(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) Publication number: **0 051 468**
A2

(12) **EUROPEAN PATENT APPLICATION**

(21) Application number: 81305163.8

(22) Date of filing: 30.10.81

(51) Int. Cl.³: B 41 J 3/04

(30) Priority: 03.11.80 US 203743

(43) Date of publication of application: 12.05.82 Bulletin 82/19

(84) Designated Contracting States: DE GB NL SE

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(54) **Drop-on-demand ink drop marking apparatus and method.**

(57) Drop-on-demand ink drop marking apparatus and method of the type employing a plurality of capillaries (8). The capillaries are coupled to a pressurized liquid source (16) to cause the liquid ink (6) to weep from the orifice (7). A drop (11) is formed by stimulating the ink in the capillary (8). High drop generation rates are possible because the weeping ink flow enables the liquid consumed in the process of forming a drop to be more rapidly replaced in the capillary than if capillary action alone is relied upon for the replacement. A laser scanning beam (10) reflected from a rotating polygon mirror (43) is one embodiment for stimulating the ink to cause its expulsion from the capillary, and into flight towards a target (4). The beam heats the ink to expel it. Alternatively, a solid state laser adjacent each capillary is disclosed for stimulating the capillary to expel a drop into flight toward a target.

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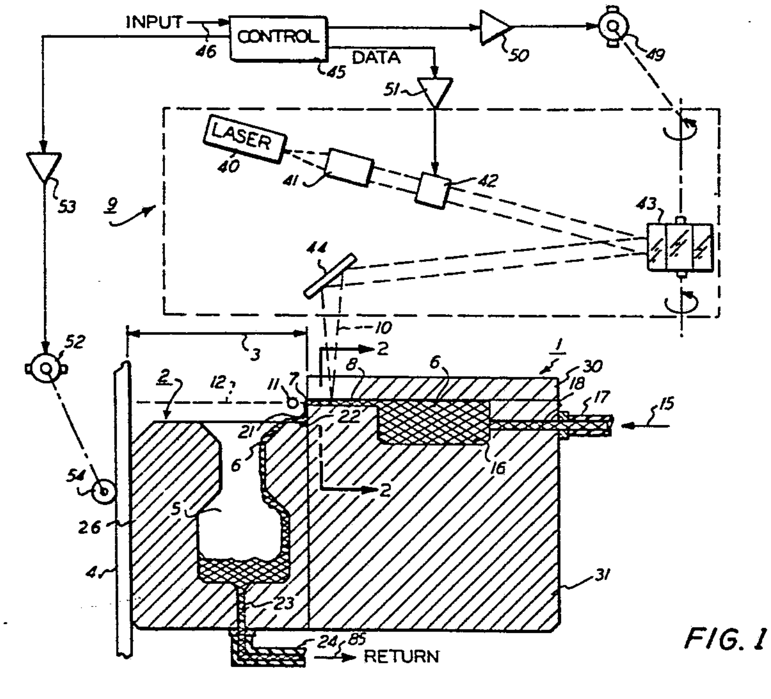

FIG. 1

Drop-on-Demand Ink Drop Marking Apparatus and Method

This invention relates to a drop-on-demand ink drop marking apparatus and method. More specifically, this invention relates to the generation of ink drops by stimulating the ink in a capillary channel so as to expel drops from the orifice of the channel into flight towards a target. Drop generators of this type find application in printing, recording or marking systems as well as drop classifying or sorting systems.

Drop-on-demand drop generators typically contain liquid in a capillary which is expelled through an orifice by methods including, by way of example, constricting the capillary, exerting electrostatic force on the liquid in the cavity, and coupling a liquid pressure pulse to the liquid in the capillary. The ink is expelled with a force adequate to propel a drop in flight to a target. All these prior art methods maintain the liquid at an ambient pressure when drops are not being generated. By ambient pressure is meant a near zero pressure that is inadequate to overcome the surface tension of the liquid meniscus formed at the capillary's orifice and other forces. The purpose is to prevent liquid from escaping from the orifice when a drop is not being generated. However, the ambient pressure inhibits the speed or rate at which drops are generated. The reason is that liquid requires time to flow into the capillary to replace that which was expelled. The main force available for refilling the capillary tube is a capillary flow force.

