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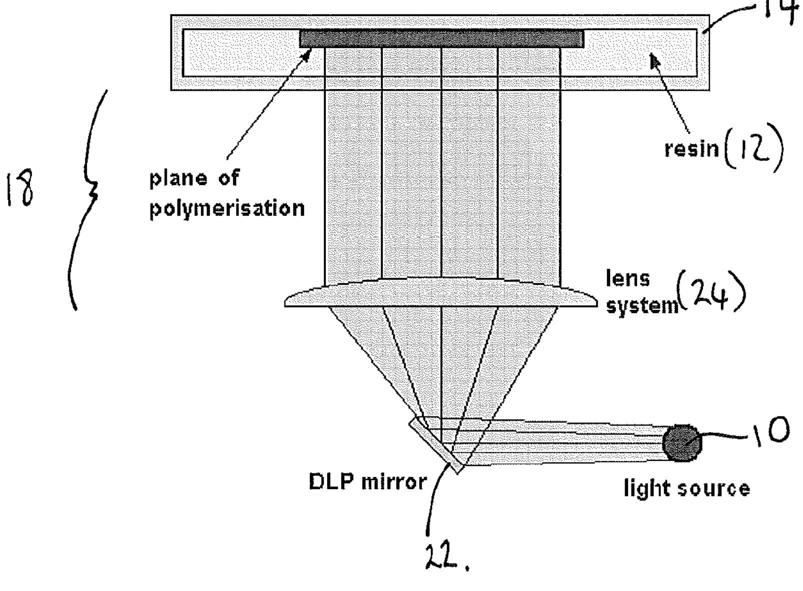
(54) **Title**: THREE-DIMENSIONAL OPTICAL AND MATERIAL STRUCTURES

Figure 2a



(57) **Abstract**: A method and apparatus for manufacturing a structure (40) using stereolithography comprising developing design data comprising physical characteristic data and compositional data for the structure, and controlling an excitation controlling element (22) and an excitation means (10) to cause polymerisation of a photo - reactive resin (12) in a controlled manner in dependence on the physical characteristic data and the compositional data.

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Three-Dimensional Optical and Material Structures

Description

The present invention relates to a method and apparatus for manufacturing three-dimensional (3D) structures. In particular the present invention relates to a method and apparatus for manufacturing 3D optical structures using a modified stereolithography process.

One of the main driving forces for integrated techniques is to produce small reproducible structures and devices that perform optimally in a given range of applications. Generally speaking, this approach has been applied to silicon and similar materials for the purpose of producing semiconductor devices such as processors in computers, radio systems, and so on.

A particularly important development is that of integrated optics and related structures that are used for routing, collecting, modulating, processing or distributing visible or near infrared wavelengths. These are important in the modern communications infrastructure because of the extensive use of optical fibre communication channels in carrying the world's internet traffic, commercial information, and data of many types such as financial information.

For some time there has been interest in three-dimensional (3D) structures that can be used alongside the fibre infrastructures. There is also interest in optical structures for energy collection, as used in photovoltaic cells, and sensors using visible or infrared light, as example parts of the electromagnetic spectrum. Such structures are also useful for the lenses of miniatures cameras, such as are used in mobile phones, and also surveillance and military applications.

A further use for 3D optical structures in particular is the concept of optical computing, in which light or energy is guided and/or switched on or off or modulated in an analogue form, in a manner which represents information flow through or along the structures, and which enable mathematical, computational or other processes, such as signal processing, to be performed.

Control of material properties, such as refractive index, absorption, dielectric constant and physical density, also leads to applications in the area of radio communications, signal processing, transducers, and acoustic systems for imaging and sensing.

Known manufacturing techniques for fabricating optical devices and other structures include: bulk machining techniques, such as grinding lenses; precision moulding to create aspheric surfaces; and planar technological methods to produce thin film devices. These processes generally produce components which require assembly into a system.

Known fabrication methods for creating 3D structures for radio frequency and acoustic systems also require energy-consumptive processing, and are time-consuming to manufacture.

Furthermore, there are limitations as to the complexity of the structures which can be made using existing techniques.

According to one aspect of the invention there is provided a method of manufacturing a structure using stereolithography comprising: developing design data comprising physical characteristic data and compositional data for the structure; and controlling an excitation controlling element and an excitation means to cause polymerisation of a photo-reactive resin in a controlled manner in dependence on the physical characteristic data and the compositional data.

Physical characteristic data in this sense means the physical layout data or geographic shape data regarding the structure being made. The structure is typically split into a plurality of layers and each layer has a plurality of voxels defining a volume. The compositional data comprises data specifying the material properties and composition of material within the structure. Again, typically, this may be defined for each of the plurality of voxels or for a group of voxels.

Preferably, the controlling step comprises controlling the excitation controlling element and the excitation means in accordance with one or more exposure parameters selected from the group comprising: light intensity, wavelength, exposure duration, and beam shape.

In a preferred embodiment, the method may further comprise creating the design data for the structure to correspond to a set of requirements for physical and material properties of the structure, and determining the exposure parameters in accordance with the set of requirements.

Optionally, the method further comprises determining the exposure parameters in accordance with one or more environmental factors, the one or more environmental factors being selected from the group comprising: material composition of the photo-reactive resin; type of excitation means; temperature of the photo-reactive resin; chemical layout of the photo-reactive resin; layer depth; degree of focussing of the excitation means; and age of resin.

Preferably, the determining step comprises retrieving the exposure parameters from a look-up table in response to the set of requirements.

In a preferred embodiment, the determining step comprises retrieving the exposure parameters from a look-up table in response to the one or more environmental factors.

Optionally, the compositional data corresponds to a set of requirements for the material properties of a portion of the structure, and the material properties of the portion comprise one or more of the group selected from: refractive index, dielectric constant, hardness, density and material composition of the polymerised structure.

Preferably, the method further comprises incorporating the exposure parameters into the design data.

In a preferred embodiment, the method may further comprise introducing one or more compounds to the photo-reactive resin, prior to polymerisation, to cause the material properties of the structure to correspond to the set of requirements for the material properties of the structure, the compositional data including instructions relating to the introduction of the one or more compounds.

Optionally, the method may further comprise selecting the one or more compounds from the group comprising: conductive, ceramic, and magnetic particles.

According to another aspect of the invention there is provided an apparatus for producing a structure using stereolithography comprising: a resin tray containing a photo-reactive resin; an excitation means; and an excitation controlling element, wherein the excitation means and the excitation controlling element are arranged to cause polymerisation of the photo-reactive resin in a controlled manner in dependence on a set of requirements for physical and material properties of the structure.

In a preferred embodiment, the excitation controlling element is arranged to expose the photo-reactive resin to the excitation means through a bottom portion of the resin tray, the bottom portion of the resin tray being transparent to electromagnetic radiation produced from the excitation means.

Advantageously, the stereolithography is arranged to be performed upside down in order to provide fine control over the depth of new layers as they are polymerised. In addition, this arrangement minimises disturbances to the resin during the polymerisation process and so minimises unwanted variations to the physical and material properties of the cured resin.

Preferably, a build controller is arranged to control the excitation controlling element and the excitation means in accordance with one or more exposure parameters selected from the group comprising: light intensity, wavelength, exposure duration, and beam shape.

Optionally, a design controller is arranged to determine the exposure parameters in accordance with the set of requirements for physical and material properties of the structure, and to create design data for the structure corresponding to the set of requirements; and the exposure parameters.

Preferably, the excitation means is one or more light sources selected from the group comprising: a light emitting diode, a laser, and an incandescent light bulb.

In a preferred embodiment, the light source is combined with a pixellated imaging device to produce an interrupted image on a surface of the photo-reactive resin such that the structure is a diffraction grating.

In a preferred embodiment, the apparatus is configured to create a structure selected from the group comprising: a 2D diffraction grating, a 3D diffraction grating, graded index optical or infrared (GRIN) lens, a dielectric lens, a multi-layer data recording disk, a multi-layer optical memory, a holographic data storage device; a smart card comprising a hologram or watermark; a 2D optical circuit; a 3D optical circuit; and integrated optical and electrical circuit; a monolithic optical microwave integrated circuit; and a sound distribution circuit comprising acoustic paths for the transmission of ultrasound or audio frequencies.

Preferably, the structure may be a diffraction grating suitable for wavelength division multiplexing in optical fibre communication channels or free-space optical communication channels.

According to another aspect of the invention there is provided a computer-aided design software program arranged to perform a method of modified stereolithography as described herein.

According to another aspect of the invention there is provided a computer-aided design software program arranged to control the apparatus performing the method of modified stereolithography as described herein.

Advantageously, the invention provides a process for fabricating integrated optical structures more quickly and more efficiently that traditional manufacturing techniques which required glass or polymer materials to be heat treated.

In addition, fine control of the material processing, and therefore of the material characteristics is possible by accounting for environmental factors of a stereolithographic process. This fine control means that complex 3D structures and systems can be produced, many of which cannot be produced by any other method.

