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(54) Title: OPTICAL DIFFUSER CONTAINING DEVITRITE

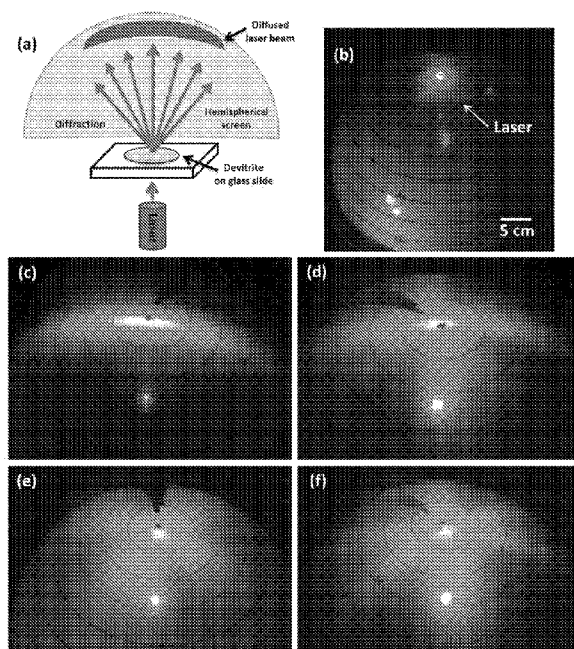


Fig. 3

(57) Abstract: The present invention provides an optical diffuser containing needles of devitrite, $\text{Na}_2\text{Ca}_3\text{Si}_6\text{O}_{16}$. The diffuser may be used for diffusing the light of a laser (such as a medical or engineering laser), diffusing the light of an LED, diffusing light emitted by a photon source of a photonic communication system, or diffusing light emitted by a backlight of a backlit display device



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OPTICAL DIFFUSER CONTAINING DEVITRITE

Field of the Invention

The present invention relates to an optical diffuser.

Background of the Invention

- 5 Devitrite, $\text{Na}_2\text{Ca}_3\text{Si}_6\text{O}_{16}$, is the primary crystallisation product formed when commercial soda–lime–silica glasses are heat treated for extended periods around 900°C [1][2]. Historically, devitrite used to occur as one of many unwanted crystalline forms found in commercial glassware [3][4], but with improvements in commercial manufacturing methods for glasses, interest in devitrite largely disappeared in the scientific literature once it was
- 10 appreciated how to remove it from the final glass product. For this reason, little attention has been given to technological use of this devitrification product in soda–lime–silica glasses, in contrast to other inorganic glasses in which controlled devitrification has given rise to the family of materials known as glass-ceramics [5].

- The optical properties of devitrite were summarised by Peck [6]. The three principal
- 15 refractive indices of this triclinic material are 1.565, 1.570 and 1.580. In deliberate devitrification of soda–lime–silica glasses, devitrite grows as fans of needles [7]. The axes of the needles are parallel to the direction along which the refractive index is 1.580, so that the needles have a positive optical elongation [6].

Summary of the Invention

- 20 Optical diffusers are widely used in the optical industry for distributing or spreading the light intensity from focussed light sources, producing soft light [8]. The wide range of applications for diffusers varies from optical imaging, photovoltaic [9], photolithography [10], and in the health industry for producing diffused therapeutic thermal energy [11]. Visual display systems also require diffusers for increasing the field of view; with the emergence of light
- 25 emitting diodes (LEDs) as alternative solid state light sources, there is a need for diffusers for spreading concentrated light [12]. The engineering applications of specific diffusers are dependent on their performance, homogenisation capability and efficiency [8].

The present invention is at least partly based on a realisation that highly effective optical diffusers based on suitably heat-treated devitrified soda–lime–silica glass can be produced

by a straightforward fabrication process and have potential for use in a range of optical applications.

Accordingly, in a first aspect, the present invention provides an optical diffuser formed of devitrite, $\text{Na}_2\text{Ca}_3\text{Si}_6\text{O}_{16}$.

5 Advantageously, the devitrite optical diffuser can be produced cost-effectively.

The devitrite optical diffuser can provide a higher transmission efficiency than, e.g. conventional frosted glass diffusers. Although conventional holographic diffusers can also rival the devitrite optical diffuser in terms of high transmission efficiencies, the dispersion produced by such diffusers is directional, whereas the dispersion produced by the devitrite
10 optical diffuser can be much more uniform.

