

A Light Coupling Device, and Method of making the Device

Field of the invention

5 This invention relates to a light coupling device, and methods of making the device. In particular it relates to the architecture and construction of a light coupling device, such as one suitable for use in fiber optic networks.

Background of the Invention

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A number of approaches are known for coupling light between a light-emitting element or a light-receiving element and an optical waveguide. This typically involves changing the direction of a light beam, such as by 90 degrees. Unfortunately, these techniques typically have a low light coupling efficiency.

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First, diffraction gratings have been used to change the light direction by diffraction and allow the angle of the incident light to be changed 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
20 utilizing diffraction gratings. In order to provide good coupling efficiency, expensive integrated technologies 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
25 waveguide is typically low in applications utilizing such mirrors. Furthermore, the accuracy of mirror angle, position and surface flatness can affect the coupling efficiency. Also, alignment of mirrors or reflectors is a problem. Mirror angles are crucial in achieving the results desired. These problems are exacerbated when the waveguide dimensions are reduced, for example when the waveguide thickness is less than 50 μm .

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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 direction mode is excited to facilitate light coupling. However, this method uses a very thin waveguide, e.g. less than $50\text{ }\mu\text{m}$, which is typically not very efficient.

There remains a need for a light coupling structure which permits light to be coupled into a waveguide efficiently and at acceptable cost.

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In view of the points above the present inventors have previously proposed an optical coupler which may address some of these issues. This was described in PCT application number PCT/SG2011/000317 which was unpublished at the priority date of the present application, but the disclosure of which is incorporated herein in its entirety.

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The optical couplers of PCT/SG2011/00317 have a coupling spot which is arranged to transmit light into one or more waveguides. One such optical coupler is shown in cross-section in Fig. 1. Fig. 1 shows two elongate waveguide cores 1, extending to either side of the diagram. The waveguide cores 1 are above a cladding layer 2. Between the waveguide cores is a coupling spot 4 composed of a polymer matrix with embedded nano-sized particles. The term "nano-particles" is used in this document to refer to particles which have a maximum diameter of less than one micron (that is, sub-micron particles). Desirably, all the particles have a diameter in the sub-micron range. Note that the optical coupler may include further waveguide cores touching the coupling spot 4 which are not shown in Fig. 1 since they are not in the plane of the diagram. These extend away from the coupling spot 4 in directions out of the plane of the diagram.

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The upper surface of the coupling spot 4 carries a first reflection mirror 5 (shown in cross-section), including a central aperture. Incident light 11 (shown propagating downwardly in the figure) can enter the coupling spot 4 through the aperture in the first reflection mirror 5. In the coupling spot 4, the light is scattered by nano-particles in the

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coupling spot into the surrounding waveguide cores 1. The cladding layer 2 is of a lower refractive index than the waveguide core material to confine the coupled light within the waveguide core. There is a back reflection mirror 6 between the cladding layer 2 and the coupling spot 4 to allow unscattered or forward scattered light to be reflected off the back reflection mirror 6 and in the process have another opportunity to be scattered by the nano-particles and get coupled into the surrounding waveguides 1. The first reflection mirror 5 inhibits light from exiting the coupling spot upwardly. Note that the coupling spot 4 and its mirrors 5,6 function as an optical cavity.

10 The arrangement of Fig. 1 provides a significant advantage over the publicly-known systems described above, specifically high efficiency and low alignment tolerance of coupling light into the waveguide cores 1.

One convenient method for fabricating such an optical coupler (not given explicitly in PCT/SG2011/000317) is illustrated in Fig. 2. Fig. 3 shows the steps of this method. The starting point is a substrate 3 shown in Fig. 2(a). Onto this in step 21 (shown on Fig. 3) is deposited a cladding layer 2 of desired thickness such as $5\ \mu\text{m}$, as shown in Fig. 2(b). In step 22, a back reflection mirror 6 is deposited onto the cladding layer 2, as shown in Fig. 2(c). Then in step 23 the waveguide cores 1 are deposited as shown in Fig. 2(d), leaving a cavity between them and over part of the back reflection mirror 6. Then, as shown in Fig. 2(e), in step 24 liquid polymer containing scattering elements is dispensed into the cavity, and cured to form the coupling spot 4. After curing, the first reflection mirror 5 is formed over the coupling spot 4, as shown in Fig. 2(f). This is done by forming a patterned photo-resist structure in step 25 using a photo-lithographic technique (depositing a layer of photo-resist, and removing selected portions of the layer by shining ultraviolet (UV) light onto the photo-resist through a patterned photo-mask, and then in a developing step, removing portions of the photo-resist which were exposed to the UV), and in step 26 depositing a metal layer on top of the patterned photo-resist structure, and performing a lift-off process in which the patterned photo-resist structure and the parts of the metal layer over it are removed.

