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(54) **MAGNETICALLY-ACTUATED MICROPUMP**

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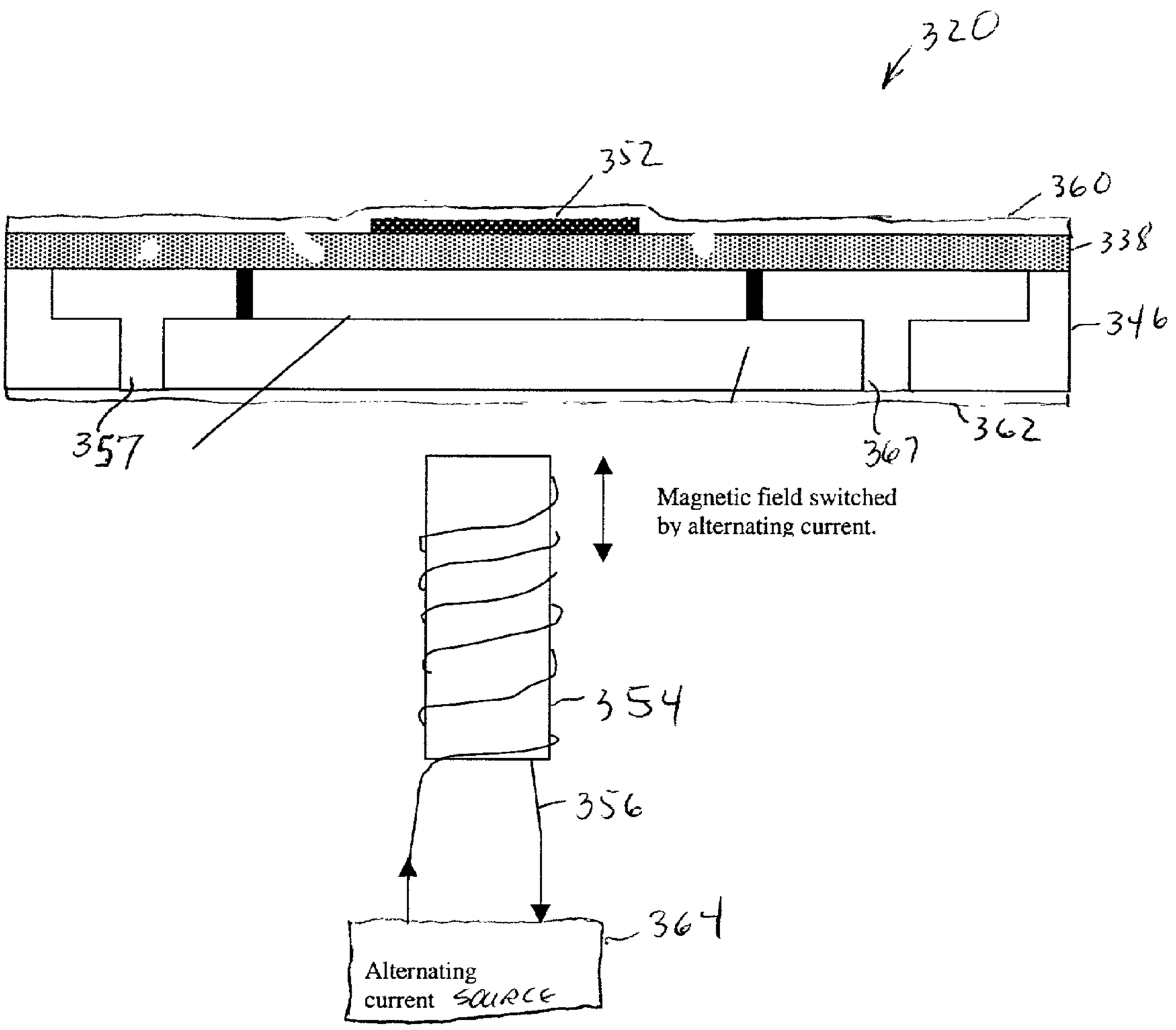
(57) **ABSTRACT**

A microfluidic pump having a substrate with a pump chamber and at least one channel in communication with the pump chamber for transporting a substance into or out of the pump chamber. A flexible diaphragm overlies the pump chamber, and a magnetic member is attached to the diaphragm. A magnet, such as an electromagnet, is positioned to attract and repel the magnetic member, thereby actuating the diaphragm, and causing a substance to be drawn into or out of the channel. A uni-directional or bi-directional check valve can be positioned in the channel to prevent backflow into the pump chamber. A control system can be coupled to the pump to adjust actuation rate of the diaphragm.



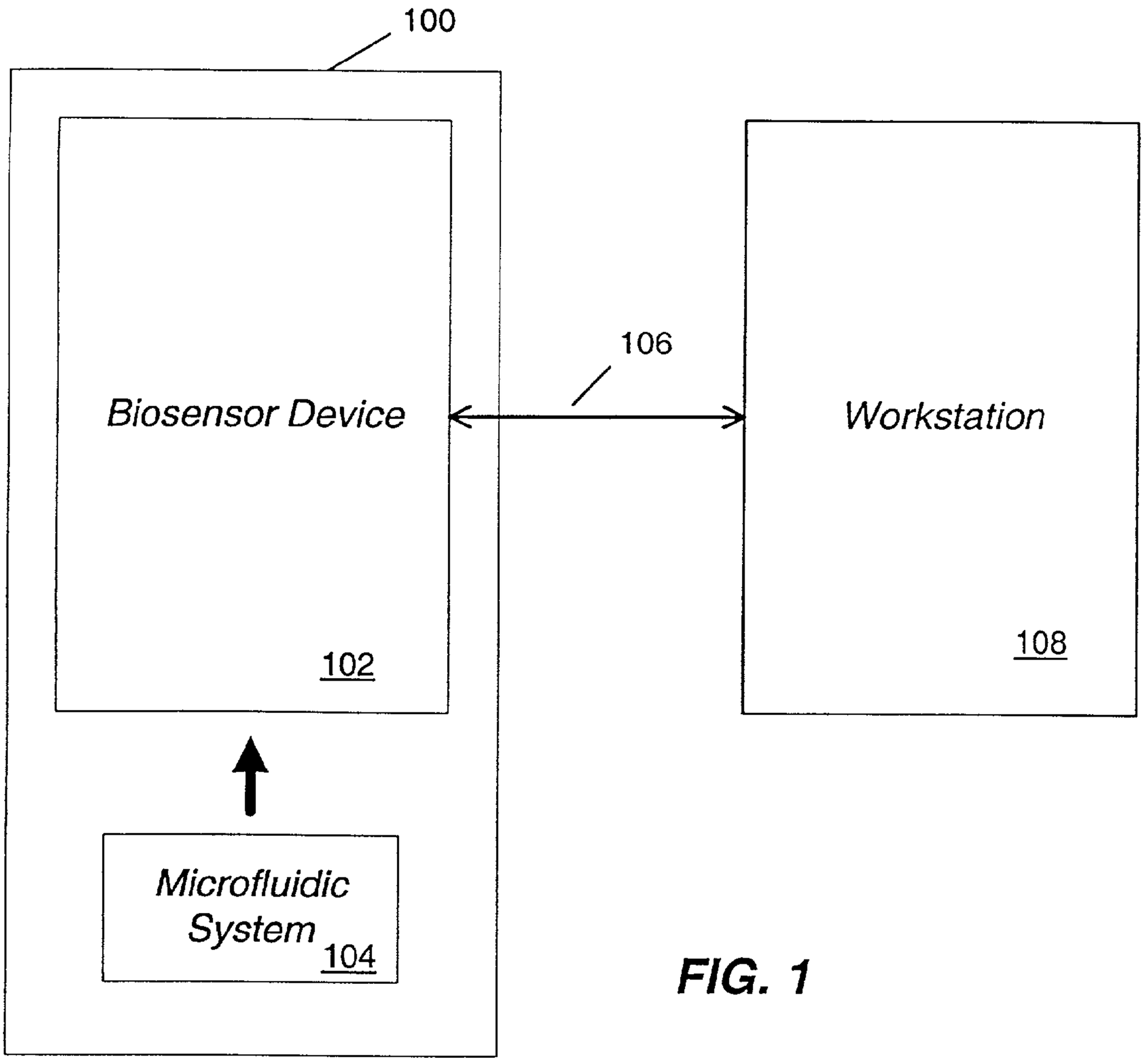

100
Biosensor Device
102
106
Workstation
108
Microfluidic System
104

FIG. 1

Figure 1a: FUNCTIONAL BLOCK DIAGRAM OF SYSTEM 100 (includes 5 schematics)