An advantage of the devitrite optical diffuser relative to conventional plastic-based diffusers is that, being inorganic glass-based, it can operate at higher powers and higher temperatures.

Optional features of the invention will now be set out. These are applicable singly or in any
15 combination with any aspect of the invention.

The optical diffuser typically contains needles of devitrite. These needles generally have a [100] growth direction [2]. The devitrite needles may be arranged into fans, and the needles can thus effectively act as diffraction gratings. The fans are preferably arranged such that light passing through the optical diffuser passes through plural overlapping fans. This allows
20 the light to pass through fans in which the needles extend in different directions, helping to diffuse the light more uniformly about the incident direction of the light. Further, the overlapping fans allow the light to experience greater effective variation in needle spacing, reducing the wavelength-dependency of the dispersion produced by the diffuser. The spacing between adjacent needles may be in the range from 0.1 to 1 micron. The needle
25 length may be in the range from 0.5 to 5 mm or from 1 to 5 mm (about 1 mm is typical). The thickness of the diffuser can be set in order to achieve a balance between uniform dispersion and the need to reduce transmission losses. For example, the thickness of the diffuser may be greater than 20 μm (and preferably greater than 50 μm) to promote uniform dispersion and/or may be less than 200 μm (preferably less than 100 μm) to reduce transmission
30 losses.

The needles of devitrite may occupy a volume fraction of the material of the diffuser of at least 5%, and preferably of at least 10, 20 or 30%.

The transmission efficiency of the diffuser may vary by no more than about 5% for wavelengths of light in the range from 450 to 650 nm. Thus, advantageously, the diffuser
5 can be used to diffuse white light without preferentially absorbing particular wavelengths.

The optical diffuser may diffuse light to an angle of at least 40° from the incident direction of the light, preferably to an angle of at least 50° or 60° from the incident direction of the light.

The material of the diffuser may be a glass composition having up to 3% MgO by weight, preferably having up to 2% or 1% of MgO by weight, and more preferably having
10 substantially no MgO. Modern commercial float glasses typically contain about 4% MgO by weight in order to suppress the formation of devitrite. By lowering the amount of MgO, however, devitrite formation can be encouraged.

The optical diffuser may be configured for: diffusing the light of a laser (such as a medical or engineering laser – e.g. the diffuser being used to safely diffuse the laser when the laser is
15 not being used to make an incision, cut a hole, perform ablation etc., or being used in a safety screen so that any unwanted laser speckle/reflection is diffused before reaching an operator/patient), diffusing the light of an LED, diffusing the light of a photonic communication system, or diffusing the light emitted by a backlight of a backlit display device.

20 The devitrite can be formed by heat treating a glass composition at a temperature in the range from 850°C to 1000°C. In particular, glass compositions having lower amounts of MgO can be heat treated at higher temperatures to encourage a more rapid growth of devitrite. Thus a further aspect of the invention provides a method of forming the optical diffuser of the first aspect, the method including: providing a glass composition; heat treating
25 the glass composition at a temperature in the range from 850°C to 1000°C (and preferably from 900°C to 970°C) to form devitrite needles in the glass composition; and forming the optical diffuser from the heat treated glass composition.

A further aspect of the invention provides the use of devitrite as an optical diffuser. Other more specific aspects of the invention provide the use of an optical diffuser formed of
30 devitrite for: diffusing the light of a laser (such as a medical laser), diffusing the light of an

LED, diffusing light emitted by a photon source of a photonic communication system, and diffusing light emitted by a backlight of a backlit display device.

Further aspects of the invention provide: a laser system having a laser (such as a medical or engineering laser) and an optical diffuser formed of devitrite for diffusing the light of the laser; an LED system having an LED and an optical diffuser formed of devitrite for diffusing the light of the LED; a photonic communication system having a photon source and an optical diffuser formed of devitrite for diffusing light emitted by the photon source; and a backlit display device having an optical diffuser formed of devitrite for diffusing light emitted by a backlight of the device.

10 Brief Description of the Drawings

Embodiments of the invention will now be described by way of example with reference to the accompanying drawings:

Figure 1 (a-d) Polarised light microscope images showing different arrangements of devitrite crystals within a 30 μm thin slice of heat-treated soda–lime–silica float glass. Fans of needle-like crystals originate from the glass surface growing and overlapping in three dimensions into the bulk glass. (e) An image of several devitrite crystals formed at the edge of the glass, taken with a polarised light microscope. (f) The image of the region in (e) taken with a sensitive tint wave plate (whole wave plate) inserted at 45° to the polariser and analyser.

