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Inventor Alan L. Huston
 Brian L. Justus

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2
3 HIGH RESOLUTION IMAGING USING OPTICALLY TRANSPARENT PHOSPHORS
4

5 **Background of the Invention**

6 **1. Field of the Invention**

7 The present invention relates generally to high resolution imaging, and more specifically to
8 high resolution imaging of objects using sources of ionizing radiation.
9

10 **2. Description of the Background Art**

11 A variety of methods exist for imaging objects using UV, x-ray, and other ionizing radiation
12 sources. These methods have used photographic films, phosphor screens in conjunction with CCD
13 cameras, and thermoluminescent or optically stimuable luminescent phosphor powders in
14 conjunction with a scanning laser readout system. In these techniques, the dimensions of the
15 photosensitive grains in the film or phosphor and scattering effects limit the obtainable resolution.
16 Grain sizes in typical phosphors are on the order of tens of microns, and crushing the phosphor to
17 sub micron dimensions often results in a loss of phosphor activity. Grain sizes in photographic films
18 range from $0.15 \mu\text{m}^2$ for very slow speed (low sensitivity) film to $2.6 \mu\text{m}^2$ for very high speed (high
19 sensitivity) film. For film, the resolution is from 10 to 100 times the grain size because of the
20 chemistry involved in the developing process. Problems with photographic films include the
21 necessity for chemical developing, nonlinear response, limited dynamic range and single use. The

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1 resolution for direct imaging using a CCD camera is determined by the individual pixel size of the
2 CCD array and the magnification factor used for collecting the image. Modern CCD cameras have
3 pixel dimensions of approximately $8 \mu\text{m} \times 8 \mu\text{m}$.

4
5 **Summary of the Invention**

6
7 Accordingly, it is an object of this invention to provide improved spatial resolution when
8 imaging objects using high energy sources such as uv, x-ray, and γ -ray photon sources, and ionizing
9 radiation particles.

10 It is another object of the present invention to provide a media for image storage and a
11 method to readout images without the need for photographic development.

12 It is yet another object of the present invention to provide a reusable media, with a linear
13 response and good dynamic range, for the storage and readout of images made by exposing objects
14 to high energy photon and particle sources.

15
16 These and additional objects of the invention are accomplished by exposing optically
17 transparent, optically stimuable luminescent glasses including luminescent centers and trapping
18 centers, to a projection formed by directing ionizing radiation at an object (Throughout this
19 specification and the claims that follows, the terms "projection" encompasses forms created by
20 radiation transmitted through an object, forms created by radiation transmitted around an object,
21 and/or forms created by radiation scattered from an object. Typically, projections imaged according

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1 to this invention are formed by the interpositioning of an object between the source of ionizing
2 radiation and the optically stimuable luminescent glass, which will hereinafter be referred to as a
3 backside projection). These optically stimuable luminescent glasses are fully described in United
4 States Patent No. 5,811,822, issued September 22, 1998 and entitled "OPTICALLY
5 TRANSPARENT, OPTICALLY STIMULABLE GLASS COMPOSITES FOR RADIATION
6 DOSIMETRY" (the entireties of which are incorporated by reference herein for all purposes). In
7 these glasses, the trapping centers are capable of storing charges for extended periods of time. The
8 trapped charges may be electrons or holes that were generated upon exposure to ionizing radiation.
9 The trapped charges may be optically stimulated to recombine by the application of light at optical
10 frequencies, resulting in the emission of light energy at higher optical frequencies. This optical
11 stimulation is direct, i.e., it does not involve conversion of the optical excitation energy to thermal
12 energy that heats the glass sufficiently to detrapp the electron. This direct optical stimulation may,
13 however, include optical absorption with the release of a phonon that participates in phonon-assisted
14 detrapping of an electron. This direct optical stimulation process is known as optically-stimulated
15 luminescence (OSL). In several embodiments, the glass (e.g., fused quartz, fused silica, alumina
16 glass, or borate glass) matrix includes Cu (typically Cu^{1+}) as an activator (sometimes referred to as
17 a "dopant" in the glass). In other embodiments, the glass matrix includes an activator/co-activator
18 pair of samarium and another rare earth element. In other alternative embodiments, the glass (e.g.,
19 silica, alumina, or borate glass) matrix is doped with ZnS and copper, lead, manganese, or cerium.
20 In yet another embodiment, a glass (e.g., silica, alumina, or borate glass) matrix is doped with Cu
21 or Ce ions.