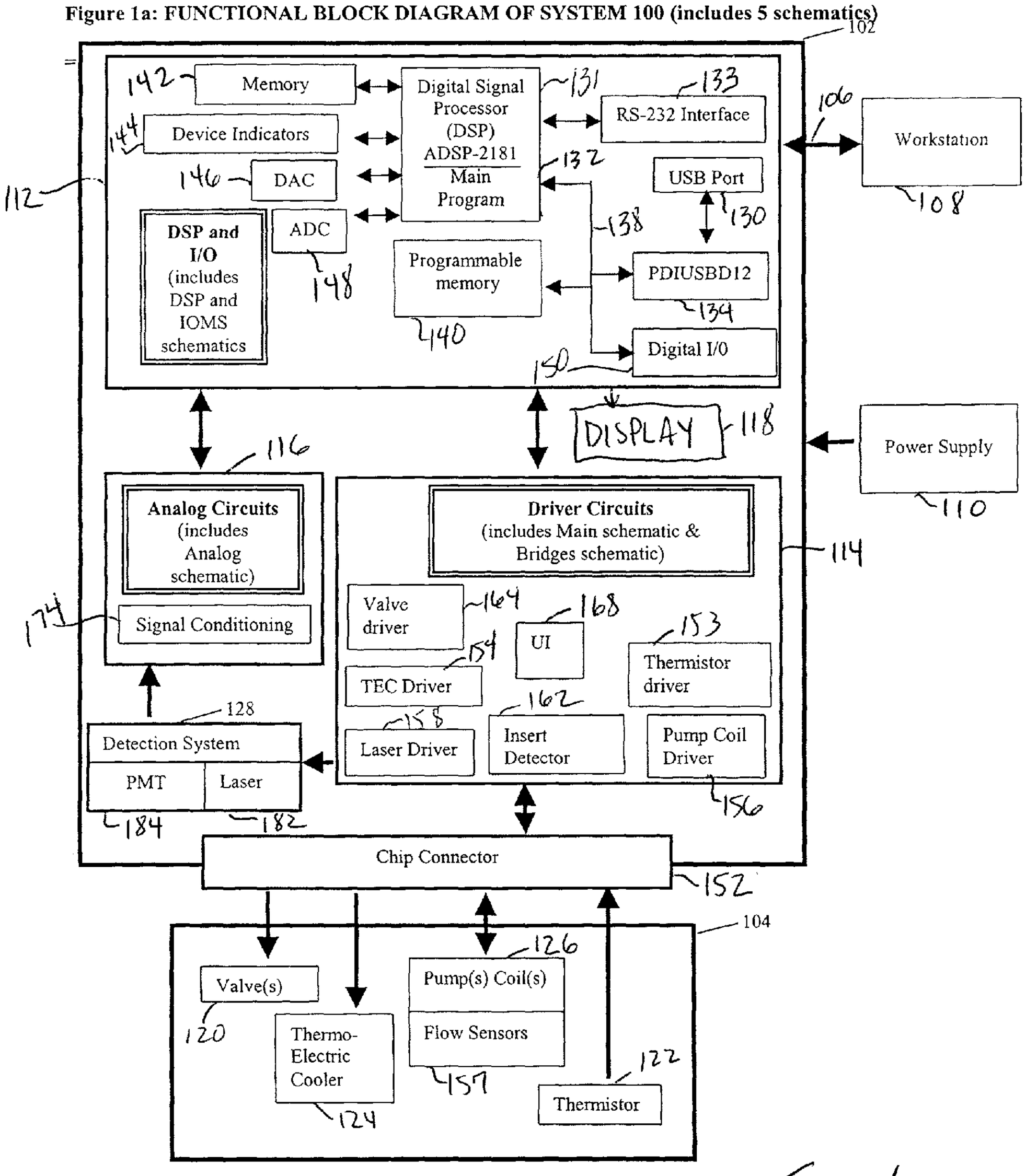


FIG. 1a

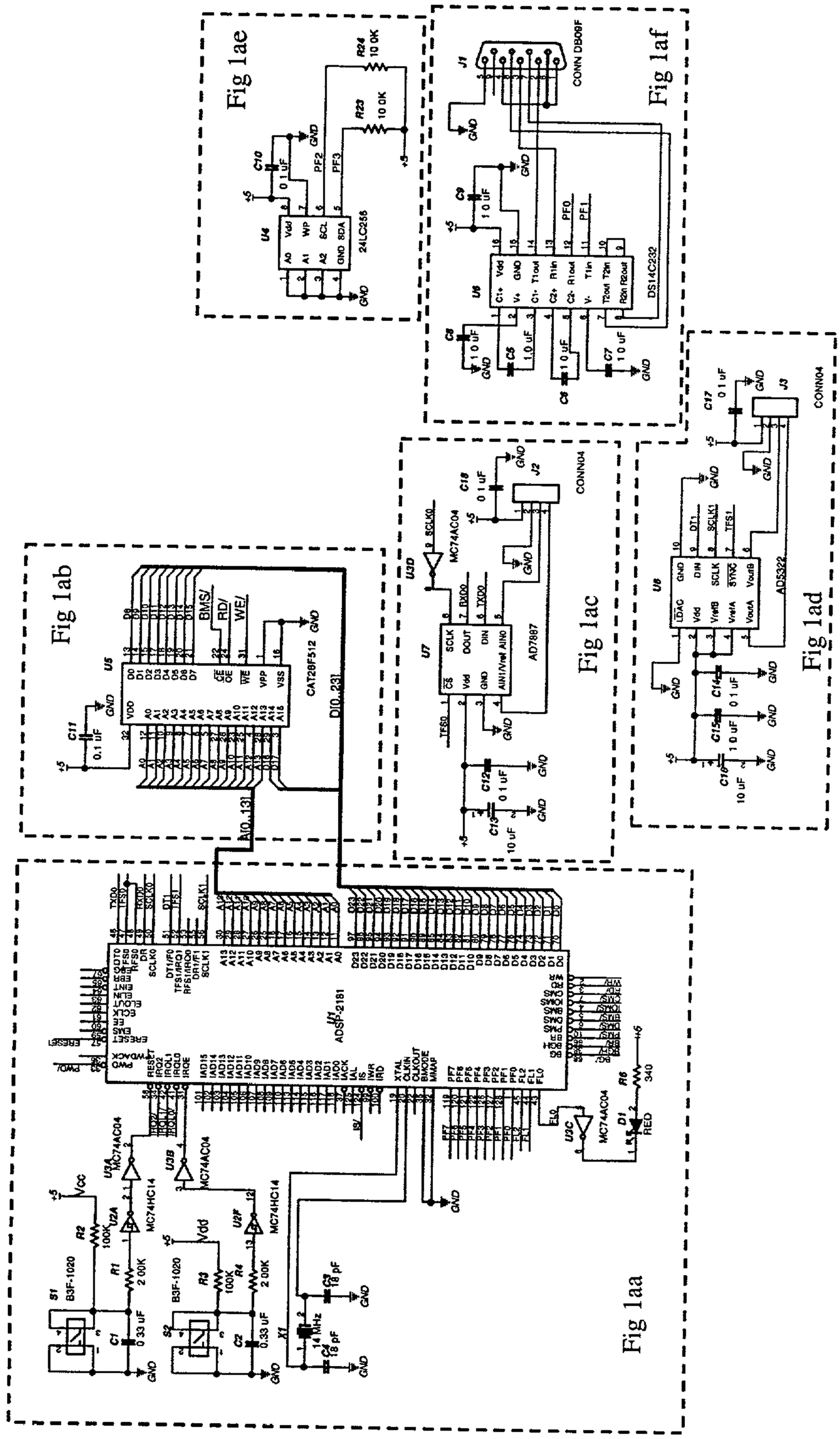


Fig 1ae
Fig 1af
Fig 1ab
Fig 1ac
Fig 1ad
Fig 1aa
DSP Schematic

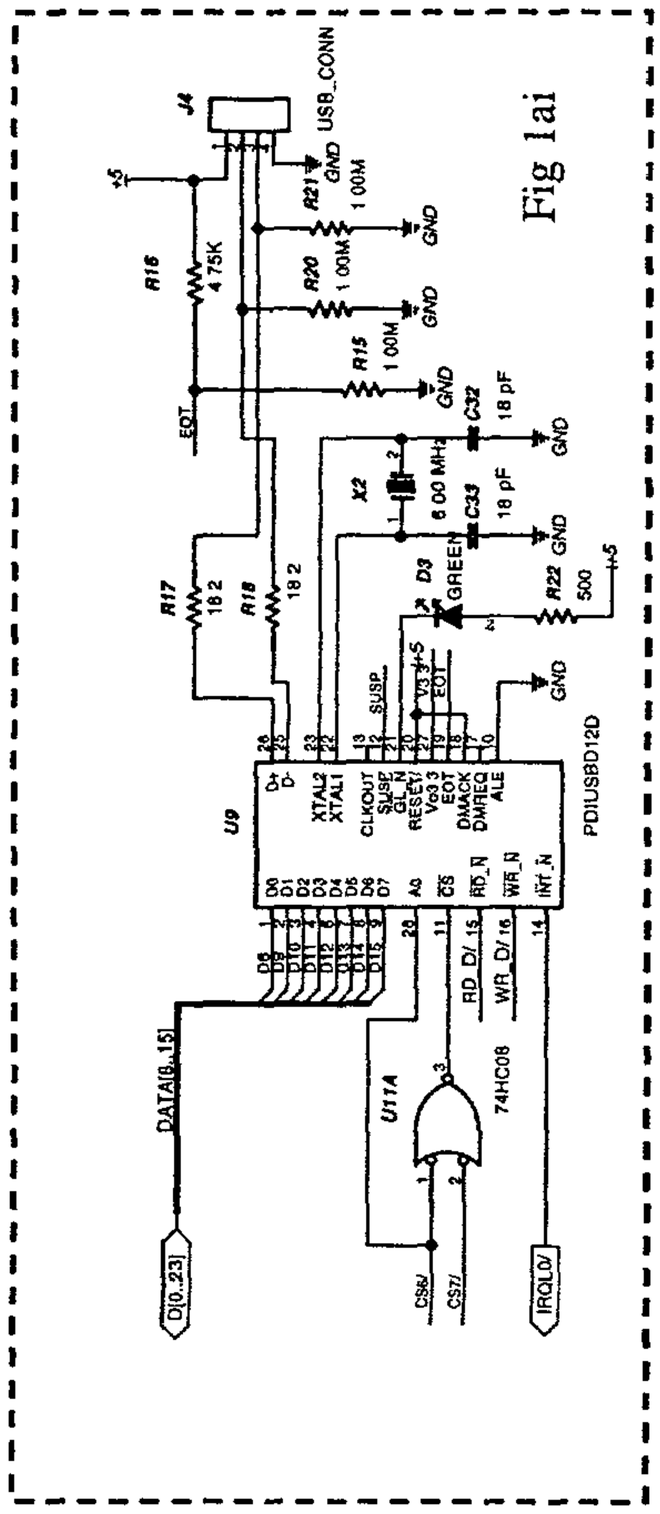


Fig 1ai

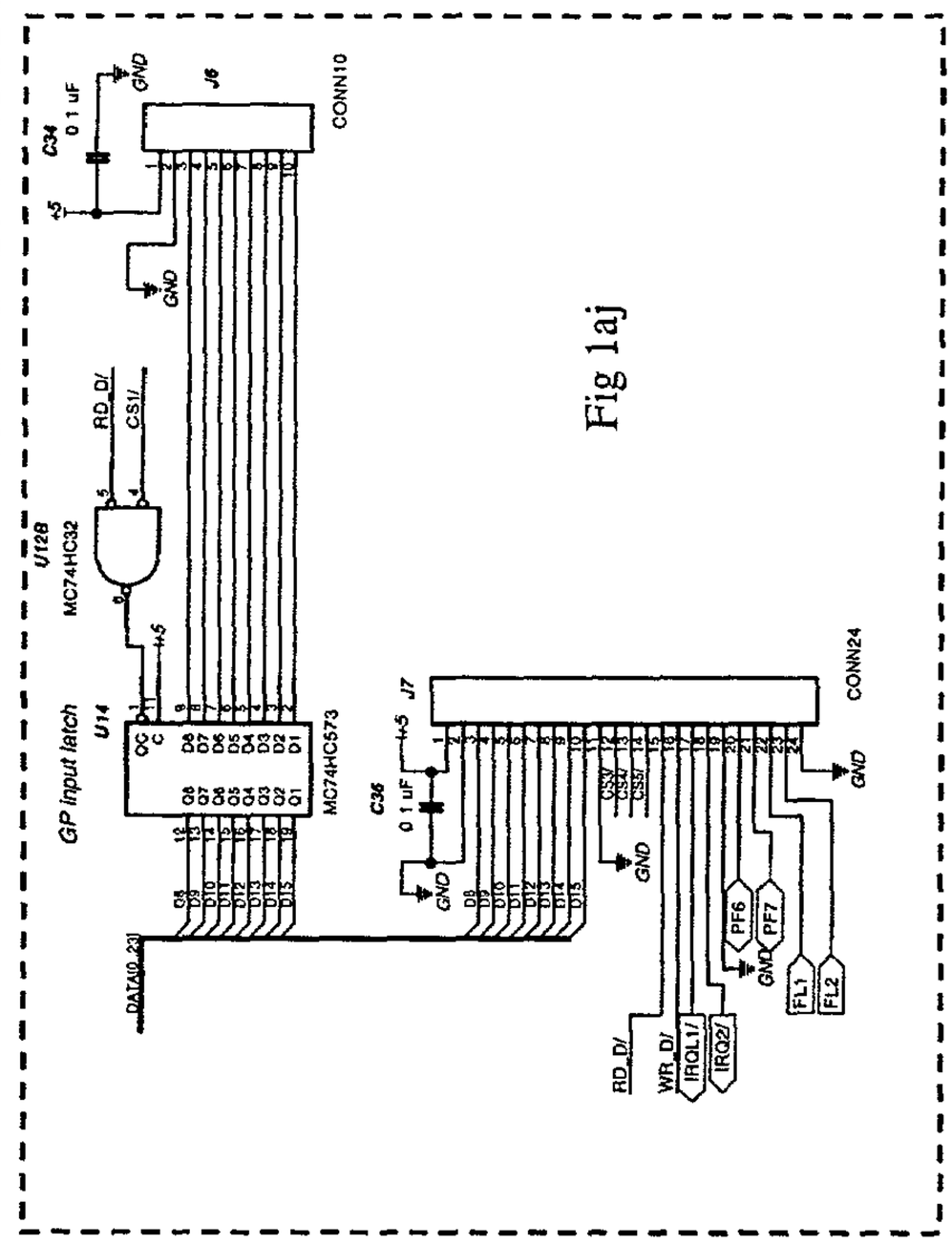


Fig 1aj

IOMS Schematic

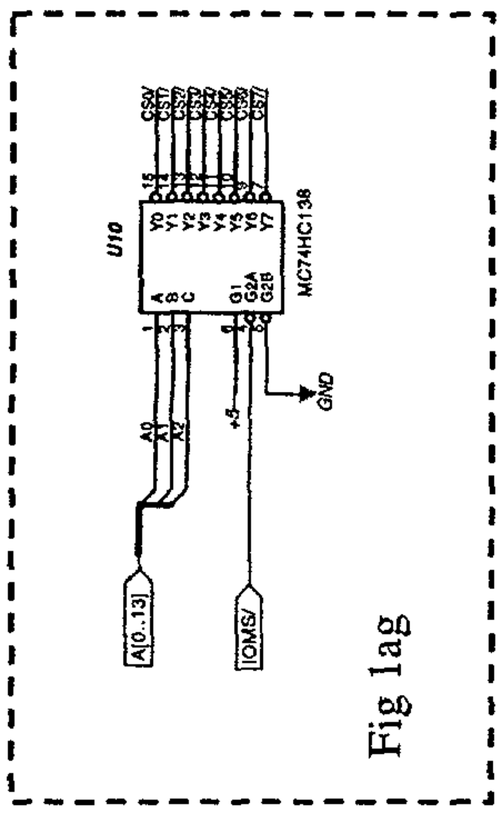


Fig 1ag

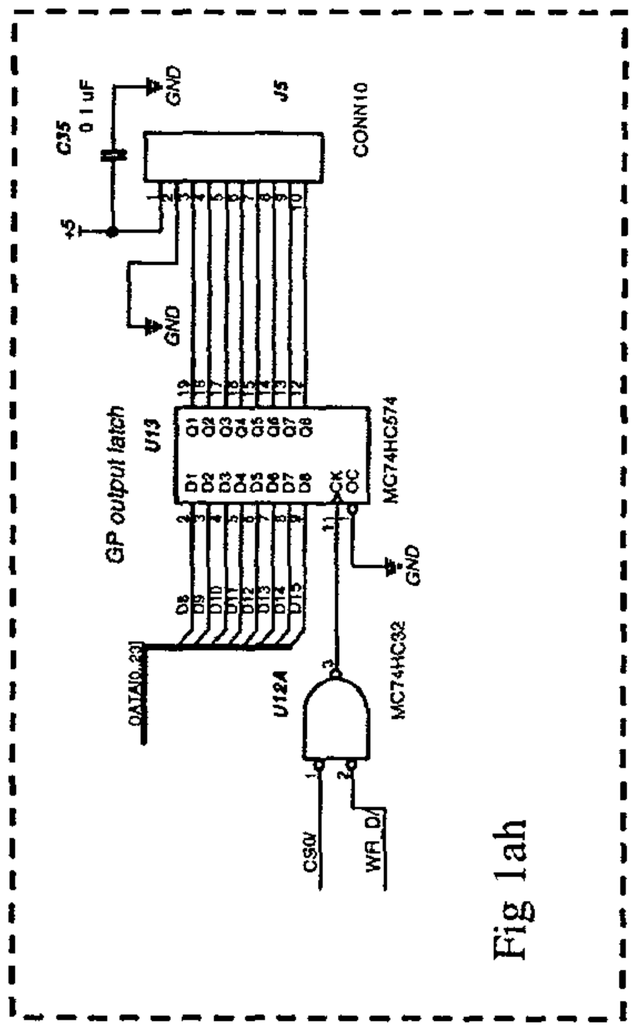


Fig 1ah

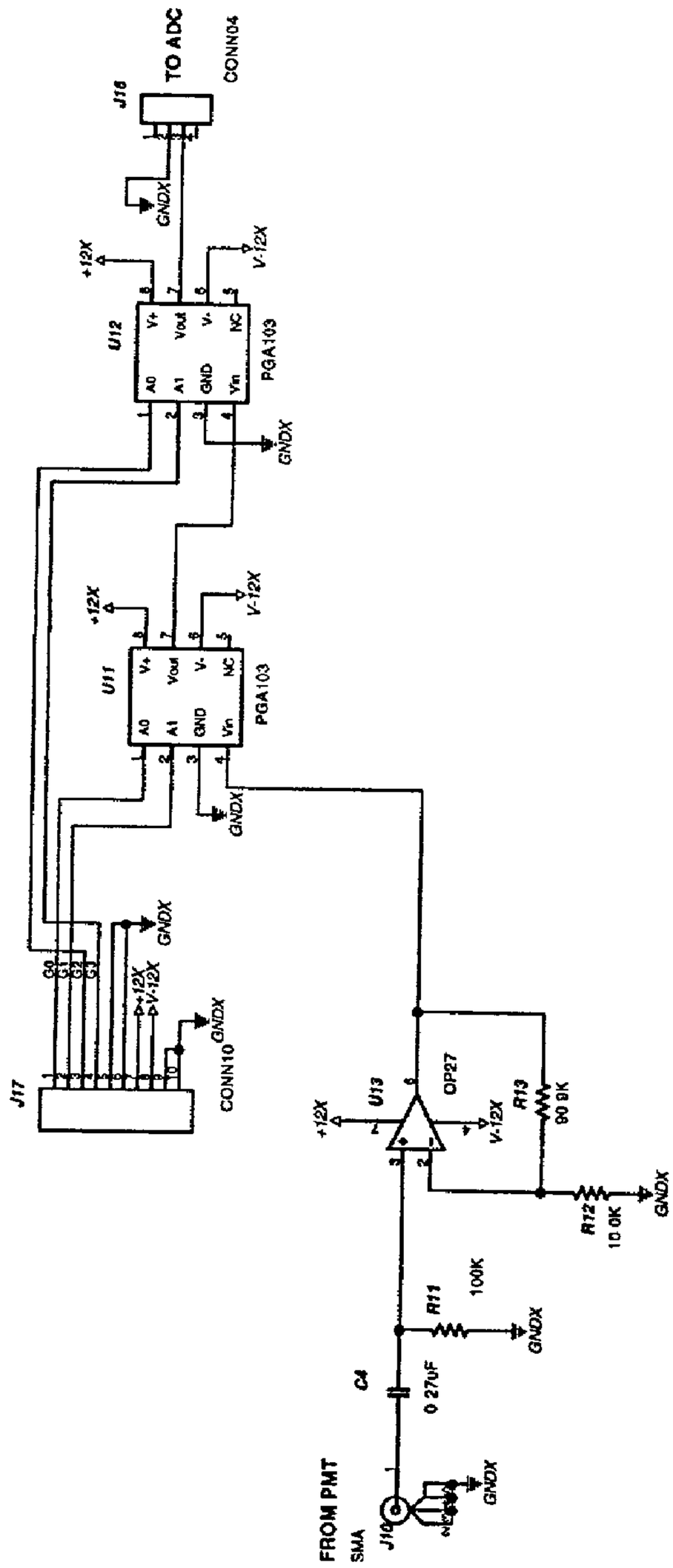

Analog Schematic
TO ADC
CONN04
J16
GNDX
+12X
V-12X