However, the present inventors have found that for certain formulations of the polymer, the result of curing the liquid polymer is that the structure is as shown in Fig. 4(a) rather than as shown in Fig. 2(e). That is, the polymer may exhibit shrinkage upon curing. In this case, the height of the coupling spot 4 is no uniformly the same height as the waveguide and the upper surface of the coupling spot is uneven. Figs 4(b)-(f) show the consequences of this during the steps of forming the first reflection mirror 5. As mentioned above, this process involves depositing a layer of photoresist 131 over the structure of Fig. 4(a) as shown in Fig. 4(b), and, as shown in Fig. 4(c), exposing portions of it to UV light through a photo-mask 133. There is then a developing stage, which removes the portions of the photo-resist which were exposed to UV. This patterns the photo-resist 131.

Following this, as shown in Fig. 4(d), the surface is coated with metal atoms 135 (e.g. by evaporation, sputtering, or chemical-vapor deposition (CVD)), to produce the structure shown in Fig. 4(e). Then the photoresist 131 is removed, leaving the structure as shown in Fig. 4(f), including the first reflection mirror 5. The first reflection mirror 5 is composed of the metal atoms 135 which were not deposited over the photoresist 131. As shown in Fig. 4(f), the first reflection mirror 5 is not flat. The overall arrangement may be subject to dimensional inaccuracy. In particular, this technique may not reproduce the aperture pattern with very good fidelity.

Summary of the Invention

The present invention aims to provide a new and useful light coupling device, and a method of fabricating the device.

The invention builds upon the principles of PCT/SG2011/000317. In general terms, the invention proposes that the coupling spot is formed over a transparent substrate, and that in use the light enters the coupling spot through the transparent substrate. Thus, the surface of the coupling spot which may become uneven on curing is the surface opposite from that through which light enters the coupling spot. This reduces the importance of any unevenness. This inverted configuration allows a method of

fabrication that mitigates the effects of the shrinking of the coupling spot material upon curing.

As in PCT/SG2011/000317, the coupling spot is sandwiched between a first reflection mirror containing an aperture, and a back reflection mirror. However, unlike the arrangement illustrated in Fig. 1, the first reflection mirror is on the surface of the coupling spot which faces towards the transparent substrate. The first reflection mirror is fabricated before the coupling spot is fabricated, minimizing, or even eliminating, any change in the aperture when the coupling spot material is cured.

Also as in PCT/SG2011/000317, the light coupling device includes a cladding layer. This cladding layer is formed over the transparent layer, and beneath the coupling spot (i.e. the coupling spot is over the transparent layer, but not touching it; the coupling spot is spaced from the transparent layer at least by the cladding layer).

A second reflection mirror is preferably provided between the cladding layer and the transparent layer, with an aperture in register with the aperture in the first reflection mirror. This minimizes stray light and thus improves signal-to-noise ratios during the transmission of data in optical mediums. The second reflection mirror serves two purposes. Firstly, the size of the aperture serves to control the incident angle of stray light reflected out of the coupling spot, and this allows the aperture to be configured to minimize internal reflection of stray light within the transparent substrate. Secondly, the second reflection mirror serves to dissipate any stray light propagating within the transparent substrate by absorbing a portion of the stray light each time it is reflected.

Brief Description of the Drawings

The advantages of this invention can be more readily ascertained from the following description of the embodiments of the invention when read in conjunction with the accompanying drawings in which:

Fig. 1 is a diagram showing a light coupling device from PCT/SG2011/000317.

Fig. 2, which is composed of Figs. 2(a)-2(f), is a diagram showing the steps of one way of producing a device as shown in Fig. 1.

Fig. 3 is a flow diagram of the process of Fig. 4.

Fig. 4, which is composed of Figs. 4(a)-4(f), shows a possible problem with the process
5 of Figs. 2 and 3.

Fig. 5 shows in cross-section a first embodiment of the invention, having first and second reflection mirrors.

Fig. 6 shows in cross-section a second embodiment of the invention without the second reflection mirror, and a possible path that stray light reflected out of the coupling spot
10 may take in the second embodiment.

Fig. 7 is a top view of the embodiment of Fig. 5.

Fig. 8 is an enlarged top view of a central part of the embodiment of Fig. 5.

Fig. 9 is a diagram showing a possible path that stray light reflected out of the coupling spot may take in the embodiment of Fig. 5.

Fig. 10 is a diagram showing how the maximum incident angle of stray light reflected out of the coupling spot can be calculated, in the embodiment of Fig. 5.

Fig. 11 is a graph showing the propagation loss as a function of the cladding mode in the embodiment of Fig. 5.

Fig. 12 is a graph illustrating the relationship between the minimum thickness of the cladding layer required as a function of the transparent substrate refractive index in the
20 embodiment of Fig. 5

Fig 13 is a diagram showing how stray light propagating along the transparent substrate may be diminished in intensity by the second reflection mirror, in the embodiment of Fig. 5.

