should be manufactured from a material that has the same or similar thermal energy absorption characteristics of the optical fiber **16** to thermally form the optical surface **18** as discussed herein. The entire ferrule **14** could also be manufactured from a material that has the same or similar thermal energy absorption characteristics of the optical fiber **16**.

**[0032]** Before discussing examples of materials and compositions of the ferrule **14** and the optical fiber **16** to allow for the end face **20** of the ferrule **14** and end portion **22** of the optical fiber **16** to be thermally formed into the optical surface **18** by a laser, more detail regarding the exemplary fiber optic connector sub-assembly **10** is first described below. In this regard as illustrated in **FIG. 1A**, the ferrule **14** laterally and angularly aligns the end portion **22** of the optical fiber **16** at the end face **20** of the ferrule **14**. The ferrule **14** includes a first end **24**, a second end **26**, and a ferrule bore **28** (also known as a "microbore") extending between the first end **24** and the second end **26**. The optical fiber **16** is disposed through the ferrule bore **28** that extends along the center optical axis $\mathbf{A_1}$ of the ferrule **14**. A first opening **30** is disposed at the first end **24** of the ferrule **14**. The first opening **30** provides a passageway by which the end portion **22** of the optical fiber **16** enters the ferrule bore **28** of the ferrule **14**. The first opening **30** may be cone-shaped to provide easy entry of the optical fiber **16** into the ferrule bore **28**. The end portion **22** of the optical fiber **16** exits the ferrule bore **28** and extends past the end face **20** through the second opening **23** in the second end **26** of the ferrule **14** to an initial height $\mathbf{H_1}$ before thermal forming. The optical fiber **16** may be secured within the ferrule bore **28** with a bonding agent**.** The bonding agent may prevent movement of the optical fiber **16** within the ferrule bore **28** to minimize signal attenuation between the optical fiber **16** and the complementary receptacle (not shown), which may include an opposing optical fiber. Movement of the optical fiber **16** within the ferrule bore **28** may be undesirable because the movement may cause attenuation.

**[0033]** With continuing reference to **FIG. 1A**, the ferrule **14** may be disposed at a front end **32** of the fiber optic connector sub-assembly **10**. The first end **24** of the ferrule **14** may be at least partially disposed within a ferrule holder body **34**. The ferrule holder body **34** supports the ferrule **14** within the fiber optic connector sub-assembly **10**. The ferrule holder body **34** may support the end face **20** of the ferrule **14** to be disposed orthogonal to the optical axis $\mathbf{A_1}$ or angled at angle ϕ (phi) with respect to the optical axis $\mathbf{A_1}$. For example, the angle ϕ (phi) may be within ten (10) degrees of orthogonal with respect to the optical axis $\mathbf{A_1}$, as depicted in **FIG. 1A**. The angle ϕ (phi) may be angled to be non-orthogonal to increase the contact area between the optical fiber **16** and another optical fiber of the complementary receptacle (not shown).

**[0034]** With continuing reference to **FIG. 1A**, the ferrule holder body **34** may include a body alignment surface **36** which may be disposed to allow easy insertion of the ferrule holder body **34** within a housing **38** of the fiber optic connector sub-assembly **10**. The housing **38** in this embodiment includes an inner housing **40** including a housing alignment surface **42**. The second end **26** of the ferrule **14** may be at least partially disposed within the inner housing **40**. In this regard, the ferrule **14** may be protected from random perturbation forces ("side loads") orthogonal to the optical axis $\mathbf{A_1}$ when unmated to the complementary receptacle (not shown). It is noted that the ferrule holder body **34** may also be used in other fiber optic connectors including a spring-loaded ferrule holder body **34** without the inner housing **40**, for example, non-SC type fiber optic connectors. In these other fiber optic connectors, the housing may be an enclosure (not shown) around the ferrule holder body **34**. The ferrule **14** may also include a ferrule notch **44**. The ferrule notch **44** may be filled with a portion **46** of the ferrule holder body **34** to prevent the ferrule **14** from disengaging from the ferrule holder body **34**. The ferrule holder body **34** may comprise molded plastic as a non-limiting example.

**[0035]** With continuing reference to **FIG. 1A**, the fiber optic connector sub-assembly **10** may also include a lead-in tube **48** engaged to a rear end **50** of the ferrule holder body **34** to facilitate alignment of the optical fiber **16**. The lead-in tube **48** generally restricts a location of a bonding agent used during installation of the optical fiber **16** and prevents the bonding agent from escaping. Otherwise, the bonding agent may come into contact with other areas of the fiber optic connector sub-assembly **10**, such as a spring (discussed below), which must be free to move unfettered by the bonding agent. The lead-in tube **48** also facilitates guiding the end portion **22** of the optical fiber **16** into the ferrule holder body **34**, where the optical fiber **16** can then be guided to the ferrule **14**. The lead-in tube **48** may also prevent sharp bends from occurring in the optical fiber **16** during insertion that could damage the optical fiber **16** as the end portion **22** of the optical fiber **16** is disposed in the ferrule holder body **34** and into the ferrule **14**.

**[0036]** The lead-in tube **48** may be made of a flexible and resilient material with high surface lubricity, for example, polyethylene, silicone, or thermoplastic elastomer. This material may also include additives, for example, mineral fill or silica-based lubricant or graphite. In this manner, the optical fiber **16** may smoothly travel the lead-in tube **48** without being caught during insertion. The material may be a type of material that would not be degraded by a bonding agent, such as an epoxy or other chemical agent in standardized testing (e.g., Telcordia GR-326-CORE) and would not allow bonding by a bonding agent.

**[0037]** With continuing reference to **FIG. 1A**, a spring **50** may be disposed between a spring seat base **52** of a crimp body **54** attached to the inner housing **40** and a spring seating surface **56** of the ferrule holder body **34**. The spring **50** in this example is biased to apply a spring force $\mathbf{F_S}$ to the spring seating surface **56** to push the ferrule holder body **34** and thereby push the end face **20** of the ferrule **14** against a complementary receptacle. When contact is made between the end face **20** of the ferrule **14** and a complementary receptacle, the ferrule holder body **34** translates in the rear direction $\mathbf{X_1}$, and the force $\mathbf{F_S}$ will press the end face **20** against a complementary receptacle to minimize attenuation. A bonding agent **28**, which may be used during the installation of the optical fiber **16**, should not come into contact with the spring **50**. Otherwise, the bonding agent would prevent movement of the spring **50**. The lead-in tube **48** may generally restrict a bonding agent to an area within the ferrule holder body **34**, and prevent a bonding agent from reaching the spring **50**.

**[0038]** The optical surface **18** in the ferrule **14**, as illustrated in **FIG. 1B**, is formed as a result of simultaneously thermally forming the end face **20** of the ferrule **14** and the end portion **22** of the optical fiber **16**. It may be desired to form the optical surface **18** planar or substantially planar to the end face **20** of the ferrule **14** rather than at a height distance away, such as height $H_1$, as illustrated in **FIG. 1A**. The ferrule **14** is constructed from a material or material composition having the same or similar thermal energy absorption characteristics for at least one wavelength as the optical fiber **16**, so that the end face **20** of the ferrule **14** and the end portion **22** of the optical fiber **16** can both be thermally formed together simultaneously into the optical surface **18** by exposure to wavelength energy containing the at least one wavelength.

**[0039]** With reference back to **FIG. 1B**, because the ferrule **14** includes a material having the same or similar thermal energy absorption characteristics for at least one wavelength as the optical fiber **16** in this example, the end face **20** of the ferrule **14** and end portion **22** of the optical fiber **16** can be thermally formed together into a planar or substantially planar end optical surface **18** in one laser processing step that is geometrically compliant with desired design parameters or standards. In this regard, the optical surface **18** may be planar between points $P_1$ and $P_2$ on the thermally formed optical surface **18**, meaning points $P_1$ and $P_2$ are disposed in the same plane orthogonal to the optical axis $A_1$ of the ferrule **14**. In another embodiment, the optical surface **18** may be thermally formed having a radius of curvature between approximately 1 millimeter (mm) and 30 mm between point $P_1$ and point $P_2$, and may further be from about five (5) mm to twenty-five (25) mm. In another embodiment, the optical surface **18** may be thermally formed below the surface of the end face **20** of the ferrule **14** in **FIG. 1A** proximate the ferrule bore **28**. This is possible, because as discussed in more detail below by example, the ferrule **14** may be manufactured to provide a gradiated composite material, wherein an inner portion(s) of the ferrule **14** proximate the ferrule bore **28** may have the same or similar thermal characteristics as the optical fiber **16**, whereas outer portion(s) of the ferrule **14** may be less absorptive than the optical fiber **16**.

