

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization

International Bureau



(10) International Publication Number

WO 2017/069705 A1

(43) International Publication Date

27 April 2017 (27.04.2017)

WIPO | PCT

(51) International Patent Classification:

G02B 13/18 (2006.01) G02B 11/20 (2006.01)
G02B 27/18 (2006.01)

AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(21) International Application Number:

PCT/SG2016/050512

(22) International Filing Date:

21 October 2016 (21.10.2016)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

62/245,082 22 October 2015 (22.10.2015) US

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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM,

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

(54) Title: ATHERMAL OPTICAL ASSEMBLY

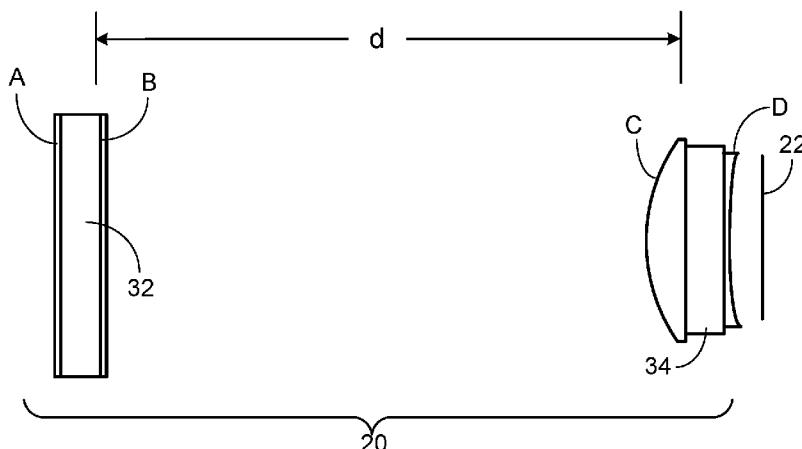


FIG. 1

(57) Abstract: This disclosure describes optical assemblies that generate output with substantial stability over a wide variation in temperature. The optical assemblies can be integrated, for example, as part of array generators arranged to project an array or other pattern of dots onto an object or projection plane.

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A THERMAL OPTICAL ASSEMBLY

TECHNICAL FIELD

[0001] This disclosure relates to optical assemblies.

BACKGROUND

[0002] Optical assemblies are used in a wide range of commercial, industrial and military devices and systems. The assemblies may include, for example, various types of passive optical elements such as diffractive, refractive or reflective components. For some applications, hybrid optical elements can be advantageous. A hybrid optical element can have a diffractive surface that is etched, micro-machined or embossed, for example, onto the surface of a refractive or reflective optical component. Such hybrid elements can, in some cases, provide enhanced flexibility in the selection of materials based, for example, on dispersion and thermal behavior of the refractive materials.

[0003] Depending on the application, various factors such as temperature variations may adversely impact the performance of the optical assembly. For example, in some situations, an optical assembly may be integrated into an optoelectronic module that also includes a light emitting element such as a vertical cavity surface-emitting laser (VCSEL) operable to emit infra-red (IR) radiation. Operation of the VCSEL in close proximity to the optical assembly may result in thermally-induced changes to the optical elements of the assembly. For example, if the optical assembly includes polymeric lenses, changes in temperature may result in changes to the dimensions and/or the refractive index of the lenses. Such changes can, in turn, cause the output of the optical assembly to deviate from the optimal specifications.

[0004] In view of the foregoing or other problems, it is desirable in some applications to provide an athermal optical assembly (i.e., an optical assembly that generates output with substantial stability over a wide variation in temperature).

SUMMARY

[0005] This disclosure describes athermal optical assemblies, in other words, optical assemblies that generate output with substantial stability over a wide variation in temperature. The optical assemblies can be integrated, for example, as part of array generators arranged to project an array or other pattern of dots onto an object or projection plane.

[0006] For example, in one aspect, a hybrid optical assembly includes a first transmissive substrate and a second transmissive substrate separated from the first transmissive substrate. A first aspherical lens is on a first side of the first transmissive substrate, and a second hybrid diffractive/refractive lens is on a second side of the first transmissive substrate. Likewise, a third aspherical lens is on a first side of the second transmissive substrate, and a fourth aspherical lens is on a second side of the second transmissive substrate. The third aspherical lens faces the second hybrid diffractive/refractive lens. The output of the hybrid optical assembly exhibits substantial stability over a temperature range of 20°C - 100°C.

[0007] In another aspect, the hybrid optical assembly can be integrated into an optical pattern generator that includes an array of light emitting elements (e.g., VSCELS). The array of light emitting elements is disposed such that light generated by the light emitting elements passes through the fourth lens, the third lens, the second lens and the first lens of the hybrid optical assembly, in that order, so as to project a pattern of optical dots corresponding to the arrangement of the light emitting elements.

[0008] In accordance with another aspect, a method of generating a pattern of optical dots includes emitting light from a plurality of light emitting elements arranged in an array or other pattern. The emitted light is passed through a hybrid optical assembly comprising three aspherical lenses and a hybrid diffractive/refractive lens. The light that passes through the hybrid optical assembly is projected onto an object or plane and forms a pattern of dots.

[0009] Some implementations include one or more of the following features. For example, the first and second transmissive substrates of the hybrid optical assembly can be separated from one another by a distance in a range of 4 mm – 10 mm. In some instances, the first and second transmissive substrates are composed of clear borosilicate glass and the first, second, third and fourth lenses are composed of epoxy. In some cases, the light emitting elements of the optical array generator are VCSELs.

[0010] Some implementations provide one or more of the following advantages. For example, in some cases, the quality of the projected dots can be relatively high over a wide temperature range (i.e., most of the optical energy for each dot is contained within a respective centroid having a relatively small radius, e.g., of about 3.5 μm or less for the range of 20°C to 100°C).

[0011] Other aspects, features and advantages will be readily apparent from the following detailed description, the accompanying drawings, and the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] FIG. 1 illustrates an example of an optical array generator that includes an athermal optical assembly.

[0013] FIG. 2 illustrates an example of an array of optical dots projected onto a projection plane by the optical array generator of FIG. 1.

[0014] FIG. 3 illustrates an example of an aspheric lens.

[0015] FIG. 4 illustrates properties of an example of a hybrid diffractive/refractive lens that can be included in the optical assembly.

[0016] FIGS. 5A, 5B and 5C are graphs illustrating performance of the optical assembly at different temperatures.

DETAILED DESCRIPTION

[0017] The present disclosure describes hybrid athermal optical assemblies that can be integrated, for example, into array generators arranged to project an array or other pattern of dots. Optical pattern projection can be used in a variety of applications such as three-

dimensional (3D) or depth mapping, area illumination, and LCD backlighting. 3D (or depth) mapping, for example, refers to a set of 3D coordinates representing the surface of an object. As part of the process of depth mapping, light (i.e., visible, infra-red, or other radiation) can be projected onto a region with a pattern of high quality (e.g., good resolution, and with dots of optimal encircled energy) and well-controlled intensity, so that depth values can be found reliably over a substantial part of an object or objects in a scene and over a range of operating temperatures (e.g., from 20°C to 100°C).