Fig. 14 is a diagram showing how the incident angle of stray light may be controlled by the apertures of the first and second reflection mirrors of the embodiment of Fig. 5.

Fig 15, which is composed of Figs. 15(a)-15(g), is a diagram showing the steps of a process for fabricating the embodiment of Fig. 6.

Fig. 16 is a flow diagram of the process of Fig. 15.

Fig. 17, which is composed of Figs. 17(a)-17(g), is a diagram showing the steps of a process for fabricating the embodiment of Fig. 5.

Fig. 18 is a flow diagram of the process of Fig. 17.

Detailed Description of Embodiments

An embodiment of the invention will now be described with reference to Fig. 5.

5 Reference numerals are given the same meaning they have in Figs. 1 and 2. The embodiment is a light coupling device includes a transparent substrate 13, upon which is formed a cladding layer 2. A coupling spot 4 is formed on the cladding layer 2. The coupling spot 4 is co-planar with a plurality of waveguide cores 1 formed of a waveguide core material. The waveguide cores 1 lie in a waveguide plane. Only two
10 waveguide cores 1 are visible in Fig. 1, but as will be explained below this embodiment includes other waveguide cores which are not shown since they do not lie in the plane of the diagram. The term "light" is used in this document to mean electromagnetic radiation with one or more components of any wavelength in the range 400nm to 1600nm.

15 Incident light 21 enters the light coupling device through the lower surface of the transparent substrate 13, which it traverses. The transparent substrate 3 allows light of the desired wavelengths to pass through without substantial interference and absorption. The light then traverses the cladding layer 2, and enters the coupling spot 4 from *below*.
20 The coupling spot includes a polymer matrix transparent to light of the frequency of the incident light 21, and nano-particles to function as scattering centres. More specifically, the polymer matrix and the transparent substrate are transparent for at least one wavelength λ such that $a/\lambda < 1$ where a is the mean particle diameter.

25 In the coupling spot 4 the light is scattered by the nano-particles into the surrounding waveguide cores 1. The incident light 21 is preferably normal to the waveguide plane as this can provide better radial intensity distribution of scattered light. The cladding layer 2 is of a lower refractive index than the waveguide core material to confine the coupled light within the waveguide cores. There is a first reflection mirror 5 between
30 the cladding layer 2 and the coupling spot 4 to allow back scattered light to get reflected off the first reflection mirror 5 and in the process have another opportunity to be scattered by the nano-scatterers and get coupled into the surrounding waveguide cores

1. An aperture in the first reflection mirror lets incident light 21 into the coupling spot 4. A back reflection mirror 6 serves a similar function of confining backscattered or reflected light within the coupling spot 4. In addition, there is a second reflection mirror 7 between the cladding layer 2 and the transparent substrate. The purpose of this second reflection mirror 7 is to reduce the propagation of stray light. Also, the aperture of the second reflection mirror 7 controls the range of angles at which light escaping from the coupling spot 4 can enter the transparent substrate 13. As described below, this can minimize the proportion of the light which is reflected back into the transparent substrate 13.

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In contrast to the arrangement of Fig. 1, the inverted design of Fig. 5 facilitates the process of creating the coupling spot 4 without having to worry about problems with the dimensional accuracy of the aperture in the first reflection mirror 5 caused by curing.

15 Fig. 6 shows a second embodiment of the invention which differs from the first embodiment in that it has no second reflection mirror. It shares with the first embodiment the advantage that the first reflection mirror 5 is on the lower surface of the coupling spot 4, and therefore is not compromised by the curing process.

20 However, in both embodiments there is a danger that some of the light which enters the coupling spot 4 may be reflected back through the aperture and to the transparent substrate 3. This is more serious in the embodiment of Fig. 6 since the transparent substrate 3 together with the cladding layer 2 and waveguide core 1 can support a "cladding mode" which allows stray light 302 to travel to and fro between the layers of the waveguide core 1, cladding 2 and the transparent substrate 3. This can cause poor signal-to-noise ratios during data processing, as the stray light propagating within this "cladding mode" may affect sensor readings at the detectors positioned at the end of the waveguides core 1 channel. In the embodiment of Fig. 5, by contrast, the second reflection layer means that light cannot re-enter the channel from the transparent substrate 13. Furthermore, light moving in the cladding layer 2 is quickly dissipated due to the first and second reflection mirrors 5,7.

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Fig. 7 shows the embodiment of Fig. 5, but viewed from the top of the light coupling device (the embodiment of Fig. 6 looks much the same from this direction). It may be seen that there are twelve waveguide cores 1, all in the waveguide plane. The waveguide cores 1 are arranged radially around the coupling spot 4 which is hidden by the back reflection mirror 6. The portions of the cladding layer 2 which are not covered by the waveguide cores 1 can be seen through the gaps between the waveguide cores 1.

