MULTI-MATERIAL FIBERS AND METHODS OF MANUFACTURING THE SAME

Statement Regarding Federally Sponsored Research or Development

[0001] This invention was made with U.S. Government support under Agreement Number W15QKN-16-3-0001 awarded by the Army Contracting Command – New Jersey (ACC-NJ). The Government has certain rights in the invention.

Cross-Reference To Related Applications

[0002] This application claims priority to and the benefit of United States Provisional Patent Application Number 63/015,115 filed on April 24, 2020 and United States Provisional Patent Application Number 63/086,757 filed on October 2, 2020, the disclosures of which are incorporated herein by reference in their entireties.

Field of the Invention

[0003] Embodiments of the present invention relate generally to the field of drawing multi-material fibers from a preform material and, more specifically, to methods of drawing multi-material fibers for use in textiles and garments.

Background of the Invention

[0004] The incorporation of semiconductor technology within fibers, producing multi-material fibers, promises to revolutionize the textile market, converting traditional fibers, filaments, yarns, and the like into sophisticated devices. These multi-material fibers can endow the textiles into which they are intertwined with functions that may yield services to the end-user.

[0005] Conventional media for communication of data include wireless communication systems (e.g., WiFi), vacuum or fiber optic cable systems, hard-wired (cable) communication systems, and the like. The abundance of communication devices operating in and thereby saturating the radiofrequency (RF) domain demonstrates a need for new communication media. Advantageously, free space optical (FSO) communication provides a communication medium offering secure, line-of-sight (LoS), high-bandwidth data transmission to send information from one location to another using light.

[0006] More specifically, FSO communication propagates electromagnetic (EM) radiation through the air wherever light can travel, but only where light can travel. Advantageously, optical wireless communication systems operate in the visible to near infra-red (NIR) portion of the light spectrum, which offers 10^4 times more bandwidth compared to the RF region of most wireless communication systems.

[0007] Until recently, the fusion of FSO technology with textiles, e.g., wearable garments, has been negligible. However, because the average human body provides 1.5 to 2 square meters of surface area, which is fertile space for receiving FSO signals, especially in the context of LoS communications, opportunities for such fusion exist.

[0008] As multi-material fibers are developed, a prerequisite for successful productization of the technology is the development of reliable, robust, functional fibers that are capable of surviving the rigors of typical textile use cases. For example, over their usable life, all textiles, including those that contain multi-material fibers, should be capable of undergoing significant mechanical and environmental abuse (e.g., bending, stretching, twisting, machine washing, exposure to sunlight, exposure to temperature changes, and so forth) that expose the textile to a myriad of force types (e.g., tension, compression, torsion, and so forth). Conventional multi-material fibers are limited in their abilities to withstand these stimuli.

[0009] Indeed, in developing multi-material fibers, the textile industry has learned that standard thermoplastics, cross-sectional architectures, and internal electrical and electronic connection strategies cannot produce fibers with adequate reliability with respect to, for example, bend testing, machine washing, fabric incorporation, and/or use case survivability. Moreover, the incorporation of semiconductor devices at the preform fabrication stage may affect the resulting multi-material fiber by: limiting control over the location of the devices at the fiber level, reducing the density of devices per unit length that can be incorporated in the fibers, and/or restricting the types of cladding material(s) that can be used. These limitations may lead to lower yields as the number of connections between multi-material fibers intertwined in the textile increases.

[0010] Accordingly, a need exists for improved multi-material fibers and methods of manufacturing the same.

Summary ~~of the Invention~~

[0011] In a first aspect, ~~embodiments of~~ the present ~~invention~~ disclosure ~~relate to~~ provides a method of manufacturing a multi-material fiber having at least one ~~or more~~ electrically-connectable devices. ~~In some embodiments,~~ the method may include the steps of: positioning each electrically-connectable device within a corresponding pocket provided in a preform material; positioning a first electrical conductor longitudinally within a first conduit provided in the preform material; and drawing the multi-material fiber by causing the preform material to flow, such that the first electrical conductor extends within the multi-material fiber along a longitudinal axis thereof and makes an electrical contact with a first electrode located on each electrically-connectable device. ~~In pertinent part,~~ At least one of (i) a metallurgical bond may be formed between the first electrical conductor and the first electrode while drawing the multi-material fiber ~~and/~~or~~,~~ (ii) after drawing the multi-material fiber, the first electrical conductor may be located substantially along a neutral axis of the multi-material fiber. Alternatively, after drawing the multi-material fiber, the connection between the first electrical conductor and the first electrode of each electrically-connectable device may be located substantially along the neutral axis of the multi-material fiber.

