United States Patent Application Publication 20250264713
Kind Code A1
Publication Date August 21, 2025
Inventor(s) BRANIGAN; Kyle et al.

VARIABLE RADIUS MIRROR

Abstract

A variable radius mirror includes a mirror element having a deformable face with an outer surface incorporating a reflective element. The deformable face is deformable in response to a pressure applied by a pressure medium acting on an inner surface of the deformable face. A ring extends around a perimeter of the deformable face and protrudes from the inner surface of the deformable face. The mirror element further includes at least one of a plurality of steps recessed at different depths into the inner surface of the deformable face, a cooling cavity having a pair of manifolds between the outer surface and the inner surface of the deformable face, and a sidewall of the ring having a curved inner surface and a curved outer surface.

Inventors: **BRANIGAN; Kyle (Pittsburgh, PA), Davis; Gregg E. (Gibsonia, PA), Schnur; Scott (Cabot, PA)**

Applicant: **II-VI Delaware, Inc.** (Wilmington, DE)

Family ID: **1000008578110**

Appl. No.: **19/200147**

Filed: **May 06, 2025**

Related U.S. Application Data

parent US continuation 18492346 20231023 parent-grant-document US 12320969 child US 19200147
parent US continuation 16552388 20190827 parent-grant-document US 11828930 child US 18492346

Publication Classification

Int. Cl.: **G02B26/08** (20060101); **G02B5/10** (20060101); **G02B26/06** (20060101)

U.S. Cl.:

CPC **G02B26/0825** (20130101); **G02B26/06** (20130101); G02B5/10 (20130101)

Background/Summary

BACKGROUND OF THE DISCLOSURE
Field of the Disclosure
[0001] The present disclosure relates generally to a variable radius mirror and, in particular, to a variable radius mirror for use with laser optics systems.
Description of Related Art
[0002] A variable radius mirror (VRM) is a form of an adaptive optic element used in industrial laser applications to control the convergence and/or divergence of a laser beam. A VRM is configured to vary a radius of curvature of a reflective mirror surface by deflecting or flexing a deformable face having the mirror surface via selective actuation of an actuator, such as via delivery of pressurized air to a cavity behind the mirror surface, to control where a laser beam comes to focus as the beam propagates.
[0003] There are many competing performance requirements that govern design of VRMs. A large curvature range is desirable in VRM design because it allows for more adjustment of focal position and spot size while making the overall system design more compact and lightweight. The requirement for a large curvature range must be balanced with material characteristics. In addition, VRMs used in high power laser optics systems need to dissipate heat efficiently from the mirror surface. These performance requirements are balanced by material selection and physical design to achieve the desired VRM characteristics.
[0004] Due to these and other design criteria, existing VRMs are associated with a number of structural and performance deficiencies. Achieving a large curvature range is challenging and requires an increasingly thin deformable face. While it is desired to have the deformable face bend under pressure in a spherical manner, such bending may happen only over a small portion in the center of the deformable face before the radius of curvature departs in a parabolic or catenary manner at outer edges of the deformable face. An existing solution for correcting these irregularities of the mirror surface is by contouring the back of the deformable face with a complex 3D curve. However, complex 3D curves are difficult to manufacture and verify for dimensional accuracy.
[0005] Stresses on the deformable face during manufacture of the VRM and/or from connecting the mirror cap having the deformable face onto a rigid mirror base can pass distortions through to the mirror surface. Existing VRMs compensate for such distortions by combining the mirror cap and the mirror base as a matched pair. However, due to high tolerance specifications, it can be difficult to match the mirror cap with the mirror base, especially if the mirror cap has a complex 3D curve on an inside surface of the deformable face.
[0006] Cooling channels are provided as close as possible to the mirror surface in order to increase heat transfer. However, the pressure within the cooling channels and thermal gradients across the deformable face due to irregular cooling medium flow within the cooling channels can impart various irregularities to the mirror surface, thereby impacting the desired performance of the VRM.
[0007] Conventional VRMs are typically made from copper alloys and/or stainless steel. These materials are selected for their ratio of stiffness to yield strength, which determines a degree to which the deformable face can be deformed while still showing a full elastic recovery. In addition to increasing the mass of the VRM, these materials create a galvanic potential across the cooling medium, thereby resulting in corrosion and scale buildup within the cooling channels.

Conventional VRMs are also machined to have sharp outer edges which define stress rising corners that may reduce the service life of the VRM.

[0008] Accordingly, there is a need in the art for an improved VRM that addresses these and other drawbacks and deficiencies associated with existing VRMs.