Detailed embodiments of the invention will now be described with reference to the drawings in which:

Figure 1a is a side view of a known stereolithographic apparatus used for the creation of 3D physical structures;

Figure 1b is an expanded view of a portion of Figure 1a showing a resin tray, build platform and 3D structure in greater detail;

Figure 2a is a side view of a modified stereolithographic apparatus of one embodiment of the present invention;

Figure 2b is an expanded view of a portion of Figure 2a showing a resin tray, build platform and 3D structure in greater detail;

Figure 3a is a perspective view of a simple 3D structure showing a plurality of layers and voxels;

Figures 3b to 3d are 2D representations of each of the layers of the simple 3D structure of Figure 3a;

Figure 4 is a flowchart of the method steps of a design process according to one embodiment of the present invention;

Figure 5 is a flowchart of the method steps of a build process according to one embodiment of the present invention;

Figure 6 is a schematic diagram showing the correlation between a spatially-modulated light pattern and refractive index;

Figure 7 is a schematic diagram showing a diffraction grating produced according to one embodiment of the present invention and using the light pattern shown in Figure 6;

Figure 8 is a cross sectional view of a Gradient Index Lens (GRIN);

Figure 9 is perspective view of a multiple layer memory disk;

Figure 10 is perspective view of a 3D hologram/memory array and a planar view of a single layer within the 3D hologram/memory array;

Figure 11 is perspective, exploded diagram of a smart card with an internal hologram layer;

Figure 12 is a top view of two separate layers of an optoelectronic integrated circuit with integral light guides;

Figure 13 is a perspective, exploded diagram of a two layer optoelectronic IC;

Figure 14 is a perspective, exploded diagram of a Microwave Optical Monolithic Integrated Circuit (MOMIC);

Figure 15 is a schematic side view diagram of a diffraction grating used in a Wavelength Division Multiplexed (WDM) optical communication system using optical fibre; and

Figure 16 is a schematic side view diagram of a diffraction grating used in a WDM optical communication system using free space optical communications (otherwise known as FSO communications).

The present invention uses a modified stereolithographic technique to fabricate optical structures. Such structures may be used in a variety of applications as described below.

Stereolithography (SL), also known as microstereolithography (MSL), is a rapid prototyping technology in which the automatic construction of physical objects is achieved using additive manufacturing technology. It is referred to as an additive layer process in which a three-dimensional (3D) structure is formed by creating multiple two-dimensional (2D) layers (or slices) of the 3D structure. Each layer is manufactured as an extruded 2D structure, one after another until the final object is formed.

This manufacturing process is based on the polymerisation of a photo-reactive resin, whereby a liquid is converted into a solid through exposure to an excitation means, such as a light source. During polymerisation, light reacts with a photo-initiator to produce free radicals. These radicals react with reaction sites on the monomer causing polymer chains to bind together or cross-link.

The polymerisation process can be achieved using a number of different light sources, for example LEDs, lasers, and incandescent light bulbs. Thermal methods may also be used to generate or enhance polymerisation in suitable materials.

A typical setup for MSL material fabrication is shown in Figures 1a and 1b. As shown, a light source 10 is used to illuminate a photo-reactive resin 12. The liquid resin 12 is held in a resin tray 14, having a bottom portion 14a and wall portions 14b. Within the resin tray is a build platform 16. There is an air gap 18 between the light source 10 and the surface of the photo-reactive resin 12a. New layers 20 of the structure are built nearest to the surface of the photo-reactive resin 12.

The build platform 16 is manoeuvrable within the resin tray 14 in at least a vertical direction. The build platform 16 is configured to control the volume of resin between the light source10 / air gap 18 and the build platform 16 or a previously cured layer 20. This provides control over the thickness **d** of each layer during the fabrication process.

A light controlling element 22 is used to direct a pattern of light 23 towards the photo-reactive resin 12. The light controlling element 22 may be one or more of a mask, an LCD panel, or system using micro-mirrors, as within a DLP (Digital Light Processing) mirror system.

A DLP mirror 22, as shown in Figure 1a creates the pattern of light 23 which passes through a lens system 24 in order to focus an image within the photo-reactive resin or materials. The image may be focused onto a substrate surface 26 situated on the build platform 16 or onto a previously deposited plane layer.

Advanced computer-aided design (CAD) software is used to create the designs and in turn is used during the fabrication process to control the fabrication parameters, such as the excitation means 10 and the build platform 16. The CAD software mathematically slices the computer model of the object into a plurality of thin layers 201, 20b, 20c. The process then builds the object layer by layer starting with the bottom layer on the build platform as it is lowered in the direction of arrow X, further into the resin tray, after solidification/curing of each layer.

Stereolithography (SL) and microstereolithography (MSL) as described above have previously been used to fabricate prototype parts far quicker than traditional prototyping techniques. However, there are many limitations to stereolithography. As described above this process has not previously been suitable for fabricating complex models or parts. This means that its use for certain applications has not previously been feasible.

The inventors of the present invention have appreciated that modifications can be made the stereolithography process in order to give an increased degree of control over material properties of the structure being fabricated. In particular, the inventors have appreciated that it is possible to tailor specific material properties of the 3D structure being manufactured such that the modified stereolithography technique can be extended to manufacture optical, optoelectronic, and hybrid structures more quickly and more cheaply than through existing manufacturing techniques.

Examples of the material properties of a 3D structure which may be tailored according to one embodiment of the present invention include: refractive index, hardness, dielectric constant, opacity, and actual material composition. For the latter material property may be tailored through inclusion of conductors such as Tungsten or Copper powders to provide electrical properties; ceramics to provide favourable dielectric properties in microwave circuits, magnetic materials, and/or piezoelectric materials to allow ultrasound to be generated and channelled. Tailoring the material properties of the structure in this manner permits complex 3D structures to be created. Tailoring the material properties can also be used to affect the optical polarisation, and reflectivity at an interface, as required. However, the material/compositional properties are not easily controllable because of the large number of environmental factors which affect the material properties of the resin both before and during the polymerisation process. These include:

- material composition of the resin;

- type of light source used;
- temperature of resin;
- chemical layout of resin;
- layer depth
- degree of focussing of the light; and
- age of resin.

The above list is not exhaustive, and other factors may also affect the material properties of the 3D structure. It is to be appreciated that in existing SL and MSL arrangements, the material properties of the structure have not previously been noted as being of a concern to the designers and manufacturers. This is because primarily the purpose of SL and MSL manufacturing has been to create a prototype and as such it is the physical dimensions of such a structure which were of primary concern. The modified stereolithography process according to one embodiment of the invention is arranged to define the physical dimensions of the structure and the material properties of the polymer material, either simultaneously or sequentially.

In addition to the list of factors which affect the material properties of the structure, the polymerisation process can be disturbed due to ripples/disturbances in the resin as a result of vibration. These disturbances simultaneously cause changes in the depth of the polymerised/cured layer, which in turn, results in structural and material changes in the cured resin of the 3D structures. For these reasons the configuration of the equipment shown in Figures 1a and 1b is not optimal. Modifications may be made to the configuration of Figures 1a and 1b in order to minimise these disturbances and/or to improve control of the layer depth of the cured resin.

One such modification is described with reference to Figures 2a and 2b, showing the stereolithographic process being arranged to be carried out “upside down”. Similar components are given the same reference numerals as Figures 1a and 1b above.

As shown in Figures 2a and 2b, the light source is arranged to direct light into the resin tray from below. The resin tray, which is transparent to the light source, contains the photo-reactive resin as before, but now the light is transmitted through the bottom portion of the resin tray. The build platform, as before, also moves in at least the vertical direction. Initially, the build platform is positioned close to the bottom portion of the resin tray and as the polymerisation process builds layer upon layer of the 3D structure, the build platform is raised away from the bottom portion of the tray in the direction of the arrow. As the build platform16 is raised in the direction Y after polymerisation of each layer 20a, 20b, 20c, resin 12 is caused to fill the gap between an inner surface of the bottom portion 14a of the resin tray and the newest polymerised layer 20a. The first polymerised layer 20 c adheres to a substrate surface 26 attached to the build platform 16, and subsequent layers 20b, 20a adhere to previously built layers. The depth **d** of any new layer 20a is defined by the gap between the substrate or previously built layer and the inner surface of the bottom portion 14a of the resin tray 14, and is controlled by controlling the vertical movement of the build platform 16.

As before, the light controlling element 22 is used to direct a pattern of light 23 towards the photo-reactive resin 12. The light controlling element 22 may be one or more of a mask, an LCD panel, or system using micro-mirrors, as within a DLP system.

The above modification to the stereolithographic process provides a mechanism for more accurately controlling and modifying the material properties of the 3D structure.

One advantage of this technique ensures precise control of the depth of each new layer, because a fixed distance **d** can be maintained between the substrate/ previous layer of induced polymerisation and the top of the new layer (i.e. the inner surface of bottom portion of resin tray). This minimises any structural and material changes caused by disturbances to the resin during the polymerisation process.

In addition to controlling the depth of newly formed layers, the stereolithographic equipment may be arranged to control other parameters which have been determined to alter the material properties of the polymerised resin.

The inventors have appreciated that fine control of one or more exposure parameters comprising: wavelength, intensity and duration of the exposure process and beam shape of the incident light on the surface of the resin, can be used to tailor the material properties of the structure as desired. For example, the refractive index has been identified by the inventors as being higher for a photopolymer which has been less exposed to the curing illumination, and lower where it has been more exposed. Therefore, controlling these parameters provides a mechanism for tailoring the material, including optical, properties of the 3D structure. Various applications for this technique in 3D optical structures are described later, after a description of the operation of the design and fabrication processes.

Stereolithography requires the structure to be broken down into individual layers. The modified stereolithographic process of one embodiment of the present invention requires the structure to be broken down into layers and within each layer, voxels.

Figure 3a shows a simple structure 40 of three layers 20a, 20b, 20c . A voxel is akin to a three-dimensional pixel, and a single voxel 42 is shown greyed out in Figure 3a. According to one embodiment of the present invention, the light controlling element 22 is arranged to control the light directed to each voxel in each layer. As described above a DLP mirror may be used, and is able to direct a desired pattern of light onto the resin to form each layer. For example, Figures 3b to 3d show the 2D patterns for each layer 20c, 20b, 20a of the structure 40 of Figure 3a. Other light control means, for example, masks, may be used for the same purpose.

Controlling the light in this manner enables the overall control mechanism effectively to switch voxels “on” or “off”. In other words, if a voxel is switched on, light is directed toward that voxel, polymerisation takes place and that voxel solidifies, becoming part of the solid 3D structure. Alternatively, if a voxel is switched off, no light is directed to the voxel and polymerisation in that voxel does not take place leaving a gap in the 3D structure.

Such fine control of individual voxels in the 3D structure enables further control of the material properties of each voxel.