[0018] As shown in FIG. 1, a hybrid optical assembly 20 includes several passive optical elements, i.e., lenses A, B, C and D. Two of the lenses, A and B, are disposed on opposite sides of a first transmissive (e.g., glass or wafer) substrate 32; the other two lenses, C and D, are disposed on opposite sides of a second transmissive (e.g., glass or wafer) substrate 34. The optical axes of the lenses A, B, C and D are aligned with one another, and the inner surfaces of the lenses B and C are separated from one another by a distance d, which for some applications is in the range of several (e.g., four) millimeters (mm) to about ten mm. In some implementations, although the optical axes may be aligned, the geometric path may not be aligned; for example, in implementations having a folded optical path, the geometric path is not aligned, whereas the optical axes of the lenses A, B, C and D are aligned. An array 22 of light emitting elements, such as a VCSELs, can be placed in front of the optical assembly 20 such that lens D is closest to the VCSEL array 22 and the lens A is furthest from the VCSEL array 22. Such an implementation can be particularly advantageous in some cases because the overall footprint of the assembly can be reduced (i.e., by increasing its thickness – the dimension orthogonal to the footprint).

[0019] As illustrated in FIG. 2, the optical assembly 20 is arranged such that when light (e.g., IR light) from the VCSEL array 22 is emitted toward the optical assembly 20, an array of well-defined optical dots 38 appears on the projection plane 36. Collectively, the various lenses A, B, C and D help collimate and focus the light, such that the array of dots 38 appearing on the projection plane 26 corresponds, for example, to the arrangement of the VCSELs in the array 22. FIG. 2 illustrates a particular arrangement

of the VCSEL array 22; other arrangements, and other numbers of VCSEL emitters within the array 22, can be provided for other implementations.

[0020] In the illustrated example, lenses A, C and D are implemented as aspherical lenses. In general, aspheric lenses can be designed, for example, with surfaces of the form:

$$z(r) = \frac{r^2}{R \left(1 + \sqrt{1 - (1 + \kappa) \frac{r^2}{R^2}} \right)} + \alpha_1 r^2 - \alpha_2 r^4 + \alpha_3 r^6 + \dots$$

where the optic axis is presumed to lie in the z-direction, and $z(r)$ is the sag, i.e., the z-component of the displacement of the surface from the vertex, at distance r from the axis. The aspheric coefficients α_i describe the deviation of the surface from the axially symmetric quadric surface specified by R and κ . See FIG. 3. On the other hand, lens B is implemented as a hybrid diffractive/refractive lens. Lens B can be described using the aspheric equation above in combination with the following polynomial expansion describing the diffractive phase Φ of lens B:

$$\Phi = M \sum_{i=1}^N A_i \rho^{2i}$$

where M is the diffraction order of the hybrid diffractive/refractive lens, N is the number of polynomial coefficients in the series, A_i is the coefficient on the $2i^{\text{th}}$ power of ρ , and ρ is the normalized radial aperture coordinate. Specific examples of the lens characteristics and their respective properties for particular implementations are described below.

[0021] The specific properties of the lenses A through D are such that the optical assembly 20 is substantially athermal (i.e., its output exhibits substantial stability over a wide variation in temperature, for example, over the range 20°C to 100°C). Further, lenses (e.g., lenses A through D) also can provide for aberration correction.

[0022] Computer modeling was used to determine how different properties of the lenses and the optical assembly would vary with changes in temperature. Data describing implementations of hybrid optical assemblies are indicated in Tables I – VI, below. The dimensions (radius, thickness and diameter) associated with each surface based on the computer modeling is set forth in Table I and VI (in microns (μm)). Further surface coefficients describing the shapes of lens surfaces and the characteristics of the hybrid refractive/diffractive element B are described in Tables II and V. Different dimensions may be appropriate for other implementations, however. Further the example hybrid optical assemblies described below can be modeled or simulated by, for example, sequential and/or non-sequential ray-tracing simulation software such as Zemax, the numerals included below describe the various components (e.g., thicknesses, diameters, surface shapes, coefficients) and their position within the illumination assembly, these numerals include a plurality of decimal places. For example the aspheric coefficients used to describe the aspheric surfaces of various components below can include as many as nine decimals places or more. However, although up to nine decimals places are included, in some cases far fewer decimal places are needed to adequately describe the various components and their respective position within the illumination assembly. For example, in some cases no more than two or three or four decimal places are required in order to effectively describe various components and their respective position within the hybrid optical assembly further described below.

[0023] Multiple surfaces define the optical assembly 20, including the lenses A through D. Table I, below, describes the various surfaces in the optical assembly 20 and the VCSEL array 22 for some implementations with a total track length of about 4 mm.

Table I

Surface ID	Type	Radius (mm)	Thickness (mm)	Glass	Diameter (mm)	Conic	Comment
OBJ	STANDARD	Infinity	377.6232		93.05419	0	-
1	STANDARD	Infinity	0.1321681	D263TECO	1.385926	0	-
2	STANDARD	Infinity	0.01258744	R14	1.385039	0	-
STO	STANDARD	Infinity	0.0314686		1.287502	0	-
4	EVENASPH	26.0797	0.01236523	R14	1.384618	0	lens A
6	STANDARD	Infinity	0.00629372	R14	1.373109	0	base layer
7	STANDARD	Infinity	0.1888116	D263TECO	1.374509	0	wafer AB
8	STANDARD	Infinity	0.00629372	R14	1.416218	0	base layer
9	STANDARD	Infinity	0.03689987	R14	1.417614	0	-
10	BINARY_2	0.06585	0		1.384618	0	lens B defined by glass
12	STANDARD	Infinity	2.968914		1.425223	0	-
13	EVENASPH	0.95528	0.1888116	R14	0.9911429	0	lens C
14	STANDARD	Infinity	0.00629372	R14	0.9598653	0	base layer
15	STANDARD	Infinity	0.1888116	D263TECO	0.9568284	0	wafer CD
16	STANDARD	Infinity	0.00629372	R14	0.8663031	0	base layer
17	STANDARD	Infinity	0.02517424	R14	0.8632862	0	-
18	EVENASPH	2.22158	0.1888116		0.8308089	0	lens D
19	STANDARD	Infinity	0		0.7770572	0	-
IMA	STANDARD	Infinity	N/A		0.7015326	0	VCSEL array

[0024] Thus, lens A is defined by surfaces 4 and 6; lens B is defined by surfaces 8, 9 and 10; lens C is defined by surfaces 13 and 14; and lens D is defined by surfaces 16, 17 and 18. Table II describes the various surface shapes, coefficients, and characteristics of the optical surfaces within the optical assembly 20 and the VCSEL array 22 for some implementations with a total track length of about 4 mm. In this implementation, the conic for each of the surfaces is zero. Further, although this implementation is described by an aspheric polynomial and a polynomial expansion describing the diffractive phase of lens B, other ways of describing the surfaces are within the scope of this disclosure.

Table II

Surface ID	Surface type
OBJ	STANDARD
Surface ID	Surface type
1	STANDARD
Surface ID	Surface type
2	STANDARD
Surface ID	Surface type
STO	STANDARD
Surface ID	Surface type
4	EVENASPH
Coefficient on r^2	0
Coefficient on r^4	-0.10313738
Coefficient on r^6	0
Coefficient on r^8	0
Coefficient on r^{10}	0
Coefficient on r^{12}	0
Coefficient on r^{14}	0
Coefficient on r^{16}	0
Floating Aperture	Aperture
Maximum Radius	0.6923692

Surface ID	Surface type
6	STANDARD
Surface ID	Surface type
7	STANDARD
Surface ID	Surface type
8	STANDARD
Surface ID	Surface type
9	STANDARD

Surface ID	Surface type
10	BINARY_2
Diffraction Order	4
Coefficient on r^2	0
Coefficient on r^4	-0.11494915
Coefficient on r^6	-0.85854795
Coefficient on r^8	5.7044976
Coefficient on r^{10}	-17.848874
Coefficient on r^{12}	28.092385
Coefficient on r^{14}	-17.554371
Coefficient on r^{16}	0
Maximum term #	3
Normalization	
Radius	0.69230919
Coefficient on p^2	-525.28684
Coefficient on p^4	71.54595
Coefficient on p^6	-30.983
	Floating
Aperture	Aperture
Maximum Radius	0.6923092