SUMMARY OF THE DISCLOSURE

[0009] In accordance with some non-limiting examples or aspects of the present disclosure, provided is an improved VRM that may include a mirror element including a deformable face having an outer surface with a reflective element. The deformable face may be deformable in response to a pressure applied by a pressure medium acting on an inner surface of the deformable face. The mirror element may further include a ring extending around a perimeter of the deformable face and protruding from the inner surface of the deformable face. The mirror element may further include at least one of: (A) a plurality of steps recessed into the inner surface of the deformable face, each of the plurality of steps recessed at a different depth relative to the inner surface of the deformable face; (B) a cooling cavity between the outer surface and the inner surface of the deformable face, the cooling cavity comprising a pair of manifolds fluidly connected to each other and each having a first curved end wall spaced apart from a second curved end wall; and (C) a sidewall of the ring having a curved inner surface and a curved outer surface.

[0010] In accordance with some non-limiting examples or aspects of the present disclosure, a VRM may have a base element and a mirror element connected to the base element with a pressure cavity defined between the base element and the mirror element. The mirror element may have a deformable face having an outer surface with a reflective element. The deformable face may be deformable in response to a pressure applied by a pressure medium within the pressure cavity acting on an inner surface of the deformable face. The mirror element may further have a ring extending around a perimeter of the deformable face and protruding from the inner surface of the deformable face. The mirror element may further have at least one of: (A) a plurality of steps recessed into the inner surface of the deformable face, each of the steps recessed relative to the inner surface of the deformable face at an increasing or decreasing depth in a direction away from a central axis; (B) a cooling cavity between the outer surface and the inner surface of the deformable face, the cooling cavity comprising a pair of manifolds each having a first curved end wall spaced apart from a second curved end wall, the manifolds fluidly connected to each other by a plurality of cooling channels extending through the first curved end wall of each manifold; and (C) a sidewall of the ring having a curved inner surface and a curved outer surface.

[0011] In accordance with some non-limiting examples or aspects of the present disclosure, a variable radius mirror may include a base element and a mirror element connected to the base clement with a pressure cavity defined between the base element and the mirror element. The mirror element may include a deformable face having an outer surface with a reflective element. The deformable face may be deformable in response to a pressure applied by a pressure medium within the pressure cavity acting on an inner surface of the deformable face. The mirror element may further include a ring extending around a perimeter of the deformable face and protruding from the inner surface of the deformable face. A sidewall of the ring may have a curved inner surface and a curved outer surface. A plurality of steps may be recessed into the inner surface of the deformable face, with each of the steps being recessed at a different depth relative to the inner surface of the deformable face. A cooling cavity may be provided between the outer surface and the inner surface of the deformable face. The cooling cavity may include a pair of manifolds fluidly connected to each other and each having a first curved end wall spaced apart from a second curved end wall. The mirror element may be made from a metal material having an elastic modulus less than or equal to 100 GPa.

[0012] These and other features and characteristics of the present disclosure, as well as the methods of operation and functions of the related elements of structures and the combination of parts and economics of manufacture, will become more apparent upon consideration of the following description and the appended claims with reference to the accompanying drawings, all of which form a part of this specification, wherein like reference numerals designate corresponding parts in the various figures. It is to be expressly understood, however, that the drawings are for the purpose of illustration and description only and are not intended as a definition of the limits of the disclosure.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] FIG. **1** is a top perspective view of a VRM in accordance with some non-limiting examples or aspects of the present disclosure;

[0014] FIG. **2** is an exploded side view of the VRM shown in FIG. **1**;

[0015] FIG. **3** is a first side cross-sectional view of the VRM shown in FIG. **1**;

[0016] FIG. **4** is a second side cross-sectional view of the VRM shown in FIG. **1**;

[0017] FIG. **5** is top perspective view of a mirror element for use with a VRM in accordance with some non-limiting examples or aspects of the present disclosure;

[0018] FIG. **6** is a side view of the mirror element shown in FIG. **5**;

[0019] FIG. **7** is a bottom view of the mirror element shown in FIG. **5**;

[0020] FIG. **8** is a detailed cross-sectional view of a plurality of steps on an inner surface of the mirror element shown in FIG. **5**;

[0021] FIG. **9** is a side cross-sectional view of the mirror element shown in FIG. **5**; and

[0022] FIG. **10** is a side cross-sectional view of the mirror element shown in FIG. **5**.

DETAILED DESCRIPTION OF THE DISCLOSURE

[0023] As used herein, the singular form of “a”, “an”, and “the” include plural referents unless the context clearly dictates otherwise.

[0024] Spatial or directional terms, such as “left”, “right”, “inner”, “outer”, “above”, “below”, and the like, relate to the invention as shown in the drawing figures and are not to be considered as limiting as the invention can assume various alternative orientations.

[0025] All numbers used in the specification and claims are to be understood as being modified in all instances by the term “about”. By “about” is meant plus or minus ten percent of the stated value, such as plus or minus five percent of the stated value.

