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# United States Patent [19]

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Stettner et al.

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[54] **3D IMAGING UNDERWATER LASER RADAR**

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[75] Inventors: **Roger Stettner; Howard W. Bailey,**  
both of Santa Barbara, Calif.

### [57] ABSTRACT

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Santa Barbara, Calif.

A three dimensional imaging device and method is presented which uses a pulsed light source for detecting objects enveloped by a light-transmitting and light-reflecting and scattering medium such as water or biological tissues. By means of high-speed switching between many storage capacitors the third dimension is recorded by the device with a single pulse from the light-source. The device consists of the pulsed light source, optics for collecting the reflected and scattered light, one or more sensors for detecting the light, drive and output electronics for timing and signal conditioning of data generated by the sensors and processing electronics and software for converting the sensor data to a three dimensional image. The sensors use known technologies for light amplification but collect and process the light-amplified data in a unique manner, using an analog-processing readout chip. The readout chip is a two dimensional array of collectors or detectors combined in very close proximity with associated storage and switching electronics. The two dimensional array defines two dimensions of the image. The third dimension is associated with the time of return of the light pulse.

[21] Appl. No.: **467,216**

[22] Filed: **Jun. 6, 1995**

### Related U.S. Application Data

[60] Division of Ser. No. 15,627, Feb. 9, 1993, Pat. No. 5,446, 529, which is a continuation-in-part of Ser. No. 856,019, Mar. 23, 1992, Pat. No. 5,475,225.

[51] Int. Cl.<sup>6</sup> ..... **G01C 3/08**

[52] U.S. Cl. .... **356/4.01; 250/332**

[58] Field of Search ..... **250/332, 330,**  
**250/339; 356/5.01, 4.01**

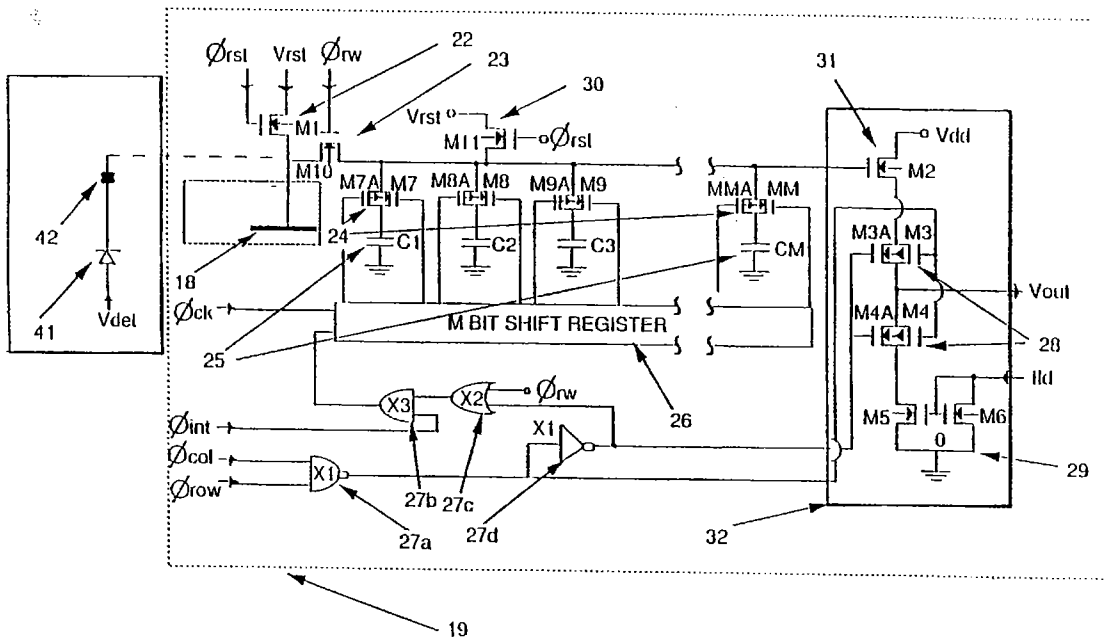
### [56] References Cited

#### U.S. PATENT DOCUMENTS

4,652,766	3/1987	Wang et al.	250/578
5,101,108	3/1992	Gaalema et al.	250/332
5,446,529	8/1995	Stettner et al.	356/4.01