Figure 4 shows a flowchart of the method steps for the design process for a desired 3D structure. As described above, this design process is carried out using CAD software. The use of such suitable CAD software is within the skilled persons skill set. The requirements for the desired structure will be understood by a person skilled in the art, and some examples of the requirements and structures are described later in greater detail.

Initially, the design process requires the designer or automatic process to specify, at step 101, key design constraints for the structure being designed. These may include the type of resin to be used, and the physical dimensions of the structure, including the depth **d** of each layer. Templates may be utilised to assist in this process. Details regarding these design constraints may be stored for later use in the design and build processes.

Thereafter, the design layout for a first layer is determined, at step 102. This design layout is the determination of the required light pattern for the structure being designed, similar to the examples shown in Figures 3b to 3d.

The required material or optical properties for each voxel in the layer are specified, at step 103. In other words, in relation to the purpose and function of the overall design of the 3D structure, a set of material and physical requirements will be understood. These requirements are broken down to specify the required material properties for each voxel or group of voxels.

In order to ensure that the required material properties are achieved during the build process, it is necessary to control one or more of the exposure parameters (wavelength, intensity and duration). The exposure parameters are determined, at step 104. According to one embodiment, the exposure parameters are determined using a look-up table. The look-up table represents a correlation between the desired material properties and exposure parameters, while taking the environmental factors into consideration.

In one embodiment, the desired material properties and environmental factors may be input to the look-up table in order to retrieve the exposure parameters. In an alternative embodiment, in addition to the desired material properties and environmental factors, one or more of the exposure parameters may be predetermined (for example to accord with a particular light source being used) such that the look-up table is arranged to provide the exposure parameter(s) not predetermined.

The look-up table of one embodiment populated with result data from a series of experiments using test samples. Test samples are created for a variety of different environmental factors as above, and are exposed according to different exposure parameters. The material properties for the resulting cured structure are determined and are used to populate the look-up table.

For example, in relation to variations in the duration exposure parameter, a plurality of test samples for resin type A, light source B, temperature C, etc are each exposed for various durations (e.g. 1/10th of a second, 2/10ths of a second, 3/10ths of a second etc) at a intensity X, and wavelength Y. The experiments may then be varied for different intensities and wavelengths.

The material properties of each of the plurality of cured test samples are determined and stored in the look-up table accordingly.

Retrieving data from the look-up table will be a process which is understood by the skilled person. For example, a look-up table retriever module, within a controller of the design process is arranged to extrapolate the necessary exposure parameters for given environmental factors.

Returning to Figure 4, the determined exposure parameters are incorporated, at step 105 into design data for the layer. The design data includes the design layout and the exposure parameters for each voxel, or group of voxels, within the layer.

When the design data for the layer is complete, it is determined, at step 106, if the layer being designed is the last layer. If it is the last layer, the design process is completed. If is it not the last layer, the layer number is incremented, at step 107, and the process returns to step 102 to design the next layer. The process is repeated until each layer is designed.

Figure 5 shows a flowchart of the method steps for the build process of a designed 3D structure. As described above, this build process is also carried out using CAD software.

At the start of the build process, a build controller receives or modifies design data for a 3D structure, at step 201. The design data may be determined as described in Figure 4, or any other suitable design process.

In one embodiment, the received design data may be complete taking into account all environmental factors to be specified and adhered to during the build process. In an alternative embodiment, skeleton design data may stipulate key design data in relation to the structure and material properties of the design and the exposure parameters may be determined during the initial stages of the build process. The exposure parameters may then be tailored to the particular equipment being used for the build process. In this way, skeleton design data may be used in a plurality of different build machines and can be completed to accord to specific environmental factors (for example wavelength) of a particular machine.

In addition, certain environmental factors, for example temperature, may vary during the build process, and a feedback loop may be provided to enable alterations to the exposure parameters to take account of variations in temperature during the build process.

The build process is initialised at step 202, in relation to the resin, substrate, specified environmental factors and exposure parameters.

The light controlling element is configured, at step 203, to deliver a pattern of light in accordance with the design layout for the first layer. The light controlling element is further configured, at step 204, to deliver light exposure in accordance with the exposure parameters in the design data.

After the determined exposure duration expires, it is determined, at step 205, if the newly cured layer is the last layer, in which case the controller exists this phase of the build process. If the current layer is not the last layer, the layer number is incremented, at step 206, and the build platform is moved up by depth d, at step 207. Control then returns to step 203 to build the next layer. The process is repeated until all the layers have been built.

A person skilled in the art will appreciate the vast plurality of different photo-reactive resins which may be suitable for the above process. A desired resin may be determined for a particular application. Resins may be designed or modified from existing recipes in order to create a preferred resign for the application. For example, changing just one linker on the backbone of a resin may result in a whole new resin. Most resins use either an acrylic or epoxy group of linkers which perform the cross-linking of the polymer chains during the polymerisation process. This cross-linking is one factor in the material properties of the cured resin.

All acrylate groups photocure (one example is superglue) and convert into acrylic. Using this principle a resin may be designed as a combination of a number of different acrylates with a filler (for example acrylic acid) and photo-initiator to ensure the curing process starts at higher light frequencies and a photoinhibitor to provide layer control (i.e. to ensure that only a desired depth of resin is polymerised at a time). A person skilled in the art will appreciate that there are many different options of the above properties which are available and which may be suitable for a specific application, and will be able to make a necessary design choice. For example, the acrylate groups need to be chosen to be transparent at the required frequencies of light that are to be transmitted through it.

One example resin which may be suitable for required applications is a polyethylene glycol (PEG) resin with an acrylate linker group with between 1 and 6 linker sites per molecule. A person skilled in the art will appreciate that the upper number of linker sites in this example is not a limitation and that any suitable resin with the properties described above may be suitable.

Similar design choices may be made for wavelength and intensity of the light being used in the polymerisation process. In some cases, the wavelength of the light will be determined by the equipment being used. For example, desired results may be achieved using wavelengths in the visible and near ultraviolet spectrums, i.e. between approximately 200 and 750 nm. One particular light source (for example an LED) may provide light having a peak wavelength of around 365nm. A person skilled in the art will appreciate that the examples given above are not limitations of the design and build processes, and that suitable exposure parameters may be determined and/or modified during the design and build processes.

In relation to the intensity of the light, this too may be modified in accordance with a degree of focussing of the light source by the light controlling element. It is to be appreciated that the intensity of a focussed light is higher that that of a light which is diffused in some manner. In relation to the DLP mirror chip, focussing/diffusing the light source may be controlled by slight variations in the tilt of the mirrors and as such provides a mechanism for controlling the intensity of the light source.

The duration of the exposure may vary from between 1/100th of a second to several seconds per layer. An exposure of ½ a second may be a typical duration for a particular resin, wavelength, optical intensity etc.

The beam shape of the incident light may be varied to change the sharpness of the boundaries between the voxels. For example, a Gaussian intensity distribution across the profile of the voxel will produce regions of tapered refractive index or other material properties at the edges/sides of the voxel, whereas a rectangular intensity profile, uniform across the profile of the voxel would result in the sharpest and most abrupt transitions between voxels.

As described above the exposure parameters are determined from a look-up table in connection with desired material properties and environmental factors. Examples provided above are non-limiting and serve to explain a range of typical values. The actual values are determined as part of the design process and even values outside the typical ranges may be suitable to achieve desired results.

Having described the principles behind the design and build processes, the following description details example applications for the method and apparatus of the present invention.

The deposition and illumination process of the modified stereolithographic process can be used to create a regular pattern of varying refractive index within an optically-transmitting polymer. When a light source is combined with a pixellated imaging device (for example an array of LEDs), a focussed image of an apparently uniform image field produces an interrupted image on the photopolymer substrate. This is because in between each pixel is a darker region, imperceptible to the naked eye. This causes variations in the light intensity as shown in Figure 6.

Variations in the light intensity cause periodic changes in refractive index induced by the modified stereolithographic process, and this produces a diffraction pattern as shown in Figure 6, where a low refractive index 50 corresponds with areas of high light intensity 52, and a high refractive index 54 corresponds with areas of low light intensity 56.

After the curing process, a coherent light source, such as a laser, may be used to illuminate a slab of the polymer which has been treated in the above manner. This is shown in Figure 7. As a result of the variations in refractive index, the coherent light shown through the slab causes a pattern which can be seen on the other side. This pattern is known as a diffraction grating and can be represented by the following equation:

$$\mathbf{g.\sin\theta = n\lambda}$$

where **g** is the element spacing (i.e. the distance between the dark regions), θ (theta) is the angle between the normal axis to the surface of a plane slab of the polymer material and the emergent beams, and **n** takes the value 0, 1, 2, ...

In one example, using an illumination wavelength of 630 nm, results in a diffraction pattern at 2 metres producing a spot spacing of approximately 8 cm. This translates to an illumination pixel spacing of around 15 μm (micrometers) for a typical sample. It should be noted that the diffraction grating produced by this process may be a 2-D grating, or a 3-D grating.

As described above, the structure and material properties induced through the modified stereolithographic process is adjustable according to the design data and exposure parameters in terms of light intensity, beam shape, duration of exposure, and material composition. Therefore, the designer is able to formulate a range of desired optical properties that can be made to vary spatially within an object.

The above process may be used in variety of applications, examples of which are described below.

1) Polymer GRIN (graded index) lenses: These are frequently fabricated from glass, and the refractive index varied with position by inducing chemical and/or thermal changes within the glass. They are used to focus light using flat surfaces and they can be easily mounted onto other components. Graded index optical fibres are also used to minimise dispersion in optical fibre communication systems. The structure is shown in Figure 8, and the refractive index profile is achieved by illuminating the centre either at less intensity for the same period of time as at the edges, or for less time at the edges but at constant intensity overall.