[0026] As used herein, “at least one of” is synonymous with “one or more of”. For example, the phrase “at least one of A, B, or C” means any one of A, B, or C, or any combination of any two or more of A, B, or C. For example, “at least one of A, B, and C” includes A alone; or B alone; or C alone; or A and B; or A and C; or B and C; or all of A, B, and C.

[0027] The term “includes” is synonymous with “comprises”.

[0028] As used herein, the terms “parallel” or “substantially parallel” mean a relative angle as between two objects (if extended to theoretical intersection), such as elongated objects and including reference lines, that is from 0° to 5°, or from 0° to 3°, or from 0° to 2°, or from 0° to 1°, or from 0° to 0.5°, or from 0° to 0.25°, or from 0° to 0.1°, inclusive of the recited values.

[0029] As used herein, the terms “perpendicular” or “substantially perpendicular” mean a relative angle as between two objects at their real or theoretical intersection is from 85° to 90°, or from 87° to 90°, or from 88° to 90°, or from 89° to 90°, or from 89.5° to 90°, or from 89.75° to 90°, or from 89.9° to 90°, inclusive of the recited values.

[0030] As used herein, the term “and/or” refers to both or either of two stated possibilities.

[0031] With initial reference to FIGS. **1-2**, a variable radius mirror (VRM) **100** is shown in accordance with some examples or aspects of the present disclosure. The VRM **100** may be configured for use as an adaptive optic element in optical systems. For example, the VRM **100** may be used in industrial laser applications to control the convergence and/or divergence of a laser beam. The VRM **100** generally has a mirror element **200** and a base **300**. The mirror element **200** may be removably connected to the base **300**, such as using a plurality of fasteners **302**. The mirror element **200** is configured to vary a focus point of the laser beam reflected from a reflective surface on the mirror element **200**.

[0032] With continued reference to FIGS. **1-2**, the mirror element **200** includes a deformable face **202** having an outer surface **204** and an inner surface **206** (shown in FIGS. **3-4**). A reflective mirror surface or element **207** is positioned on at least a portion of the outer surface **204** and is configured to reflect the laser beam. The mirror element **200** is configured to vary a radius of curvature of the deformable face **202** by deflecting or flexing the deformable face **202** in a direction along a central axis **210** via selective actuation of an actuation mechanism, as described herein. Deflection of the deformable face **202** in turn changes a radius of curvature of the reflective clement **207** to control the convergence, divergence, or collimation of the reflected laser beam. In some examples or aspects, the actuation mechanism for deflecting the deformable face **202** may be pressure applied by a pressure medium acting on the inner surface **206** of the deformable face **202**. By varying the radius of curvature of the reflective clement **207** via deflection of the deformable face **202**, a focus point of a laser beam can be controlled to diverge the beam, converge the beam, or collimate the beam.

[0033] In some examples or aspects, the mirror element **200** has a circular cross-sectional shape. For example, as shown in FIG. **1**, the deformable face **202** of the mirror element **200** has a circular shape with points along an outer edge of the deformable face **202** being substantially equidistant from a central axis **210**. In other examples or aspects, the mirror element **200** may have an oval. elliptical, or oblong shape having one or more axes of symmetry. In such examples or aspects, the central axis **210** may define an approximate midpoint of the deformable face **202**. In further examples or aspects, the mirror element **200** may have any other cross-sectional shape.

[0034] In some examples, the mirror element **200** may have a radius of 0.8 m concave to 0.8 m convex, with a usable clear aperture of 5% to 90% of a surface area of the deformable face **202**. The size of the mirror clement **200** is selected based on a desired application, such as the power of the laser beam or a desired focal length.

[0035] With reference to FIGS. **3-4**, and with continued reference to FIGS. **1-2**, the mirror clement **200** has a ring **208** protruding away from the deformable face **202**. In some examples or aspects, the ring **208** extends around a perimeter of the deformable face **202** and protrudes away from the inner surface **206**. In examples or aspects where the deformable face **202** has a circular shape, the ring **208** is revolved around the central axis **210** and has a corresponding circular shape that is centered around the central axis **210** and extends from the inner surface **206** at or near an outer edge **212** of the deformable face **202**. In examples or aspects where the deformable face **202** has an oval, elliptical, or oblong shape, the ring **208** has a corresponding oval, elliptical, or oblong shape that extends from to the inner surface **206** at or near the outer edge **212**. In some examples or aspects, a sidewall defined by the ring **208** extends in a direction that is substantially perpendicular to a plane defined by the deformable face **202**. In other examples or aspects, the sidewall defined by the ring **208** extends in an acute or obtuse angle relative to the plane defined by the deformable face **208**. A groove **209** is cut into the ring **208**. The groove **209** is continuous along an entire perimeter of the ring **208**.