Primary Examiner—Mark Hellner

17 Claims, 11 Drawing Sheets



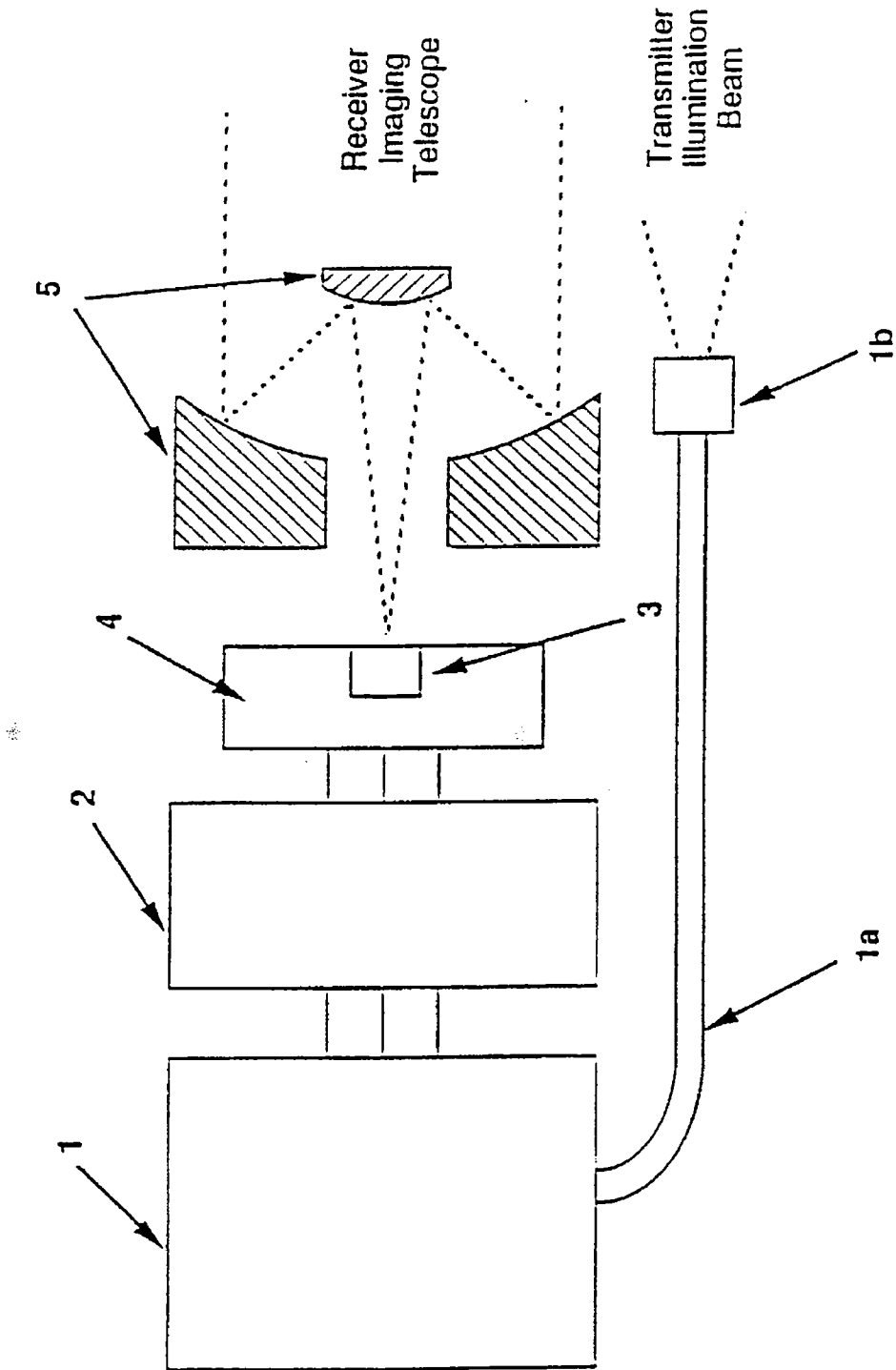


FIG. 1

FIG. 2

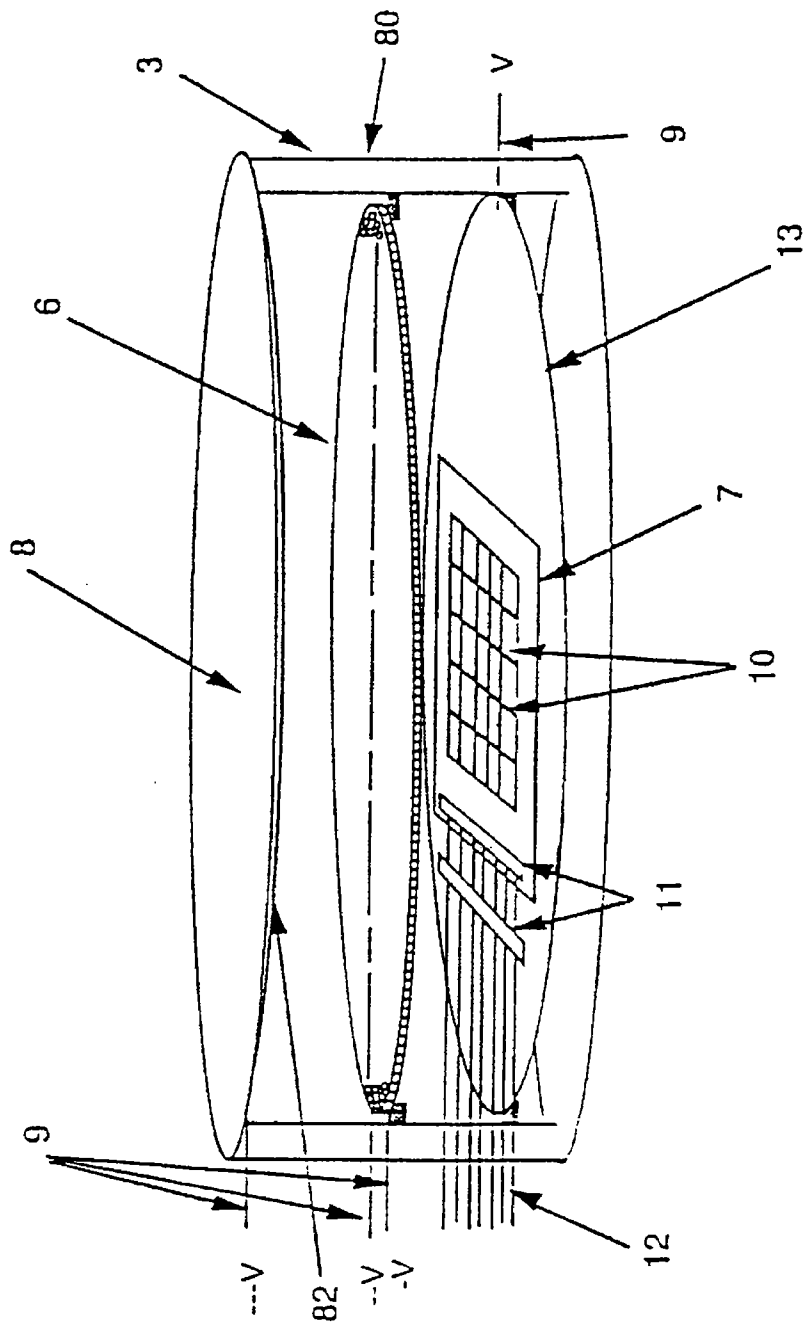


