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EUROPEAN PATENT APPLICATION

21 Application number: **87311224.7**

51 Int. Cl.4: **B41J 3/04**

22 Date of filing: **18.12.87**

30 Priority: **19.12.86 US 944286**

43 Date of publication of application:
06.07.88 Bulletin 88/27

84 Designated Contracting States:
DE FR GB IT

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54 Droplet ejectors.

57 Provision is made for varying the size of the pixels or spots printed by an acoustic printer of the type in which one or more droplet ejectors (12) are driven by rf voltage pulses to produce focused acoustic beams for ejecting droplets of ink on demand from a free surface of an ink supply (23). It has been found that the size of the individual droplets of ink that are ejected from the free surface of the ink can be varied by modulating the frequency, duration or amplitude of the pulses applied to such a droplet ejector. Furthermore, it also has been found that the trajectory along which the ink droplets are propelled from the free surface of the ink supply to a nearby record medium (11) is sufficiently well defined and repeatable that multiple droplets can be deposited on the record medium in rapid sequence, one on top of the other, before the ink has time to dry, to print variable diameter pixels

or spots. The control techniques of this invention may be employed for variable resolution printing and for imparting a controlled pseudo-gray scale shading to the printed image. Each of the pixels of the printed image may be composed of a single cell for one spot per pixel printing or may be subdivided into a plurality of cells for multiple spot per pixel printing.

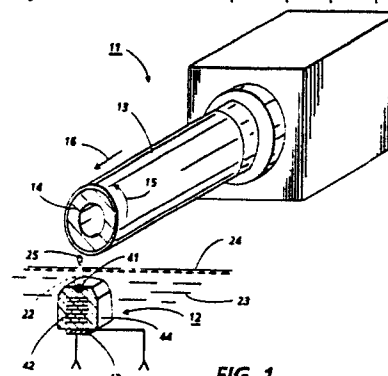


FIG. 1

This invention relates to acoustic printing or marking and, more particularly, to methods and means for controlling the diameter of the spots printed by such a process, thereby providing a representation of the gray scale contents of the images it prints.

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. Unfortunately, the size of these ejection orifices cannot be increased without sacrificing resolution, because they determine the size of the individual droplets of ink which are ejected. Likewise, the size of the ink droplets ejected by an ink jet are not readily controllable because of their dependence on the size of the ejection orifice.

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 nozzles 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.

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

The foregoing principles have been utilized in prior ink jet and acoustic printing systems for releasing small droplets of ink from ink filled pools. 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, spherical piezoelectric shells as used as transducers for supplying focused acoustic beams to eject droplets of ink from the free surface of a pool of ink. Acoustic horns, driven by planar transducers, may also be used to eject droplets of ink from an ink-coated belt.

The fundamental factors which underlie the perceived quality of a printed image are its resolution (i. e., the pixel density), the optical density of its individual pixels (i. e., gray scale), and the size of the individual pixels. Images having a generally uniform, high contrast and a moderate resolution usually are satisfactory for the printing of text and other alphanumerics. However, increased resolution and controlled shading will notably enhance the perceived quality of more complex printed images, such as pictorial representations. As is known, some modern digital printers utilize half-tone screening patterns for image shading, while others utilize gray scale control techniques for that purpose. Half-tone screening involves the processing of groups of spatially adjacent pixels on a cell-by-cell basis to create a half-toning effect. Gray scale control, on the other hand, adjusts the shading of the printed image by increasing and decreasing the optical densities of its individual pixels. A similar effect (i. e., a psuedo-gray scale effect) can be achieved by controlling the size of the individual pixels. This technique provides a gray scale representation because the resolutions which are normally used for printing are sufficiently high to cause the human eye to blur or average the adjacent pixels of the image.

In accordance with the present invention, provision is made for varying the size of the pixels or spots printed by an acoustic printer of the type in which one or more droplet ejectors are driven by rf voltage pulses to produce focused acoustic beams for ejecting droplets of ink on demand from a free surface of an ink supply. It has been found that the size of the individual droplets of ink that are released from the free surface of the ink supply can be varied by modulating the frequency, duration or amplitude of the pulses applied to such a droplet ejector. Furthermore, it also has been found that the trajectory with which the ink droplets are propelled from the free surface of the ink supply to a nearby record medium is sufficiently well defined and repeatable that multiple droplets can be deposited on the record medium in rapid sequence, one on top of the other, before the ink has time to dry, to print variable diameter pixels or spots. The control techniques of this invention may be employed for variable resolution printing and for im-

parting a controlled pseudo-gray scale shading to the printed image. Each of the pixels of the printed image may be composed of a single cell for one spot per pixel printing or may be subdivided into a plurality of cells for multiple spot per pixel printing.