**[0040]** As a non-limiting example, the optical fiber **16** may be formed from silica. In this example, only wavelength energy that is absorbed by a silica optical fiber **16** is available to enable the thermal forming to create the optical surface **18.** To further illustrate by example, **FIG. 2** is a chart **60** of a percentage transmission of wavelength energy through a one-hundred (100) micrometer (μm) thick sample of silica (i.e., silicon dioxide ($SiO_2$)) versus wavelength energy, such as energy in a laser beam emitted by a laser. The wavelength ranges in nanometers (nm) are provided on the X-axis labeled "WAVELENGTH." The transmission percentage of energy at a given wavelength that transmits through the silica sample is provided on the Y-axis as "$SiO_2$ TRANSMISSION (%)." Wavelength energy that is not transmitted through the silica sample is absorbed or reflected. Empirical data indicates that within the wavelength range $\mathbf{R_2}$ (5,000 nm – 6,200 nm) more than ninety (90) percent of wavelength energy is absorbed by the silica sample and available for thermal forming. Thus, a laser emitting a laser beam in the wavelength range of $\mathbf{R_2}$ would be able to be used to thermally form a silica optical fiber **16**. If the ferrule **14** were also manufactured from silica, both the silica ferrule **14** and the optical fiber **16** would have the same wavelength energy absorption characteristics, and would both thermally form when exposed to a laser beam having a wavelength in the wavelength range of $\mathbf{R_2}$.

**[0041]** With continuing reference to the chart **60** in **FIG. 2**, data point $\mathbf{P_3}$ can be defined where, at a wavelength of five thousand (5,000) nm, twenty-five percent (25%) of the wavelength energy may be transmitted through the silica example. Wavelengths shorter than five thousand (5,000) nm may exhibit a significantly higher transmission rate through the silica sample as wavelength energy passes through the one-silica sample and is not available to heat and thermally form the material. Empirical evidence shows in this case a carbon dioxide laser or carbon-monoxide laser, emitting a laser beam including wavelengths within the range $\mathbf{R_3}$, (approximately 5200 to 5800 nm), would efficiently provide power to enable thermal forming to occur for a ferrule **14** and optical fiber **16** comprising silica.

**[0042]** Other materials may also be used for the ferrule **14** and optical fiber **16** and be absorptive or substantially absorptive of wavelength energy. For example, a silica material may be doped with hydroxide or a hydroxide composite and provided in the ferrule **14** and optical fiber **16** to expand the range of absorption of wavelength energy. For example, the absorption range may be expanded between three thousand (3,000) nm and eight thousand (8,000) nm, as shown by the wavelength range $\mathbf{R_4}$. In this example, a laser configured to emit a laser beam at a wavelength or wavelength range contained in the wavelength range $\mathbf{R_4}$ could provide power to enable thermal forming of the end face **20** of the ferrule **14** and the end portion **22** of the optical fiber **16** to thermally form the optical surface **18**.

**[0043]** Other materials besides silica that have the same or similar thermal energy absorption characteristics may be used to manufacture the ferrule **14**. For example, the ferrule **14** may be manufactured from a borosilicate material or composite for an optical fiber **16** manufactured from a silica or silica composite. As another example, the ferrule **14** may be manufactured from a ceramic glass material or composite for an optical fiber **16** manufactured from a silica or silica composite. As a non-limiting example, the ferrule **14** may be manufactured from a material having a lower coefficient of thermal expansion than zirconia.

**[0044]** The ferrule **14** may not be manufactured from a purely zirconium oxide ($ZrO_2$) material if the optical fiber **16** is manufactured from silica. Zirconium oxide does not have similar enough thermal energy absorption characteristics to silica to allow the end face **20** of the ferrule **14** to be thermally formed with the end portion **22** of a silica optical fiber **16** to thermally form the optical surface **18**. For example, for a half-millimeter thick sample of zirconium dioxide, sixty-five (65) percent of wavelength energy may be transmitted through the zirconium dioxide sample at wavelength energy of six thousand, two hundred (6,200) nm.

**[0045]** A thermally forming process can be employed using wavelength energy from a laser to simultaneously thermally form the end face **20** of the ferrule **14** and the end portion **22** of the optical fiber **16** into the optical surface **18**. In this regard, **FIG. 3** is a flowchart diagram of an exemplary process **62** of simultaneously exposing the end face **20** of the ferrule **14** and the end portion **22** of the optical fiber **16** to a laser beam emitting a wavelength or wavelength range to thermally form at least a portion of the end face **20** of the ferrule **14** and the end portion **22** of the optical fiber **16** into the optical surface **18**. The laser is provided such that the wavelength or wavelength range of the laser beam emitted by the laser is absorptive to the ferrule **14** and the optical fiber **16**, which have the same or similar thermal energy absorption characteristics at the wavelength or wavelength range of the laser beam. The exemplary process in **FIG. 3** will be described in conjunction with **FIGS. 4A** and **4B**, which illustrate an exemplary laser processing apparatus **80** that includes a laser **82** for emitting a laser beam **84** at a wavelength or wavelength range to thermally form the optical surface **18**.

**[0046]** In this regard, the process **62** starts (block **64** in **FIG. 3**). For discussion purposes, it is assumed that the process **62** is employed to thermally form the optical surface **18** in the ferrule **14** in the ferrule assembly **12** in **FIG. 1**. However, note that the process **62** is not limited to thermally forming an optical surface in the ferrule assembly **12**. With continuing reference to **FIG. 3**, the ferrule **14** is provided (block **66**). As previously discussed in **FIG. 1A**, the ferrule **14** has the first end **24** and the second end **26** opposite the first end **24** along optical axis **A1**. A ferrule bore **28** extends in the ferrule **14** between a first opening **30** of the first end **24** and a second opening **23** of the second end **26**. The end face **20** is disposed at the second end **26** of the ferrule **14**. At least a portion of the end face **20** is absorptive to the wavelength or wavelength range of the laser beam **84** emitted by the laser **82** in **FIG. 4A**. The ferrule **14** may be provided of any material, including the materials described above, as long as the ferrule **14** is absorptive of the wavelength or wavelength range of the laser beam **84** emitted by the laser **82** in **FIG. 4A**.

**[0047]** With continuing reference to **FIG. 3,** the optical fiber **16** is provided. The optical fiber **16** is provided that is absorptive to the wavelength energy of the laser beam **84** emitted by the laser **82** in **FIG. 4A** (block **68**). Thus, both the ferrule **14** and the optical fiber **16** are manufactured from a material that has the same or similar thermal energy absorption characteristics to wavelength energy, which in this example is the wavelength or wavelength range of the laser beam **84** emitted by the laser **82** in **FIG. 4A**. The end portion **22** of the optical fiber **16** is disposed through the ferrule bore **28** of the ferrule **14** until the end portion **22** of the optical fiber **16** is extended through the second opening **23** and through the end face **20** of the ferrule **14** to height $\mathbf{H_1}$, as illustrated in **FIG. 4B** (block **70** in **FIG. 3**). For example, the end portion **22** of the optical fiber **16**

may be extended at least five-hundred (500) nm past the end face **20** of the ferrule **14** (block **70**).

**[0048]** With continuing reference to **FIG. 3**, the process **62** includes emitting the laser beam **84** from the laser **82** in **FIG. 4A** (block **72** in **FIG. 3**). The laser processing apparatus **80** in **FIG. 4A** is configured to simultaneously expose the end face **20** of the ferrule **14** and the end portion **22** of the optical fiber **16** to the laser beam **84** at the wavelength or wavelength range of the laser beam **84**. Simultaneously exposing the end face **20** of the ferrule **14** and the end portion **22** of the optical fiber **16** to thermally form at least a portion of the end face **20** of the ferrule **14** and the end portion **22** of the optical fiber **16** to thermally form the optical surface **18**. As illustrated in **FIG. 4B**, the laser beam **84** may be directed to be incident to the end portion **22** of the optical fiber **16** and within the geometric plane $\mathbf{P_4}$ intersecting the optical axis $\mathbf{A_1}$ of the end portion **22** of the optical fiber **16**. The laser beam **84** may be emitted within the geometric plane $\mathbf{P_4}$ orthogonal or substantially orthogonal to the optical axis $\mathbf{A_1}$ of the optical fiber **16**.

**[0049]** As discussed above, the laser beam **84** may be emitted from the carbon-monoxide or carbon-dioxide laser such as laser **82** in **FIG. 4A**, as non-limiting examples. As a further non-limiting example, the wavelength range of the laser beam **84** may be provided between 3,000 nm to 8,000 nm if the ferrule **14** and optical fiber **16** are manufactured from material or material composition being absorptive of wavelength energy at such wavelengths. As an example, the wavelength range of the laser beam **84** may be provided between 5,200 nm to 5,800 nm. As another non-limiting example, the optical fiber **16** and the ferrule **14** could be configured to absorb at least twenty-five (25) percent of the energy of the wavelength or wavelength range of the laser beam **84**.

**[0050]** With continuing reference to **FIG. 3**, the process **62** may include exposing the end portion **22** of the optical fiber **16** to the laser beam **84** for a period of time sufficient to form the optical surface **18** (block **74** in **FIG. 3**). The period of time may be less than ten (10) seconds as a non-limiting example. The period of time may be chosen to be sufficient to allow at least a portion of the end face **20** of the ferrule **14** and the end portion **22** of the optical fiber **16** to become reflow material. The process **62** may further include removing the end face **20** of the ferrule **14** and the end portion **22** of the optical fiber **16** from exposure to the laser beam **84** to allow the reflow material of the portion of the end face **20** of the ferrule **14** and the end portion **22** of the optical fiber **16** to cool into the optical surface **18** (block **76** in **FIG. 3**). The processes in blocks **74** and **76** may be repeated until the desired optical surface **18** is thermally formed, until the process **62** is desired to end (block **78** in **FIG. 3**).