FIG. 3

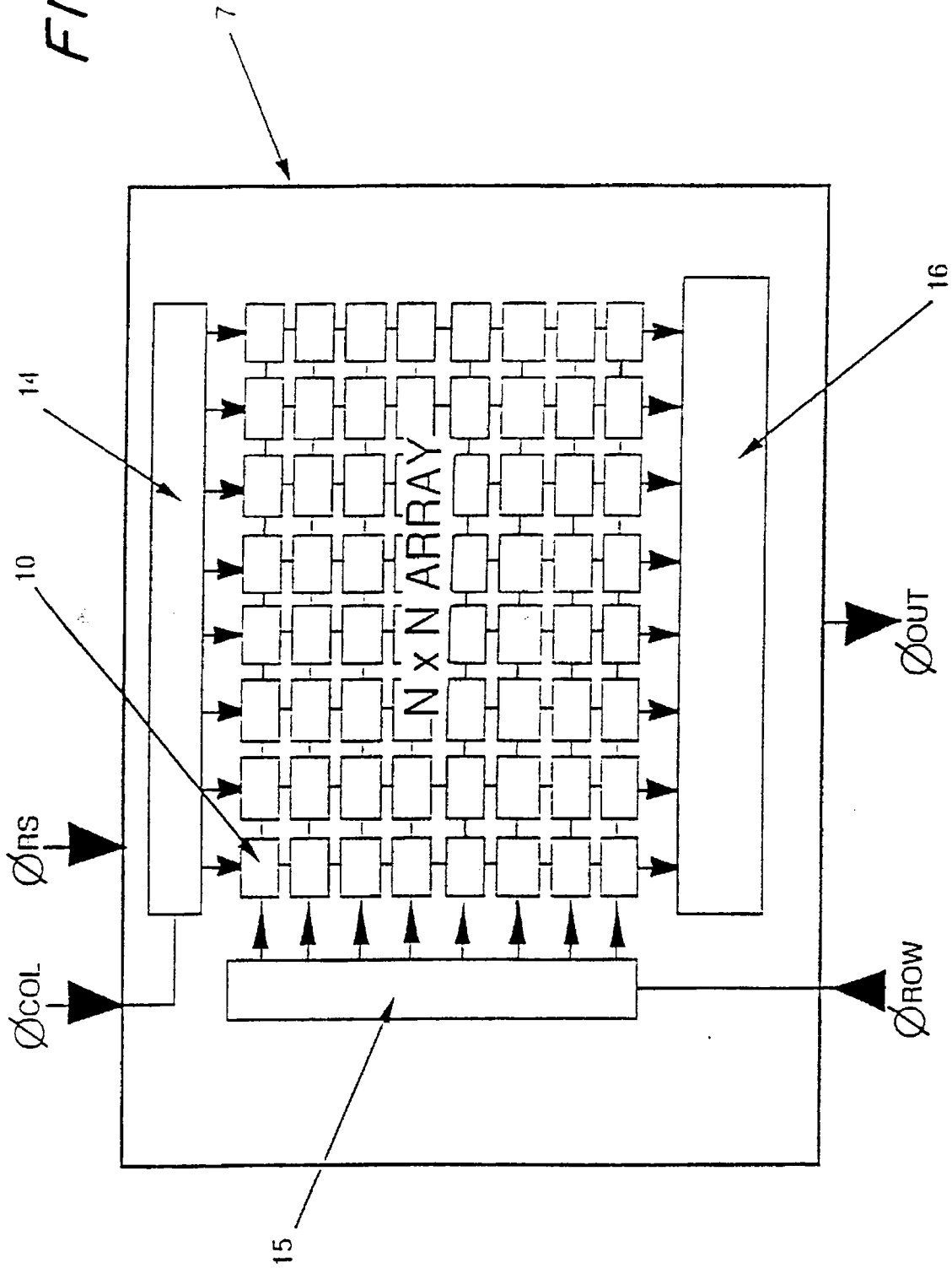


FIG. 4

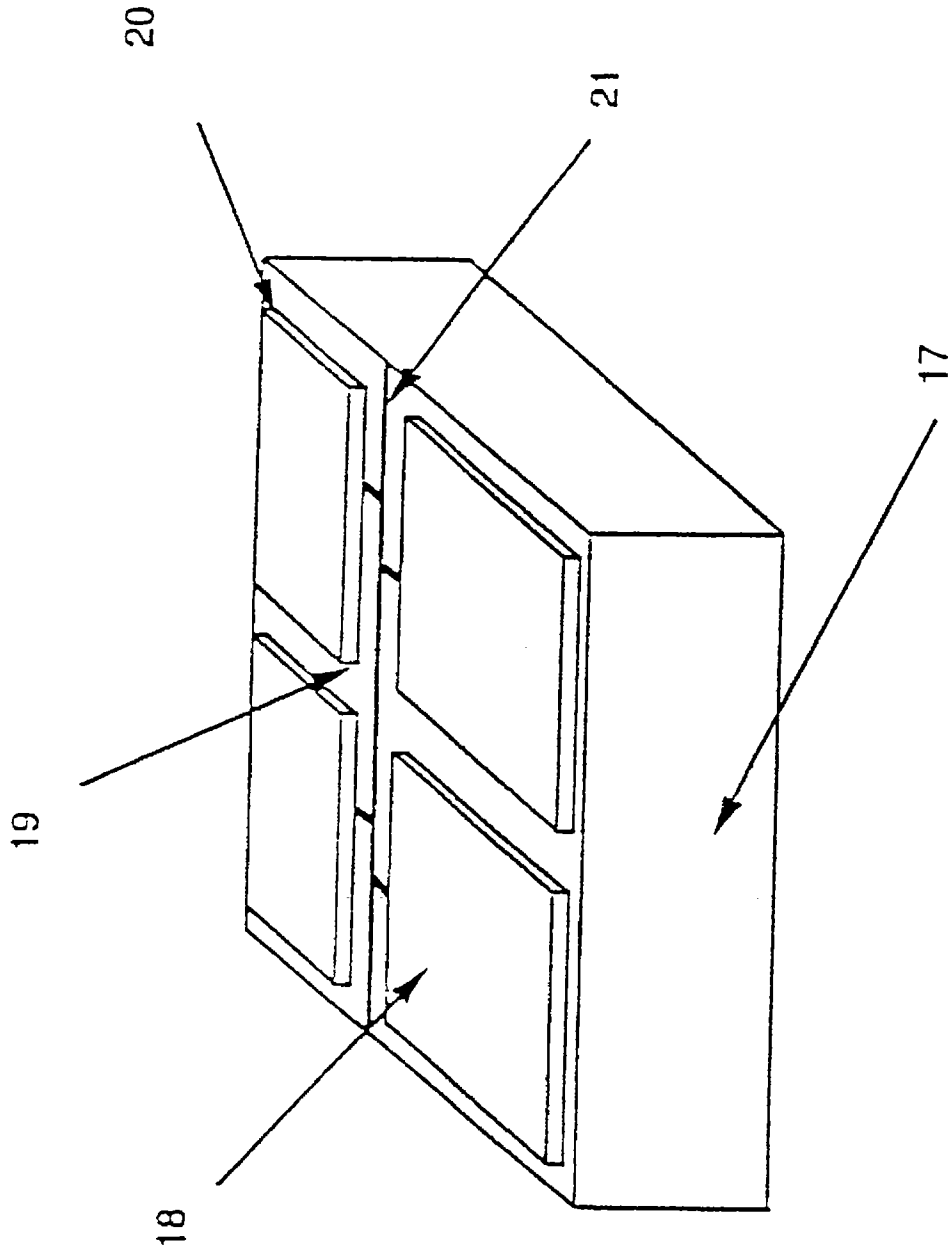
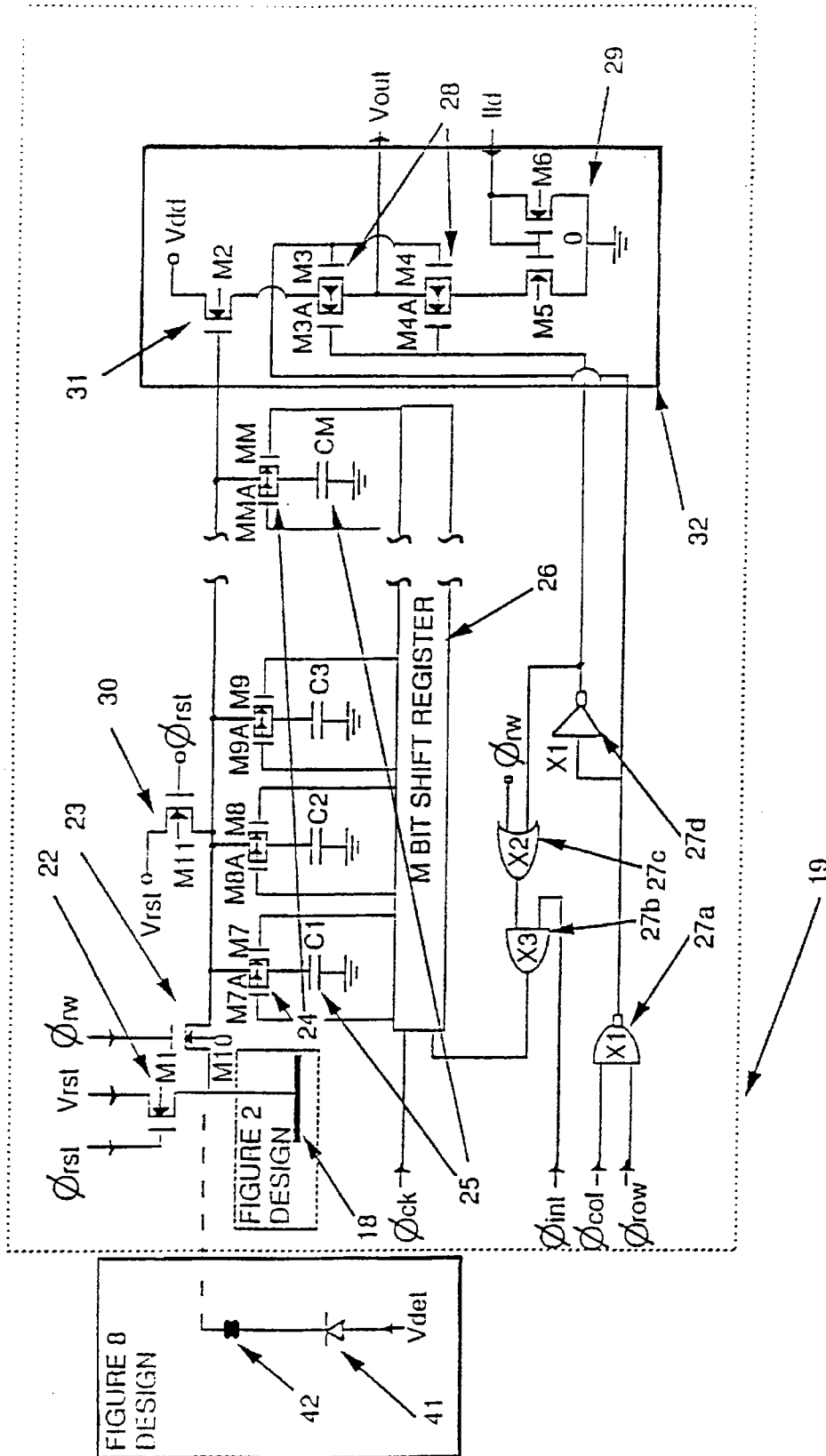