Still other features and advantages of this invention will become apparent when the following detailed description is read in conjunction with the attached drawings, in which:

Fig. 1 is a simplified, fragmentary isometric view of an acoustic printer of the general type in which this invention may be utilized to advantage;

Fig. 1A illustrates an alternative transport for the printer shown in Fig. 1;

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

Fig. 3 is a basic waveform diagram for illustrating a rf drive voltage for a droplet ejector as a function of time;

Fig. 4 is an enlarged plan view of a controlled diameter spot that is printed by depositing multiple droplets of ink on a single center in accordance with one of the aspects of this invention;

Fig. 5 is an plan view of a pixel which is subdivided into a plurality of cells so that variable size spots can be printed in each of the cells to extend the gray scale shading of the pixel;

Fig. 6 is a sectional view of a piezoelectric spherical shell transducer which may be employed in lieu of the acoustic lens-type droplet ejector shown in Figs. 1 and 2, and

Fig. 7 is a plan view of an interdigitated piezoelectric transducer (IDT) which also may be employed in lieu of the droplet ejector shown in Figs. 1 and 2.

Fig. 1, shows an acoustic printer 11 having a droplet ejector 12 for printing an image on a suitable record medium 13. This simplified embodiment illustrates the application of the present invention to acoustic printers in general because it will be understood that the droplet ejector 12 may be replicated to provide an array of such devices. Indeed, droplet ejector arrays of various geometries can be constructed to perform, for example, line printing, matrix printing, and multi-line raster scan printing.

As illustrated, the record medium 13 is wrapped around and secured (by means not shown) to a drum 14 which, in turn, is rotated at a fast scan rate in the direction of the arrow 15 while being axially translated at a slow scan rate in the direction of the arrow 16 (by means also not shown). As a result, the record medium 13 is advanced relative to the ejector 12 in accordance with a suitable raster scanning pattern. Various alternatives for affecting such a raster scan will suggest themselves. For example, the slow-scan component of the relative motion could be provided

by mounting the ejector 12 on a carriage for translation axially of the rotating drum 14 at the slow-scan rate. Furthermore, as shown in Fig. 1A, the drum 14 could be eliminated in favor of employing pinch rollers 17, 18 and 19, 20 for translating the record medium 13 back and forth in the fast-scan direction.

Referring to Figs. 2 and 3, it will be seen that a controller 21 supplies a pulsed rf drive voltage (Fig. 3) for driving the droplet ejector 12. As described in more detail hereinbelow, this drive voltage causes the droplet ejector 12 to launch a converging acoustic beam 22 into an ink supply 23, such as an ink-filled pool, such that the acoustic beam 22 is brought to focus approximately at the free surface (i. e., liquid/air interface) 24 thereof. The controller 21 modulates the amplitude, frequency or duration of the rf voltage applied to the transducer to control the pressure which the acoustic beam 22 exerts against the free surface 24, so that individual droplets of ink 25 (Fig. 1) are ejected therefrom on demand. The ejection velocity of these ink droplets 25 is sufficiently high to propel them across the narrow gap between the free surface 24 of the ink supply 23 and the record medium 13 with a well-defined and repeatable trajectory. Indeed, the precision with which the droplets 25 can be deposited on the record medium 13 is surprisingly high.

In the illustrated embodiment, the droplet ejector 12 is submerged in the ink supply 23. Alternatively, however, it may be acoustically coupled to the ink supply 23 through an intermediate medium (not shown). For example, the ink 23 can be carried on a suitable transport, such as a thin film of 'Mylar' or like sheet material, and the droplet ejector 12 can be acoustically coupled to the ink 23 via a liquid and/or solid interface layer.