U.S. Patents 3.466,659 to Ascoli; 3,683,212 to Zoltan and 3,946,398 to Kyser and Sears are representative of drop-on-demand ink drop generators. Each maintains a liquid pressure at an orifice that is unable to overcome the surface tension of the liquid meniscus at the orifice and other forces, if any. The object is to prevent escape of ink, i.e. weeping, when the generator is not producing a drop for flight toward a target.

Ascoli specifies an electric field between the ink and an external electrode for pulling ink drops from the meniscus formed at an orifice. Zoltan discloses a capillary including a piezoelectric transducer that squeezes the liquid in the capillary to expel drops. Kyser et al discloses a drop-on-demand generator wherein a diaphram imparts a liquid pressure pulse on a volume of ink to expel a drop. U.S. Patents 3,907,429 to Kuhn, Myers, Pennington and Shah; 4,047,183 to Taub; and 4,097,373 to Allred all disclose ink drop systems employing radiant energy or light. All three of these patents describe continuous drop generators and not drop-on-demand generators as discussed here. Also, all three patents describe the use of light as a sensor: to detect the presence of a drop relative to a mask (Kuhn et al); to detect the shape of the liquid prior to drop formation (Taub); and to detect the composition of the liquid (Allred). None of these patents use light to transfer energy to a liquid in a capillary to create a drop.

The present invention is intended to increase the rate at which drops can be generated in drop-on-demand drop generators.

The invention is characterised in that the ink is supplied to the capillary channel under sufficient pressure to cause the ink to weep from the orifice when drops are not being expelled.

Radiant energy, hereinafter "light" may be used for stimulating the expulsion of a liquid drop from a capillary, and in a typical marking apparatus, a plurality of capillaries in a single drop generator body are employed, and individual capillaries are stimulated selectively by a modulated light beam from a scanning laser to generate a row of drops on a target. In an alternative embodiment, a plurality of solid state lasers stimulate individual capillaries and thereby generate drops.

In the apparatus of this invention a continuous flow of liquid is created in drop-on-demand capillaries due to a positive pressure exerted on the liquid feeding the capillaries. That is, the capillary is coupled to a liquid source under a pressure capable of overcoming the surface tensions of the liquid meniscus at the orifice and any other force preventing a flow. Consequently, the capillary orifice weeps when drops are not being generated or expelled. A sump is provided adjacent the capillary orifice to collect the weeping ink. Preferably, the ink collected in the sump is recirculated back to the capillary.

Two embodiments are used for light stimulation of a capillary for drop expulsion. One is a scanning laser beam which heats the liquid to a temperature causing expulsion of a drop. The laser beam is scanned over a single or an array of capillary channels by a rotating polygon mirror. Alternatively, a solid state light emitting diode (LED) is positioned adjacent a capillary. The light from the LED also acts to heat the liquid sufficiently to expel a drop with a force enabling it to fly to a desired location on a target. Other embodiments using external stimuli other than light are possible. The prior art drop expulsion means using capillaries also benefit from the weeping capillary of this invention.

In all embodiments, the location on a target addressed by a drop from a specific capillary is normally either a specific pixel location within a scan line of a raster image or a pixel location within an N x M character matrix.

An apparatus and method according to the invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a schematic diagram of a drop-on-demand printing system using the weeping drop generator of this invention and one embodiment of a drop expulsion means using light to cause drop formation. The light comes from a scanning laser beam.

Figure 2 is a sectional view of the drop generator of Figure 1 taken along section lines 2-2 through its body showing the plurality of capillary channels.

Figure 3 is a sectional view like that of Figure 2 but with a lenticular lens member replacing the transparent planar cover member in Figure 2.

Figure 4 is a sectional view like that of Figure 2 illustrating another embodiment of drop expulsion means using light to generate drops. The light comes from LED's associated with each capillary channel.

