CLAIMS

1. A lens comprising a refractive index profile configured such that rays of light propagating in the lens form an at least substantially plane wavefront at an at least substantially vertical plane of the lens.

2. The lens as claimed in claim 1, wherein the at least substantially vertical plane of the lens is a facet of the lens.

3. The lens as claimed in claim 1 or 2, wherein the refractive index profile is configured to vary in an at least substantially bell curve shape along a radial direction of the lens.

4. The lens as claimed in any one of claims 1 to 3, comprising a plurality of layers configured to generate the refractive index profile, wherein each layer of the plurality of layers comprises at least a first film and at least a second film arranged one above the other.

5. The lens as claimed in claim 4, wherein the first film comprises a first material having a first refractive index and the second film comprises a second material having a second refractive index, and wherein the first refractive index is higher than the second refractive index.

6. The lens as claimed in claim 4 or 5, wherein each layer of the plurality of layers comprises a plurality of the first films and a plurality of the second films, wherein the first films and the second films are arranged alternately.

7. The lens as claimed in any one of claims 4 to 6, wherein a thickness of the first films and a thickness of the second films of the plurality of layers are configured to change along the refractive index profile.

8. The lens as claimed in claim 7, wherein the thickness of the first films decreases and the thickness of the second films increases, along the refractive index profile from a maximum refractive index to an at least one minimum refractive index.

9. The lens as claimed in any one of claims 4 to 8, wherein the plurality of layers comprises between about 20 layers to about 1000 layers.

10. The lens as claimed in any one of claims 4 to 9, wherein each layer of the plurality of layers has an at least substantially same thickness or a different thickness.

11. The lens as claimed in any one of claims 4 to 10, wherein the thickness of each layer of the plurality of layers is between about 100 nm to about 300 nm.

12. The lens as claimed in any one of claims 4 to 10, wherein the thickness of each layer of the plurality of layers is $\leq$ 100 nm.

13. The lens as claimed in any one of claims 4 to 12, wherein the refractive index profile is configured to vary from about 3.5 to about 1.45 along the radial direction of the lens.

14. The lens as claimed in any one of claims 4 to 12, wherein the refractive index profile comprises at least one minimum refractive index of between about 1.5 to about 3.5.

15. The lens as claimed in any one of claims 4 to 14, wherein the lens is configured to have a numerical aperture of between about 1.5 to about 3.5.

16. The lens as claimed in any one of claims 4 to 14, wherein the lens is configured to have a numerical aperture of $\geq$ 3.1.

17. The lens as claimed in any one of claims 4 to 16, wherein a thickness of the lens is between about 3 μm to about 16 μm or about 15.6 μm.

18. The lens as claimed in any one of claims 4 to 17, wherein a length of the lens is between about 10 μm to about 25 μm.

19. The lens as claimed in any one of claims 4 to 18, wherein the lens is configured to have a focusing length of between about 10 μm to about 16 μm.

20. The lens as claimed in any one of claims 4 to 19, wherein the refractive index profile comprises a maximum refractive index, a first minimum refractive index and a second minimum refractive index, and wherein the refractive index profile is configured to vary at least substantially symmetrically along the radial direction of the lens, such that the first minimum refractive index and the second minimum refractive index are arranged on opposite sides of the maximum refractive index along the radial direction of the lens.

21. The lens as claimed in claim 20, wherein the maximum refractive index is at an at least substantially central position along the radial direction of the lens.

22. The lens as claimed in any one of claims 4 to 19, wherein the refractive index profile comprises a maximum refractive index and a minimum refractive index, and wherein the refractive index profile is configured to vary asymmetrically along the radial direction of the lens, such that the minimum refractive index and the maximum refractive index are arranged along the radial direction of the lens.