FIG. 5





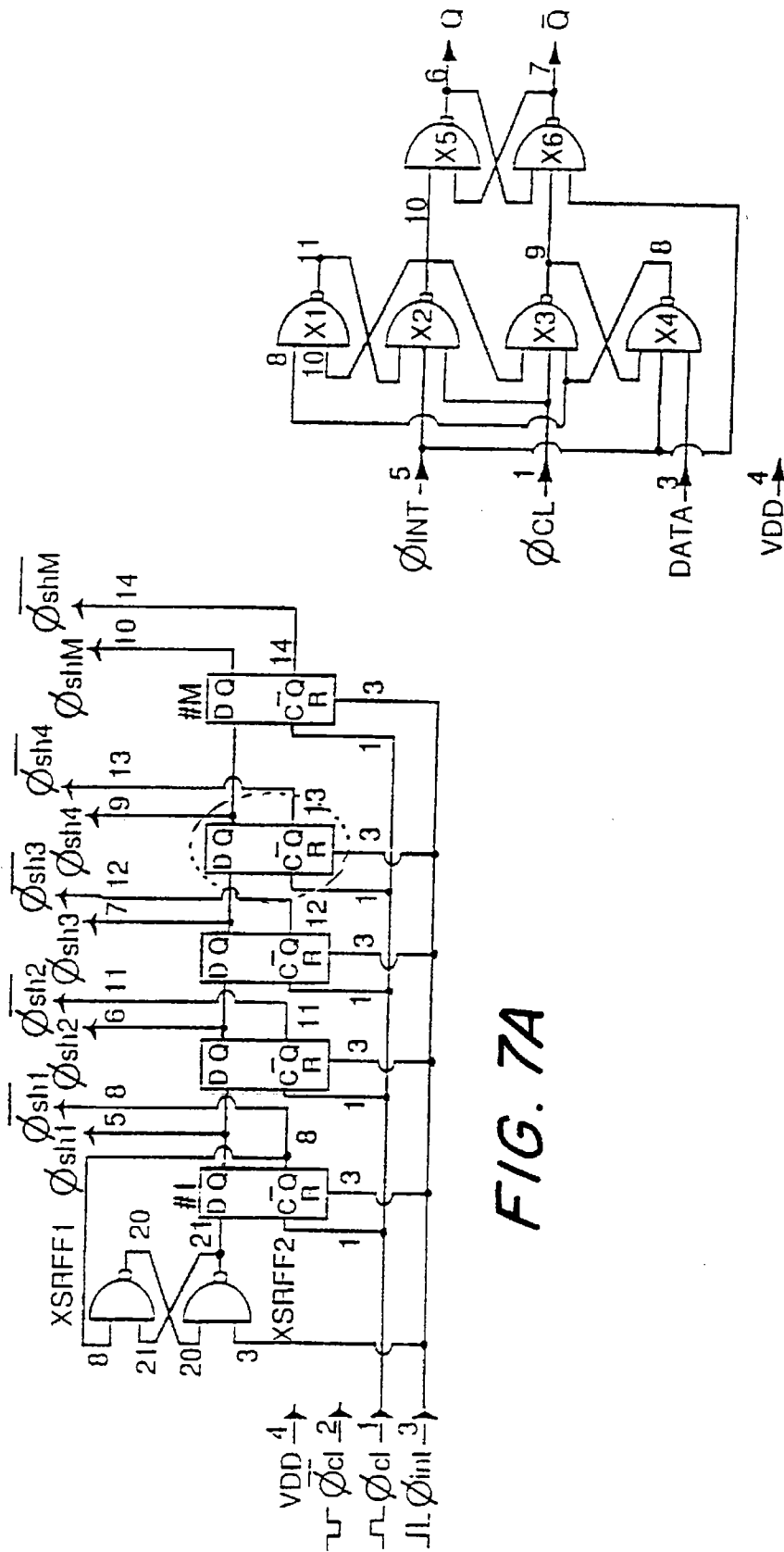


FIG. 7A

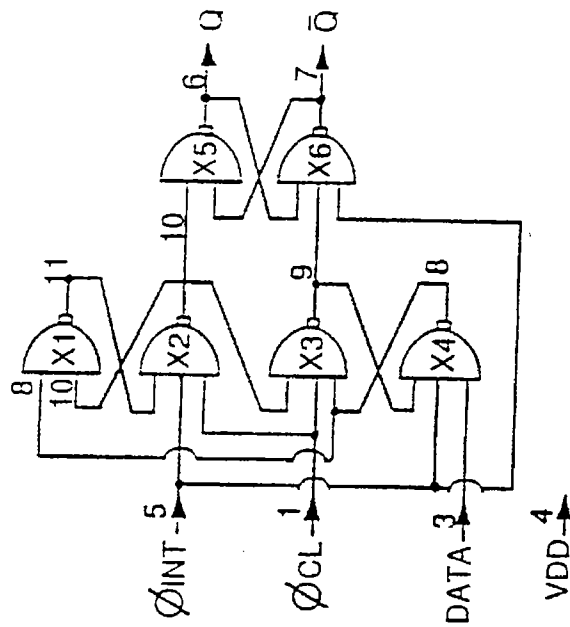