To control the droplet ejection process, the pressure which the acoustic beam 22 exerts against the free surface 24 of the ink supply 23 is controlled with respect to the threshold pressure required to release individual droplets of ink 25 from the surface 24. This threshold is dependent on the surface tension of the particular ink that is employed and may be determined empirically. To stabilize the process, provision advantageously is made for maintaining the free surface 24 of the ink supply 23 at a fixed distance from the droplet ejector 12 (i. e., in the focal plane of the droplet ejector 12). Various techniques may be employed to accomplish that. For instance, as shown in Fig. 2, there is a closed loop control system 31 comprising a laser 32 for supplying a light beam 33 which strikes the free surface 24 of the ink supply 23 at a grazing angle of incidence, together with a split photodetector 34 which intercepts the light beam 33 after it reflects from the surface 24. The

photodetector 34 is optically aligned so that the light beam 33 centers on it only if the free surface 24 of the ink supply 23 is at its desired set level. Thus, any significant change in the level of the surface 24 unbalances 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 23 via a supply line 39 as required to restore its free surface 24 to the desired set level. Alternatively, a knife-edge liquid level control technique, such as shown in US-A-4,580,148 could be utilized.

The basic construction of the droplet ejector 12 is similar to an acoustic microscope objective, although its function and its mode of operation are unique. See, for example, C. F. Quate., "Acoustic Microscopy," Physics Today, Vol. 38, No. 8, August 1985, pp. 34-42. More particularly, the droplet ejector 12 comprises an acoustic lens 41 which is irradiated by an acoustic wave 42 that is generated by a piezoelectric transducer 43 in response to the rf drive voltage supplied by the controller 21. The lens 41 is defined by a small part-spherical cavity or indentation which is formed in a surface (e. g., the upper surface) of a solid substrate 44 which, in turn, is composed of a material, such as silicon, silicon nitride, silicon carbide, alumina, sapphire, fused quartz, and certain glasses, having an acoustic velocity which is much higher than the acoustic velocity of the ink 23. The piezoelectric transducer 43, on the other hand, is deposited on or otherwise intimately mechanically coupled to the opposite or lower surface of the substrate 44.

In operation, the rf voltage supplied by the controller 21 is applied across the transducer 43, thereby exciting it into oscillation to generate the acoustic wave 42 in the substrate 44. The wave 42 propagates through the substrate 44 at a relatively high speed until it strikes the lens 41, from which it emerges into a medium (e. g., the ink supply 23, as shown) having a much lower acoustic velocity. Accordingly, the lens 41 imparts a spherical wavefront to the acoustic wave 42, thereby producing the converging beam 22. The change in the refractive index as measured by the change in the acoustic velocity across the interface between the substrate 44 and the ink 23 is large, and the angle of refraction for rays crossing this interface also is large, with the result that the focal length of the lens 41 is roughly equal to its radius of curvature. For example, when the aperture of the lens 41 is about the same as its focal length (f number ≈ 1), the waist diameter of the acoustic beam 22 at focus is approximately equal to its wavelength. If small aberrations of the acoustic beam 22 are tolerable, the acoustic velocity of the substrate 44

may be only about 2.5 times higher than the acoustic velocity of the ink 23. The aberrations, however, can be reduced to a negligibly-low level, simply by fabricating the substrate 44 from a material having an acoustic velocity which is roughly four or more times higher than the acoustic velocity of the ink 23. That is practical because the acoustic velocity of the ink 23 typically is only about 1 - 2 km/sec.

The wavelength, λ_i , of the acoustic beam 22 in the ink supply 23 is, of course, inversely proportional to the frequency, f , of the rf voltage (Fig. 3) applied to the transducer 43 (i. e., $\lambda_i = v_i/f$, where v_i is the velocity of sound in the ink 23). Taking this analysis a step further, it will be recalled that the waist diameter of the beam 22 at focus is directly dependent on its wavelength, λ_i . Consequently, in accordance with one of the aspects of this invention, provision may be made in the controller 21 for altering the frequency, f , of the rf drive voltage for the transducer 43 so as to vary the waist diameter of the beam 22 and, therefore, the size of the droplets of ink 25 which are ejected. Although this droplet size control technique is effective, its utility may be limited if the transducer 43 is tuned to have a narrow band resonant response characteristic in the interest of increasing its efficiency. Even then, however, the frequency of the voltage supplied by the controller 21 can be switched, such as under the control of an operator, between the fundamental resonant frequency of the transducer 43 and an odd harmonic of that frequency. This is a relatively coarse adjustment, but it may be utilized, for example, to change the size of the ink droplets 25 for printing at different resolutions.