2) New types of CD/DVD data storage devices: Because the refractive index can be made to vary at different depths within an optically transparent a photo-reactive resin, it is possible to lay down data storage tracks either on the surface or within subsurface layers of a polymer. This advantageously increases the potential storage capacity of a DVD or CD substantially, leading to much improved storage media. The concept is shown in Figure 9. Data readout can be undertaken using techniques for “Blue-Ray” DVD disks, or depth from defocus imaging. A person skilled in the art will appreciate how this is achieved but may refer to webpage:

http://homepages.inf.ed.ac.uk/rbf/CVonline/LOCAL_COPIES/FAVARO1/dfdtutorial.html

published in June 2002 for more details.

3) Holographic data storage devices: The changes in refractive index are used to store data in a volume of polymer, and read out as a holographic storage medium. This leads to the realisation of 3D memory chips using optical and/or optoelectronic techniques, as shown in Figure 10. This realisation can be achieved at much higher manufacturing speeds than methods using heating, and can provide custom designs with rapid turn-around time, at low cost.

4) Embedded watermark images: The modified stereolithographic process is used to create patterns at a desired depth within the polymerised photo-reactive resin. These effectively could be embedded watermarks, either in a conventional manner as used on bank notes, or as an embedded hologram. This technique is suitable for use in credit cards and ID cards equally, and is shown in Figure 11.

5) New forms of optical fibre technology: The graded index capabilities lead to the possibility of creating optical fibre channels within solid polymer objects. For example, using the modified stereolithographic process described above it is possible to design and create optical communication channels between elements in 3D electronic circuits, as well as in other applications. An example is shown in Figure 12, where there are two layers, for simplicity. A person skilled in the art will appreciate that many more layers and more complex structures may be achieved using the processes described above. Optical channels are formed during the modified stereolithographic process to form interconnects between optical components, or optoelectronic components, designated X in Figure 12. In a similar manner it is possible to design in vertical optical pathways, designated A and B in Figure 12, which are like chimney structures, formed the same way as the optical channels to permit optical signals to travel between layers. A further example of a two-layer, 3D optoelectronic circuit is shown in Figure 13, showing in more detail a vertical optical pathway.

As with the horizontal optical pathways, the vertical ones do not have to go simply straight up or down, but can, by virtue of the flexibility of the modified stereolithographic process, take curved or diagonal paths. These optical pathways can also be supplemented by electrical or acoustic pathways, caused in the latter case by altering the exposure times so as to optimise the material density gradients.

A person skilled in the art will appreciate how electrical pathways may be implemented by embedding conducting nanoparticles in the polymer within in selected regions, using the modified stereolithographic process to define these regions. The combination of conducting pathways and optical pathways, interconnecting with optoelectronic and/or microwave devices can constitute a Microwave-Optical Monolithic Integrated Circuit, thereafter designated a MOMIC. This technique is illustrated in Figure 14.

6) Wavelength Division Multiplexing (WDM): This is a technique for transmitting multiple channels of information along a fibre at different optical wavelengths. According to one embodiment of the present invention, the modified stereolithographic process described above may be used to create a suitable diffraction grating for this purpose. In one embodiment this is achieved by using particular properties of a diffraction grating when implemented using a spatially-varying refractive index.

Alternatively, the modified stereolithographic process may be used in the design of a prism within the structure. This technique is illustrated in Figure 15 for an optical fibre communication system using three wavelengths.

Additionally, this same technique can also be configured for a free-space optical communication system or any other free-space optical structure where several different wavelengths are involved, as shown in Figure 16.

A person skilled in the art will appreciate how the structures of the above different applications may be designed. Knowledge of these design requirements is then used in the creation of the design layouts for each layer, and in the desired material properties of the voxels within each layer in order to achieve a desired 3D structure.

While the described processes for designing and building 3D structures using the modified stereolithographic process have utilised a look-up table, it is to be appreciated that this is not the only way in which the exposure parameters may be determined. For example, it is conceivable that the CAD software may be arranged to make decisions regarding required exposure parameters on the basis of an expected correlation between various environmental factors, exposure parameters and material properties. As such, controller modules within the CAD software may be arranged to calculate the required exposure parameters.

Claims

1. A method of manufacturing a structure using stereolithography comprising:

developing design data comprising physical characteristic data and compositional data for the structure; and

controlling an excitation controlling element and an excitation means to cause polymerisation of a photo-reactive resin in a controlled manner in dependence on the physical characteristic data and the compositional data.

2. The method as claimed in Claim 1, wherein the controlling step comprises controlling the excitation controlling element and the excitation means in accordance with one or more exposure parameters selected from the group comprising: light intensity, wavelength, exposure duration, and beam shape.

3. The method as claimed in Claim 2, further comprising:

creating the design data for the structure to correspond to a set of requirements for physical and material properties of the structure; and

determining the exposure parameters in accordance with the set of requirements.

4. The method as claimed in Claim 3, further comprising determining the exposure parameters in accordance with one or more environmental factors, the one or more environmental factors being selected from the group comprising: material composition of the photo-reactive resin; type of excitation means; temperature of the photo-reactive resin; chemical layout of the photo-reactive resin; layer depth; degree of focussing of the excitation means; and age of resin.

5. The method as claimed in Claim 3 or Claim 4, wherein the determining step comprises retrieving the exposure parameters from a look-up table in response to the set of requirements.

6. The method as claimed in Claim 4 or Claim 5, wherein the determining step comprises retrieving the exposure parameters from a look-up table in response to the one or more environmental factors.

7. The method as claimed in any one of Claims 3 to 6, wherein the compositional data corresponds to a set of requirements for the material properties of a portion of the structure, and the material properties of the portion comprise one or more of the group selected from: refractive index, dielectric constant, hardness, opacity, density and material composition of the polymerised structure.

8. The method as claimed in any one of Claims 4 to 7, further comprising incorporating the exposure parameters into the design data.

9. The method as claimed in any one of Claims 3 to 8, further comprising introducing one or more compounds to the photo-reactive resin, prior to polymerisation, to cause the material properties of the structure to correspond to the set of requirements for the material properties of the structure, the compositional data including instructions relating to the introduction of the one or more compounds.

10. The method as claimed in Claim 9, further comprising selecting the one or more compounds from the group comprising: conductive, ceramic, and magnetic particles.

11. An apparatus for producing a structure using stereolithography comprising:
a resin tray containing a photo-reactive resin;
an excitation means; and
an excitation controlling element,
wherein the excitation means and the excitation controlling element are arranged to cause polymerisation of the photo-reactive resin in a controlled manner in dependence on a set of requirements for physical and material properties of the structure.

12. The apparatus as claimed in Claim 11, wherein the excitation controlling element is arranged to expose the photo-reactive resin to the excitation means through a

bottom portion of the resin tray, the bottom portion of the resin tray being transparent to electromagnetic radiation produced from the excitation means.

13. The apparatus as claimed in Claim 11 or Claim 12, further comprising a build controller arranged to control the excitation controlling element and the excitation means in accordance with one or more exposure parameters selected from the group comprising: light intensity, wavelength, exposure duration, and beam shape.

14. The apparatus as claimed in any one of Claims 11 to 13, further comprising a design controller arranged to determine the exposure parameters in accordance with the set of requirements for physical and material properties of the structure, and to create design data for the structure corresponding to the set of requirements; and the exposure parameters.

15. The apparatus as claimed in any one of Claims 11 to 14, wherein the excitation means is one or more light sources selected from the group comprising: a light emitting diode, a laser, and an incandescent light bulb.

16. The apparatus as claimed in Claim 15, wherein the light source is combined with a pixellated imaging device to produce an interrupted image on a surface of the photo-reactive resin such that the structure is a diffraction grating.

17. The apparatus as claimed in any one of Claims 11 to 16 configured to create a structure selected from the group comprising: a 2D diffraction grating, a 3D diffraction grating, graded index optical or infrared (GRIN) lens, a dielectric lens, a multi-layer data recording disk, a multi-layer optical memory, a holographic data storage device; a smart card comprising a hologram or watermark; a 2D optical circuit; a 3D optical circuit; and integrated optical and electrical circuit; a monolithic optical microwave integrated circuit; and a sound distribution circuit comprising acoustic paths for the transmission of ultrasound or audio frequencies.

18. The apparatus as claimed in Claim 17, wherein the structure is a diffraction grating suitable for wavelength division multiplexing in optical fibre communication channels or free-space optical communication channels.

