US 20040013384A1

(19) United States
(12) Patent Application Publication
(10) Pub. No.: US 2004/0013384 A1
(43) Pub. Date: Jan. 22, 2004
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(54) **OPTICAL WAVEGUIDE STRUCTURE**

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(21) Appl. No.: **10/196,727**

(22) Filed: **Jul. 17, 2002**

Publication Classification

(51) **Int. Cl.[7]** **G02B 6/10**

(52) **U.S. Cl.** **385/129**

(57) **ABSTRACT**

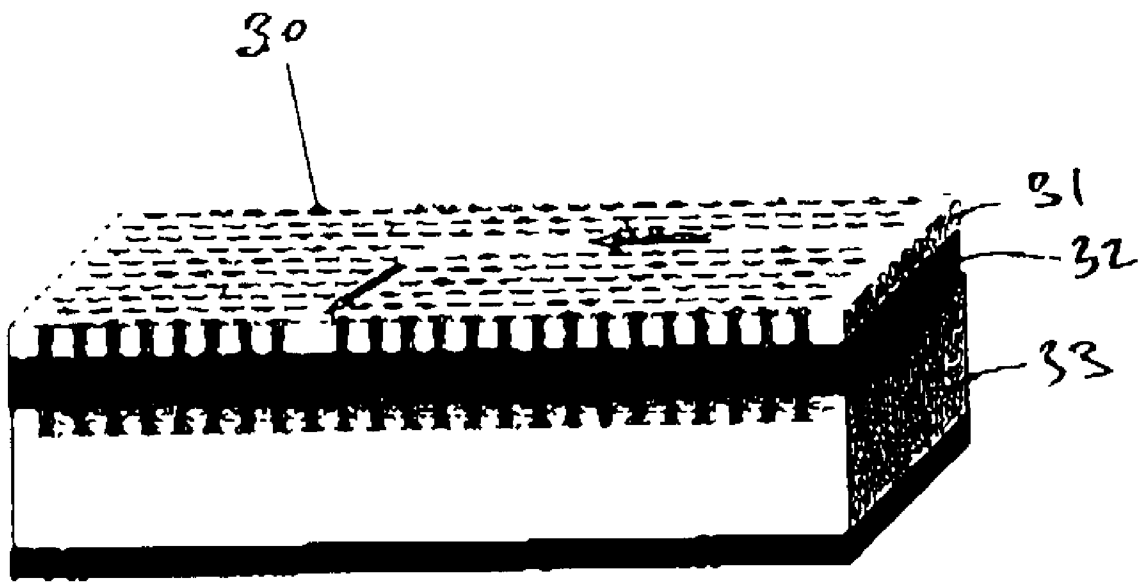
A waveguide structure according to the invention comprises a core layer (10), having a refractive index n_{core}, and an array of rods (11) in the core layer having a refractive index n_{rods} The refractive indices satisfy the inequality

$$n_{rods}>n_{core}$$

In a planar waveguide structure buffer (12) and cladding (13) layers are included, having a refractive index n_{buffer} and $n_{cladding}$ respectively The refractive indices then satisfy the inequality

$$n_{rods}>n_{core}>n_{cladding} \text{ and } n_{buffer}$$

This condition provides greater vertical confinement of the E-field of an optical signal passing through the waveguide. Furthermore, it allows waveguides to be formed of a glassy material having a similar refractive index and core dimensions to that of a fibre A high refractive index contrast within the photonic crystal region is used while totally eliminating the need for mode conversion to launch light in and out of the waveguide