Surface ID	Surface type
12	STANDARD
Surface ID	Surface type
13	EVENASPH
Coefficient on r^2	0
Coefficient on r^4	0.11351174
Coefficient on r^6	2.4017377
Coefficient on r^8	-41.190946
Coefficient on r^{10}	324.91913
Coefficient on r^{12}	-1203.1116
Coefficient on r^{14}	1694.4363
Coefficient on r^{16}	0
Surface ID	Surface type
14	STANDARD

Surface ID	Surface type
15	STANDARD
Surface ID	Surface type
16	STANDARD
Surface ID	Surface type
17	STANDARD
Surface ID	Surface type
18	EVENASPH
Coefficient on r^2	0
Coefficient on r^4	0.38189163
Coefficient on r^6	3.5435835
Coefficient on r^8	-62.280573
Coefficient on r^{10}	523.77256
Coefficient on r^{12}	-1939.264
Coefficient on r^{14}	2348.243
Coefficient on r^{16}	0
Surface ID	Surface type
19	STANDARD
Surface ID	Surface type
INA	STANDARD

[0025] Table III, below, describes further information pertaining to the foregoing implementation.

Table III

Number of Surfaces	20
Stop	3
System Aperture	Image Space F/# = 2.2
Effective Focal Length	2.832299 (in air at system temperature and pressure)
Effective Focal Length	2.832299 (in image space)
Back Focal Length	0.1514186
Total Track	3.999999
Image Space F/#:	2.2
Paraxial Working F/#	2.200017
Working F/#	2.20032
Image Space NA	0.2216194
Object Space NA	0.001704187
Stop Radius	0.6437044
Paraxial Image Height	0.3461546
Paraxial Magnification	-0.007498492
Entrance Pupil Diameter	1.287409
Entrance Pupil Position	0.09568351
Exit Pupil Diameter	1214.639
Exit Pupil Position	-2672.286
Field Type	Real Image height in Millimeters
Maximum Radial Field	0.3461546
Primary Wavelength	0.94 μ m
Lens Units	Millimeters
Angular Magnification	0.00105794

[0026] The foregoing information (i.e., in Tables I, II and III) is non-limiting and is provided as examples to enable a person of ordinary skill to make and use the invention.

[0027] Table IV, below, describes the various surfaces in the optical assembly 20 and the VCSEL array 22 for some implementations with a total track length of about 6.356 mm.

Table IV

Surface ID	Type	Radius (mm)	Thickness (mm)	Glass	Diameter (mm)	Conic	Comment
OBJ	STANDARD	Infinity	600		92.05419	0	-
1	STANDARD	Infinity	0.21	D263TECO	1.385926	0	-
2	STANDARD	Infinity	0.02	R14	1.365029	0	-
STO	STANDARD	Infinity	0.05		1.287502	0	-
4	EVENASPH	41.4377	0.01964693	R14	1.384618	0	lens A
6	STANDARD	Infinity	0.01	R14	1.373109	0	base layer
7	STANDARD	Infinity	0.3	D263TECO	1.374508	0	wafer AB
8	STANDARD	Infinity	0.01	R14	1.416216	0	base layer
9	STANDARD	Infinity	0.05862966	R14	1.417614	0	-
10	BINARY_2	12.8157	0		1.384618	0	lens B defined by glass
12	STANDARD	Infinity	4.717264		1.425223	0	-
13	EVENASPH	1.51784	0.3	R14	0.9911429	0	lens C
14	STANDARD	Infinity	0.01	R14	0.9598653	0	base layer
15	STANDARD	Infinity	0.3	D263TECO	0.9568284	0	wafer CD
16	STANDARD	Infinity	0.01	R14	0.8663031	0	base layer
17	STANDARD	Infinity	0.03999898	R14	0.8632662	0	-
18	EVENASPH	3.52984	0.3		0.8308089	0	lens D
19	STANDARD	Infinity	0		0.7770572	0	-
IMA	STANDARD	Infinity	N/A		0.7915526	0	VCSEL array

[0028] Thus, lens A is defined by surfaces 4 and 6; lens B is defined by surfaces 8, 9 and 10; lens C is defined by surfaces 13 and 14; and lens D is defined by surfaces 16, 17 and 18. Table V, below, describes the various surface shapes and characteristics of the optical surfaces within the optical assembly 20 and the VCSEL array 22 for some implementations with a total track length of about 6.356 mm. In this implementation, the conic for each of the surfaces is zero. Further, although this implementation is described by an aspheric polynomial and a polynomial expansion describing the diffractive phase of lens B, other ways of describing the surfaces are within the scope of this disclosure.

Table V

Surface ID	Surface type
OBJ	STANDARD
Surface ID	Surface type
1	STANDARD
Surface ID	Surface type
2	STANDARD
Surface ID	Surface type
STO	STANDARD
Surface ID	Surface type
4	EVENASPH
Coefficient on r^2	0
Coefficient on r^4	-0.025712148
Coefficient on r^6	0
Coefficient on r^8	0
Coefficient on r^{10}	0
Coefficient on r^{12}	0
Coefficient on r^{14}	0
Coefficient on r^{16}	0
Aperture	Floating
Maximum Radius	1.1
Surface ID	Surface type
6	STANDARD
Surface ID	Surface type
7	STANDARD
Surface ID	Surface type
8	STANDARD

Surface ID	Surface type
9	STANDARD
Surface ID	Surface type
10	BINARY_2
Diffraction Order	4
Coefficient on r^2	0
Coefficient on r^4	-0.02865682
Coefficient on r^6	-0.084781608
Coefficient on r^8	0.22313584
Coefficient on r^{10}	-0.27655249
Coefficient on r^{12}	0.17241308
Coefficient on r^{14}	-0.042675803
Coefficient on r^{16}	0
Maximum term #	3
Normalization Radius	1.1
Coefficient on ρ^2	-834.62061
Coefficient on ρ^4	113.67832
Coefficient on ρ^6	-49.228438
Aperture	Floating
Maximum Radius	1.1
Surface ID	Surface type
12	STANDARD
Surface ID	Surface type
13	EVENASPH
Coefficient on r^2	0
Coefficient on r^4	0.028298476
Coefficient on r^6	0.23717158
Coefficient on r^8	-1.6112157
Coefficient on r^{10}	5.0343342
Coefficient on r^{12}	-7.3839288
Coefficient on r^{14}	4.1192835

Coefficient on r^{16}	0
Surface ID	Surface type
14	STANDARD
Surface ID	Surface type
15	STANDARD
Surface ID	Surface type
16	STANDARD
Surface ID	Surface type
17	STANDARD
Surface ID	Surface type
18	EVENASPH
Coefficient on r^2	0
Coefficient on r^4	0.095205578
Coefficient on r^6	0.34992886
Coefficient on r^8	-2.4361528
Coefficient on r^{10}	8.115392
Coefficient on r^{12}	-11.846725
Coefficient on r^{14}	5.7087296
Coefficient on r^{16}	0
Surface ID	Surface type
19	STANDARD
Surface ID	Surface type
IMA	STANDARD

[0029] Table VI, below, describes further information pertaining to the implementation described above.