In accordance with another feature of this invention, the size of the ink droplets 25 also may be varied by having the controller 21 modulate the duration, ζ (Fig. 3), of the rf pulses it applies to the transducer 43. It has been found that pulse width modulation may be employed to vary continuously the diameter of the droplets 25 over a range from about one wavelength (λ_i) to about two wavelengths ($2\lambda_i$), which means that it is well suited for imparting a controlled shading to the printed image. In practice pulse widths, ζ , varying between about 1 μ sec and 50 μ sec are adequate to affect a factor of two change in droplet diameter at 50 MHz. A similar effect can be achieved by modulating the amplitude of the rf pulses applied to the transducer 43, but amplitude modulation does not appear to provide as much control over the size of the droplets 25 as does pulse width modulation.

In keeping with still another important aspect of this invention, it has been found that the trajectory along which the droplets of ink 25 travel from the free surface 24 of the ink supply 23 to the record medium 13 is sufficiently well defined and repeat-

able that multiple droplets of ink 25 can be ejected in rapid sequence to deposit one on top of another, before the ink has time to dry. The physics of this phenomenon have not been explored in sufficient depth to describe precisely what is happening, but it has been experimentally demonstrated that as many as fifteen droplets 25 may be deposited on a single center. As schematically illustrated in Fig. 4, these droplets 25 appear to agglomerate to form a spot 51 having a diameter equal to approximately $2dn^{1/3}$, where d is the droplet diameter, and n is the number of droplets 25 that are provided to print the spot 51. As will be appreciated, the factor of 2 in the foregoing expression assumes that the diameter of the droplets 25 is substantially constant and is based on the observation that the diameter of the spot printed on paper by a droplet of ink is approximately twice the diameter of the droplet. Some variance in that factor and in the power factor, $n^{1/3}$, are likely to occur when different inks and different papers are utilized. The aforementioned experiments were conducted at a printed spot rate of 1 kHz, using 10 μ sec long rf bursts at 150 MHz to pulse the transducer 43 at a repetition rate, T , of 60 μ sec/pulse, but it will be understood that this spot size control technique is readily extendible and has broad utility. For example, it may be applied to print a single spot 51 per pixel, thereby providing up to $(N+1)$ different apparent shades of gray for controlling the shading of the printed image, where N is the maximum number of droplets 25 which can be deposited on a single center. Or, as shown in Fig. 5, each of the pixels may be composed of a plurality of cells 52a - 52d which are more or less symmetrically distributed about the center 53 of the pixel, and the size of the spots 54a - 54d printed in the cells 52a - 52d may be controlled as described above to provide a selection of $X(N+1)$ different apparent shades of gray for printing, where X is the number of cells per pixel. For example, it has been demonstrated that sixty four shades of gray can be produced with four cells 52a - 52d per pixel.

While the acoustic lens-type droplet ejector 12 is favored because of its stable ejection behavior and the ease with which arrays of such devices may be fabricated, the present invention may be applied to acoustic printers having other types of droplet ejectors. For example, this invention appears to be compatible with the piezoelectric spherical shell transducer 61, which is shown in Fig. 6 and described in the aforementioned US-A-4 308 547. It also is believed to be compatible with the interdigitated transducer (IDT) 62, which is shown in Fig. 7.

In view of the foregoing, it will now be understood that the present invention provides a variety of methods and means for manually or automati-

cally varying the size of the pixels or spots printed by an acoustic printer of the type in which one or more droplet ejectors are driven by rf voltage pulses to produce focused acoustic beams for ejecting droplets of ink on demand from a free surface of an ink supply. These control techniques may be employed individually or in combination with each other for printing at different resolutions and/or for imparting a controlled gray scale shading to the printed image. The droplet size control techniques of this invention are not necessarily limited to acoustic printing.

Claims

1. A droplet ejector (12) for ejecting droplets from a free liquid surface, including a piezoelectric transducer (43), and means coupled across the transducer for exciting it, whereby the ejector launches a converging acoustic beam into the liquid and brings the beam to a focus at a known distance from the ejector,

including means for modulating the excitation signal to vary the size of the droplets.

2. The ejector of Claim 1, wherein the modulator is a pulse width modulator.

3. The ejector of Claim 1 or 2, wherein the modulator is an amplitude modulator.

4. The ejector of any preceding claim, wherein the modulator is a frequency modulator.

5. An acoustic printer having at least one droplet ejector as claimed in any preceding claim for depositing individual droplets of ink on a record medium to mark it with spots of adjustable size.

