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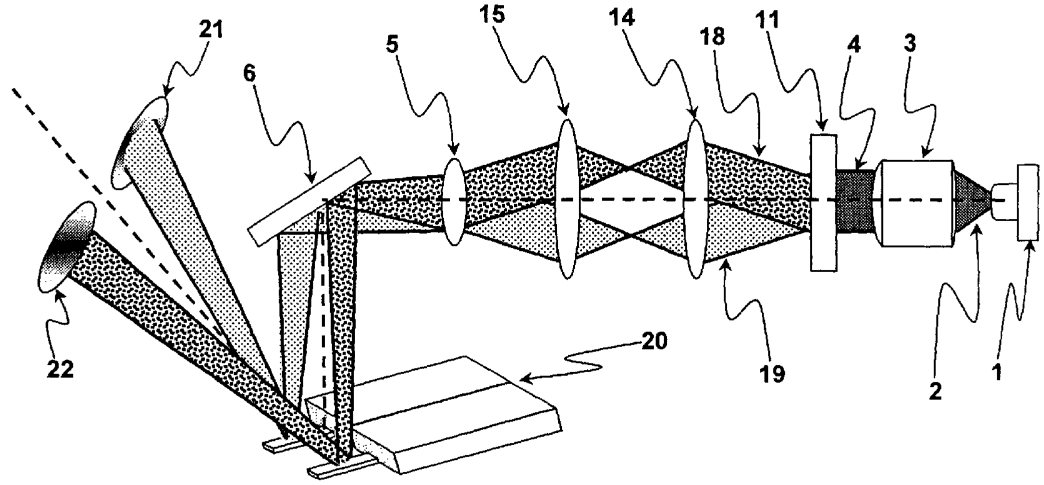
(54) **Title:** DIFFRACTIVE OPTICAL POSITION DETECTOR



(57) **Abstract:** An apparatus and method for measuring optically the position or angle of a variety of objects or arrays of objects, including cantilevers in scanning probe microscopy, micromechanical biological and chemical sensors and the sample or a probe in a surface profilometry. The invention involoves the use of one or more diffractive optical elements, including diffraction gratings and holograms, combined with conventional optical elements, to form a plurality of light beams, each with a selectable shape and intensity, from a single light source, reflect the beams off mechanical objects and process the reflected beams, all to the end of measuring the position of such objects with a high degree of precision. The invention may also be used to effect mechanical changes in such objectsd. Devices with these improvements have numerous applications, including molecular force measurements, atomic force microscopy and manipulation technology, lithographic manufacturing, nanometer scale surface profiling and other aspects of nanotechnology.

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DIFFRACTIVE OPTICAL POSITION DETECTOR

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority of U.S. Provisional Application No. 60/314,075, filed on August 23, 2001, the disclosures of which are incorporated fully herein by reference.

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U.S. PATENT DOCUMENTS

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BACKGROUND AND SUMMARY OF THE INVENTION

The present invention is related to a general method and apparatus for optically measuring the position of a single or multiple mechanical components.

There are numerous examples of using the deflection from a single optical beam for positional measurements, the optical lever detection system commonly used in atomic force microscopes (AFMs) being perhaps the most notable. One such optical lever system is illustrated in FIG. **1**. In this system a light beam **2**, preferably formed by a laser **1** (including a superluminescent laser or diode) with sufficient intensity and lack of pointing or other noise, is directed through a collimation lens or lens assembly **3** and a focusing lens or lens assembly **5** and onto a mirror **6** which directs the focused light beam **7** onto a particular spot on a cantilever **8** in the same reference frame as the optical lever system. The reflected beam **9** is then collected by detection optics, which often include an adjustable mirror and a translation stage for providing an offset to the beam position (not shown), and made to illuminate a position sensitive detector **10** (PSD). As the cantilever moves in response to various forces, the position of the reflected spot on the PSD changes, causing a change in the output. It will be noted that the optical axis of the system **27** coincides with the axis of the light beam as it propagates through the system.

Another prior art AFM optical lever system, in which the cantilever and the optical lever system are in different reference frames, attempts to track the position of the cantilever as it is scanned over a surface. There are a number of schemes to accomplish this. The most successful, based on a tracking lens that moves with the piezo tube scanning the cantilever, is described in US Patent No. 6,032,518.

There has been a great deal of work on optimizing the sensitivity of AFM optical lever detection systems. All of the optimization techniques can be implemented using the invention disclosed herein and most are easier to implement using the invention.

The employment of two- or multiple-beam systems in positional measurement instruments provides significant advantages. In the case of AFMs and other scanning probe instruments, a second beam can provide a reference for more accurate positional measurements. A second or multiple beams can also allow more than one cantilever probe to be used in imaging. In the case of micromechanical sensors, a second or multiple optical beams can be used to provide a baseline reference signal for comparison with the active sensor element to compensate for thermal drift or other effects. Two or more beams also make it possible to simultaneously observe more sensors, thereby increasing throughput. For optical profilometers, multiple beams offer the possibility of increasing throughput or simultaneous monitoring of several positions.

There are a number of multiple beam systems in the literature. To date, these systems rely upon two or more separate light sources focused onto different locations. This complexity has limited the use of multiple beam sensor arrays in any number of commercial applications including high throughput scanning probe microscopes or micromechanical sensors containing numerous sensing elements and control levers for background measurements.

Diffractive Optical Elements (DOEs) provide a flexible and powerful means for splitting the beam from a single source of light into multiple beams and varying the intensity and shape of each beam. Using a DOE it is possible to illuminate an array of cantilevers or other mechanical structures using only one light source. The spacing between the focused spots and the spot geometry can be controlled. The multiple beams can also be shaped to vary the sensitivity of the measurement and the beams can be steered either individually or as a group.

Shaping the spot has important consequences for cantilever based force measurements; it is possible to minimize lost optical power and therefore spurious interference effects as well as optimizing the optical lever sensitivity with a correctly chosen beam shape. By changing the beam shape as well as the position, it is possible to vary the optical lever sensitivity. It is also possible to vary the dc offset of the detector. DOEs make a continuum of beam shapes available to the experimenter. For optical profiling applications, changing the beam shape allows the resolution of the profilometer to be tuned to the application.

Finally DOEs may be used to modulate the intensity of a single or multiple beams, allowing a variety of other measurements to be made. One example is that this modulation can be used to allow synchronous detection of the position or angle of the sensing element. In the case of sensitive transducers, it is also possible to use the modulated optical energy to actuate the illuminated object, either through light pressure or a number of thermal effects.

There are a variety of commercial DOEs available off the shelf. Numerous manufacturers can fabricate OEM components to a variety of specifications. If active DOEs are used (such as phase shifting liquid crystals or phase shifting reflective mirrors) the beam shape can be dynamically changed as different cantilevers are used. A further advantage of active DOEs is that not only beam shape but also the beam position can be controlled. This allows the beam position to be chosen without any moving mechanical parts. It also makes it possible to change the relative position of the cantilever and detector during the experiment while maintaining the spot focused on the lever. This ability to track the cantilever position means that a variety of beam-tracking AFMs can be realized that do not depend on complicated mechanical apparatus or on heavy optical systems that are scanned along with the moving sensor.

One challenge of a multiple sensor system used for chemical, biological or other sensing applications is separating the beams once they have reflected off the sensors. This can be accomplished with a suitable arrangement of lenses that are used to collect the light and separate it allowing the use of multiple PSDs. As mentioned above, programmable DOEs allow the possibility of modulating the intensity of individual beams in an array, allowing it to be unambiguously identified by a PSD even in the presence of other beams or other background noise. Again, as mentioned above, all of this is accomplished without the use of any moving parts. These arrays can also be translated by changing the DOE diffraction grating or hologram to account for changes in the cantilever position, either intentional (such as a positional change associated with scanning) or incidental (such as thermal drift) during the course of an experiment or measurement.