**[0051]** More detail regarding the exemplary laser processing apparatus **80 in FIG. 4A** will now be described. **FIG. 4A** is a top view of the laser **82** configured to emit the laser beam **84** having a wavelength or wavelength range. The laser **82** is controlled by controller **86** to emit the laser beam **84** to simultaneously expose the end face **20** of the ferrule **14** and the end portion **22** of the optical fiber **16** to thermally form at least a portion of the ferrule end face and the optical fiber end portion to thermally form the optical surface **18**. The laser processing apparatus **80** in this example includes the laser **82**, at least one focusing lens **88**, and at least one steering mirror **90**. The laser **82** is supported by a fixture **92**. The ferrule **14** is supported by fixture **94**.

**[0052]** With continuing reference to **FIG. 4A**, the laser **82** emits the laser beam **84** in a wavelength or wavelength range that is absorptive to the ferrule **14** and the optical fiber **16** towards the end face **20** of the ferrule **14** and the end portion **22** of the optical fiber **16**. The optical fiber **16** may extend from the end face **20** of the ferrule **14**. The laser **82** can be modified or chosen to purposefully emit the laser beam **84** at one or more wavelengths that are absorptive or substantially absorptive to the material composition of the ferrule **14** and optical fiber **16**, as previously discussed above. It is noted that a carbon-monoxide laser may be able to provide the increased power to create the optical surface **18**.

**[0053]** With continuing reference to **FIGS. 4A** and **4B**, the focusing lens **88** focuses the laser beam **84** to a smaller focused laser beam **84'** of width $\mathbf{W_1}$ to concentrate the wavelength energy of the laser beam **84** to be efficiently directed to the end face **20** of the ferrule **14** and the end portion **22** of the optical fiber **16**. Providing the laser beam **84** into laser beam **84'** having a concentrated width may accelerate the melting or ablation of the end face **20** of the ferrule **14** and the end portion **22** of the optical fiber **16**. The focusing lens **88** may be made of a high-grade optical material, such as calcium fluoride (CaF) or zinc selenide (ZnSe) as non-limiting examples. For purposes of comparison, an exemplary width or diameter of the optical fiber **16** may be one-hundred twenty-five

(125) μm. The laser beam **84** with a wavelength in the range of $\mathbf{R_2}$ in **FIG. 2** may be 5,500 nm and may be focused by the focusing lens **88** to an exemplary width of 5.5 μm.

**[0054]** With continuing reference to **FIG. 4A**, the steering mirror **90** steers or direct the emitted laser beam **84** towards the end face **20** of the ferrule **14** and the end portion **22** of the optical fiber **16** extending from the end face **20**, as illustrated in **FIG. 4B**. The steering mirror **90** may be a one-dimensional (1-D) scanner, which translates back and forth along a velocity vector $\mathbf{V_1}$, thereby causing the laser beam **84** to translate back and forth along a velocity vector $\mathbf{V_2}$. The velocity vectors $\mathbf{V_1}$, $\mathbf{V_2}$ may be the same so there is no angular movement of the steering mirror **90**. The steering mirror **90** may translate the laser beam **84** within a geometric plane $\mathbf{P_4}$ intersecting the optical axis $\mathbf{A_1}$ of the end portion **22** of the optical fiber **16**. In this manner, as shown in **FIGS. 4A** and **4B**, the laser beam **84'** may be translated back and forth with velocity $\mathbf{V_2}$ across the width or the diameter of the end face **20** of the ferrule **14** and the end portion **22** of the optical fiber **16** to transfer wavelength energy to thermally form the optical surface **18**.

**[0055]** Alternatively, the steering mirror **90** may be a galvanometer one dimensional (1-D) scanner that angularly moves back and forth at a velocity $\mathbf{V_3}$. The steering mirror **90** may steer or direct the emitted laser beam **84'** towards the end face **20** of the ferrule **14** and the end portion **22** of the optical fiber **16** extending from the end face **20**. The steering mirror **90** may angularly direct the laser beam **84'** within the geometric plane $\mathbf{P_4}$ intersecting the optical axis $\mathbf{A_1}$ of the end portion of the optical fiber **16**. In this manner, the laser beam **84'** may be angularly directed back and forth with a velocity $\mathbf{V_3}$ across the width or the diameter of the optical fiber **16** to transfer energy along the width or the diameter of the optical fiber **16** to create the optical surface **18**.

**[0056]** The optical surface **18** may be created by thermal forming involving a conversion of solids to liquids and gases encompassing melting and/or ablation. Melting involves transforming a solid phase of a material into a liquid or liquid phase. Ablation involves transforming a solid phase of a material into a gas or gaseous phase. Both melting and ablation can occur during thermal forming. The transfer of energy from the laser beam **84'** thermally forms the optical surface **18**, where material of the end face **20** of the ferrule **14** and the end portion **22** of the optical fiber **16** may melt and reflow before cooling to form the optical surface **18**. A surface tension of the melted material during reflow and cooling forms a planar-shaped or substantially planar-shaped optical surface **18** free or relatively free of optical defects. The resulting optical surface **18** created by thermal forming may have fewer optical imperfections than if polished.

**[0057]** With continued reference to **FIGS. 4A** and **4B**, the geometric plane $\mathbf{P_4}$ of the movement of the laser beam **84** may be parallel to the end face **20** of the ferrule **14** at the second opening **26** to create an optical surface **18** parallel to the end face **20**. The geometric plane $\mathbf{P_4}$ may be angled at an angle $\boldsymbol{\theta_1}$ relative to the optical axis $\mathbf{A_1}$ and as discussed earlier, the end face **20** may be angled at the angle $\boldsymbol{\phi}$ relative to the optical axis $\mathbf{A_1}$. The angle $\boldsymbol{\phi}$ and the angle $\boldsymbol{\theta}$ may be equal and may be orthogonal to the optical axis $\mathbf{A_1}$. Efficient creation of the optical surface **18** may occur when the θ (theta) angle is orthogonal to the optical axis $\mathbf{A_1}$ to minimize reflections.

**[0058]** With continued reference to component details of the laser processing apparatus **80** of **FIGS. 4A** and **4B**, the steering mirror **90** and the fixture **92** are now discussed in detail. The steering mirror **90** may steer the laser beam **84** from the laser **82** and/or focusing lens **88** to the ferrule **14** and/or end portion **22** of the optical fiber **16**. The steering mirror **90** may be made, for example, of a highly reflective material for the laser beam **84** having the desired wavelength range. The steering mirror **90** may be comprised of, for example, an aluminum material or a silicon carbide material.

**[0059]** The fixture **94** may be configured to support the ferrule **14** having the optical fiber **16** disposed therein and the end portion **22** of the optical fiber **16** extending through the end face **20** of the ferrule **14**. The fixture **94** may engage and thereby prevent axial and/or angular movement of the ferrule holder body **34** and/or ferrule **14** relative to the fixture **94**. Thus, the position of the end face **20** of the ferrule **14**, the second opening **23** in the end face **20**, and/or the end portion **22** of the optical fiber **16** may be known during the thermal forming of the optical surface **18**. Accurate positioning of the optical surface **18** may be achieved when these positions are known during manufacturing.

**[0060]** It is noted that the fixture **94** may be rotated with a rotational velocity of $\mathbf{RPM_1}$ about the optical axis $\mathbf{A_1}$ to more uniformly distribute the laser energy along a circumference of the end portion **22** of the optical fiber **16**. The fixture **94** may be rotated with a motor (not shown), which may be, for example, electrically powered. In this manner, the optical surface **18** may be thermally formed in a shape that is more uniform and planar or substantially planar.

**[0061]** As an alternative to sweeping the laser beam **84** in the laser processing apparatus **80** in **FIGS. 4A** and **4B**, the energy distribution of the laser beam **84** may be shaped by a diffractive optic in place of the focusing lens **88** and steering mirror **90**. The diffractive optic can control the energy distribution of the laser beam **84** to thermally form the optical surface **18** in the ferrule assembly **12** in **FIG. 1B**. In this regard, **FIG. 5** is an exemplary cross-sectional energy distribution **100** of an exemplary diffractive optic that can be employed in the laser processing apparatus **80** of **FIGS. 4A** and **4B**. The energy distribution of the diffractive optic is 150 μm by 300 μm. As a non-limiting example, a diffractive optic can be manufactured from zirconia selenium (ZnSe). The controller **86** can control the laser **82** to emit and not emit the laser beam **84** on and off without needing to translate the laser beam **84** or the ferrule **14**. The laser **82** and the diffractive optic can be sized to match the desired energy distribution to thermally form and polish the optical surface **18**.