19. A computer-aided design software program arranged to perform the method of Claims 1 to 10.

20. A computer-aided design software program arranged to control the apparatus of Claims 11 to 18.

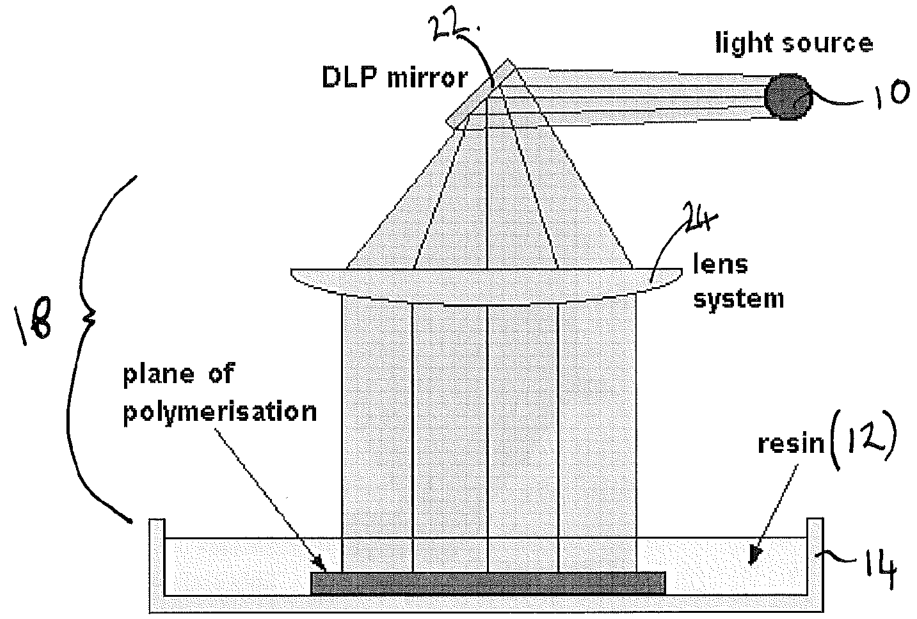


Figure 1a

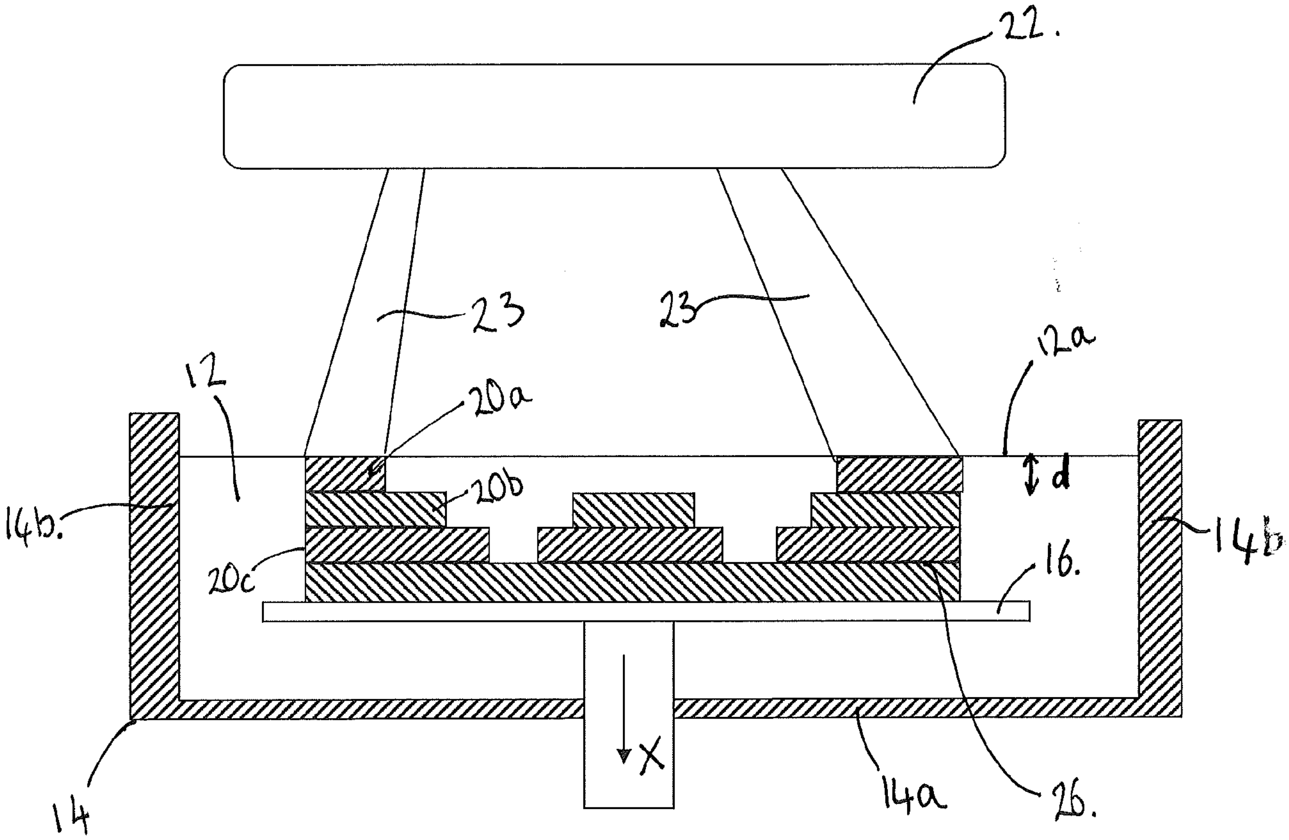


Figure 1b

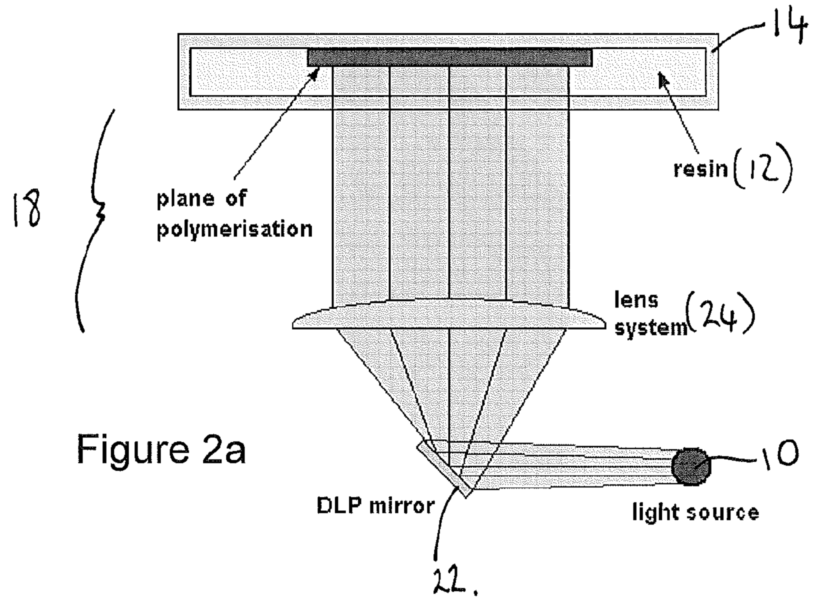


Figure 2a

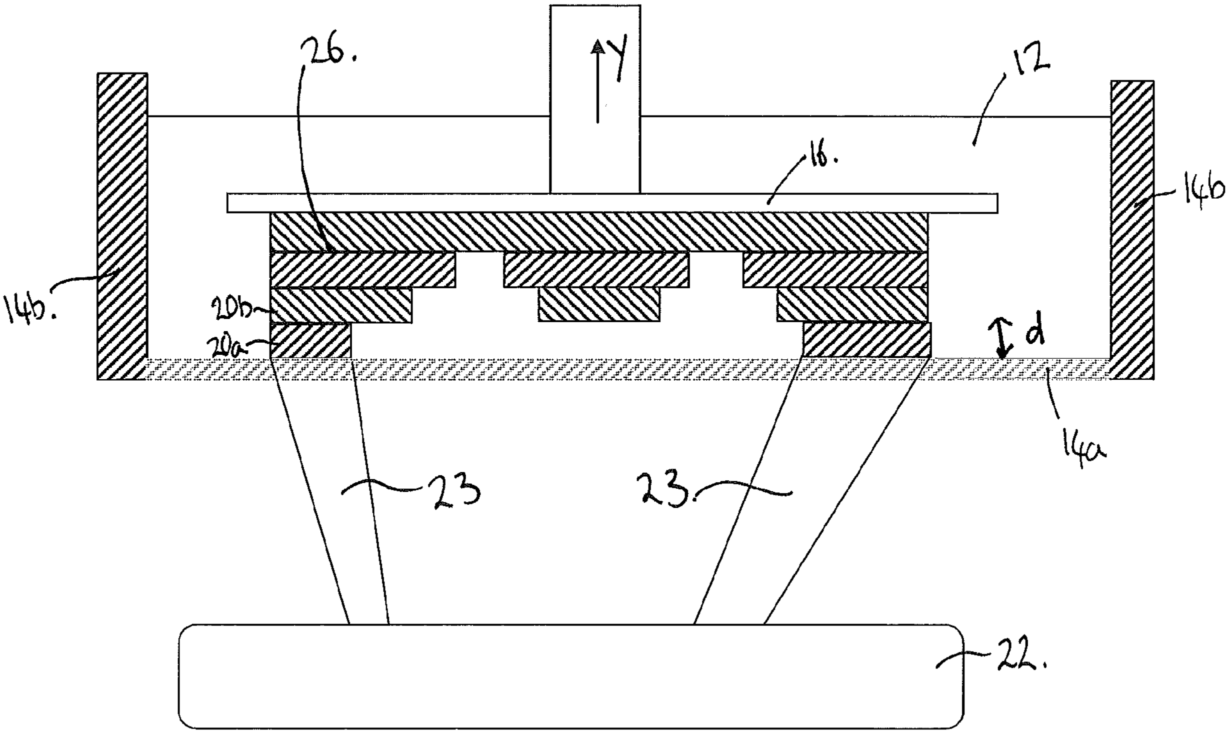


Figure 2b

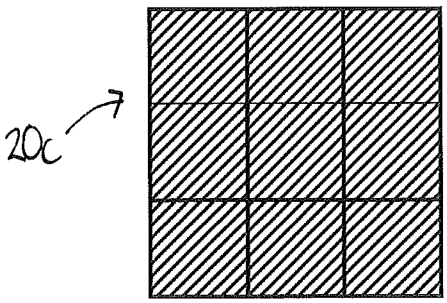


Figure 3b

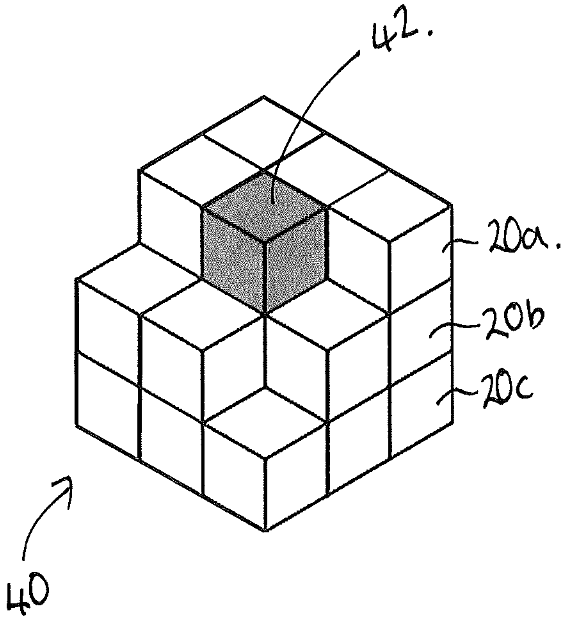


Figure 3a

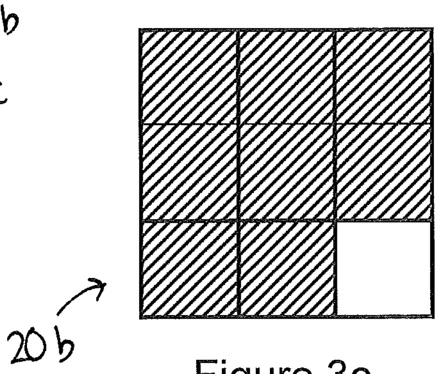


Figure 3c

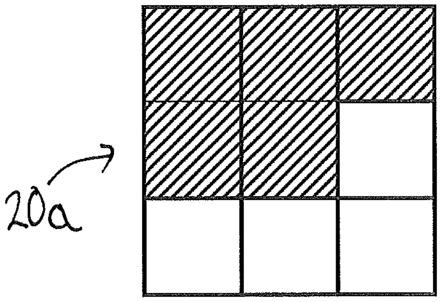


Figure 3d

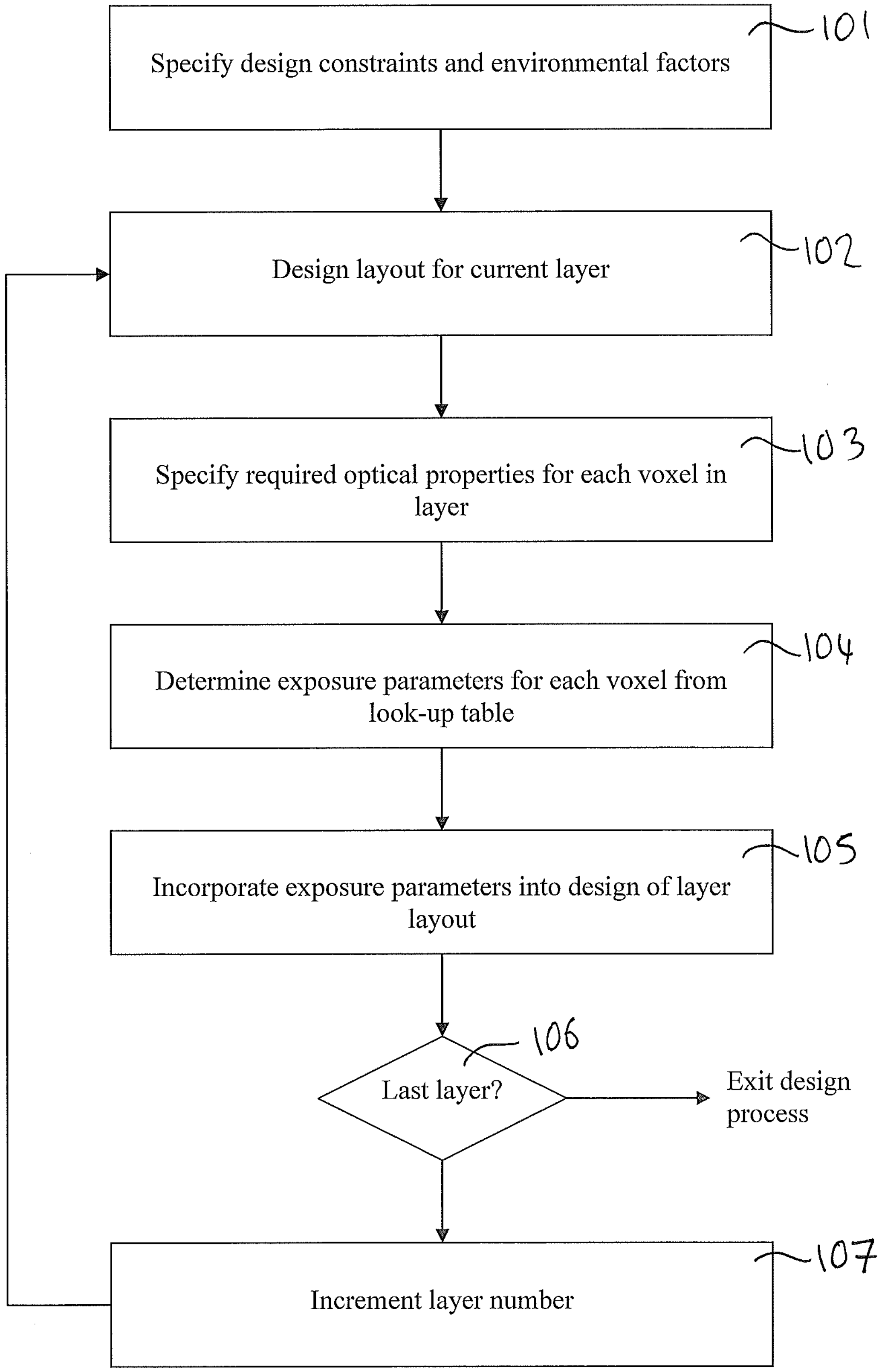

Specify design constraints and environmental factors