It has been pointed out that optical beams either through photon momentum changes, thermal effects or other means can cause mechanical changes in micromechanical components. DOE based sensors are compatible with a positional measurement being made with one beam while another is used to effect mechanical changes. Again, this can be accomplished with one light source if the experimenter wishes. Examples include exciting oscillations in a cantilever by sinusoidally varying the optical intensity and canceling the effects of thermal noise to enable low noise force measurements. As above, it is also possible to do this with an arbitrarily shaped array of a plurality of micromechanical components. Also as above, the beams can be translated either individually or as a unit during the course of the experiment by appropriate changes of the DOE diffraction grating or hologram.

In the case of translating beam spots, the appropriate diffraction or hologram could be calculated ahead of time, stored and simply played back to the active DOE when necessary.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**: Prior art showing the optical detector for a scanning probe microscope with the cantilever fixed in the reference frame of the detector.

FIG. **2**: An optical detector for an SPM using a DOE that allows tracking of the cantilever position as it is scanned over a sample surface relative to the optical components.

FIG. **3**: Prior art showing the use of two independent beams to detect an array of two or more SPM cantilevers.

FIG. 4: An optical detector using a DOE to form two beams to detect an array of SPM cantilevers or micromechanical sensors.

FIG. **5**: An optical detector using a DOE to form two beams to detect an array of SPM cantilevers or micromechanical sensors that allows the signal from the beams to be identified and measured by a single detector.

FIG. **6**: An optical detector using a DOE to form two beams to detect an array of profilometer styli.

FIG. **7**: An optical detector using a DOE to form two beams to detect an array of torsional micromechanical sensors.

FIG. **8**: Prior art showing variation of the laser beam spot size in a SPM optical detector to change sensitivity.

FIG. **9**: A specular reflection optical profilometer using a DOE for measuring several surface profiles or positions simultaneously

FIG. **10**: A diffuse reflection optical profilometer using a DOE for measuring several surface profiles or positions simultaneously.

FIG. **11**: A DOE used to position two or more beams of light on an array of non-mechanical sensors.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. **2** shows an optical detector for an AFM using a DOE according to the invention disclosed herein. The purpose of this embodiment is to redirect an incident beam onto the cantilever as the cantilever moves, for example, as it scans over a surface relative to the optical assembly, where the cantilever and the optical detector are in different reference frames. Previous schemes devised to solve the problems presented by AFMs which decouple the cantilever and the optical detector have employed conventional optical technology. The most successful, based on a tracking lens that moves with the piezo tube scanning the cantilever, is described in US Patent No. 6,032,518. . A major disadvantage of this and other schemes to deal with these problems is that they require the optical elements to be carried along with the cantilever. This adversely affects the AFM performance by requiring time consuming and imperfect factory adjustments of the optical elements to optimize the tracking performance and by adding extra mass to the cantilever scanning mechanism, slowing its response. The apparatus described in FIG.2 overcomes both these difficulties. Because the DOE can be computer controlled, the tracking can be automatically and continuously adjusted to optimize tracking. Furthermore, since the DOE is positioned in the optical assembly, fixed in the reference frame of the other optical elements, there are no extra masses carried by the cantilever scanning mechanism, allowing much faster operation and a much simpler design.

The FIG. **2** optical detector, like the prior art optical lever system illustrated in FIG. **1**, employs a light beam **2**, preferably formed by a laser **1** (including a superluminescent laser diode) with sufficient intensity and lack of pointing or other noise, which is directed through a collimation lens or lens assembly **3**. The function of this light beam in the FIG. **2** optical detector and the others elements of this detector are however different and distinct from the prior art optical lever system illustrated in FIG. **1.** In the FIG. **2** optical detector, the collimated or nearly collimated beam **4** emerging from the collimation lens or lens assembly **3** is directed through an adjustable DOE **11** which transmits the incoming beam **4** in a first beam **12**. At a later time, in order to track the position of the cantilever, the DOE is adjusted to transmit a second beam **13** instead of the original beam **12**. Those skilled in the art will appreciate that transmitting the beam **4** in two successive but different beams is arbitrary and, were it necessary for tracking multiple excursions of the cantilever, the beam could be redirected an arbitrary number of times. The redirected beams are passed through an optional dual lens array **14** and **15,** having the functionality of an optical telescope. The magnification of the telescope can be adjusted to optimize the angular displacement of first beam **12** and second beam **13** and their widths on the focusing lens **5.** In another embodiment of the invention, the telescope can be omitted from the instrument. The light then is directed onto the focusing lens or lens assembly **5** and onto a mirror **6** which will direct the first beam **12** onto a cantilever when it is in the first position **16** or the second beam **13** onto the same cantilever when it is in the second position **17**. The focus lens or lens assembly **5** could be replaced with almost any focusing assembly including any number of objective lens assemblies. The beam reflected from the cantilever, either the first beam **12** or the second beam **13,** is then collected by detection optics, which often include an adjustable mirror and a translation stage for providing an offset to the beam position (not shown), and made to illuminate a PSD **10**. As the cantilever deflects in response to various forces, the position of the reflected spot on the PSD changes, causing a change in the output.

The DOE **11** is shown as being normal to the incident beam **4**. One problem associated with DOEs is that they sometimes allow the zeroth order diffraction energy through to the focal plane. This is often referred to as a "hot spot". By allowing the light to enter at an angle, it is possible to avoid this "hot spot" and only pass through controllable diffracted light.

The DOEs used in this invention can be of the phase-encoding or amplitude-encoding or mixed types. They can be fixed, manually adjustable or computer controllable. Examples of commercially available fixed DOEs include the 7x7 matrix generator (Part A54-195), from Edmund Scientific. Examples of manually adjustable DOEs include single and multiple slit diffraction gratings. Computer control provides some attractive features, one being that the computer can either dynamically calculate or pre-calculate the holograms and then "play" them out to the DOE. An example of a phase-encoding DOE (sometimes referred to as a Spatial Light Modulator, SLM) is the Hamamatsu X7550 or the one dimensional "Shape Shifter" SLM from Meadowlark Optics. Numerous other similar devices are being developed and released as this is written.

This ability to steer the beam has implications for improving the ease of use for an AFM. In current AFMs, cantilevers are loaded mechanically or by hand into a holder. Since there are small variations in the indexing of a cantilever each time one is loaded, it is necessary to adjust the spot position. This is typically accomplished using a mechanical system that changes the inclination and position of the optical axis to maximize the light reflected off of the cantilever. DOE based optics provide a means for making this adjustment without the use of any mechanical components. This has obvious advantages over the current mechanical scheme, both for reliability and for automating the process.

As previously indicated, multiple beam optical detector systems, relying on two or more separate light sources focused onto different locations, have previously been disclosed in the literature. FIG. **3** illustrates one such system (Altmann et al.) employed in an AFM.FIG. **4** shows a multiple beam optical detector for an AFM using a DOE with one light source and split beams focused onto cantilevers locations according to the invention disclosed herein. In this embodiment, **11** is an adjustable DOE that splits the incoming beam **4** into two or more beams. The DOE is adjusted to position the two light beams **18** and **19** on two cantilevers shown as part of an array **20**. In this embodiment, the reflected beams are detected by spatially separated PSDs **21** and **22**. FIG. **5** shows a similar embodiment where the position signals from the two or more reflected beams are detected by a single PSD **23**.

