

HOLDER FOR ALIGNING OPTICAL ENDCAPS CONNECTED TO OPTICAL FIBERS

CROSS REFERENCE TO RELATED APPLICATIONS

[001] This application is a PCT Application, which claims the benefit of priority of Israeli Patent Application No. 300635, filed on February 14, 2023, entitled "HOLDER FOR ALIGNING OPTICAL ENDCAPS CONNECTED TO OPTICAL FIBERS". The contents of the above applications are all incorporated by reference as if fully set forth herein in their entirety.

FIELD OF THE INVENTION

[002] The present invention relates generally to aligning optical fibers. More specifically, the present invention relates to a holder for aligning optical endcaps connected to optical fibers for high-power lasers.

BACKGROUND OF THE INVENTION

[003] Producing a high-power laser requires combining a plurality of laser beams. For the combination to be effective all of the beams must be accurately aligned and positioned. In addition, the beams need to be aligned in a compact structure.

[004] Working in high laser power causes the power density in the fiber core to be extremely high. To enable the laser beam to exit the fiber to free space environment a decrease of the power density must be performed. An Endcap is a glass window with a significantly larger diameter than the fiber core that enables the beam to expand with the fiber Numerical Aperture to a larger beam and a lower power density.

[005] The endcap length and diameter are equivalent to the power density reduction required and limited by the pitch between the endcaps and the mechanics of the structure holding all of the endcaps together.

[006] Internal reflections in the endcap may cause light to travel to the surrounding mechanics and may cause heat resulting in retention misalignments. The absorption of the glass can also cause heating of the endcap and the surrounding mechanics. Straying light in the system can also cause the surrounding mechanics to heat. The heating may also cause a temperature gradient which can potentially lead to laser efficiency loss.

[0007] Several attempts were made to overcome the heating and alignment deficiencies.

[0008] For example includes the V groove array, which is a mechanical plate with an accurate single row of V grooves milled into it. The Endcaps are attached to the V grooves and by that, they are aligned parallel to each other and in the correct spacing. This method uses for one-dimensional (1D) arrays only.

[0009] Therefore, there is a need for a different approach that will allow aligning a two-dimensional (2D) array of endcaps accurately while /reducing dramatically the thermal effects such as, thermal expansion and thermal distortion.

SUMMARY OF THE INVENTION

[0010] Some aspects of the invention may be directed to a holder for aligning optical endcaps each connected to an optical fiber, comprising: a body comprising: at least one row of bores, each being dimensioned to receive a single optical endcap; at least one adhesive channel, crossing at least one row of bores and configured to deliver and hold an adhesive material for fixating each optical endcap to a corresponding bore; and an array of cooling channels connected to at least one inlet and at least one outlet for circulating a cooling fluid, wherein the array of cooling channels is arranged to encompass at least a portion of the outer walls of each bore.

[0011] In some embodiments, each bore is dimensioned to receive the single optical endcap at a diameter tolerance up to 50 microns. In some embodiments, each row of bores comprises at least 2 bores. In some embodiments, the central axes all bores 122 deviate from being parallel to a reference optical axis by at most 0.05° . In some embodiments, a location of the central axes of all bores deviates from a reference point on the body by at most 0.007 mm.

[0012] In some embodiments, body is made from an alloy, selected from aluminum alloy, copper, titanium alloys, tungsten-based metal composites, carbon base composites.

[0013] In some embodiments, the array of cooling channels is arranged to encompass at least a portion of the outer walls of each bore such that any direct contact of the endcaps with the cooling fluid is avoided. In some embodiments, the holder may further include at least one pump in fluid connection with the at least one inlet and at least one outlet for circulating the cooling fluid. In some embodiments, the cooling fluid is selected to be fluid between -40°C to $+70^\circ\text{C}$.

[0014] Some additional aspects of the invention may be directed to an optical system comprising: a holder according to any one of the embodiments disclosed herein and an array

of optical fibers each welded to an endcap. In some embodiments, each endcap is inserted into a corresponding bore of the holder and fixated using the adhesive.