Fig. 8 shows a close-up top view of the same embodiment of the invention. Besides the radially arranged waveguide cores 1 and the cladding layer 2, also visible are the outer edge 61 of the back reflection mirror 6. Dashes show the positions of the outer edge 51 of the first reflection mirror 5, the outer edge 41 of the coupling spot 4, the outline 71 of the aperture in the second reflection mirror 7, and the outline 52 of the aperture in the first reflection mirror 5. The coupling spot 4 is a cylindrical body having a central axis, and its outer edge 41 is circular. Note that the apertures 52, 71, as well as the first and back reflection mirrors 51, 61, are circular and concentrically aligned to the central axis of the coupling spot 4.

Fig. 9 is a cross-sectional view of the same embodiment (i.e. the embodiment of Fig. 5). In particular, it shows how incident light 21 directed at the coupling spot 4 may undergo one or more scattering events, and hopefully be coupled into one of the waveguide cores 1. The first reflection mirror 5 can reflect some of scattered light back to the coupling spot 4 for further scattering events. Fig. 9 also shows how stray light 602 reflected out of the coupling spot 4 and into the transparent substrate 3 may be controlled by the aperture of the second reflection mirror 7 such that it exits the transparent substrate 3 entirely, and does not propagate along the cladding layer 2 in a "cladding mode" and cause noisy readings.

Calculating the Dimensions of the Light Coupling Device

Fig. 10 is similar to Fig. 9, but shows the definitions of several parameters. They are used below in calculating the maximum incident angle of stray light that may exit the

coupling spot and still enter the transparent substrate. This in turn is used to set a minimum suitable limit on the thickness of the cladding layer 2.

5 In order to reduce stray light, the second reflection mirror with aperture can be designed as follows:

Firstly, the definitions of symbols depicted in Fig. 10 are:

- $\vartheta_{\min}$: Minimum angle of incidence of light scattered though the aperture 71 from the aperture 52 in the first reflection mirror 5
- 10 ϑ_{inc} : Maximum angle of incidence of light scattered though aperture 52 to the cladding/substrate interface.
- r_{ap} : Radius of the “scattering aperture” (i.e. the aperture 52)
- r_{sh} : Radius of the “backscattering aperture shield” (i.e. the aperture 71)
- t_{clad} : Thickness of the cladding layer 2
- 15 n_{clad} : Refractive index of the cladding layer 2
- n_{sb} : Refractive index of the transparent substrate 13
- ϑ_r : Angle of refraction at the cladding/substrate interface
- ϑ_{pr} : Angle of propagation for the guided wave in the substrate.

20 From the geometry of Fig. 10 we can write:

$$\theta_{\text{inc}} = \frac{\pi}{2} - \theta_{\min}$$

$$\theta_{\min} = \tan^{-1} \left[\frac{t_{\text{clad}}}{r_{\text{sh}} + r_{\text{ap}}} \right]$$

Next, applying Snell's law at the cladding/substrate interface for the refracted light we obtain:

$$n_{\text{clad}} \sin \theta_{\text{inc}} = n_{\text{sb}} \sin \theta_r$$

$$25 \quad \theta_r = \sin^{-1} \left[\frac{n_{\text{clad}}}{n_{\text{sb}}} \cdot \sin \theta_{\text{inc}} \right]$$

Thus, the propagation angle for the air/substrate/metal waveguide is:

$$\theta_{pr}|_{\min} = \frac{\pi}{2} - \theta_r = \frac{\pi}{2} - \sin^{-1} \left[\frac{n_{clad}}{n_{sb}} \cdot \sin \theta_{inc} \right]$$

From waveguide theory, the propagation angle of a guided mode can be written as a function of the effective refractive index (n_{eff}) of the mode as:

$$\begin{aligned} \theta_{pr} &= \cos^{-1} \left(\frac{n_{eff}}{n_{sb}} \right) \\ n_{eff}|_{cutoff} &= n_{sb} \cdot \cos \left\{ \frac{\pi}{2} - \sin^{-1} \left(\frac{n_{clad}}{n_{sb}} \cdot \sin \theta_{inc} \right) \right\} \end{aligned} \quad (A)$$

The cut-off effective refractive index of the guided mode in the air/substrate/metal waveguide can be found by placing a reasonable threshold on the propagation loss of the guided mode in the waveguide. As the metal clad waveguide is dissipative in nature, all the guided modes experience propagation loss due to the presence of the metal layers 5, 7 as part of the waveguide structure.