[0012] In further applications, the method may include positioning a second electrical conductor longitudinally within a second conduit provided in the preform material and drawing the multi-material fiber by causing the preform material to flow, such that the second electrical conductor extends within the multi-material fiber along the longitudinal axis thereof and makes an electrical contact with a second electrode located on each electrically-connectable device. Advantageously, during the drawing, a metallurgical bond may be formed between the second electrical conductor and the second electrode and/or, after drawing the multi-material fiber, the second electrical conductor may be located substantially along the neutral axis of the multi-material fiber. Alternatively, after drawing the multi-material fiber, the connection between the second electrical conductor and the second electrode of each electrically-connectable device may be located substantially along the neutral axis of the multi-material fiber.

[0013] In some implementations, positioning the first electrical conductor may include positioning a copper alloy wire (e.g., a copper wire with a silver coating) within the first conduit. A bonding material (e.g., a metal alloy material such as a tin-bismuth solder) may be deposited on the first electrode prior to drawing the multi-material fiber. Preferably, the melting point of the bonding material substantially matches a glass transition temperature of

the preform material. In some variations, depositing the bonding material on the first electrode utilizes a hot press device.

[0014] In further implementations, the method may also include one or more of the following: controlling an aspect ratio (e.g., to be between about 1.1:1 and about 2.7:1) of the drawn multi-material fiber; overcoating the drawn multi-material fiber (e.g., using a thermoplastic elastomer material as an overcoat); positioning a support wire longitudinally within an additional conduit in the preform material to provide mechanical stability to each electrically-connectable device, such that, after the multi-material fiber is drawn, the support wire contacts each electrically-connectable device without making electrical contact with the first electrical conductor or the first electrode; and positioning one or more outer wires longitudinally within a corresponding conduit in the preform material, so that, after drawing the multi-material fiber, each outer wire may be located substantially along the neutral axis of the drawn multi-material fiber. In some variations, controlling the aspect ratio may include adding sidewalls to the drawn multi-material fiber. Sidewalls may be made of materials that are any one of: the same as the preform material, materials having the same or substantially the same glass transition temperature as the preform material but having other mechanical properties that differ, and the like. Advantageously, the twisting behavior can be better tuned (e.g., against twisting behavior) if the sidewalls have the same or substantially the same glass transition temperature of the preform material but have other mechanical properties that differ.

[0015] In some ~~embodiments~~examples, the method may also include interlacing the drawn multi-material fiber with additional fibers to form a textile. In some applications, the method may include adding rigidity to the textile, for example by one or more of: adding tubing to the textile; adding a plurality of stiffeners to the textile; adding a backing to the textile; and/or adding a ribbon-cable backing to the textile. In some variations, the method may further include wrapping the drawn multi-material fiber with an overwrap (e.g., cotton, polyester or any other textile yarn, high performance filaments, and/or high tensile strength fibers, such as aramids, dyneema, basalt fibers, and the like) prior to the interlacing and/or producing a composite yarn that includes a high modulus and/or high strength mono- or multi-filament yarn placed in parallel with a multi-material fiber and overwrapping the composite yarn with similar or other textile yarns.

[0016] In a second aspect, ~~embodiments of~~ the present ~~invention~~ disclosure ~~relate to~~ provides a textile that includes at least one ~~or more~~ multi-material fibers and a plurality of additional fibers interlaced with the multi-

material fiber~~(s)~~. ~~In some embodiments, t~~The multi-material fiber may include a cladding material, an electrically-connectable device (e.g., a light-emitting diode, a light-emitting device, a microphone, an inertial measurement unit, an interposer, an interconnect device, a temperature sensor, a light-responsive device, a photodetector, or a photodiode) disposed within the cladding material, and a first electrical conductor (e.g., a copper wire, a copper wire having a silver coating, a tungsten wire, a high tension wire, or an extra high tension wire) disposed within the cladding material and in electrical communication with a first electrode on the electrically-connectable device. ~~In pertinent part,~~ At least one of (i) the first electrical conductor ~~may be~~is in electrical communication with the first electrode via a first metallurgical bond ~~whose~~ that comprises a bonding material (e.g., a metal alloy material, such as a solder made of tin and bismuth) ~~has~~ having a melting temperature that substantially matches a glass transition temperature of the cladding material ~~and/~~or (ii) the first electrical conductor ~~may be~~is located substantially along a neutral axis of the multi-material fiber. Alternatively, after drawing the multi-material fiber, the connection between the first electrical conductor and the first electrode of the electrically-connectable device may be located substantially along the neutral axis of the multi-material fiber.