Figure 2 (a-d) 2D Fast Fourier Transforms (FFTs) of Fig. 1(a-d) respectively. Log_{10} plots of the FFTs were produced to suppress the zero order intensity and to help make the higher orders in the diffraction patterns more visible. It is evident from the FFTs that the orientation of the devitrite crystals dictates the far field pattern of diffused light.

Figure 3 (a) Schematic diagram of the experimental setup employed to capture the diffraction patterns from the devitrite crystals. (b) The laser beam passing through bare float glass and illuminating a small area on the hemispherical screen. (c-f) The laser beam passing through different regions of devitrified glass (shown in Fig.1 (a-d) respectively) producing various patterns of optical diffusion. The concentrated laser beam has been diffused to angles as high as 40° , as is evident from the 10° latitude angular markers on the hemispherical screen. The limitations of the camera used to take this photographs was such

that the true extent of the angle over which optical diffusion takes place appears less than the angle seen by the naked eye.

Figure 4 (a) Transmitted light intensity as a function of angle for the arrangement shown in the inset where a diffuse diffraction pattern is produced from a devitrite region containing a single fan of needles of devitrite. (b) The measured visible transmission through the fan of devitrite.

Figure 5 (a) A diverging beam of white light passing through ordinary soda–lime–silica glass. (b) The same beam after passing through a 30 μm thick sample of devitrite.

Detailed Description and Further Optional Features of the Invention

10 *Fabrication and Optical Microscopy*

Devitrite crystals are formed heterogeneously on the surfaces of commercial float glass as a result of prolonged heat treatment [2]. The crystal growth takes place both parallel to the surface and into the bulk of the glass. The length of the individual devitrite needles of crystals produced and their concentration depend on the heat treatment time and temperatures used [2][7].

A 7 x 10 x 50 mm block of float glass was heat treated for 17 hr at 900°C to produce individual needles of devitrite up to 3.5 mm long. Thin sections were cut transverse to the length of the block for the optical experiments. These were then ground and polished to a standard 30 μm thickness using standard mineralogical and petrological specimen preparation methods and subsequently covered with a clear microscope glass cover slip.

Examples of fans of devitrite crystals nucleated at the surface of the glass block clearly visible in these thin sections are shown in the polarised light microscope images in Fig. 1(a-e), with the polariser at 90° to the analyser, as is usual for such microscopes. The areas containing glass which has not devitrified appear dark under the crossed polarisers, as do needles of devitrite crystals oriented with their axes parallel to either the polariser or analyser. In general, colourful devitrite crystals are viewed at different angular positions within the 30 μm thin sections, their colour consistent with the colours expected from Michel-Lévy charts of birefringence. These observations confirm the highly anisotropic nature of the devitrite crystals and that, as a consequence, they change the polarisation of light [6]. The birefringent behaviour of the devitrite crystals can be further appreciated by inserting a

sensitive tint plate into the transmitted light beam at 45° to the polariser and analyser, as shown in Fig. 1(f). It is evident from Fig. 1 that it is difficult to resolve individual needles of devitrite within the fans. This is because the needles typically have cross-sections of the order of the wavelength of visible light. In addition, the spacings between the needles are also of this order.

In three dimensions the fans of devitrite can overlap one another when seen in projection normal to the surface of the $30\text{ }\mu\text{m}$ thick sample. This overlapping introduces randomness in the change of polarisation of the light as it is transmitted through the thin sample. The scale of the spacings between the needle-shaped crystals enables these crystals to display strong interaction with light and produce optical diffusion. In common with other ceramics and minerals, the refractive indices of devitrite are wavelength-dependent, so that different optical wavelengths undergo different phase retardance. Hence, optical dispersion is observed in devitrite. This is also of technological interest, as it shows that the devitrite crystals could also be used as large area phase modulators for visible light and other optical device applications such as optical holograms [13].