[0036] With continued reference to FIGS. **3-4**, a pressure cavity **306** is defined between the mirror element **200** and the base **300**. The pressure cavity **306** is in fluid communication with a pressure source **308** having a pressure medium that is used to pressurize the pressure cavity **306** in order to deform the deformable face **202**. In some examples or aspects, the pressure medium is a gas (such as air), or a liquid. The mirror element **200** and the base **300** are connected together in a leak-proof manner to prevent escape of the pressure medium from the pressure cavity **306**. For example, a gasket **304** may be provided at an interface between the ring **208** and the base **300**.

[0037] With reference to FIG. **3**, the base **300** has one or more passages **310** having a first end in fluid communication with the pressure source **308** and a second end in fluid communication with the pressure cavity **306**. The pressure source **308** may include at least one of a storage tank for storing the pressure medium, a pump for pressurizing the pressure medium and/or delivering the pressure medium from the storage tank, and one or more fluid lines for delivering the pressure medium from the storage tank and/or the pump to the base **300**. In addition, one or more valves may be provided to control the flow of the pressure medium between the pressure source **308** and the pressure cavity **306**.

[0038] In some examples or aspects, the base **300** may have one or more inlet passages **310***a* for introducing the pressure medium from the pressure source **308** into the pressure cavity **306** and one or more outlet passages **310***b* for exhausting the pressure medium from the pressure cavity **306**. In other examples or aspects, the base **300** may have a single passage **310** for introducing the pressure medium into the pressure cavity **306** and exhausting the pressure medium from the pressure cavity **306**. One or more valves (not shown) may be provided to control the flow of the pressure medium into and out of the pressure cavity **308** via the one more passages **310**.

[0039] With continued reference to FIG. **3**, a pressure controller **312** controls the passage of pressure medium into and out of the pressure cavity **306**. For example, the pressure controller **312** is configured to increase the pressure of the pressure medium within the pressure cavity **306** in order to increase a deflection of the deformable face **202** and change its radius of curvature or decrease the pressure of the pressure medium within the pressure cavity **306** in order to decrease a deflection of the deformable face **202**. For example, the pressure controller **312** may control the output of a pump or other pressurization system used to pressurize the pressure medium and/or deliver the pressurized medium to the pressure cavity **306**. Desirably, the pressure controller **312** is configured to control the pressure of the pressure medium within the pressure cavity **306** without introducing perturbations into the reflective surface of the reflective element **206** which would otherwise disturb focus of the laser beam. In some examples or aspects, the pressure controller **312** is configured to control the pressure within the pressure cavity **306** between 0 bar to 15 bar absolute pressure.

[0040] With continued reference to FIG. **3**, the mirror clement **200** has a cooling cavity **214** defined between the outer surface **204** and the inner surface **206** of the deformable face **202**. The cooling cavity **214** is in fluid communication with a cooling medium source **314** having a cooling medium that is delivered to the cooling cavity **214** to cool the deformable face **202**. In some examples or aspects, the cooling medium is a gas (such as air), or a liquid. The cooling cavity **214** has a plurality of cooling channels **216** configured for flowing the cooling medium therethrough.

[0041] With reference to FIG. **4**, the base **300** has one or more cooling passages **316** having a first end in fluid communication with the cooling medium source **314** and a second end in fluid communication with the cooling cavity **214**. The cooling medium source **314** may include at least one of a storage tank for storing the cooling medium, a pump for delivering the cooling medium from the storage tank, and one or more fluid lines for delivering the cooling medium from the storage tank and/or the pump to the base **300**. In addition, one or more valves may be provided to control the flow of the cooling medium between the cooling medium source **314** and the cooling cavity **214**.

[0042] In some examples or aspects, the base **300** may have one or more inlet cooling passages **316***a* for introducing the cooling medium into the cooling cavity **214** and one or more outlet cooling passages **316***b* for exhausting the cooling medium from the cooling cavity **214**. A cooling controller **318** controls the passage of the cooling medium into and out of the cooling cavity **214**. For example, the cooling controller **318** is configured to increase or decrease a flow rate and/or pressure of the cooling medium delivered to the cooling cavity **214** in order to increase or decrease a rate of heat dissipation from the deformable face **202**. In some examples or aspects, the cooling controller **318** is configured to control the flow rate of the cooling medium delivered to the cooling cavity **214** between 0.01 L/min to 100 L/min. Desirably, the cooling controller **318** is configured to control the flow rate and/or pressure of the cooling medium flowing through the cooling cavity **214** without introducing perturbations into the reflective surface of the reflective element **207** which would otherwise disturb focus of the laser beam. In some examples or aspects, the pressure controller **312** and the cooling controller **318** may be combined into a single device.