101
Design layout for current layer
102
Specify required optical properties for each voxel in layer
103
Determine exposure parameters for each voxel from look-up table
104
Incorporate exposure parameters into design of layer layout
105
106
Last layer?
Exit design process
Increment layer number
107

Figure 4

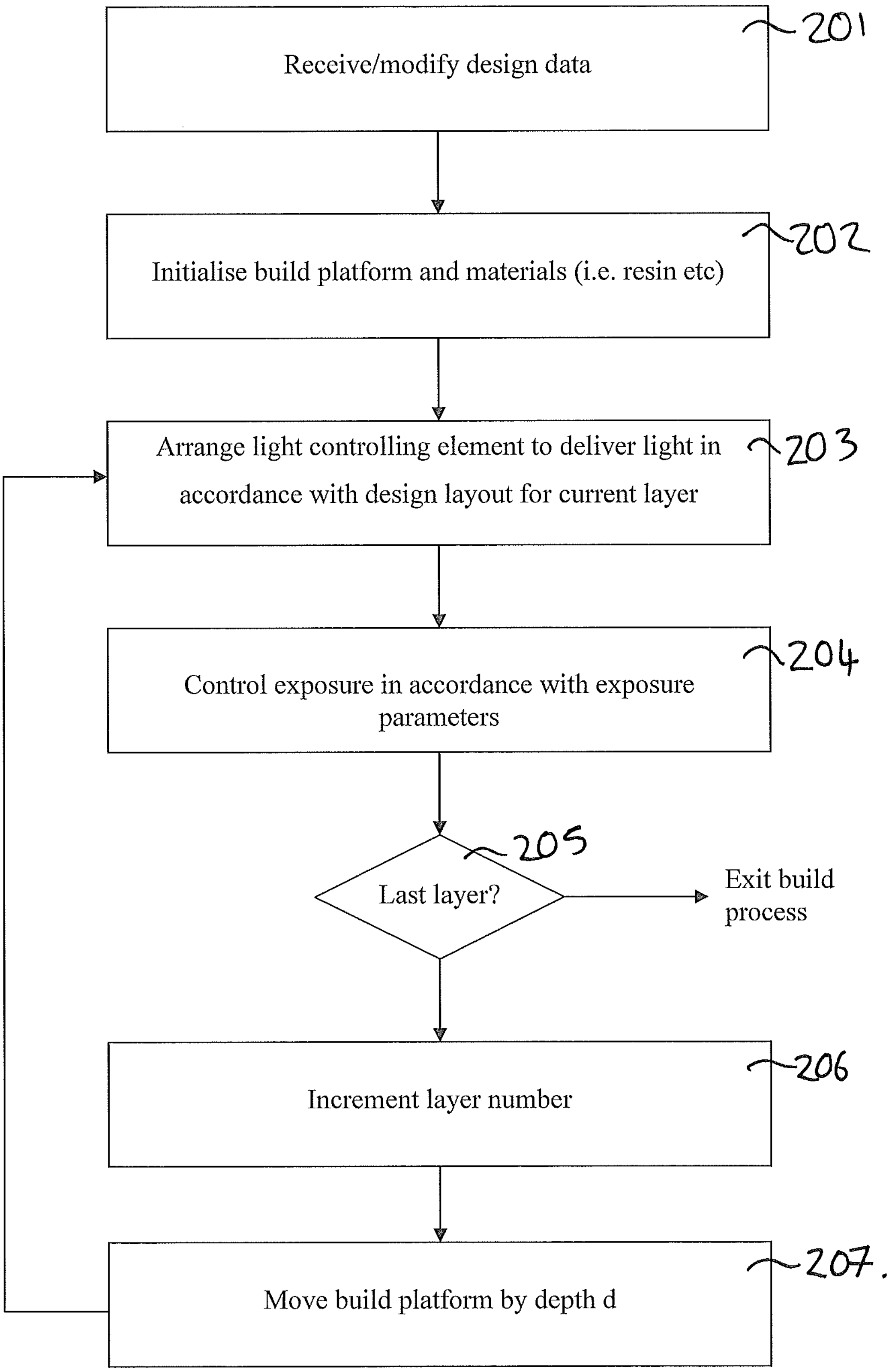

Receive/modify design data
201
Initialise build platform and materials (i.e. resin etc)
202
Arrange light controlling element to deliver light in accordance with design layout for current layer
203
Control exposure in accordance with exposure parameters
204
Last layer?
205
Exit build process
Increment layer number
206
Move build platform by depth d
207.