U12
PGA103
U11
J17
CONN10
G0
G1
G2
G3
FROM PMT
SMA
J10
C4
0 27uF
R11
100K
U13
OP27
R13
90 9K
R12
10 0K

Fig 1ak

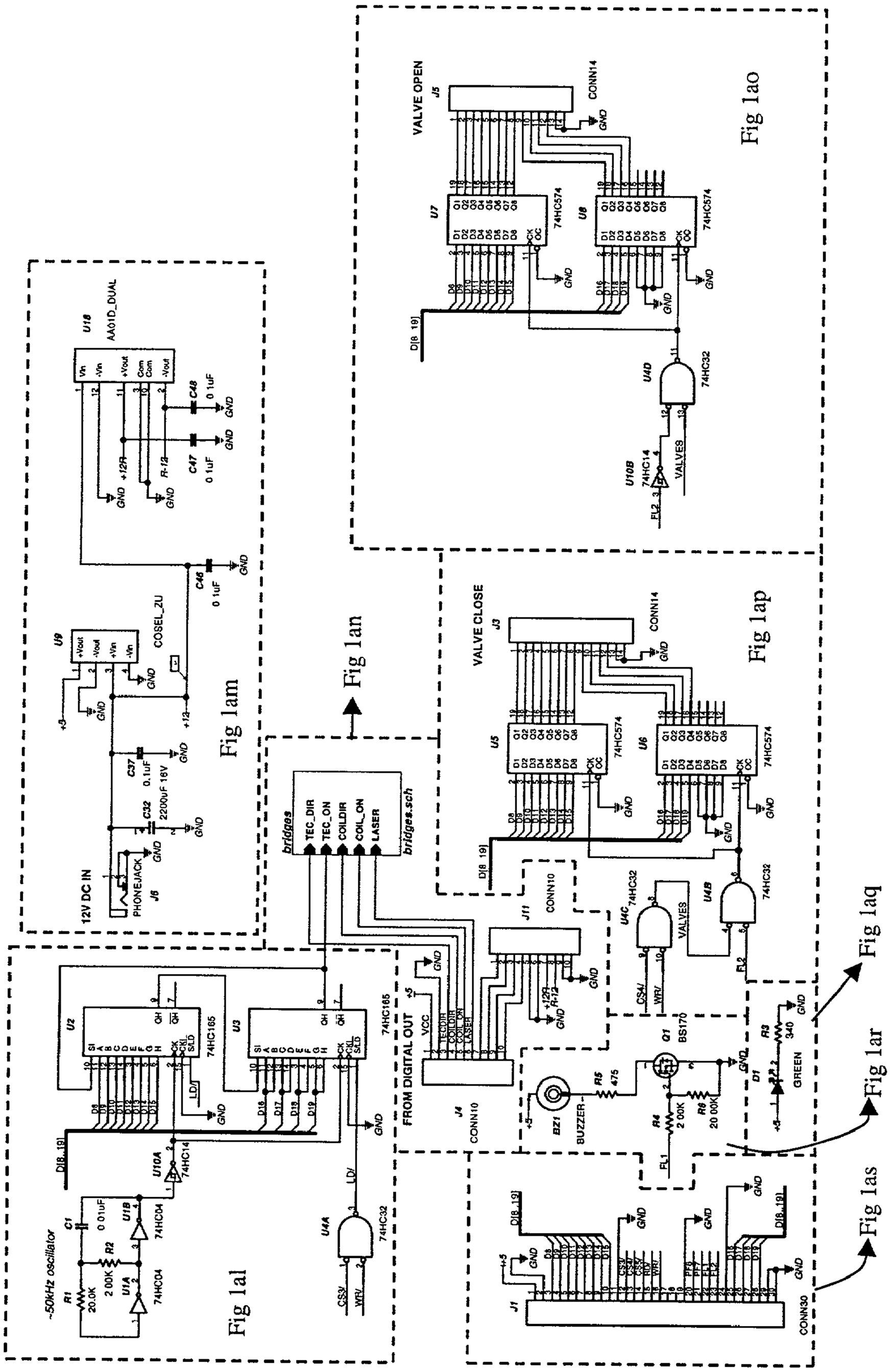

Main Schematic
Fig 1ao
Fig 1ap
Fig 1aq
Fig 1ar
Fig 1as
Fig 1an
Fig 1am
Fig 1al
VALVE OPEN
VALVE CLOSE
CONN14
74HC574
74HC32
74HC14
74HC165
74HC04
COSEL_ZU
AA01D_DUAL
PHONEJACK
12V DC IN
FROM DIGITAL OUT
CONN10
CONN30
BUZZER
GREEN
BS170
bridges
bridges.sch
TEC_DIR
TEC_ON
COILDIR
COIL_ON
LASER
VALVES
~50kHz oscillator
GND