[0017] In some implementations, the multi-material fiber may further include a second electrical conductor in electrical communication with a second electrode on the electrically-connectable device. The second electrical conductor may be in electrical communication with the second electrode via a second metallurgical bond whose bonding material has a melting temperature that substantially matches the glass transition temperature of the cladding material and/or the second electrical conductor may be located substantially along the neutral axis of the multi-material fiber. Alternatively, after drawing the multi-material fiber, the connection between the second electrical conductor and the second electrode of the electrically-connectable device may be located substantially along the neutral axis of the multi-material fiber.

[0018] In some applications, the multi-material fiber may have one or more of the following: an aspect ratio between about 1.1:1 and about 2.7:1; an overcoating (e.g., a thermoplastic elastomer material); an overwrap (e.g., cotton, polyester or any other textile yarn, high performance filaments, and/or high tensile strength fibers, such as aramids, dyneema, basalt fibers, and the like), a support wire to provide mechanical stability to the device, and/or one or more outer wires (e.g., wires made from aramids, dyneema, tungsten, and so forth) that are located substantially along the neutral axis of the multi-material fiber.

Alternatively, the multi-material fiber may include a composite yarn that includes a high modulus and/or high strength mono- or multi-filament yarn placed in parallel with the multi-material fiber and overwrapping the composite yarn with similar or other textile yarns.

[0019] In an ~~third aspect~~ example, embodiments of the present ~~invention~~ disclosure relate to a method of manufacturing a multi-material fiber having one or more electrically-connectable devices. In some embodiments, the method may include the steps of: positioning a first electrical conductor longitudinally within a first conduit provided in a preform material; drawing the multi-material fiber by causing the preform material to flow; creating one or more pockets (e.g., by removing preform material using a laser and/or a milling machine) in the drawn multi-material fiber to expose the first electrical conductor; positioning an electrically-connectable device within each pocket, such that a first electrode on the electrically-connectable device is aligned with the first electrical conductor; forming a metallurgical bond between the first electrical conductor and the first electrode; and filling each pocket with an encapsulant material or an epoxy to protect the electrically-connectable device.

[0020] In some implementations, the method may also include positioning a second electrical conductor longitudinally within a second conduit provided in the preform material. In some variations: a pocket may be created to expose the second electrical conductor, the electrically-connectable device may be positioned within the pocket, such that a second electrode on the electrically-connectable device is aligned with the second electrical conductor, and/or a metallurgical bond between the second electrical conductor and the second electrode may be formed.

[0021] In further applications, the method may include one or more of: minimizing fluctuation of an outer diameter of the drawn multi-material fiber; coating the first electrode with a bonding material before the electrically-connectable device is positioned within the pocket; interlacing the drawn multi-material fiber with additional fibers to form a textile; removing preform material in a first drawn multi-material fiber in the textile to expose electrical conductors of the first drawn multi-material fiber; removing preform material in a second drawn multi-material fiber that, in the textile, intersects the first drawn multi-material fiber to expose electrical conductors of the second drawn multi-material fiber; and interconnecting the electrical conductors of the first drawn multi-material fiber to the electrical conductors of the second drawn multi-material fiber. In some variations, interconnecting the electrical conductors of the first drawn multi-material fiber to the

electrical conductors of the second drawn multi-material fiber includes inserting one or more of an interposer or a transposer therebetween.

[0022] In an ~~fourth aspect~~example, embodiments of the present ~~invention~~ disclosure relate to a textile that includes one or more multi-material fibers and additional fibers interlaced with the multi-material fiber(s). In some implementations, the multi-material fiber includes a drawn preform material (e.g., a thermoplastic material, a thermoplastic elastomer (e.g., polyetherimide (PEI)), or glass), an electrically-connectable device (e.g., a light-emitting diode, a light-emitting device, a microphone, an inertial measurement unit, an interposer, an interconnect device, a temperature sensor, a light-responsive device, a photodetector, or a photodiode) disposed within the drawn preform material, and a first electrical conductor (e.g., a copper wire, a copper wire comprising a silver coating, a tungsten wire, a high tension wire, or an extra high tension wire) disposed within the drawn preform material and in electrical communication with the electrically-connectable device. Preferably, the electrically-connectable device and some portion of the first electrical conductor are disposed in a pocket filled with a filling material or encapsulant (e.g., a photocured epoxy) to protect the electrically-connectable device.