Let α_{th} be the threshold propagation loss (dB/cm) of the n^{th} guided mode, shown below, in which all the modes should be blocked by the aperture structure. The propagation loss is related to the imaginary part of the effective refractive index of the guided mode, depicted as:

$$\text{Im}(n_{eff}^n) = \frac{\alpha_{th} \lambda_0}{4\pi \cdot 10 \cdot \log_{10}(e)}$$

Where, λ_0 is the wavelength of light in vacuum. The corresponding real part of the modal refractive index should then satisfy equation (A) above, which can be rewritten as:

$$\text{Re}(n_{eff}^n) = n_{sb} \cdot \cos \left[\frac{\pi}{2} - \sin^{-1} \left\{ \frac{n_{clad}}{n_{sb}} \cdot \sin \left(\frac{\pi}{2} - \tan^{-1} \left(\frac{t_{clad}}{r_{sh} + r_{ap}} \right) \right) \right\} \right] \quad (B)$$

Now, from the above expression we can obtain the correct thickness of the lower cladding as:

$$t_{clad}(n_{sb}, r_{sh}, n_{clad}) = (r_{sh} + r_{ap}) \cdot \tan \left[\frac{\pi}{2} - \sin^{-1} \left\{ \frac{n_{sub}}{n_{clad}} \cdot \sin \left[\frac{\pi}{2} - \cos^{-1} \left(\frac{n_{eff}^n}{n_{sub}} \right) \right] \right\} \right] \quad (C)$$

In the above expression, n_{eff}^n is itself a function of the thickness and refractive index of the substrate. This expression gives the minimum thickness that is needed for the cladding layer given a certain refractive index such that the aperture of the second reflection mirror can block all propagation modes that have a propagation loss below the pre-selected value of α_{th} . Therefore, this equation (C) is the defining equation that can provide the various values needed to design the geometrical dimensions and optical properties of the cladding layer, the transparent substrate, as well as the aperture diameter of the second reflection mirror.

For instance, to calculate a cladding layer thickness, the steps to take would be to:

- (1) Measure the refractive indices of the substrate, lower cladding, and the core layer at the desired wavelength. Measure the thickness of the substrate.
- (2) Set the first aperture radius: r_{ap}
- (3) Set the lower threshold for the second aperture radius: r_{sh}
- (4) Calculate all the propagation modes of the metal-substrate-air waveguide
- (5) Set the threshold for the propagation loss for the mode that will be allowed to propagate in the metal-substrate-air waveguide (α_{th}).
- (6) Get the value of the effective index of the propagating mode corresponding to the threshold propagation loss (n_{eff}^n).
- (7) Calculate the value of the threshold for the thickness (t_{clad}) of the lower cladding from expression (C).
- (8) Choose a suitable thickness of the cladding which has a value larger than t_{clad} .

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By way of example, consider the graph in Fig. 11. Here, the refractive indices of the transparent substrate and cladding layer have been set to be $n_{sb} = 1.73$ and $n_{clad} = 1.51$, respectively. For the reflection mirror material, gold is selected and the wavelength of operation is set to 650nm. Further, the first reflection mirror's aperture diameter is set to 125 μm and the cladding layer's thickness is set to 50 μm . After solving for the

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Eigen-modes of the air/PEN/gold waveguide structure, we can calculate the complex refractive indices of all the guided modes of the waveguide. The resulting plot is shown as Fig. 11. Thus, if we choose a threshold propagation loss of 4dB/cm, for the lowest guided propagation mode, the effective refractive index (real part) of the guided mode is then 1.500914 and its propagation angle is 29.8 degrees. Substituting in equation (B), we get a value of $r_{sh} = 330 \mu m$.

Fig. 12 illustrates the relationship between the minimum thickness of the cladding layer required as a function of the transparent substrate refractive index, given a first reflection mirror's aperture diameter of $250 \mu m$ and a second reflection mirror's aperture diameter of $500 \mu m$ respectively. In addition, the thickness of substrate was assumed to be $200 \mu m$, and the threshold propagation loss for the metal clad waveguide formed by the substrate, the second aperture layer, and air was assumed to be 4dB/cm. The metal material was assumed to be gold.

While plotting Fig. 12, the radius of the second reflection mirror's aperture is chosen so that it can be patterned with reasonable alignment tolerance. Any reasonable multiple of the first reflection mirror's aperture radius will suffice depending upon the type of manufacturing equipment used. In the above example a factor of two was chosen as a reasonable multiple in consideration of a very relaxed photo-lithography alignment tolerance.

From Fig. 12 we can see that there is a definite cut-off point given a specific cladding layer and transparent substrate refractive index combination. This condition arises when the effective refractive index for the propagating mode in the metal-substrate-air waveguide is equal to or larger than the refractive index of the cladding layer. In order to excite these modes, stray light has to enter the second reflection mirror's aperture at a 90 degree incident angle which is practically physically impossible. Hence, this condition can be very useful as almost any thickness of cladding layer will block the propagating modes having propagation losses less than the pre-defined threshold propagation loss for the metal-substrate-air propagation modes. The thickness of the

cladding layer should be enough so there is no coupling of power between the light propagating in the waveguide core and the transparent substrate. For example, a thickness of $2\text{--}5\text{ }\mu\text{m}$ is sufficient if the wavelength of operation is 650nm .