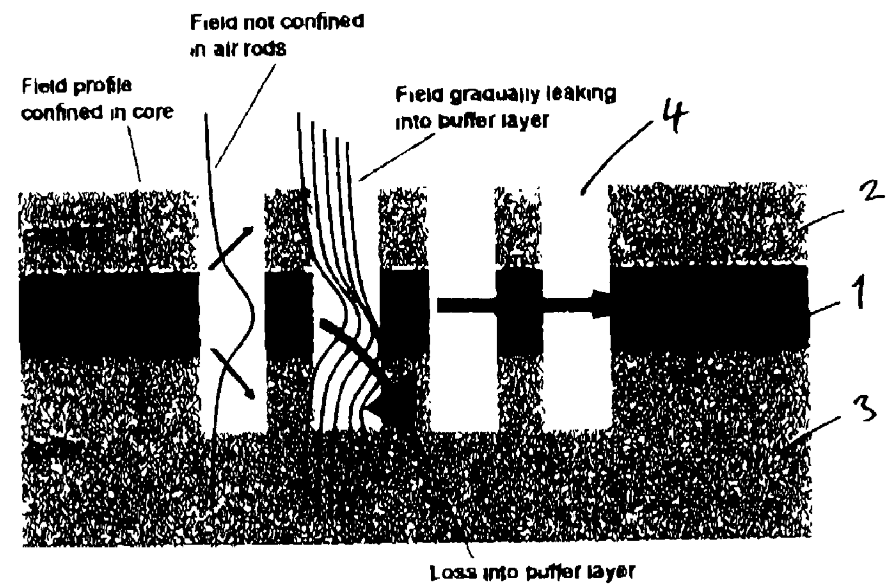


Figure 1

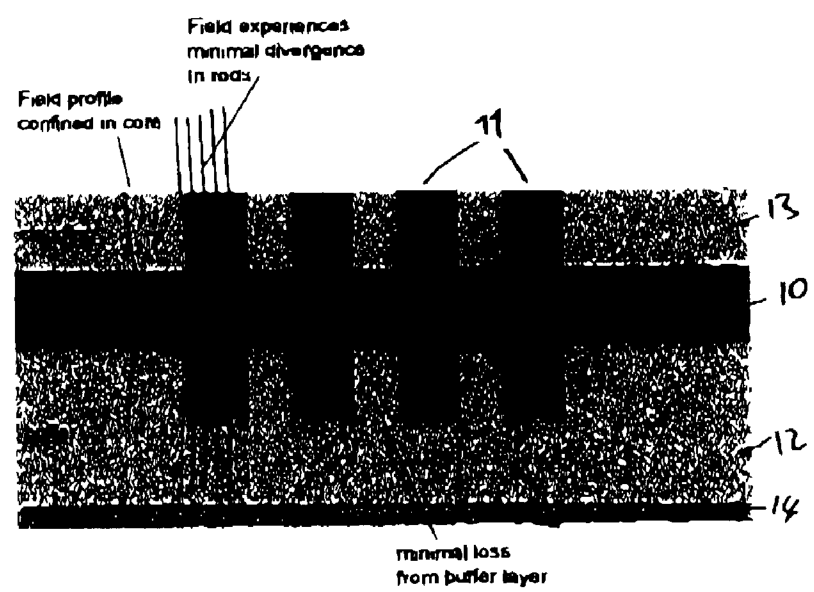


Figure 2

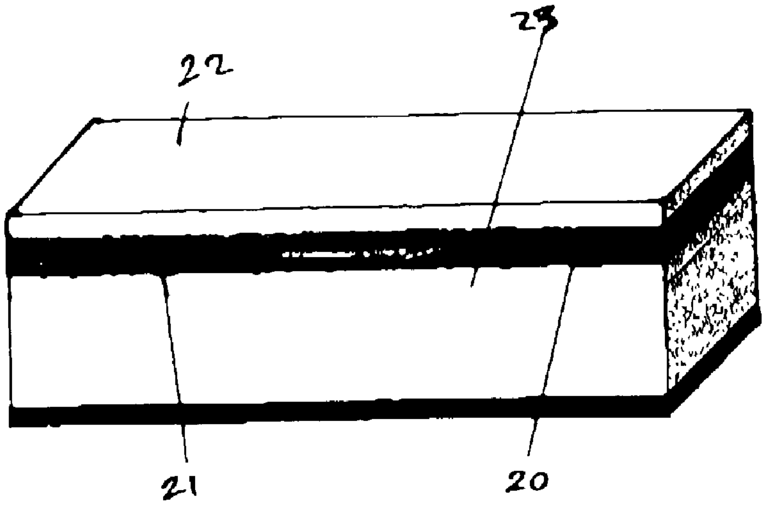


Figure 3

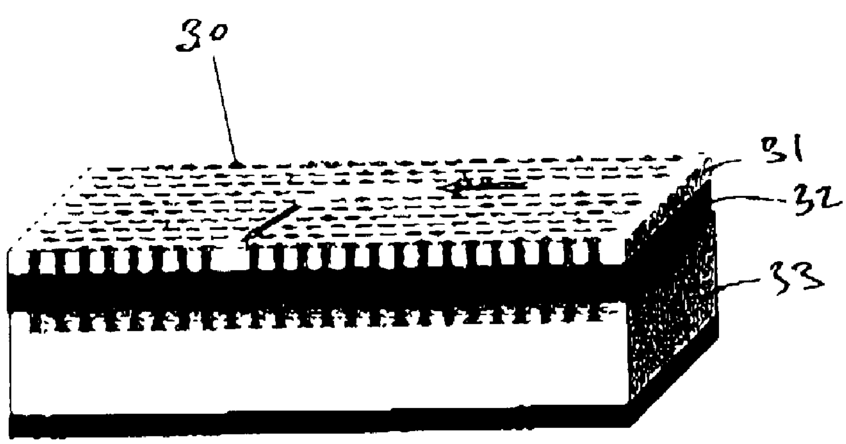


Figure 4

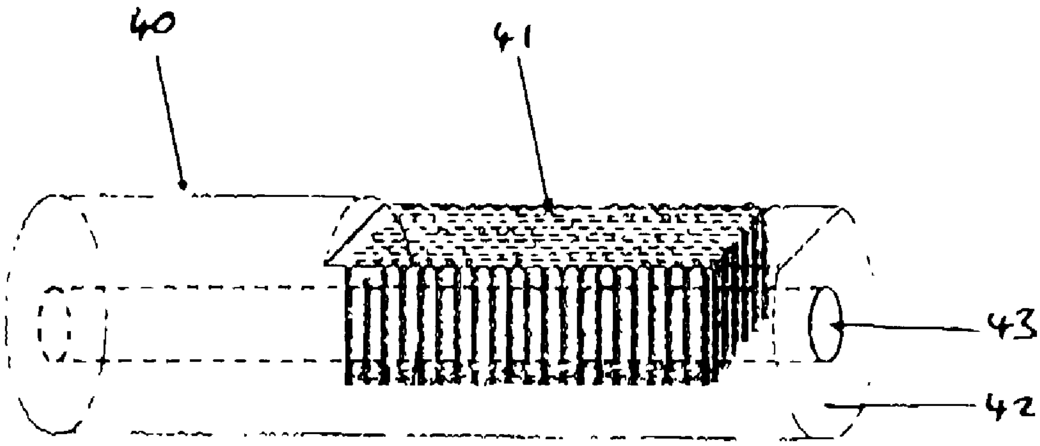


Figure 5

OPTICAL WAVEGUIDE STRUCTURE

FIELD OF THE INVENTION

[0001] The present invention relates to the field of optical devices and in particular but not exclusively to waveguide structures in integrated optical circuits.

BACKGROUND OF THE INVENTION

[0002] It is increasingly recognised that integrated optical circuits have a number of advantages over electrical circuits However, it has been difficult to produce integrated optical circuits which are comparably small, primarily due to the difficulty in producing waveguides which can include tight bends without large signal losses. It has also been difficult to produce integrated optical circuits including signal processing devices which can be easily coupled to current optical fibres, owing to a difference in the refractive index of the material used for optical fibres and those materials typically used for integrated optical devices, whilst still maintaining compact sizes

[0003] Photonic crystals comprising a lattice of air holes formed in a core material, typically silicon, have been fabricated, which exhibit a photonic bandgap By not including some holes in the lattice a defect state waveguide can be formed Confinement of light within the waveguide is provided by using light within the photonic bandgap wavelength range However, it has been found that devices of this type suffer from large losses, mainly due to the escape of light from the waveguide in a vertical direction. Furthermore, in order to provide a strong and complete bandgap at optical frequencies, it has been necessary to use a high refractive index material, typically silicon This makes it difficult to couple light into the waveguides from existing optical fibres, which typically have a core having a much lower refractive index This problem necessitates complicated, lossy mode coupling devices