A technology closely related to AFM is surface profilometry. US Patent No. 4,669,300 discloses an illustrative profilometer. Profilers have a sharp stylus that is scanned over a surface. By plotting stylus deflection as a function of position, they develop a surface profile of the sample. The profilometer can be raster scanned in a manner exactly analogous to an AFM cantilever to form a two dimensional image of a surface. As with AFMs, these instruments have significant speed limits. FIG. **6** shows an embodiment with enhanced speed where a DOE is used to project optical spots onto two or more profilometer styli. As with the AFM examples above, the DOE can be used to vary both the beam shape and position, allowing the sensitivity of the detection scheme to vary and to track the position of moving styli.

Cantilevers and profilometer styli are simply two examples of a variety of mechanical sensors that can be measured with the optical beam detection method discussed here. FIG.**7** shows an embodiment similar to that of FIG. **5** where two or more beams are used to measure the angular motion of an array of torsional oscillators **30**.

The position of the optical beam is not the only parameter that can be controlled with an optical detector using DOEs. FIG. **8**, taken from Schaffer et al., shows four successively longer spots, incident on a cantilever visible in the center of the four photographs, resulting from changes in a single slit. This change in beam shape resulted in a change in the optical lever sensitivity. Adjustable DOEs provide much greater flexibility than the methods employed by Schaffer et al., allowing a beam or multiple beams to be shaped dynamically. One disadvantage of the scheme used by Schaffer et al. is that closing the slit to increase the beam length focused on the lever reduces the overall intensity of the beam. Typically, the sensitivity of an optical beam measurement is proportional to the beam intensity. Schaffer et al. were forced to normalize the spot size sensitivity measurements to the reduced intensity. On the other hand, phase shifting DOEs have the advantage of not attenuating the intensity of the transmitted radiation, improving the performance of DOE based beam shaping relative to the scheme used by Schaffer et al. This technique has the advantage of the larger, cantilever beam filling spot size demonstrated by Schaffer et al. without sacrificing light intensity.

Optical profilometers have been used for some time to provide information about the shape of surfaces. Although these profilometers do not have the spatial resolution of an AFM, they do have the advantage of providing a relatively rapid, non-contact measurement. FIG. **9** shows an application of DOEs to optical profilometry where two or more beams can replace the single beam of a conventional optical profilometer characterizing a sample **24**. The optical profilometer shown in FIG. **9** relies on specular reflection from the surface of the sample **24**, while the optical profilometer shown in FIG. **10** relies on diffuse reflection from the surface of the sample **24**. In the embodiment shown in FIG. **10**, the signal from the two or more beams is measured by a single detector **25**. That single detector scheme could be used in the case of the optical profilometer shown in FIG. **9** as well.

There are a number of applications where arrays of sensors that change their optical properties, including reflectance, polarization, transmissibility or fluorescence, in response to specific molecules or other environmental factors may be employed. In this case, there is no mechanical change in the sensor in response to the specific molecules or other environmental factors, but rather a change that is optically detectable. FIG. **11** shows an optical detector using DOEs contructed around such an array. As with the prior embodiments, the ability to position two or more beams has obvious advantages in terms of throughput and simplicity in the design of the detector apparatus. As mentioned above, these sorts of arrays lend themselves to measuring transmitted light using a detector **29** beneath the array surface as well as reflected light using a detector above the surface **25**.

The described embodiments of the invention are only considered to be preferred and illustrative of the inventive concept. The scope of the invention is not to be restricted to such embodiments. Various and numerous other arrangements may be devised by one skilled in the art without departing from the spirit and scope of the invention.

WHAT IS CLAIMED IS:

1. In a cantilever-based instrument, such as an atomic force microscope, an optical position detector comprising:

a light source coupled with a collimation lens or lens assembly;

an adjustable diffractive optical element or elements, such a grating or hologram, positioned to receive the light beam emitted by the collimation lens or lens assembly and transmit the beam as two or more distinct beams with distinct directions, shapes and intensities;

a focusing assembly including any number of objective lens assemblies to focus the beams emerging from the adjustable diffractive optical element or elements on a cantilever or array of cantilevers; and

a position sensitive detector to collect the beams reflected from the cantilever or array of cantilevers, with the output of this detector varying as the deflection of the cantilever or one or more of the array of cantilevers changes.