This invention involves the propulsion of a liquid drop from a weeping capillary. The drop forms when the liquid in the capillary near its orifice is struck by a high energy light source. The weeping feature permits high repetition rates for drop generation because the expelled liquid is quickly replaced in the capillary due to the pressure. The use of light to affect the expulsion enables high speed addressing of individual capillaries among a large array. Also, a radiant energy heat source also makes for simple and therefore economical, manufacturable and reliable hardware. The radiant heating coupling to the capillaries also provides excellent noise isolation between the system electrics and the fluid system from which the drops are generated.

The printing system of Figure 1 illustrates one embodiment of the invention. The system includes the drop generator 1; the spacer 2 maintaining the generator at a controlled distance 3 from a moving target 4; the ink sump 5 formed in the spacer for collecting liquid 6 weeping from the orifice 7 of the capillary channel 8; and the drop expulsion means 9 that heats liquid in the capillary with a scanning beam of light 10 to expel a drop 11 from the capillary orifice along a flight path 12 to the target.

The liquid from which the drops are formed is supplied under pressure from an appropriate source (e.g. a pump) represented by arrow 15. The source is fluid coupled to a local reservoir 16 via the external conduit 17 and the internal conduit 18. The reservoir in turn supplies liquid to the capillary 8 by capillary flow which is greatly assisted by the positive static pressure or head associated with the liquid in the reservoir 16. The pressure or head in the reservoir 16 causes the liquid—ink in the case of a printer—to flow or weep out the orifice 7.

The reservoir pressure is great enough to overcome the surface tension of a liquid associated with a meniscus at orifice 7. However, the head is less than that required to create a continuous stream from which are formed drops in flight toward a target according to the principals of Lord Rayleigh. A Rayleigh drop generator is a continuous drop generator of the type disclosed by Sweet in his U.S. Patent 3,596,275. The magnitude of the pressure in a Rayleigh device varies for various orifice sizes. Generally, when dealing with orifice sizes of from about 20 to 50 microns in diameter—preferred for good image quality in printing systems—the head in reservoir 16 can go as high as 280 to 350 $gm.cm^{-2}$ before a Rayleigh jet forms. The desired weeping of liquid 6 is achieved, therefore by setting the pressure between some small increment above the ambient atmospheric pressure adjacent the orifice 7 to about 350 $gm.cm^{-2}$ above the ambient pressure. Preferably, the head in reservoir 16 is adjusted so that liquid 6 oozes from the orifice 7 like a leaky faucet without giving rise to any clearly definable stream.

The beam 10 is directed onto the capillary at a short distance from the orifice. That distance is presently perferred to be about ten times the diameter of the capillary. A useful drop diameter for a printing system is about 25 microns. A cylindrical capillary having a diameter of about ten microns produces a drop of about 25 microns in diameter when the beam 10 heats a slug of liquid in the 100 micron length near the orifice. The slug is abruptly expelled from the capillary along flight path 12.

The mechanism for drop expulsion by radiant heating as reported herein is not fully understood. The following explanation is intended to reflect a current understanding of the drop generation mechanism and is not intended to be limiting. The energy transferred to the liquid 6 thermally expands a small volume of liquid in the capillary which thereby creates a very high local pressure for a short period of time by virtue of the fact that the heated volume is enclosed in a rigid structure. At sufficiently high energy transfer, a fraction of the liquid may also be vaporized substantially instantaneously. This momentary pressure imparts equal but opposite momentum to the liquid columns in front of and behind the heated portion resulting in ejection of the slug of liquid on the side of the orifice. The liquid in the capillary on the side of the reservoir is not driven back into the reservoir because of its relatively greater mass, the column being fabricated of sufficient length to insure the necessary mass differential. For a capillary of roughly ten microns in diameter and with 10 microjoules of energy from beam 10, a flight distance 3 of up to about 1.5 centimeters is achievable for a drop 11. The path 12 is substantially linear. Drops tend to break up into a spray at increasing distances from the orifice 7. Consequently, for good control of drop placement at a specific pixel location on target 4, the orifice to target spacing 3 is preferably kept in the range from about 0.15 cm to about 0.25 cm. The drops remain intact within this range and their flight paths are predictably linear.