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1 The OSL glasses described above may also scintillate when exposed to ionizing radiation.
2 This scintillation advantageously permits the present invention to also provide real time images
3 produced by exposure of the glass to ionizing radiation. Of course, the specific OSL glass used may
4 be selected to maximize scintillation or optically-stimulated luminescence. The resulting image may
5 be either real-time, using the prompt luminescence component of the phosphor luminescence, or it
6 may be stored in the media, using the charge trapping and storage capability of the glass.

7

8

Brief Description of the Drawings

9

10 A more complete appreciation of the invention will be readily obtained by reference to the
11 following Description of the Preferred Embodiments and the accompanying drawings in which like
12 numerals in different figures represent the same structures or elements, wherein:

13 Fig. 1 shows a schematic of a typical laser scanned readout system 10 according to the
14 presently claimed invention.

15 Fig. 2 shows an alternative embodiment of a lamp illuminated readout system according to
16 the present invention.

17 Fig. 3 shows another alternative embodiment of a laser scanned readout system according
18 to the present invention.

19

1 **Description of the Preferred Embodiments**

2
3 The optically-stimulated luminescent imaging system described in this invention utilizes a
4 novel, semiconductor- and/or metal ion-doped glass material that was recently developed by the
5 present inventors and described in the United States Patent No. 5,811,822 and in United States Patent
6 No. 5,585,640 to Huston et al., the entirety of which is also incorporated herein by reference for all
7 purposes. Basically, Huston et al. '822, describes a class of optically transparent, optically
8 stimulated glasses and details three embodiments of that class, along with various methods of
9 preparation.

10 Exposure of those composite glass materials to ionizing radiation, such as deep ultraviolet,
11 x-ray or gamma radiation, results in the formation of trapped electrons in the composite glass
12 material. The electrons remain trapped until the glass material is exposed to light at a stimulating
13 wavelength. Upon exposure to light at a stimulating wavelength, the glass emits a luminescent
14 signal. Additionally, these glass materials scintillate upon exposure to ionizing radiation to provide
15 a real-time image. To provide the best possible resolution, the glass material should be used in the
16 form of a plate or sheet sufficiently thin to satisfy the conditions imposed for diffraction limited
17 optics.

18 When used for real-time imaging, the present invention employs those composite glass
19 materials in a manner analogous to the use of a phosphor screen in conventional methods that use
20 a phosphor screen and a CCD camera. Basically, the glass materials of the present invention convert
21 X-rays to photons by scintillation. A conventional lens-coupled camera system, coupled to a light

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1 sensor, for example a CCD sensor, images the photons. The light sensor and its associated
2 conventional software convert the image to digital data, which may then be stored, printed or
3 otherwise processed.

4 The ability of the Huston et al. optically transparent, optically stimulated glasses to trap
5 charges upon exposure to u.v., x-rays or other ionizing radiation allows an alternative to real-time
6 imaging methods. Trapped charges remain trapped until the phosphor is exposed to an infrared light
7 source that is capable of releasing the traps and stimulating the recombination of the charges at a
8 luminescent recombination center. The luminescence wavelength is in the visible, and may be
9 recorded with a common, visible-light-sensitive photodetector. For imaging applications, the ir
10 stimulation light may come from a laser source that is focused to a small spot and scanned over the
11 surface of the glass plate. Alternatively, a selected region of the glass plate may be uniformly
12 illuminated with a lamp that is filtered to provide only light at wavelengths in the infrared or near
13 infrared. This light stimulates luminescent recombination in the visible that is detected and imaged
14 with a CCD camera.