[0015] In some embodiments, all the endcaps are aligned with the same plane of the holder. In some embodiments, all the optical fibers and the endcaps are aligned to provide the same polarization.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] The subject matter regarded as the invention is particularly pointed out and distinctly claimed in the concluding portion of the specification. The invention, however, both as to organization and method of operation, together with objects, features, and advantages thereof, may best be understood by reference to the following detailed description when read with the accompanying drawings in which:

[0017] Figs. 1A and 1B are illustrations of front and back perspective views of an optical system comprising a holder holding and aligning optical endcaps each connected to an optical fiber, according to some embodiments of the invention;

[0018] Figs. 2A, 2B, 2C, 2D, 2E, 2F, and 2G are illustrations of various views and cross-sections of a holder for aligning optical endcaps each connected to an optical fiber, according to some embodiments of the invention;

[0019] Figs. 3A, 3B, 3C and 3D are illustrations of adhesive channels, crossing at least one row of bores in the holder according to some embodiments of the invention;

[0020] Figs. 4A, 4B and 4C are illustrations of several flow regimes in different arrays of cooling channels in the holder according to some embodiments of the invention; and

[0021] Fig. 5 is an illustration of a perspective view of another optical system comprising a holder holding and aligning 2D array of optical endcaps, according to some embodiments of the invention; and

[0022] Fig. 6 is an illustration of a perspective view of another optical system comprising a holder holding and aligning 1D array of optical endcaps, according to some embodiments of the invention.

[0023] It will be appreciated that for simplicity and clarity of illustration, elements shown in the figures have not necessarily been drawn to scale. For example, the dimensions of some of the elements may be exaggerated relative to other elements for clarity. Further, where considered appropriate, reference numerals may be repeated among the figures to indicate corresponding or analogous elements.

DETAILED DESCRIPTION OF THE PRESENT INVENTION

[0024] One skilled in the art will realize the invention may be embodied in other specific forms without departing from the spirit or essential characteristics thereof. The foregoing embodiments are therefore to be considered in all respects illustrative rather than limiting of the invention described herein. The scope of the invention is thus indicated by the appended claims, rather than by the foregoing description, and all changes that come within the meaning and range of equivalency of the claims are therefore intended to be embraced therein.

[0025] Aspects of the invention are direct to providing a holder to hold and align 2D or 1D array of optical endcaps each being welded to an optical fiber. The holder according to embodiments of the invention may provide an accurate aligning of all endcaps in the array and a cooling mechanism for evacuating any heat produced in the endcaps during the operation of the laser.

[0026] Reference is now made to Figs. 1A and 1B which are illustrations of front and back perspective views of an optical system comprising a holder holding and aligning optical endcaps each connected to an optical fiber, according to some embodiments of the invention. An optical system 1000 may include a holder 100 holding a 2D array of endcaps 10 each being welded to an optical fiber 15. In some embodiments, both endcaps 10 and optical fibers 15 are made from optical-grade glass.

[0027] In the nonlimiting example of holder 100 illustrated in Figs. 1A-1B and 2A-2B the 2D array is a hexagonal array, however, as should be understood by the one skill in the art, the invention is not limited to 2D arrays or this specific geometry. Examples for alternative holders showing additional 2D array and 1D array are illustrated and discussed with respect to Figs. 3 and 4 herein below.

[0028] Reference is now made to 2A, 2B, 2C, 2D, 2F, and 2G which are illustrations of various views and cross-sections of a holder for aligning optical endcaps each connected to an optical fiber, according to some embodiments of the invention. Holder 100 may include a body 110 made from any suitable heat-conducting material, such as but not limited to, Copper alloys, Aluminum alloys, Titanium alloys, Tungsten-based metallic composites, Carbon-based composites, and the like.

[0029] Body 110 may be manufactured using any suitable technology that will allow forming highly accurate (optical standards) shapes and cavities, for example, additive

manufacturing powder bed fusion using laser beam, laser ablation, accurate machining, electro-etching, electro-erosion and the like. In some embodiments, the manufacturing process may require one or more thermal (e.g., heat) treatments, depending on the selected material. In some embodiments, some of the surfaces of body 110 may be coated and/or provided with a surface treatment.

[0030] Body 110 may include at least one row 120 or bores 122, each being dimensioned to receive a single optical endcap 10. In some embodiments, body 110 may include only one row 120, as illustrated in Fig. 6, or a plurality of rows 120, e.g., 2, 3, 4, 5, 6, 7, 8, 10, 15, 20 or more, as illustrated in Figs. 2A-2F (e.g., 7 rows 120) and Fig. 4 (e.g., 7 rows). In some embodiments, each row 120 may include at least 2 bores 122, for example, between 2 to 50, between 4 to 40, between 5 to 20, between 5 to 10, or any number in between.