6. The printer of Claim 5, including an ink supply with a free surface proximate the record medium.

7. The printer of Claim 6, further including means for maintaining the free surface of the ink at a substantially-constant distance from the droplet ejector, whereby the acoustic beam remains focused at the free surface during operation.

8. The printer of any of Claims 5 to 7, wherein the droplet ejector is able to provide an adjustable number of droplets of ink on each spot.

9. The printer of Claim 8, wherein the transducer has a narrow band resonant frequency response characteristic.

10. The printer of any of Claims 5 to 9, wherein the droplet ejector comprises a body of a solid in which the speed of sound is much higher than it is in the ink,

the body has a part-spherical cavity formed therein on a surface intended to face the record medium in use, to define an acoustic lens, and

the transducer is intimately mechanically

coupled to an opposing surface of the body for generating an acoustic wave which falls on the lens in response to the excitation of the transducer.

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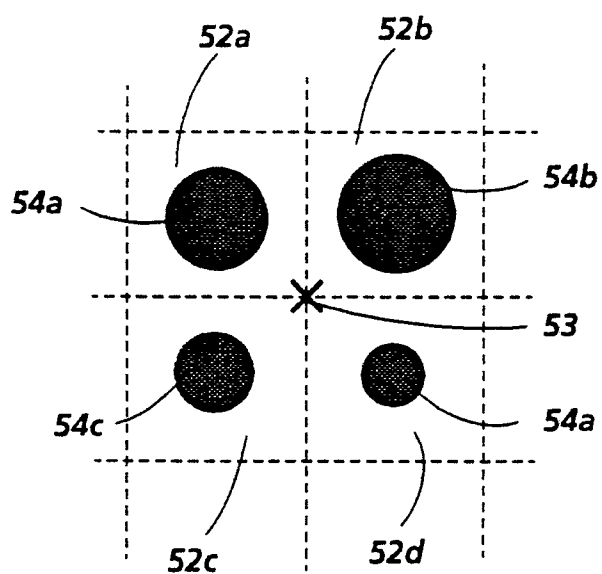
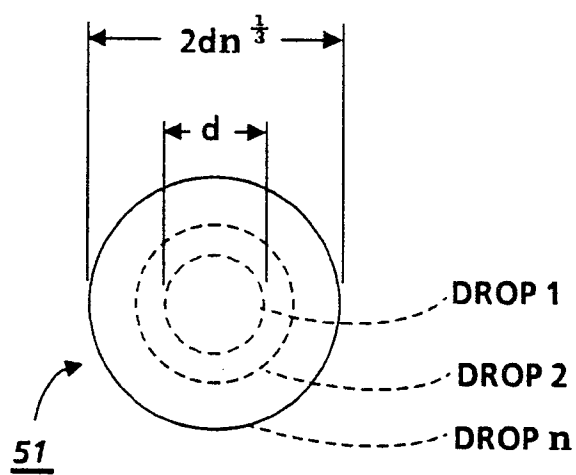
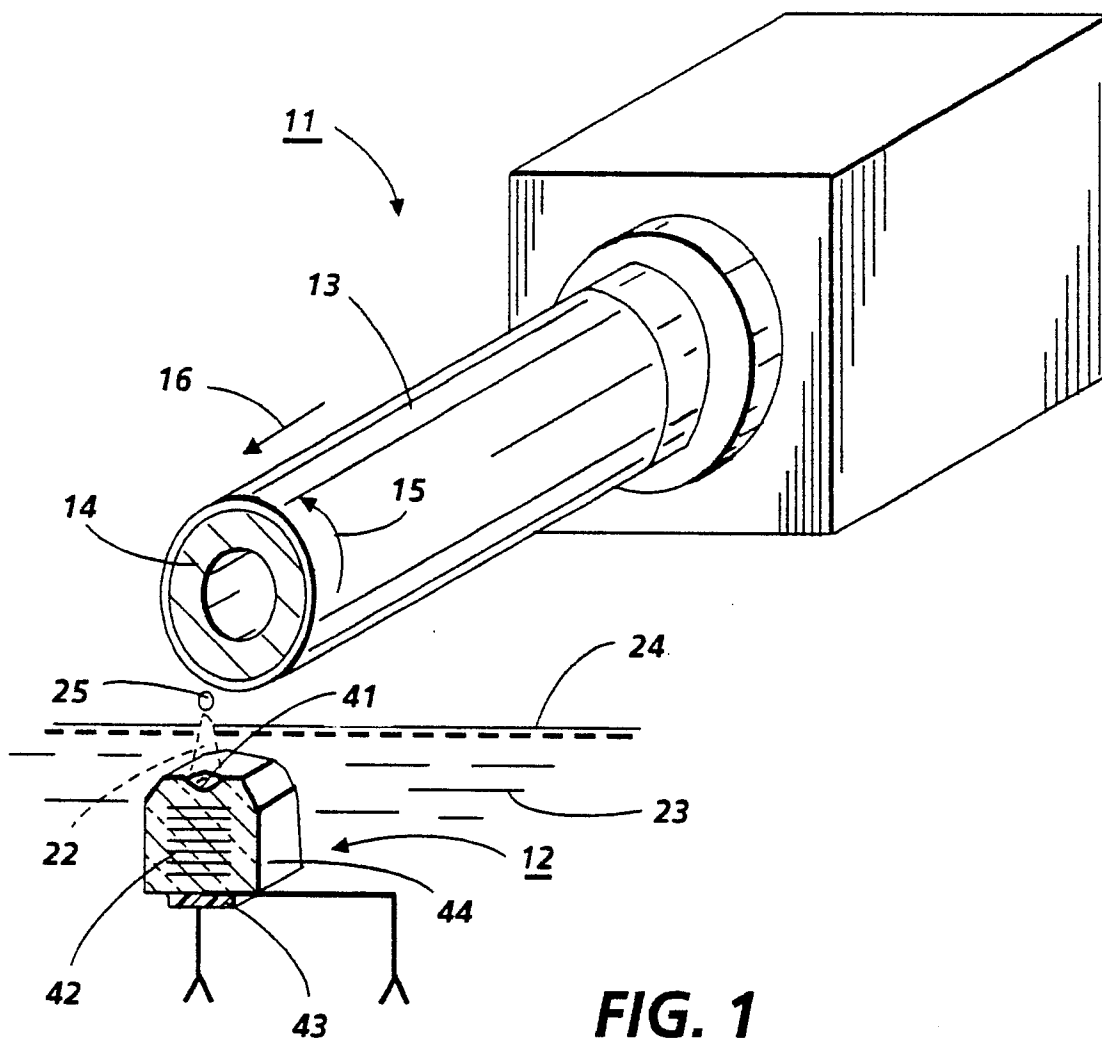
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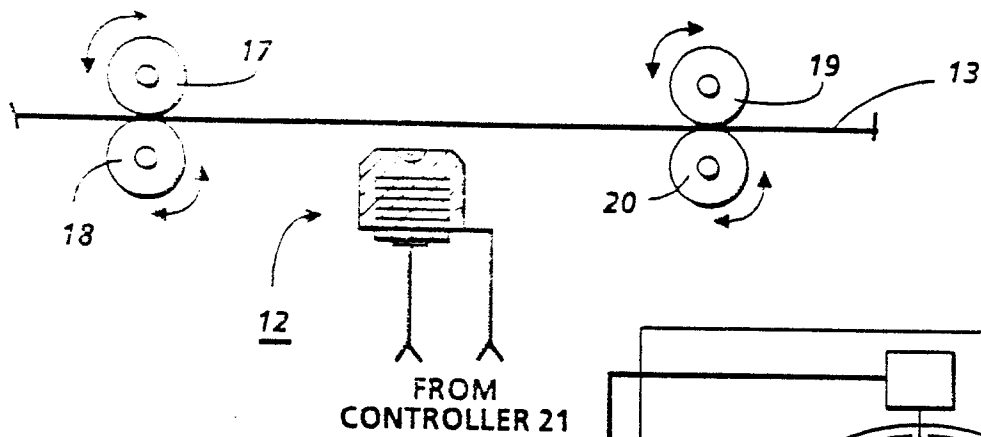