Table VI

Number of Surfaces	20
Stop	3
System Aperture	Image Space F/# = 2.2
Effective Focal Length	4.500199 (in air at system temperature and pressure)
Effective Focal Length	4.500199 (in image space)
Back Focal Length	0.2405868
Total Track	6.355539
Image Space F/#:	2.2
Paraxial Working F/#	2.200017
Working F/#	2.20032
Image Space NA	0.2216194
Object Space NA	0.001704187
Stop Radius	1.022773
Paraxial Image Height	0.55
Paraxial Magnification	-0.007498492
Entrance Pupil Diameter	2.045545
Entrance Pupil Position	0.1520301
Exit Pupil Diameter	1932.099
Exit Pupil Position	-4250.677
Field Type	Real Image height in Millimeters
Maximum Radial Field	0.55
Primary Wavelength	0.94 μ m
Lens Units	Millimeters
Angular Magnification	0.00105794

[0030] The foregoing information (i.e., in Tables IV, V and VI) is non-limiting and is provided as examples to enable a person of ordinary skill to make and use the invention

[0031] Among the listed lens materials, D263TECO is a clear borosilicate glass of high chemical resistance, and R14 is an epoxy resin. Further properties of these materials are set forth in Table VII below. Other lens materials may be used for some implementations.

Table VII

Material	Thermal coefficient of expansion (CTE) * 10E-6	Index of refraction (at 20°C)	Index of refraction (at 60°C)	Index of refraction (at 100°C)
R14	66.00000000	1.50454192	1.49980491	1.49505707
D263TECO	7.20000000	1.51365480	1.51370440	1.51374334

[0032] For a particular implementation, the diffractive/refractive surface (i.e., Surface ID 10) of the hybrid lens B can have characteristics as shown in FIG. 4, which indicates how phase and line frequency change with radius/distance from the center of the aperture. The curve 102 indicates the change in phase, whereas the curve 104 indicates the change in line frequency. Further, although the diffraction order of the hybrid diffractive/refractive surfaces described above is equal to four, in other implementations the diffraction order can be equal to one or another value. In general, the diffraction order may depend on the ease of manufacturing and/or the diameter of the hybrid diffractive/refractive lens B.

[0033] For the values of index of refraction, the computer modeling assumed that the index data is relative to air at the system temperature and pressure and that wavelengths are measured in air at the system temperature and pressure. For a wavelength of 0.940000 μ m, the absolute air index values were 1.000270 at 20°C, 1.000237 at 60°C, and 1.000212 at 100°C.

[0034] The foregoing details are illustrative only, and various properties or parameters of one or more of the lenses and lens surfaces can be adjusted in other implementations so as to obtain a substantially athermal optical assembly. For example, some parameters of

the described implementations can be additionally described in terms of effective-focal-length normalized parameters such as in Table 8 below:

Table VIII

Surface		ID	Type	Radius	Thickness	Glass	Diameter	Conic	Comment
OBJ	STANDARD	Infinity		133.3374			32.50138	0	-
1	STANDARD	Infinity		0.046665		D263TECO	0.489329	0	-
2	STANDARD	Infinity		0.004444		R14	0.481951	0	-
STO	STANDARD	Infinity		0.011111			0.454578	0	-
4	EVENASPH	9.26796		0.004366		R14	0.488867	0	lens A
6	STANDARD	Infinity		0.002222		R14	0.484804	0	base layer
7	STANDARD	Infinity		0.066664		D263TECO	0.485298	0	wafer A B
8	STANDARD	Infinity		0.002222		R14	0.500623	0	base layer
9	STANDARD	Infinity		0.013028		R14	0.500517	0	-
10	BINARY_2	2.84781		0			0.488867	0	lens B defined by glass
12	STANDARD	Infinity		1.048235			0.503204	0	
13	EVENASPH	0.33728		0.066664		R14	0.349943	0	lens C
14	STANDARD	Infinity		0.002222		R14	0.5389	0	base layer
15	STANDARD	Infinity		0.066664		D263TECO	0.337827	0	wafer C D
16	STANDARD	Infinity		0.002222		R14	0.305866	0	base layer
17	STANDARD	Infinity		0.008388		R14	0.304793	0	-
18	EVENASPH	0.78437		0.066664			0.293334	0	lens D
19	STANDARD	Infinity		0			0.274336	0	-
IMA	STANDARD	Infinity		0			0.24769	0	VCSEL array

[0035] The described implementations can be additionally described in terms of an aspect ratio where the aspect ratio is defined as the largest diameter optical surface divided by the total track length of the hybrid optical assembly. For example, in some implementations the aspect ratio of the hybrid optical assembly can be 0.5, while in other implementations that aspect ratio can be larger or smaller depending on the intended application of the hybrid optical assembly. For example, for some implementations with a total track length about 4 mm, the aspect ratio can be about 0.356, while for some other implementations with a total track length of about 6.356 the aspect ratio can be about 0.224.

[0036] As indicated previously, the optical assembly 22 can be integrated as part of an optical pattern generator arranged to project an array or other pattern of dots onto a

projection plane 36. As illustrated in the graphs of FIGS. 5A, 5B and 5C based on computer modeling, the optical assembly 22 can be used to project a high-quality array of dots onto the projection plane. In FIGS. 5A - 5C, each curve (e.g., 202, 204) represents a different field point, for example, a projected dot from the VCSEL array 22. The values above the top of the graph (i.e., 0.000mm – 0.550 mm) indicate the distance of each field point from the center of the VCSEL array plane. FIG. 5A illustrates the curves at 20°C, FIG. 5B illustrates the curves at 60°C, and FIG. 5C illustrates the curves at 100°C.

[0037] Each curve in FIGS. 5A – 5C indicates the fraction of the optical energy enclosed within a centroid having a given radius from the center of the dot projected onto the plane 36. The steepness of the slopes of the curves out to a radius of about 3.5 μm is indicative of the high quality of the projected dots (i.e., most of the optical energy for each dot is contained within a centroid having a radius of about 3.5 μm). Further, the high quality of the projected array of dots substantially is maintained over the temperature range of 20°C - 100°C. That is, at an operating temperature of about 20°C – 60°C, about 80% of light is enclosed in a circle (a dot) with a radius slightly less than about 3.4 μm for all possible light source (VCSEL) positions, whereas up to an operating temperature of about 100°C, about 80% of light is enclosed in a circle with a radius slightly less than about 3.5 μm for all possible light source (VCSEL) positions. Accordingly, the quality of the output of the athermal optical assembly 20 is substantially constant over the operating range 20°C to 100°C. Thus, high quality system performance can be achieved even as the temperature varies.

[0038] Various modifications and combinations of features will be evident from the foregoing examples and are within the spirit of the invention. Accordingly, other implementations are within the scope of the claims.

What is claimed is:

1. A hybrid optical assembly comprising:
 - a first transmissive substrate;
 - a first aspherical lens on a first side of the first transmissive substrate;
 - a second hybrid diffractive/refractive lens on a second side of the first transmissive substrate;
 - a second transmissive substrate separated from the first transmissive substrate;
 - a third aspherical lens on a first side of the second transmissive substrate; and
 - a fourth aspherical lens on a second side of the second transmissive substrate;

wherein the third aspherical lenses faces the second hybrid diffractive/refractive lens, and wherein the output of the hybrid optical assembly exhibits substantial stability over a temperature range of 20°C - 100°C.
2. The hybrid optical assembly of claim 1 wherein the first and second transmissive substrates are separated from one another by a distance in a range of 4 mm – 10 mm.
3. The hybrid optical assembly of any one of the previous claims wherein the first and second transmissive substrates are composed of clear borosilicate glass and the first, second, third and fourth lenses are composed of epoxy.
4. An optical pattern generator comprising:
 - an array of light emitting elements; and
 - a hybrid optical assembly according to any one of claims 1 – 3,

wherein the array of light emitting elements is disposed such that light generated by the light emitting elements passes through the fourth lens, the third lens, the second lens and the first lens of the hybrid optical assembly, in that order, so as to project a pattern of optical dots corresponding to the arrangement of the light emitting elements.
5. The optical array generator of claim 4 wherein the light emitting elements are VCSELs.