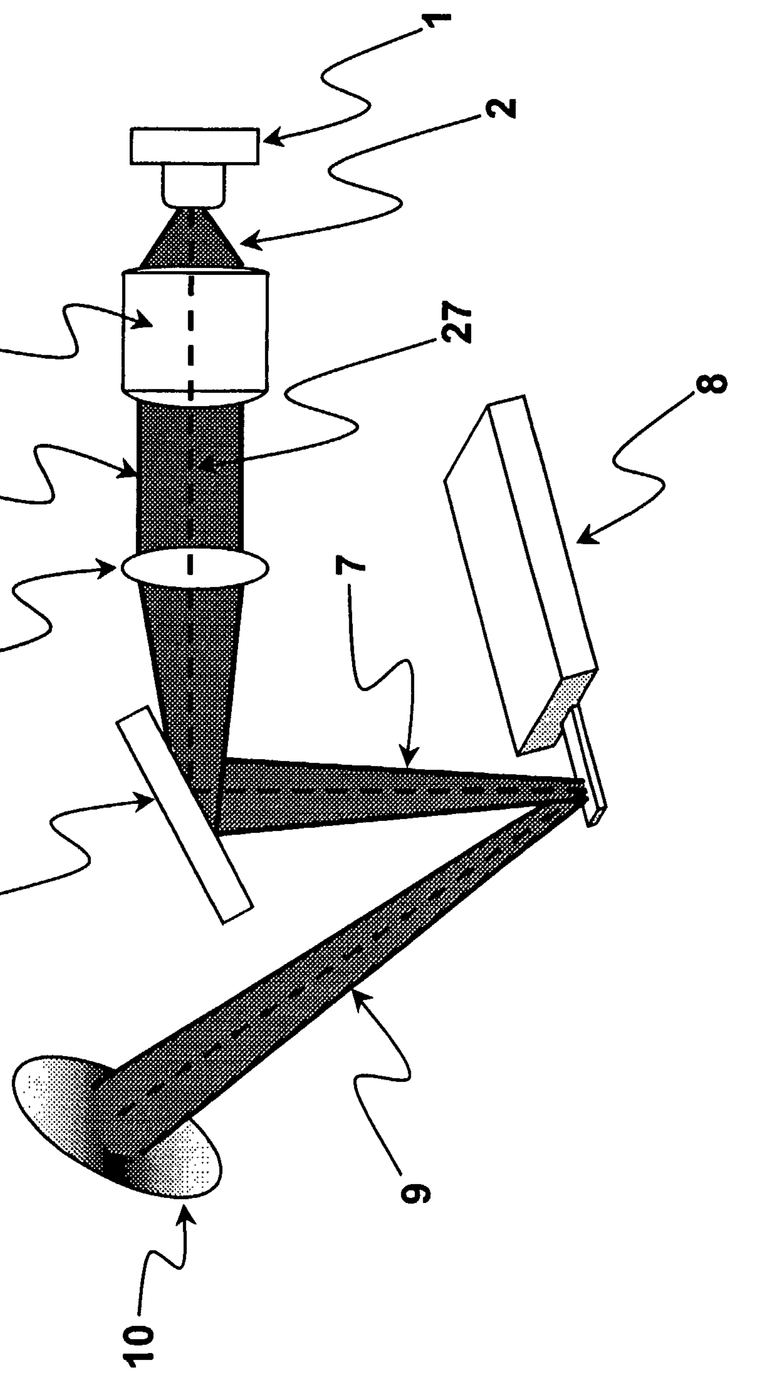

FIG. 1

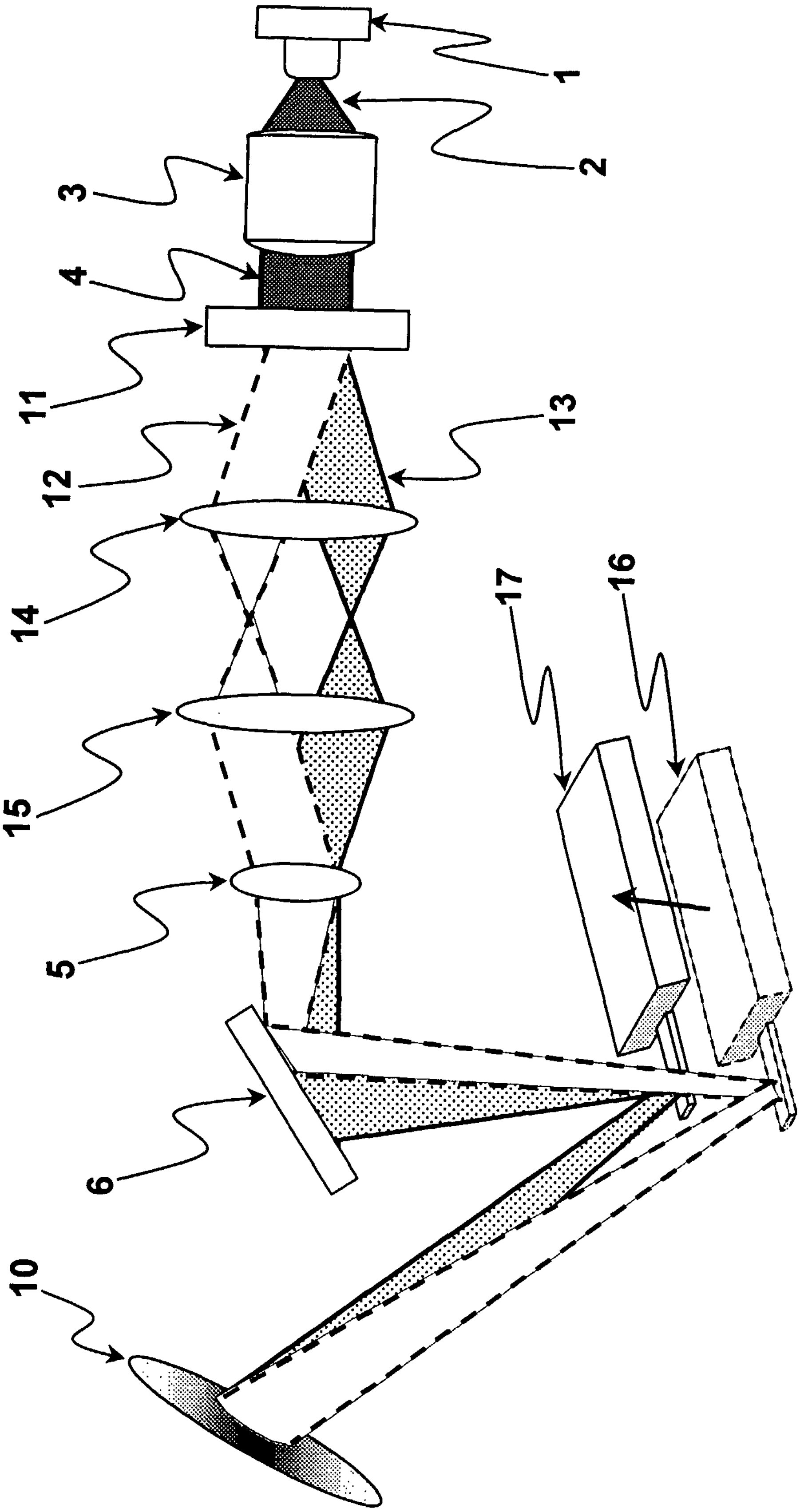

FIG. 2