**[0062]** To further illustrate an exemplary optical surface **18** that can be thermally formed in a ferrule assembly according to the embodiments disclosed herein, the plots in **FIGS. 6A** and **6B** are provided. **FIG. 6A** is an exemplary Cartesian plot **102** of an exemplary height and curvature of the optical surface **18'** that may be thermally formed in the ferrule assembly **12** of **FIGS. 1A** and **1B** according to the embodiments discussed herein. **FIG. 6B** is an exemplary three-dimensional (3-D) interferometric plot **104** of the exemplary height and curvature of the optical surface **18'** plotted in **FIG. 6A**.

**[0063]** The ferrule, such as the ferrule **14**, does not have to be uniformly manufactured from the same material or material composition. For example, it may be desired to provide the ferrule **14** that has a gradiated material or material composition having the same or similar thermal energy absorption characteristics as the optical fiber **16** proximate the second opening **23** of the ferrule **14**. The material or material composition of the ferrule **14** could be less absorptive of wavelength energy that is absorptive to the material of the optical fiber **16** at outer portions of the end face **20** of the ferrule **14**. In this manner, the outer portions of the ferrule **14** may not be thermally formed, while inner portions of the ferrule **14** are thermally formed at the end face **20** with the optical fiber **16**.

**[0064]** In this regard, **FIG. 7A** is a perspective view of an exemplary gradient material ferrule **14'** as part of a ferrule assembly **12'**. **FIG. 7B** is an end view of the gradient ferrule **14'** in **FIG. 7A** having a step-wise gradient of ferrule material. The gradient ferrule **14'** has an gradient of ferrule material **106**. The gradient of ferrule material **106** has the same or similar thermal energy absorption characteristics of the optical fiber **16** disposed in inner portion(s) **108** at least proximate to the second opening **23'** of the ferrule **14'**. The gradient of ferrule material **106** is less absorptive or not absorptive to the wavelength or wavelengths absorptive by the optical fiber **16** in outer portion(s) **110** from the second opening **23'** towards the outer perimeter of the ferrule **14'**.

**[0065]** The gradient ferrule **14'** in **FIGS. 7A** and **7B** has a step-wise gradient of the ferrule material **106**. In this regard, the ferrule **14'** is formed from a plurality of concentric ferrule material layers **112**, which is six concentric ferrule material layers **112(1)-112(6)** in this example. The ferrule material layer **112(1)** is most absorptive to the wavelength energy that is absorptive to the optical fiber **16**. The concentric ferrule material layer **112(2)** is less absorptive to the wavelength energy that is absorptive to the optical fiber **16** than the first concentric ferrule material layer **112(1)** as a function of radius, and so on until ferrule material layer **112(6)**, which may not be absorptive to the wavelength energy that is absorptive to the optical fiber **16**. In this manner, the inner portions **108** of the end face **20'** of the ferrule **14** are thermally formed with the end portion **22** of the optical fiber **16** to provide an optical surface **18'**, and to a lesser amount toward the outer portions **110** of the end face **20'** of the ferrule **14'**. The outer portion **110** of the end face **20'** of the ferrule **14'** may not be thermally formed with the end portion **22** of the optical fiber **16**.

**[0066]** Also, a gradient ferrule does not have to provide a step-wise gradient of ferrule material. For example, **FIG. 7C** is an end view of an exemplary gradient ferrule **14''** having a continuous absorption gradient of ferrule material **106''**. Like the ferrule **14'** in **FIG. 7B**, the inner portions of the gradient ferrule **14''** are comprised of ferrule material **106'** or compositions that are most absorptive to the wavelength energy that is absorptive to the optical fiber **16**. The outer portions **110'** of the gradient ferrule **14'** are less absorptive to the wavelength energy that is absorptive to the optical fiber **16** as a function of radius. In this manner, the inner portions **108** of the end face **20''** of the ferrule **14''** are thermally formed with the end portion **22** of the optical fiber **16** to provide an optical surface **18''**, and to a lesser amount toward the outer portions **110'** of the end face **20'** of the ferrule **14''**. The outer portion **110'** of the end face **20''** of the ferrule **14''** may not be thermally formed with the end portion **22** of the optical fiber **16**.

**[0067]** Different gradiated compositions of ferrule material of a gradient ferrule may be provided. For example, **FIG. 8** contains an exemplary gradiated material composition plot **112** of a gradient material composition that may be employed in a ferrule provided herein. **FIG. 8** shows a ferrule material composition of a zirconia-silica gradient ferrule as function of radius. As shown therein, at smaller radiuses of the ferrule **14'**, the composition of ferrule material **106, 106'** is of material (e.g., silica) that is absorptive to the wavelengths that are absorptive to a silica optical fiber **16**. At larger radiuses of the ferrule **14'**, the composition of ferrule material **106, 106'** is of material (e.g., zirconia) that is not absorptive to the wavelengths that are absorptive to a silica optical fiber **16**.

**[0068]** As used herein, it is intended that terms "fiber optic cables" and/or "optical fibers" include all types of single mode and multi-mode light waveguides, including one or more optical fibers that may be upcoated, colored, buffered, ribbonized and/or have other organizing or protective structures in a cable such as one or more tubes, strength members, jackets or the like. The optical fibers disclosed herein can be single mode or multi-mode optical fibers. Likewise, other types of suitable optical fibers include bend-insensitive optical fibers, or any other expedient of a medium for transmitting light signals. Non-limiting examples of bend-insensitive, or bend resistant, optical fibers are ClearCurve® Multimode or single-mode fibers commercially available from Corning Incorporated. Suitable fibers of these types are disclosed, for example, in U.S. Patent Application Publication Nos. 2008/0166094 and 2009/0169163, the disclosures of which are incorporated herein by reference in their entireties.

**[0069]** Many modifications and other embodiments of the embodiments set forth herein will come to mind to one skilled in the art to which the embodiments pertain having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the description and claims are not to be limited to the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims. It is intended that the embodiments cover the modifications and variations of the embodiments provided they come within the scope of the appended claims and their equivalents. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.

The claims defining the invention are as follows:

1. A ferrule assembly for a fiber optic connector, comprising:

a ferrule comprising a first end, a second end opposite the first end along an optical axis, a ferrule bore extending between a first opening of the first end and a second opening of the second end, and an end face disposed at the second end;

an optical fiber absorptive to the at least one wavelength, the optical fiber disposed in the ferrule bore of the ferrule, wherein at least a portion of the end face of the ferrule is absorptive to at least one wavelength such that the ferrule is made from a material or material composition that has the same or similar thermal energy absorption characteristics as the optical fiber;

an optical surface formed by thermally forming both at least a portion of the end face of the ferrule and the end portion of the optical fiber by simultaneously exposing the end face of the ferrule and the end portion of the optical fiber to a laser beam of the at least one wavelength emitted by a laser;

wherein the ferrule comprises an absorption gradient of ferrule material at the at least one wavelength disposed along a radial axis of the ferrule between an outer perimeter of the ferrule and an inner portion of the ferrule.

2. The ferrule assembly of claim 1, wherein the ferrule is comprised of a silica material.

3. The ferrule assembly at claim 2, wherein the silica material is doped with a titanium or titanium composite or a borosilicate material or glass ceramic.

4. The ferrule assembly of any one of claims 1 to 3, wherein the ferrule has a lower coefficient of thermal expansion than zirconia.

5. The ferrule assembly of any one of claims 1 to 4, wherein the absorption gradient of the ferrule material is comprised of a continuous gradient of the ferrule material.

6. The ferrule assembly of any one of claims 1 to 5, wherein the absorption gradient of the ferrule material is comprised of a plurality of concentric ferrule material layers disposed about the radial axis of the ferrule, a concentric ferrule material layer disposed adjacent the outer perimeter of the ferrule having a lower coefficient of thermal expansion than a concentric ferrule material layer disposed adjacent the inner portion of the ferrule.

7. The ferrule assembly of any one of the preceding claims, wherein the optical surface is thermally formed to have a radius of curvature between approximately 1 millimeter (mm) and 30 mm.

8. The ferrule assembly of any one of the preceding claims, wherein the optical surface is thermally formed in the ferrule bore proximate the end face of the ferrule.

9. The ferrule assembly of any one of the preceding claims, wherein the optical surface is thermally formed by simultaneously exposing the end face of the ferrule and the end portion of the optical fiber for a defined period sufficient to allow the at least the portion of the end face and the end portion of the optical fiber to become reflow material, and removing the end face of the ferrule and the end portion of the optical fiber from exposure to the laser beam to allow the reflow material of the at least the portion of the end face and the end portion of the optical fiber to cool into the optical surface.

10. A method of forming the ferrule assembly of any one of claims 1 to 9, comprising:

providing the ferrule;

disposing the optical fiber through the ferrule bore and extending the end portion of the optical fiber through the end face of the ferrule; and

simultaneously exposing the end face of the ferrule and the end portion of the optical fiber to a laser beam of at least one wavelength emitted by a laser to thermally form at least a portion of the end face of the ferrule and the end portion of the optical fiber to thermally form an optical surface.