6. A method of generating a pattern of optical dots, the method comprising:
 - emitting light from a plurality of light emitting elements arranged in an array or other pattern;
 - passing the emitted light through a hybrid optical assembly comprising three aspherical lenses and a hybrid diffractive/refractive lens; and
 - projecting the light that passed through the hybrid optical assembly onto an object or plane, wherein the projected light forms a pattern of dots.
7. The method of claim 6 including passing the emitted light through the hybrid optical assembly of any one of claims 1 – 3.
8. The hybrid optical assembly according to claim 1, wherein the first aspheric lens has a focal-length-normalized curvature of 9.21, the second hybrid diffractive/refractive lens has a focal-length-normalized curvature of 2.85, the third aspheric lens has a focal-length-normalized curvature of 0.34, and the fourth aspheric lens has a focal-length-normalized curvature of 0.78.
9. The hybrid optical assembly according to claim 1, wherein the first aspheric lens, the second hybrid diffractive/refractive lens, the third aspheric lens, and the fourth aspheric lens have focal-length-normalized diameters of 0.49, 0.49, 0.35, and 0.29, respectively.
10. the hybrid optical assembly according to claim 1, wherein the first aspheric lens, the second hybrid diffractive/refractive lens, the third aspheric lens, and the fourth aspheric lens have focal-length-normalized thicknesses of 0.0044, 1.048, 0.067, and 0.067, respectively.
11. The hybrid optical assembly according to claim 8 having an aspect ratio of 0.356.

12. The hybrid optical assembly according to claim 8, the first, third and fourth aspherical lenses have the following coefficients, respectively:

Coefficient (r)	1 st aspheric lens	3 rd aspheric lens	4 th aspheric lens
Fourth-order	-0.103	0.114	0.382
Sixth-order	0	2.4032	3.544
Eighth-order	0	-41.19	-62.281
Tenth-order	0	324.92	523.773
Twelfth-order	0	-1203.11	-1930.264
Fourteenth-order	0	1694.44	2348.243

and wherein the second hybrid diffractive/refractive lens has the following coefficients:

Coefficient (ρ)	2 nd hybrid diffractive/refractive lens
Aspheric Fourth-order	-0.115
Aspheric Sixth-order	-0.859
Aspheric Eighth-order	5.705
Aspheric Tenth-order	-17.849
Aspheric Twelfth-order	28.092
Aspheric Fourteenth-order	-17.554
Diffractive-phase Second-order	-525.287
Diffractive-phase Fourth-order	71.546
Diffractive-phase Sixth-order	-30.983

13. The hybrid optical assembly according to claim 8 having an aspect ratio of 0.224.

14. The hybrid optical assembly according to claim 8, wherein the first, third and fourth aspheric lenses have the following coefficients, respectively:

Coefficient (r)	1 st aspheric lens	3 rd aspheric lens	4 th aspheric lens
Fourth-order	-0.026	0.028	0.095
Sixth-order	0	0.237	0.350
Eighth-order	0	-1.611	-2.436
Tenth-order	0	5.034	8.115
Twelfth-order	0	-7.384	-11.847
Fourteenth-order	0	4.119	5.709

and wherein the second hybrid diffractive/refractive lens has the following coefficients:

Coefficient (ρ)	2 nd hybrid diffractive/refractive lens
Aspheric Fourth-order	-0.027
Aspheric Sixth-order	-0.085
Aspheric Eighth-order	0.223
Aspheric Tenth-order	-0.277
Aspheric Twelfth-order	0.172
Aspheric Fourteenth-order	-0.043
Diffractive-phase Second-order	-834.621
Diffractive-phase Fourth-order	113.678
Diffractive-phase Sixth-order	-49.228

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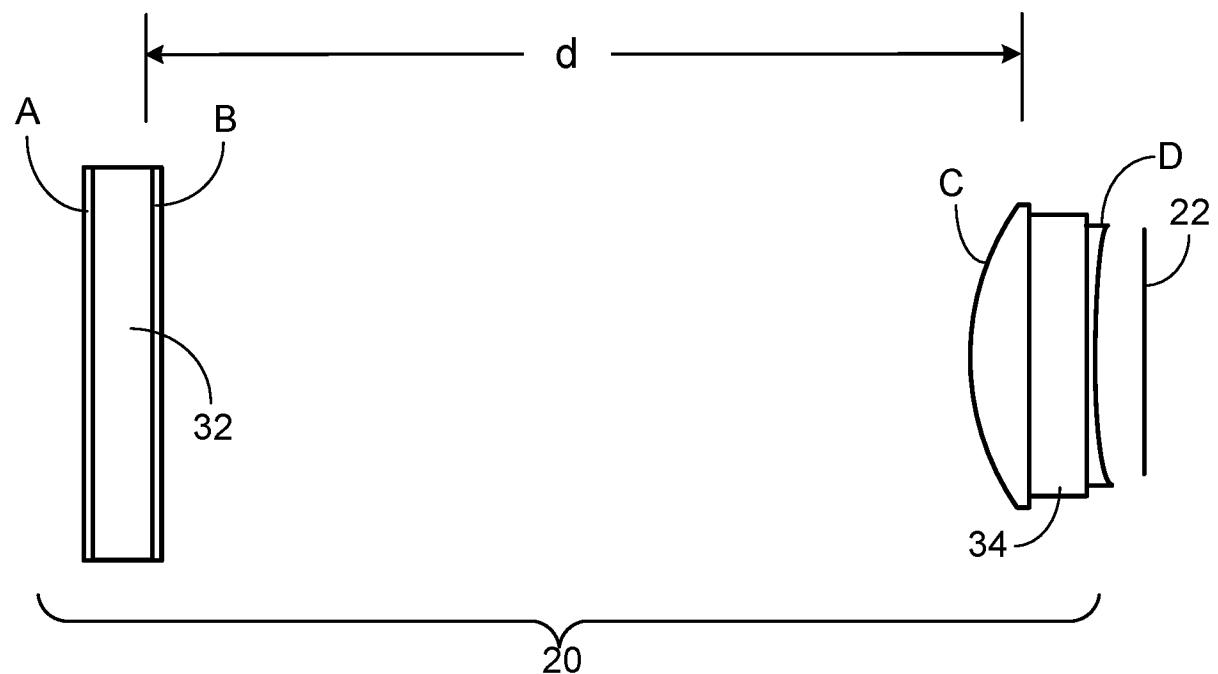