SUMMARY OF THE INVENTION

[0004] According to a first aspect of the present invention, an optical waveguide structure comprises a core layer having a first refractive index n_{core}, and an array of sub-regions within the core layer having a second refractive index n_{rods}, the array of sub-regions giving rise to a photonic band structure within the core layer wherein

$$n_{rods}>n_{core}$$

[0005] Preferably, the waveguide structure is a planar waveguide structure, the core layer being formed between a cladding layer and a buffer layer, the cladding layer having a third refractive index $n_{cladding}$, and the buffer layer having a fourth refractive index n_{buffer}, wherein

$$n_{rods}>n_{core}>n_{cladding} \text{ and } n_{buffer}$$

[0006] Alternatively, the waveguide structure may be an optical fibre, comprising a cladding layer having a third refractive index $n_{cladding}$, surrounding the core layer, wherein

$$n_{rods}>n_{core}>n_{cladding}$$

[0007] The cladding layer of the optical fibre is preferably planarised in the vicinity of the array of sub-regions, the array of sub-regions extending through the planarised cladding layer and into the core layer

[0008] Preferably, the array of sub-regions gives rise to a photonic bandgap.

[0009] Preferably, the core layer has a refractive index between 1 4 and 2.5 Preferably, the sub-regions have a refractive index between 1 8 and 4 Preferably, the cladding and buffer layers have a refractive index between 1 3 and 1 6

[0010] The use of an array of sub-regions within a waveguide structure having a refractive index higher than the core layer provides a number of benefits over the prior art. Owing to the high index of the sub-regions the out-of-plane divergence of light in the sub-regions is reduced as compared with the air holes which are typically used in photonic crystal structures As a result, more light is coupled back into the core material at the rod/core interface Additionally, as the refractive index of the sub-regions is higher than that of the buffer layer and cladding layers, coupling of light into the buffer and cladding layers is reduced Thus, the present invention provides greater vertical confinement of light within the waveguide. This fact, coupled with the existence of a photonic bandgap at optical wavelengths, allows tight waveguide bends to be formed with low loss at optical wavelengths According to the present invention, the core can be made of a material with a refractive index better matched to that of conventional optical fibre, e g. doped silica or silicon oxynitride This means that the waveguide can be easily coupled to conventional optical fibres without the need for any additional, complicated coupling structures

[0011] The nature of the band structure, which arises from using high index sub-regions, is such that the dimensions required for the lattice pitch to produce a bandgap at the wavelength typically used for telecommunications can be much larger than in conventional photonic crystals As a result, fabrication tolerances are greatly reduced, as the sub-regions can be spaced further apart and each sub-region can be larger This means that the waveguide of the present invention can be easily fabricated using conventional lithography Typically, the prior art requires much higher precision lithography, such as e-beam lithography

[0012] Furthermore, in order to produce a strong extinction ratio bandgap, fewer sub-regions are required than in conventional photonic crystals This is partly due to the properties of a structure composed of high refractive index rods in a low refractive index background and partly due to the dielectric contrast remaining large for different wavelengths.

[0013] In a conventional photonic crystal the high refractive index material is the core. Different wavelengths coupled into the core experience different effective refractive indices As wavelength increases effective refractive index decreases, which in turn reduces the effective dielectric contrast This adversely affects the bandgap extinction ratio and gap to midgap ratio. In the present invention, the high refractive index rods maintain their index irrespective of wavelength and hence the dielectric contrast is maintained at the ratio of the core index to the rod index

[0014] Preferably, the sub-regions are formed from silicon Preferably, the core layer is formed from silicon nitride, silicon oxynitride, doped silica, tantalum pentoxide or doped tantalum pentoxide The cladding layer and buffer layer are preferably formed from silicon dioxide.