5 Fig. 13 shows an example of what happens when the cladding layer 2 is thin. Stray light 102 may be able to propagate through the transparent substrate. However, in the region 103 the stray light is dissipated by the second reflection mirror due to the metal cladding effect which is the dissipation of propagated light due to the absorptive nature of metal at optical frequencies.

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In the Fig. 13 example, the following specifications were used. Transparent plastic substrate (thickness (t_{sb})= $200\text{ }\mu\text{m}$, refractive index (n_{sb})= 1.73), waveguide cladding (t_{clad} = $50\text{ }\mu\text{m}$, n_{clad} = 1.51), waveguide core (t_{core} = $50\text{ }\mu\text{m}$, n_{core} = 1.59), light coupling spot material (r_{couple} = 0.5mm , n_{couple} = 1.49), scattering center material (r_{np} = 35nm , n_{np} = 2.49),
 15 first reflection mirror (r_{m1} = 0.75mm) with aperture (r_{ap} = 0.125mm), second reflection mirror (cover all surface of transparent plastic substrate) with aperture (r_{sh} = 0.35mm). Note that the waveguide core has higher refractive index than the cladding layer, and that the transparent substrate has higher refractive index than air (the outside environment).

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Fig. 14 shows an example of what happens when the cladding layer 2 is thick. Stray light exits out of the transparent substrate and does not propagate along the channel. Basically, back-scattered stray light can be considered to create a “cladding mode”, such that stray light is propagating in the same direction as the light traveling in the
 25 waveguide core. Again, note that increased stray light due to the cladding mode results in high signal-to-noise ratio, unless there are means to decrease the stray light’s intensity. Here, by controlling the aperture of the second reflection mirror, the incident angle of stray light from that traverses through to the transparent substrate can be controlled. If the incident angle of stray light is smaller than the critical angle required
 30 to sustain the transparent substrate’s cladding mode, some or all of the stray light will exit the transparent substrate in region 112 as ray 113, and not propagate. Moreover,

any stray light which does propagate within the cladding layer or the transparent substrate is dissipated by the second reflection mirror due to the metal cladding effect.

In the Fig. 14 example, the following specifications were used. Transparent plastic
 5 substrate ($t_{sb}=200\text{ }\mu\text{m}$, $n_{sb}=1.49$), waveguide cladding ($t_{clad}=500\text{ }\mu\text{m}$, $n_{clad}=1.54$),
 waveguide ($t_{core}=50\text{ }\mu\text{m}$, $n_{core}=1.59$), light coupling spot material ($r_{couple}=0.5\text{mm}$,
 $n_{couple}=1.49$), scattering center material ($r_{np}=35\text{nm}$, $n_{np}=2.49$), first reflection mirror
 ($r_{m1}=0.5\text{mm}$) with aperture ($r_{ap}=125\text{ }\mu\text{m}$), second reflection mirror (cover all surface of
 transparent plastic substrate) with aperture ($r_{sh}=300\text{ }\mu\text{m}$).

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Fig. 15 shows the process steps for producing the embodiment of Fig. 6. A flow
 diagram is shown in Fig. 16. The process starts with a transparent substrate 13 as a base,
 as shown in Fig. 15(a). In step 31 (of Fig. 16) cladding layer 2 material is disposed on
 the transparent substrate 13 by spin-coating or bar-coating, to form a layer of thickness,
 15 for instance, $5\text{ }\mu\text{m}$, as shown in Fig. 15(b).

In step 32, the first reflection mirror 5 with an aperture is formed on the waveguide
 cladding layer 2 by conventional techniques, such as a photolithographic process,
 sputtering or metal lift-off techniques. Because of the flatness of the cladding layer 2,
 20 the dimensional accuracy of the aperture of the first reflection mirror 5 is maintained.
 The result is shown in Fig. 15(c).

Next, in step 33, waveguide core 1 material is disposed on the waveguide cladding layer
 2 by conventional techniques, such as spin-coating and photolithography. It is formed
 25 with a cavity where the light coupling spot 4 material will be dispensed, as shown in Fig.
 15(d).

Next, in step 34, the coupling spot 4 material is dispensed in the cavity, and cured. It
 shrinks upon curing, as shown in Fig. 15(e).

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Finally, in step 35, the back reflection mirror 6 is formed on the top surface of the polymerized light coupling spot 4. This may be done by several methods, such as by bombarding metal atoms 135 (formed by evaporation, sputtering, or chemical-vapor deposition (CVD)) through a shadow mask 154, as shown in Fig. 15(f). Although the top surface of the light coupling spot 4 is irregular, there is no need to maintain strict dimensional integrity for the back reflection mirror 6. The finished product is shown in Fig. 15(g).

Fig. 17 shows the process steps for producing the embodiment of Fig. 5. A flow diagram is shown in Fig. 18. The process starts with a transparent substrate 13 as a base, as shown in Fig. 17(a).