FIG. 1

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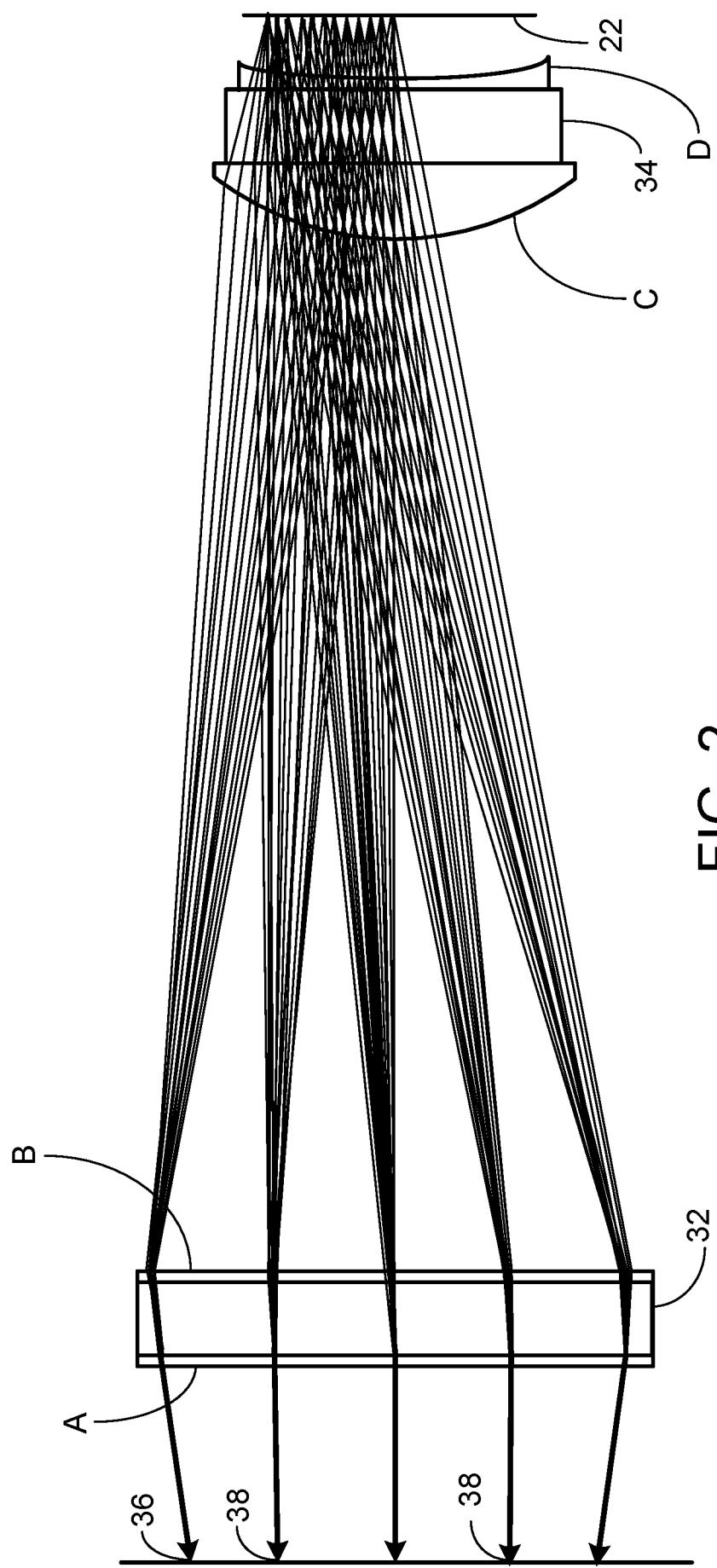


FIG. 2

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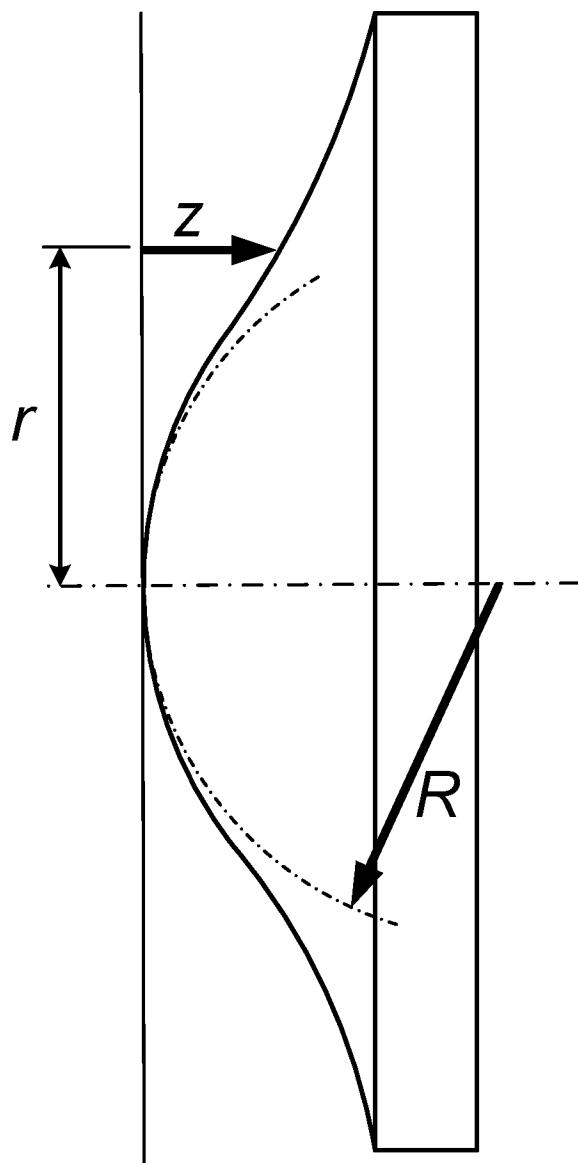