FIG. 7B

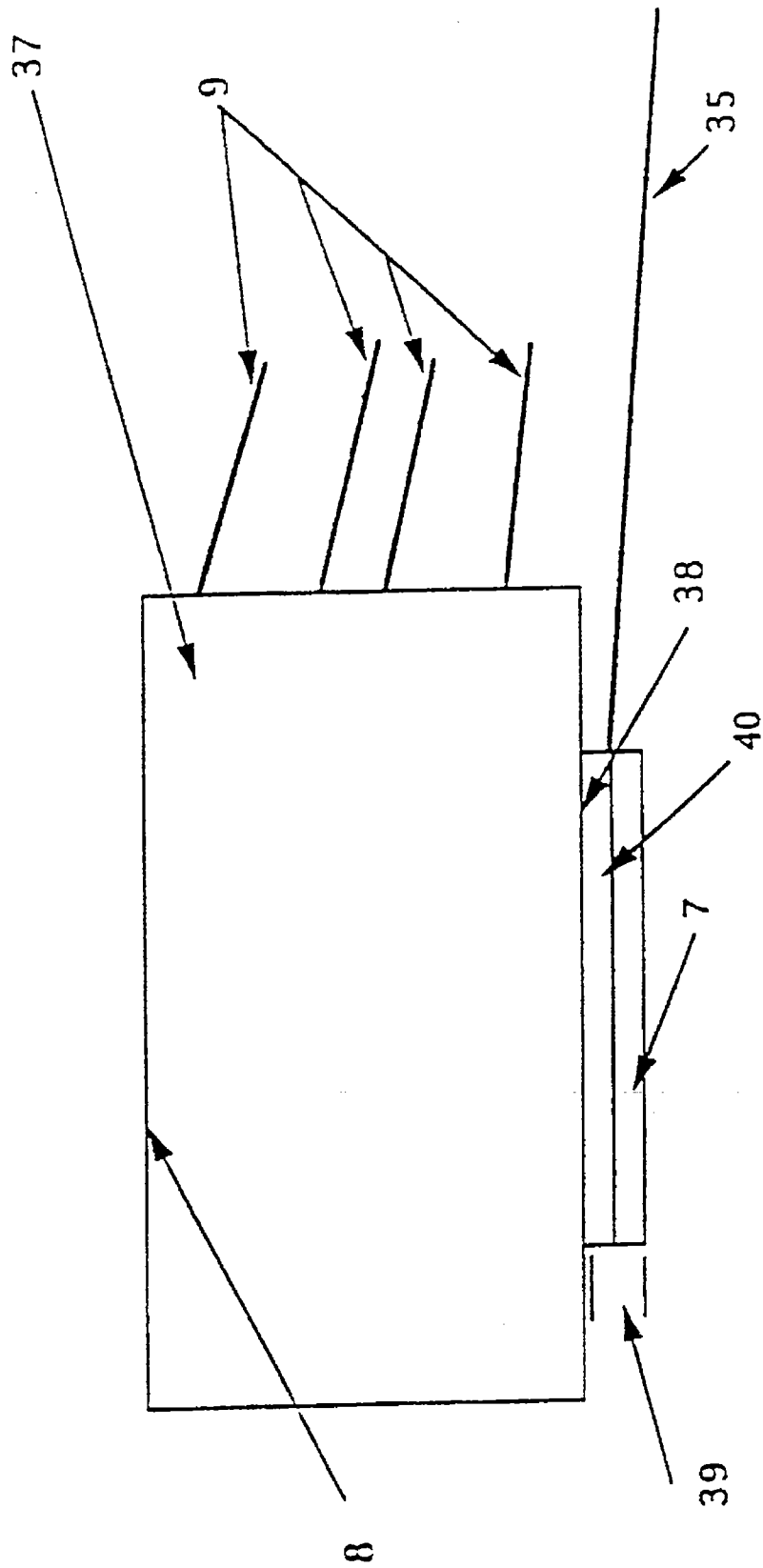


FIG. 8

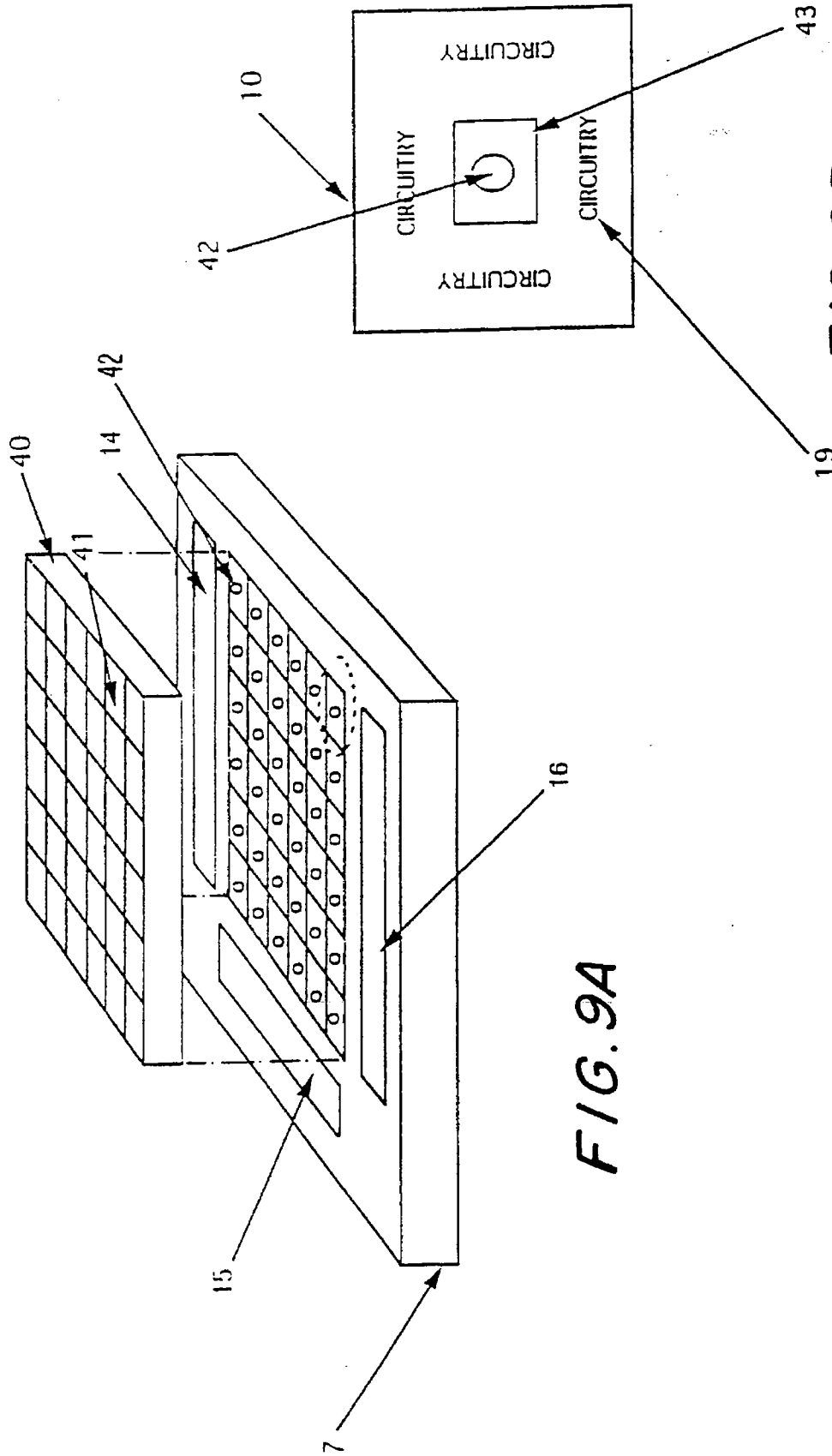


