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(54) **Acoustic printers.**

(57) Sparse arrays of ink droplet ejectors (14) are provided for acoustic printing. The arrays are capable of performing at higher print rates than single ejector printheads because of their parallelism, and they avoid many of the design limitations of ordinary page-width arrays. The increased center-to-center spacing of the droplet ejectors in these sparse arrays significantly simplifies the design of acoustic-lens-type arrays, because larger lenses and transducers may be employed, thereby enabling the transducers to operate at lower power densities, permitting the use of thicker substrates for the lenses while maintaining the diffraction of the acoustic power at a negligibly low level, and increasing the permissible focal length of the lenses so as to permit the use of thicker layers of ink.

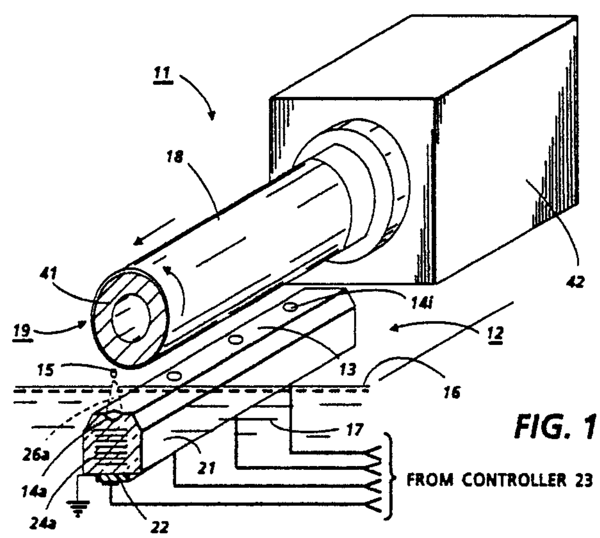

FIG. 1

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## Acoustic printers

This invention relates to acoustic printers and, more particularly, to sparse arrays of acoustic droplet ejectors for such printers.

Substantial effort and expense have been devoted to the development of plain paper compatible direct marking technologies. Drop-on-demand and continuous stream ink jet printing account for a significant portion of this investment, but these conventional ink jet systems suffer from the fundamental disadvantage of requiring nozzles with small ejection orifices, which easily clog.

Acoustic printing is a potentially important, alternative direct marking technology. It is still in an early stage of development, but the available evidence indicates that it is likely to compare favorably with ordinary ink jet systems for printing either on plain paper or on specialized recording media, while providing significant advantages of its own. More particularly, acoustic printing has increased intrinsic reliability because there are no nozzles to clog. As will be appreciated, the elimination of clogged nozzle failure is especially relevant to the reliability of arrays comprising a large number of individual printing devices. Furthermore, small ejection orifices are unnecessary, so acoustic printing is compatible with a greater variety of inks than conventional ink jet printing, including inks having higher viscosities, and inks containing pigments and other particulate components.

When an acoustic beam impinges on a free surface (i.e.. a liquid/air interface) of a pool of liquid from beneath, the radiation pressure which the beam exerts may reach a sufficiently high level to release individual droplets of liquid from the surface of the pool, despite the restraining force of surface tension. To control the droplet ejection process spatially , the acoustic beam advantageously is brought to focus on or near the surface of the pool, thereby intensifying its radiation pressure for a given amount of input power.

Ultrasonic (rf) acoustic beams have been employed in known ink jet and acoustic printing systems for releasing small droplets of ink from pools of ink. For example, K. A. Krause, "Focusing Ink Jet Head," IBM Technical Disclosure Bulletin, Vol 16, No. 4, September 1973, pp. 1168-1170 described an ink jet in which an acoustic beam emanating from a concave surface and confined by a conical aperture was used to propel ink droplets out through a small ejection orifice. US-A-4,308,547 showed that the small ejection orifice of the conventional ink jet is unnecessary. To that end, it discloses providing spherical piezoelectric shells as transducers for supplying focused acoustic beams to eject droplets of ink from the free surface of a pool of ink, and acoustic horns driven by planar transducers to eject droplets of ink from an ink-coated belt.

Classical line printing requires a separate acoustic droplet ejector for each of the picture elements ("pixels") that are needed to define a line of the printed image. This means that a very large number of densely-packed droplet ejectors must be provided to perform line printing at an acceptably high resolution. Acoustic lens arrays for printing at resolutions of 500 s.p.i. or even higher are believed to be feasible, but care has to be taken to avoid crosstalk among the lenses of such an array. The other known acoustic droplet ejection technologies, such as piezoelectric shell transducers and IDTs, are believed to be inferior to the acoustic lens for high resolution line printing, although they are fundamentally acceptable technologies. Unfortunately, raster scan printing with a single acoustic droplet ejector is too slow for many of the applications which are of interest. Accordingly, alternative printer design approaches are still needed to provide increased design flexibility for moderate speed acoustic printers, without sacrificing the pixel placement accuracy or the pixel size control capabilities which make acoustic printing such an attractive direct marking technology.

This invention responds to that need by providing sparse arrays of droplet ejectors for acoustic printing. Sparse droplet ejector arrays are capable of performing at higher print rates than single ejector printheads because of their parallelism, and they avoid many of the design limitations of ordinary page width arrays. For example the increased center-to center spacing of the droplet ejectors in these sparse arrays significantly simplifies the design of acoustic-lens-type arrays because larger lenses and transducers may be employed, thereby enabling the transducers to operate at lower power densities, permitting the use of thicker substrates for the lenses while maintaining the diffraction of the acoustic power at a negligibly low level, and increasing the permissible focal length of the lenses so as to permit the use of thicker layers of ink.

Accordingly the present invention provides an acoustic printer which is as claimed in the appended claims.

This invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a fragmentary, simplified isometric view of an acoustic printer having a printhead comprising a sparse array of acoustic lenses in accordance with this invention ;

Fig. 2 a more-detailed cross-sectional view of the printer shown in Fig. 1;

Fig. 3 is a fragmentary, isometric view of an acoustic printer having printhead comprising a sparse array of piezoelectric spherical transducer shells, and

Fig. 4 is a fragmentary, schematic plan view of a printhead having a two-dimensional sparse array of droplet ejectors in accordance with this invention.

Turning now to the drawings, and at this point especially to Figs. 1 and 2, there is shown an acoustic printer 11 (shown only in relevant part) having a printhead 12 comprising a sparse linear array 13 of acoustic lenses 14a - 14i for ejecting individual droplets of ink 15 (Fig. 1) on demand from a free surface 16 of an ink supply, such as a pool of ink 17, to print an image on a suitable record medium 18, such as a sheet of plain paper. A transport 19 supports the record medium 18 at a small gap distance (e.g., 1 - 2 mm) from the free surface 16 of the ink 17, and the transport 19 advances the record medium 18 crosswise and lengthwise of the array 13 at preselected rates as more fully described below. The speed at which the ink droplets 15 are ejected from the free surface 16 of the pool of ink 17 is sufficiently high to propel them onto the record medium 18 with a well-defined and repeatable trajectory, so the picture elements ("pixels") of the image are printed on accurately-located centers. Indeed, the droplet placement accuracy is sufficiently precise and repeatable that multiple droplets can be effectively deposited on top of each other in rapid succession, before the ink has time to dry, whereby the number of ink droplets 15 per pixel may be controlled to vary the size of the printed pixels, thereby imparting a gray scale shading to the printed image.

The lenses 14a - 14i are defined by small spherical indentations or cavities which are formed in a surface of a solid substrate 21 on relatively widely separated centers, with the center-to-center spacing of the lenses 14a - 14i being selected to ensure that they are effectively acoustically isolated from each other. A piezoelectric transducer 22 is intimately mechanically coupled to the opposite surface of the substrate 21, and a controller 23 (Fig 2) is coupled across the transducer 22 to apply independently controlled rf drive voltages across spatially-separated sites along the transducer 22 during operation. These drive voltages locally excite the transducer 22 into oscillation, thereby causing it to generate spatially separated acoustic waves in the substrate 21, such as shown at 24a in Fig. 1, for illuminating the lenses 14a - 14i, respectively.

The substrate 21 is composed of a material, such as silicon, silicon nitride, silicon carbide, alumina, sapphire, fused quartz, and certain glasses, having an acoustic speed (i. e., the speed of sound in the substrate 21) which is much higher than the speed of sound in the ink 17. Thus, the acoustic waves, such as the wave 24a (Fig. 1), propagate through the substrate 21 at a relatively high speed until they impinge upon the lenses 14a - 14i, respectively, where they exit into a lower acoustic speed medium (i.e., the ink 17 or an intermediate medium) as converging acoustic beams, such as shown in Fig. 1 at 26a. The focal lengths of the lenses 14a - 14i, which typically are approximately equal to their radius of curvature, are selected so that these acoustic beams come to focus approximately at the free surface 16 of the ink supply 17. In practice, the acoustic speed of the substrate 21 preferably is at least about 2.5 times higher than the acoustic speed of the ink 17, which is sufficient to ensure that the aberrations of the focused acoustic beams, such as 26a, are small. Indeed, an acoustic speed ratio of 4:1, or even higher, is readily achievable should it be necessary or desirable to reduce the aberrations to a negligibly-low level.

The printhead 11 may be immersed in the pool of ink 17 as shown, or provision may be made for acoustically coupling the lenses 14a - 14i to an ink supply which is carried by a suitable transport, such as a thin film of 'Mylar' or like plastics material. As a general rule, the piezoelectric transducer 22 has a relatively narrow band resonant frequency response characteristic, so the radiation pressures which the individual acoustic beams, such as the beam 26a, exert against the free surface 16 of the ink 17 may be controlled with respect to a predetermined threshold level as required for drop-on-demand printing by designing the controller 23 (Fig. 2) to modulate independently the amplitude, frequency or duration of the rf voltages it applies to the transducer 22. Amplitude control, frequency control and pulse width modulation also can be employed to control the size of the droplets of ink 15 which are ejected.

The threshold pressure for ejecting a droplet of ink 15 from the free surface 16 of the ink supply 17 is dependent on the particular ink that is employed, and can be determined empirically. To stabilize the droplet ejection control process, the free surface 16 of the ink supply 17 advantageously is maintained at a substantially constant distance of about one focal length from the lenses 14a - 14i. Various techniques may be employed to accomplish that. For example, as shown in Fig. 2, the illustrated embodiment utilizes a closed-loop control system 31 comprising a laser 32 for supplying a light beam 33 which strikes the free surface 16 of the ink supply 17 at a grazing angle of incidence, together with a split photodetector 34 which intercepts the light beam 33 after it reflects from the surface 16. The photodetector 34 is optically aligned so that the light beam 33 centers on it only if the free surface 16 of the ink supply 17 is at its desired set point level. Thus, any significant deviation of the surface 16 from that level imbalances the outputs of the photodetector 34, thereby causing a differential amplifier 35 to supply an error signal for energizing a motor 36. The motor 36, in turn, drives a plunger 37 of an ink-filled pump 38 to add or drain ink from the ink supply 17 viaa supply line 39 as required to restore its free surface 16 to the desired set point level. Alternatively, a knife-edge liquid level control technique, such as shown in US-A-4,580,148 could be utilized.

The acoustic waves, such as the wave 24(a), are diffracted as they propagate through the substrate 21. In keeping with this invention, however, the center-to-center spacing of the lenses 14a - 14i may be sufficiently great that the diffracted acoustic power has a negligible effect on adjacent lenses, either by reason of the substrate 21 having a thickness on the order of a Rayleigh length, or by virtue of the dissipation that occurs over the distance between adjacent lenses. Acoustic mismatch regions (not shown) may be built into the substrate 21, but sufficient acoustic isolation of the lenses 14a - 14i can also be achieved in a sparse array by merely locating the lenses 14a - 14i on widely-separated centers. For example, a 1mm center-to-center spacing of the lenses 14a - 14i may be employed to print a 500 s.p.i. image. The pixel diameter at 500 s.p.i. is 50 µm, so if the lenses 14a - 14i are on 1mm centers, each of them needs print only 20 pixels to form a solid line image lengthwise of the array 13. That compares favorably to a single ejector scanner which would have to print approximately 4000 - 5000 pixels to form a solid line image across a normal 8″ -10″ imaging field at a resolution of 500 s.p.i. There is a print rate penalty associated with selecting the center-to-center spacing of the lenses 14a - 14i so that it is much greater (typically, an order of magnitude or more) than the pixel diameter, but the wider separation of the lenses 14a - 14i greatly simplifies the fabrication of the printhead 12.

As best shown in Fig. 1, the transport 19 may comprise, for example, a drum 41 for supporting the record medium 18, and an actuator 42 for rotating and translating the drum 41 on an axis which is generally parallel to the longitudinal axis of the array 13. The drum 41 is rotated at a relatively high rate to advance the record medium 18 crosswise of the array 13, and is continuously or incrementally translated lengthwise of the array 13 at a much slower rate, so that the record medium 18 is longitudinally shifted approximately one pixel diameter with respect to the array per revolution of the drum 41. As a result, the image is composed by printing full lines crosswise of the array 13 and successive lines lengthwise of the array 13. Other transports will, of course, suggest themselves.

Other types of acoustic droplet ejectors may be employed to provide a sparse array in accordance with the present invention. For example, as shown, in Fig. 3, a printhead 51 comprising a suitable frame 52 for supporting a sparse array of piezoelectric spherical shell transducers 53a - 53i may be utilized to carry out this invention. Heretofore, piezoelectric shell transducers have been unattractive for use in arrays because their diameters are too great to achieve the packing density needed for the simultaneous printing of abutting pixels. This invention, however, overcomes that limitation and, therefore extends the utility of such droplet ejectors. Apart from its printhead 51, the embodiment of Fig. 3 is generally the same as the embodiment shown in Figs 1 and 2, so like reference numerals have been employed to identify like features.

As will be appreciated, the principles of the present invention may be extended to printheads comprising two or more rows of droplet ejectors. See, for example, the printhead 61 of Fig. 4.

In view of the foregoing, it will now be understood that the present invention simplifies the design of acoustic printheads having arrays of droplet ejectors, while increasing the design options relating to the choice of droplet ejectors for use in such arrays. Moreover, it will be appreciated that the foregoing has been achieved, without significantly compromising either the pixel placement accuracy or the pixel size control which make acoustic printing such an attractive direct marking technology.

## Claims

1. An acoustic printer, including means for moving a record medium (18) along a path which is close to the intended free surface of ink of which droplets are intended to mark the medium, and of which a supply is to be positioned between the record medium and a printhead (21) having an array of acoustic ejectors (14) for ejecting individual droplets of ink on demand from the free surface to print an image on the record medium, the image being composed of a plurality of individual pixels on a predetermined center-to-center spacing, the droplet ejectors having a center-to-center spacing which is approximately at least an order of magnitude greater than the center-to-center spacing of the pixels, and wherein the record medium is able to be moved lengthwise and crosswise of the array during the printing process.

2. The printer as claimed in Claim 1, wherein the droplet ejectors comprise

respective spherical acoustic lenses (53) which are substantially acoustically isolated from each other, and

piezoelectric transducers for supplying separate acoustic waves to the lenses.

3. The printer as claimed in Claim 2, wherein the center-to-center spacing of the droplet ejectors is sufficient to isolate the acoustic lenses acoustically from each other.

4. The printer as claimed in any preceding Claim, wherein the droplet ejectors are part-spherical piezoelectric transducer shells.

5. The printer as claimed in any preceding Claim, wherein the droplet ejectors are acoustically coupled to the free surface of the ink to direct focused acoustic beams at the surface.

6. The printer as claimed in any preceding Claim, wherein the droplet ejectors are aligned longitudinally of the printhead.

7. The printer as claimed in any preceding Claim, wherein

the record medium is able to be advanced crosswise of the array at a relatively high speed and synchronously translated lengthwise of the array at a much slower speed, with the speeds being selected so that the translation of the record medium per cycle is approximately equal to the center-to-center spacing of the pixels.

8. The printer as claimed in any preceding Claim, wherein the printhead is adapted to be immersed in ink

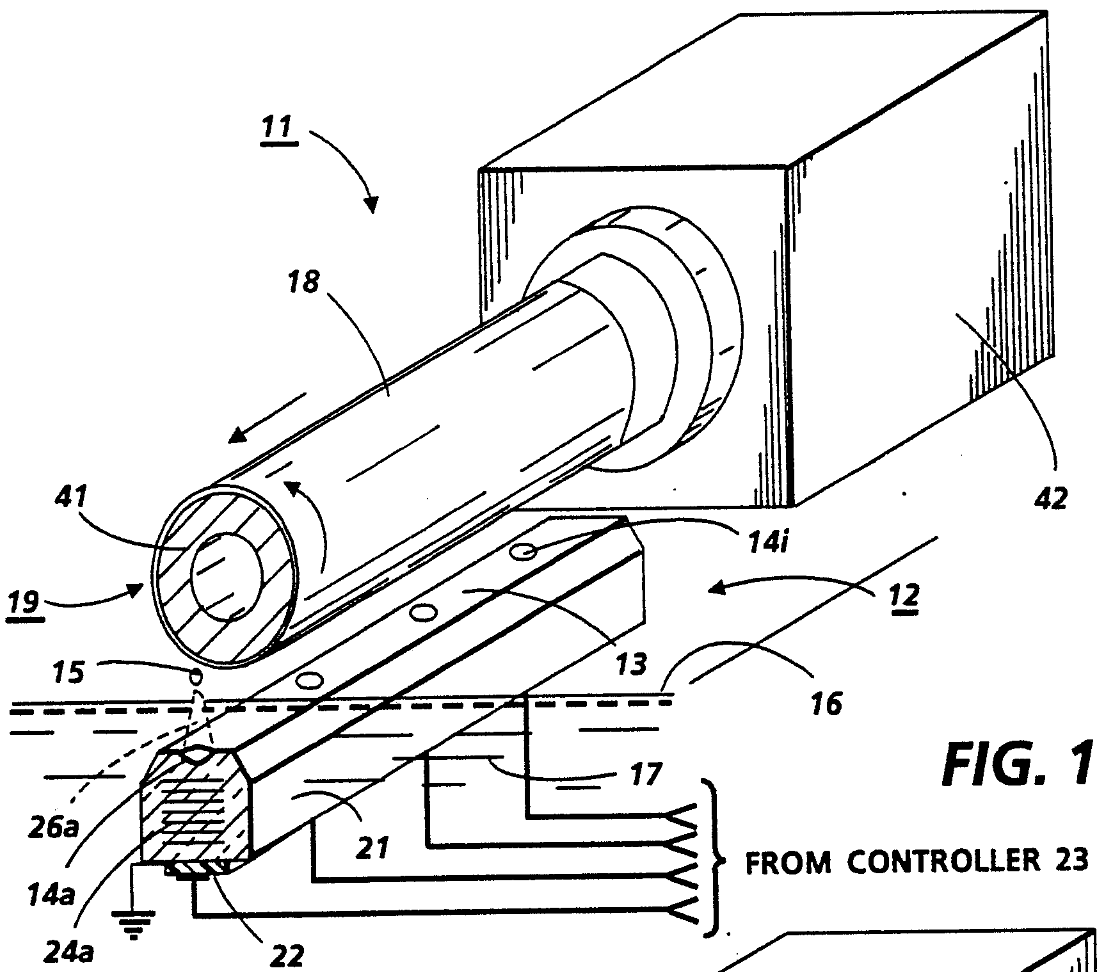
11
18
42
41
14i
19
12
15
13
16
17
26a
21
FROM CONTROLLER 23
14a
24a
22

FIG. 1

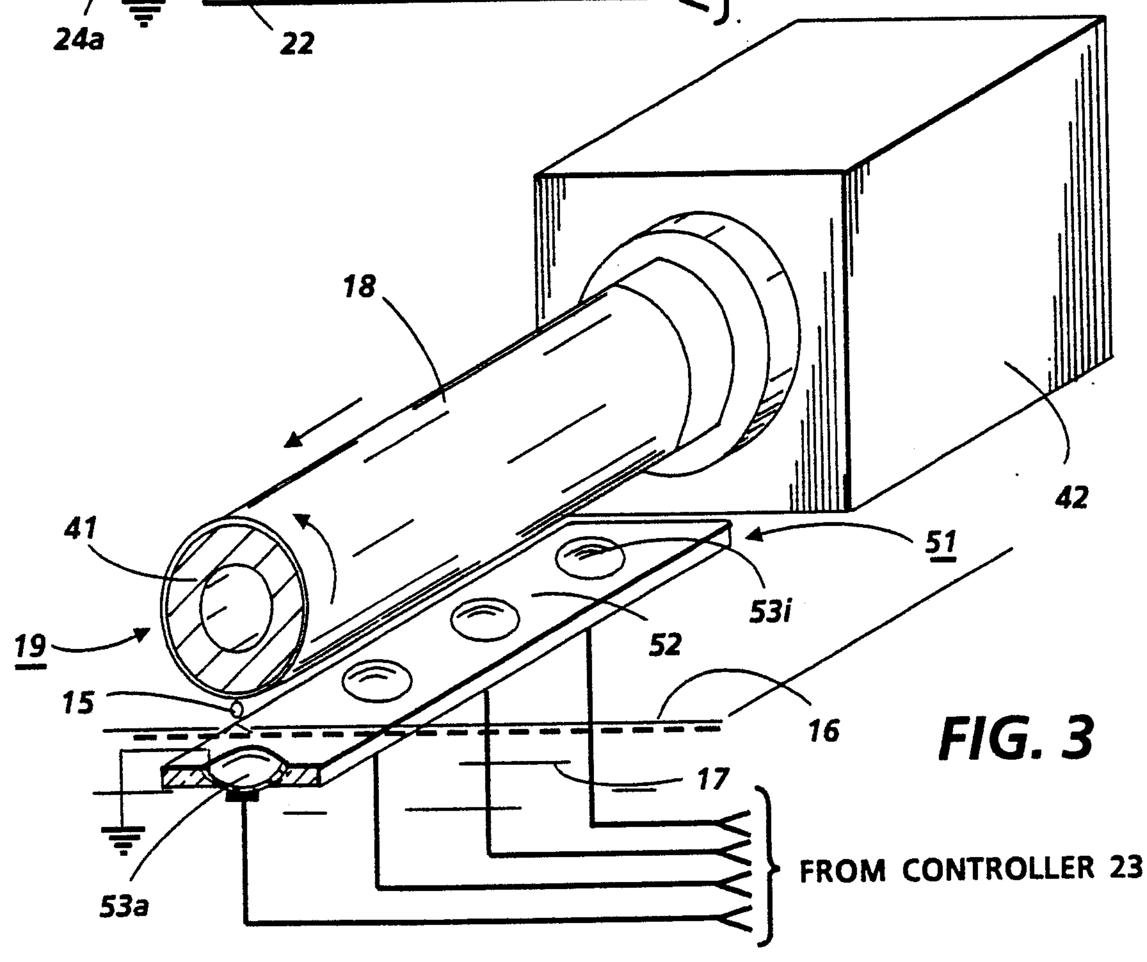
18
42
41
51
53i
19
52
15
16
17
FROM CONTROLLER 23
53a