Drops are expelled by heat delivered by beam 10 even though the ink is not weeping. However, the void created in the capillary by the expelled ink is slowly replaced when capillary flow is the sole means for refilling the channel. Repetition rates in the order of only 1 or 2 drops per second are possible with a capillary feeding action. The weep flow recommended here increases the drop repetition rate to above 4000 drops per second. A drop rate of that magnitude requires a flow rate in the capillary channel of about one meter per second (mps).

A liquid flow rate of 1 mps in a channel 8 is due solely to the liquid pressure in reservoir 16. The expulsion of drops by the laser beam 10 is the primary means for achieving high drop velocity. The laser beam is pulsed on and off at over 4000 times per second--for example, with much lower speeds being easier to achieve--to generate drops at that speed. The liquid pressure in reservoir 16 is believed to compliment the laser pumping action enabling new liquid to be supplied at the 1 mps rate to the region of the capillaries near the orifice 7.

The weeping ink flows down the vertical face 21 of the generator 1 onto the horizontal surface 22 of the spacer 2. From there the weeping ink 6 flows into the sump 5. The internal fluid conduit 23 and the external fluid conduit 24 fluid couple the sump with a primary liquid source represented by arrow 85. The primary source is that from which a pump—represented by arrow 15—supplies liquid under pressure to the local reservoir 16. Consequently, the weeping ink collected in sump 5 is recycled through the capillary channel 8. As indicated above, spacer 2 is means for maintaining constant the distance 3 between the orifice and target. In addition, the planar surface 26 on the spacer assists in holding and guiding the target 4 in the proper attitude for its upward movement past the drops flying over path 12. The spacer includes the sump 5 but if adequate space is not available in the spacer, the sump is located elsewhere. Means for guiding the weeping liquid to the sump such as surfaces 21 and 22 still must be provided.

The generator 1 includes a cover plate 30 and body 31 within which are formed a capillary channel 8, local reservoir 16 and inlet conduit 18. The cover plate is transparent—at least at the region of the capillary near orifice 7--to facilitate the radiant heating of the ink by the beam 10. The generator in Figure 1 is shown in a side, sectional view. In fact, the capillary 8 is representative of a plurality of capillaries all of which are fluid coupled to the local reservoir 16. Figure 2 is illustrative of the array of capillaries. The reservoir 16 extends the width of the array of capillaries shown in Figures 2-4.

The top surface 32 of body 31 is planar. The capillaries 8 are machined or chemically etched into the top surface using conventional high resolution ruling techniques employed in making optical defraction gratings, for example. The cover plate forms the top wall of the capillaries. The triangular shape shown in Figures 2-4 is that commonly associated with mechanical engraving. It is important that the multiple capillaries have similar cross-sectional areas at least throughout the regions between the orifice 7 and beam 10 impingement, a distance of about ten diameters. Each capillary should generate substantially the same size drop upon stimulation by beam 10 for the same length of time.

For a full page, high quality raster scan printer, body 31 includes about 4096 capillaries 8 extending over a region of about 22 cm width. The resolution associated with this geometry is about 186 capillaries per cm. The space available for a single capillary is about 50 microns and each capillary is separated from its neighbor by some amount. Preferably, the capillaries in this example are about 25-30 microns across the base 33 of the triangular cross-section of capillary 8. The sides 34 of the triangular cross-section are also about 25-30 microns. This equallateral triangle is shown by way of example. It should be understood that other cross-sectional shapes are acceptable.

The 25 micron dimensions for a triangular capillary are suited for capillary action for inks 6 having viscosities near that of water. That is, the liquid ink 6 is a water based fluid containing a dye for colorant. Since the drop forming processes does not include electric current flow in the ink, complex chemical additives are not needed in the ink to combat chemical attack of body 31 and cover plate 30 due to electrolysis or the like.

Earlier, a liquid flow rate of about one mps was described for a drop generation rate of 4000 drops per second. Assume that a slug of liquid 254 microns long is expelled on each exposure of the liquid to the laser beam 10. A 25 micron sided triangular capillary has a cross-sectional area of about 300 microns squared. The total cross-sectional area for an array of 4096 such capillaries is about 1,228,800 microns squared. Consequently, the maximum volume of liquid consumed by a printer with all capillaries expelling ink at 4096 drops per second is about 1.28 cubic centimeters (cc) per second. Of course, on a statistical basis, a raster printer does not run with all capillaries operating at the maximum drop rate at the same time. A coating machine is more likely to operate near the maximum flow rate.