[0031] In some embodiments, bore 122 may have a circular cross-section, a hexagonal cross-section, a rectangular cross-section, and the like. In some embodiments, bore 122 may be characterized by a diameter of the circular cross-section, or a diameter of an incircle inscribed inside the hexagonal or rectangular cross-sections of between 0.5 to 20 mm, for example, 0.7 mm, 1.5 mm, 2 mm, 2.5 mm, 3 mm, 4 mm, 5 mm, 7 mm, 8 mm, 10 mm, 15 mm, 20 mm or any value in between.

[0032] In some embodiments, bore 122 is dimensioned to receive the single optical endcap at a diameter tolerance up to +50 microns, for example, +40 microns, +30 microns, +25 microns, +20 microns, +15 microns, +10 microns, +5 microns, +1 micron, and any value in between. For example, if the endcap and the corresponding bore are cylindrical, the diameter of the bore may be up to 50 microns larger than the diameter of the endcap. In yet another example, if the endcap and the corresponding bore are hexagonal prisms, the diameter of the incircle inscribed inside the bore hexagonal cross-section may be up to 50 microns larger than the diameter of the incircle inscribed inside the endcap.

[0033] In some embodiments, the central axes of all bores 122 deviate from being parallel to a reference optical axis by at most 1° , 0.5° , 0.1° , 0.05° , 0.01° . In some embodiments, the reference optical axis is defined by. In some embodiments, a location of the central axes of all bores 122 deviates from a reference point on body 110 by at most, ± 0.5 mm, ± 0.1 mm, ± 0.05 mm, ± 0.01 mm, 0.007 mm, ± 0.001 mm. For example, the reference point is defined as the central axes of a first bore 122a and first line 120a illustrated in Fig. 2C. In yet another

example, the reference point is defined as a reference pin or reference key and the like, attached to or included in body 110.

[0034] In some embodiments, the external end face of all endcaps held in holder 100 are aligned in the same plane, for example, an outer face 112 illustrated in Figs. 1A and 2D. Therefore, all endcaps 10 front and/or rare facets are substantially aligned to each other and with a reference plan, such as, plane 112, by 0.01, 0.02, 0.05, 0.06, 0.1, 0.2, 0.03, 0.5, 0.7, 0.8, 1 mm and any value in between.

[0035] In some embodiments, all endcaps 10 are optically aligned to provide laser beams having the same polarization. In such case, prior to fixating by the adhesive, each endcap may be adjusted (by rotation) to be in a predetermined polarization.

[0036] In some embodiments, body 110 may further include at least one adhesive channel 130 crossing at least one row of bores 120 and configured to deliver and hold an adhesive material for fixating each optical endcap 10 to corresponding bore 122, as illustrated in Fig. 2D and discussed in detailed with respect to Figs. 3A and 3B hereinbelow.

[0037] In a nonlimiting example, adhesive channel 130 may have a diameter of between 0.5 to 1 mm of the diameter of bore 122, for example, if bore 122 has a diameter of 2 mm adhesive channel 130 may have a diameter of 1.6 mm. In some embodiments, the adhesive material is an adhesive material selected from ultraviolet (UV) Epoxy, Silicone based, and the like. The adhesive material may be introduced into adhesive channel 130 after the insertion and the aligning of endcaps 10 inside bores 122. For example, the alignment and fixating process may be conducted row by row, such that, all endcaps inserted into a single row 120 may be aligned to have the same polarization and the same front/rare facets of the endcaps are substantially aligned to each other and to a reference plan. Following the end of the alignment process, the adhesive material may be introduced into the corresponding adhesive channel 130, for fixating the endcaps to the bores in their aligned position.

[0038] In some embodiments, the adhesive material may be selected as to have sufficient fluidity inside adhesive channel 130 while providing good wettability and adhesiveness between adhesive channel 130 and endcaps 10. Therefore the viscosity of adhesive material may be selected to be between 500K to 20K cP, for example, between 500K to 100K cP, between 400 to 50 cP, between 200 to 75 cP, and any value in between.. In some embodiments, the adhesive material may further be selected to have a thermal coefficient (after hardening) which is as close as possible to the thermal coefficient of body 110 and/or

endcaps 10. The thermal coefficient is selected to minimize the formation of thermal stress on endcaps 10. Therefore, the thermal coefficient (CTE) of the adhesive material may be between 1 to 200 [ppm°C] (and any value in between) and the thermal conductivity of the adhesive material may be between 0.1 to 2.5 [W/m²K]. Some nonlimiting examples for optional adhesive material are given in table 1.

[0039] Table 1.