[0015] The sub-regions may extend through the cladding layer as well as the core layer and partially or fully into the buffer layer. Alternatively, the cladding layer may include sub-regions corresponding to the sub-regions in the core layer having a refractive index which is greater than or equal to the refractive index of the cladding layer but which is less than or equal to the refractive index of the core

[0016] The present invention is applicable to waveguides connecting integrated optical circuits as well as to individual optical devices which are used in integrated optical circuits Any device incorporating waveguide bends in a glassy core layer can be improved or at least significantly reduced in size, by use of the present invention Such devices include Arrayed Waveguide Gratings (AWGs), Mach Zehnder interferometers, directional couplers, dispersion compensators, splitters/multiplexers, polarisation compensators, optical switches and optical delay elements The fact that tight waveguide bends can be formed using the present invention, without significant loss can reduce the size of these components by several orders of magnitude

[0017] Preferably, the sub-regions are arranged in a square lattice The square lattice is useful in that it gives rise to a sequence of different bandgaps This means that a square lattice having a relatively large pitch spacing can be used, with large individual sub-regions, and it is still possible to get a higher order bandgap in the visible region or telecommunications region of the spectrum

[0018] Preferably, the core layer includes a waveguiding region having no sub-regions Preferably, the waveguiding region includes a bend

[0019] According to a second aspect of the invention, a method of manufacturing a optical waveguide structure comprises the steps of

[0020] providing a core layer having a first refractive index n_{core};

[0021] forming an array of holes in the core layer;

[0022] filling the holes with a material having a second refractive index n_{rods}, wherein

$$n_{rods}>n_{core}.$$

[0023] Preferably, the optical waveguide is a planar waveguide, the method further including the steps of

[0024] providing a buffer layer having a refractive index n_{buffer} on one side of the core layer, and

[0025] providing a cladding layer having a refractive index $n_{cladding}$ on the other side of the core layer, wherein:

$$n_{rods}>n_{core}>n_{cladding} \text{ and } n_{buffer}$$

[0026] Alternatively, the optical waveguide may be an optical fibre the method further including the steps of

[0027] providing a cladding layer having a refractive index $n_{cladding}$ surrounding the core layer, wherein

$$n_{rods}>n_{core}>n_{cladding}$$

[0028] According to a third aspect of the present invention, a method of guiding an optical signal comprises the step of passing an optical signal through a waveguiding region of an optical waveguide structure comprising a core layer having a first refractive index n_{core}, and an array of sub-regions within the core layer having a second refractive index n_{rods}, the array of sub-regions giving rise to a photonic band structure within the core layer, wherein

$$n_{rods}>n_{core}.$$

[0029] Preferably, the waveguide is a planar waveguide, wherein the core layer is formed between a cladding layer and a buffer layer, the cladding layer having a third refractive index $n_{cladding}$, and the buffer layer having a fourth refractive index n_{buffer}, and wherein

$$n_{rods}>n_{core}>n_{cladding} \text{ and } n_{buffer}$$

[0030] Alternatively, the optical waveguide may be an optical fibre, wherein a cladding layer has a third refractive index $n_{cladding}$, and surrounds the core layer, and wherein

$$n_{rods}>n_{core}>n_{cladding}$$

BRIEF DESCRIPTION OF THE DRAWINGS

[0031] Examples of the present invention will now be described in detail with reference to the accompanying drawings, in which

[0032] **FIG. 1** is a schematic cross sectional view of a photonic crystal embedded in a waveguide structure in accordance with the prior art,

[0033] **FIG. 2** is a schematic cross sectional view of a photonic crystal embedded in a waveguide structure in accordance with the present invention,

[0034] **FIG. 3** shows a waveguide design in accordance with the present invention;

[0035] **FIG. 4** shows a waveguide bend formed with a waveguide design in accordance with the present invention and,

[0036] **FIG. 5** shows an optical fibre incorporating a structure in accordance with present invention.

DETAILED DESCRIPTION

[0037] Photonic crystal waveguide structures are based on some perturbation in dielectric constant in the core of a planar waveguide structure This has most commonly been performed by the etching of air rods into the core layer of the waveguide. As light propagates through the core it interacts with the dielectric constant modulation and, in some structures, in a manner analogous to electrons in a semiconductor, certain electromagnetic fields are forbidden to propagate in the core The forbidden electromagnetic fields form a photonic bandgap More detail on the nature of the band structure of photonic crystals of this sort can be found in WO98/53351

[0038] **FIG. 1** illustrates the interaction of the E-field with the core **1** in a photonic crystal according to the prior art The light is travelling through the core **1** from left to right A profile of the E-field within the core **1**, cladding **2** and buffer **3** layers is shown It can be seen that in the photonic crystal region the mode confinement is reduced and there is out of plane loss When the light reaches the first air/core interface, the light diverges strongly in the vertical direction introducing loss Once the light is in the air region **4** there is no confinement and light escapes from the top of the structure and into the buffer layer **3**, which is of a higher refractive index than air Furthermore, owing to the fact that the structure is not symmetric, and light is not well confined in the vertical direction, light leaks into the buffer layer **3** from the air rods **4**

[**0039**] Vertical loss in the waveguide structure is very significant and limits the usefulness of the structure in practical devices especially in confinement applications such as in waveguide bends

[**0040**] **FIG. 2** shows a waveguide structure according to one aspect of the present invention and shows the interaction of between the E-field in the core **10** and in the photonic crystal section The waveguide structure shown in **FIG. 2** comprises a core layer **10**, having a refractive index n_{core}, an array of rods **11** in the core layer **10** having a refractive index n_{rods}, and buffer **12** and cladding layers **13** having a refractive index n_{buffer} and $n_{cladding}$, respectively. In this example the rods **11** extend through the cladding layer **13** and into the buffer layer **12** The refractive indices satisfy the inequality

$$n_{rods} > n_{core} > n_{cladding} \text{ and } n_{buffer}$$

[**0041**] This condition provides greater vertical confinement of the E-field of an optical signal passing through the waveguide. As shown in **FIG. 2**, the profile of the E-field experiences minimal divergence in the rods **11** The higher refractive index of the rods **11** eliminates the tendency of the light to leak into the buffer layer **12** and reduces losses from the top of the structure and into the substrate

[**0042**] The core **10** material of the structure of **FIG. 2** is a few microns in thickness ans is formed of silicon nitride (n=2 02) Alternatively, it could be a low index material such as germanium doped silica which allows simple coupling of the waveguide to standard optical fibres, or silicon oxynitride, tanatalum pentoxide doped tantalum pentoxide or doped silicon dioxide The rods **11** are composed of silicon (n=3 46), giving a high index contrast, which is required to give a strong extinction ratio bandgap using simple lattice patterns. The cladding **13** and buffer **12** layers are formed of silicon dioxide The buffer **12** and cladding **13** layers need not be formed of the same material as long as they satisfy the inequality above The materials described above are examples only The benefit of the invention will be realised as long as the inequalities are satisfied. However, for structures which are easily coupled to typical optical fibres and devices it is preferred that the core layer has a refractive index between 1 4 and 2 5 the rods nave a refractive index between 1.8 and 4 and the cladding and Puffer layers each have a refractive index between 1 3 and 1 6

[**0043**] The waveguide of **FIG. 2** also includes a substrate layer **14** underneath the buffer layer **12** The waveguide structure of **FIG. 2** can be fabricated as follows The buffer layer **12** is put on the substrate by thermal oxidation, HIPOX or plasma enhanced chemical vapour deposition (PECVD) depending on whether a thin or thick oxide is being deposited. The core layer is put down next by PECVD, CVD or sputtering The cladding layer is then deposited by PECVD, CVD or sputtering The position of the rods **11** is then defined by etching into the core **10** Wet or dry etching may be used but dry etching is preferred The position of the rods is either direct-written using an e-beam, or transferred from a mask. The high index material, in this case silicon, is then deposited into the etched holes using PECVD, chemical vapour deposition (CVD), molecular beam epitaxy (MBE) or sputtering Any silicon on top of the waveguide can be removed preferably by dry etching, but alternatively by controlled wet etching or chemical mechanical polishing Alternatively, silicon rods can be grown or etched from the substrate and a waveguide structure grown around the rods

[**0044**] The etching process used to define the rods can be performed using conventional lithography Prior photonic crystal waveguide structures nave required the use of E-beam lithography, however, the material system of the present invention gives rise to a useful band structure at larger lattice spacings than in conventional photonic crystal structures and so allows the rods to be larger and more widely spaced than the air rods of the prior art Furthermore, the present invention allows for greater manufacturing tolerances

[**0045**] Additionally, it is possible to include a different material to define the rods in the buffer and cladding layers, with a refractive index $n_{rods\ in\ cladding\ and\ buffer}$ In this instance the following inequality applies:

$$n_{rods\ in\ core} > n_{core} \geqq n_{rods\ in\ cladding\ and\ buffer} \geqq n_{cladding} \text{ and } n_{buffer}$$

[**0046**] This type of structure does not confine light so well as complete rods of a high index material but there are advantages in fabrication. The buffer **23** and core **20** layer are initially grown Rods **21** are then defined and etched through the core layer **20**. Silicon is deposited into the rods **21** and on top of the core prior to deposition of the cladding The silicon remaining on top of the core is removed by wet or dry etching or chemical mechanical polishing. Following this the cladding layer **22** is deposited using PECVD, CVD or sputtering to form the structure shown in **FIG. 3**

[**0047**] The use of high index rods in low index core materials provides a revolutionary method for the formation of a fibre compatible photonic crystal technology The waveguide core can be formed of a glassy material having similar core dimensions to that of a fibre. A high refractive index contrast within the photonic crystal region is used while the use of a core layer having a refractive index close to that of the core of conventional optical fibre eliminates the need for mode conversion to launch light in and out of the waveguide Additionally, as described above, the out-of-plane loss is also reduced as compared with conventional high index waveguides

[**0048**] As shown in **FIG. 4**, waveguides in accordance with the present invention can include tight waveguide bends The waveguide structure comprises an array of silicon rods **30** extending through a cladding layer **31** and a core layer **32** into a buffer layer **33** A number of rods are missing from the array forming a waveguide which includes a 90° bend Clearly, the waveguide could take any shape and could, for example, include a bifurcation to form a splitter The minimal vertical loss from the waveguide means that light within the bandgap of the photonic crystal region is confined With the waveguide and is forced to propagate around the bend. This allows integrated optical circuits to be fabricated over a much smaller area and optical devices incorporating waveguide bends to be made smaller. For example waveguide bends residing in an arrayed waveguide grating (AWG) are generally of the order of a couple of millimetres These can be reduced using the present invention to be of the order of a couple of microns, with minimal loss of light

[**0049**] The silicon rods of **FIG. 4** are arranged in a square lattice, which gives rise to a series of higher order bandgaps above the base bandgap These higher order bandgaps allow larger rod size and spacing to be used whilst still giving rise to a band structure which is useful at optical and telecommunications wavelengths Furthermore, the structure can be designed so that the TE and TM modes of the band structure overlap at higher order bandgaps, providing the possibility of using even larger geometries

[0050] The present invention allows a low refractive index core to be used In fact the lower the refractive index of the core the higher the refractive index contrast is This means that the waveguide can be matched to incoming and outgoing optical fibre and input/output coupling losses minimised

[0051] The present invention can be applied to any glass technology, whether it is planar or fibre For example as shown in **FIG. 5**, conventional fibre **40** could be flattened or planarised and an array of filled holes **41** incorporated into the flattened region through the cladding **42** and the core **43** The structure as a whole remains in-fibre.