[0043] With reference to FIGS. **5-10**, a mirror element **200** is shown in accordance with another example or aspect of the present disclosure. Certain components of the mirror element **200** shown in FIGS. **1-4** are substantially similar or identical to the components of the mirror element **200** described herein with reference to FIGS. **5-10**. Accordingly, reference numerals in FIGS. **5-10** are used to illustrate similar or identical components of the corresponding reference numerals in FIGS. **1-4**. As the previous discussion regarding the mirror element **200** generally shown in FIGS. **1-4** is applicable to the mirror clement **200** shown in FIGS. **5-10**. only the relative differences between the two mirror elements **200** are discussed hereinafter.

[0044] With reference to FIGS. **5-6**, the ring **208** of the mirror clement **200** has a sidewall **220** with a curved outer surface **222** extending from an edge **212** of the deformable face **202**. The curved outer surface **222** may have a constant radius of curvature or a variable radius of curvature. In some examples or aspects. the curved outer surface **222** has a first end starting at the edge **212** of the deformable face **202** and a second end terminating at the groove **209** on the ring **208**.

[0045] With reference to FIG. **9**. the sidewall **220** further may have a curved inner surface **224**. The sidewall **220** thus may have a shape of an outer surface of a toroid. The curved inner surface **224** may have a constant radius of curvature or a variable radius of curvature. In some examples or aspects. the curved inner surface **224** has a first end starting at an outer edge of the inner surface **206** of the deformable face **202** and a second end terminating at the groove **209** on the ring **208**.

[0046] In some examples or aspects. the curved inner surface **224** may have the same shape as the curved outer surface **222** such that the sidewall **220** has a constant or uniform thickness T.sub.1 at least in the area between the curved outer surface **222** and the curved inner surface **224**. In other examples or aspects. the thickness of the sidewall **220** may increase or decrease (i.e., thickness T.sub.1 may be non-uniform) in a direction from the edge **212** of the deformable face **202** toward the groove **209** on the ring **208**. A lower portion **225** of the sidewall **220** below the groove **209** may have an increased thickness compared to the thickness the sidewall **220** above the groove **209**.

[0047] The curved sidewall **220** is configured to distribute the stress of deformation across a broad curve instead of focusing the stress in one or more corners with a tight radius. In addition. the curved sidewall **220** enables maximum deformation of the deformable face **202** even when the mirror clement **200** is made from a material with a lower yield point. For example, with the mirror clement **200**, including the deformable face **202** and the ring **208**, is made from a metal material with an clastic modulus less than or equal to 100 GPa, the deformable face **202** can be deformed to a greater degree (i.e., have a larger radius of curvature) while still showing a full elastic recovery. Furthermore, stresses on the deformable face **202** from connecting the mirror element **200** onto the base **300** (shown in FIGS. **1-2**), such as due to errors in the mounting surface and torque variations between the fasteners, are absorbed by the curved sidewall **220**, thereby allowing the mirror clement **200** to be manufactured independently of a matched base **300**.

[0048] In some examples or aspects, the mirror element **200** shown in FIGS. **1-10** is made from a metal material having an elastic modulus that is less than or equal to 100 GPa. For example, the mirror element **200** may be made from aluminum or an aluminum alloy. Use of aluminum allows for a reduction in weight of the mirror element **200** compared to use of conventional materials, such as stainless steel and/or copper. Lower weight in turn contributes to a faster movement of the deformable face **202**, thereby increasing the performance response of the mirror element **200**.

[0049] In contrast to conventional VRMs, which have mirror elements made from metal materials with an elastic modulus greater than 100 GPa (i.e, stainless steel and copper), the mirror clement **200** made from a metal material with an elastic modulus less than or equal to 100 GPa allows for a greater deformation of the deformable face **202** while still showing a full elastic recovery. In addition, when used with VRMs having a cooling cavity, the aluminum or aluminum alloy does not create a galvanic potential across the cooling medium, thereby preventing corrosion and scale buildup within the cooling channels.

[0050] With reference to FIG. **9**, the deformable face **202** may have a thickness T.sub.2 of 0.5 mm to 30.0 mm measured between the outer surface **204** and the inner surface **206**. The use of aluminum allows for a thicker deformable face **202** compared to a thickness of the deformable face used in conventional mirror elements (0.8 mm to 2.9 mm) while allowing a full range of deformation. With a thicker deformable face **202**, deeper cooling channels can be easily machined to increase the cooling capacity. In addition, increased thickness of the deformable face **202** allows for easier fixturing and machining of the mirror element **200** during manufacture.