11. The method of claim 10, comprising simultaneously exposing the end face of the ferrule and the end portion of the optical fiber to the laser beam of at least one wavelength in a wavelength range from 3000 nm to 8000 nm.

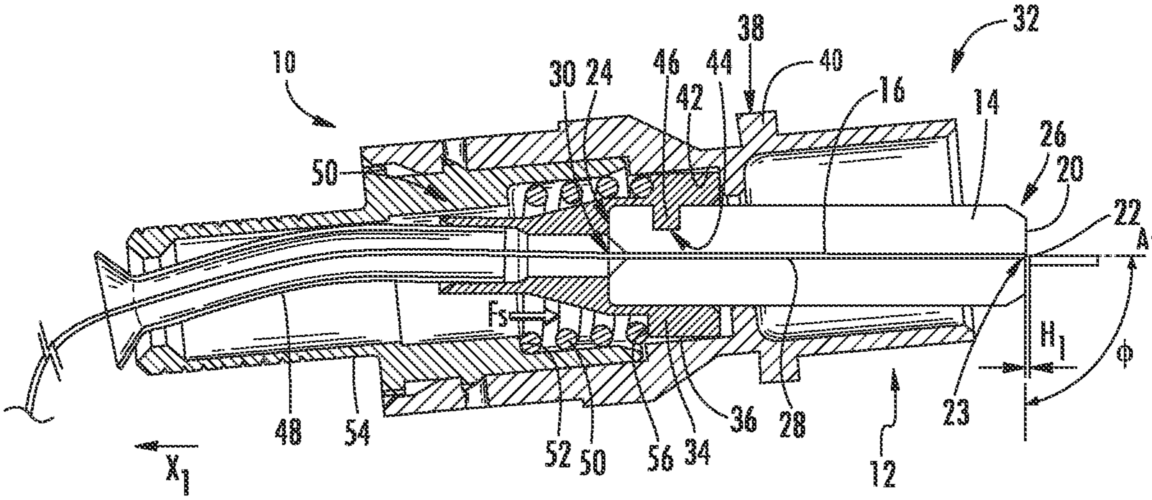
12. The method of claim 10 or claim 11, comprising simultaneously exposing the end face of the ferrule and the end portion of the optical fiber to the laser beam of the at least one wavelength from either a carbon dioxide laser or a carbon monoxide laser.

13. The method of any one of claims 10 to 12, comprising simultaneously exposing the end face of the ferrule and the end portion of the optical fiber for a defined period sufficient to allow the at least the portion of the end face of the ferrule and the end portion of the optical fiber to become reflow material; and

further comprising removing the end face of the ferrule and the end portion of the optical fiber from exposure to the laser beam to allow the reflow material of the at least the portion of the end face and the end portion of the optical fiber to cool into the optical surface.

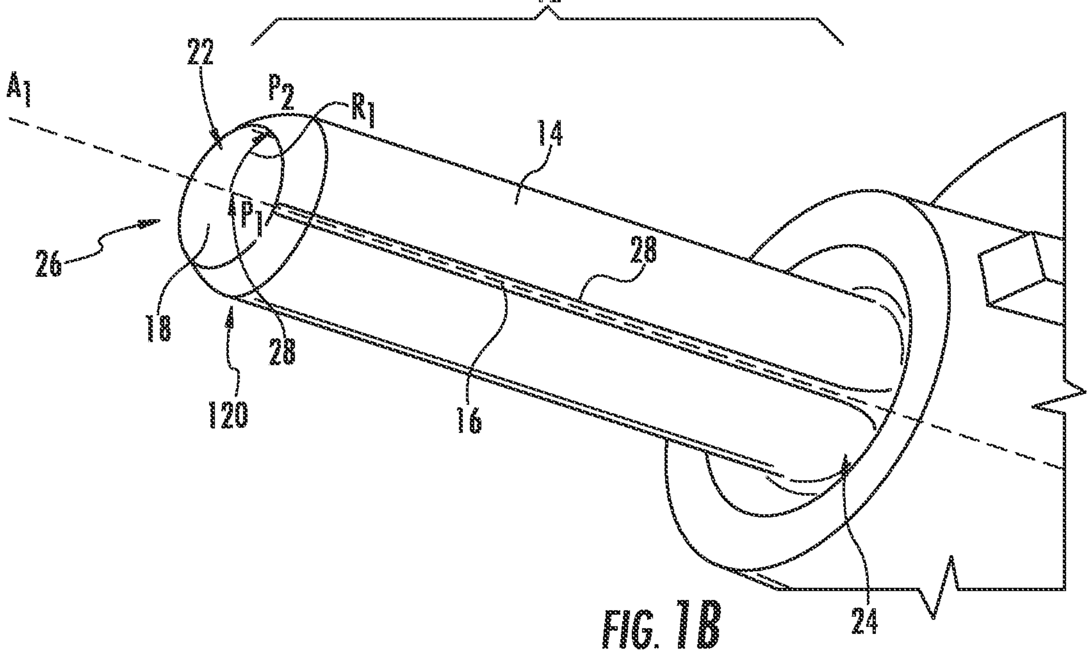
14. The method of any one of claims 10 to 13, further comprising simultaneously exposing the end face of the ferrule and the end portion of the optical fiber to be incident to the laser beam within a geometric plane intersecting an optical axis of the end portion of the optical fiber.

15. The method of any one of claims 10 to 14, wherein simultaneously exposing the end face of the ferrule and the end portion of the optical fiber further comprises sweeping the laser beam from the laser across the end face of the ferrule and the end portion of the optical fiber.



10
50
30
24
46
44
42
38
40
32
16
14
26
20
22
A1
Fs
H1
φ
48
54
52
50
56
34
36
28
23
12
X1


FIG. 1A



12
22
A1
P2
R1
14
26
P1
28
18
28
120
16
24


FIG. 1B

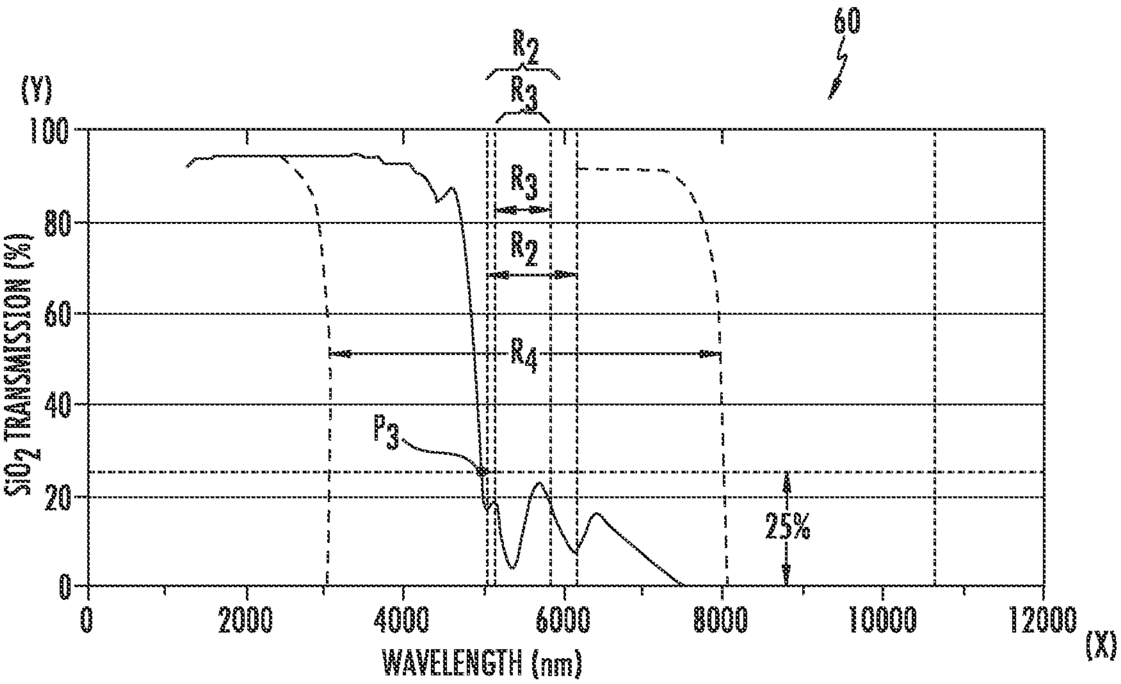

60
(Y)
R2
R3
R3
R2
R4
P3
25%
SiO2 TRANSMISSION (%)
100
80
60
40
20
0
0
2000
4000
6000
8000
10000
12000
(X)
WAVELENGTH (nm)