FIG. 3

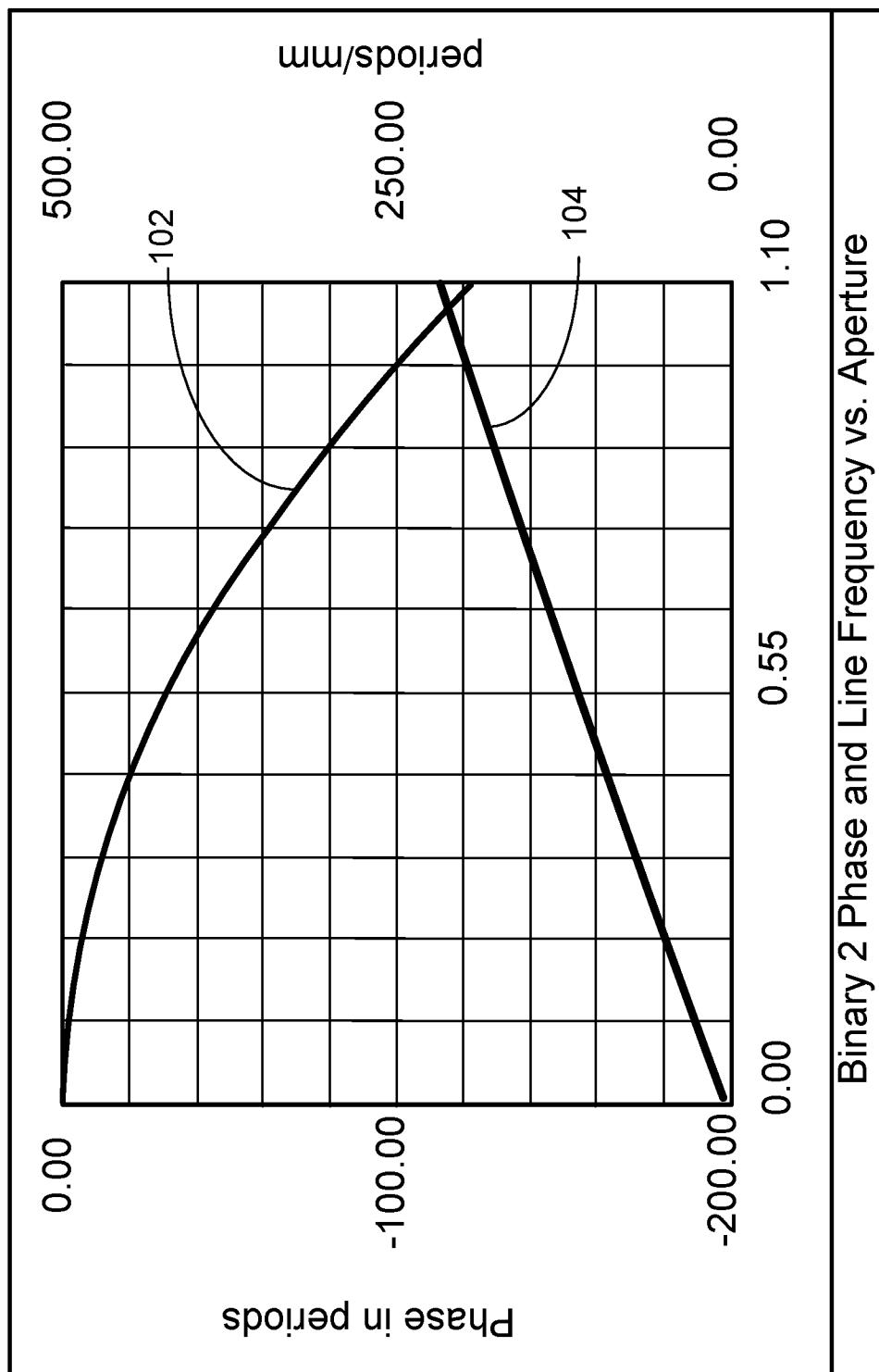
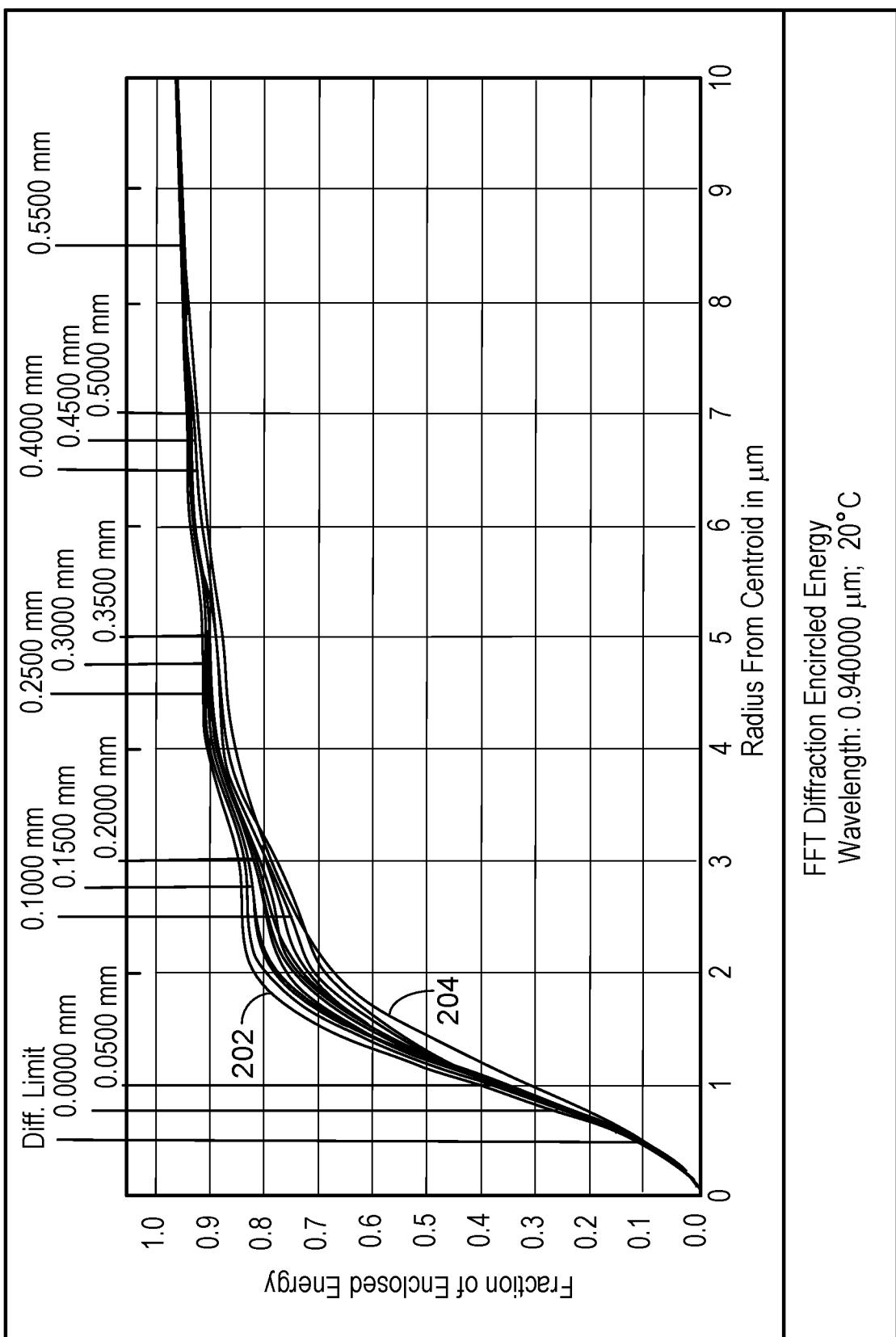