23. The lens as claimed in any one of claims 4 to 22, wherein the first film is silicon or titanium dioxide.

24. The lens as claimed in any one of claims 4 to 23, wherein the second film is silicon dioxide or aluminium oxide.

25. The lens as claimed in any one of claims 4 to 24, wherein the lens is a gradient-index (GRIN) lens.

26. Use of a lens as claimed in any one of claims 1 to 25 for optical coupling.

27. The use as claimed in claim 26, for optical coupling between a waveguide and an optical fiber.

28. A photonic package comprising:
a lens as claimed in any one of claims 1 to 25; and
a waveguide coupled to the lens.

29. The photonic package as claimed in claim 28, wherein the waveguide is configured to propagate a light with a sub-wavelength spot size, and wherein the lens is configured to expand the light from the waveguide or focus the light into the waveguide.

30. The photonic package as claimed in claim 28 or 29, wherein the lens comprises a plurality of layers, and wherein the lens is arranged adjacent to the waveguide, such that a first layer of the plurality of layers of the lens is configured to contact the waveguide.

31. The photonic package as claimed in claim 30, wherein the first layer of the plurality of layers of the lens has an at least substantially same refractive index as a waveguide core of the waveguide.

32. The photonic package as claimed in 31, wherein the waveguide core has a refractive index of about 3.5.

33. The photonic package as claimed in claim 31 or 32, wherein the waveguide core has a thickness of between about 300 nm to about 800 nm.

34. The photonic package as claimed in any one of claims 28 to 33, further comprising an optical fiber coupled to the lens.

35. The photonic package as claimed in claim 34, wherein the lens is arranged in between the waveguide and the optical fiber.

36. The photonic package as claimed in any one of claims 28 to 35, wherein the photonic package is configured to employ wavelength-division multiplexing (WDM).

37. The photonic package as claimed in any one of claims 28 to 36, wherein the photonic package is configured for use at a wavelength between about 1500 nm to about 1600 nm.

38. The photonic package as claimed in any one of claims 28 to 37, wherein the photonic package is a photonic chip or a photonic integrated circuit.

39. A method of generating a refractive index profile for a lens as claimed in any one of claims 1 to 25, the method comprises:

dividing the lens into a plurality of layers, wherein a thickness of each layer of the plurality of layers is at least substantially same; and

determining a refractive index of each layer of the plurality of layers, from a layer comprising a maximum refractive index to a layer comprising a minimum refractive index.

40. The method as claimed in claim 39, wherein determining the refractive index of each layer of the plurality of layers comprises approximating an input light as a point source, such that rays of light from the point source form an at least substantially plane wavefront at a focusing length of the lens.

41. The method as claimed in claim 40, wherein determining the refractive index of each layer of the plurality of layers further comprises:

determining a first refractive index of a first layer, wherein the first refractive index is the maximum refractive index; and

determining a second refractive index of a second layer arranged above the first layer from the following equation:

$$n_2 = \frac{L_f}{\sqrt{L_f^2 + h_l^{\,2}}} n_1$$

where

n_1 : refractive index of the first layer,

n_2 : refractive index of the second layer,

h_l : thickness of each layer,

L_f : focusing length of the lens.

42. The method as claimed in claim 41, wherein determining the refractive index of each layer of the plurality of layers further comprises:

determining a refractive index of an i-th layer of the plurality of layers from the following equation:

$$L_f = \sum_{k=1}^{i-1} \frac{h_l}{\sqrt{\frac{n_k^2}{n_i^2} - 1}}$$

where

n_i : refractive index of the i-th layer,

n_k : refractive index of a k-th layer, wherein the k-th layer refers to the first layer to an (i-1)-th layer, and wherein the i-th layer is arranged above the (i-1)-th layer,

h_l : thickness of each layer,

L_f : focusing length of the lens.

43. The method as claimed in claim 41 or 42, wherein the first refractive index is at least substantially same as a refractive index of a waveguide core of a waveguide coupled to the lens.

44. A method of forming a lens comprising a refractive index profile as claimed in any one of claims 1 to 25 or a lens comprising a refractive index profile generated by a method as claimed in any one of claims 39 to 43, the method comprises:

forming a plurality of layers configured to generate the refractive index profile along a radial direction of the lens, and

wherein forming the plurality of layers comprises forming at least a first film and at least a second film arranged one above the other for each layer of the plurality of layers.