FIG. 2

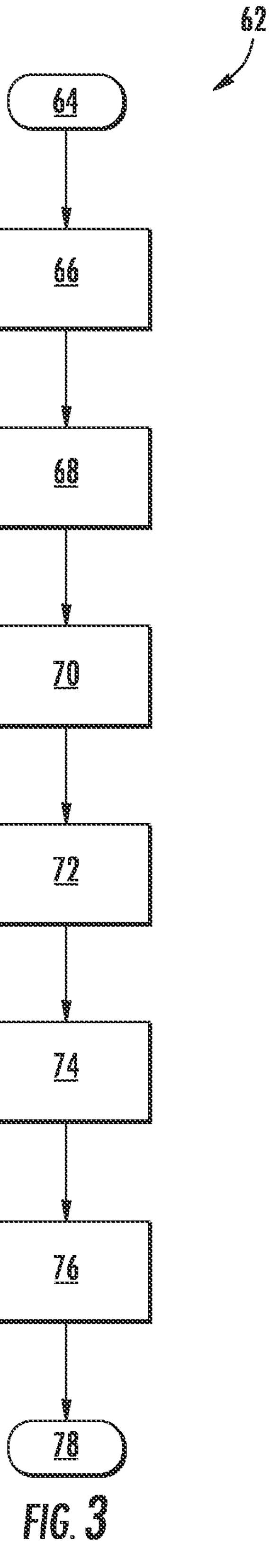



FIG. 3

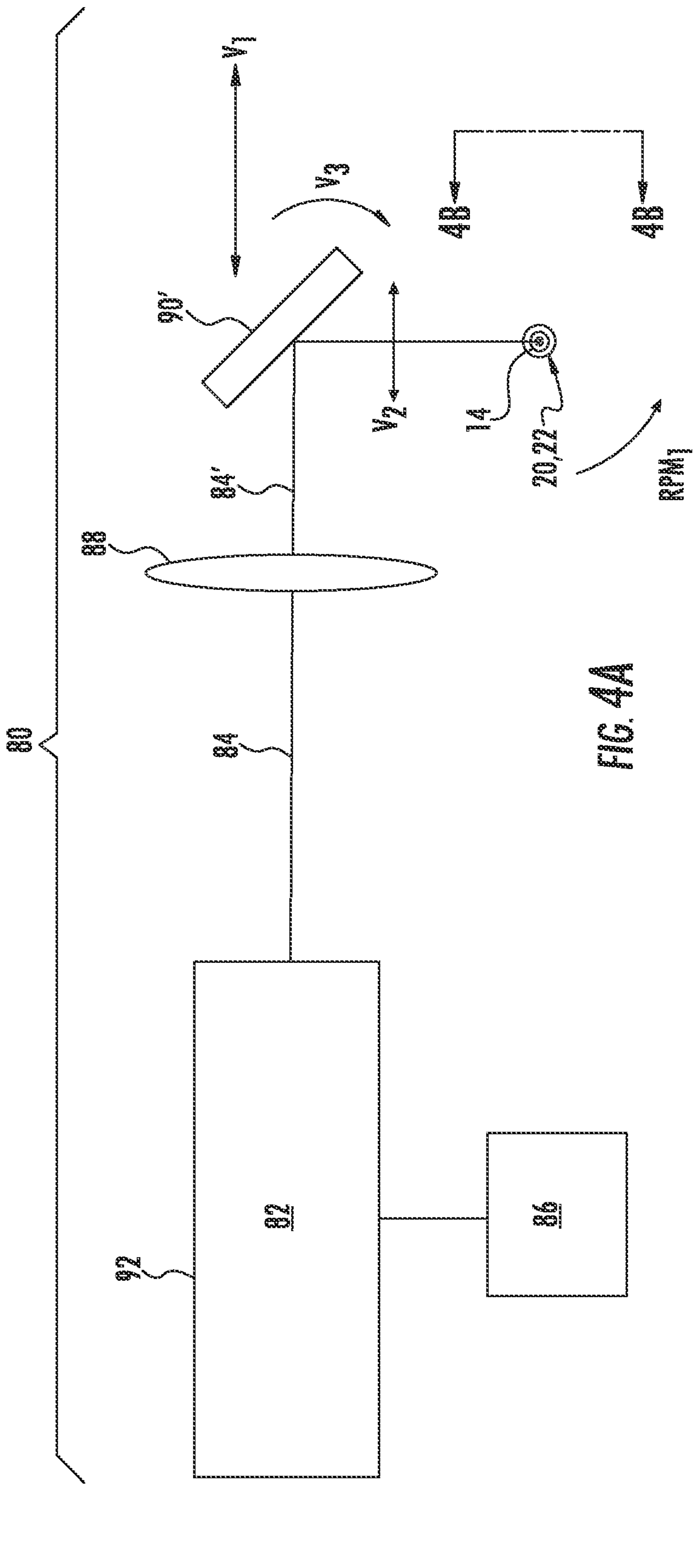



FIG. 4A

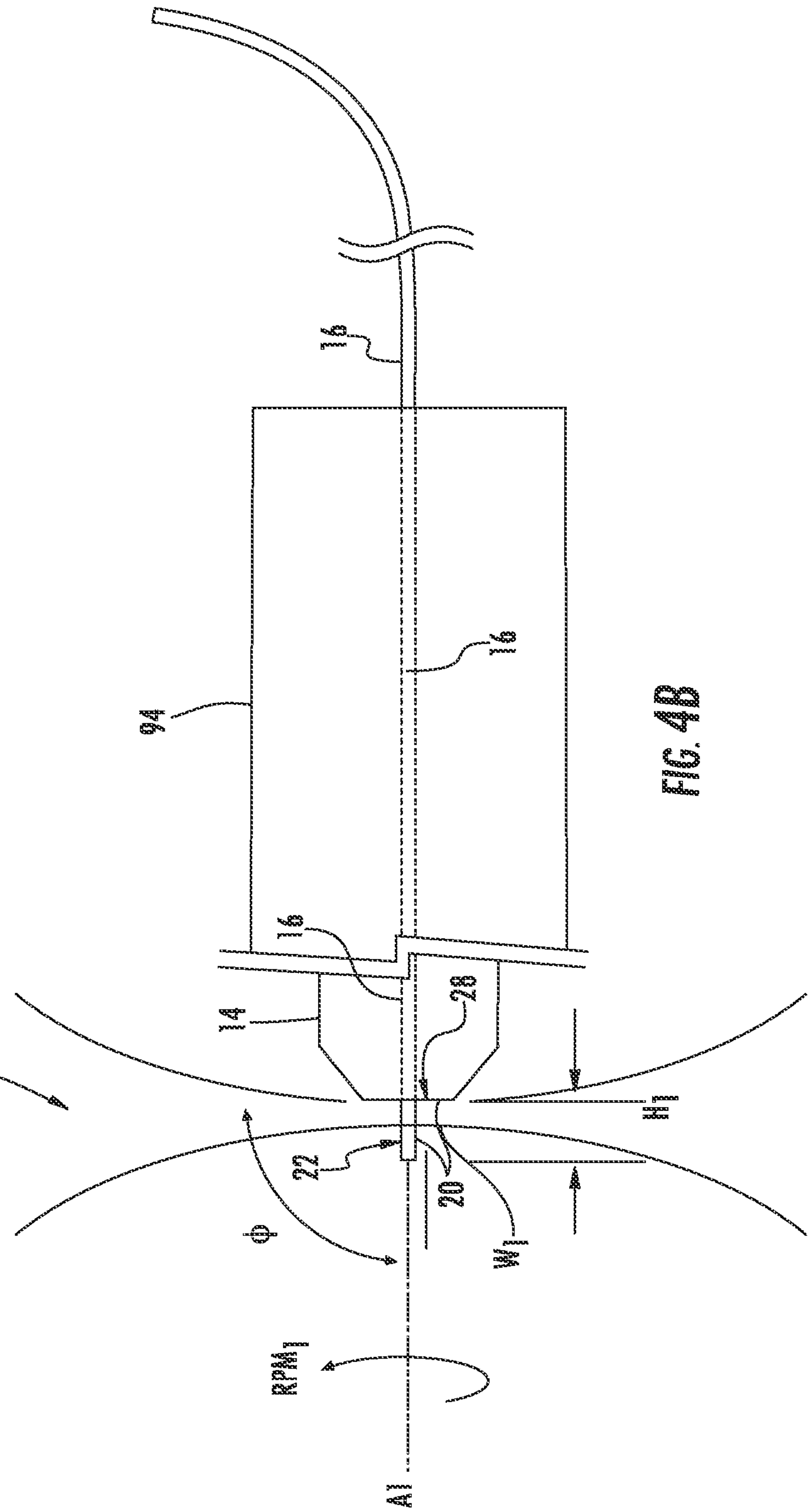



FIG. 4B

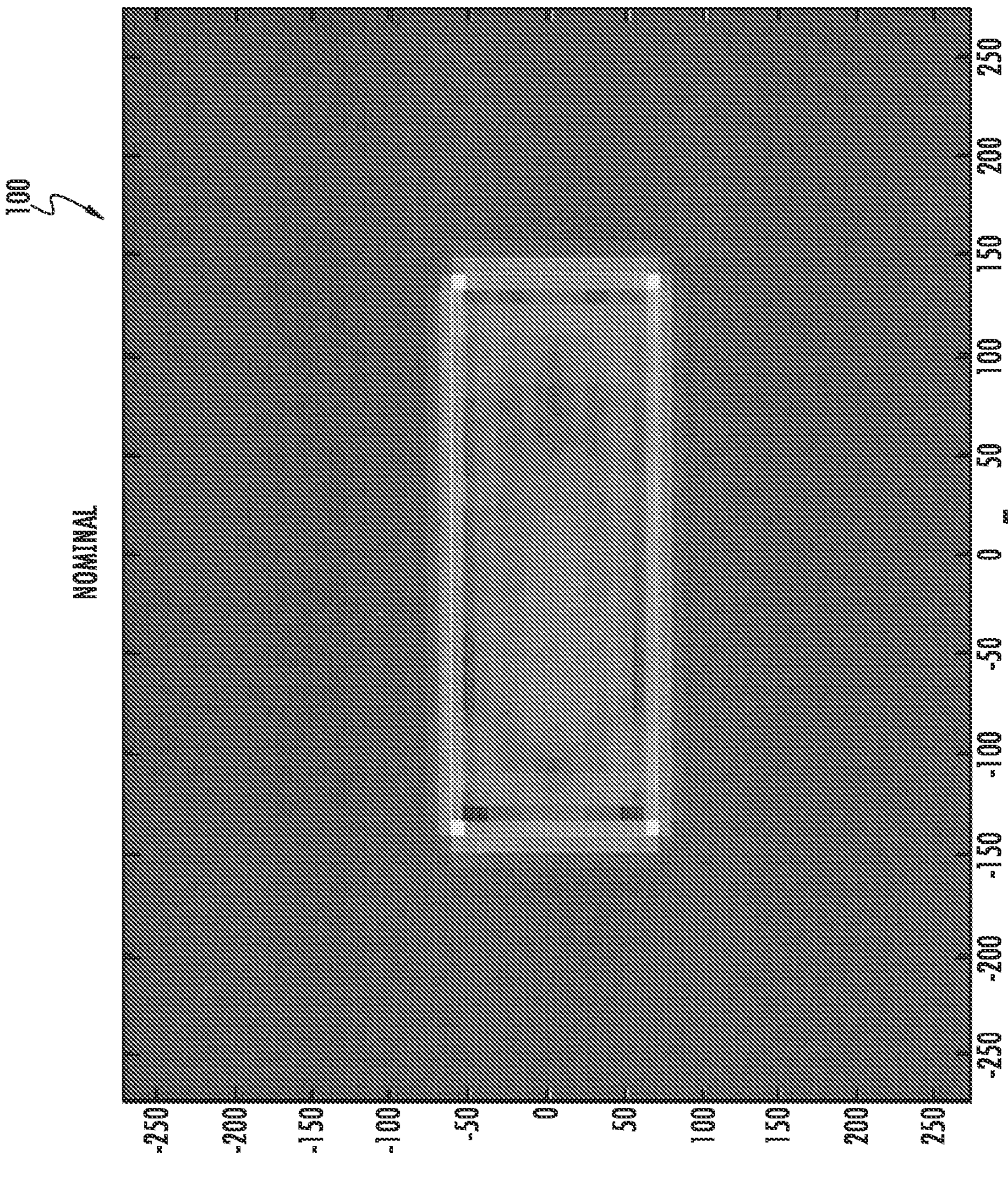

NOMINAL
100
-250
-200
-150
-100
-50
0
50