FIG. 4



FFT Diffraction Encircled Energy
Wavelength: 0.940000 μm ; 20°C

FIG. 5A

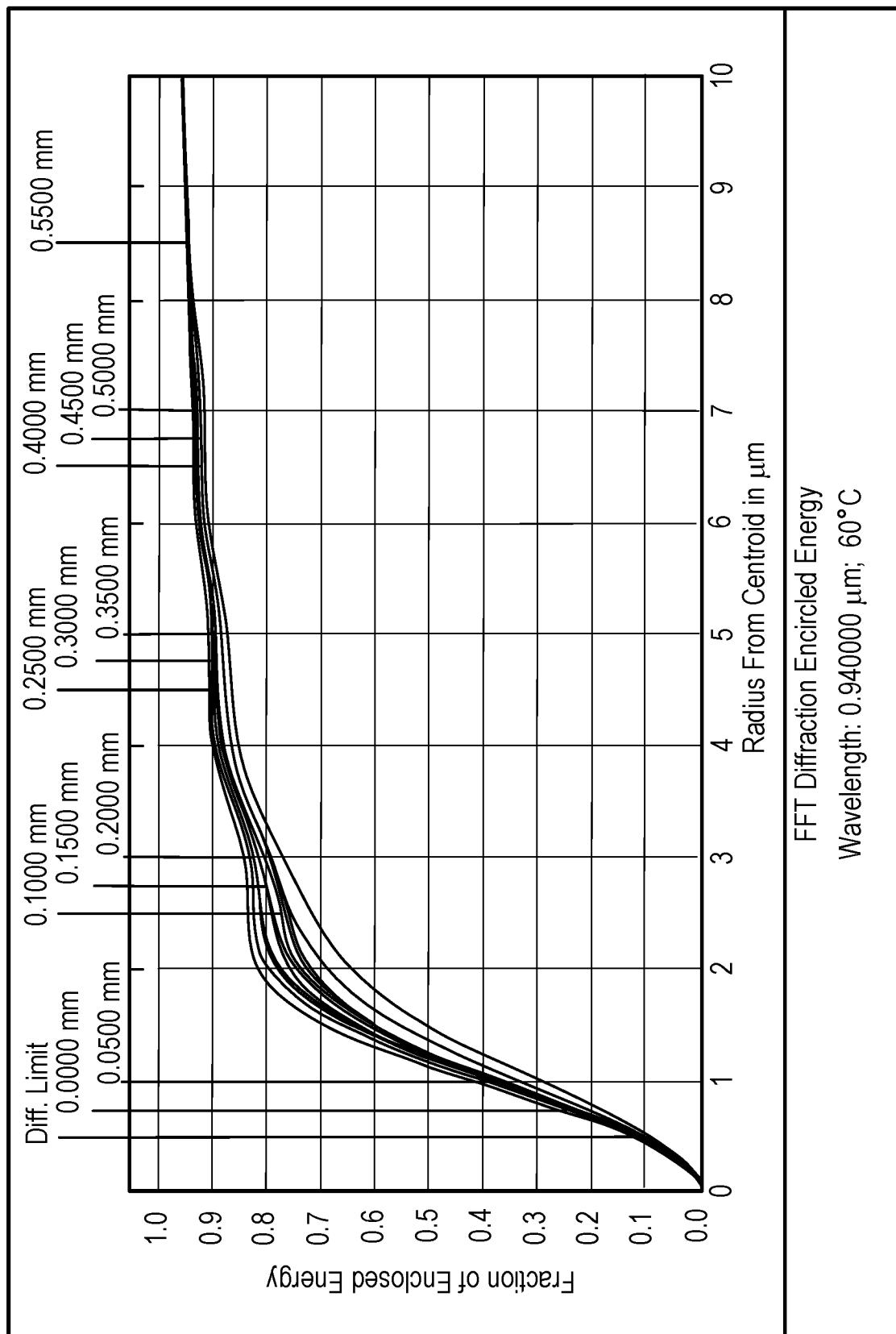


FIG. 5B

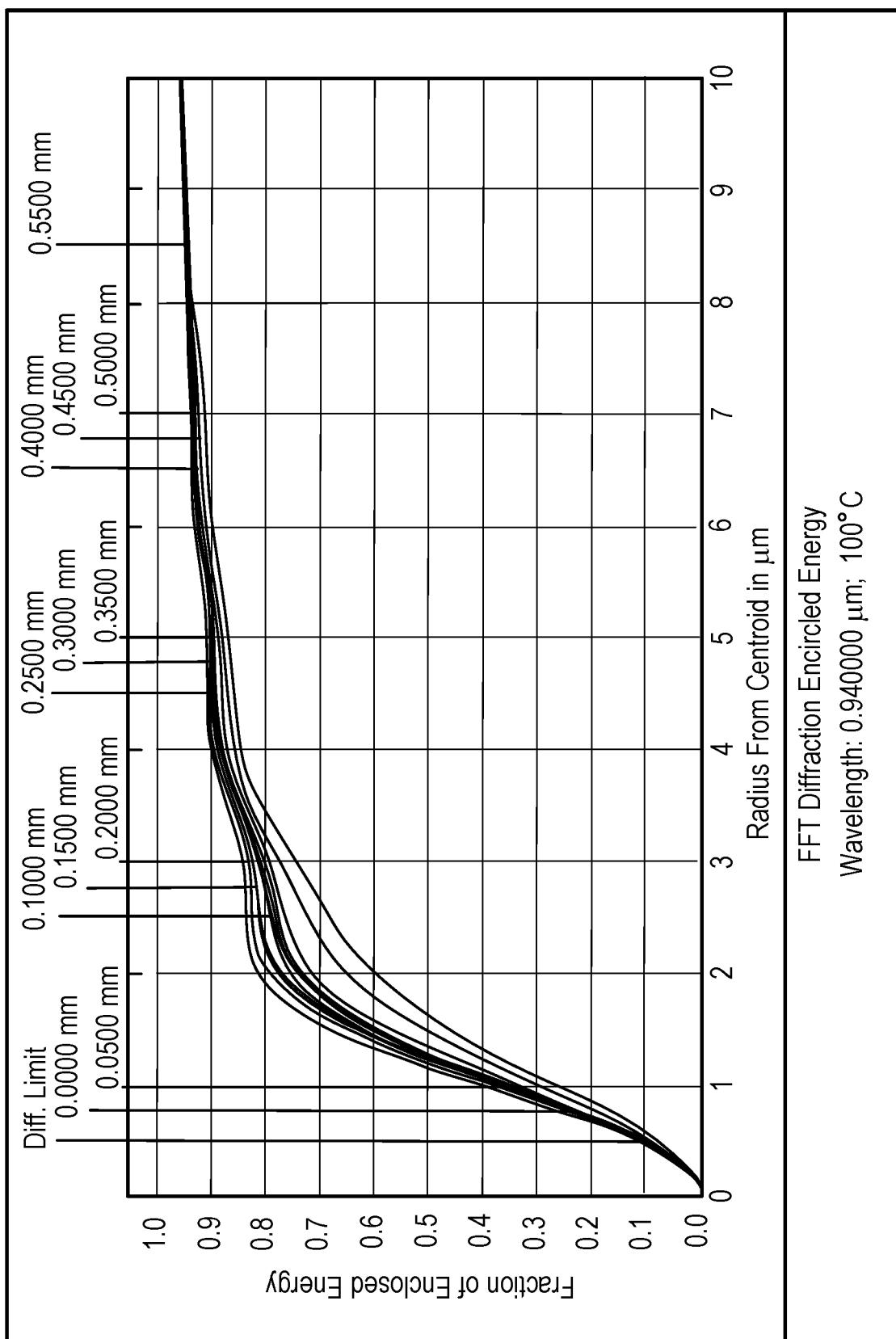


FIG. 5C

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2016/050512

A. CLASSIFICATION OF SUBJECT MATTER

G02B 13/18 (2006.01) G02B 27/18 (2006.01) G02B 11/20 (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPODOC, WPIAP, INSPEC keywords: OPTICAL ASSEMBLY, TRANSMISSIVE, ASPHERICAL, ATHERMAL, HYBRID LENS, VCSEL, OPTICAL PATTERN GENERATOR, HYBRID DIFFRACTIVE REFRACTIVE and similar terms and phrases. EPODOC CPC:G02B13/002, G02B27/003 and lower indexes further limited by similar terms and phrases

GOOGLE keywords: OPTICAL ASSEMBLY, TRANSPARENT, ASPHERICAL, ATHERMAL, HYBRID DIFFRACTIVE REFRACTIVE, OPTICAL PATTERN GENERATOR, FRESNEL, DEPTH MAP, LITHOGRAPHY and similar terms and phrases.

Applicant(s)/Inventor(s) names searched in Esp@cenet, Auspat and internal databases provided by IP Australia.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	Documents are listed in the continuation of Box C	

 Further documents are listed in the continuation of Box C See patent family annex

* "A"	Special categories of cited documents: document defining the general state of the art which is not considered to be of particular relevance	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"E"	earlier application or patent but published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means	"&"	document member of the same patent family
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search 20 December 2016	Date of mailing of the international search report 20 December 2016
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA Email address: pct@ipaaustralia.gov.au	Authorised officer Bayer Mitrovic AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No. 0262832164

INTERNATIONAL SEARCH REPORT		International application No.
C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		PCT/SG2016/050512
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6154323 A (KAMO) 28 November 2000 Whole document, especially abstract, column 1 line 60 - column 2 line 9, column 10 lines 1-10, column 16 line 1 - column 19 line 50, Figs. 1-9, examples 1-9, claims 11, 13.	1-14
X	GB 2246876 A (BRITISH AEROSPACE PUBLIC LIMITED COMPANY) 12 February 1992 Whole document, especially abstract, page 1 lines 1-20, page 2 line 3 - page 4 line 18, page 5 lines 22-25, Fig.1	1-14

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/SG2016/050512

This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document/s Cited in Search Report		Patent Family Member/s	
Publication Number	Publication Date	Publication Number	Publication Date
US 6154323 A	28 November 2000	US 6154323 A	28 Nov 2000
		JP H11295598 A	29 Oct 1999
		JP 3686253 B2	24 Aug 2005
GB 2246876 A	12 February 1992	GB 2246876 A	12 Feb 1992
		EP 0461856 A1	18 Dec 1991

End of Annex