Figure 3 shows a structure similar to that of Figure 2 with the transparent cover plate 30 replaced by the lenticular lens plate 36. The lens plate is transparent. It includes a planar surface 37 that closes the open air channels 8 formed in body 31, as does plate 30, thereby forming the base of the triangular capillaries. The lens plate also includes the plurality of parallel half-cylindrical surfaces 38. These cylindrical surfaces have a curvature—not necessarily circular—that focuses the beam 10 to a line onto the liquid within a capillary 8. The spatial frequency of the half-cyclinders is twice that of the triangular capillaries in this example. The lens surfaces can be larger than the dimension 33 so that there is one lens surface for each capillary. The extra lens is optically superfluous. However, the extra set of lenses—those aligned over the spaces between capillaries--is a reserve set of lenses. In the event an individual lens is damaged, the lens plate 36 is shifted one lens element to align a new set of lenses over the capillaries.

The lens plate 36 or the planar plate 30 are preferably made with a transparent polymer. The plates 36 and 30 are formed by injection molding process. The mold for a plate 36 includes a master having surfaces complementary to the lens surfaces 38.

The drop expulsion means 9 shown in Figure 1 includes a laser scanning system. Laser 40 is a high power laser, for example, a one to ten watt device. The light produced by the laser is shaped and focused by a collimating lens 41. The lens focuses the light beam from the laser down to a small spot at a capillary 8. For example, the spot size for the beam is about 25 microns or less in diameter. After passing through lens 41, the beam is modulated "on" and "off" by modulator 42. The modulator is either an acoustic-optic or electro-optic device well known in the art including such devices available from the Electronic Systems Division of the Harris Corporation of Melbourne, Florida and Lasermetrics, Incorporated of Teaneck, New Jersey.

The modulator 42 is set between its "on" and "off" states under the supervision of controller 45 to selectively generate a drop from a capillary. The controller is, for example, a microcomputer with associated peripherial and interface devices. The microcomputer or a data register which it operates is selected to have an operating speed capable of handling the desired drop printing rate.

The controller 45 orchestrates the operation of the entire printing system of Figure 1. It receives digital data representative of a full or a partial raster image to be printed on input line 46. The data representative of the image is presented serially to the modulator 42 on a scan line by scan basis. The polygon mirror 43is journalled for rotation at about 5120 revolutions per minute (rpm). It is rotated by a motor 49 which in turn is controlled via amplifier 50 by the controller 45. An angular encoder on the motor (not shown) supplies angular position information for the polygon to the controller. The polygon shown has eight equal mirror faces. To obtain 4096 scans per second rate, the polygon rotating at 5120 rpm has forty-eight facets. Each facet on polygon 43 sweeps the beam 10 through an angle (less than 45 degrees) that encompasses the width of body 31 containing the plurality of capillaries 8. The feedback from the encoder on motor 49 provides the controller 45 with information on the instantaneous location of beam 10. Each time the scanning beam crosses over a capillary, the controller 45 issues a signal to gate 42 via the amplifier 51. The signal sets the gate to its first state if a drop is desired and to its second state if no drop is desired from a particular capillary. Each capillary is addressed by the beam 10 in this fashion.

The beam 10 is blanked—that is, gate 42 is set to its second state--by controller 45 after the beam scans the plurality of capillaries 8 shown in Figure 2. At this time, the target 4 has had at least one scan line of drops placed on it by virtue of the beam 10 activating selected capillaries to generate a row of drops. The beam 10 is therefore blanked long enough for the target to move upward a distance to bring the next scan line on the target in alignment with the drop trajectories 12. The controller 45 regulates the motion of the target by appropriately energizing motor 52 via amplifier 53. The motor drives a target transport means represented by the wheel 54.

A full raster image is created on target 4 under the control of microprocessor 45 as the polygon 43 rotates at a suitable rpm and the target is advanced upward at an appropriate velocity. During this time, the pump (represented by arrow 15) supplying ink to the local reservoir 16 is also regulated by controller 45 by a suitable amplifier and control mechanism (not shown). The pump 15 is regulated to maintain the local reservoir pressure substantially constant. Of course, the pump 15 can be regulated independently of controller 45 if desired.