Fig 1av

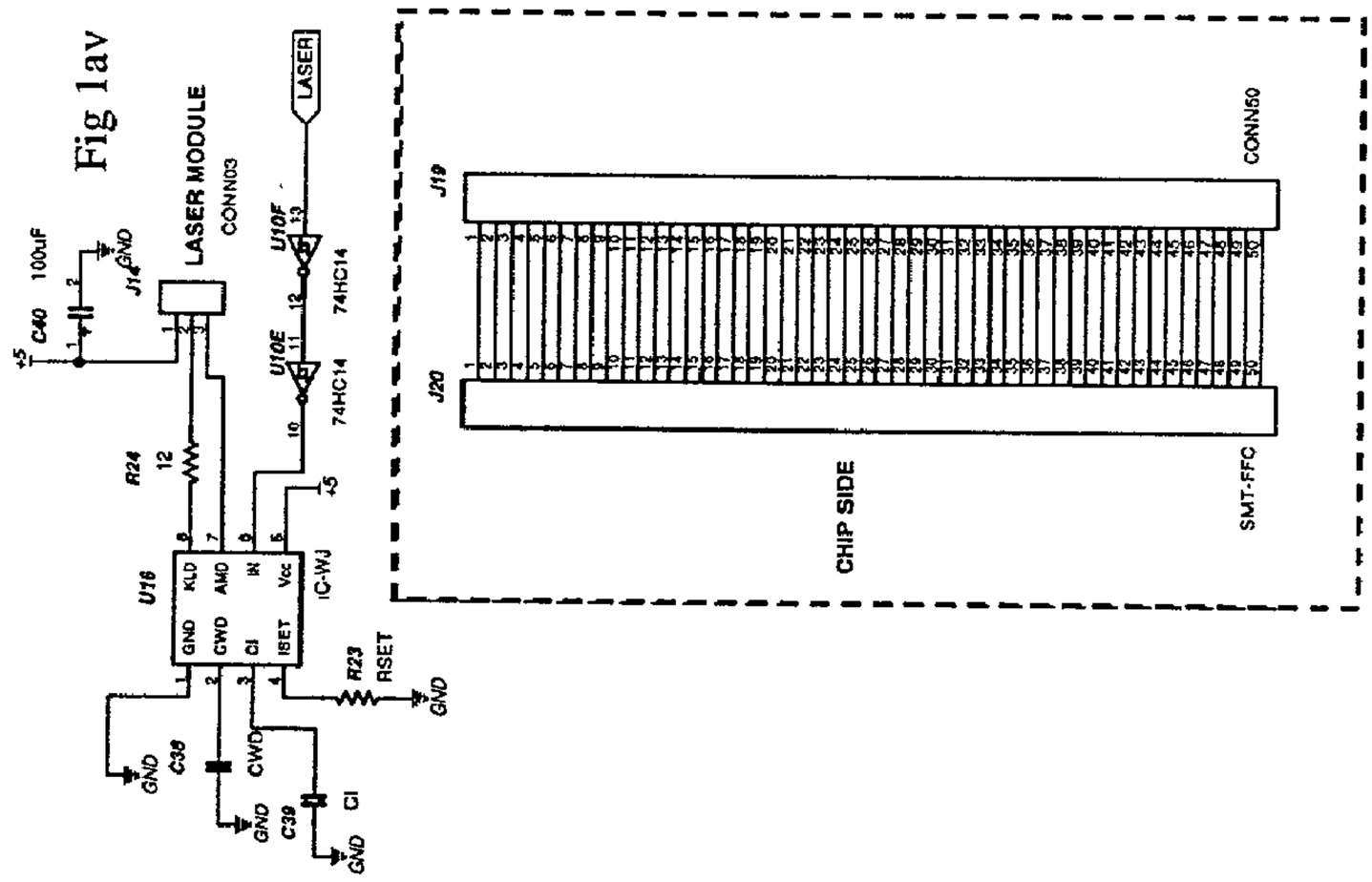


Fig 1aw

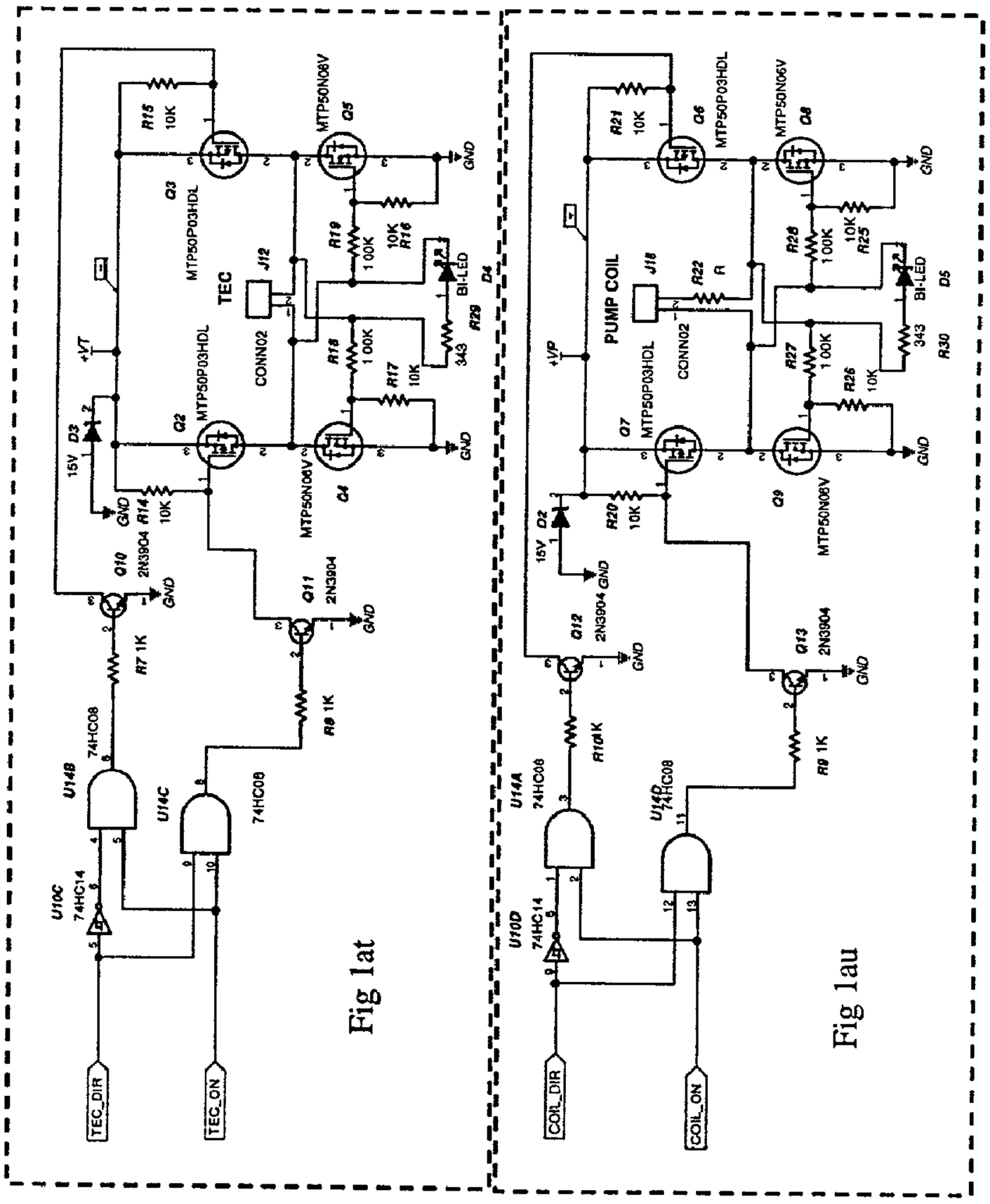


Fig 1at

Fig 1au

Bridges Schematic

Top View

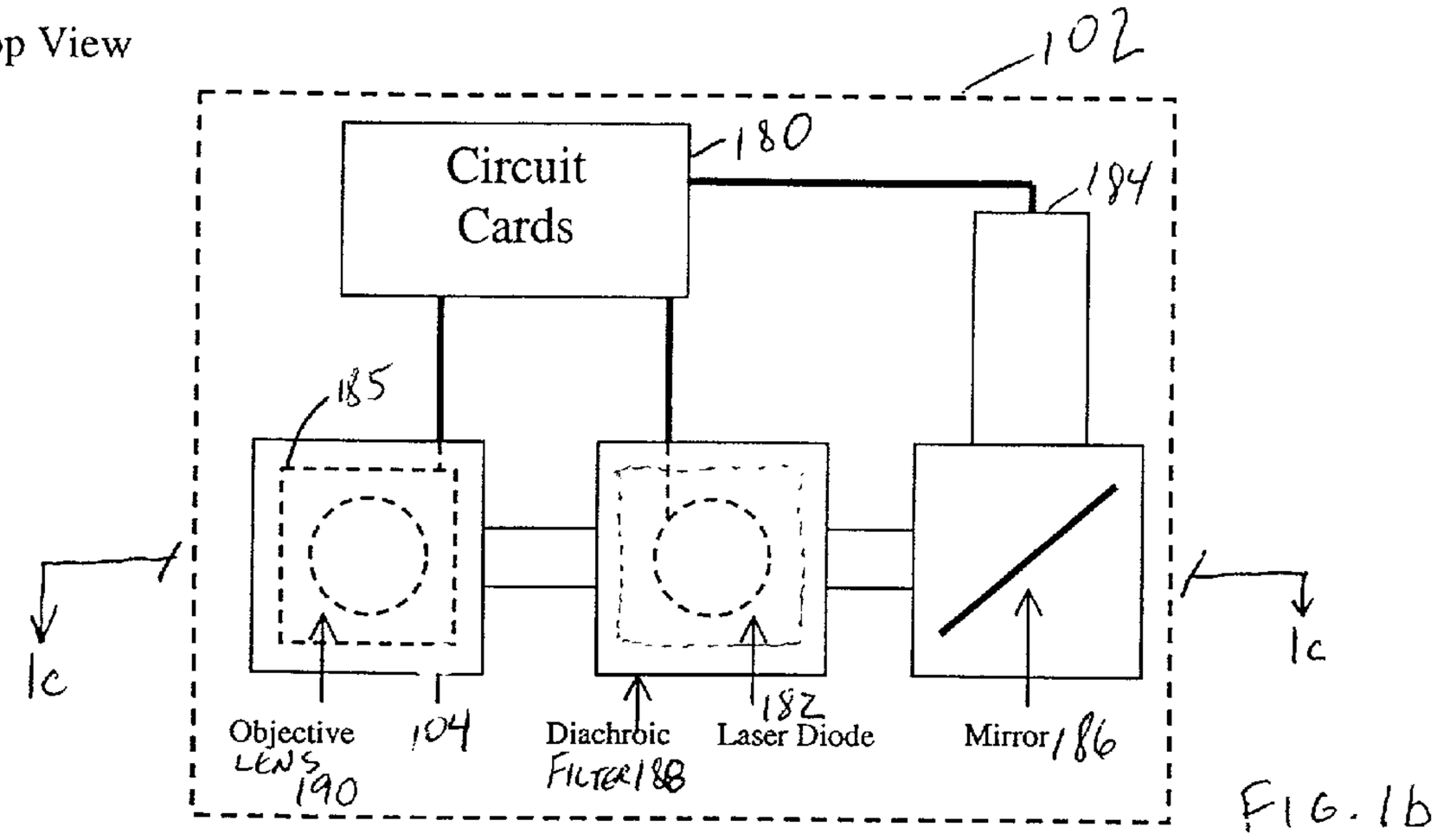


FIG. 1b

Side View Cross-Section

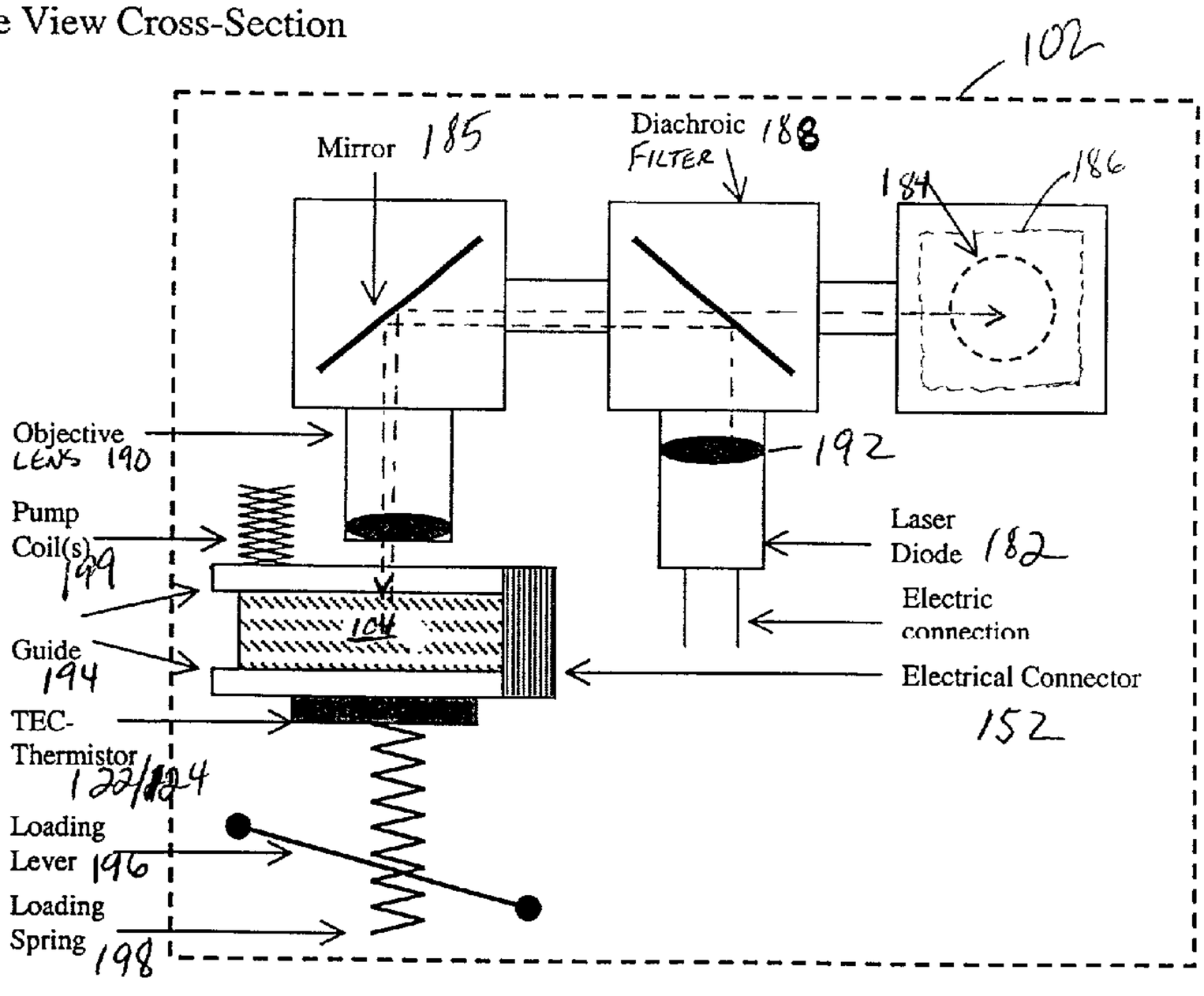


FIG. 1c

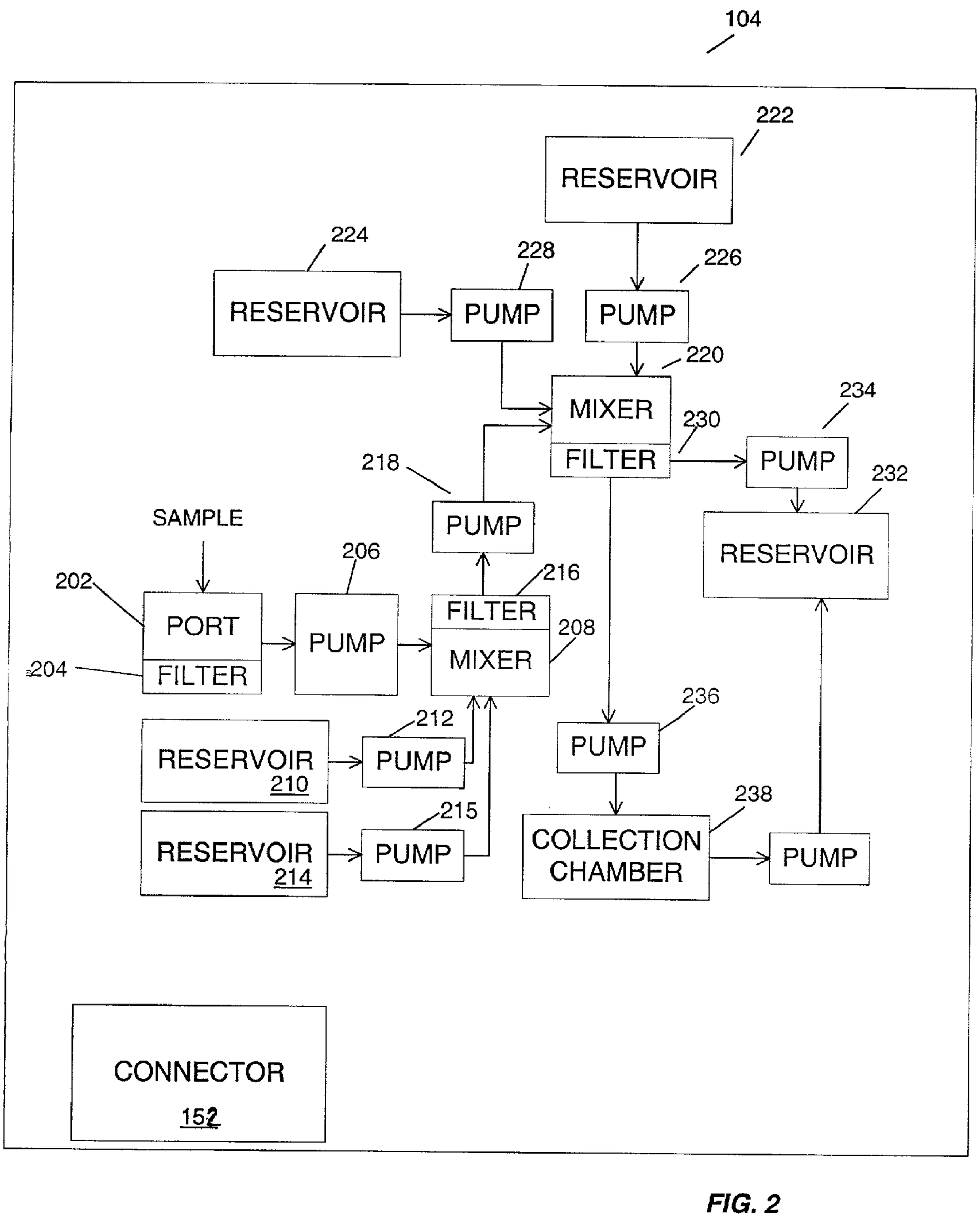

104
222
RESERVOIR
224
228
226
RESERVOIR
PUMP
PUMP
220
MIXER
234
230
FILTER
PUMP
218
232
SAMPLE
PUMP
RESERVOIR
206
216
202
PORT
FILTER
PUMP
208
204
FILTER
MIXER
236
212
RESERVOIR
210
PUMP
PUMP
238
215
RESERVOIR
214
PUMP
COLLECTION CHAMBER
PUMP
CONNECTOR
152