15 In addition to the use of monolithic clear OSL glass sheets for recording images, the OSL
16 glass may also be powdered and dispersed in a film such as a sol gel glass film or a polymer film.
17 In the case of a sol gel film, a fine, e.g., one to two micron (400 mesh) powder can be suspended in
18 an acidic solution consisting of an appropriate vehicle, such as tetraethyl-orthosilicate, methanol, and
19 water, for the formation of thin glass film by a sol-gel process.. The glass powder may be used, for
20 example, in a proportion of between about 1% and about 10% by weight. A thin film can be formed
21 by dipping a substrate material into the sol-gel solution and then withdrawing the substrate at a

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1 controlled rate. The substrate with the applied film is then placed in a furnace and heated to
2 transform the organosilicate film into a purely inorganic film. A film prepared in this way will
3 typically have a thickness of about 1 to about 2 microns and will appear essentially transparent due
4 to the refractive index match between the silica powder and the sol-gel-based film.

5 Instead of using a sol-gel solution, the powdered OSL glass may be dispersed in a polymer
6 solution and then coated onto a substrate using the dip-coating technique described above. The
7 polymer solution can contain any optically transparent polymer or mixture of polymers that can be
8 dissolved in a solvent to an extent between about 1% and about 50% by weight. Typically, a
9 polymer solution with a dissolved solids content of about 5% to about 20% by weight provides good
10 optical quality film on a substrate material. A mixture of polymers may be used to reduce the
11 refractive index difference between the polymer and the glass powder material thereby reducing
12 scattering within the film. The polymer-glass powder solution may consist, for example, of a
13 mixture of 1% to 50% by weight of polymethylmethacrylate dissolved in methyl ethyl ketone with
14 the glass powder used in a proportion of between 1% and 50% by weight. The thickness of the film
15 can be controlled by varying the viscosity of the polymer solution. If desired, polymer-glass films
16 can be prepared on or as flexible substrates, for example, by spin-coating a flexible substrate with
17 the OSL glass powder in either the sol-gel or the polymer matrix, or by casting or extrusion of the
18 sol-gel or polymer matrix as a free-standing film or sheet, to provide a flexible imaging medium.
19 Such a flexible imaging medium could be useful for applications such as dental x-ray imaging.

20 The use of OSL powders still provides significant improvement in the spatial resolution of
21 an image compared to the current art. As stated in the Description of the Background Art, the spatial

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1 resolution that can be achieved using current techniques is on the order of tens of microns. Crushing
2 inorganic phosphors to smaller size diminishes their activity and hence, their sensitivity. OSL glass
3 powders having grains sizes of 1 to 2 μm retain their sensitivity. In addition, the index of refraction
4 of many OSL glass powders used in the present invention is ~ 1.4 . Therefore, polymer or sol-gel
5 films containing dispersed OSL glass powder will be optically transparent since many suitable
6 polymer and sol-gel glass hosts can be selected that have an index of refraction of 1.4. The indices
7 of refraction of inorganic phosphors are typically larger (generally greater than about 3) and
8 inorganic phosphor powders dispersed in a polymer or sol-gel glass film will not be index-matched.
9 The resulting films using inorganic phosphors would scatter light to a significant degree, thereby
10 limiting the achievable spatial resolution of the stored image.

11 Fig. 1 shows a schematic of a typical laser scanned readout system 10 according to the
12 presently claimed invention. For the highest resolution images, the thickness of imaging plate 12
13 (for example, a sheet of the Huston et al. '822 glass) must satisfy the conditions imposed for
14 diffraction limited optics. Specifically, the thickness of imaging plate 12 should be limited to $2 \cdot z_0$,
15 where :

16 $z_0 = (nw_0^2/\ell)$, n is the index of refraction of the glass, ℓ is the wavelength of the light, and w_0 is the
17 radius of the laser spot size which is given by:

18 $w_0 = 0.635\ell f/d$, f is the focal length of lens 18 and d is the diameter of the input, collimated light
19 beam at lens 18.