Unlike the method of Figs. 15 and 16, the method of Figs. 17 and 18 has an initial step 81 (in Fig. 18) of patterning the second mirror reflector 7 on the surface of the transparent substrate 13, as shown in Fig. 17(b), using standard photo-lithographic techniques, such as photo-resist deposition followed by ultra-violet light exposure. This is then followed by standard metal patterning techniques such as a metal lift-off process.

In step 82, cladding layer 2 material is disposed on the transparent substrate 13 by spin-coating or bar-coating, to form a layer of thickness, for instance, $5\text{ }\mu\text{m}$, as shown in Fig. 17(c).

In step 83, the first reflection mirror 5 with an aperture is formed on the waveguide cladding layer 2 by conventional techniques, such as a photolithographic process, sputtering or metal lift-off techniques. Because of the flatness of the cladding layer 2, the dimensional accuracy of the aperture of the first reflection mirror 5 is maintained. The result is shown in Fig. 17(d).

Next, in step 84, waveguide core 1 material is disposed on the waveguide cladding layer 2 by conventional techniques, such as spin-coating and photolithography. It is formed

with a cavity where the light coupling spot 4 material will be dispensed, as shown in Fig. 17(e).

Next, in step 85, the coupling spot 4 material is dispensed in the cavity, and cured. It
5 shrinks upon curing, as shown in Fig. 17(f).

Finally, the back reflection mirror 6 is formed. As mentioned above in relation to Fig. 16, this may be done in several ways. In the method of Fig. 18, it is done in a step 86 in which a patterned layer of photo-resist is formed, and a step 87 in which a metal layer is
10 formed over the photoresist, which is then removed. Again, although the top surface of the light coupling spot 4 is irregular, there is no need to maintain strict dimensional integrity for the back reflection mirror 6. The finished product is shown in Fig. 17(g).

Material Selection

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The coupling spot 4 in this invention comprises a polymer matrix and scattering centers which may be nano-sized particles to cause Mie-scattering. The polymer matrix may comprise any material, as long as the material is sufficiently transparent at the desired wavelength. The scattering efficiency of the coupling spot 4 is dependent on the
20 particle size, refractive index difference from polymer matrix (medium), and wavelength of the light. The nano-particles may be formed of any material, but it is preferable that the refractive index difference between the polymer matrix and particle is large. For example, in the case of particles of size 100 nm in diameter, and where the refractive index of polymer matrix (n_{couple}) is 1.488, the refractive index of each particle
25 (n_{np}) needs to be more than 1.888 to achieve light scattering efficiency of more than 1% for the entire visible wavelength range.

Material for the first reflection mirror 5 and back reflection mirror 6 can be metal. Ideally, reflectivity of the mirrors should be as high as possible, for example, higher
30 than 50% at the desired wavelength of light.

Material for the second reflection mirror 7 can be any light absorptive material. Alternatively, it may also be metal to provide a metal-cladding effect.

Other Considerations

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The use of scattering centers within a polymer matrix as a coupling means has various advantages. By way of example, for a waveguide thickness of less than $100\text{ }\mu\text{m}$, a diameter of the coupling spot can be 1 mm. In this way, the alignment tolerances between the light source and the waveguide may be relaxed. A simple butt-coupled
10 light source may have problems aligning with a $100\text{ }\mu\text{m}$ thick waveguide, but a coupling spot of 1mm can allow the light source to be easily aligned. For example, if we have a $50\text{ }\mu\text{m}$ waveguide and we utilize a $50\text{ }\mu\text{m}$ core diameter optical fiber to excite the optical waveguide, we may need a positional accuracy of less than $\pm 25\text{ }\mu\text{m}$ to achieve a reasonable coupling efficiency without too much increase in the signal-to-
15 noise ratio.

Variations

Although only two embodiments of the invention has been described in detail, many variations are possible within the scope of the invention, as will be clear to a skilled
20 reader. For example the multiple waveguide cores 1 may, in other embodiments, be replaced with a single slab waveguide core. This is a body of waveguide material which is deposited as a substantially uniform layer over the waveguide cladding layer, except that it includes a cavity for receiving the material which subsequently forms the coupling spot. That is, in the final product the slab waveguide core surrounds the
25 coupling spot, and extends away from the coupling spot in all directions parallel to the surface of the transparent substrate.

Claims

1. A light coupling device, comprising:
 - one or more waveguide cores extending in a plane;
 - 5 a coupling spot disposed in said plane and containing scattering centres;
 - a cladding layer parallel to said plane and positioned alongside said one or more waveguide cores;
 - a transparent substrate parallel to said plane and positioned alongside said cladding layer; and
 - 10 a back reflection mirror disposed on said coupling spot, on the opposite side of said coupling spot from said transparent substrate;
 - wherein upon light traversing said transparent substrate, at least some of the light traverses the cladding layer and passes into said coupling spot, and the scattering centres couple at least a portion of the light into said one or more waveguide cores via
 - 15 scattering.
2. The light coupling device according to any one of the preceding claims, further comprising a first reflection mirror disposed between said coupling spot and said cladding layer, wherein said first reflection mirror has an aperture for allowing light
- 20 traversing said cladding layer into said coupling spot.
3. The light coupling device according to any preceding claim, further comprising a second reflection mirror between said cladding layer and said transparent substrate, wherein said second reflection mirror has an aperture for allowing light traversing said
- 25 transparent layer into said cladding layer.
4. The light coupling device according to any preceding claim, wherein said coupling spot comprises a polymer matrix.
- 30 5. The light coupling device according to claim 4, wherein said polymer matrix comprises a polymer that is transparent for at least one wavelength λ such that $a/\lambda < 1$ where a is the mean particle diameter.