[0023] In some applications, the multi-material fiber may further include a second electrical conductor disposed within the drawn preform material and in electrical communication with the electrically-connectable device. In some variations, a first electrode of the electrically-connectable device is bonded to the first electrical conductor via a bonding material and/or the first electrical conductor is located substantially along a neutral axis of the multi-material fiber. Alternatively, the connection between the first electrical conductor and the first electrode of the electrically-connectable device may be located substantially along the neutral axis of the multi-material fiber.

[0024] In some applications, the multi-material fiber may have one or more of the following: an aspect ratio between about 1.1:1 and about 2.7:1; an overcoating (e.g., a thermoplastic elastomer material); an overwrap (e.g., cotton, polyester or any other textile yarn, high performance filaments, and/or high tensile strength fibers, such as aramids, dyneema, basalt fibers, and the like), a support wire to provide mechanical stability to the device, and/or one or more outer wires (e.g., wires made from aramids, dyneema, tungsten, and so forth) that are located substantially along the neutral axis of the multi-material fiber. Alternatively, the multi-material fiber may include a composite yarn that includes a high

modulus and/or high strength mono- or multi-filament yarn placed in parallel with the multi-material fiber and overwrapping the composite yarn with similar or other textile yarns.

[0025] In a ~~fifth~~ third aspect, ~~embodiments of~~ the present ~~invention~~ disclosure provides ~~relate to~~ a method of manufacturing a multi-material fiber ~~having~~ comprising at least one ~~or more~~ electrically-connectable devices. ~~In some embodiments, t~~The method includes the steps of: fabricating a core portion of a composite preform, encasing the core portion within an outer sheath portion to form the composite preform, and thermally drawing the composite preform. ~~In some implementations, the~~the core portion includes a core material, at least one ~~or more~~ electrically-connectable device~~s~~, and at least one ~~or more~~ electrical conductor~~s~~ in electrical communication with the electrically-connectable device~~s~~. In some applications, the core portion and the outer sheath portion are manufactured from different materials having substantially similar glass transition temperatures. For example, the core portion may be manufactured from a thermoplastic (e.g., a cyclic olefin copolymer (COC)) and the outer sheath portion may be manufactured from a thermoplastic elastomer (e.g., an elastomeric-cyclic olefin copolymer (e-COC)).

[0026] In some variations, fabricating the core portion may include one or more of: providing multiple layers of the core material; forming a slot in at least two of the layers (e.g., in a first layer and a second layer); forming a pocket in a third layer disposed between the first and second layers; positioning a first electrical conductor in a first slot in the first layer; positioning a second electrical conductor in a second slot in the second layer; positioning an electrically-connectable device in the pocket in the third layer; and consolidating the first, second, and third layers (e.g., using a hot press device) to form the core portion. In some embodiments, encasing the core portion may include: placing the core portion between first and second clam shell portions of the outer sheath portion and consolidating the core portion, the first clam shell portion, and the second clam shell portion (e.g., using a hot press device). In some applications, the method may also include interlacing the drawn multi-material fiber with additional fibers to form a textile.

[0027] In a ~~sixth~~ fourth aspect, ~~embodiments of~~ the present ~~invention~~ disclosure ~~relate to~~ provides a textile. ~~In some embodiments, the~~the textile includes at least one ~~or more~~ multi-material fibers and a plurality of additional fibers interlaced with the multi-material fiber~~(s)~~. ~~In some applications, t~~The multi-material fiber includes a composite material, an electrically-connectable device disposed within the composite material, and at least one ~~or more~~ electrical conductors disposed within the composite material and in electrical communication with the

electrically-connectable device. ~~Preferably, t~~The composite material includes a first preform material having a first glass

transition temperature and a second preform material having a second glass transition temperature substantially similar to the first glass transition temperature and encasing the first preform material. In some variations, the electrically-connectable device and the electrical conductor(s) are disposed in the first preform material.