[0051] With reference to FIGS. **7-8**, the mirror element **200** has one or more steps **226** recessed into the inner surface **206** of the deformable face **202**. Each step **226** has a rise **227**, expressed as a distance measured in a direction along the central axis **210**, and a run **229**, expressed as a distance measured in a direction perpendicular to the central axis **210**. Each step **226** may have the same rise **227** as the other steps **226** or a different rise **227** relative to the other steps. The rise **227** may be substantially parallel to the central axis **210** or angled at an obtuse or acute angle relative to the central axis **210**.

[0052] Regardless of the rise **227**, the steps **226** are recessed at a different depth relative to the inner surface **206**. The depth of the steps **226** may increase and/or decrease in a direction away from the central axis **210**. For example, the depth of each step **226** may increase in a direction away from the central axis **210**, decrease in the direction away from the central axis **210**, or the depth of at least one of a plurality of steps **226** may increase while a depth of at least another one of the plurality of steps **226** decreases in the direction away from the central axis **210**. As shown in FIG. **8**, the depth of the steps **226** continuously increases in a direction away from the central axis **210**. The step **226** closest to the central axis **210** may be in the same plane as the inner surface **206** or recessed relative to the plane defined by the inner surface **206**.

[0053] In some examples or aspects, such as shown in FIG. **7**, the steps **226** may be formed as a series of concentric rings centered about the central axis **210**. Each step **226** may have the same run **229** as the other steps **226** or a different run **229** relative to the other steps. The run **229** or width of the steps **226** may increase and/or decrease in a direction away from the central axis **210**. For example, the run **229** or width of each step **226** may increase in a direction away from the central axis **210**, decrease in the direction away from the central axis **210**, or the run **229** of at least one of a plurality of steps **226** may increase while a run **229** of at least another one of the plurality of steps **226** decreases in the direction away from the central axis **210**. The run **229** may be substantially perpendicular to the central axis **210** or angled at an obtuse or acute angle relative to the central axis **210**. The steps **226** may be continuous or discontinuous in a circumferential direction about the central axis **210**.

[0054] The steps **226** may be added during manufacture of the mirror element **200** to correct any irregularities on the outer surface **204** which may prevent deformation of the deformable face **202** in a spherical or torroidal manner. The steps **226** may be added to correct the figure of the deformed outer surface **204** away from the natural catenary shape to an optically-desirable spherical shape. The steps **226** can be easily machined into the inner surface **206** of the deformable face **202**. A mirror clement **200** having the steps **226** on the inner surface **206** of the deformable face **202** can be mounted on a fixturing tool, such as a vacuum chuck, having corresponding steps. In this manner, vibrations of the outer surface **204** of the deformable face **202** during machining can be minimized or eliminated The geometry of the steps **226** is independent of the thickness and material of the deformable face **202**, thereby permitting use of the steps **226** on any deformable face of sufficient thickness as long as the steps do not cause a stress rise above the yield point of the material.

[0055] With reference to FIG. **10**, the cooling cavity **214** has a pair of manifolds **228** fluidly connected to each other by the plurality of cooling channels **216**. Each manifold **228** has a first curved end wall **231** spaced apart from a second curved end wall **233**, with each of the cooling channels **216** extending through the first curved end wall **231** of each manifold **228**. In some examples or aspects, a curvature of the first curved end wall **231** and/or the second curved wall **233** may be selected to correspond to a curvature of the outer surface of the mirror element **200**.

[0056] The cooling cavity **214** is in fluid communication with a cooling medium source **314** (shown in FIG. **4**) via at least one cooling cavity inlet **230** and at least one cooling cavity outlet **232**. The at least one cooling cavity inlet **230** may be provided in a first of the pair of manifolds **228** and at least one cooling cavity outlet **232** may be provided in a second of the pair of manifolds **228**.

[0057] With continued reference to FIG. **10**, the plurality of cooling channels **216** that fluidly connect the pair of manifolds **228** may be arranged substantially parallel to each other. The length of the cooling channels **216** depends on the shape of the manifolds **228**. For example, as shown in FIG. **10**, cooling channels **216** that are radially closer to an edge of the mirror element **200** are shorter than the cooling channels **216** that are closer to the middle of the mirror element **200** due to the curved shape of the manifolds **228**. In this manner, the longer cooling channels have a larger heat absorption rate compared to the shorter cooling channels **216** due to their larger surface area.

[0058] An efficient cooling medium flow within the cooling cavity **214** reduces thermal gradients across the deformable face **202** and irregularities in the mirror surface which can impact the desired performance of the VRM **100**.

[0059] As shown in FIG. **8**, each cooling channel **216** has a width W and a height H. The width W and height H of the cooling channels **216** may be uniform. In some examples of aspects, the width W and height H of the cooling channels **216** may vary across the surface of the deformable face **202**. Cooling channels **216** may be provided as close as possible to the outer surface **204** of the deformable face **202** in order to increase heat transfer and enable increased radius of curvature.