Type	Thermal conductivity (W/m ² K)	CTE (ppm°C)	viscosity (Cp)
Urethane	1.59	167	500000
Silicon	0.31	120	30000
Epoxy	0.39	102	75000
Epoxy		35	80000

[0040] In some embodiments, body 110 may further include an array 140 of cooling channels 142 connected to at least one inlet 144 and at least one outlet 146 for circulating a cooling fluid, wherein array 140 of cooling channels 142 is arranged to encompass at least a portion of the outer walls of each bore 122, as illustrated in Fig. 2F. In some embodiments, array 140 of cooling channels 142 is arranged to encompass at least a portion of the outer walls of each bore 122 such that any direct contact of endcaps 10 with the cooling fluid is avoided. Some nonlimiting examples of optional arrays of cooling channels and flow regimes are illustrated and discussed with respect to Figs. 4A, 4B and 4C, herein below.

[0041] In some embodiments, holder 100 may further include at least one pump 150 in fluid connection with at least one inlet 144 and at least one outlet 146 for circulating the cooling fluid, for example, between array 140 and a chiller 160. Pump 150 and chiller 160 may be any commercially suitable components. In some embodiments, pump 150 and chiller 160 may be included in a single device, or may be two separate devices fluidically connected by a set of pipes. In some embodiments, the cooling fluid is selected to be fluid between -40 °C to +70 °C. In some embodiments, the cooling fluid may be in a gas or liquid phase. Some nonlimiting examples for cooling fluids may include, desalinated water, water with ethylene glycol, ethylene glycol, oil and the like.

[0042] Reference is now made to Figs. 3A, 3B, 3C and 3D which are illustrations of adhesive channels, crossing at least one row of bores 120 in the holder according to some embodiments of the invention. In some embodiments, the adhesive material may be

introduced into adhesive channel 130 via adhesive entrance 132, for example, by any injection means. For example, the nozzle of an adhesive gun (also known in the art as an injection gun or glue gun) may be attached/inserted into entrance 132 as to form an appropriate contact between the nozzle and entrance 132 prior to the injection of the adhesive material.

[0043] In some embodiments, each intersection 134 between any adhesive channel 130 and any bore 122 in holder 100 (marked in the dashed ellipsoid in Fig. 3B, the dashed circle in Fig. 3C, and shown in Fig. 3D), may have substantially the same area/size, such that substantially the same amount of adhesive may come in contact with each endcap 10. In some embodiments, adhesive channel 130 may cross a portion of the circumference of bore 122. For example, the portion may be about 15% of the circumference of bore 122, as illustrated. In other examples the portion may be about 5% of the circumference of bore 122, 10% of the circumference of bore 122, 20 % of the circumference of bore 122, 30 % of the circumference of bore 122, 40% of the circumference of bore 122, 50 % of the circumference of bore 122, or any value in between.

[0044] In some embodiments, each bore may be crossed by two adhesive channels 130, for example, the upper and lower 10% of the circumference of bore 122 may each be crossed by a respective adhesive channel 130.

[0045] Reference is now made to Figs. 4A, 4B, and 4C which are illustrations of several flow regimes in different arrays of cooling channels in the holder according to some embodiments of the invention. Each one of the arrays of cooling channels has a different number and different arrangements of cooling fluid inlets and outlets. As should be understood by the one skilled in the art, the illustrations in Figs. 4A, 4B, and 4C are given as examples only and the invention as a whole is not limited to these specific designs.

[0046] In some embodiments, the design of the array 140 of cooling channels, inlet(s) 144 and outlet(s) 146 was made to ensure uniform temperature distribution at all bores 122 in holder 100 and to minimize any thermal stresses applied on endcaps 10. The design may ensure that all bores 122 are exposed to substantially the same temperature (e.g., not more than 10 °C difference between the temperatures of different endcaps 10, for example, between 0.1 to 10 °C difference and any value in between) and this temperature applies neglectable thermal stresses on endcaps 10.

[0047] Holder 100 of Fig. 4A includes a single inlet 144 and a single outlet 146. The inlet flow is denoted by dark grey arrows and the outlet flow is denoted by light grey arrows. Such an arrangement may result in a full fluid mixture, ensuring uniform temperature distribution.

[0048] Holder 100 of Fig. 4B includes three inlets 144, 144A, and 144B and three outlets 146, 146A, and 146B in a mirror symmetry arrangement. Such an arrangement ensures a full internal fluid mixture in each channel 142 in array 140.