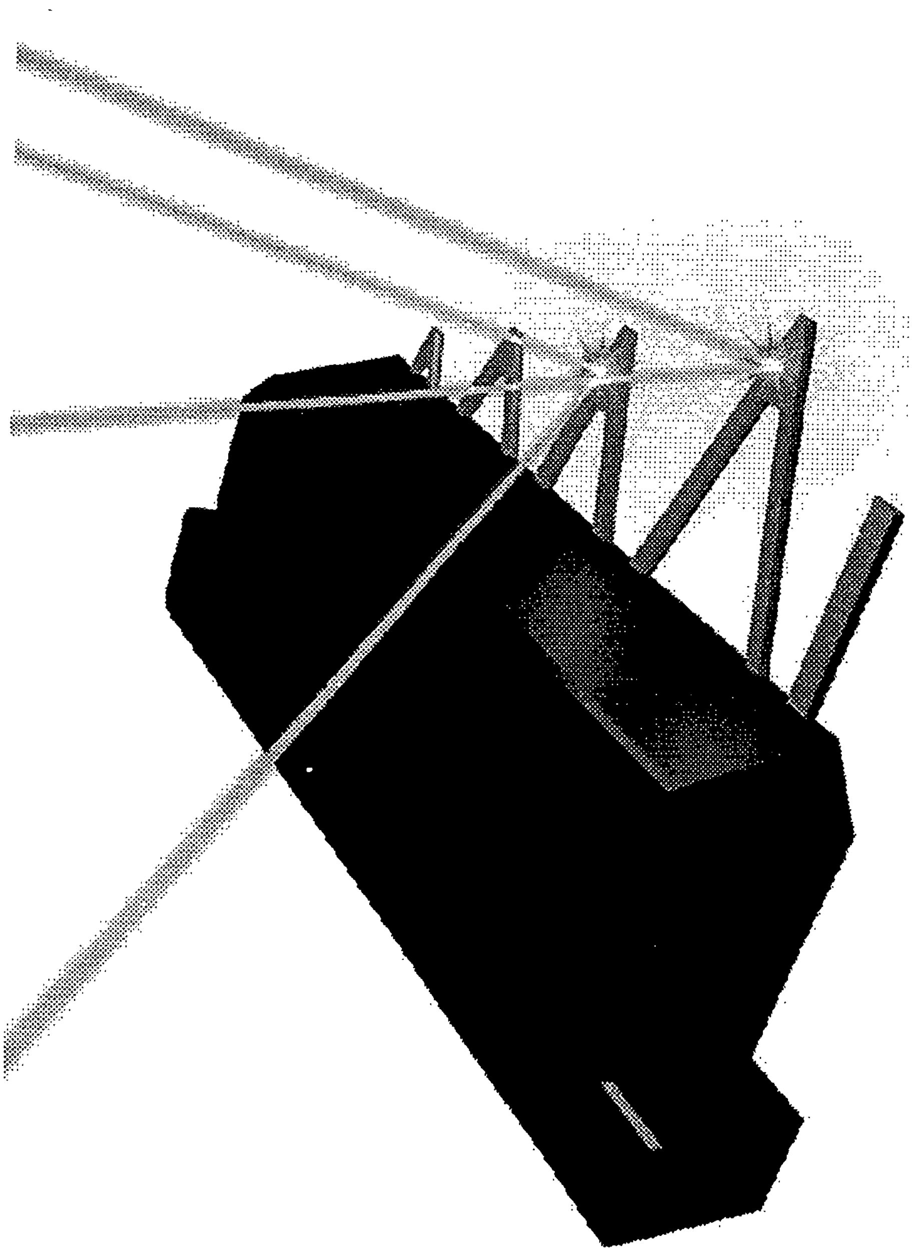

FIG. 3

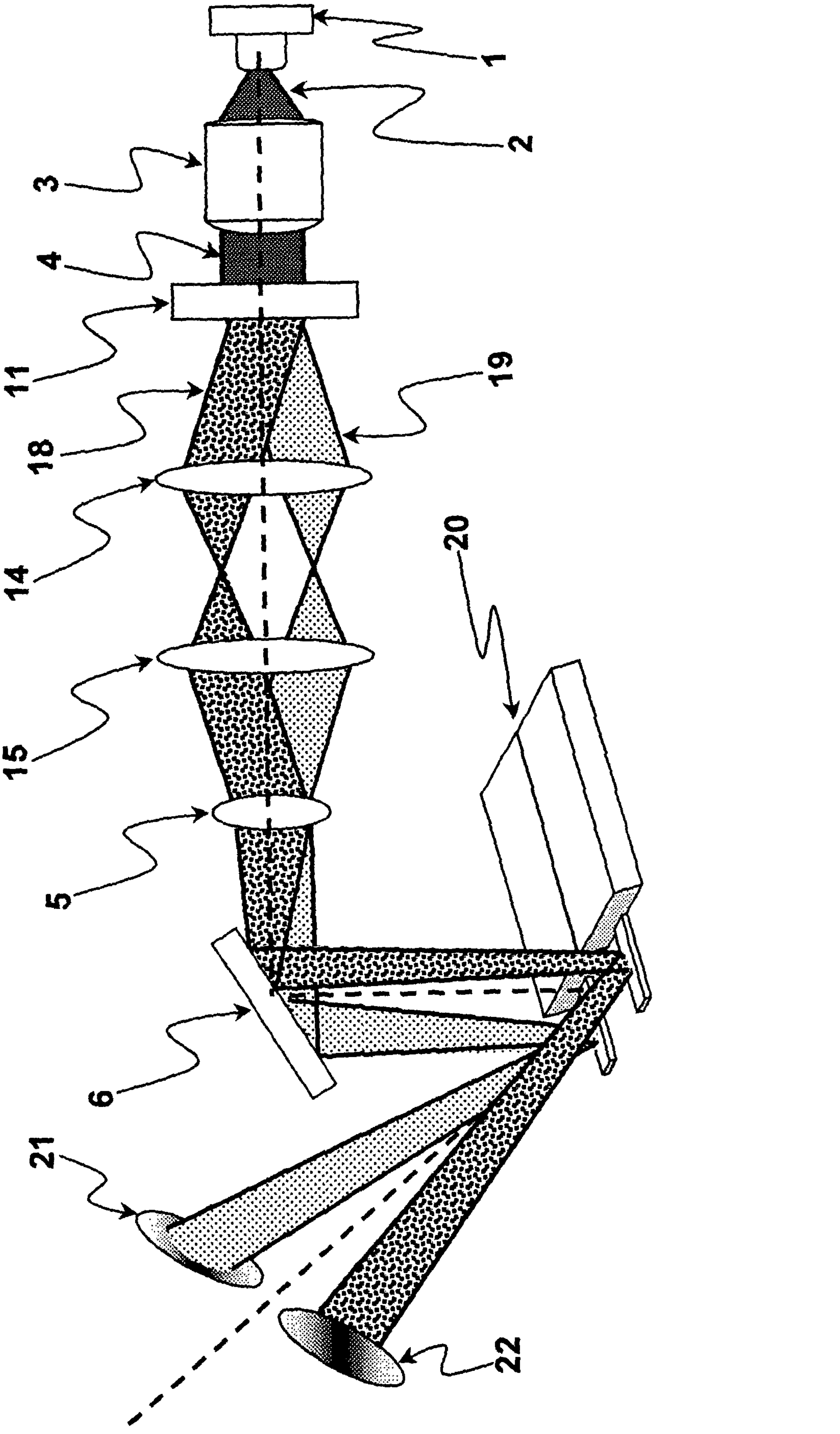

FIG. 4