The printing system of Figure 1 (and that of Figure 4 described below) has an inherent resistance to electrical noise. The reason is that light, for example the light of beam 10, is the means giving rise to the generation of a drop and not any electrical signal coupled to the capillaries or ink. Also, cross talk between adjacent capillaries is easily suppressed by appropriately spacing the capillaries and shaping of the profile of beam 10 striking the capillaries. The profile is simply made too small to strike two capillaries at the same time.

The structure shown in Figure 4 is an example of another drop expulsion means. The system of Figure 4 is identical to that of Figure 1 with the laser scanning system 9 replaced by a plurality of solid state lasers in the form of power LED's 60. The LED's emit radiation upon application of a drive current coupled to the LED via conductors 61 and 62. Each LED is independently addressed. When activated, the light generated by an LED heats the liquid in a capillary near the orifice (at about 10 drop diameters away) to generate a drop. An LED 60 is provided for each capillary 8. The controller 45 is wired to the plurality of LED's rather than the optical scanning device of Figure 1. In this embodiment, an entire scan line can be generated simultaneously by energizing all the desired LED's at one time.

The speed at which a full array of LED's 60 can be addressed greatly exceeds the speed at which a target transport, e.g. wheel 54, is able to advance a target 4 one scan line. Consequently, a time sharing or multiplexed addressing of sub-groups of the LED's is preferred to simultaneously addressing a full array of LED's. In addition, the time sharing technique is more economical for printing systems of the type shown in Figure 1 in that it reduces the number of wires that must be coupled to the array of LED's.

The foregoing embodiments of this invention are subject to variations and modification for adapting the invention to specific applications. For example, the target 4 of Figure 1 could be mounted on a high speed rotating drum. In this case, the generator and spacer 2 are mounted on a screw or other translating device to translate the generator along the axis of the drum. Here the generator need include only a limited number of capillaries, for example, 7, 8, 9 or 10 that create characters on a target by a matrix printing scheme. A 9 x 12 drop matrix pattern is possible with a linear array of nine capillaries 8. The 9 x 12 matrix pattern is repeated each time the nine capillaries are displaced relative to the target a distance of twelve rows.

CLAIMS:

1. Drop-on-demand ink drop marking apparatus comprising

a drop generator (1) including at least one capillary channel (8) having an orifice (7) for expelling an ink drop (11) into flight towards a target (4), drop expulsion means (9) for stimulating ink (6) in the capillary channel (8) for expelling the drop of ink, and pressure means (15) coupled to the drop generator for supplying ink to the capillary channel, characterised in that the pressure means (15) supplies the ink (6) to the capillary channel (8) under sufficient pressure to cause ink to weep from the orifice (7) when drops are not being expelled.

2. The apparatus of claim 1 wherein the expulsion means (9) includes means (40 or 60) for thermally stimulating liquid in the channel near the orifice to effect the expulsion of a drop.

3. The apparatus of claim 2 wherein the drop generator (1) includes a transparent section (30) adjacent the capillary channel at least in the region near the orifice and wherein the expulsion means (9) includes means (40, 41, 43) for exposing liquid in the capillary to a laser beam (10) through the transparent section to heat the liquid to expel a drop.

4. The apparatus of claim 3 wherein the transparent section of the generator includes lens means (36) for focusing the incident laser beam onto the liquid in a capillary channel.

5. The apparatus of claim 1 wherein the drop generator (1) includes a transparent section (30) adjacent the capillary channel at least in the region near the orifice and wherein the expulsion means includes a solid state laser (60) adjacent the transparent region for exposing liquid in the capillary channel to radiation generated by the solid state laser to heat the liquid to expel a drop.

6. The apparatus of any one of claims 1 to 5, wherein the drop generator includes a plurality of capillary channels arranged in a linear array.