FIG. 2

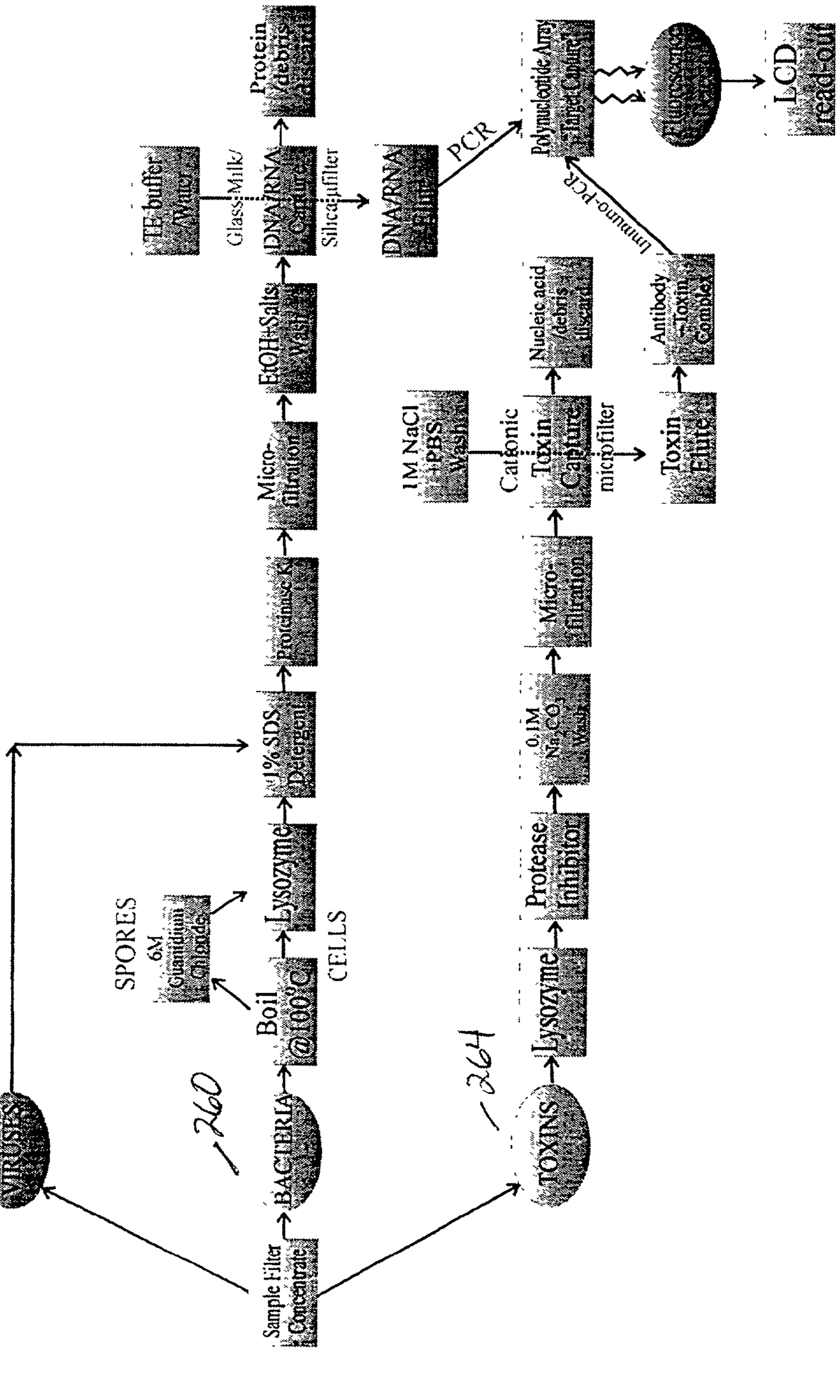

VIRUSES
SPORES
6M Guanidium Chloride
Boil
BACTERIA
@100°C
CELLS
Lysozyme
1% SDS Detergent
Proteinase K
Micro-filtration
EtOH+Salts Wash
Protein /debris discard
TE buffer Wash
Glass Milk/ DNA/RNA Capture
Silica/filter
DNA/RNA Elute
PCR
Polynucleotide Array +Target Capture
Fluorescence
LCD read-out
Immuno-PCR
Sample Filter
Concentrate
TOXINS
Lysozyme
Protease Inhibitor
0.1M Na2CO3 Wash
Micro-filtration
1M NaCl +PBS Wash
Cationic Toxin Capture
microfilter
Nucleic acid /debris discard
Toxin Elute
Antibody -Toxin Complex
262
260
264