6. The light coupling device according to claim 5 when dependent on claims 2 and 3, wherein the thickness of said cladding layer is configured according to the equation

$$t_{clad}(n_{sb}, r_{sh}, n_{clad}) = (r_{sh} + r_{ap}) \cdot \tan \left[\frac{\pi}{2} - \sin^{-1} \left\{ \frac{n_{sb}}{n_{clad}} \cdot \sin \left[\frac{\pi}{2} - \cos^{-1} \left(\frac{n_{eff}^n}{n_{sb}} \right) \right] \right\} \right],$$

5 where t_{clad} stands for the thickness of said cladding layer,

n_{sb} stands for the refractive index of said transparent substrate,

r_{sh} stands for the radius of the aperture in said second reflection mirror,

n_{clad} stands for the refractive index of said cladding layer,

r_{ap} stands for the radius of the aperture in said first reflection mirror,

10 n_{eff}^n is a function of the thickness and refractive index of the substrate according to the equation

$$n_{eff} \Big|_{cutoff} = n_{sb} \cdot \cos \left\{ \frac{\pi}{2} - \sin^{-1} \left(\frac{n_{clad}}{n_{sb}} \cdot \sin \theta_{inc} \right) \right\},$$

n is a positive integer; and

θ_{inc} stands for the maximum possible incidence angle at which stray light exiting the

15 aperture of said first reflection mirror may enter the aperture of said second reflection mirror.

7. The light coupling device according to any one of the preceding claims, wherein there are a plurality of said waveguide cores arranged around said coupling spot, said
20 waveguide cores being elongate and extending in respective directions away from said coupling spot.

8. A method for fabricating a light coupling device comprising:

forming a cladding layer over a transparent substrate;

25 forming one or more waveguide cores over the cladding layer, the one or more waveguide cores extending in a plane;

forming a coupling spot over the cladding layer, the coupling spot being disposed in said plane and containing scattering centres; and

forming a back reflection mirror on said coupling spot;

said scattering centres being operative to scatter light traversing the transparent layer and cladding layer and into said coupling spot, into said one or more waveguide cores.

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9. The method according to claim 8 further comprising forming a first reflection mirror over said cladding layer before said step of forming said one or more waveguide cores, said first reflection mirror having an aperture allowing light traversing said cladding layer into said coupling spot.

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10. The method according to claim 8 or claim 9, further comprising forming a second reflection mirror over said transparent substrate before said step of forming said cladding layer, said second reflection mirror having an aperture for allowing light traversing said transparent substrate into said cladding layer.

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11. The method according to any one of claims 8 to 10 in which, in said step of forming one or more waveguide cores, a plurality of said waveguide cores are formed and a cavity is defined between said waveguide cores,

said step of forming said coupling spot being performed after said step of forming the waveguide cores, and comprising depositing material into said cavity.

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12. The method according to any one of claims 8 to 11, wherein said cladding layer has a thickness of at least about $5\ \mu\text{m}$.

13. The method for fabricating an optical coupling structure according to any one of claims 8 to 12, wherein said cladding layer is formed by a spin-coating technique.

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14. The method for fabricating an optical coupling structure according to any one of claims 8 to 12, wherein said cladding layer is formed by a bar-coating technique.

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15. The method for fabricating an optical coupling structure according to any one of claims 8 to 14, wherein said waveguide core is formed by a spin-coating technique.
16. The method for fabricating an optical coupling structure according to any one of
5 claims 8 to 14, wherein said waveguide core is formed by a photolithographic technique.
17. The method for fabricating an optical coupling structure according to claims 9, or any one of claims 10 to 16 when dependent upon claim 9, wherein said first reflection mirror is formed using a photolithographic technique followed by a metal patterning
10 technique.
18. The method for fabricating an optical coupling structure according to claim 17, wherein said metal patterning technique is a metal lift-off process.
- 15 19. The method for fabricating an optical coupling structure according to any one of claims 9, or any one of claims 10 to 16 when dependent upon claim 9, wherein said first reflection mirror is formed using a shadow mask deposit technique.
20. The method for fabricating an optical coupling structure according to claim 10, or
20 any one of claims 11 to 19 when dependent upon claim 10, wherein said second reflection mirror is formed using a shadow mask deposit technique.