20 Referring again to Fig. 1, when laser beam 14 from source 16 is focused by lens 18 onto an
21 exposed area of the imaging plate, the resulting stimulated luminescence 17 is collected by lens 18,

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1 collimated, and directed back through a dichroic beamsplitting mirror 20 and onto photodetector 22.
2 The intensity of the signal is proportional to the exposure intensity. An image in exposed imaging
3 plate 12 is then obtained by translating image plate 12 in the plane of the focus of lens 18 and
4 measuring the luminescence 17 as a function of the position of plate 12. The glass material used for
5 the imaging plate has a demonstrated dynamic range of response of over 7 orders of magnitude. The
6 combination of the dynamic range and the optical transparency provide for unprecedented optical
7 image resolution.

8 Fig. 2 shows an alternative system 100 of the present invention using microscope 102 and
9 CCD camera 104. Lamp 106 is a broadband incoherent light source such as a tungsten lamp. The
10 output of lamp 106 is spectrally filtered by optical glass filter 108 that transmits infrared and near
11 infrared radiation 109. The infrared radiation 109 uniformly illuminates imaging plate 110,
12 stimulating visible luminescence 111 from those regions of imaging plate 110 that were previously
13 exposed to ionizing radiation. The colored glass filter 112 blocks the stimulation light 109 from
14 interfering with the detection of the luminescence 111. The lens or microscope objective 102 images
15 light 111 from all or part of imaging plate 110 onto CCD camera 104. The magnification of the
16 image is determined by the characteristics of the lens or microscope 102. The arrows show how the
17 image may be inverted and magnified, without distortion, by the microscope objective.

18 An image stored on an OSL sheet may be read out using a device such as a modified flatbed
19 scanner. As shown in Fig. 3, the light output from an OSL stimulating light source, such as a diode
20 laser bar 102, can be projected to form an extended narrow line 104, and used in conjunction with
21 an extended linear CCD array 106 to record an image stored in an OSL sheet 108. OSL sheet 108

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1 can be translated with respect to light source 102 and CCD array 106, or light source 102 and CCD
2 array 106 can be translated together while OSL sheet 108 remains stationary. A filter 110 can be
3 placed in front of CCD array 108 to filter out the stimulation light and only allow passage of the OSL
4 signal light.

5
6 The present invention has a number of useful applications. For example, the present
7 invention is useful in quality control for photolithography. Photolithographic processing methods
8 for integrated circuit chips are now capable of submicron feature sizes. At the present time, before
9 a production run is undertaken, a test run is conducted to assure that all of the lithographic
10 parameters are within specifications, including the beam quality and the mask integrity. This is a
11 very time consuming process, requiring that the system be opened up to remove the test wafer,
12 followed by etching and microscopic analysis of the circuits. The present invention provides a
13 method for determining the beam quality and a high resolution image of the circuit without having
14 to wait for a lengthy wafer processing procedure.

15 For nondestructive evaluation applications, an object may be placed on top of a thin sheet
16 of the optically transparent phosphor glass and then exposed to an x-ray source. Any
17 inhomogeneities present inside of the object, such as bubbles or cracks, or material differences such
18 as metal lines will appear as contrast differences in the phosphor image. The outstanding dynamic
19 range of the image storage material will allow for unprecedented detection capabilities.

20 Medical imaging applications include mammography and osteoporosis screening. The
21 enhanced resolution and dynamic range will provide improved diagnostics for detecting and

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1 distinguishing between fibrous cysts and cancerous tumors in breast tissue and allow very precise
2 measures of variations in bone density.

3 The present invention also has applications in stereotactic imaging: High precision
4 radiotherapy procedures require extensive modeling using phantoms for treatment planning. Part
5 of the planning process involves obtaining images of the radiation beam profile near the focal region.
6 The glass imaging plates of the present invention provide significant advantages over currently used
7 films. The glasses offer orders of magnitude improvements in dynamic range and are reusable.

8
9 Obviously, many modifications and variations of the present invention are possible in light
10 of the above teachings. It is therefore to be understood that
11 the invention may be practiced otherwise than as specifically described.

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ABSTRACT

Images are formed by exposing optically transparent, optically stimulable luminescent glasses including luminescent centers and trapping centers, to patterned, ionizing radiation. The images may be read immediately, using scintillation, or may be stored in the glasses for subsequent reading using optically stimulated detrapping of stored charges.