45. The method as claimed in claim 44, wherein the first film comprises a first material having a first refractive index and the second film comprises a second material having a second refractive index, and wherein the first refractive index is higher than the second refractive index.

46. The method as claimed in claim 44 or 45, wherein forming the plurality of layers further comprises determining a thickness of the first film from the following equation:

$$f_H = \frac{n^2 - n_L^2}{n_H^2 - n_L^2} f_T$$

where

f_H : thickness of the first film,

f_T : total thickness of the first film and the second film,

n_H : refractive index of the first film,

n_L : refractive index of the second film, and

n : effective refractive index of the first film and the second film.

47. The method as claimed in any one of claims 44 to 46, wherein forming the plurality of layers further comprises determining a thickness of the second film from the following equation:

$$f_L = f_T - f_H$$

where

f_H : thickness of the first film,

f_L : thickness of the second film,

f_T : total thickness of the first film and the second film.

48. The method as claimed in any one of claims 44 to 47, wherein forming the plurality of layers further comprises determining an effective refractive index for each layer of the plurality of layers comprising the at least first film and the at least second from the following equation:

$$n^2 = \frac{n_H^2 f_H + n_L^2 f_L}{f_T}$$

where

f_H : thickness of the first film,

f_L : thickness of the second film,

f_T : total thickness of the first film and the second film,

n_H : refractive index of the first film,

n_L : refractive index of the second film, and

n : effective refractive index of the first film and the second film.

49. The method as claimed in any one of claims 44 to 48, wherein forming the plurality of layers comprises forming a plurality of the first films and a plurality of the second films for each layer of the plurality of layers, wherein the first films and the second films are arranged alternately.

50. The method as claimed in any one of claims 44 to 49, wherein forming the plurality of layers comprises a thin film deposition process.

CLAIMS

1. A method of generating a refractive index profile for a lens comprising the refractive index profile configured such that rays of light propagating in the lens form an at least substantially plane wavefront at an at least substantially vertical plane of the lens, the method comprises:

dividing the lens into a plurality of layers, wherein a thickness of each layer of the plurality of layers is at least substantially same; and

determining a refractive index of each layer of the plurality of layers, from a layer comprising a maximum refractive index to a layer comprising a minimum refractive index,

wherein determining the refractive index of each layer of the plurality of layers comprises approximating an input light as a point source, such that rays of light from the point source form an at least substantially plane wavefront at a focusing length of the lens, and

wherein determining the refractive index of each layer of the plurality of layers further comprises:

determining a first refractive index of a first layer, wherein the first refractive index is the maximum refractive index; and

determining a second refractive index of a second layer arranged above the first layer from the following equation:

$$n_2 = \frac{L_f}{\sqrt{L_f^2 + h_l^2}} n_1$$

where

n_1 : refractive index of the first layer,

n_2 : refractive index of the second layer,

h_l : thickness of each layer,

L_f : focusing length of the lens.

2. The method as claimed in claim 1, wherein determining the refractive index of each layer of the plurality of layers further comprises:

determining a refractive index of an i-th layer of the plurality of layers from the following equation:

$$L_f = \sum_{k=1}^{i-1} \frac{h_l}{\sqrt{\frac{n_k^2}{n_i^2} - 1}}$$

where

n_i : refractive index of the i-th layer,

n_k : refractive index of a k-th layer, wherein the k-th layer refers to the first layer to an (i-1)-th layer, and wherein the i-th layer is arranged above the (i-1)-th layer,

h_l : thickness of each layer,

L_f: focusing length of the lens.

3. The method as claimed in claim 1 or 2, wherein the first refractive index is at least substantially same as a refractive index of a waveguide core of a waveguide coupled to the lens.