[0060] An increased thickness T**2** of the deformable face **202** allows for wider and deeper cooling channels **216**, thereby increasing the flow rate of the cooling medium at a given pressure. The flow rate is further improved and regulated by the curved shape of the manifolds **228** which urge the cooling medium along the curved walls and into the cooling channels **216**.

[0061] Further examples or aspects of a variable radius mirror are detailed in the following numbered clauses.

[0062] Clause 1. A variable radius mirror comprising: a mirror element comprising: a deformable face having an outer surface with a reflective element, the deformable face being deformable in response to a pressure applied by a pressure medium acting on an inner surface of the deformable face; a ring extending around a perimeter of the deformable face and protruding from the inner surface of the deformable face; and at least one of: a plurality of steps recessed into the inner surface of the deformable face, each of the plurality of steps recessed at a different depth relative to the inner surface of the deformable face; a cooling cavity between the outer surface and the inner surface of the deformable face, the cooling cavity comprising a pair of manifolds fluidly connected to each other and each having a first curved end wall spaced apart from a second curved end wall; and a sidewall of the ring having a curved inner surface and a curved outer surface.

[0063] Clause 2. The variable radius mirror according to clause 1, wherein the plurality of steps are formed as a plurality of concentric rings centered about a central axis

[0064] Clause 3. The variable radius mirror according to clause 1 or 2, wherein the depth of the plurality of steps decreases in a direction away from a central axis.

[0065] Clause 4. The variable radius mirror according to any of clauses 1-3, wherein the depth of the plurality of steps increases in a direction away from a central axis.

[0066] Clause 5. The variable radius mirror according to any of clauses 1-4, wherein a width of the plurality of steps measured along the inner surface of the deformable face increases or decreases in a direction away from a central axis, or wherein the width of at least one of the plurality of steps

increases while the width of at least another one of the plurality of steps decreases in the direction away from the central axis.
[0067] Clause 6. The variable radius mirror according to any of clauses 1-5, wherein the cooling cavity further comprises at least one cooling inlet in a first of the pair of manifolds and at least one cooling outlet in a second of the pair of manifolds.
[0068] Clause 7. The variable radius mirror according to any of clauses 1-6, wherein the cooling cavity further comprises a plurality of cooling channels fluidly connecting the pair of manifolds.
[0069] Clause 8. The variable radius mirror according to clause 7, wherein each of the cooling channels extends through the first curved end wall of each manifold.
[0070] Clause 9. The variable radius mirror according to clause 7 or 8, wherein the plurality of cooling channels are parallel to each other.
[0071] Clause 10. The variable radius mirror according to any of clauses 1-9, wherein a thickness of the sidewall between the curved inner surface and the curved outer surface is uniform.
[0072] Clause 11. The variable radius mirror according to any of clauses 1-10, wherein the sidewall of the ring is shaped as an outer surface of a toroid.
[0073] Clause 12. The variable radius mirror according to any of clauses 1-11, wherein the mirror element is made from a metal material having an elastic modulus less than or equal to 100 GPa.
[0074] Clause 13. The variable radius mirror according to any of clauses 1-12, wherein the mirror element is made from aluminum or an aluminum alloy.
[0075] Clause 14. The variable radius mirror according to any of clauses 1-13, further comprising a base element connected to the ring of the mirror element, and a pressure cavity defined between the mirror element and the base element.
[0076] Clause 15. The variable radius mirror according to clause 14, wherein the base element has at least one passage in fluid communication with the pressure cavity.
[0077] Clause 16. A variable radius mirror comprising: a base element; and a mirror element connected to the base element with a pressure cavity defined between the base element and the mirror element, the mirror element comprising: a deformable face having an outer surface with a reflective element, the deformable face being deformable in response to a pressure applied by a pressure medium within the pressure cavity acting on an inner surface of the deformable face; a ring extending around a perimeter of the deformable face and protruding from the inner surface of the deformable face; and at least one of: a plurality of steps recessed into the inner surface of the deformable face, each of the steps recessed relative to the inner surface of the deformable face at an increasing or decreasing depth in a direction away from a central axis; a cooling cavity between the outer surface and the inner surface of the deformable face, the cooling cavity comprising a pair of manifolds each having a first curved end wall spaced apart from a second curved end wall, the manifolds fluidly connected to each other by a plurality of cooling channels extending through the first curved end wall of each manifold; and a sidewall of the ring having a curved inner surface and a curved outer surface.
[0078] Clause 17. The variable radius mirror according to clause 16, wherein the mirror clement is made from a metal material having an elastic modulus less than or equal to 100 GPa.
[0079] Clause 18. The variable radius mirror according to clause 16 or 17, wherein the base element has at least one passage in fluid communication with the pressure cavity.
[0080] Clause 19. The variable radius mirror according to any of clauses 16-18, wherein the cooling cavity further comprises at least one cooling inlet in a first of the pair of manifolds and at least one cooling outlet in a second of the pair of manifolds.
[0081] Clause 20. A variable radius mirror comprising: a base element; and a mirror element connected to the base element with a pressure cavity defined between the base element and the mirror element, the mirror element comprising: a deformable face having an outer surface with a reflective element, the deformable face being deformable in response to a pressure applied by a pressure medium within the pressure cavity acting on an inner surface of the deformable face; a