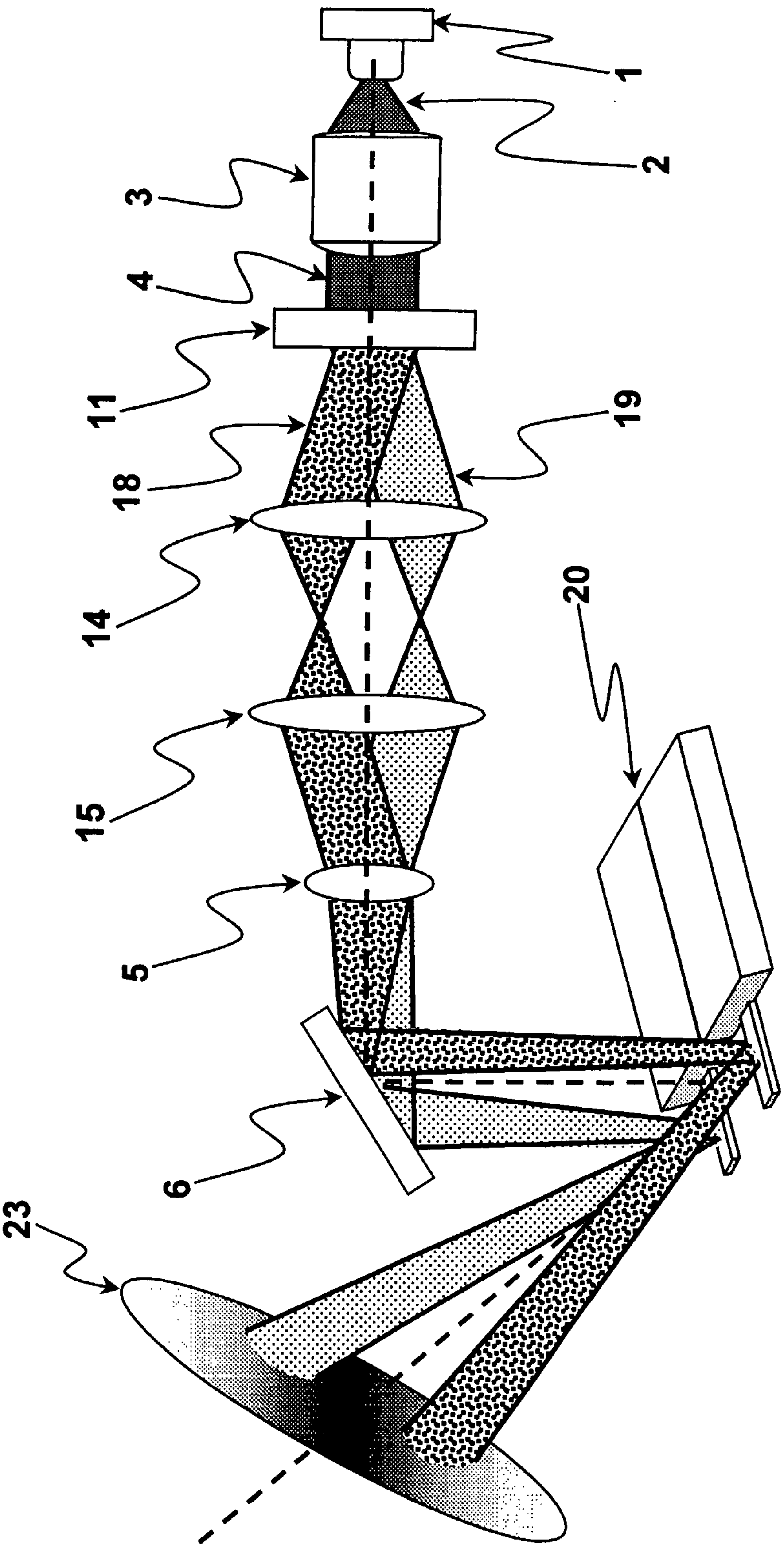

FIG. 5

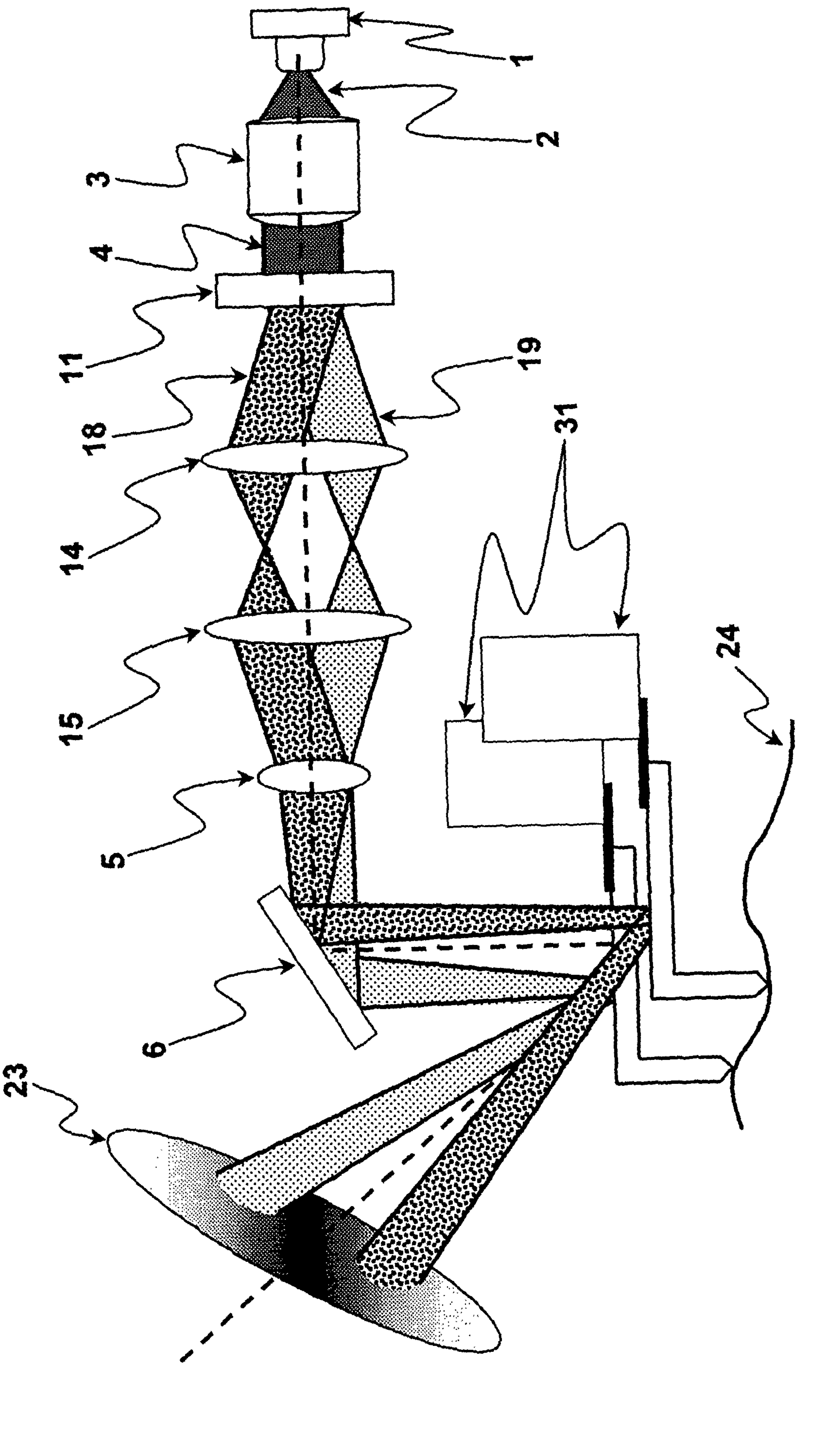

FIG. 6

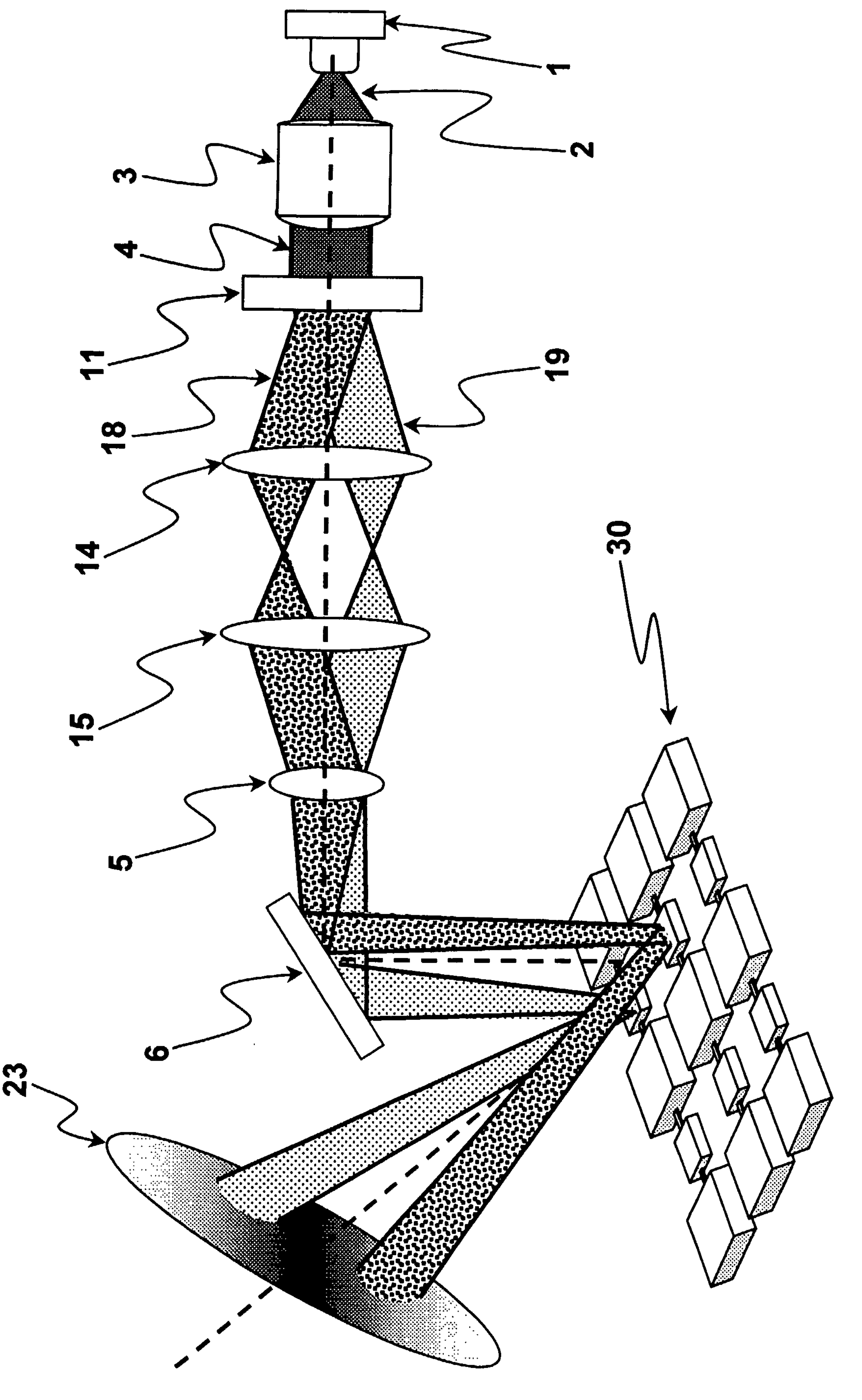