FIG. 9A

FIG. 9B

FIG. 10

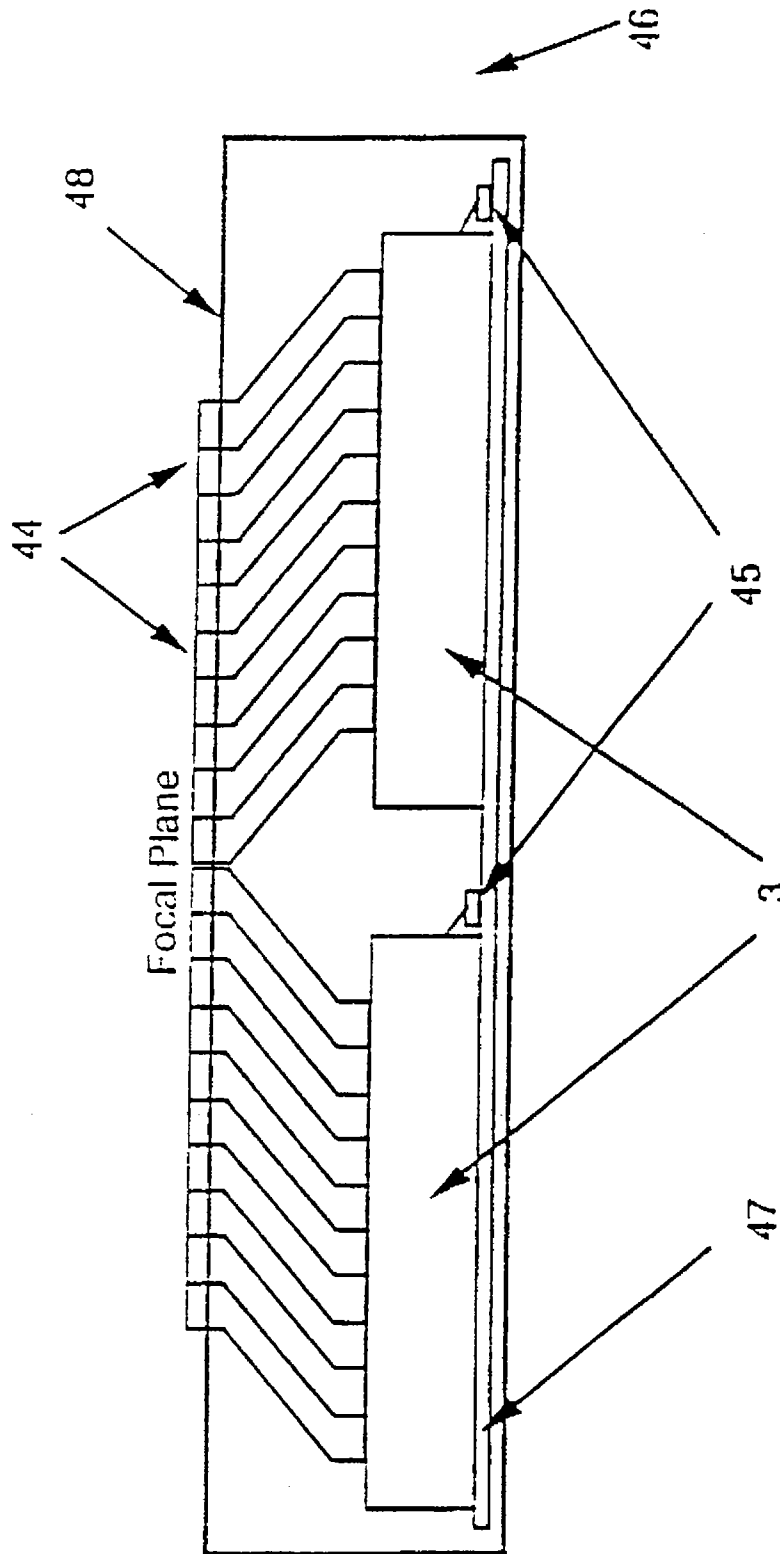
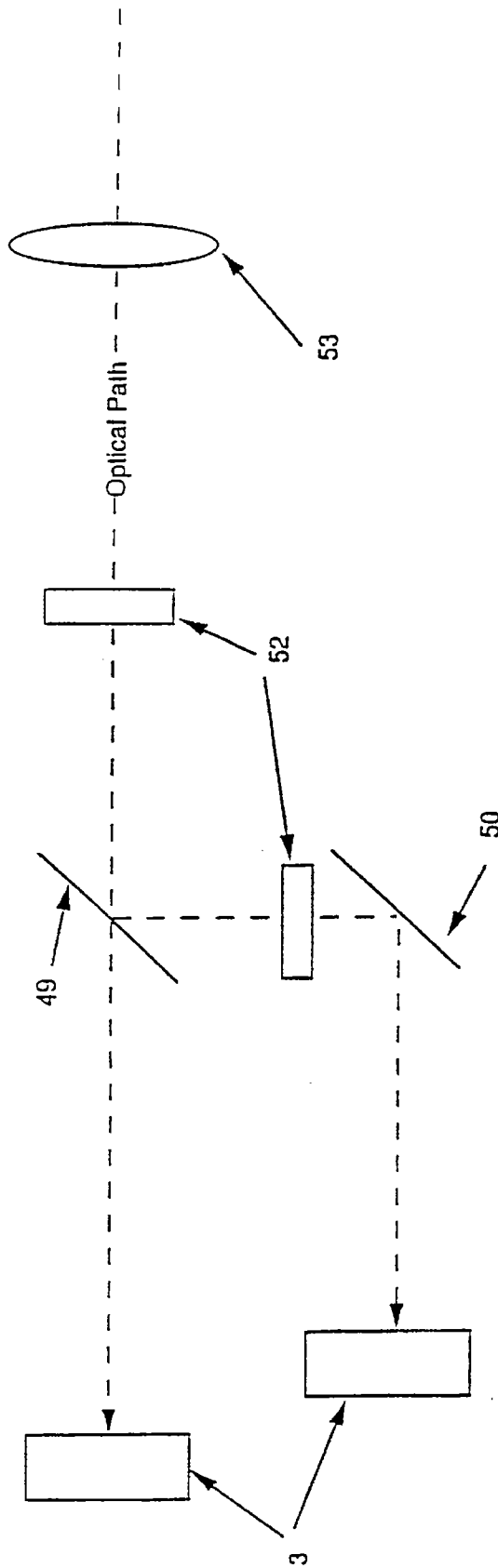