FIG. 2a

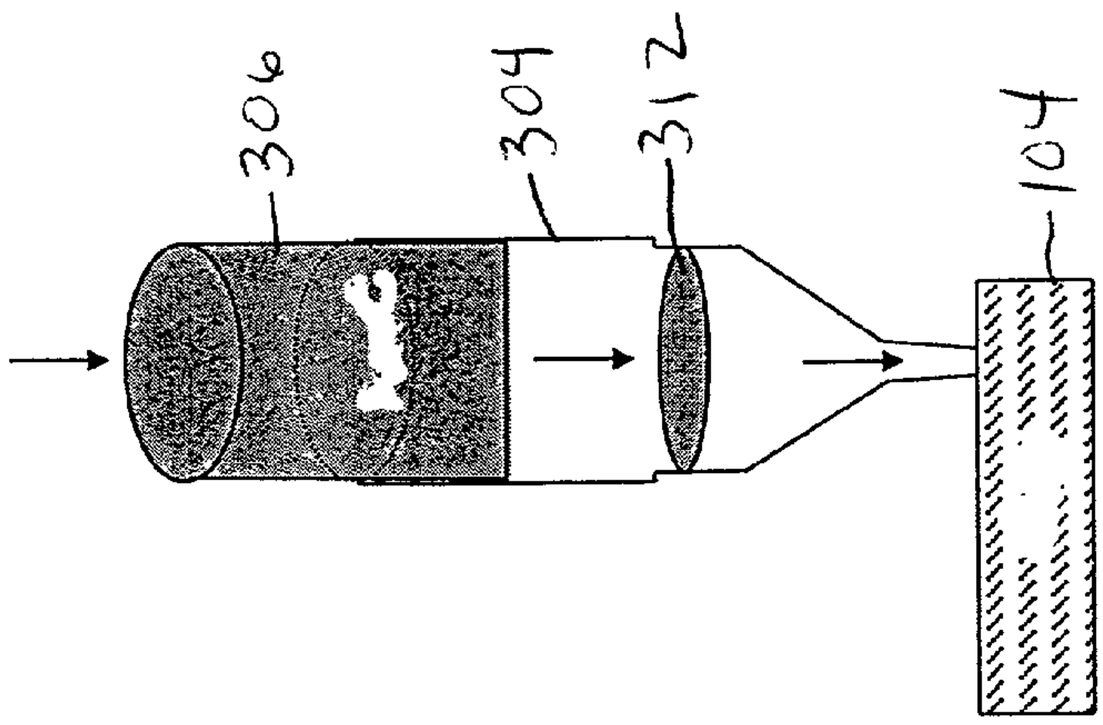

306
304
312
104

FIG. 3b

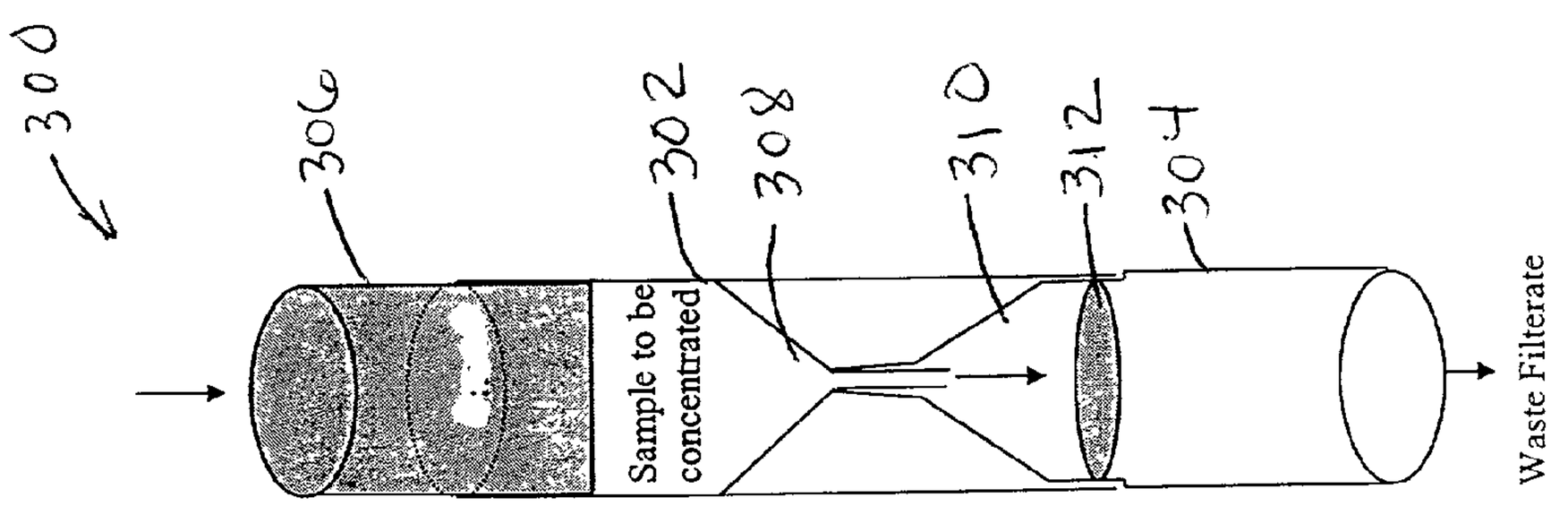

300
306
302
308
310
312
304
Sample to be concentrated
Waste Filterate

FIG. 3a

Fig. 3c

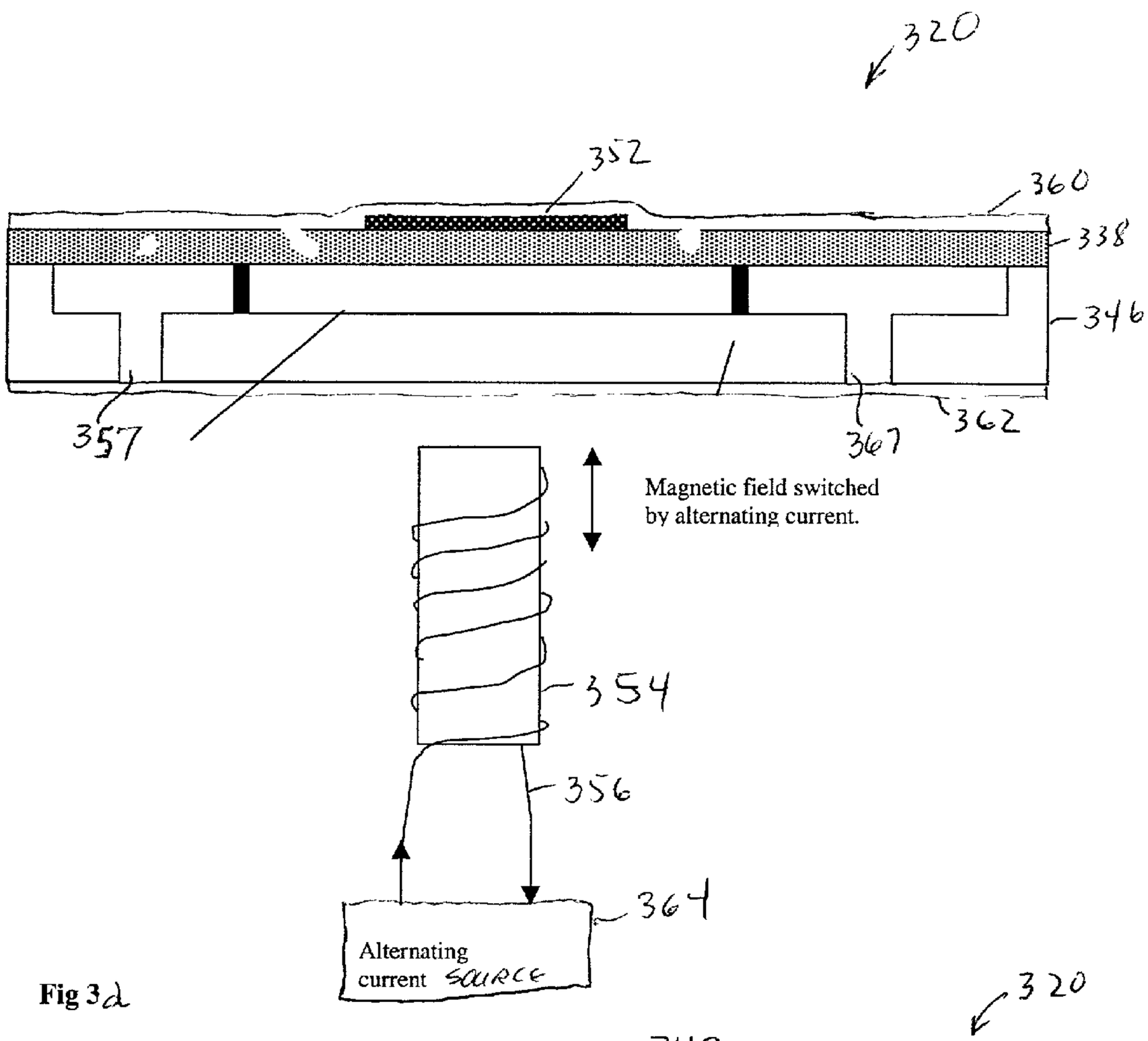
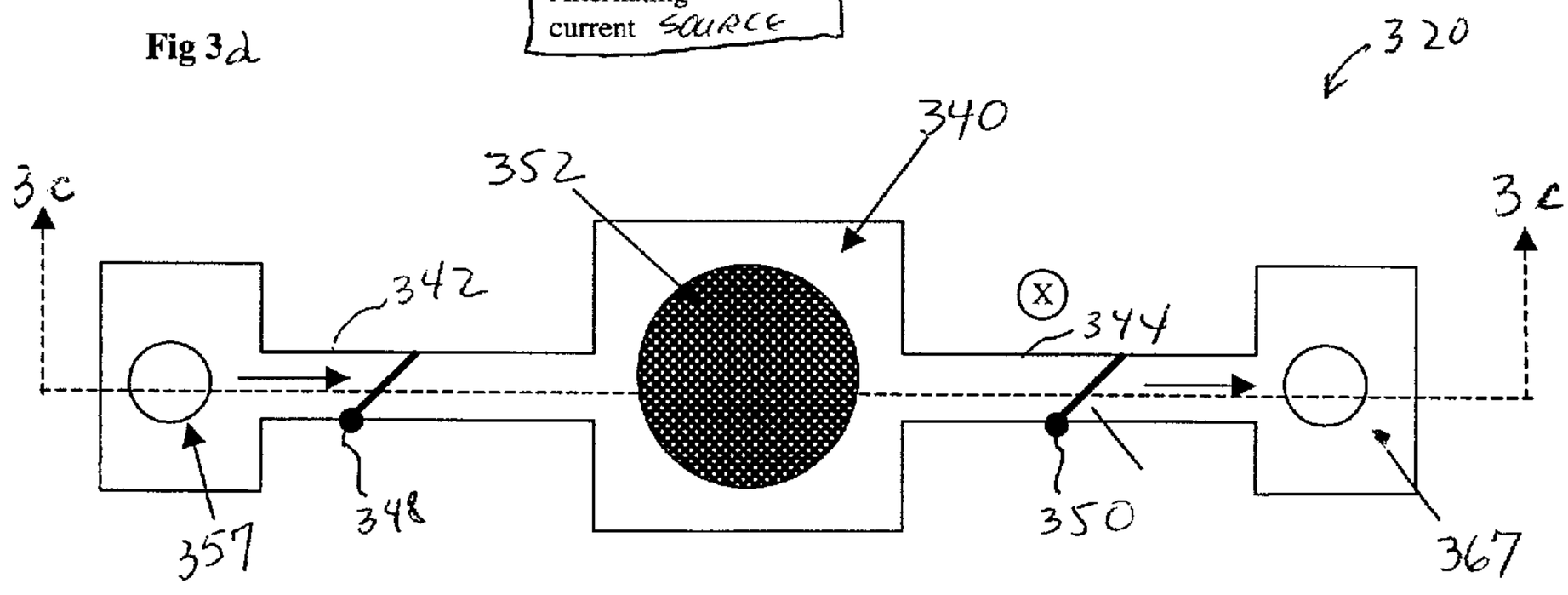

320
352
360
338
346
357
367
362
Magnetic field switched by alternating current.
354
356
364
Alternating current source

Fig 3d


320
340
352
3c
3c
342
344
348
350
357
367

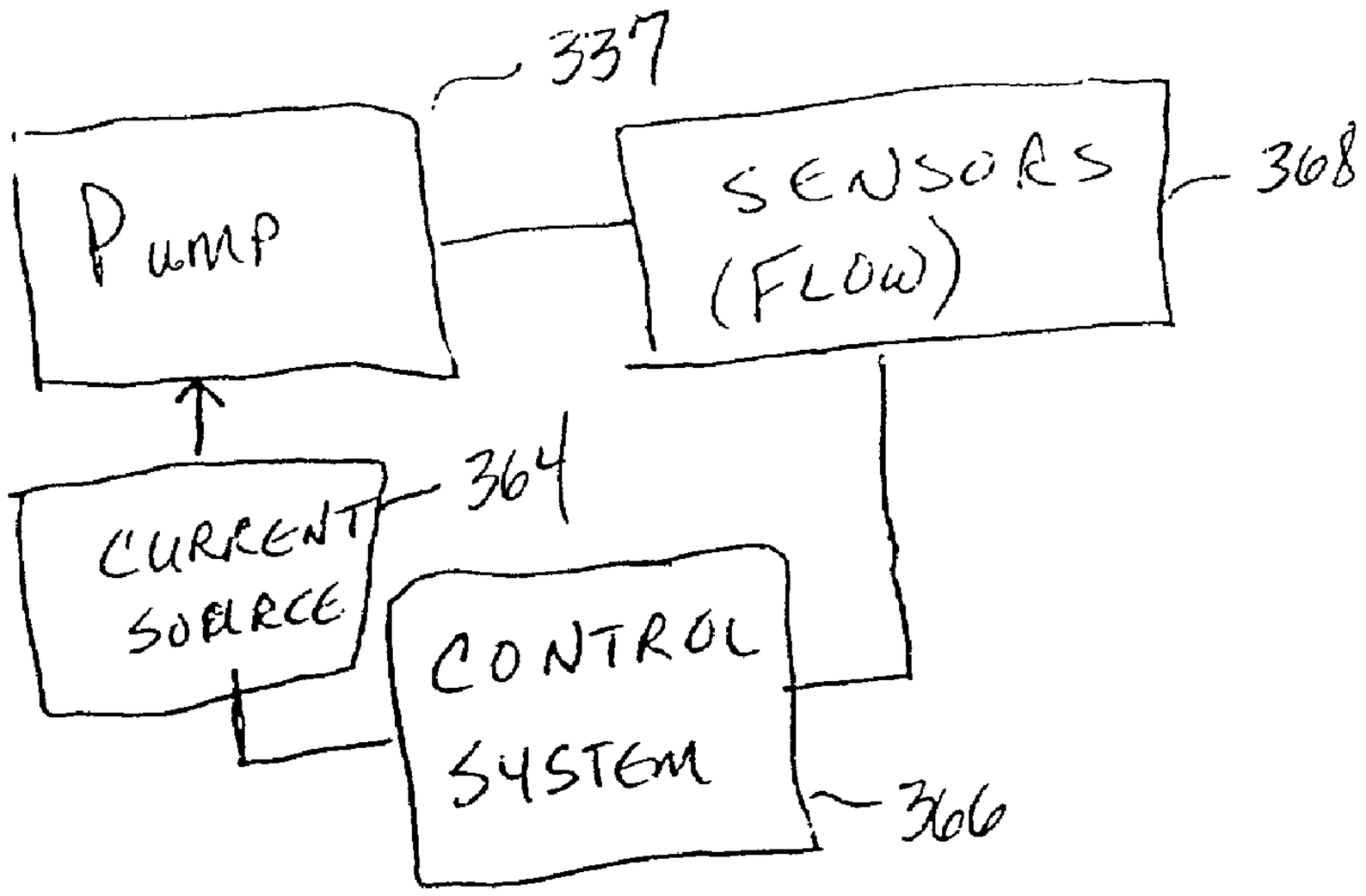
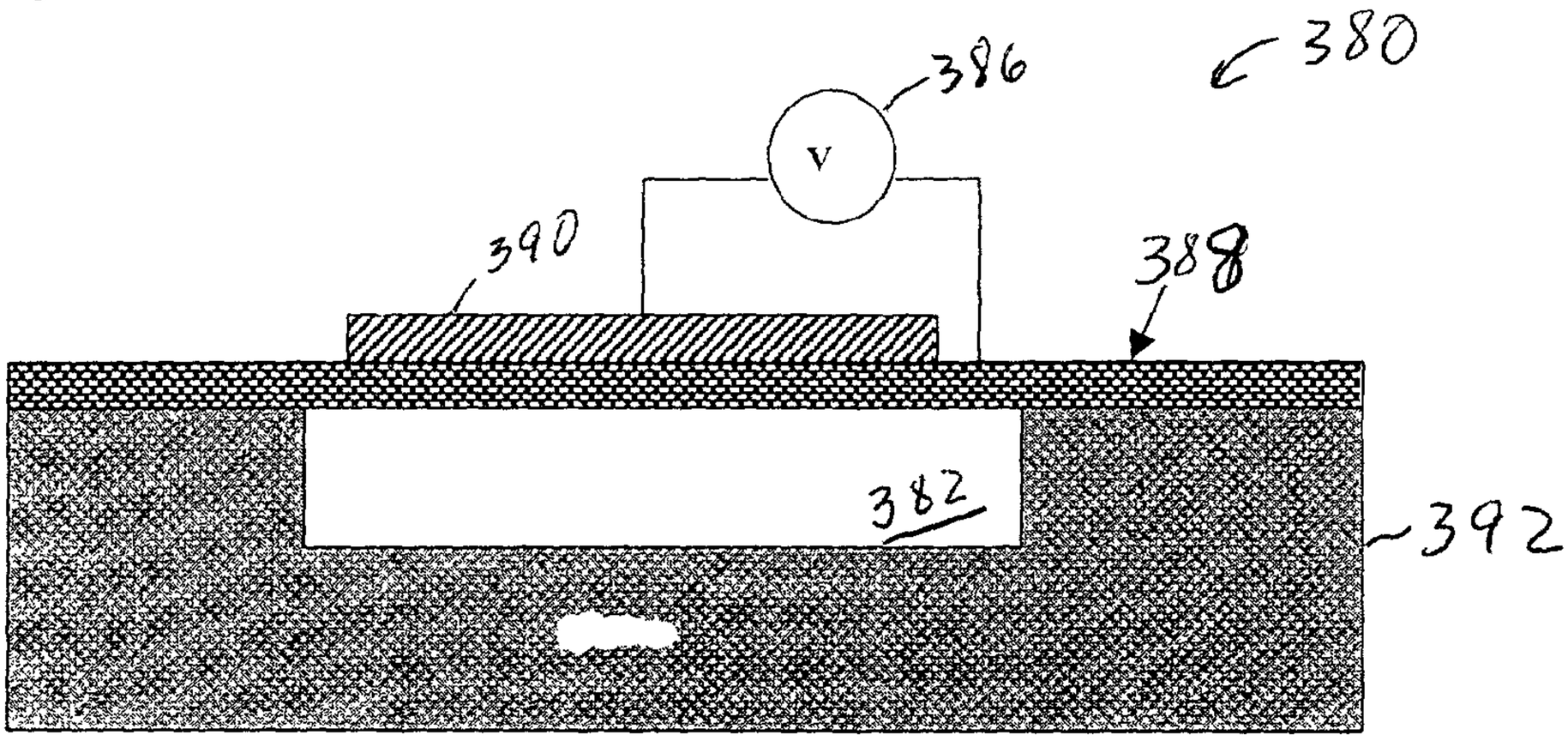