100
150
200
250
-250
-200
-150
-100
-50
0
50
100
150
200
250

FIG. 5

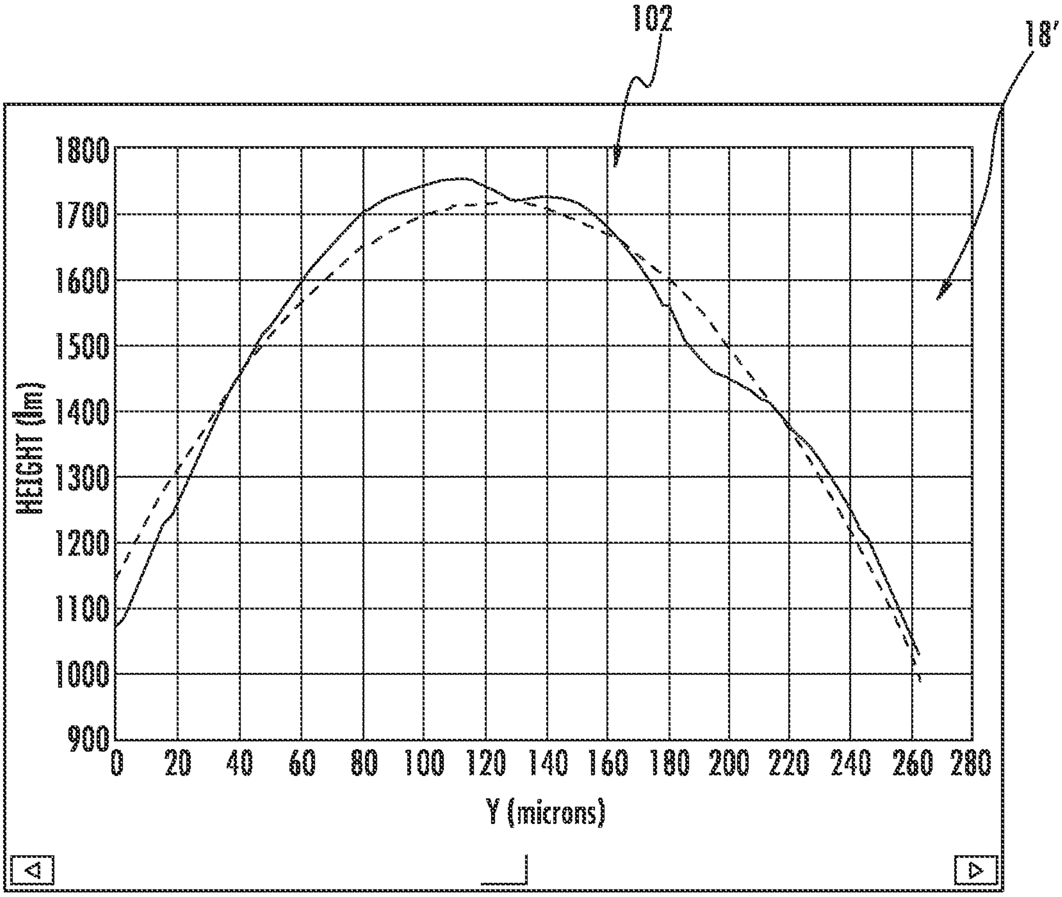

102
18'
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
HEIGHT (ãm)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
Y (microns)