Figure 5

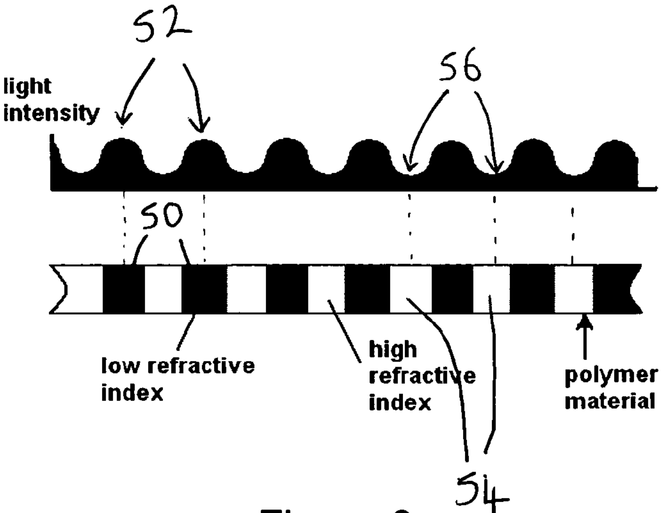


Figure 6

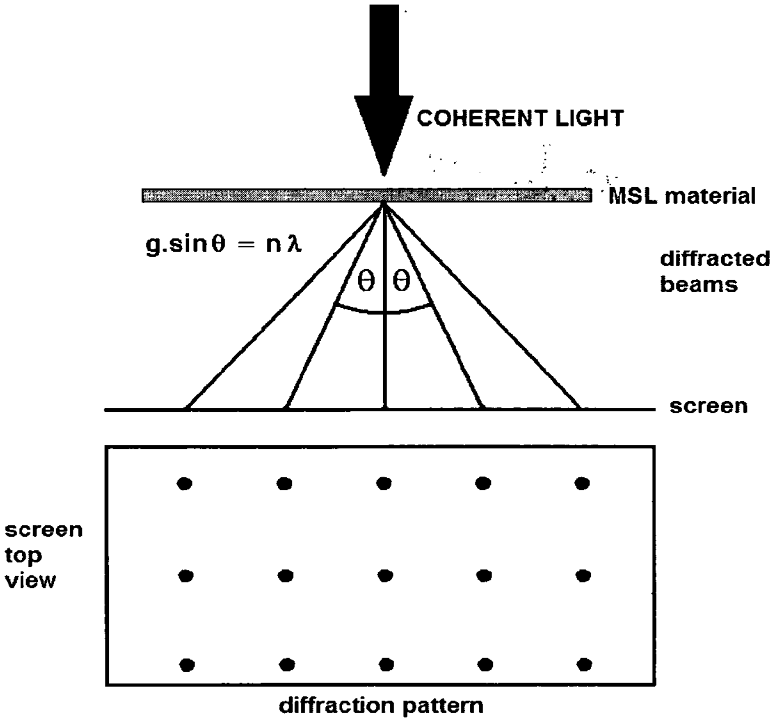


Figure 7

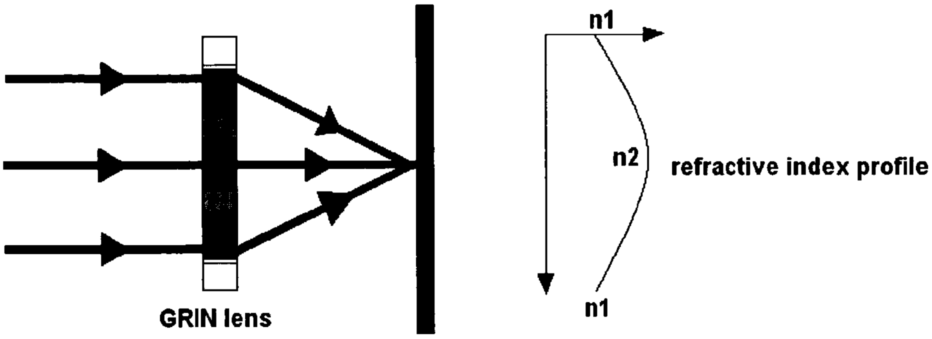


Figure 8

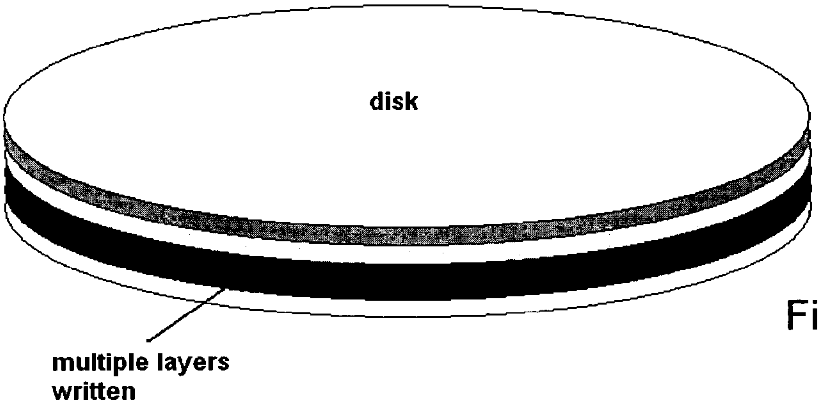


Figure 9

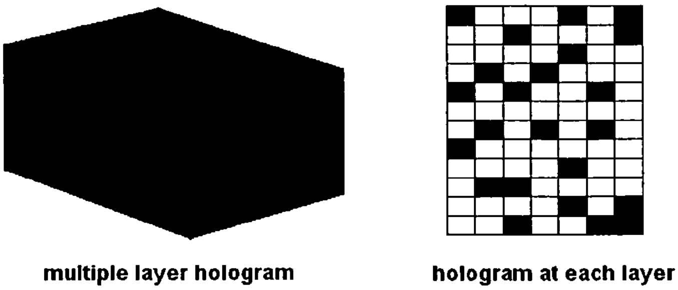


Figure 10

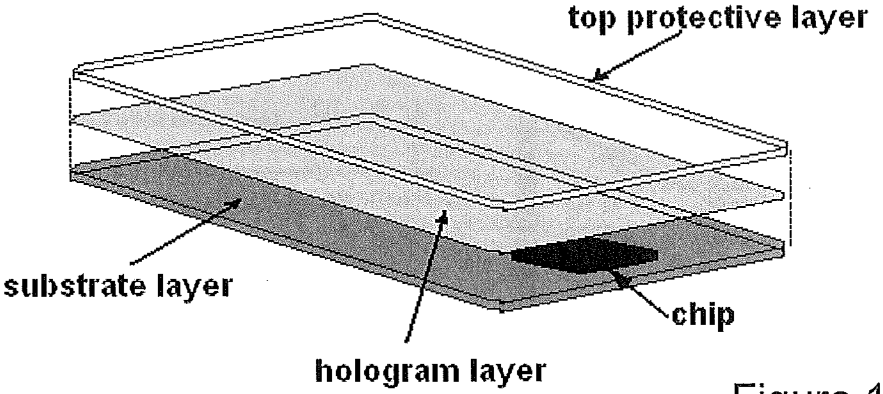
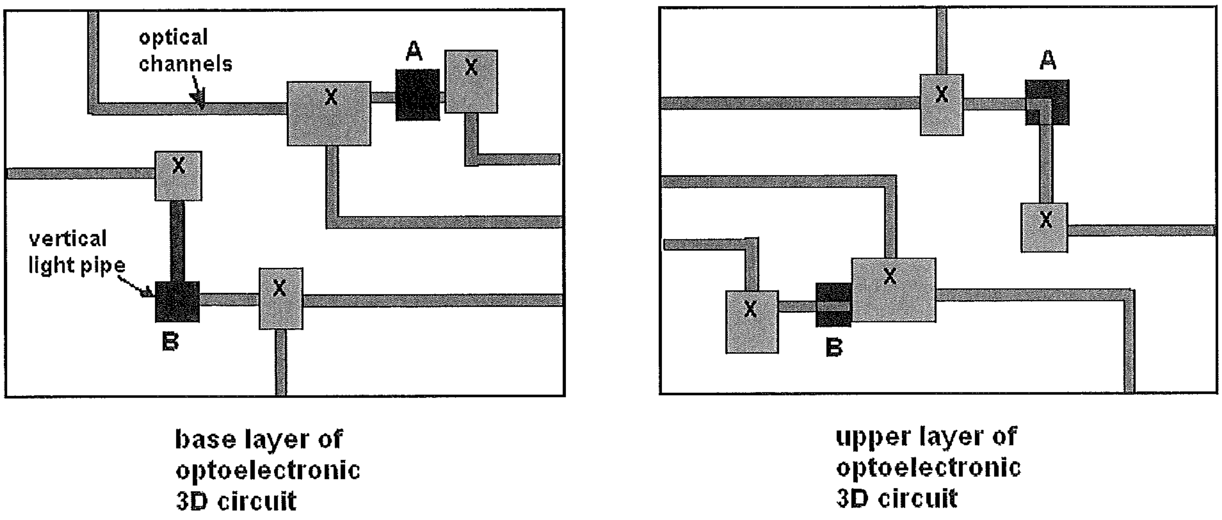