[0028] In a ~~seventh~~ fifth aspect, ~~embodiments of~~ the present ~~invention~~ disclosure provides ~~relate to~~ a method of manufacturing a multi-material fiber ~~having~~ comprising at least one ~~or more~~ electrically-connectable device~~s~~. ~~In some embodiments, t~~The method may include the steps of: thermally drawing a core preform, ~~manufactured from~~ comprising a first material ~~(e.g., thermoplastic polycarbonate)~~, at a first temperature to produce a first drawn fiber; inserting the first drawn fiber within a hollow portion of a second preform to form a composite preform, wherein the second preform ~~is manufactured from~~ comprises a second material (e.g., an elastomeric-cyclic olefin copolymer (e-COC)) that differs from the first material; and thermally drawing the composite preform at a second temperature to provide the multi-material fiber. The first drawn fiber includes at least one electrically-connectable device and at least one electrical conductor in electrical communication with the electrically-connectable device. In some implementations, the glass transition temperature of the second preform is less than the glass transition temperature of the core preform and/or the second temperature is less than the glass transition temperature of the core preform. ~~In some applications, the first drawn fiber includes one or more electrically-connectable devices and one or more electrical conductors in electrical communication with the electrically-connectable device(s).~~ In some variations, the method may also include interlacing the multi-material fiber with a plurality of additional fibers to form a textile.

[0029] In a~~n~~ ~~eighth~~ sixth aspect, ~~embodiments of~~ the present ~~invention~~ disclosure ~~relate to~~ provides a textile. ~~In some embodiments, the~~the textile includes at least one ~~or more~~ multi-material fiber~~s~~ and a plurality of additional fibers interlaced with the multi-material fiber~~(s)~~. ~~In some implementations, t~~The multi-material fiber includes a composite material, an electrically-connectable device disposed within the composite material, and at least one ~~or more~~ electrical conductor~~s~~ disposed within the composite material and in electrical communication with the electrically-connectable device. ~~Preferably, the~~the composite material ~~is manufactured from~~ comprises a first preform material and a second preform material encasing the first preform material, wherein the first preform material has a first glass transition temperature and the second preform material has a second glass transition temperature that is less than the first glass transition temperature. In some variations, the

electrically-connectable device and the electrical conductor(s) are disposed in the first preform material.

[0030] In a ~~ninth~~ seventh aspect, ~~embodiments of~~ the present ~~invention~~ disclosure provides ~~relate to~~ a method of manufacturing a multi-material fiber ~~having~~ comprising at least one ~~or more~~ electrically-connectable device~~s~~

(e.g., a light-emitting diode, a light-emitting device, a microphone, or an inertial measurement unit). ~~In some embodiments, t~~The method may include positioning a plurality of electrical conductors longitudinally within corresponding conduits provided in a preform material; drawing the multi-material fiber by causing the preform material to flow; creating at least one ~~or more~~ pockets in the drawn multi-material fiber to expose the electrical conductors; electrically coupling at least one of an interconnector ~~and/~~or an interposer to the exposed electrical conductors within the pocket; positioning an electrically-connectable device outside of the pocket; electrically coupling the electrically-connectable device to at least one of the interconnector ~~and/~~or the interposer; and encapsulating the electrically-connectable device and at least one of the interconnector ~~and/~~or the interposer.

[0031] In an ~~tenth~~ eighth aspect, ~~embodiments of~~ the present ~~invention~~ disclosure ~~relate to~~ provides a textile. ~~In some embodiments, t~~The textile includes at least one ~~or more~~ multi-material fiber~~s~~ and a plurality of additional fibers interlaced with the one or more multi-material fibers. ~~In some applications, t~~The multi-material fiber includes a cladding material; at least one ~~or more~~ of an interconnector or an interposer; an electrically-connectable device (e.g., a light-emitting diode, a light-emitting device, a microphone, or an inertial measurement unit) disposed outside of the cladding material; and a plurality of electrical conductors disposed within the cladding material and in electrical communication with at least one of the interconnector ~~and/~~or the interposer. Advantageously, the electrically-connectable device and at least one of the interconnector ~~and/~~or the interposer are encapsulated by a material.

[0032] These and other objects, along with advantages and features of the embodiments of the present ~~invention~~ disclosure herein disclosed, will become more apparent through reference to the following description, the accompanying drawings, and the claims. Furthermore, it is to be understood that the features of the various embodiments described herein are not mutually exclusive and can exist in various combinations and permutations.

Brief Description of the Drawings

[0033] In the drawings, like reference characters generally refer to the same parts throughout the different views. Also, the drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following description, various embodiments of the present invention are described with reference to the following drawings, in which: