

METHOD AND STRUCTURE FOR COUPLING LIGHT INTO A WAVEGUIDE

5 FIELD OF INVENTION

The present invention relates broadly to a method and structure for coupling light into a waveguide.

10 BACKGROUND

For coupling of light between a light-emitting element or a light-receiving element and an optical waveguide, there is typically a problem of low light coupling efficiency. A number of current approaches for light coupling are discussed below.

15 Diffraction gratings have been used to change the light direction by diffraction and allow changing of the incident light angle to a desired direction. However, diffraction gratings are limited to specific wavelengths of light. Also, the coupling efficiency between the light source and the waveguide is typically low in applications utilizing diffraction gratings. In order to provide good coupling efficiency, expensive integrated technologies
20 will need to be implemented.

45-degree mirrors have also been used to change the light direction by 90 degrees via reflection. However, the coupling efficiency between the light source and the waveguide is typically low in applications utilizing such mirrors. Furthermore, the accuracy of mirror angle, position and surface flatness can affect the coupling efficiency.
25 Also, it is appreciated that alignment of mirrors or reflectors is also a problem. In particular, mirror angles and therefore mirror alignment is crucial in achieving the results desired. These problems associated with mirrors are exacerbated when the waveguide dimensions are reduced for example, when the waveguide thickness is less than e.g. 50 μ m.

30 Prism coupling has been used for phase matching between a propagation constant in the waveguide and in the incident light using a high index prism. However, prisms are typically expensive and a degree of alignment is still required for light coupling. An evanescent wave method has also been used whereby a propagation

mode is excited to facilitate light coupling. However, such a method uses a very thin waveguide e.g. less than 50 μ m, and is typically not efficient.

In view of the above, there exists a need for a light coupling structure and a method of coupling light into a waveguide that seek to address at least one of the above problems.

SUMMARY

In accordance with a first aspect of the present invention there is provided a method of coupling light into a waveguide comprising the steps of providing nano-sized or sub-micron scattering elements in a coupling spot disposed in a plane of a waveguide core of the waveguide; directing the light into the coupling spot; and subjecting the light to scattering at the scattering elements such that at least a portion of the scattered light is coupled into the waveguide core.

The method may further comprise reflecting the light or the scattered light at a first boundary of the coupling spot for re-direction towards the scattering elements.

The method may further comprise reflecting the reflected light at a second boundary of the coupling spot for re-direction towards the scattering elements.

The first and second boundaries may be disposed in respective planes of opposing faces of the waveguide core.

A mirror used for reflection at the second boundary may comprise an aperture for directing the light into the coupling spot.

The first and second boundaries may form an optical cavity configured such that a cavity resonance is matched to a wavelength of the light.

The scattering elements may be configured such that a dipole or multipolar resonance is matched to a wavelength of the light.

The method may comprise subjecting the light to scattering at the scattering elements such that at least respective portions of the scattered light are coupled into respective multiple waveguide core portions of the waveguide.

The multiple waveguide core portions may be disposed in a star configuration around the coupling spot.

The method may further comprise using a coupling unit to direct the light into the coupling spot.

The coupling unit may comprise a collimating element for collimating the light.

The coupling unit may comprise a focusing element for focusing the light into the coupling spot.

5 In accordance with a second aspect of the present invention there is provided a structure for coupling light into a waveguide comprising nano-sized or sub-micron scattering elements in a coupling spot disposed in a plane of a waveguide core of the waveguide, the scattering elements configured for coupling at least a portion of the light into the waveguide core via scattering.

10 The structure may further comprise means for reflecting the light or the scattered light at a first boundary of the coupling spot for re-direction towards the scattering elements.

15 The structure may further comprise means for reflecting the reflected light at a second boundary of the coupling spot for re-direction towards the scattering elements.

The first and second boundaries may be disposed in respective planes of opposing faces of the waveguide core.

The means for reflection at the second boundary may comprise an aperture for directing the light into the coupling spot.

20 The first and second boundaries may form an optical cavity configured such that a cavity resonance is matched to a wavelength of the light.

The scattering elements may be configured such that a dipole or multipolar resonance is matched to a wavelength of the light.

25 The structure may comprise multiple waveguide core portions of the waveguide, the structure being configured such that at least respective portions of the scattered light are coupled into the respective multiple waveguide core portions.

The multiple waveguide core portions may be disposed in a star configuration around the coupling spot.

30 The structure may further comprise a coupling unit to direct the light into the coupling spot.

The coupling unit may comprise a collimating element for collimating the light.

The coupling unit may comprise a focusing element for focusing the light into the coupling spot.

A material of the coupling spot may be the same or optically matched to a material of the waveguide core.

A material of the scattering elements may be different from the material of the waveguide core.

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BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of example only, and in conjunction with the drawings, in which:

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Figure 1 is a schematic drawing illustrating a structure and method for coupling light into a waveguide according to an example embodiment.

Figure 2 shows simulated light coupling efficiencies for the structure and method of Figure 1.

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Figure 3 is a schematic drawing illustrating a structure and method for coupling light into a waveguide according to an example embodiment.

Figure 4 shows simulated light coupling efficiencies for the structure and method of Figure 3.

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Figure 5 is a schematic drawing illustrating a structure and method for coupling light into a waveguide according to an example embodiment.

Figure 6 shows simulated light coupling efficiencies for the structure and method of Figure 5.

Figures 7a and b are schematic drawings illustrating a structure and method for coupling light into a waveguide according to an example embodiment.

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Figures 7c to e show schematic drawings illustrating a structure and method for coupling light into a waveguide according to an example embodiment.

Figure 8 is a schematic drawing illustrating a structure and method for coupling light into a waveguide according to an example embodiment.

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Figure 9 shows a chart illustrating an example effective surface range for total internal reflection for the structure of Figure 8.

Figure 10 shows a chart illustrating an example effective surface range for total internal reflection for the structure of Figure 8, expressed for a different parameter than in Figure 9.

Figure 11 is a schematic drawing illustrating a structure and method for coupling light into a waveguide according to an example embodiment.

Figure 12 is a schematic drawing illustrating a structure and method for coupling light into a waveguide according to an example embodiment.

5 Figure 13 shows a chart illustrating an example effective surface range for total internal reflection for another structure according to an example embodiment.

Figure 14 is a schematic drawing illustrating a structure and method for coupling light into a waveguide according to an example embodiment.

10 Figure 15 is a schematic drawing illustrating a structure and method for coupling light into a waveguide according to an example embodiment.

Figures 16a and b are schematic drawings illustrating a statistical approach to multiple scattering of photons, according to an example embodiment.

Figures 17a and b show respective flow-chart illustrating methods for calculating a coupling efficiency according to respective example embodiments.

15 Figure 18 is a schematic drawing illustrating probability calculations for scattering of photons in an optical cavity, according to an example embodiment.

Figure 19 shows a flowchart 1900 illustrating a method of coupling light into a waveguide.

20 Figure 20 is a schematic drawing illustrating a computer system for implementing a design calculation method and system of example embodiments.

DETAILED DESCRIPTION

25 Example embodiments described provide the disposition of one or more nano-sized or sub-micron scattering centers of e.g. less than $1\mu\text{m}$ in diameter at a localized region in the core of the e.g. a polymer waveguide. The localized region comprising the scattering centers may be referred to as a scattering spot or scattering volume.

30 In one example embodiment, when incident light from an external light source passes through the waveguide, the light is scattered by the scattering centers and the incident light changes trajectory to propagate within the confines of the waveguide such that light coupling is achieved.

Similarly, light propagating in the waveguide may be coupled out of the waveguide by means of a scattering spot comprising scattering centers in a different embodiment.

5 In example embodiments, the scattering centers are dispersed in a polymer matrix, which has a refractive index close to that of the core material of the polymeric waveguide. The polymer material forming the polymer matrix i.e. can be any material which preferably satisfies the criteria described below.

10 The dispersed scattering centers in the waveguide scatter (i.e. re-radiate) light depending upon their specific configurations such as the nano-particle size distributions, concentration gradients, or material configurations. For example, the scattering can be isotropic or directional (anisotropic) depending upon the specific configuration of the nano-particle scatterers.

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 Some example embodiments of light scattering for coupling light into the waveguide are as follows:

 A first example embodiment (Single Pass) is shown in Figure 1 and comprises a
20 waveguide core 101, a waveguide cladding 102, and a light coupling spot 103. Simulations were performed to observe the relationship among structure parameters, such as waveguide core thickness (t), light coupling spot diameter (d), particle number density (N), and particle radius (r). The light coupling spot 103 comprises of a matrix, in this embodiment the waveguide core 101 material, and scattering particles. The
25 refractive indices of the waveguide core 101, cladding 102, and the particles at an example wavelength of 633 nm are 1.5918, 1.5389, and 2.87, respectively. The ranges of the simulation parameters are listed in Table 1. The details of coefficients used in the governing equations used, which will be described in detail below, are listed in Table 4 further below. Simulated light coupling efficiencies, in the case of $t=20$ μm , $d=1000$ μm ,
30 and $r=150$ nm, are shown in Figure 2. A coupling efficiency of about 1 % can be achieved at this condition.

	Parameter range
t	5, 10, 20, 50, 100 (μm)
d	50, 100, 200, 500, 1000 (μm)
r	50, 100, 150, 200, 250, 300 (μm)
N	1, 2, 4, 10, 20, 40, 100, 200, 400, 1000 ($\times 10^{11} / \text{cm}^3$)

Table 1

Another example embodiment (Double Pass) is shown in Figure 3, and comprises a waveguide core 301, a waveguide cladding 302, a light coupling spot 303, and a reflection mirror 306. Simulations were performed to observe the relationship among structure parameters, such as waveguide core thickness (t), light coupling spot diameter (d), particle number density (N), and particle radius (r). The light coupling spot 303 comprises of a matrix, in this embodiment the waveguide core material, and scattering particles. The refractive indices of the waveguide core 301, cladding 302, and the particles at an example wavelength of 633 nm are 1.5918, 1.5389, and 2.87, respectively. The ranges of the simulation parameters are listed in Table 2. The details of coefficients used in the governing equations are listed in Table 4. Simulated light coupling efficiencies, in the case of $t=20 \mu\text{m}$, $d=1000 \mu\text{m}$, and $r=150 \text{ nm}$, are shown in Figure 4. A coupling efficiency of about 3 % can be achieved at this condition.

	Parameter range
t	5, 10, 20, 50, 100 (μm)
d	50, 100, 200, 500, 1000 (μm)
r	100, 150, 200, 250, 300 (μm)
N	1, 2, 4, 10, 20, 40, 100, 200, 400 ($\times 10^{10} / \text{cm}^3$)

Table 2

Another example embodiment (Multiple Pass) is shown in Figure 5, and comprises a waveguide core 501, waveguide cladding 502, light coupling spot 503, reflection mirror 506, aperture with reflective surface 507, and focusing lens 508.

- 5 Simulations were performed to observe the relationship among structure parameters, such as waveguide core thickness (t), light coupling spot diameter (d), particle number density (N), and particle radius (r). The light coupling spot comprises of a matrix, in this embodiment the waveguide core material, and scattering particles. The refractive indices of the waveguide core 501, cladding 502, and the particles at an example wavelength of
- 10 633 nm are 1.5918, 1.5389, and 2.87, respectively. The aperture 507 diameter is fixed at about 250 μm . The distance between the focusing lens 508 and top surface of the coupling spot 503 (D), the curvature of the focusing lens 508 (R), and all other simulation parameters ranges are listed in Table 3. The details of coefficients used in the governing equations are listed in Table 4. Simulated light coupling efficiencies, in the case of t=20
- 15 μm , d=1000 μm , and r=150 nm, D=1.62 mm, and R=1.88 mm, are shown in Figure 6. A coupling efficiency of about 4.2 % can be achieved at this condition. The aperture 507 effectively acts as another mirror to provide reflection of light scattered at an angle, but does not provide resonating functions in this embodiment.

	Parameter range
t	5, 10, 20, 50 (μm)
d	1000 (μm)
r	50, 100, 150, 200, 250, 300 (μm)
N	1, 2, 4, 10, 20, 40, 100, 200, 400, 1000, 2000, 4000 ($\times 10^9 / \text{cm}^3$)
D, R	(1.62, 1.88), (2.99, 3.76), (7.42, 9.32) (mm)

Table 3

	Example 1	Example 2	Example 3
a0	1.326E-05	1.529E-05	1.852E-05
a1	153.315	164.631	173.014
a2	0.007	0.005	0.003
a3	0.002	0.001	0.000
a4	0.002	0.005	0.006
a5	0.428	0.360	0.000
a6	0.072	0.177	0.697
b0	0.079	0.144	0.026
b1	0.967	1.039	1.743
b2	0.147	0.270	0.389
b3	0.009	0.196	0.178
b4	1.252	0.855	0.496
c0	28.688	21.490	27.809
c1	1.017	1.002	1.075
c2	1.022	0.204	0.252
c3	0.130	0.138	0.100
c4	2.126	1.762	1.748

Table 4

In another example embodiment (Dipolar or Multipolar Resonance) shown in
 5 Figures 7a and b, the light 700 incident on the scatterers in the coupling spot 703 are
 chosen to match the dipole resonance (or multipole) wavelength of the nano-particle.
 This resonance condition depends upon the size and material of the nano-particle
 scatterers. The scattering efficiency of the nano-particle scatterers can be enhanced
 when the wavelength of the input light 700 matches that of the nano-particle scatterers,
 10 as illustrated by a comparison of the coupled light intensity graphs 704, 706 in Figures
 7a and b respectively, for incident light 700 chosen to match the dipole resonance (or
 multipole) wavelength of the nano-particle on the one hand, and for incident light 708 not
 matching the dipole resonance (or multipole) wavelength of the nano-particle. This
 scheme can be combined with embodiments described herein to improve scattering
 15 efficiency for the respective cases.

In another example embodiment (Cavity Multi Pass), an optical cavity may be
 implemented. The nano-particle is preferably resonant at the wavelength of the incoming
 light, which is further preferably also resonant with the optical cavity. In this case, the
 scattering efficiency depends upon the interaction between the incoming light, optical
 20 resonant cavity, and the dipole nano-particles as an entire system. If the resonances of

the nano-particles and the optical cavity are "tuned" to a single wavelength, maximum scattering efficiency can be achieved. As illustrated in Figure 7c, the nano-particle 720 is resonant at the wavelength within the wavelength range of the incoming light 722. On the other hand, an optical cavity 724 at the coupling spot 733, as shown in Figure 7d, is capable of trapping light to resonate at one or more wavelengths. In combination in one embodiment, when the input light source produces an incident light 725 of a wavelength λ_{res} , which matches the nano-particle resonant wavelength, and λ_{res} is one of the plurality of cavity 724 at the coupling spot 733 resonant wavelengths, the overall scattering efficiency can be preferably maximized, as illustrated by the coupled light coupling graph 726, as shown in Figure 7e. In this embodiment, the optical cavity 724 is formed by a two-way mirror 728 formed on the waveguide core 730, and a mirror 731 formed on the the bottom cladding or substrate 732. The mirror 731 is a metallic mirror in one example embodiment to provide a broad-band highly reflecting surface preferably without any appreciable absorption. Since a completely reflective metallic cladding or substrate 732 can result in a lossy waveguide, the bottom mirror 731 is preferably localised to the cavity 724 area in this embodiment. In an alternative embodiment, where the light loss is acceptable, the substrate or cladding 732 may be a reflective metallic layer, and hence also incorporates the function of the bottom mirror 731. The two way mirror 728 can e.g. be implemented as a partially reflecting Bragg grating in one embodiment.

It is noted that in another embodiment, the cavity can be implemented without matching nanoscatterer resonance.

The scattering centers in a host medium preferably have a significant refractive index difference with the host polymer. For example, in example embodiments, the refractive index of the polymer is 1.59 while the refractive index of the scatterers is about 2.87. The combination of nano-scatterer size and its refractive index difference with the host medium decides the directionality and amount of scattered light in example embodiments. Examples include inorganic nano-scatterers in the form of nano-particles such as titanium dioxide (TiO_2), silicon dioxide (SiO_2), diamond, silicon, silicon nitride (Si_3N_4), Zirconium Oxide (ZrO_2), Zinc Oxide (ZnO), Aluminum Oxide (Al_2O_3), etc. ; metallic nano-particles such as gold, silver, aluminum, chromium, platinum, etc.; or organic scatterers such as polystyrene, polymethyl methacrylate, polycarbonate, polyimide. In other example embodiments, nano-sized or sub-micron air bubbles in a polymer matrix can also act as scatterers for coupling light into the waveguide.

One of the advantages of utilizing scattering based coupling mechanism in example embodiments is the significant reduction in mechanical alignment tolerance between the light source and the coupling spot. The coupling spot can for example be a few hundred microns to a few millimetres in diameter and can couple light into waveguides having thicknesses in the order of for example a few microns. This relaxation in the alignment tolerance can provide an advantage when one considers the actual cost involved in aligning a light source to a planar waveguide.

For an optical waveguide, the propagation angle is defined by the critical angle of the waveguide configuration. The propagation angle of the waveguide should be larger than the critical angle, which can be written as:

$$\theta_c = \sin^{-1}\left(\frac{n_{clad}}{n_{core}}\right) \quad (1)$$

where, n_{clad} and n_{core} are the refractive indices of the core and cladding of the optical waveguide. In the case of an asymmetric waveguide, n_{clad} is the refractive index of the cladding material having the higher refractive index. Thus, only the light scattered from the scattering spot in a direction defined by the cone of acceptance of the waveguide will be coupled and guided in the waveguide in example embodiments.

With reference to the Cavity Multi Pass embodiments described herein, the total power coupled into the waveguide from the cavity varies for different distributions of scatterers. This averaged coupled power can be written as:

$$P_{wg} = \sum_{N=1}^{N_{crit}} \int_{\theta=\frac{\pi}{2}-\theta_c}^{\theta=\frac{\pi}{2}+\theta_c} P_{scat} \cdot \Gamma_B \cdot f(z) d\theta \quad (2)$$

$$\langle P_{wg} \rangle = N_{crit} \cdot \Gamma_B(N_{crit}) \cdot \int_{\theta=\frac{\pi}{2}-\theta_c}^{\theta=\frac{\pi}{2}+\theta_c} \sigma_{sca} d\theta$$

Here, $f(z)$ is a distribution function of the nano-scatterers inside the optical cavity and the averaging is done over many distributions of the nano-scatterers in the optical cavity.

In the above, the inventors have ignored the Purcell factor enhancement in the above analysis due to the very small value of Q/V considered in the example

embodiments, where Q and V are the quality factor and the mode volume of the optical cavity, respectively. At best, for the optical cavity in example embodiments, limited by the losses due to the partial mirror and the nano-scatterers, Q/V is of the order of a few tens to a few hundred which is very low for a typical optical cavity. In this case, there are no preferential directions for scattering inside the optical cavity and the nano-scatterers scatter light depending upon their individual scattering patterns when there is no further confining structure

Further, due to the addition of nano-scatterers, there is a modification of the refractive index of the medium inside the optical cavity which manifests itself as a shift in the resonance wavelength. This shift can be estimated through the Maxwell-Garnet effective medium theory, which takes into account the change in the homogeneous refractive index of a medium due to the presence of nano-inclusions. The change in refractive index can be written as:

$$\begin{aligned}\varepsilon_{eff} &= \varepsilon_{med} \frac{\varepsilon_{NP} \cdot (1 + 2 \cdot \delta) - \varepsilon_{med} \cdot (2 \cdot \delta - 2)}{\varepsilon_{med} \cdot (2 + \delta) + \varepsilon_{NP} \cdot (1 - \delta)} \\ \delta &= \frac{N \cdot \frac{4}{3} \cdot \pi \cdot a^3}{V_{cav}} \\ n_{eff} &= \sqrt{\varepsilon_{eff}(N)} = n_{med} + \Delta n(N) \\ \Delta n &= \sqrt{\varepsilon_{eff}(N) - \varepsilon_{med}} = \sqrt{n_{eff}^2(N) - n_{med}^2}\end{aligned}\quad (3)$$

where, ε_{NP} , ε_{med} , n_{eff} , n_{med} , are the dielectric constants and refractive indices of the nano-scatterer and the medium of the optical cavity respectively and δ is the volume fraction of the nano-scatterers in the optical cavity. Through the change in the refractive index of the medium, the shift in the resonance wavelength (frequency) can be calculated as:

$$\Delta \lambda_{res} = \lambda_{res} \frac{\sqrt{n_{eff}^2(N) - n_{med}^2}}{n_{med}} \quad (4)$$

thus, the frequency (wavelength) of the light 504 should be chosen so as to take into account the change in the resonance condition of the optical cavity 509 due to the presence of nano-scatterers.

Due to the radiation pattern and the polarization properties of scattered light, the incident light 504 is preferably s-polarized so that the scattered light due to the nano-scatterers has a radiation pattern which is preferred for coupling light into the waveguide 505 oriented in a direction perpendicular to the incident light 504. Also, due to the polarization properties of the scattered light, the light coupled in the waveguide 505 is preferentially p-polarized with respect to the direction of propagation of light in the waveguide.

The coupling spot in the example embodiments may comprise nanoparticles made of any material. The size of the nanoparticle has a preferred range as defined by the governing equations described in detail below. The nanoparticle surface can be modified chemically in order to disperse the particle in the polymer matrix uniformly. A milk-like material, such as emulsion, can be prepared by mixing of immiscible two or more polymer materials by using phase separation.

For the matrix polymer which the nanoparticle is disposed within, any material having a refractive index close to or equal to the waveguide core can be selected. The optical transparency of the polymer is preferred to be more than 80%/cm although lower optical transparencies are possible. A UV curable property is preferred for a simple lithography process or a UV molding process. For high temperature characteristics, more than 150 °C of T_g (glass transition temperature) is preferred.

In one embodiment, the surface of nanoparticle is chemically modified, such as by introducing the monomer component of the polymer matrix used in order to increase the dispersivity of nanoparticle into the polymer solution (polymer is dissolved into the solvent) or changing the hydrophobic/hydrophilic property in order to increase the dispersivity of nanoparticle into the solvent.

The treated nanoparticle is dispersed into the polymer solution through a solvent of the polymer.

The polymer solution dispersed with nanoparticles is disposed onto the designated area, which is defined by the surface of the bottom cladding and side-walls of the waveguide core in example embodiments.

The polymer solution is solidified by photo-setting, thermo-setting, or a drying method.

In order to achieve efficient light coupling, the diameter of the coupling spot of more than 500 micron is preferable in example embodiments. For diameters below 500 micron, desired performance can be achieved by utilizing proper alignment schemes. The thickness (depth) of the coupling spot is substantially determined by the thickness of the waveguide.

As described above, a reflective mirror can be disposed on the waveguide cladding surface for double pass, multiple pass, and cavity multiple pass. Furthermore, a reflective mirror, e.g. a metal mirror/aperture, can also be disposed on the waveguide core surface for multiple pass. Furthermore, a partially reflective mirror, e.g. a Bragg grating, can be disposed on the waveguide core surface for cavity multiple pass

For the polymer waveguide in the example embodiments, any material can be selected as long as the refractive index of the core material is higher than the cladding material. The optical transparency of the polymer is preferred to be more than 80%/cm. A UV curable property is preferred for a simple lithography process or a UV molding process. For high temperature characteristics, more than about 150 °C of T_g (glass transition temperature), and a low coefficient of thermal expansion (CTE) is preferred.

In the example embodiments, the incident light is isotropically scattered at the coupling spot unless polarized light is used as the incident light. Therefore, the waveguide core receiving the scattered light can be radially disposed from the light coupling spot as the center, such as a "star shape", or can have a focusing structure, such as an "ellipsoidal shape", for effective coupling of the scattered light into the waveguide.

Figure 8 shows a top view of an example embodiment of the present invention, illustrating an ellipsoidal shape focusing structure. Coupling spots are located at focal point F as shown in Figure 8. Another focal point F' is also shown.

$$\bar{F} = \left(-\sqrt{a^2 - b^2}, 0 \right) \quad (5)$$

$$\bar{F}' = \left(\sqrt{a^2 - b^2}, 0 \right) \quad (6)$$

The direction of the major axis (x) is the waveguide propagation direction. The light emitted from one focal point is focused at the other focal point based on the focusing properties of an ellipse 800 and the total internal reflection properties of the core 802/cladding 804 interface as shown in Figure 8. When the incident angle, θ_p , is larger than the critical angle, $\theta_c = \sin^{-1}(n_0/n_1)$, the interface of the focusing structure works as the mirror. The light emitted from the coupling spot at local point F is reflected by the interface of the coupling structure and the reflected light is then focused on the other local point F'.

An effective surface range for the total internal reflection can be calculated as follows.

The point $\vec{P}$ is expressed by the parameterized coordinate

$$\vec{P} = (a \cos t, b \sin t) \quad (7)$$

The direction of the tangent line of the ellipsoid at $\vec{P}$ is defined as

$$\vec{T} = \left(\frac{1}{\sqrt{1 + b^2/a^2 \tan^2 t}}, \frac{-b/a \tan t}{\sqrt{1 + b^2/a^2 \tan^2 t}} \right) \quad (8)$$

The incident angle θ_p is expressed as follows.

$$\begin{aligned} \cos\left(\frac{\pi}{2} - \theta_p\right) &= \frac{\vec{T} \cdot F\vec{P}}{|\vec{T}| \cdot |F\vec{P}|} \\ \theta_p &= \frac{\pi}{2} - \cos^{-1}\left(\frac{\vec{T} \cdot F\vec{P}}{|F\vec{P}|}\right) \quad \because |\vec{T}| = 1 \end{aligned} \quad (9)$$

In order to satisfy the total internal reflection condition at the point $\vec{P}$, θ_p satisfies the condition,

$$\sin\left(\frac{\pi}{2} - \cos^{-1}\left(\frac{\vec{T} \cdot F\vec{P}}{|F\vec{P}|}\right)\right) > \left(\frac{n_0}{n_1}\right) \quad (10a)$$

$$\frac{\vec{T} \cdot F\vec{P}}{|F\vec{P}|} > \frac{n_0}{n_1} \quad (10b)$$

where,

$$|F\vec{P}| = a + \cos t \sqrt{a^2 - b^2} \quad (11a)$$

$$\vec{T} \cdot F\vec{P} = \frac{\sqrt{a^2 - b^2} (a + \cos t \sqrt{a^2 - b^2})}{\sqrt{a^2 + b^2 / \tan^2 t}} \quad (11b)$$

Therefore,

$$\frac{\sqrt{a^2 - b^2}}{\sqrt{a^2 + b^2 / \tan^2 t}} > \frac{n_0}{n_1} \quad (12)$$

On the other hand, θ_{guide} satisfies the total internal reflection condition.

$$\sin \theta_{guide} = \frac{(P\vec{F}')_x}{|P\vec{F}'|} = \frac{\sqrt{a^2 - b^2} - a \cos t}{a - \sqrt{a^2 - b^2} \cos t} > \frac{n_0}{n_1} \quad (13)$$

These two equations can be rewritten by using the ratio of the major axis to the minor axis.

$$\frac{\sqrt{\left(\frac{a}{b}\right)^2 - 1}}{\sqrt{\left(\frac{a}{b}\right)^2 + 1/\tan^2 t}} > \frac{n_0}{n_1} \quad (14)$$

$$\frac{\sqrt{\left(\frac{a}{b}\right)^2 - 1} - \left(\frac{a}{b}\right) \cos t}{\frac{a}{b} - \left(\sqrt{\left(\frac{a}{b}\right)^2 - 1}\right) \cos t} > \frac{n_0}{n_1} \quad (15)$$

As a result, the effective surface range for total internal reflection is defined by equations (14) and (15). In the case of $a/b=4$, $n_0=1$, and $n_1=1.5918$, the relationship between the parameter t and the left side of these equations is shown in Figure 9. As seen in Figure 9, the shaded area, bounded by the three curves, shows values of the parameter t which would satisfy equations (14) and (15) above. From Figure 9, t -values of about 30 to 165 would satisfy equations (14) and (15). The relationship between the θ_F and t is expressed as follows.

$$\theta_F = \tan^{-1} \left(\frac{\sin t}{\left(\frac{a}{b} \right) \cos t + \sqrt{\left(\frac{a}{b} \right)^2 - 1}} \right) \quad \left(\left(\frac{a}{b} \right) \cos t + \sqrt{\left(\frac{a}{b} \right)^2 - 1} \geq 0 \right)$$

$$= \frac{\pi}{2} - \tan^{-1} \left(\frac{\sin t}{\left(\frac{a}{b} \right) \cos t + \sqrt{\left(\frac{a}{b} \right)^2 - 1}} \right) \quad \left(\left(\frac{a}{b} \right) \cos t + \sqrt{\left(\frac{a}{b} \right)^2 - 1} < 0 \right)$$

(16)

Replacing the values of t with θ_F , the chart of Figure 9 can be redrawn as shown in Figure 10. In this example, the acceptance angle of scattered light from the scattering spot is about 5-100 degrees, as can be seen from the shaded area bounded by the three curves.

As the light scattered from the scattering spot is omni-directional, light can be scattered into more than one waveguides, thus maximizing the total light captured by waveguides. However, in order to optimize the light utilization such that light coupled into each waveguide is maximized, it is expected that the number of waveguides should also be kept to a minimum. Therefore, a balance is preferably struck between maximizing the total coupled light, and minimizing the total number of waveguides.

Figure 11 shows an example embodiment where two ellipsoid structures 1100, 1102 are combined to couple light from a single scattering spot 1104 into two waveguide channels 1106, 1108. This example embodiment can be useful when the effective maxima of θ_F is between 90° and 180° . Similarly, when the effective maxima of θ_F is between 60° and 90° , three ellipsoid structures 1200, 1202, 1204 can be combined to utilize the scattered light effectively, as shown in Figure 12.

When the refractive index contrast is small, such as $\Delta n = 0.01$ ($n_0 = 1.5818$, $n_1 = 1.5918$ as an example), the ratio of major axis to the minor axis becomes large in order to have some value for θ_F satisfying eq. (16). For example, in the case of the ratio of major axis to the minor axis being 12, the angle of θ_F between 3.5° and 10.7° satisfy the eq. (16), as shown by the shaded area in Figure 13. This means that the coupling structure can have a total of 20° ($-10^\circ < \theta_F < +10^\circ$) for light coupling. Therefore, a star shape structure 1400 having 18 channels of waveguides can be an ideal structure for this refractive index contrast, as shown in Figure 14.

For the fabrication of optical waveguides in example embodiments, any polymeric material can be selected provided it but preferably the material does not have a large propagation loss at the operating wavelength. Three methods of fabricating waveguides using polymer materials are described below, by way of example, not limitation:

Photo-lithography: In this case, the polymer can be directly patterned by exposing selected parts of the polymer through an optical mask to UV light. The exposed areas of the polymer get polymerized on exposure to UV light and define the waveguiding structure.

Physical etching: In this method, a waveguide structure is defined by physically bombarding selected areas of the polymer with suitable ions in a vacuum chamber. This process of etching can be performed in a variety of ways including Reactive Ion Etching (RIE), Inductively Coupled Plasma (ICP) etching, Ion Beam Etching (IBE), Electron Cyclotron Resonance (ECR) etching, etc. For selective etching, a mask is preferably created above the polymer film which is to be patterned. This mask can be either a patterned commercial photo-resist, or a patterned hard material such as silicon dioxide (SiO_2), silicon nitride (Si_3N_4), etc.

Molding: In this method, a mold of the waveguide pattern is first formed using for example photo-lithographic, physical etching, or electron-beam lithography processes and the waveguide pattern is formed by filling the mold with the polymer and applying a selected amount of temperature and pressure. The resulting molded structure made from the core polymer defines the waveguiding structure. The mold can for example be a hard mold made of any hard metal such as Nickel, Chromium, etc. or a soft mold which could be made from commercially available polymers such as PDMS, SU8, etc.

Another way of molding is by using UV curable polymers and exposing the polymer through a UV transparent mold. In this case, the mask can be made from any polymer or glass structure that is transparent at UV wavelengths.

As shown in Figure 15 the system may further comprise of a light source, for example in the form of a laser diode 1501, preferably a laser diode, a collimation lens 1502, a focusing lens 1503, a metallic aperture 1504 of defined size to provide a diverging beam of a specific diameter to the scattering volume/coupling spot 1505, a bottom reflective mirror 1506, an optical waveguide core 1507, and an optical waveguide

cladding 1508. Preferably, the light source 1501 may provide a light frequency of between 400nm to 2500nm, covering the visible and near IR spectrum.

5 The metallic aperture 1504 also functions as a mirror for preventing back reflection of scattered light and directing the back-reflected light into the scattering medium for further scattering. The metallic aperture 1504 diameter in this embodiment is of a fixed diameter which is a fixed fraction, e.g. less or equal to about 0.5, of the diameter of the cylindrical scattering volume/coupling spot 1505.

10 In order to achieve a beam having a diameter substantially equal to the aperture 1504 diameter, the focusing lens 1503 is placed at a certain fixed distance from the aperture 1504. This distance depends upon the focal length of the lens 1503 and the beam diameter beyond the focal length can be determined analytically through Gaussian Beam optics.

15 Prior to focusing the beam from the laser diode 1501, the beam is collimated to provide the desired focusing effect. This collimation of the beam from the laser diode 1501 can be provided by a suitable aspheric collimation lens 1502. The collimation and focusing package can also be a combined unit. The main purpose of this optical unit is to advantageously provide a uniform diverging beam of photons that enters the scattering volume and has a higher probability of being scattered into the waveguide structure.

20 For scattering centers, the probability of scattering in a direction perpendicular to the direction of the incident light is generally low. By utilizing a diverging beam, the incident light can preferably be spread over a large angular extent. This angular spread of the incident light depends upon the focusing lens 1503 through its numerical aperture. Also, the extent of the light source (beam diameter) can depend upon the diameter of the aperture 1504, the choice of which can depend upon the requirement on the
25 reflecting surface 1506 and the illumination of the scattering volume. Also, the reflecting aperture 1504 is placed at a specific distance from the focal length of the focusing lens 1503 in this example embodiment. This distance can be calculated by fixing the aperture 1504 diameter and the parameters of the focusing lens 1503.

30 Some portions of the description which follows are explicitly or implicitly presented in terms of algorithms and functional or symbolic representations of operations on data within a computer memory. These algorithmic descriptions and functional or symbolic representations are the means used by those skilled in the data processing arts to convey most effectively the substance of their work to others skilled in

the art. An algorithm is here, and generally, conceived to be a self-consistent sequence of steps leading to a desired result. The steps are those requiring physical manipulations of physical quantities, such as electrical, magnetic or optical signals capable of being stored, transferred, combined, compared, and otherwise manipulated.

5 Unless specifically stated otherwise, and as apparent from the following, it will be appreciated that throughout the present specification, discussions utilizing terms such as "scanning", "calculating", "determining", "replacing", "generating", "initializing", "outputting", or the like, refer to the action and processes of a computer system, or similar electronic device, that manipulates and transforms data represented as physical
10 quantities within the computer system into other data similarly represented as physical quantities within the computer system or other information storage, transmission or display devices.

The present specification also discloses apparatus for performing the operations of the methods. Such apparatus may be specially constructed for the required purposes,
15 or may comprise a general purpose computer or other device selectively activated or reconfigured by a computer program stored in the computer. The algorithms and displays presented herein are not inherently related to any particular computer or other apparatus. Various general purpose machines may be used with programs in accordance with the teachings herein. Alternatively, the construction of more specialized
20 apparatus to perform the required method steps may be appropriate. The structure of a conventional general purpose computer will appear from the description below.

In addition, the present specification also implicitly discloses a computer program, in that it would be apparent to the person skilled in the art that the individual steps of the method described herein may be put into effect by computer code. The
25 computer program is not intended to be limited to any particular programming language and implementation thereof. It will be appreciated that a variety of programming languages and coding thereof may be used to implement the teachings of the disclosure contained herein. Moreover, the computer program is not intended to be limited to any particular control flow. There are many other variants of the computer program, which
30 can use different control flows without departing from the spirit or scope of the invention.

Furthermore, one or more of the steps of the computer program may be performed in parallel rather than sequentially. Such a computer program may be stored on any computer readable medium. The computer readable medium may include storage devices such as magnetic or optical disks, memory chips, or other storage

devices suitable for interfacing with a general purpose computer. The computer readable medium may also include a hard-wired medium such as exemplified in the Internet system, or wireless medium such as exemplified in the GSM mobile telephone system. The computer program when loaded and executed on such a general-purpose computer
 5 effectively results in an apparatus that implements the steps of the preferred method.

In order to estimate the preferable conditions or parameters for the scattering spot in example embodiments, the inventors have identified governing equations which define the light coupling efficiency in the example embodiments.

10 To determine such an equation, a statistical approach to photon scattering is first considered. As illustrated in Figure 16a, the photon scattering process is assumed to be based on the classical interaction between photons and scattering centers which is governed by the Gaussian random process. In this case, a photon can have a number of scattering events in a scattering volume which depend on the mean-free path of the
 15 photon in the scattering volume as well as the optical path length of the photon in the scattering volume.

Next, a scattering volume or spot embedded in a waveguiding structure which consists of randomly distributed nano-scatterers having a number density of $n_0 \text{ cm}^{-3}$ was considered. Assuming the scattering volume were a cylindrical volume with height L
 20 and radius R. If there are N_0 number of photons per second striking the scattering volume in a direction along the axis of the cylindrical volume, then the probability that a given photon gets scattered k times in the scattering volume is governed by Poisson's distribution which can be written as [1]:

$$P(k) = \exp[-\langle s \rangle] \cdot \frac{\langle s \rangle^k}{k!} \quad (17)$$

25 Here, $\langle s \rangle$ is the average number of photon nano-scatterer interaction for an ensemble of photons which can be written as [2]:

$$\langle s \rangle = n_0 \cdot \sigma_{sca} \cdot L \cdot n_{med} \quad (18)$$

Where, σ_{sca} and n_{med} are the scattering cross-section of the nano-scatterer and the refractive index of the medium respectively. Thus, the probability that there is no
 30 scattering event can be simply written as $P(0)$ and the probability that a photon undergoes at least one scattering event can be written as:

$$P_{scat} = \sum_{i=1}^{\infty} P(i) = P(0) \cdot \sum_{i=1}^{\infty} \frac{\langle s \rangle^i}{i!} = 1 - p(0) \quad (19)$$

Assuming that the scattered photons are distributed uniformly in the scattering volume before being scattered out, the differential probability per unit volume of the photons that are scattered in the scattering volume which get coupled into the waveguiding structure can be defined. Figure 16b shows a top view of the scattering spot. For this case, consider an infinitesimal volume defined by an annular ring of the cylindrical scattering volume at a distance r from the axis of the scattering volume and of width dr . Then, the differential probability of photons in this volume element to get coupled into the waveguide e.g. the acceptance cone defined by the critical angle, can be written as:

$$dP(i)_{wg} = \frac{P(i)}{V_{cav}} \cdot 2\pi r \cdot dr \cdot L_{cav} \cdot \exp(n_0 \cdot \sigma_{sca} \cdot [R - r]) \cdot \int_{\frac{\pi}{2} - \theta_c}^{\frac{\pi}{2} + \theta_c} \sigma_d(\theta) \cdot d\theta \quad (20)$$

In the above expression, it is assumed that the photons present in the annular ring have to travel an average distance of $(R-r)$ before getting coupled into the waveguide and σ_d is the differential cross-section of the nano-scatterer that radiated scattered light into the acceptance cone of the waveguiding structure. θ_c is the critical angle of the waveguide and is determined from the refractive indices of the core and cladding material of the waveguide. Integrating the above expression with respect to r and assuming that the differential cross-section integral is independent of the position of the nano-scatterers in the scattering volume:

$$P(i)_{wg} = \frac{2P(i)}{R^2} \cdot \left[\frac{R}{n_0 \cdot \sigma_{sca}} - \frac{1}{(n_0 \cdot \sigma_{sca})^2} + \frac{\exp(-n_0 \cdot \sigma_{sca} \cdot R)}{(n_0 \cdot \sigma_{sca})^2} \right] \cdot \int_{\frac{\pi}{2} - \theta_c}^{\frac{\pi}{2} + \theta_c} \sigma_d(\theta) \cdot d\theta \quad (21)$$

Combining with the previous equation, the total probability of coupled photons into the cavity and hence the coupling efficiency is:

$$\eta(\%) = \left(\sum_{i=1}^{\infty} P(i)_{wg} \right) \cdot 100$$

$$= \left(\frac{2}{R^2} \cdot \left[\frac{R}{n_0 \cdot \sigma_{sca}} - \frac{1}{(n_0 \cdot \sigma_{sca})^2} + \frac{\exp(-n_0 \cdot \sigma_{sca} \cdot R)}{(n_0 \cdot \sigma_{sca})^2} \right] \cdot \int_{\frac{\pi}{2} - \theta_c}^{\frac{\pi}{2} + \theta_c} \sigma_d(\theta) \cdot d\theta \cdot P(0) \sum_{i=1}^{\infty} \frac{\langle s \rangle^i}{i!} \right) \cdot 100 \quad (22)$$

thus, the total efficiency depends upon the length and radius of the scattering volume, the number density and scattering coefficients of nano-scatterers and the waveguide core and cladding materials. The above expression applies for Mie scattering and for identical nano-scatterers which scatter light isotropically. The above result is shown to be applicable for nano-scatterers having a radius of less than 50nm.

Figure 17a shows a flow chart illustrating the steps 1701 to 1705 of calculating a coupling efficiency of an example embodiment where one scattering event takes place, from parameters L , R , n_{med} , N_0 , σ_{sca} , θ_c . Figure 17b shows another flowchart illustrating steps 1711 to 1716 of calculating a coupling efficiency of another example embodiment where multiple scattering events take place, from parameters: L , R , n_{med} , N_0 , σ_{sca} , θ_c .

An empirical approach was also evaluated to expand the applicability to double pass and multiple pass configurations in different embodiments. In order to evaluate the coupling efficiency of the scattering based coupling structure, non-sequential ray tracing method, ZEMAX™ (Radiant ZEMAX LLC. USA), with Mie scattering function (Mie.dll) was used.

Embodiments of the invention comprising a waveguide core, a waveguide cladding, and a light coupling spot, were simulated to observe the relationship among structure parameters, such as waveguide core thickness (t), light coupling spot diameter (d), particle number density (N), and particle radius (r). The light coupling spot comprises of waveguide core material and particle. Mean free path (MFP) is calculated from particle number density (N) and scattering cross section (σ_{sca}).

$$MFP = 1 / \sigma_{\text{sca}} N \quad (23)$$

Based on the relationship among structure parameters and the light coupling efficiency, the inventors have discovered that the efficiency can be estimated to be described by a Gaussian-like function as follows.

$$E = c \exp \left(- \frac{(\log_{10}(MFP) - a)^2}{b^2} \right) \quad (24)$$

Parameter a, b, and c were further analyzed and a relationship between the structure parameters were discovered.

$$\begin{aligned}
 a &= a_0 (r - a_1)^2 + \frac{a_3 \log_{10}(t) + a_4}{\left(\frac{1}{d}\right) + a_2} + a_5 \log_{10}(t) + a_6 \\
 b &= b_0 (\log_{10}(d) - b_1 \log_{10}(t) - b_2)^2 + b_3 \log_{10}(t) + b_4 \quad (25) \\
 c &= c_0 \exp \left(- \frac{(\log_{10}(d) - c_1 \log_{10}(t) + c_2)^2}{\left(\frac{c_3}{t}\right) + c_4} \right)
 \end{aligned}$$

5

Resonator

An optical resonator can trap light at a specific wavelength (energy) and the trapped light stays in the resonator until it can get dissipated away by means of absorption or scattering losses. The trapped light inside the resonator can be enhanced relative to the incident intensity due to the constructive interference of light waves bouncing back and forth in the resonator. The magnitude of enhancement depends upon the ways by which light can get lost from the resonator. If there are nano-scatterers inside the optical cavity which have a significant scattering cross-section at the resonant wavelength of the optical resonator (or displaying a resonating behavior themselves at the resonant wavelength of the cavity), then the scattering can be enhanced due to the enhanced intensity circulating inside the optical resonator. However, this enhancement in the scattering is only at the resonant wavelength of the optical resonator.

A further theoretical approach was also evaluated for an optical resonator with the presence of scattering centers inside the optical cavity structure in example embodiments. If there are nano-particle scatterers in the path of incident light, light will be scattered in all directions depending upon the optical properties and size of the nanoparticle scatterer. In the case of a waveguide, if the waveguide were oriented in a plane perpendicular to the direction of the incident light, then only light scattered in the directions, which lie within the acceptance cone of the waveguide, will be guided along the waveguide i.e. coupled into the waveguide. However, if the light were confined in a cavity comprising nano-particle scatterers, light circulating back and forth inside the cavity will have an increased possibility of scattering multiple times, depending upon the photon-lifetime inside the cavity. This can lead to enhancement of scattered light in the

waveguide and can enhance the light coupling intensity. Figure 18 illustrates the scattering of incident light 1800 by a nano-particle 1802 within a cavity 1804.

Placing identical nano-scatterers for coupling light into the waveguide can cause the losses in the optical cavity to increase, thereby changing the round-trip loss factor terms in the expressions for the optical cavity. The scattering of light in the cavity has two components:

- Light that is scattered in the forward direction ($\theta=0^\circ$, this is the part that stays in the optical cavity); and

- Light that is scattered out from the optical cavity.

It is assumed that the phase delay between the un-scattered and forward scattered light in the cavity is negligible. Also, it is further assumed that the scattering from many identical nanoparticles follows independent scattering whereby, the phase difference between the fields scattered by the individual scatterers is random.

Firstly, the amplitude round-trip loss factor due to nano-particle scatterers in the optical cavity is calculated. In order to estimate this, a Fabry-Perot optical cavity of length L_{cav} , cross-sectional area A_{cav} is considered, with P_{f1} being the power incident on the nanoparticle scatterers. It is assumed that the incident light is in the form of a plane-wave with its spatial extent matching the cross-sectional area of the optical cavity. The total power in the forward direction (P_{f1}) on its way to the mirror gets extinguished by an amount determined by the incident intensity (P_{f1}/A_{cav}), and the scattering cross-section of the nano-scatterers.

All light that is scattered is assumed to be lost from the optical resonator except the fraction of light that is scattered in the forward direction ($\theta=0^\circ$). This remaining power $P_{f2}=P_{b1}$, then gets reflected from the mirror and is incident again at the nano-scatterers and the same process repeats again. It is assumed that the incident light and scattered light can be reasonably approximated to be plane waves. Thus, in one round-trip, light has two opportunities of being scattered by the nano-scatterers. The power returning after one round-trip (P_{b2}) can then be written as:

$$P_{b2} = P_{f1} - \text{light losses from the cavity into waveguide}$$

= P_{f1} – light scattered into waveguide from first pass – light scattered into waveguide from second reflected pass

= P_{f1} – (light scattered from first pass – light scattered forward from first pass) – (light scattered from second pass – light scattered forward from second pass)

$$P_{b2} = P_{f1} - \frac{P_{f1}}{A_{cav}} \cdot \sigma_{sca} + \frac{P_{f1}}{A_{cav}} \cdot \sigma_{sca}|_{\theta=\pi} - \left(P_{f1} - \frac{P_{f1}}{A_{cav}} \cdot \sigma_{sca} + \frac{P_{f1}}{A_{cav}} \cdot \sigma_{sca}|_{\theta=\pi} \right) \cdot \frac{\sigma_{sca}}{A_{cav}} \quad (26)$$

$$+ \left(P_{f1} - \frac{P_{f1}}{A_{cav}} \cdot \sigma_{sca} + \frac{P_{f1}}{A_{cav}} \cdot \sigma_{sca}|_{\theta=\pi} \right) \cdot \frac{P_{f1}}{A_{cav}} \cdot \sigma_{sca}|_{\theta=\pi}$$

The above expression simplified and written as:

$$P_{b2} = P_{f1} \cdot \left\{ 1 - 2 \cdot \frac{\sigma_{sca}}{A_{cav}} + \frac{\sigma_{sca}^2}{A_{cav}^2} + 2 \cdot \frac{\sigma_{sca}|_{\theta=\pi}}{A_{cav}} - \frac{\sigma_{sca} \cdot \sigma_{sca}|_{\theta=\pi}}{A_{cav}^2} + \frac{(\sigma_{sca}|_{\theta=\pi})^2}{A_{cav}^2} \right\} \quad (27)$$

The above expression expresses the power scattered as a function of the scattering cross-section and the cross-sectional area of the cavity for a single nano-scatterer. For a total of N identical scatterers, assuming independent scattering, the above expression can be written as:

$$P_{b2} = P_{f1} \cdot \left\{ 1 - 2 \cdot \frac{N \cdot \sigma_{sca}}{A_{cav}} + \frac{(N \cdot \sigma_{sca})^2}{A_{cav}^2} + 2 \cdot \frac{N \cdot \sigma_{sca}|_{\theta=\pi}}{A_{cav}} - \frac{N^2 \cdot \sigma_{sca} \cdot \sigma_{sca}|_{\theta=\pi}}{A_{cav}^2} + \frac{(N \cdot \sigma_{sca}|_{\theta=\pi})^2}{A_{cav}^2} \right\} \quad (28)$$

Thus, for amplitudes the above expression can be written as:

$$E_{b2} = E_{f1} \cdot \sqrt{\left\{ 1 - 2 \cdot \frac{N \cdot \sigma_{sca}}{A_{cav}} + \frac{(N \cdot \sigma_{sca})^2}{A_{cav}^2} + 2 \cdot \frac{N \cdot \sigma_{sca}|_{\theta=\pi}}{A_{cav}} - \frac{N^2 \cdot \sigma_{sca} \cdot \sigma_{sca}|_{\theta=\pi}}{A_{cav}^2} + \frac{(N \cdot \sigma_{sca}|_{\theta=\pi})^2}{A_{cav}^2} \right\}}$$

(29)

Thus, the amplitude round-trip loss factor for the optical cavity in the presence of nano-scatterers can be written as:

$$a_{NP} = \sqrt{\left\{ 1 - 2 \cdot \frac{N \cdot \sigma_{sca}}{A_{cav}} + \frac{(N \cdot \sigma_{sca})^2}{A_{cav}^2} + 2 \cdot \frac{N \cdot \sigma_{sca}|_{\theta=\pi}}{A_{cav}} - \frac{N^2 \cdot \sigma_{sca} \cdot \sigma_{sca}|_{\theta=\pi}}{A_{cav}^2} + \frac{(N \cdot \sigma_{sca}|_{\theta=\pi})^2}{A_{cav}^2} \right\}}$$

(30)

In the presence of both scattering and absorption loss in the optical cavity, the combined amplitude loss-factor can be written as:

$$a = a_{abs} \cdot a_{NP} \quad (31)$$

Thus, to satisfy the critical coupling condition of the optical cavity, the following condition is to be satisfied:

$$r = a = a_{abs} \cdot a_{NP} \quad (32)$$

By substituting the expressions for a_{abs} and a_{NP} , the approximate number of total nanoparticles that satisfy the critical coupling condition for the optical cavity can be calculated. The approximation neglects the second order terms in the expression for the amplitude round-trip loss coefficient due to scattering. Thus, the "critical number" of nanoparticles can be estimated approximately by the formula:

$$N_{crit} \approx \frac{1 - \left(\frac{|r|}{\exp[-2 \cdot L \cdot \alpha_{abs}]} \right)^2}{\left(2 \frac{\sigma_{sca}}{A_{cav}} + 2 \cdot \frac{\sigma_{sca}|_{\theta=0}}{A_{cav}} \right)} \quad (33)$$

This number depends on the scattering properties of the nanoparticles, the amplitude reflection coefficient of the partial mirror, the absorption coefficient of the optical cavity, and the total length of the cavity. This expression is the governing equation for determining the concentration of nano-scatterers required in the optical cavity to achieve optimum coupling efficiency.

The enhancement factor of the optical cavity also depends upon the loss factor and it varies as a function of number of nano-particles. For a given cavity design, the enhancement factor reduces as the number of nano-scatterers increase. This is because, as the number of nano-scatterers increase, the scattering loss in the optical resonator also increases due to increased loss of light from the resonator due to scattering. This loss corresponds to a decrease in the photon lifetime inside the cavity which reduces the intensity enhancement factor of the optical resonator. Also, the bandwidth of resonance,

signified by the Full Width at Half Maximum (FWHM), is an indicator of the losses present in the optical resonator. The bandwidth of resonance thus increases as the number of scatterers inside the optical resonator increases. Thus, a balance is to be struck between the number of nano-scatterers in the optical cavity and the properties of the optical cavity. The performance of the optical cavity enhanced scattering based coupler is a complex interplay between the optical cavity and the scattering properties of the nano-scatterers. The coupling of scattered light into the waveguide depends upon the properties of the scattered light from the optical cavity as well as the refractive indices of the core and cladding material of the waveguides.

Figure 19 shows a flowchart 1900 illustrating a method of coupling light into a waveguide. At step 1902, nano-sized or sub-micron scattering elements are provided in a coupling spot disposed in a plane of a waveguide core of the waveguide. At step 1904, the light is directed into the coupling spot. At step 1906, the light is subjected to scattering at the scattering elements such that at least a portion of the scattered light is coupled into the waveguide core.

Example embodiments of the present invention can provide high efficiency and low alignment tolerance of coupling of light into an optical waveguide. The combination of materials to form the coupling spot can be very flexible. In one embodiment, a star-shape waveguide can provide efficient use of coupled light into the waveguide.

The design calculation method and system of example embodiments can be implemented on a computer system 2000, schematically shown in Figure 20. It may be implemented as software, such as a computer program being executed within the computer system 2000, and instructing the computer system 2000 to conduct the method of the example embodiment.

The computer system 2000 comprises a computer module 2002, input modules such as a keyboard 2004 and mouse 2006 and a plurality of output devices such as a display 2008, and printer 2010.

The computer module 2002 is connected to a computer network 2012 via a suitable transceiver device 2014, to enable access to e.g. the Internet or other network systems such as Local Area Network (LAN) or Wide Area Network (WAN).

The computer module 2002 in the example includes a processor 2018, a Random Access Memory (RAM) 2020 and a Read Only Memory (ROM) 2022. The computer module 2002 also includes a number of Input/Output (I/O) interfaces, for example I/O interface 2024 to the display 2008, and I/O interface 2026 to the keyboard 2004.

The components of the computer module 2002 typically communicate via an interconnected bus 2028 and in a manner known to the person skilled in the relevant art.

The application program is typically supplied to the user of the computer system 2000 encoded on a data storage medium such as a CD-ROM or flash memory carrier and read utilising a corresponding data storage medium drive of a data storage device 2030. The application program is read and controlled in its execution by the processor 2018. Intermediate storage of program data maybe accomplished using RAM 2020.

It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

For example, while the embodiments have been described with reference to polymer waveguides/materials, it will be appreciated that the present invention is applicable to other waveguides/materials such as Si, Ge, SiO₂, LiNbO₃.

Also, while the embodiments have been described with reference to planar waveguides, it will be appreciated that the present invention is applicable to other waveguides such as strip-loaded, fiber, photonic crystal fibers

CLAIMS

1. A method of coupling light into a waveguide comprising the steps of:
providing nano-sized or sub-micron scattering elements in a coupling spot
disposed in a plane of a waveguide core of the waveguide;
5 directing the light into the coupling spot; and
subjecting the light to scattering at the scattering elements such that at least
a portion of the scattered light is coupled into the waveguide core.

2. The method as claimed in claim 1, further comprising reflecting the
10 light or the scattered light at a first boundary of the coupling spot for re-direction
towards the scattering elements.

3. The method as claimed in claim 2, further comprising reflecting the
reflected light at a second boundary of the coupling spot for re-direction towards the
15 scattering elements.

4. The method as claimed in claim 3, wherein the first and second
boundaries are disposed in respective planes of opposing faces of the waveguide
core.
20

5. The method as claimed in claims 3 or 4, wherein a mirror used for
reflection at the second boundary comprises an aperture for directing the light into
the coupling spot.

25 6. The method as claimed in claims 3 or 4, wherein the first and second
boundaries form an optical cavity configured such that a cavity resonance is
matched to a wavelength of the light.

7. The method as claimed in any one of the preceding claims, wherein
30 the scattering elements are configured such that a dipole or multipolar resonance is
matched to a wavelength of the light.

8. The method as claimed in any one of the preceding claims,
comprising subjecting the light to scattering at the scattering elements such that at

least respective portions of the scattered light are coupled into respective multiple waveguide core portions of the waveguide.

9. The method as claimed in any one of the preceding claims, wherein
5 the multiple waveguide core portions are disposed in a star configuration around the coupling spot.

10. The method as claimed in any one of the preceding claims, further
10 comprising using a coupling unit to direct the light into the coupling spot.

11. The method as claimed in claim 10, wherein the coupling unit
comprises a collimating element for collimating the light.

12. The method as claimed in claims 10 or 11, wherein the coupling unit
15 comprises a focusing element for focusing the light into the coupling spot.

13. A structure for coupling light into a waveguide comprising nano-sized
or sub-micron scattering elements in a coupling spot disposed in a plane of a
waveguide core of the waveguide, the scattering elements configured for coupling at
20 least a portion of the light into the waveguide core via scattering.

14. The structure as claimed in claim 13, further comprising means for
reflecting the light or the scattered light at a first boundary of the coupling spot for re-
direction towards the scattering elements.
25

15. The structure as claimed in claim 14, further comprising means for
reflecting the reflected light at a second boundary of the coupling spot for re-
direction towards the scattering elements.

16. The structure as claimed in claim 15, wherein the first and second
30 boundaries are disposed in respective planes of opposing faces of the waveguide
core.

17. The structure as claimed in claims 15 or 16, wherein the means for reflection at the second boundary comprises an aperture for directing the light into the coupling spot.

5 18. The structure as claimed in claims 15 or 16, wherein the first and second boundaries form an optical cavity configured such that a cavity resonance is matched to a wavelength of the light.

10 19. The structure as claimed in any one of claims 13 to 18, wherein the scattering elements are configured such that a dipole or multipolar resonance is matched to a wavelength of the light.

15 20. The structure as claimed in any one of claims 13 to 19, comprising multiple waveguide core portions of the waveguide, the structure being configured such that at least respective portions of the scattered light are coupled into the respective multiple waveguide core portions.

20 21. The structure as claimed in any one of claims 13 to 20, wherein the multiple waveguide core portions are disposed in a star configuration around the coupling spot.

22. The structure as claimed in any one of claims 13 to 21, further comprising a coupling unit to direct the light into the coupling spot.

25 23. The structure as claimed in claim 22, wherein the coupling unit comprises a collimating element for collimating the light.

24. The structure as claimed in claims 22 or 23, wherein the coupling unit comprises a focusing element for focusing the light into the coupling spot.

30 25. The structure as claimed in any one of claims 13 to 24, wherein a material of the coupling spot is the same or optically matched to a material of the waveguide core.

26. The structure as claimed in claim 24, wherein a material of the scattering elements is different from the material of the waveguide core.