FIG. 11



### 3D IMAGING UNDERWATER LASER RADAR

This is a division of application Ser. No. 08/015,627, filed Feb. 9, 1993, now U.S. Pat. No. 5,446,529, which is a continuation-in-part of application Ser. No. 856,019, entitled "Autoradiographic Digital Imager, filed Mar. 23, 1992, now U.S. Pat. No. 5,475,225.

#### BACKGROUND OF THE INVENTION

This invention relates to underwater laser radar vision apparatus capable of viewing from either above or below the water surface. In particular, it relates to electronic apparatus for capturing a three dimensional image of a target from reflected laser pulses.

Laser radars determine depth in a medium by measuring the time difference between the transmission and receipt of a pulse of light and dividing by twice the velocity of light in the medium. Depth resolution in such devices is related to the accuracy of this time difference measurement. At the same time, it is often desirable to image a large surveillance area at each depth. Examples of high-speed underwater viewing applications involving large surveillance areas are bottom, reef and harbor terrain mapping as well as fish school location and evaluation from an aircraft. Examples of underwater viewing where accuracy of object identification is more critical than large-area surveillance are underwater vision for divers and vision for underwater remotely piloted vehicles engaged in inspection and salvaging. Current underwater laser radar designs are limited by their area and depth coverage rate, by their spatial resolution, by their depth resolution, by the weight of their receiver and by the high receiver power necessary to operate the design.

One current underwater laser radar technology utilizes a system employing a single detector. That system requires a separate laser pulse for every pixel in the two dimensional area associated with each depth. J. Banic, S. Sizgorio, and R. O'Neil, "Airborne Scanning Lidar Bathymeter Measures Water Depth", SPIE Proceedings, Vol. 663. That system is severely limited in both area and volume coverage rate because lasers lose their efficiency at high pulse rates. For an  $N \times N$  pixel array, at a single depth, the present invention could be as much as  $N^2$  times faster. To achieve wider area coverage, laser radars employing a single detector use a mechanical two-dimensional scanner. This scanner is a drawback because of its additional weight, the problem of mechanical unreliability and the complexities of its attendant pixel-registration processing.

Some single-detector underwater laser radars combine the single pixel with a high-speed real-time digitizer to improve depth coverage. The slowness of the digitizer, however, limits the dynamic range of depth values that can be digitized. A laser return signal from deep underwater objects can be four or five orders of magnitude weaker than the return signal from near surface objects. Current real-time digitizers are not fast enough to convert analogue values over such a large range into digital values. A logarithmic depth scale is sometimes used to increase dynamic range but this results in an undesirable reduction of depth resolution. The small dynamic range of available digitizers means that only a limited depth can be explored by a single pulse in these devices. As a result, the field of this invention is characterized by requiring many laser radar pulses to scan both depth and area.

The limited dynamic range of current underwater laser radars is due in part to the use of real-time, high-speed digitizers to continuously digitize the return signal. The

return signal which must be digitized is continuous due in part to water scattering light back into the receiver and attenuating the return signal approximately exponentially with depth. To further complicate matters, the time during which returns are possible is short (about a microsecond for light to travel from the water surface to the maximum depth and back to the receiver) and digitization of an analog signal is a complex process requiring that many operations be compressed into that short time. The requirement of high-speed digitization therefore requires high power and much supporting hardware. Thus, the single pixel real-time digitization scheme has limited application because of its relatively large weight, large volume and high-power requirements. A remotely piloted vehicle, for example, may run its motor and all other equipment on batteries and cannot afford sensors with large power requirements.

Attempts to use standard or modified two dimensional detector arrays to solve the area coverage problem of single detectors has not satisfactorily solved the depth resolution problem. Two dimensional detector arrays employing charge coupled devices (CCDs), have been proposed, in combination with gated microchannel plate image tubes, for underwater laser radar receivers. Barry A. Swartz, Laser ranged-gated underwater imaging including polarization discrimination, Pg. 42, SPIE Vol. 1537. Underwater Imaging, Photography and Visibility (1991). They are unsatisfactory for depth coverage because of the substantial time (milliseconds) required to read the information off the arrays. Only a single depth slice can be acquired with one laser pulse and one image tube. Depth resolution depends upon measuring differences in the arrival time of light in nanoseconds (ns) and more than one depth slice cannot be acquired by slow CCD detector array readouts. For example, it would be necessary to resolve arrival time to 5 ns, in order for the position of an underwater object to be resolved to 50 cm.