337
PUMP
SENSORS
(FLOW)
368
CURRENT
SOURCE
364
CONTROL
SYSTEM
366

FIG. 3e

Fig 3f



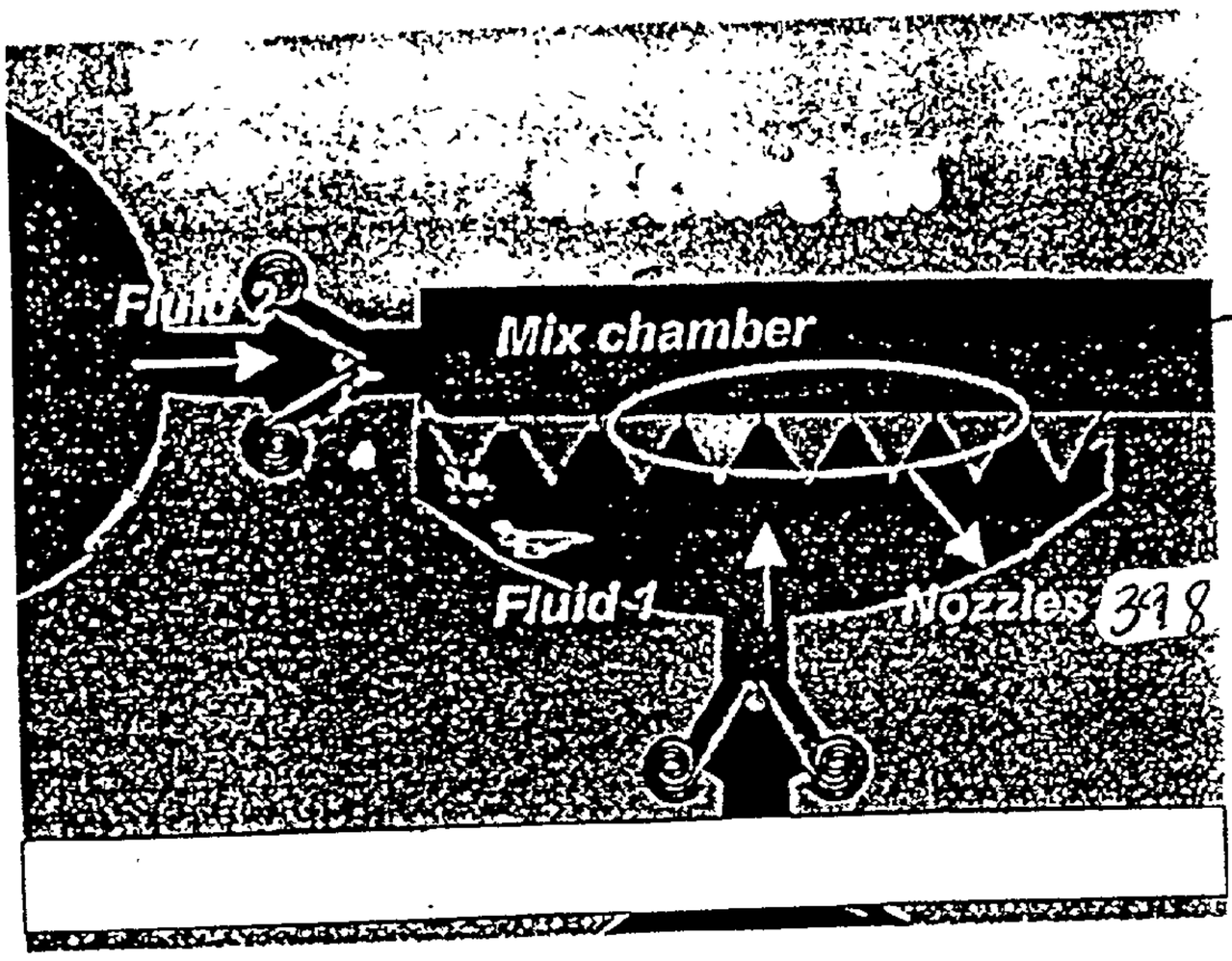


FIG. 3g

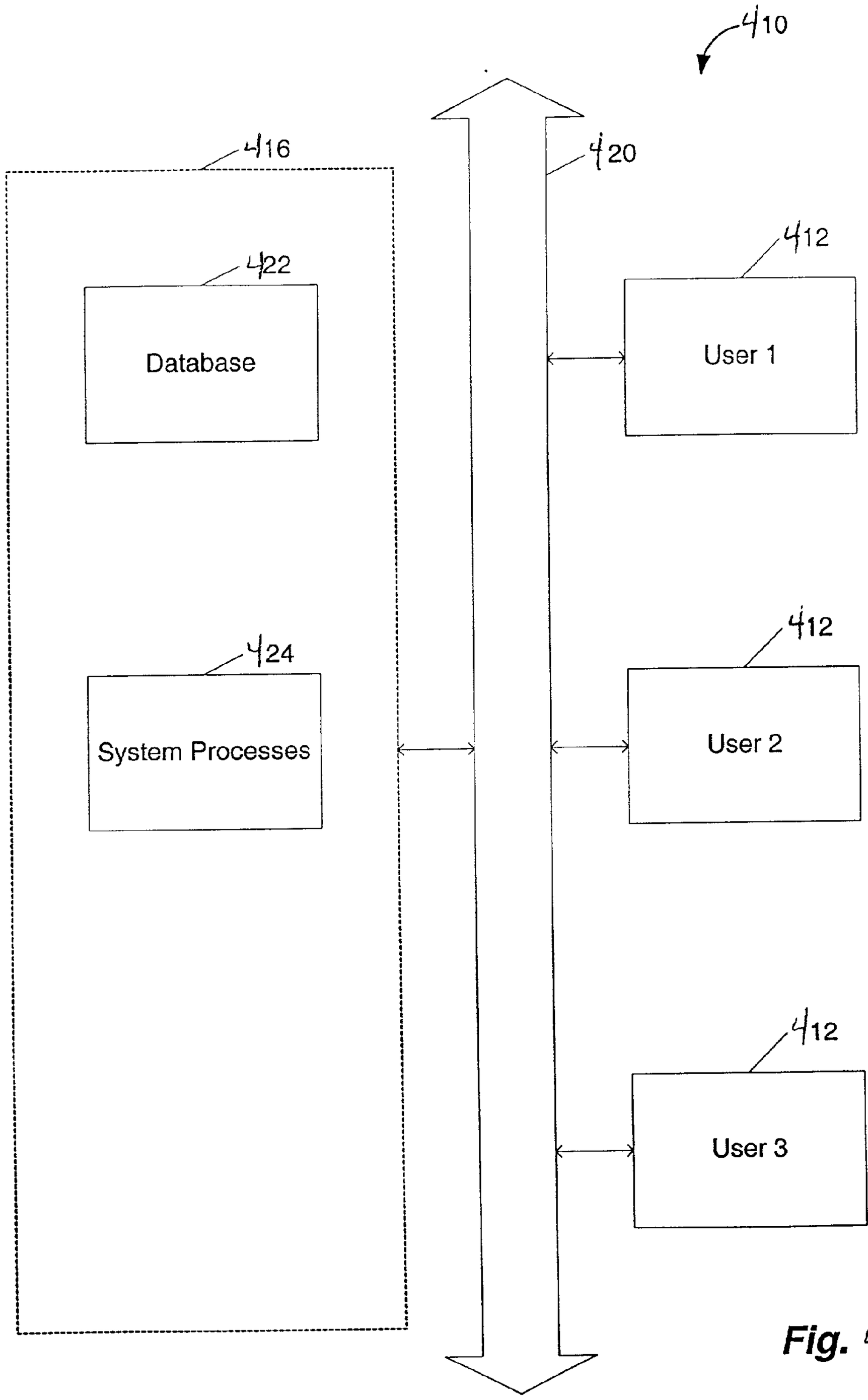

410
416
420
422
Database
412
User 1
424
System Processes
412
User 2
412
User 3

Fig. 4

MAGNETICALLY-ACTUATED MICROPUMP

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application is related to and incorporates by reference herein in its entirety the commonly owned and concurrently files patent application Attorney Docket Number M-9289 entitled "AUTOMATED MICROFABRICATION-BASED BIODETECTOR" by Angad Singh and Shahzi S. Iqbal.

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] This invention relates generally to micropumps. More specifically, this invention relates to a micropump that is magnetically actuated.

[0004] 2. Description of the Related Art

[0005] There are several applications that require pumps for transporting substances from one location to another. Some of these applications include medical implants, miniature scrubbing systems, chemical analysis of very small samples, and medical diagnosis. Pumps having nanometer-scale dimensions are required in some of these situations. Microfabrication techniques are well-known in the art, and are capable of producing very small scale components with moving parts. It is nonetheless desirable to provide a micropump that is capable of delivering the appropriate amount of a substance using a minimum number of moving parts to simplify fabrication.

SUMMARY OF THE INVENTION

[0006] A pump (also called "microfluidic pump") in accordance with the invention has a substrate with a chamber (also called "pump chamber") and at least one channel in communication with the pump chamber for transporting a substance into or out of the pump chamber through one or more channels. A flexible diaphragm forms a wall of the pump chamber, and the pump operates when the diaphragm is flexed.

[0007] In one embodiment, a magnetic member is attached to the diaphragm. A magnet, such as an electromagnet, is positioned to attract and repel the magnetic member, thereby actuating the diaphragm, and causing a substance to be drawn into or out of the pump chamber through the channel. Depending on the embodiment, a uni-directional or bi-directional check valve can be positioned in the channel to allow flow of the substance into the chamber or to prevent backflow into the pump chamber. Also depending on the embodiment, a control system can be coupled to the pump to sense the flow rate of the substance in the channel, and to adjust actuation rate of the diaphragm based on the flow rate. Moreover, as an option, a protective layer can be included to cover the top of the diaphragm. Another protective layer can be included to cover the bottom of the substrate.

[0008] Depending on the implementation, the substrate and diaphragm can be fabricated with polymer materials that are injection molded, etched, or embossed with the components such as the chamber, channels, and valves.

[0009] The present invention advantageously provides a micropump with a minimum number of moving parts to improve reliability and cost-effectiveness. The micropump is also decoupled from the actuating mechanism. The advantage of this feature is that the pump can be included in a disposable portion of a system, while the actuating mechanism is included on a non-disposable portion of the system and can be used to actuate other micropumps.

[0010] The foregoing has outlined rather broadly the features and technical advantages of the present invention so that the detailed description of the invention that follows can be better understood.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] **FIG. 1** is a block diagram of components included in an embodiment of a bio-sensor system in accordance with the present invention.

[0012] **FIG. 1***a* is a block diagram of components included in an embodiment of a bio-sensor device in accordance with the present invention.

[0013] **FIGS. 1***aa*-**1***aw* are schematic diagrams of circuits included in a biosensor system in accordance with an embodiment of the present invention.

[0014] **FIG. 1***b* is a top view of components included in an embodiment of a bio-sensor device in accordance with the present invention.

[0015] **FIG. 1***c* is a side cross-section view of components included in an embodiment of a bio-sensor device in accordance with the present invention.

[0016] **FIG. 2** is a block diagram of components included in an embodiment of a microfluidic system for the bio-sensor in accordance with the present invention.

[0017] **FIG. 2***a* is a flowchart of protocols for detecting viruses, bacteria, and toxins using a bio-sensor system in accordance with the present invention.

[0018] **FIG. 3***a* is a side of view of a filtration/concentration assembly in accordance with the present invention.

[0019] **FIG. 3***b* is a side of view of a portion of the filtration/concentration assembly that is used to introduce a sample to a microfluidic system in accordance with the present invention.

[0020] **FIG. 3***c* is a side of view of the electro-magnetically actuated pump in accordance with the present invention.

[0021] **FIG. 3***d* is a top view of the electro-magnetically actuated pump and check valve in accordance with the present invention.

[0022] **FIG. 3***e* is a block diagram of a microfluidic pump coupled to a feedback and control system in accordance with the present invention.

[0023] **FIG. 3***f* is a block diagram of a piezoelectric pump coupled to a feedback and control system in accordance with the present invention.

[0024] **FIG. 3***g* is a diagram of a mixer in accordance with the present invention.

[0025] **FIG. 4** is a diagram of an information network in accordance with the present invention.

[0026] The present invention may be better understood, and its numerous objects, features, and advantages made apparent to those skilled in the art by referencing the accompanying drawings. The use of the same reference symbols in different drawings indicates similar or identical items.

DETAILED DESCRIPTION

[0027] Referring to **FIG. 1**, biosensor system **100** is shown including bio-sensor device **102**, microfluidic system **104**, and network interface **106** to workstation **108**. In one embodiment, microfluidic system **104** incorporates components that are required for performing chemical and/or biological processes on a sample of a substance to be analyzed. Microfluidic system **104** can be inserted and removed from biosensor device **102**. Biosensor device **102** is a portable, hand-held unit that includes a user interface and display, an interface to microfluidic system **104**, and an network interface **106** to one or more workstations **108** that allows a user at workstation **108** to access data collected using biosensor system **100**. Biosensor system **100** can also be used as a workstation **108**.

[0028] Referring now to **FIGS. 1 and 1***a*, a block diagram of one embodiment of biosensor device **102** is shown in **FIG. 1***a*. Power supply **110** provides operating power to various components on biosensor device **102** including digital signal (DSP) and input/output (I/O) processor **112**, driver circuits **114**, analog circuits **116**, a display **118**, valves **120**, thermistor **122**, thermo-electric cooler **124**, pump coils **126**, and detection system **128**. Power supply **110** can be one or more commercially available power supplies, such as an internal DC battery or a power regulator that interfaces to an external AC supply. Power supply **110** is capable of providing one or more operating voltages at the levels required by the components of biosensor device **102**. Biosensor device **102** can also be powered via a universal serial bus (USB) port **130** with the workstation **108**.