FIG. 7

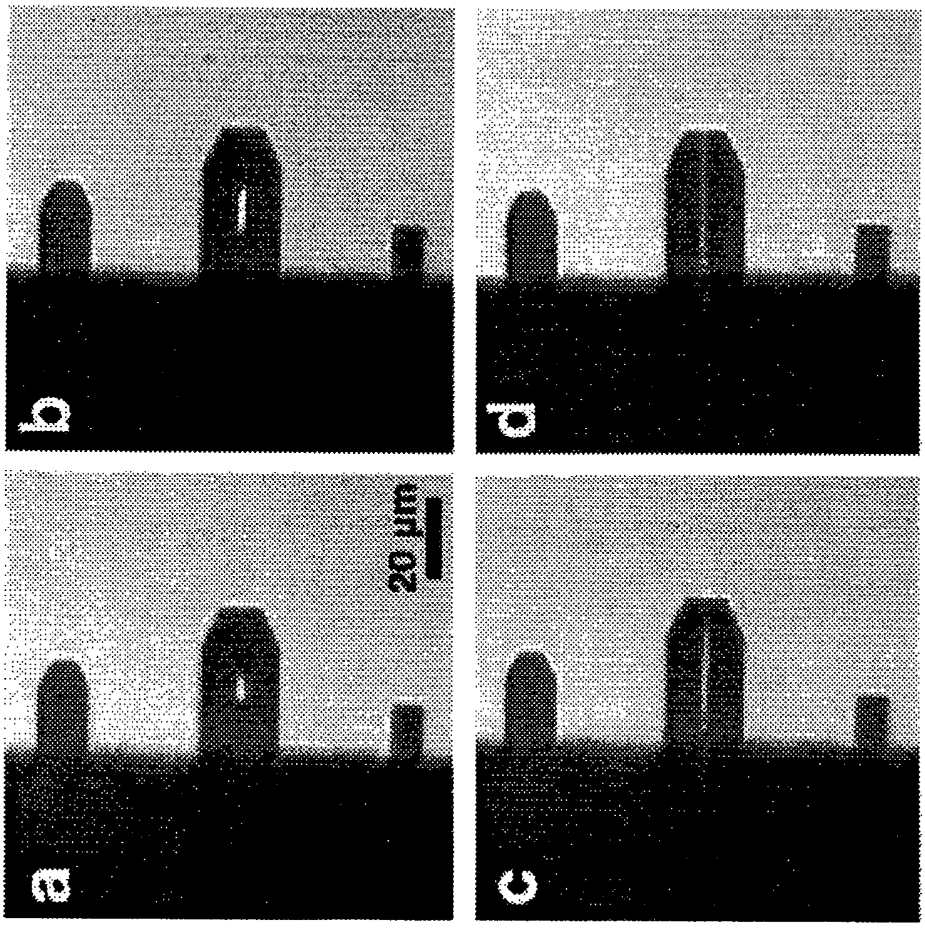

FIG. 8

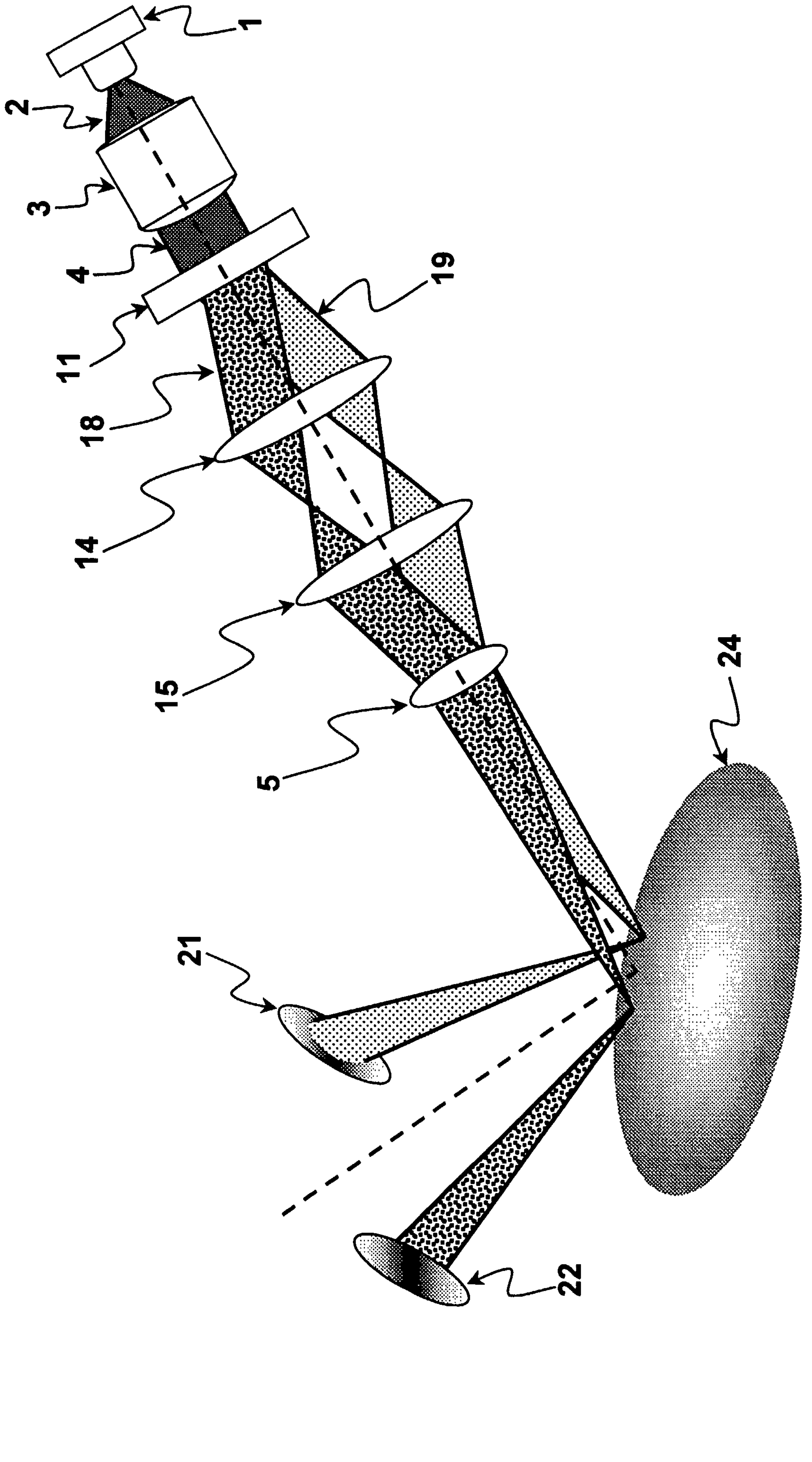