FIG. 1A

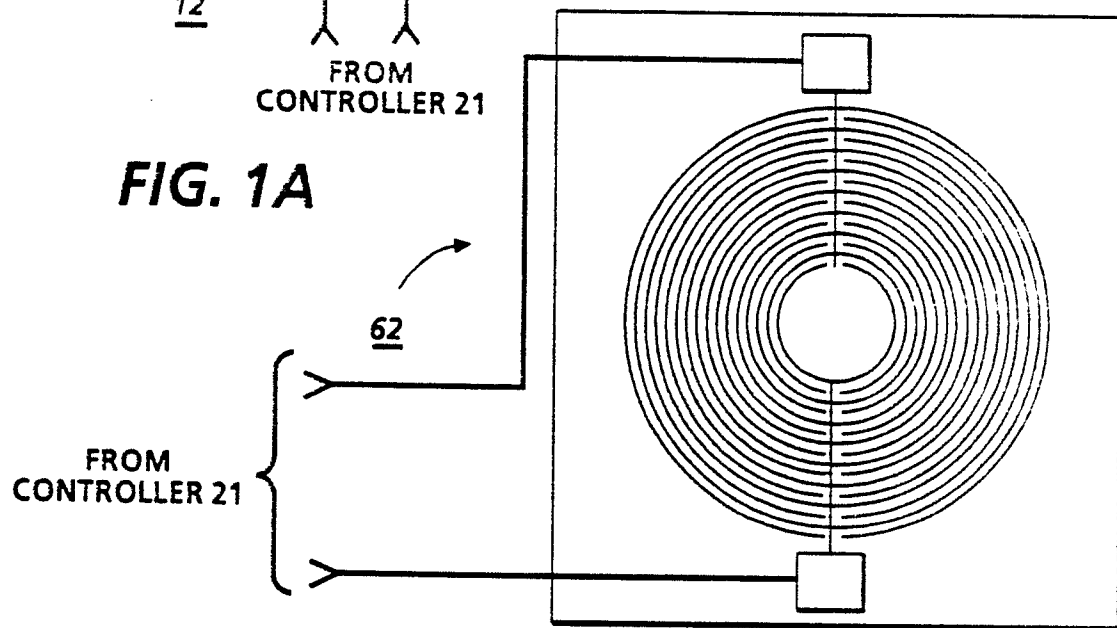


FIG. 7

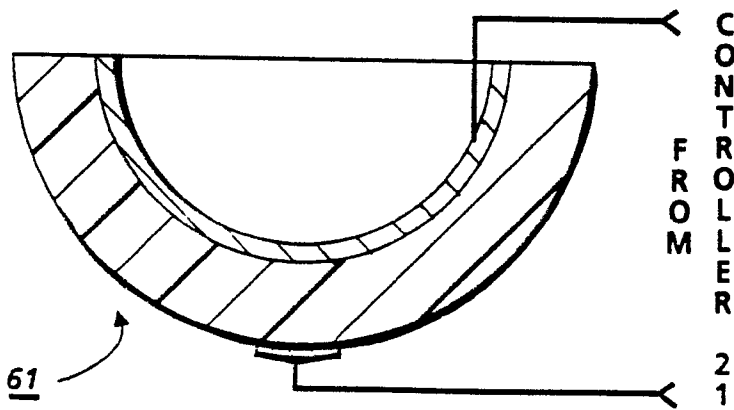