Simulated Diffraction

To simulate diffraction patterns from the fans of devitrite crystals, Fast Fourier Transforms (FFTs) of the polarised light microscopy images of devitrite crystals in Fig. 1(a-d) were performed. Different FFT simulations of the far field diffraction patterns produced from the devitrite crystals in Fig. 1(a-d) by the process of Fraunhofer diffraction are shown in Fig. 2(a-d) respectively. It is evident that the specific arrangement of devitrite crystals in Fig. 1 dictates the diffraction patterns seen in Fig. 2. In accordance with the principle of Fourier Transforms [14], the diffraction patterns are always spatially extended (enlarged) in the direction orthogonal to the thin features causing the diffraction. Thus, in Fig. 1(a), the image of the needles of devitrite has a vertical direction relative to which they fan, while its FFT in Fig. 2(a) shows a horizontally extending random distribution of light, with extra intensity along a central horizontal line.

The same is true for other arrangements of devitrite crystals as well, such as in Fig. 1(c) where two fans of devitrite crystals are extending diagonally and overlapping each other. In its FFT in Fig. 2(c), the light is diffused into two directions, giving the appearance of a cross within the intensity distribution in the diffraction pattern. Hence, different patterns of diffused light can be obtained by modifying the directional distribution of the devitrite crystals, e.g.

either by overlapping different thin sections of devitrified soda–lime–silica glass or choosing parts of a 30 μm thin section from corners of the original block of glass where overlapping fans of needles arise as a natural consequence of the nucleation and growth process of these fans.

5 *Experimental Characterisation of Optical Diffusion*

To characterise the optical diffusion properties of the thin sections of devitrite experimentally, the thin sections were mounted onto a post with a semi-transparent hemispherical screen set above it. The hemispherical screen had a radius of the order of 15 cm. This allowed sufficient distance from the sample to capture diffraction patterns in the far field. The base of the screen was placed parallel to the plane of the sample as shown in the schematic diagram in Fig. 3(a). The sample was illuminated using a 633 nm (red) laser. The laser was mounted below the sample, arranged so that the 1 mm wide beam was normally incident at the sample.

The transmitted laser light was diffracted vertically towards the hemispherical screen. The resultant diffraction patterns produced were captured by a camera. A photograph of the red laser beam passing through bare float glass and then shining on the screen is shown in Fig. 3(b). As expected, the laser beam passes through the glass undistorted and is observed shining on the hemispherical screen and occupying a very small area. However, when the same beam is transmitted through the devitrified glass, a strong optical diffusion is observed and the light is spread at large angles (Fig. 3(c-f)).

Fig. 3(c-f) are the experimentally observed diffraction patterns from different arrangement of devitrite crystals shown in Fig. 1 (a-d) respectively and are in excellent agreement with the calculated results from FFT shown in Fig. 2(a-d) respectively. Of particular significance is the extent of the diffusion of the light: up to 40° symmetrically from the centre.

These results are very encouraging as they suggest that it is possible to use devitrite, a material which is inexpensive to produce, for applications such as optical diffusers and beam shapers without significant loss in total intensity of the light. Desired beam shapes and intensity distributions can be obtained by using engineered devitrite crystal distributions. Such devitrite-based diffusers could also be used in industry for diffusing LED light.

Angular Experiments

Further experiments were undertaken to characterise the exact angular distribution (field of view) of light diffused by devitrite samples because of the limitations imposed by the camera used to take the photographs in Fig. 3. A goniometer setup was used to measure the angular distribution of optical intensity. The devitrite sample was placed in the centre of a goniometer and was then illuminated using a red laser at normal incidence angle. The angular measurements were done on the other side of the sample using a photodiode mounted on a rotating arm.

An example of the transmitted light intensity as a function of angle is shown in Fig. 4(a). For this, the region containing unidirectional fans of devitrite crystals (as in Fig. 1(a)) was illuminated, so that the resulting diffused pattern was also distributed mostly in one dimension, as shown in the inset of Fig. 4 (a). It can be seen that the devitrite crystals are distributing the intensity of light to angles up to 60° from the normal, i.e. to significantly higher angles than is apparent from Fig. 3. The other important feature observed is that at 0° there is no very intense peak present from the zero order beam from the laser. Hence, these data confirm that the fans of devitrite produce a phase modulation of the light, rather than an amplitude modulation.