FIG. 9

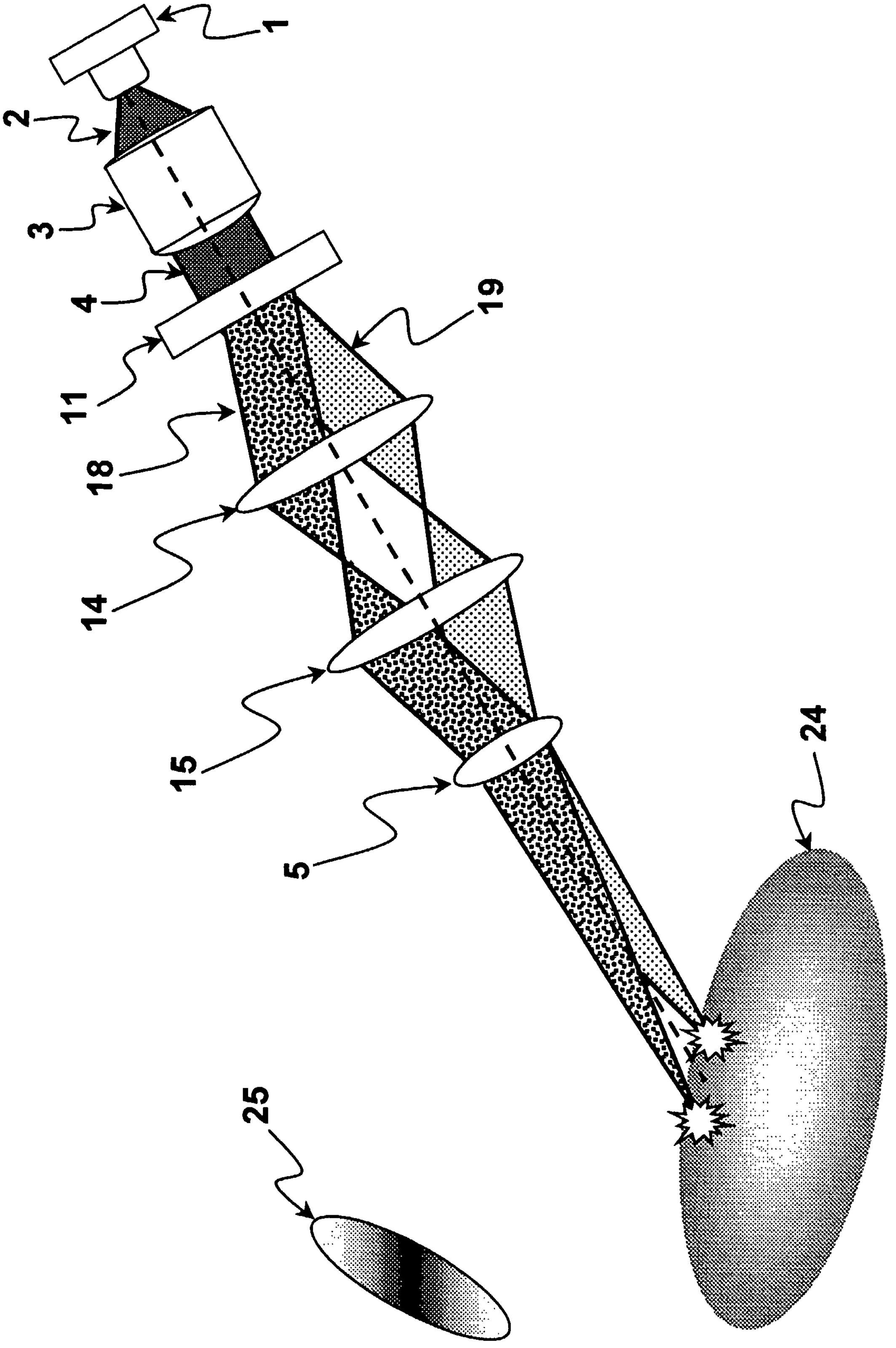

FIG. 10

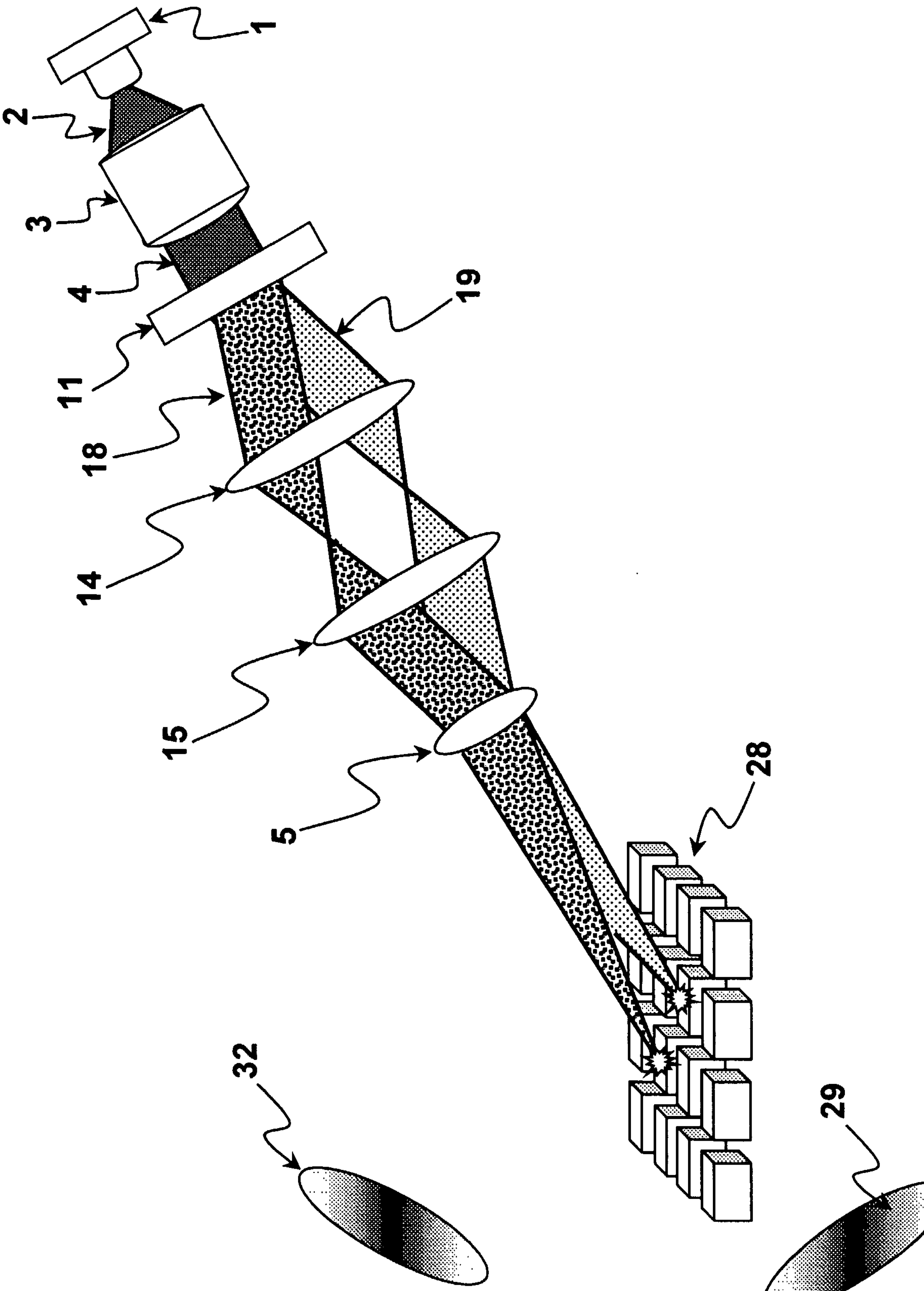

FIG. 11