4. A method of forming a lens comprising a refractive index profile configured such that rays of light propagating in the lens form an at least substantially plane wavefront at an at least substantially vertical plane of the lens or a lens comprising a refractive index profile generated by a method as claimed in any one of claims 1 to 3, the method comprises:

forming a plurality of layers configured to generate the refractive index profile along a radial direction of the lens, and

wherein forming the plurality of layers comprises forming at least a first film and at least a second film arranged one above the other for each layer of the plurality of layers, and

wherein forming the plurality of layers further comprises determining a thickness of the first film from the following equation:

$$f_H = \frac{n^2 - n_L^2}{n_H^2 - n_L^2} f_T$$

where

f_H : thickness of the first film,

f_T : total thickness of the first film and the second film,

n_H : refractive index of the first film,

n_L : refractive index of the second film, and

n : effective refractive index of the first film and the second film.

5. The method as claimed in claim 4, wherein the first film comprises a first material having a first refractive index and the second film comprises a second material having a second refractive index, and wherein the first refractive index is higher than the second refractive index.

6. The method as claimed in any one of claims 4 to 5, wherein forming the plurality of layers further comprises determining a thickness of the second film from the following equation:

$$f_L = f_T - f_H$$

where

f_H : thickness of the first film,

f_L : thickness of the second film,

f_T : total thickness of the first film and the second film.

7. The method as claimed in any one of claims 4 to 6, wherein forming the plurality of layers further comprises determining an effective refractive index for each layer of the plurality of layers comprising the at least first film and the at least second from the following equation:

$$n^2 = \frac{n_H^2 f_H + n_L^2 f_L}{f_T}$$

where

f_H : thickness of the first film,

f_L : thickness of the second film,

f_T : total thickness of the first film and the second film,

n_H : refractive index of the first film,

n_L : refractive index of the second film, and

n : effective refractive index of the first film and the second film.

8. The method as claimed in any one of claims 4 to 7, wherein forming the plurality of layers comprises forming a plurality of the first films and a plurality of the second films for each layer of the plurality of layers, wherein the first films and the second films are arranged alternately.

9. The method as claimed in any one of claims 4 to 8, wherein forming the plurality of layers comprises a thin film deposition process.

10. A method of forming a lens comprising a refractive index profile configured such that rays of light propagating in the lens form an at least substantially plane wavefront at an at least substantially vertical plane of the lens or a lens comprising a refractive index profile generated by a method as claimed in any one of claims 1 to 3, the method comprises:

forming a plurality of layers configured to generate the refractive index profile along a radial direction of the lens, and

wherein forming the plurality of layers comprises forming at least a first film and at least a second film arranged one above the other for each layer of the plurality of layers, and

wherein forming the plurality of layers further comprises determining an effective refractive index for each layer of the plurality of layers comprising the at least first film and the at least second from the following equation:

$$n^2 = \frac{n_H^2 f_H + n_L^2 f_L}{f_T}$$

where

f_H : thickness of the first film,

f_L : thickness of the second film,

f_T : total thickness of the first film and the second film,

n_H : refractive index of the first film,

n_L : refractive index of the second film, and

n : effective refractive index of the first film and the second film.

11. The method as claimed in claim 10, wherein the first film comprises a first material having a first refractive index and the second film comprises a second material having a second refractive index, and wherein the first refractive index is higher than the second refractive index.

12. The method as claimed in claim 10 or 11, wherein forming the plurality of layers further comprises determining a thickness of the first film from the following equation:

$$f_H = \frac{n^2 - n_L^2}{n_H^2 - n_L^2} f_T$$

where

f_H : thickness of the first film,

f_T : total thickness of the first film and the second film,

n_H : refractive index of the first film,

n_L : refractive index of the second film, and

n : effective refractive index of the first film and the second film.

13. The method as claimed in any one of claims 10 to 12, wherein forming the plurality of layers further comprises determining a thickness of the second film from the following equation:

$$f_L = f_T - f_H$$

where

f_H : thickness of the first film,

f_L : thickness of the second film,

f_T : total thickness of the first film and the second film.

14. The method as claimed in any one of claims 10 to 13, wherein forming the plurality of layers comprises forming a plurality of the first films and a plurality of the

second films for each layer of the plurality of layers, wherein the first films and the second films are arranged alternately.

15. The method as claimed in any one of claims 10 to 14, wherein forming the plurality of layers comprises a thin film deposition process.