Two methods have been proposed to get around the detector-array slow-readout depth-resolution problem. The first method uses multiple CCD arrays with image tubes which are turned on or gated-on at different times. A drawback of this method is still the unwieldy number of detector arrays required to obtain acceptable depth coverage over the full depth range with one laser pulse. The method merely makes a compromise between the number of detector arrays and the number of laser pulses required for complete depth coverage. The maximum number of pulses are required for depth coverage in the limit of a single detector array. Because of the limitation in gating speed and the fact that only one two dimensional array of data is obtained for each laser pulse, a number of pulses is still required in the multiple gating-on image tube system for complete area and depth coverage. Aside from compromising on the number of pulses, the gating-on of multiple photo-cathodes is difficult to optimize for maximum depth penetration. Maximum penetration requires not only gating-on but also gating-off the image tubes in a short time consistent with the laser pulse length.

The failure of prior systems to optimize depth penetration is a serious matter. Depth penetration is limited for underwater laser radars even in the clearest water, and maximum depth penetration is needed for system flexibility. Penetration at best is only about 100 m-200 m and depends directly upon the return signal-to-noise ratio, which is maximized if the minimum number of extraneous photons are counted along with the object-reflected return photons. Extraneous photons, however, are always present from water backscatter and other light sources, particularly in daytime. The

maximum signal-to-noise ratio is achieved if the photon integration time is the same as or smaller than the laser pulse interval (about 10 ns). It is difficult to gate the detector-array image tubes on and off in so short a time to achieve this level of signal-to-noise optimization. In addition, in prior systems, practical depth resolution requirements, with a reasonable number of arrays or cameras, also prohibits signal-to-noise optimization.

The second prior system to circumvent detector-array slowness uses an alternate gating scheme where the receiver consists of a detector array and a separate single detector. Two or more series of laser pulses are required; the first series of pulses finds the target depth much as the single-pixel underwater radar described above, except that the pixel of the single detector may now cover the same areas as the entire detector array. Once the target depth is determined, the detector array is gated to produce a two dimensional image at the correct depth. This system could be used with microchannel-plate image tubes or a Digicon. (A Digicon is a magnetic image tube which uses a diode array instead of a phosphor as the anode. A phosphor is used in a microchannel-plate image tube. Photocathode electrons are amplified by impact with the diodes rather than by means of a microchannel plate.) Again, the shortcomings of this system are the complexity of the need to link two systems and the number of pulses required for the initial depth scan.

Another multiple detector approach avoids the gating problem of detector arrays by providing each detector with its own high-speed digitizer. However, even an 10x10 array—a very low spatial resolution system—requires 100 times the weight and volume of the single detector system. For almost any practical application this is an extremely unsatisfactory system. Nevertheless, such a system has been tested to a limited extent for a space-based Strategic Defense Initiative (SDI) application. The system uses a Digicon and an 8x8 silicon diode detector array. Robert Ginaven, Erik Odeen, Mike Urbach, Frank Feiock, "Laser Radar IV", Proceedings of SPIE, Vol. 1103, pg. 61, Mar. 29-30, 1989. The result was a diode array with a very small field-of-view that must be electronically scanned over its photocathode to obtain the full field of view. Each scan requires a single laser pulse and introduces the same type of problem as the mechanical scanner. Roughly 1000 laser pulses are required to obtain the full field-of-view. However, at present because of the Digicon system's poor field-of-view, the inherent weight and power requirements of its magnetic subsystem, and its 64 digitizing systems, it is not a practical solution to the multiple detector underwater laser radar imaging problem.

A photon amplifier, either in the form of a Digicon or microchannel plate image tube, in the case of multiple-pixel laser radar configurations, is required to overcome internal sensor noise, increase signal-to-noise ratio and therefore optimize penetration depth. A single pixel system uses a photomultiplier tube for the same reason. As described in U.S. Pat. No. 5,099,128 a CCD array is not the only option to reading out multiple-pixel data. In the present invention a readout chip can be configured inside the image tube, using anodes or diodes to collect the signal rather than an external CCD array, thus allowing analog processing, in particular, high-speed data storage.

#### BRIEF DESCRIPTION OF THE PRESENT INVENTION

The present invention overcomes the aforementioned limitations by employing multiple capacitors in a specially

designed integrated circuit capable of storing at each pixel the return signal over its full depth range. Rather than working in effect with arrays of cameras, each with a separate detector array, the present invention uses a single detector array, each detector having the ability to store multiple signals. Each detector in the two dimensional detector array is provided with on the order of 100 storage capacitors and switching between them can occur in less than 10 ns. It is not necessary to gate a photocathode on and off to obtain a depth slice. Switching from one capacitor to another, in effect, is a series of high-speed electronic range-gating operations which allows the acquisition of multiple depth slices. The data from this 100 or so depth slices are digitized and read out from the chip during the time it takes the laser to ready for the next pulse. Due to the design of the apparatus and its unique attendant electronics, there is sufficient time during the relatively long period between laser peaks in which to slice the incoming signal into planner segments, store them in capacitors and read out the information, thereby giving a microtome-like sectioning of the three dimensional returning attenuated light pulse. The photon amplifier incorporated into the present invention has sufficient gain to allow photon detection. Multiple image tubes and CCDs, rack mounted electronics and high speed digitizers are avoided, thereby providing orders of magnitude weight and power reduction.

Embodiments are provided where either electrons are collected at anodes or PIN diodes or phosphor produced photons are collected at PIN diodes during the time a return signal is expected.

It is an object of the present invention to provide a device for three dimension imaging of objects enveloped by transmitting and scattering medium and to overcome the problems of such prior systems associated with the need for mechanical scanning, small viewing areas, multipulse depth coverage and multiple two dimensional arrays. The device comprises a pulsed light source, means for projecting the light towards the object, optics for collecting any reflected or scattered light, improved sensors for detecting the reflected and scattered light, and novel drive and output electronics for timing and signal conditioning of data from the sensors and processing electronics and software for converting the sensor data of even a single pulse to a well resolved three dimensional image.

It is further the object of the present invention to provide such sensors which amplify the light and detect and store the light on an improved analog processing readout chip in sequential time intervals indicative of a depth dimension, without the need for a cumbersome sequence of cameras.

It is still further the object of the present invention to provide an analog-processing readout chip comprised of such an array of readout, storage and switching electronics and associated with a corresponding array of collectors or detectors.

It is yet a further object of the present invention to provide such apparatus for imaging sections of biological tissue in vivo near the skin surface.

Other objects of the invention will be disclosed in the detailed descriptions of the preferred embodiments that follow, and from the claims at the end of this disclosure.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a side view of the preferred embodiment of the Three-Dimension Imaging Under Water Laser Radar (3DI-UDAR).

FIG. 2 is a perspective view of one of the sensors of the present invention.