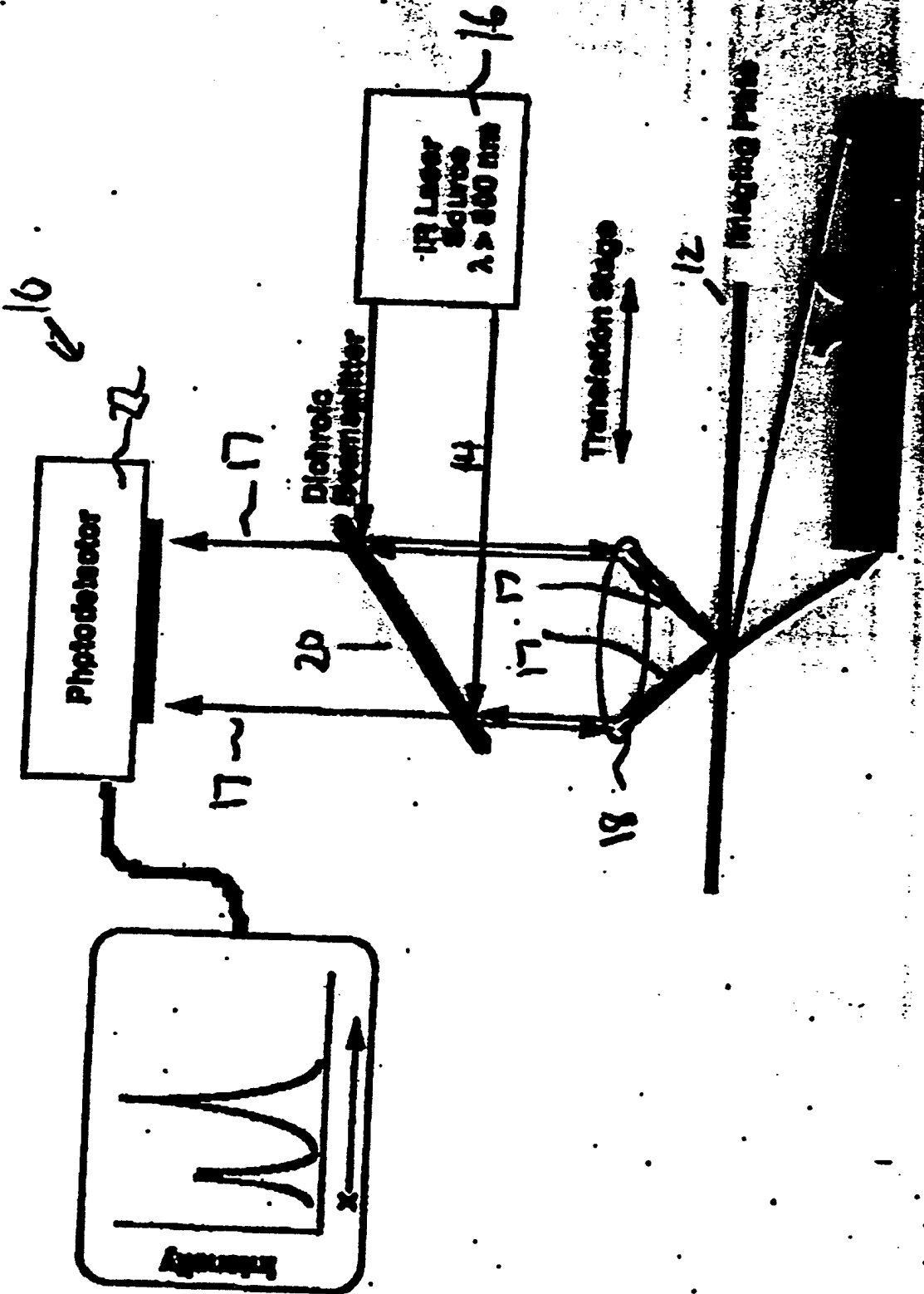
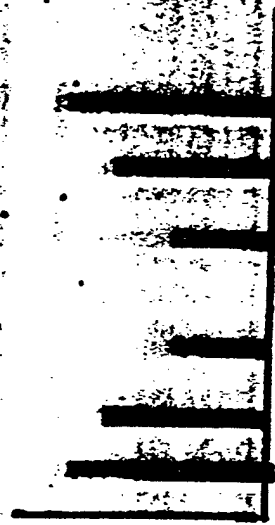
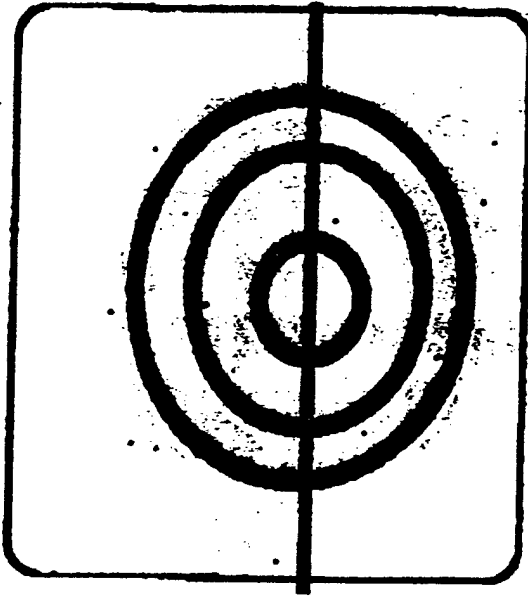