For a light beam at normal incidence angle to a periodic grating, the maximum diffraction angle produced can be easily calculated from the equation $\lambda = d \sin \theta$, where λ is the wavelength of incident light, d is the spacing between the elements of the gratings, and θ is the angle between the incident beam and the scattered beam [14]. For $\theta = 60^\circ$ and a wavelength λ of 633 nm, the value for the minimum spacing d between such grating elements is 730 nm. This figure is consistent with the scale of the spacings between the needle-shaped crystals. It is this fine scale aspect of the microstructure which enables these diffused diffraction patterns with a wide field of view to be produced.

Optical transmission measurements were also conducted on the devitrite samples. The transmission of the visible light was measured using a spectrometer with a resolution of the order of 2 nm connected to an optical microscope. The devitrite samples were viewed in the transmission mode at 60x magnification. This allowed the microscope objective to be placed very close to the sample to collect most of the light transmitted through the devitrite. The measurements for unpolarised light were taken at several regions of the devitrite sample and similar results were obtained. The measured average visible transmission through devitrite

is shown in Fig. 4(b). The results show that, on average, between the wavelengths of 450 and 650 nm, over 75% of the light is transmitted through the fans of devitrite crystals – a very encouraging result. In fact, because of the spreading of light by the devitrite crystals to high angles, the results in Fig. 4(b) represent lower bounds on the true transmittance levels because the objective is unable to capture all the light. Further the results show that, between the wavelengths of 450 and 650 nm, the transmission efficiency through the fans of devitrite crystals varies by no more than about 5%.

Finally, the diffuser performance of devitrite was established for white light. The results obtained are shown in Fig. 5. A white light source was used to illuminate the devitrite sample. The transmitted beam was captured on a flat surface and then recorded on camera. The beam of white light was observed to diffuse noticeably after passing through the sample of devitrite.

Conclusions

The results discussed above demonstrate useful optical diffusers based on the synthetic material devitrite, $\text{Na}_2\text{Ca}_3\text{Si}_6\text{O}_{16}$. An almost random arrangement of needle-shaped devitrite crystals causes the almost random phase modulation of light and its angular diffusion in the far field. Because of the scale of the spacing between these needles, the light is diffused to large scattering angles. The high efficiency of these diffusers and their inexpensive fabrication process together enable them to have the potential to be used in a variety of applications and industries, such as in medical laser treatments, photonic communication systems, display systems, and for diffusing high power lasers and LEDs.

While the invention has been described in conjunction with the exemplary embodiments described above, many equivalent modifications and variations will be apparent to those skilled in the art when given this disclosure. Accordingly, the exemplary embodiments of the invention set forth above are considered to be illustrative and not limiting. Various changes to the described embodiments may be made without departing from the spirit and scope of the invention.

All references referred to above are hereby incorporated by reference.

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CLAIMS

1. An optical diffuser containing needles of devitrite, $\text{Na}_2\text{Ca}_3\text{Si}_6\text{O}_{18}$.
2. The optical diffuser of claim 1, wherein devitrite needles are arranged into fans.
3. The optical diffuser of claim 1 or 2, wherein the fans are arranged such that light
5 passing through the optical diffuser passes through plural overlapping fans.
4. The optical diffuser of any one of the previous claims, wherein the spacing between adjacent needles is in the range from 0.1 to 1 micron.
5. The optical diffuser of any one of the previous claims, wherein the needle thickness is in the range from 0.1 to 1 micron.
- 10 6. The optical diffuser of any one of the previous claims, wherein the needle length is in the range from 0.5 to 5 mm.
7. The optical diffuser of any one of the previous claims, wherein the needles of devitrite occupy a volume fraction of the material of the diffuser of at least 5%.
8. The optical diffuser of any one of the previous claims, wherein the transmission
15 efficiency of the diffuser varies by no more than about 5% for wavelengths of light in the range from 450 to 650 nm.
9. The optical diffuser of any one of the previous claims, wherein the optical diffuser diffuses light to an angle of at least 40° from the incident direction of the light.
10. The optical diffuser of any one of the previous claims which is configured for diffusing
20 the light of a laser.
11. The optical diffuser of any one of claims 1 to 9 which is configured for diffusing the light of an LED.
12. The optical diffuser of any one of claims 1 to 9 which is configured for diffusing the light of a photonic communication system.
- 25 13. The optical diffuser of any one of claims 1 to 9 which is configured for diffusing the light emitted by a backlight of a backlit display device.