ring extending around a perimeter of the deformable face and protruding from the inner surface of the deformable face, a sidewall of the ring having a curved inner surface and a curved outer surface; a plurality of steps recessed into the inner surface of the deformable face, each of the steps recessed at a different depth relative to the inner surface of the deformable face; and a cooling cavity between the outer surface and the inner surface of the deformable face, the cooling cavity comprising a pair of manifolds fluidly connected to each other and each having a first curved end wall spaced apart from a second curved end wall, wherein the mirror element is made from a metal material having an elastic modulus less than or equal to 100 GPa.

[0082] Although the disclosure describes what are currently considered to be the most practical and preferred examples or aspects, it is to be understood that such detail is solely for that purpose and that the disclosure is not limited to the disclosed examples or aspects, but, on the contrary, is intended to cover modifications and equivalent arrangements that are within the spirit and scope of the appended claims. For example, it is to be understood that the present disclosure contemplates that, to the extent possible, one or more features of any example or aspect can be combined with one or more features of any other example or aspect.

Claims

1-20. (canceled)

21. A deformable variable radius mirror comprising a deformable face, the deformable face comprising: an outer surface that is reflective; and an inner surface that opposes the outer surface, the inner surface comprising steps that are recessed towards the outer surface, wherein: the deformable face defines cooling channels sandwiched between the outer surface and the inner surface, the outer surface, when the deformable face is in an undeformed state, is at a first level of the deformable variable radius mirror, the inner surface at a central portion of the deformable face, when the deformable face is in the undeformed state, is at a second level of the deformable variable radius mirror, and the cooling channels, in the undeformed state, are closer to the first level than to the second level.

22. The deformable variable radius mirror of claim 21, wherein at least some of the cooling channels that are radially outward of the cooling channels at the central portion are closer to the inner surface than the cooling channels at the central portion.

23. The deformable variable radius mirror of claim 21, wherein a central axis of the deformable face extends through the central portion of the deformable face.

24. The deformable variable radius mirror of claim 21, wherein a center of each of the cooling channels is closer to the first level than to the second level.

25. The deformable variable radius mirror of claim 21, wherein a width of each of the cooling channels is the same.

26. The deformable variable radius mirror of claim 21, wherein a width of at least one cooling channel of the cooling channels is different from a width of at least one other cooling channel of the cooling channels.

27. The deformable variable radius mirror of claim 21, wherein a height of each of the cooling channels is the same.

28. The deformable variable radius mirror of claim 27, wherein a width of each of the cooling channels is the same.

29. The deformable variable radius mirror of claim 27, wherein a width of at least one cooling channel of the cooling channels is different from a width of at least one other cooling channel of the cooling channels.

30. The deformable variable radius mirror of claim 21, wherein a height of at least one cooling channel of the cooling channels is different from a height of at least one other cooling channel of the cooling channels.

31. The deformable variable radius mirror of claim 30, wherein a width of each of the cooling channels is the same.

32. The deformable variable radius mirror of claim 30, wherein a width of at least one cooling channel of the cooling channels is different from a width of at least one other cooling channel of the cooling channels.

33. The deformable variable radius mirror of claim 21, wherein the deformable face is integral between the outer surface and the inner surface.

34. The deformable variable radius mirror of claim 21, further comprising a ring extending around a perimeter of the deformable face and protruding in a direction away from the outer surface.

35. The deformable variable radius mirror of claim 34, wherein the ring comprises a curved side wall with a constant thickness.

36. The deformable variable radius mirror of claim 34, wherein the ring comprises a curved side wall with a constant radius of curvature.

37. The deformable variable radius mirror of claim 21, wherein each of the steps are recessed at different depths relative to the inner surface.

38. The deformable variable radius mirror of claim 37, wherein the different depths decrease in a direction away from a central axis of the deformable variable radius mirror.

39. The deformable variable radius mirror of claim 37, wherein the different depths increase in a direction away from a central axis of the deformable variable radius mirror.

40. The deformable variable radius mirror of claim 21, wherein the steps define concentric rings centered about a central axis of the deformable variable radius mirror.