FIG. 6A

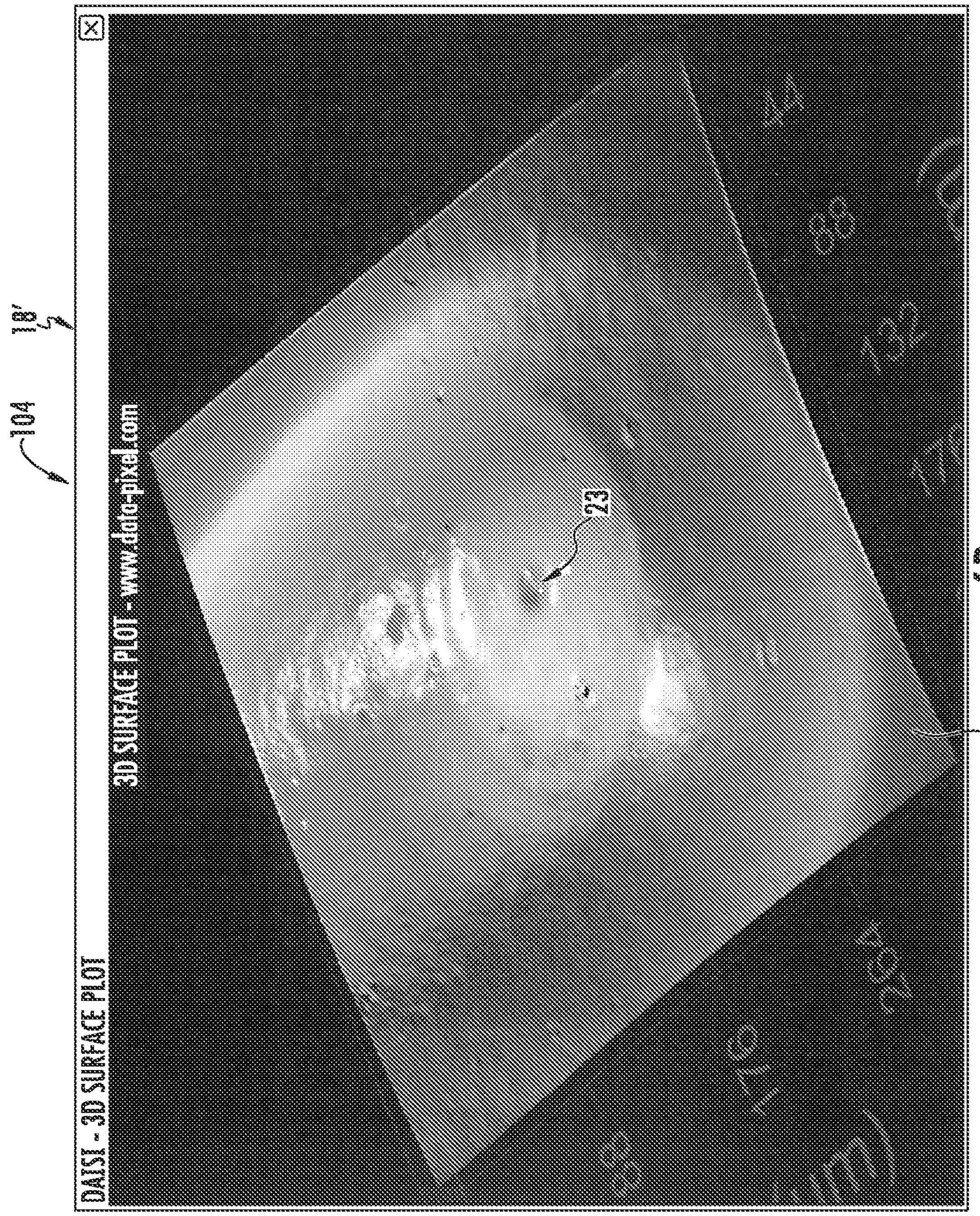

104
18'
DAISI - 3D SURFACE PLOT
3D SURFACE PLOT - www.data-pixel.com
23
20
44
88
132

FIG. 6B

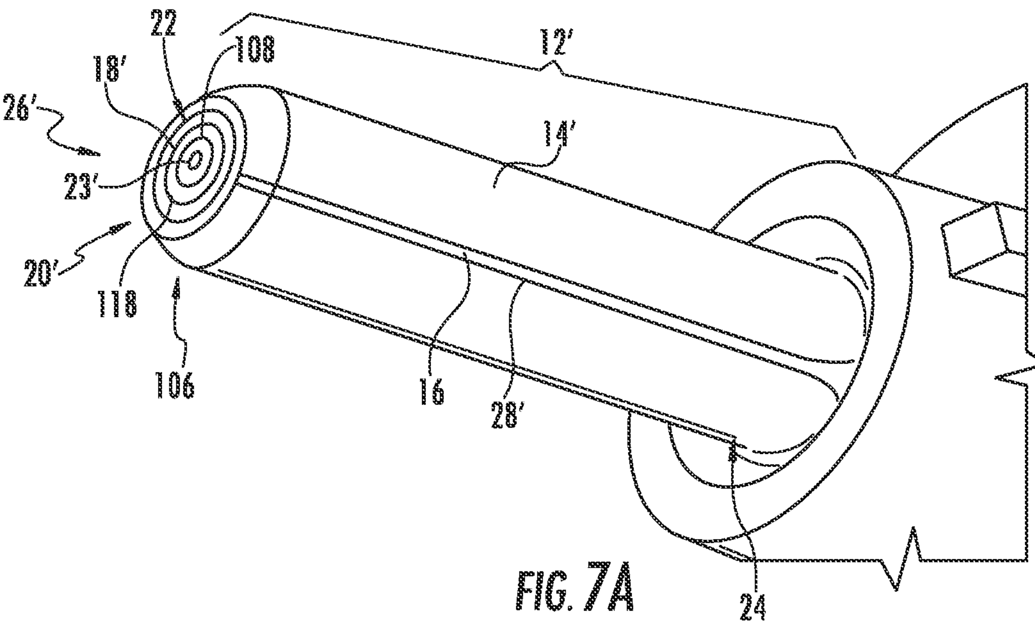



FIG. 7A

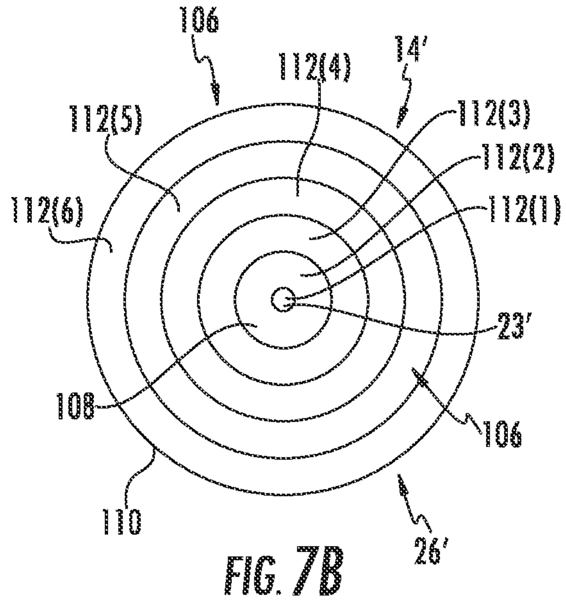



FIG. 7B

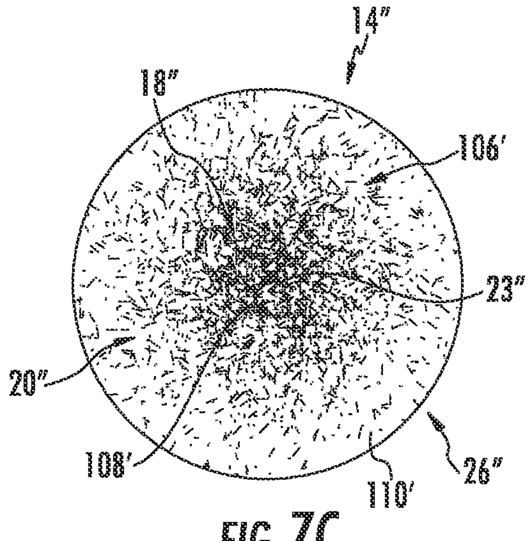



FIG. 7C

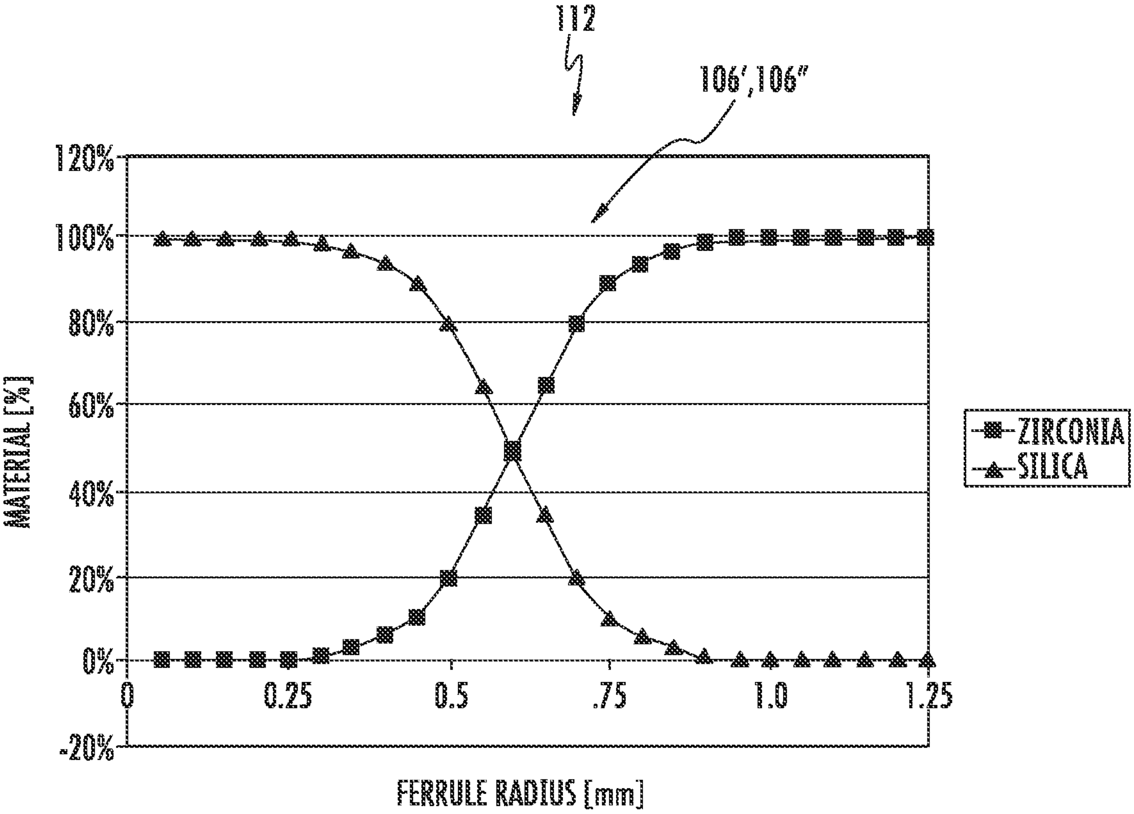

112
106',106"
120%
100%
80%
60%
40%
20%
0%
-20%
MATERIAL [%]
0
0.25
0.5
.75
1.0
1.25
FERRULE RADIUS [mm]
ZIRCONIA
SILICA

*FIG. 8*