[0049] Holder 100 of Fig. 4C includes three inlets 144, 144A, and 144B and three outlets 146, 146A, and 146B, where the central inlet 144 is located between two side outlets 146A and 146B and the central outlet 146 is located between two side inlets 144A and 144B. Such an arrangement ensures immediate thermal uniformity.

[0050] Reference is now made to Figs. 5 and 6 which are illustrations of perspective views of two optical systems each comprising a holder holding and aligning optical endcaps each connected to an optical fiber, according to some embodiments of the invention.

[0051] An optical system 2000, illustrated in Fig. 5, may include a holder 200 holding a 2D array of endcaps 10 each being welded to an optical fiber 15. An optical system 3000, illustrated in Fig. 4, may include a holder 300 holding a 2D array of endcaps 10 each being welded to an optical fiber 15.

[0052] Holders 200 and 300 may include substantially the same elements and components as holder 100 discussed above. Holders 200 and 300 are different from holder 100 in the geometrical arrangement of bores 122. In holder 200 all bores 122 are arranged in a cubic 2D array and in holder 300 all bores 122 are arranged in a 1D array comprising a single row 120. As should be understood by one skilled in the art the 7 X 7 bore array illustrated in Fig. 5 and the 7 bores row illustrated in Fig. 6 are given as examples only and the invention is not limited to this configuration. In some embodiments, a rectangular 2D array may include any number of $n \times m$ bores 122, where n and m are integers.

[0053] In some embodiments, all the endcaps in systems 1000, 2000, and 3000 are aligned with the same plane of the holder, for example, outer surface 112.

[0054] In some embodiments, all the optical fibers 15 and the endcaps 10 of systems 1000, 2000, and 3000 are aligned to provide the same polarization.

[0055] Unless explicitly stated, the method embodiments described herein are not constrained to a particular order or sequence. Furthermore, all formulas described herein are

intended as examples only and other or different formulas may be used. Additionally, some of the described method embodiments or elements thereof may occur or be performed at the same point in time.

[0056] While certain features of the invention have been illustrated and described herein, many modifications, substitutions, changes, and equivalents may occur to those skilled in the art. It is, therefore, to be understood that the appended claims are intended to cover all such modifications and changes as fall within the true spirit of the invention.

[0057] Various embodiments have been presented. Each of these embodiments may of course include features from other embodiments presented, and embodiments not specifically described may include various features described herein.

CLAIMS

1. A holder for aligning optical endcaps each connected to an optical fiber, comprising:
 - a body comprising:
 - at least one row of bores, each being dimensioned to receive a single optical endcap;
 - at least one adhesive channel, crossing at least one row of bores and configured to deliver and hold an adhesive material for fixating each optical endcap to a corresponding bore; and
 - an array of cooling channels connected to at least one inlet and at least one outlet for circulating a cooling fluid, wherein the array of cooling channels is arranged to encompass at least a portion of outer walls of each bore.
2. The holder of claim 1, wherein each bore is dimensioned to receive the single optical endcap at a diameter tolerance up to 50 microns.
3. The holder according to claim 1 or claim 2, wherein each row of bores comprises at least 2 bores.
4. The holder according to any one of claims 1 to 3, a central axis of each bore deviates from being parallel to a reference optical axis by at most 0.05° .
5. The holder according to any one of claims 1 to 4, wherein a location of the central axis of each bore deviates from a reference point on the body by at most 0.007 mm.
6. The holder according to any one of claims 1 to 5, wherein the body is made from an alloy, selected from aluminum alloy, copper, titanium alloys, tungsten-based metal composites, carbon base composites.
7. The holder according to any one of claims 1 to 6, wherein the array of cooling channels is arranged to encompass at least a portion of the outer walls of each bore such that any direct contact of the endcaps with the cooling fluid is avoided.
8. The holder according to any one of claims 1 to 7, further comprising at least one pump in fluid connection with the at least one inlet and at least one outlet for circulating the cooling fluid.

9. The holder according to any one of claims 1 to 8, wherein the cooling fluid is selected to be fluid between -40°C to $+70^{\circ}\text{C}$.
10. An optical system comprising:
 - a holder according to any one of claims 1 to 9; and
 - an array of optical fibers each welded to an endcap, wherein each endcap is inserted into a corresponding bore of the holder and fixated using an adhesive.
11. The optical system of claim 10, wherein all the endcaps are aligned with the same plane of the holder.
12. The optical system of claim 9 or claim 10, wherein all the optical fibers and the endcaps are aligned to provide the same polarization.