FIG. 6

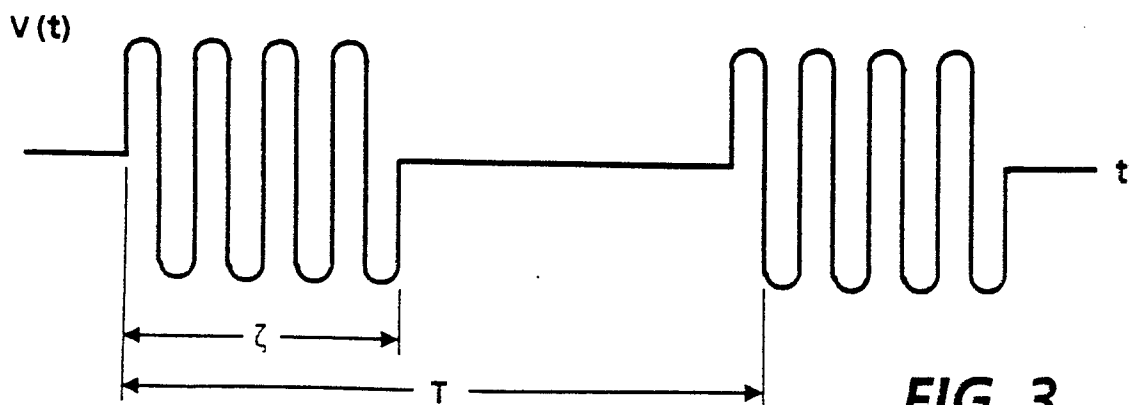


FIG. 3

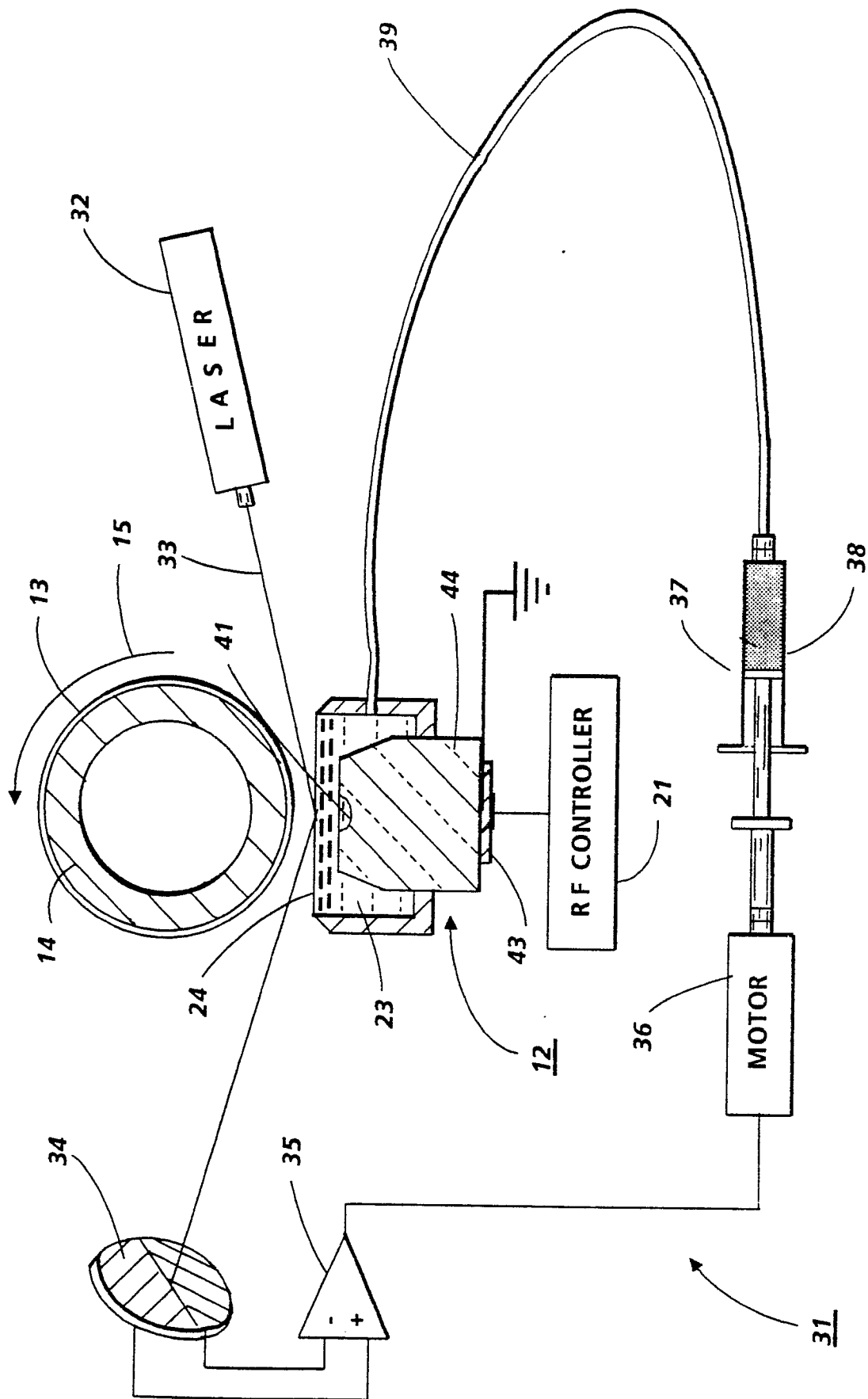


FIG. 2