7. The apparatus of claim 3, wherein the drop generator (1) includes a plurality of capillary channels (8) arranged in a linear array and a transparent cover plate (30) forming one wall of the channels at least in the region of the channels near the orifices and wherein said drop expulsion means includes a laser beam light source (40), a laser beam modulator (42), and a rotating polygon mirror (43) for scanning the laser beam (10) over the plurality of capillaries for selectively expelling drops in accordance with an input signal to the modulator.

8. The apparatus of any one of claims 1 to 7 including sump means (5) for collecting ink weeping from the capillary orifice.

9. The apparatus of claim 8 including means (23, 24) for returning ink collected in the sump to the drop generator.

10. A drop-on-demand ink drop marking method comprising generating drops of ink by stimulating the ink in a capillary channel so as to expel drops from the orifice of the channel into flight towards a target, characterised by supplying ink to the capillary channel under sufficient pressure to cause ink to weep from the orifice when drops are not being expelled.

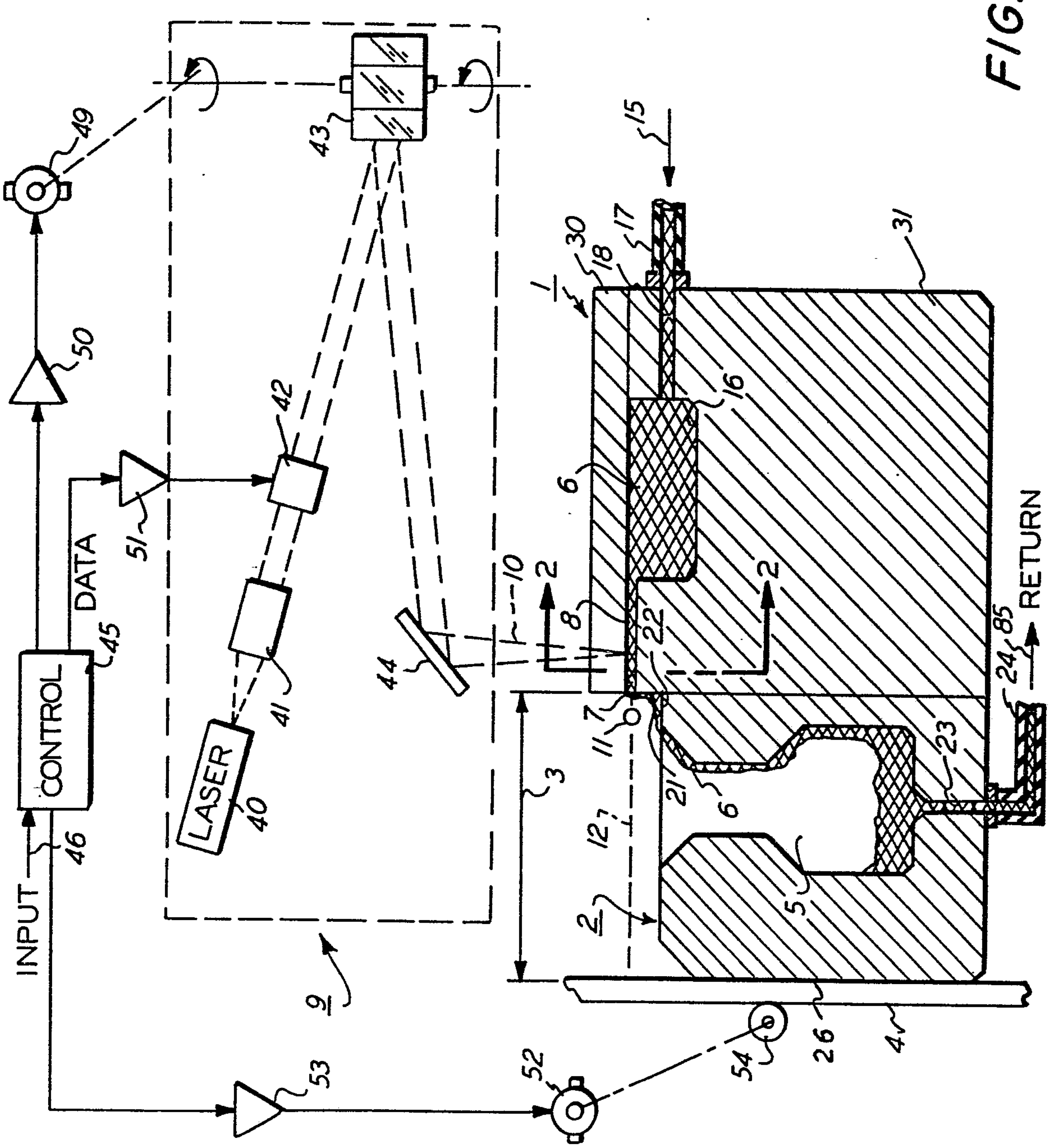

FIG. 1

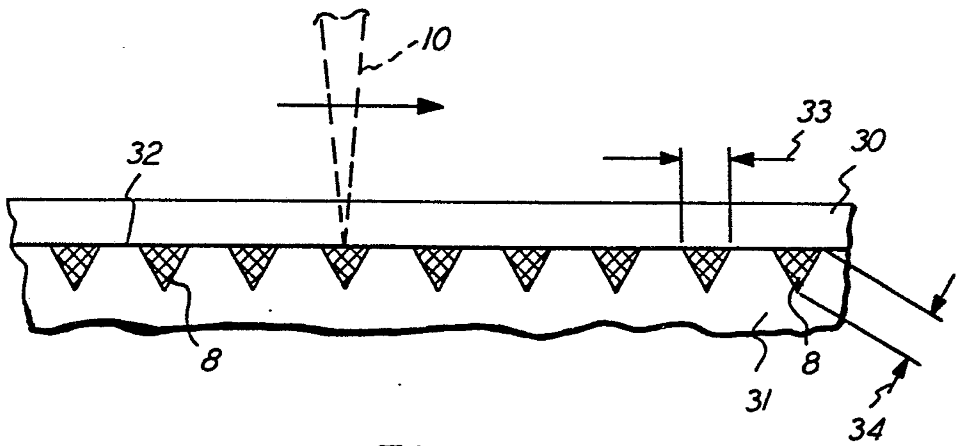

FIG. 2

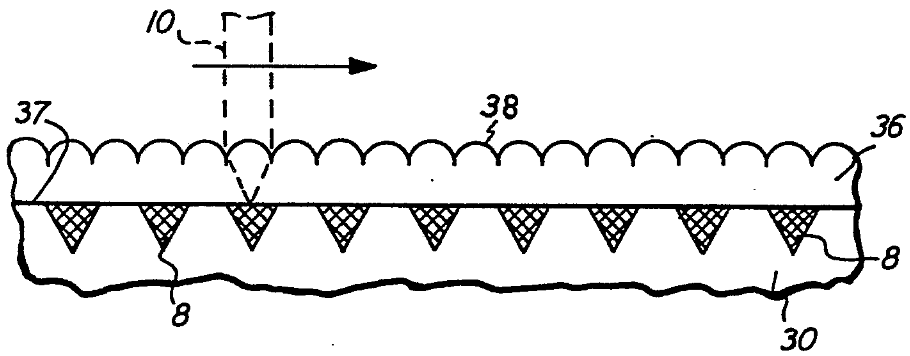

FIG. 3

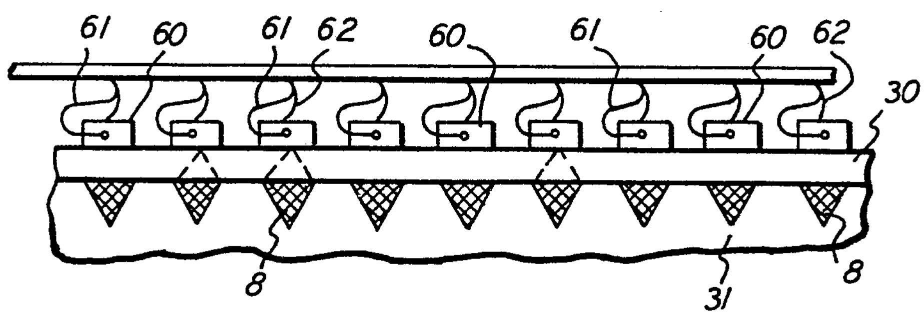

FIG. 4