FIG. 3

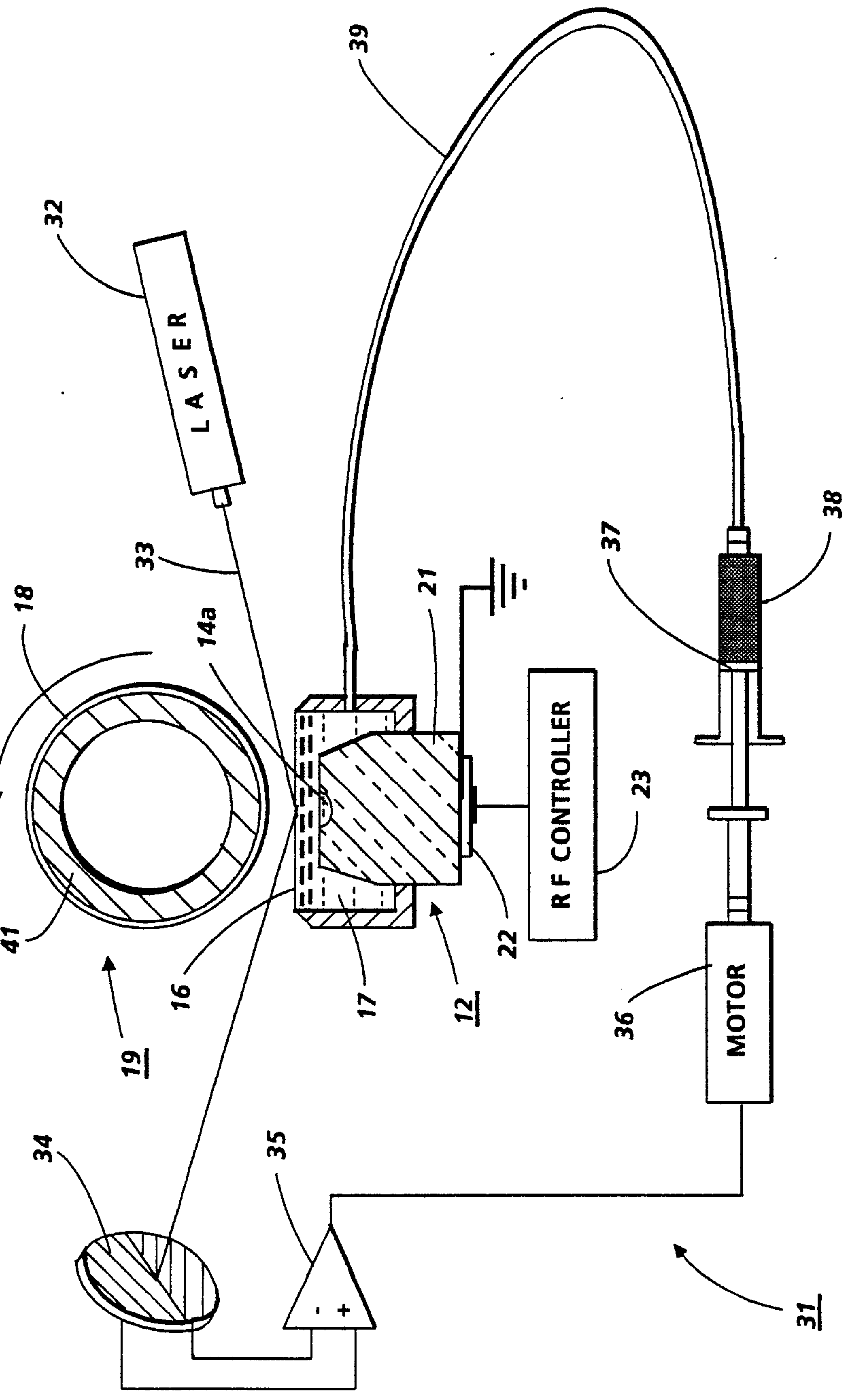
LASER
32
39
33
18
14a
21
R F CONTROLLER
23
22
16
17
12
41
19
34
35
36
MOTOR
37
38
31

FIG. 2

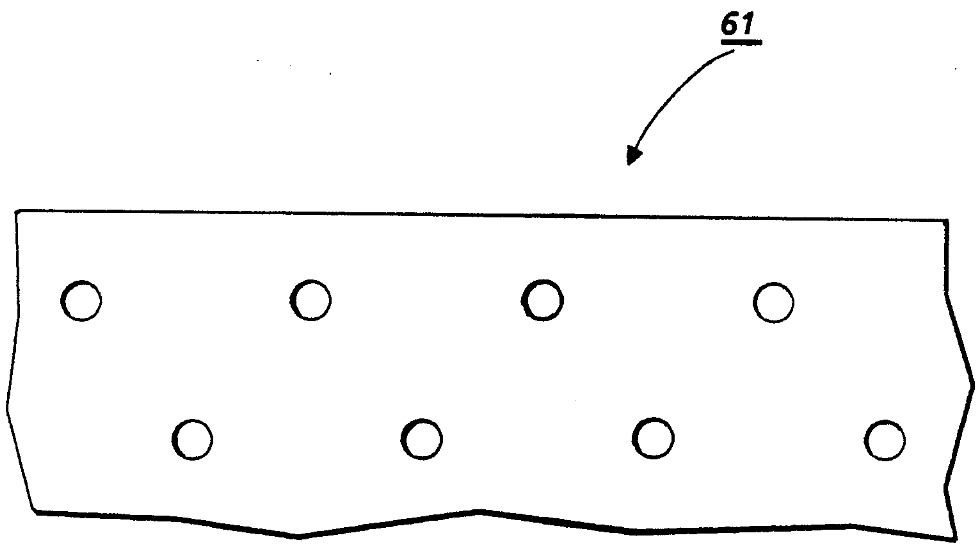


FIG. 4