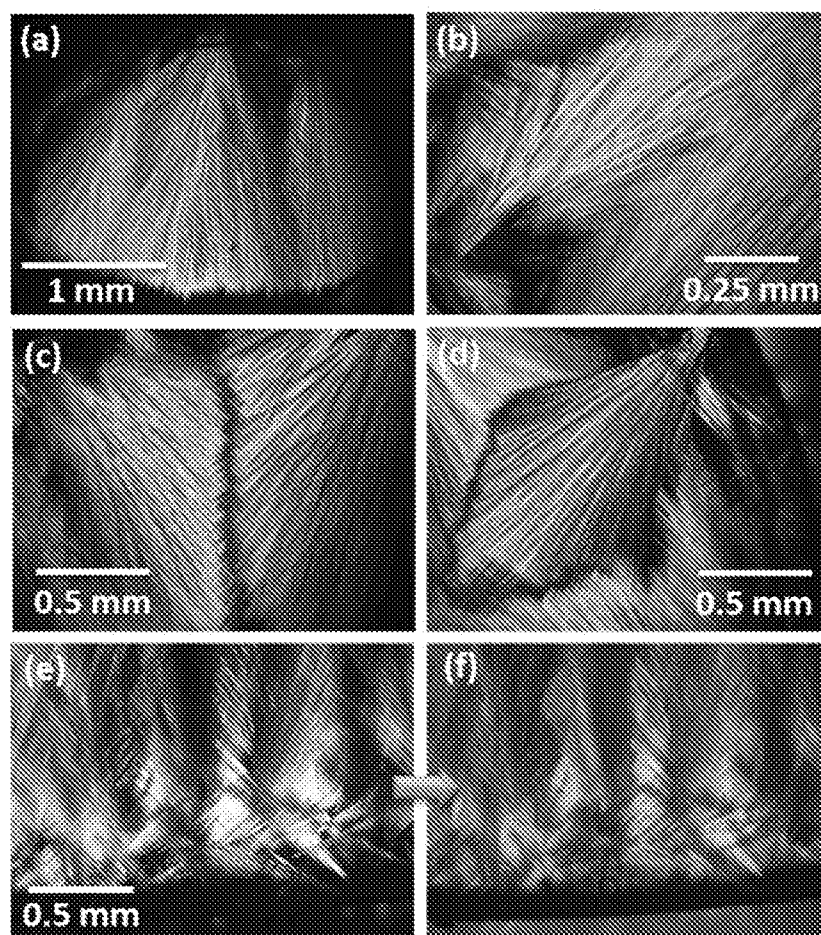


Fig. 1

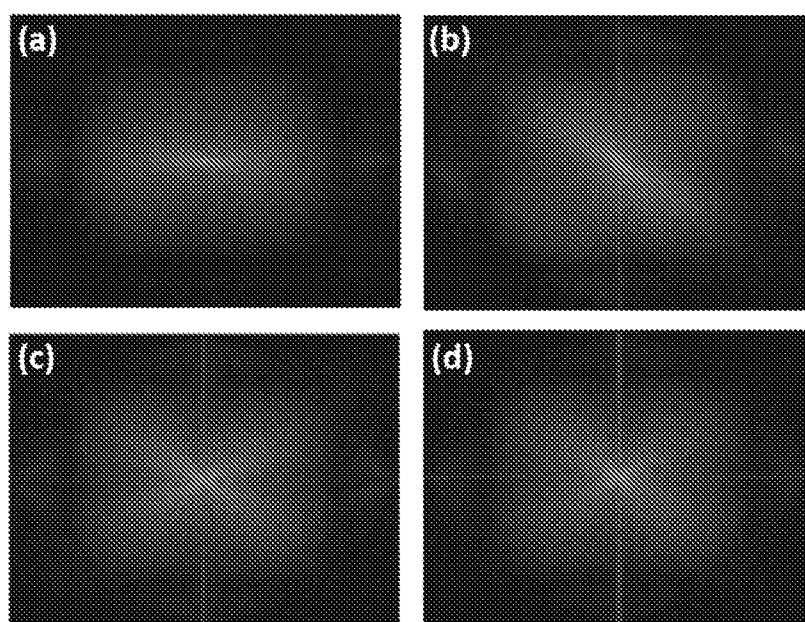


Fig. 2

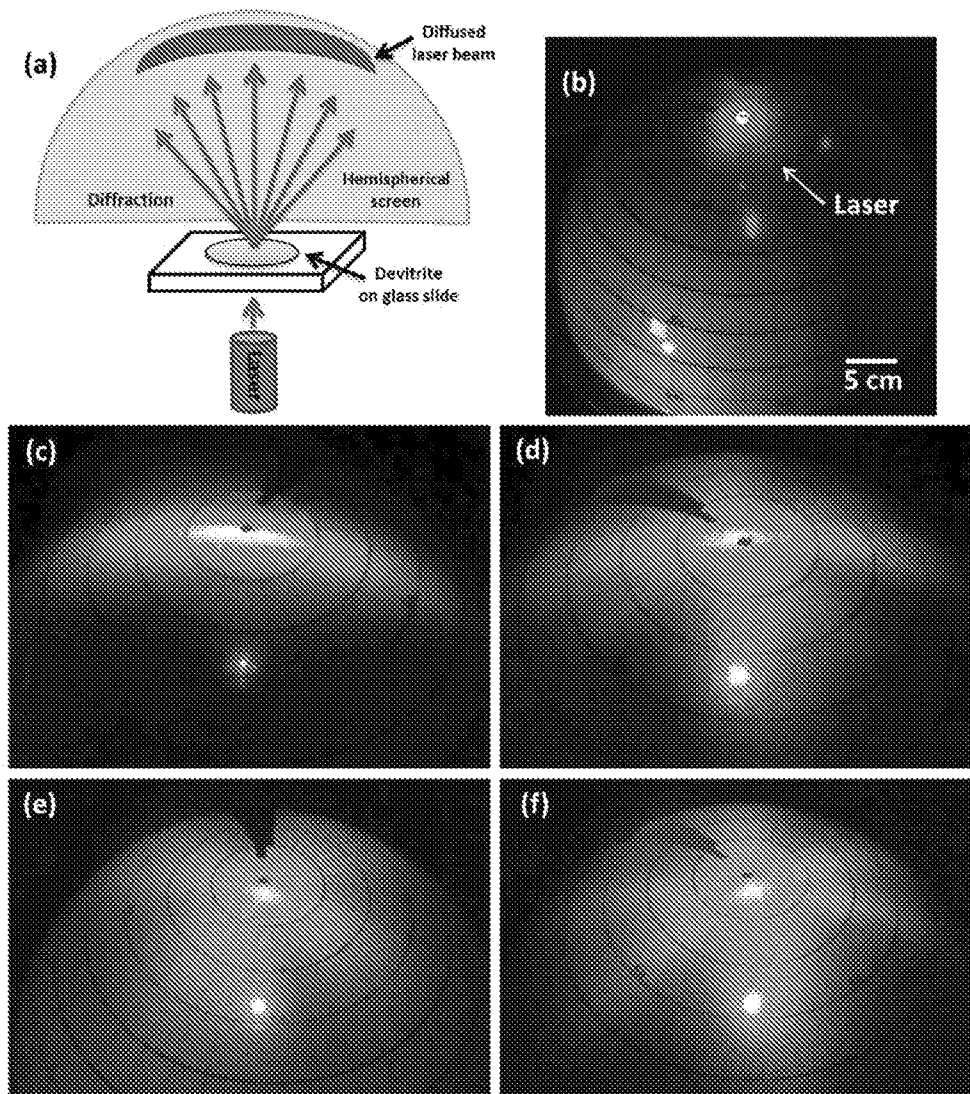


Fig. 3

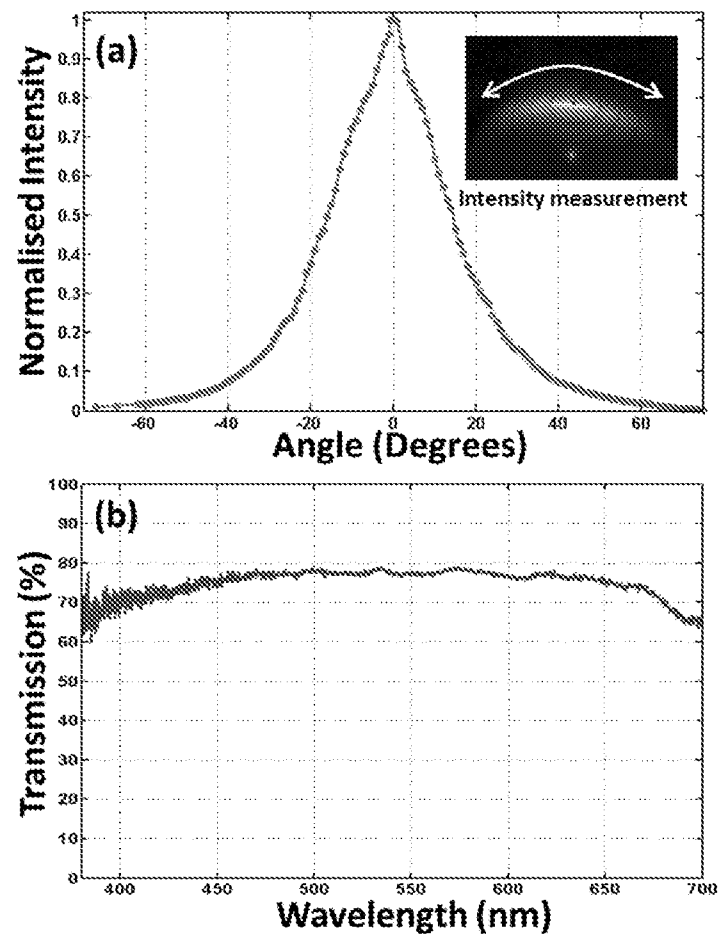


Fig. 4

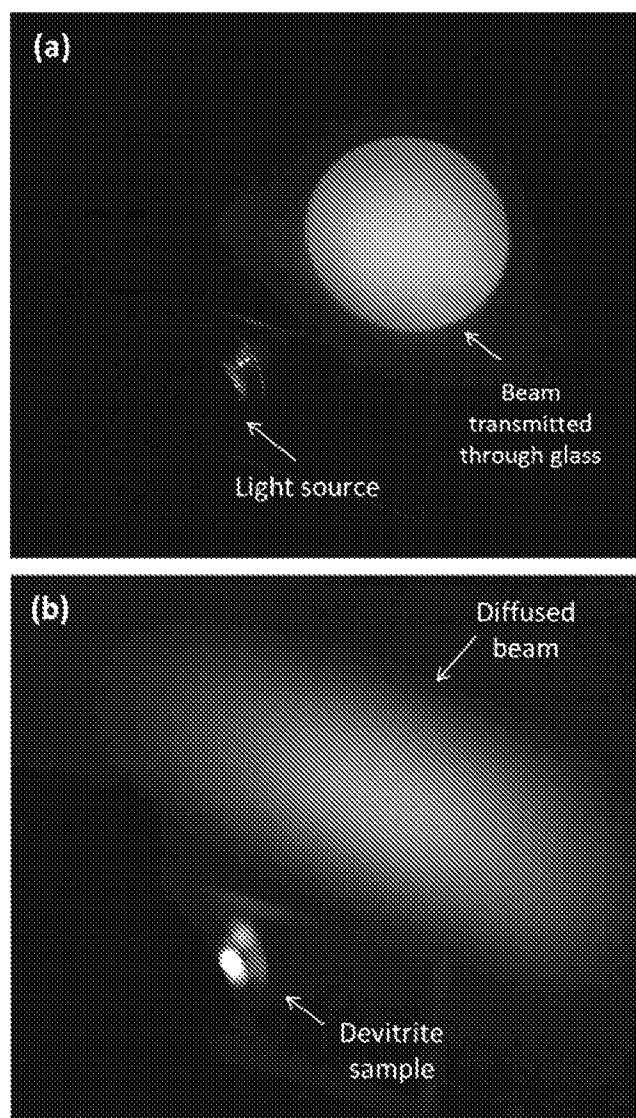


Fig. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2014/052648

A. CLASSIFICATION OF SUBJECT MATTER INV. G02B5/02 C03C10/00 C03C3/00 C03B17/00 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) G02B C03C C03B		
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 practicable, 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	VOLKER KAHLENBERG ET AL: "Devitrite (Na ₂ Ca ₃ Si ₆ O ₁₆)â structural, spectroscopic and computational investigations on a crystalline impurity phase in industrial soda-lime glasses", MINERALOGY AND PETROLOGY, SPRINGER-VERLAG, VI, vol. 100, no. 1-2, 30 May 2010 (2010-05-30), pages 1-9, XP019853705, ISSN: 1438-1168 the whole document -----	1-13
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