Figure 11



X = optoelectronic device embedded

Figure 12

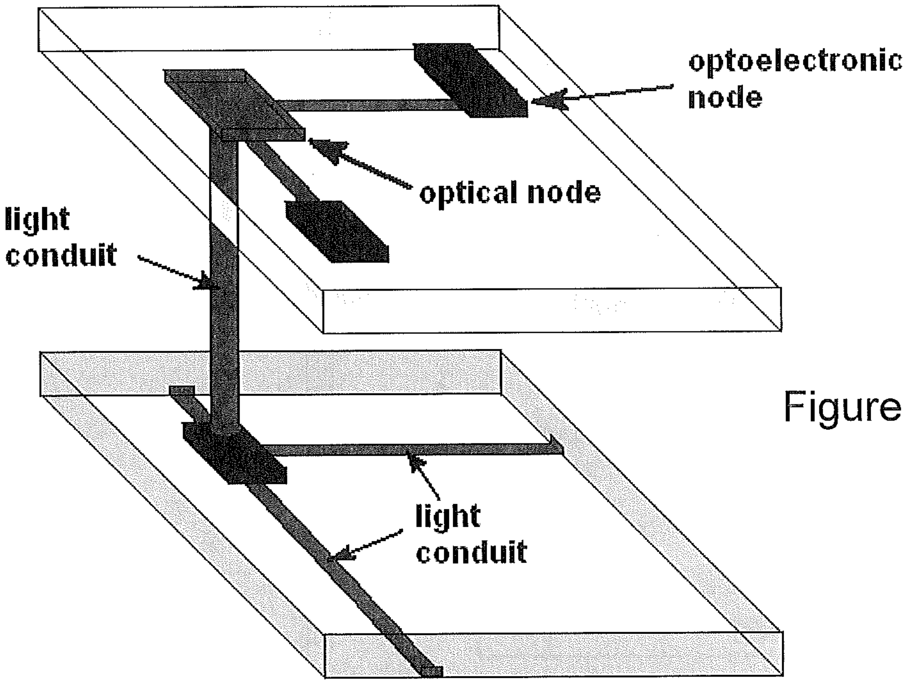


Figure 13

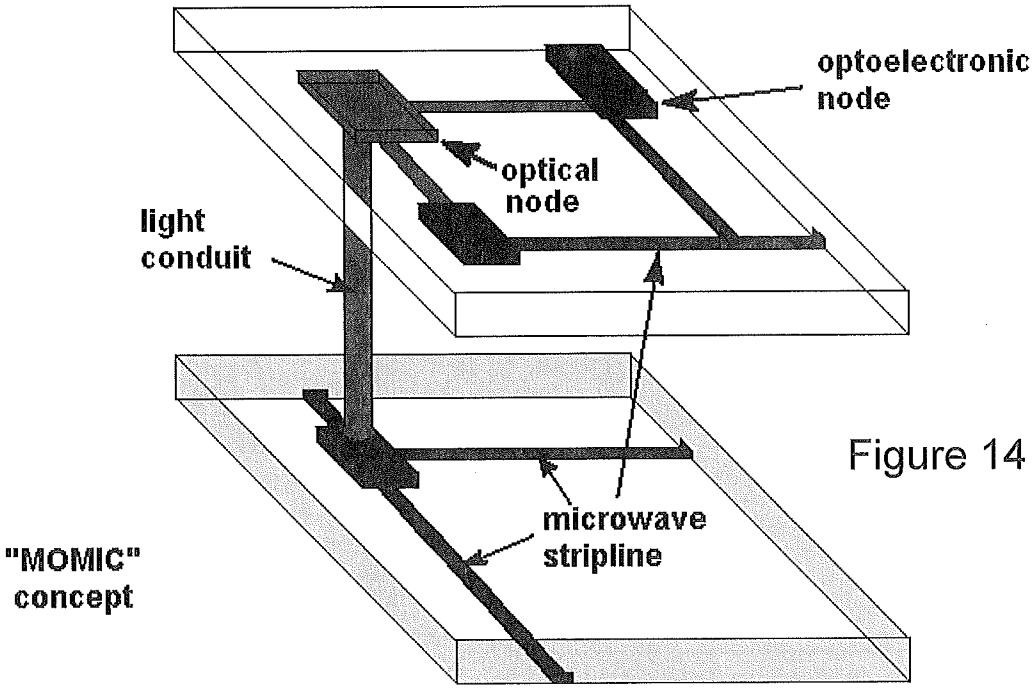


Figure 14

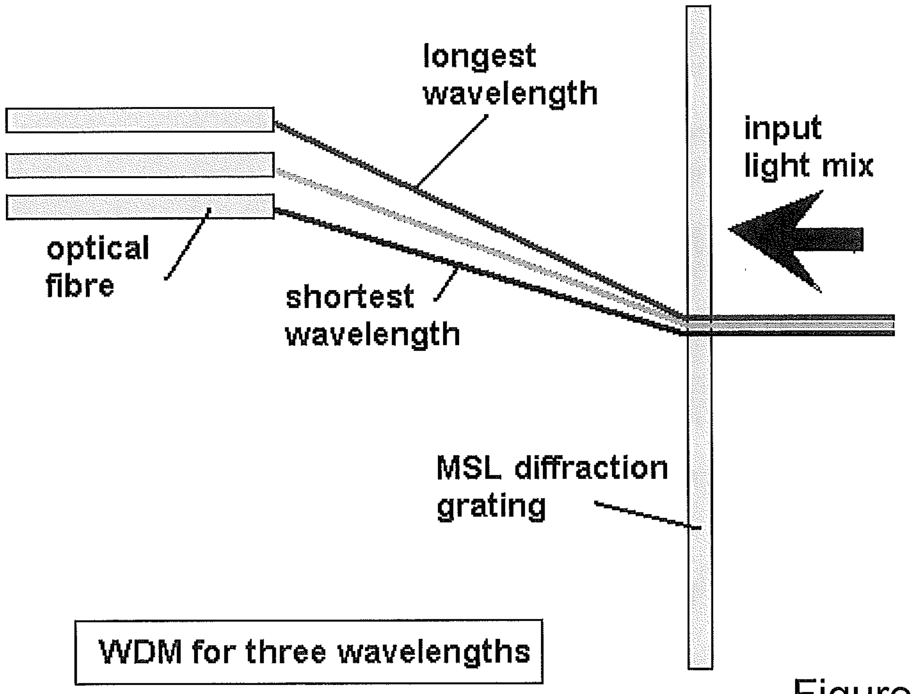


Figure 15

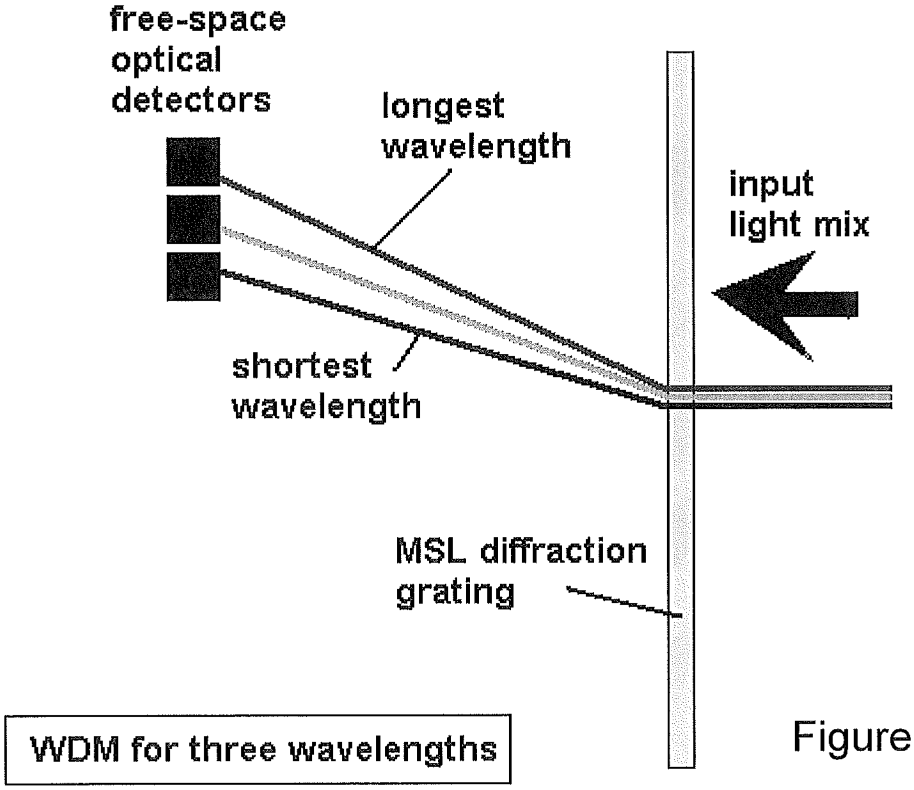


Figure 16

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2011/052151

A. CLASSIFICATION OF SUBJECT MATTER
INV. B29C67/00
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B29C G11B

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

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

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 1 151 849 A1 (3D SYSTEMS INC [US]) 7 November 2001 (2001-11-07)	1-3,7, 11, 13-15, 17-20
Y	figure 1 page 2, paragraph [0001] page 4, paragraph [0025] page 7; table II page 8, lines 7-10, 48-58, 56-58 page 9, lines 1-8, 23-25 -----	4-6, 8-10,12, 16
Y	US 2002/188369 A1 (GUERTIN MICHELLE D [US] ET AL) 12 December 2002 (2002-12-12) page 4, paragraphs [0052], [0053] page 6, paragraph [0067] ----- -/--	4-6,8

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search 23 June 2011	Date of mailing of the international search report 07/07/2011
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Gasner, Benoit

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2011/052151

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	EP 0 637 281 A1 (EOS ELECTRO OPTICAL SYST [DE]) 8 February 1995 (1995-02-08) page 1, 4th paragraph page 4; claim 1 -----	9,10
Y	US 6 391 245 B1 (SMITH JEFFREY M [US]) 21 May 2002 (2002-05-21) figure 7 column 6, lines 6-15 -----	12,16

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2011/052151

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
EP 1151849	A1	07-11-2001	DE	60115136	D1	29-12-2005
			DE	60115136	T2	17-08-2006
			JP	3556923	B2	25-08-2004
			JP	2002001827	A	08-01-2002
			US	6574523	B1	03-06-2003
US 2002188369	A1	12-12-2002	NONE			
EP 0637281	A1	08-02-1995	DE	4305201	C1	07-04-1994
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			JP	7503680	T	20-04-1995
US 6391245	B1	21-05-2002	NONE			