[0052] The material forming the high index rods is not necessarily silicon, it may for example be a non-linear material of high refractive index, providing the possibility of a tuneable device, for example a tuneable filter

[0053] The present invention provides a waveguiding structure having a photonic band structure with lower loss than prior structures of the same type This means that a larger number of rows of rods, equating to conventional holes, can be used in a device structure for the same amount of loss High losses in prior structures has limited the effect of the band structure With the present invention it is feasible to produce longer structures for the same loss, and hence longer time delays and higher resolution filters and demultiplexers

1 An optical waveguide structure comprising a core layer having a first refractive index n_{core}, and an array of sub-regions within the core layer having a second refractive index n_{rods}, the array of sub-regions giving rise to a photonic band structure within the core layer, wherein

$n_{rods}>n_{core}$

2 An optical waveguide structure according to claim 1, wherein the waveguide structure is a planar waveguide structure, the core layer being formed between a cladding layer and a buffer layer, the cladding layer having a third refractive index $n_{cladding}$, and the buffer layer having a fourth refractive index n_{buffer}, wherein

$n_{rods}>n_{core}>n_{cladding}$ and n_{buffer}

3 An optical waveguide structure according to claim 1, wherein the waveguide structure is an optical fibre, further comprising a cladding layer having a third refractive index $n_{cladding}$, surrounding the core layer, wherein

$n_{rods}>n_{core}>n_{cladding}$

4 An optical fibre according to claim 3, wherein the cladding layer is planarised in the vicinity of the array of sub-regions, the array of sub-regions extending through the planarised cladding layer and into the core layer

5 An optical waveguide structure according to claim 1, wherein the array of sub-regions gives rise to a photonic bandgap.

6 An optical waveguide structure according to claim 1 wherein the sub-regions are formed from silicon

7 An optical waveguide structure according to claim 1, wherein the core layer is formed from silicon nitride, silicon oxynitride doped silica, tantalum pentoxide or doped tantalum pentoxide

8 An optical waveguide structure according to claim 2 or **3**, wherein the cladding is formed from silicon dioxide.

9 A planar optical waveguide structure according to claim 2, wherein the sub-regions extend through the cladding layer as well as the core layer

10 A planar optical waveguide structure according to claim 2, wherein the sub-regions extend partially into the buffer layer.

11 An optical waveguide structure according to claim 2 or **3**, wherein the cladding layer includes sub-regions corresponding to the sub-regions in the core layer, having a refractive index which is greater than or equal to the refractive index of the cladding layer but which is less than or equal to the refractive index of the core

12. An optical waveguide structure according to claim 1, wherein the array of sub-regions are arranged in a square lattice

13. An optical waveguide structure according to claim 1, wherein the core layer includes a waveguiding region having no sub-regions

14 An optical waveguide structure according to claim 10, wherein the waveguiding region includes a bend

15 An optical device incorporating an optical waveguide structure according to claim 1

16 A method of manufacturing a optical waveguide structure comprising the steps of

providing a core layer having a first refractive index n_{core},

forming an array of holes in the core layer,

filling the holes with a material having a second refractive index n_{rods}, wherein

$n_{rods}>n_{core}$.

17 A method according to claim 16, wherein the optical waveguide is a planar waveguide, the method further including the steps of

providing a buffer layer having a refractive index n_{buffer} on one side of the core layer, and

providing a cladding layer having a refractive index $n_{cladding}$ on the other side of the core layer, wherein

$n_{rods}>n_{core}>n_{cladding}$ and n_{buffer}

18. A method according to claim 16 wherein the optical waveguide is an optical fibre, the method further including the steps of

providing a cladding layer having a refractive index $n_{cladding}$ surrounding the core layer wherein

$n_{rods}>n_{core}>n_{cladding}$

19. A method of guiding an optical signal comprising the step of passing an optical signal through a waveguiding region of an optical waveguide structure comprising a core layer having a first refractive index n_{core}, and an array of sub-regions within the core layer having a second refractive index, n_{rods}, the array of sub-regions giving rise to a photonic band structure within the core layer, wherein

$n_{rods}>n_{core}$

20 A method according to claim 19 wherein the waveguide is a planar waveguide, wherein the core layer is formed between a cladding layer and a buffer layer, the cladding layer having a third refractive index $n_{cladding}$, and the buffer layer having a fourth refractive index n_{buffer}, and wherein

$$n_{rods}>n_{core}>n_{cladding} \text{ and } n_{buffer}$$

21 A method according to claim 19, wherein the optical waveguide is an optical fibre, wherein a cladding layer has a third refractive index $n_{cladding}$, and surrounds the core layer, and wherein

$$n_{rods}>n_{core}>n_{cladding}$$

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