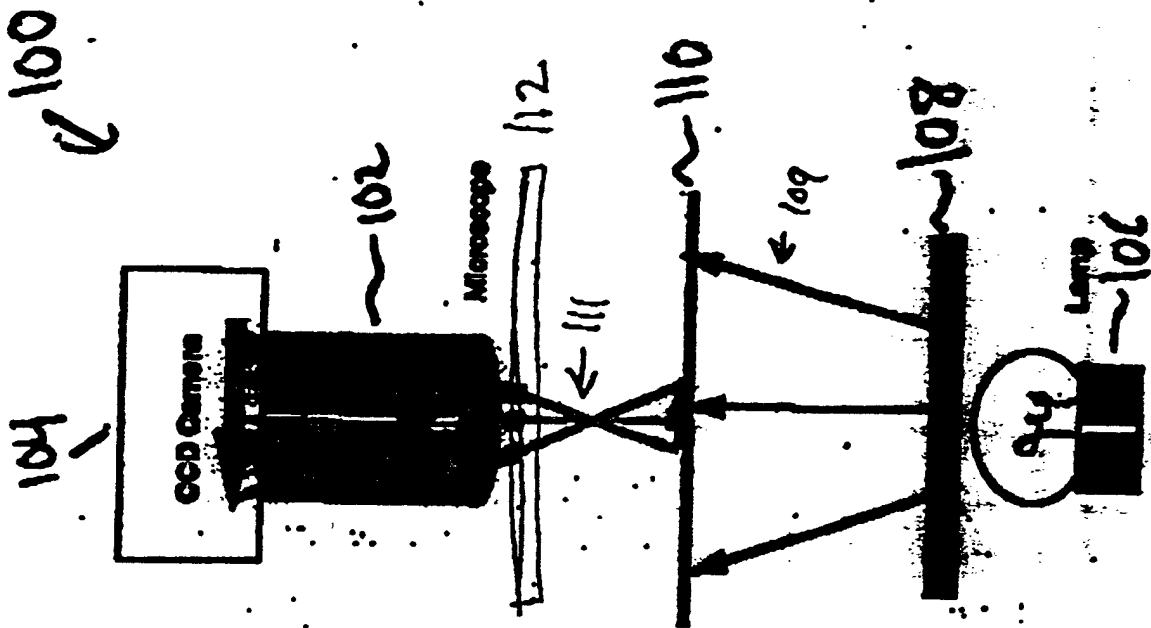
Figure 1

2-D + grayscale intensity representation



Cross-sectional view

Figure 2



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Linear CCD Array Detector 106

Image Sheet 108

Projected Laser Line

Diode Laser Bar 102

110
104

Fig. 3