[0029] In the embodiment shown in **FIG. 1***a*, data processing functions are divided among DSP and input/output (I/O) processor **112**, driver circuits **114**, and analog circuits **116**. It is important to note, however, that data processing functions can be distributed using additional or fewer processors than shown in **FIG. 1***a*. **FIGS. 1***aa* through **1***aj* are schematic diagrams showing examples of interface circuits between DSP **131** and components in DSP and I/O processor **112**. **FIG. 1***ab* shows an example of an interface to programmable memory **140** for storing DSP program instructions. **FIG. 1***ac* shows an example of an interface to Analog to Digital converter ADC **148** which converts analog voltage level (e.g., temperature & fluorescence level) to a digital signal which can be used by the DSP. **FIG. 1***ad* shows an example of an interface to digital to analog signal converter DAC **146** which provides analog output voltage. **FIG. 1***ae* shows an example of an interface to memory **142** for non-volatile memory storage. **FIG. 1***af* shows an example of an interface to RS-232 serial interface **133**. **FIG. 1***ag* shows an example of an interface to device indicators **144**. **FIGS. 1***ah* and **1***aj* show examples of an interface to digital I/O **150**, which also interfaces with the driver circuits **114**. **FIG. 1***ai* shows an example of an interface to USB port **130**.

[0030] **FIG. 1***ak* is an example of a schematic on analog circuits board **116** of a programmable amplifier that can be used to amplify the signal from the photo-multiplier-tube (PMT) **184**.

[0031] **FIGS. 1***al* through **1***aw* show examples of schematics for driver circuits **114**. **FIG. 1***al* shows an example of a programmable duty cycle generator for controlling the amount of power to TEC **124**. **FIG. 1***am* shows an example of a DC to DC converter which conditions power supply voltage. For example, the circuit in **FIG. 1***am* converts a +12 volt (V) supply voltage to +5V, +12V and regulated +12V. **FIG. 1***an* shows an example of an interface between DSP and I/O circuits **112**, analog circuits **116**, and driver circuits **114**.

[0032] **FIGS. 1***ao* and **1***ap* show examples of circuits which provide a set of digital control output signals for opening and closing, respectively, valves **120**. **FIG. 1***aq* shows an example of a light emitting diode to indicate when power to the system **100** (**FIG. 1**) is turned ON. **FIG. 1***ar* shows an example of a circuit for a piezoelectric buzzer for chip insert detection or user input detection. **FIG. 1** shows an example of an interface connector for connecting DSP **131** to other components in DSP and I/O processor **112**.

[0033] Biosensor system **100** also includes bridge circuits, examples of which are shown in schematics in **FIGS. 1***at* through **1***aw*. **FIG. 1***at* is an example of circuit for controlling TEC **124** (**FIG. 1***a*). **FIG. 1***au* is a bridge circuit used for controlling the current through the pump coil(s) **126** (**FIG. 1***a*). **FIG. 1***av* is a laser diode driver circuit which maintains a constant light output from the laser **182** (**FIG. 1***a*) by regulating the current to the laser. **FIG. 1***aw* is an example of a connector **152** which can be used to interface the microfluidic system **104** to biosensor device **102**.

[0034] Examples of commercially available components which are suitable for use in the circuits shown in **FIGS. 1***aa* through **1***aw* are as follows: **FIG. 1***aa*: DSP chip ADSP-2181, part # ADSP-2181KS-115 by Analog Devices, Norwood, Mass.; **FIG. 1***ab*: EEP ROM (memory) chip, part # CAT28F512 by Catalyst Semiconductor, Sunnyvale, Calif.; **FIG. 1***ac*: Analog-to-digital converter chip, part # AD7887 by Analog Devices, Norwood, Mass.; **FIG. 1***ad*: Digital-to-analog converter chip, part # AD5322 by Analog Devices, Norwood, Mass.; **FIG. 1***ae*: EEPROM (memory) chip, part # 24LC256 by Microchip Technology, Farmington Hills, Mich.; **FIG. 1***af*: RS-232 chip, part #DS14C232 by Dallas Semiconductor, Dallas, Tex.; **FIG. 1***ag*: demultiplexer chip, part # MC74HC138 by ON Semiconductor, Phoenix, Ariz.; **FIG. 1***ah*: Digital output gates and flip-flop chips, part #s MC74HC32 and MC74HC574 by ON Semiconductor, Phoenix, Ariz.; **FIG. 1***ai*: USB interface chip, part # PDIUSBD12D by Phillip Semiconductor, Sunnyvale, Calif., and gate 74HC08 by ON Semiconductor, Phoenix, Ariz.; **FIG. 1***aj*: flip-flop and gate chips, part #s MC74HC573 and MC74HC32 respectively by ON Semiconductor, Phoenix, Ariz.; **FIG. 1***ak*: Programmable gain amplifier chips, part # PGA103 by Burr-Brown Corporation/Texas Instruments, Dallas, Tex., and operational amplifier OP27 by Analog Devices, Norwood, Mass.; **FIG. 1***al*: Shift registers, part #74HC165 by ON Semiconductor, inverters, part #74HC14 and #74HC04 by ON Semiconductor, Phoenix, Ariz.; **FIG. 1***am*: DC-DC converter chips COSEL_ZU, part # ZUS 1R5 1205 by Cosel USA, San Jose, Calif. and AA01D_DUAL, part # AA01D-012L-120D by Astec America, Carlsbad, Calif.; **FIG. 1***ao*: Flip-flop, part # 74HC574 by ON Semiconductor, and gate 74HC32 also by ON Semiconductor, Phoenix, Ariz.; **FIG. 1***ap*: Same as **FIG. 1***ao*; **FIG. 1***at*: Gates, part #74HC14 and part #74HC08 by ON Semicon-

ductor, Phoenix, Ariz.; **FIG. 1***au*: Same as **FIG. 1***at*; **FIG. 1***av*: inverters, part # 74HC14 by ON Semiconductor, and laser diode driver, part # iC-WJ by iC-Haus, Bodenheim, Germany.

[**0035**] Microfluidic system **104** includes microfabricated components for performing biological and chemical analysis. Such components can include, for example, filters, valves, pumps, mixers, channels, reservoirs, and actuators. Detection system **128** is used to detect target molecules that are the subject of the assay(s) that are performed using microfluidic system **104**. One such detection system **128** includes an infrared (IR) laser and detector which is used to illuminate and detect IR dye, respectively, known as deoxynucleotide triphosphates (dNTPs) that can be used in the assays performed by microfluidic system **104**. Other suitable detection systems can be implemented with microfluidic system **104** in addition to, or instead of, an IR detection system. Detection system **128**, and microfluidic system **104** are discussed more fully hereinbelow.

[**0036**] In one embodiment, microfluidic system **104** is disposable and can be inserted and removed from biosensor device **102** as required. This allows a new microfluidic system **104** to be used for each new sample to be analyzed, thereby reducing the risk of contamination from previous samples.

[**0037**] DSP and I/O processor **112** includes a digital signal processor **131** for digital signal processing along with main program instructions **132** that control execution of components included in processor **112**. Main program instructions **132** also control communication with components external to processor **112**. In one embodiment, digital signal processor **131** is a single-microfluidic system **104** microcomputer optimized for digital signal processing (DSP) and other high speed numeric processing applications. Digital signal processor **131** includes one or more serial data interfaces such as RS2-32 interface **133** and Universal Serial Bus (USB) interface **130**. A peripheral device interconnect USB **134** shown, for example, as PDIUSBD12, allows conventional peripherals to be upgraded to USB devices and take advantage of the "hot plug and play" capability of the USB, as known in the art. The USB **134** interfaces with most device class specifications such as imaging, mass storage, communications, printing and human interface devices. USB **134** communicates with digital signal processor **131** using a high-speed, general-purpose parallel interface **138**. Other data interfaces can be included in addition to or instead of interfaces **133** and **134**.

[**0038**] Digital signal processor **131** also interfaces with other devices well-known in the art, including program and data memory **140**, **142** for storing data and executing program instructions, device indicators **144**, such as switches and lights, digital to analog (DAC) and analog to digital (ADC) converters **146**, **148**, and digital I/O controller **150**. Digital signal processor **131** can also include a programmable timer and interrupt capabilities, as known in the art. Power-down circuitry can also be provided to conserve power when operating biosensor device **102**. One example of a microprocessor currently available that is suitable for use with present invention is model number ADSP-2181 manufactured by Analog Devices, Inc. in Norwood, Mass.

[**0039**] Driver circuits **114** interface with microfluidics system **104** via connector **152** to communicate with valves **120**, thermistor **122**, thermoelectric cooler (TEC) **124**, pumps **126**. Driver circuits **114** also interface with detection system **128** in biosensor device **102**. Connector **152** can be one of several connectors that are well known in the art and commercially available. One such connector is part # FH12-50S-0.5SH by Hirose Electric Co. Ltd.

[**0040**] Driver circuits include thermistor driver **153** and TEC driver **154** which generate signals to control the operation of thermistor **122** and TEC **124**, respectively. Pump driver **156** includes logic to determine voltage signals required to operate pumps **126**. The signals input to microfluidic system **104** to drive pumps **126** can be based on information provided by flow sensors **157** microfluidic system **104**, wherein the sensors **157** indicate the amount or rate of flow of a substance through one or more pumps **126**. Laser driver **158** generates signals to control operation of a laser in detection system **128**. Such a laser is used for fluorescence detection, as further discussed hereinbelow.

[**0041**] Insert detector **162** receives information from microfluidic system **104** that indicates when microfluidic system **104** is inserted in biosensor device **102**. When microfluidic system **104** is inserted in biosensor device **102**, processors **112**, **114**, and **116** use the signal to begin operating other components in biosensor device **102**.

[**0042**] Valve driver **164** sends signals to open and close valves **120** microfluidic system **104**. A variety of valve and pump configurations can be implemented in microfluidic system **104**, depending on the processes to be performed. The processes typically occur in a particular sequence, and can also be timed. Thus, valve driver **164** includes instructions for opening and closing each valve in microfluidic system **104** for respective processes and reactions. Valve driver **164**, pump coil driver **156**, thermistor driver **153**, TEC driver **154**, and laser driver **158**, can also share information to determine which functions to perform at the appropriate time.

[**0043**] User interface (UI) module **168** provides information and/or options to a user that is presented on display **118** and via device indicators **144**. UI module **168** also receives input from one or more of a variety of known user input devices such as a keyboard, mouse, light pen, audio commands, or other data input device known in the art. It is important to note that a variety of suitable user input devices and displays, including audio, visual, and tactile input/output devices, are known in the art and can be incorporated with the present invention. The foregoing examples are not intended to limit the present invention to any particular input or display device, or combination of devices.

[**0044**] Detection system **128** generates data signals representing the substances detected microfluidic system **104**, and the data signals are input to analog circuits module **116**. Analog circuits module **116** includes appropriate signal conditioning components **174**, as required, such as a sample and hold circuit, filter(s), and/or an amplifier(s). The output from analog circuits module **116** is input to an analog to digital (A/D) converter **148** in DSP and I/O processor **112** for conversion from analog to digital form. This digital data can be further processed in DSP and I/O processor **112**, and the results output to display **118** and/or network interface **106**.

[**0045**] A variety of processes are required to perform different biological and chemical assays. For example,

detecting a particular biological or chemical agent in a sample can include distilling and purifying a sample, heating the sample, mixing the sample with various reactants, and filtering the treated sample to isolate the target agent. Biosensor device **102** provides signals to actuate valves, pumps, and mixers to control the flow and mixing of the sample and various reactants to and from reservoirs in microfluidic system **104**. Biosensor device **102** also provides control signals to thermistor driver **153** and TEC driver **154**, which in turn provide signals to control operation of thermistor **122** and TEC **124**, respectively, during processes such as DNA/protein denaturation, single strand DNA annealing, and primer extension. Biosensor system **102** can be programmed to perform a variety of assays that are performed automatically, or when selected by a user through UI module **168**.

[**0046**] DSP and I/O processor **112**, driver circuits **114**, and analog circuits **116** in biosensor device **102** can be implemented using a combination of hardware circuits, software, and firmware, as known in the art.

[**0047**] One application of biosensor device **102** is automating PCR analysis. Nano-scale devices for automating PCR and post-PCR analysis are available in the prior art, however, sample preparation including DNA/RNA isolation, and detection by PCR are still carried out manually as two different processes. Therefore, to fully exploit the potential of PCR-based detection, biosensor device **102** advantageously integrates sample preparation, target amplification, and fluorescence detection into a single, portable, cost-effective device. Biosensor device **102** can also be used for biological and chemical analysis processes in addition to, or instead of, PCR-based analysis.

[**0048**] Referring now to **FIGS. 1, 1***a*, **1***b*, and **1***c*, **FIGS. 1***b* and **1***c* show a top view and side cross-sectional view of components of biosensor system **100** with microfluidics system **104** inserted into the biosensor device **102**. Electronic circuit cards **180** control the operation of the optics in biosensor system **100**, including laser diode source **182** and photo-multiplier tube (PMT) **184**. In an alternate implementation, any other light source, such as a blue LED, can be used instead of, or in addition to, laser diode source **182**. Photodiode(s), or any other photo or electrical signal detection system, can be used, instead of, or in addition to, photomultiplier tube **184** for fluorescence detection and/or measurement. Electronic circuit cards **180** also include DSP and I/O processor **112**, driver circuits **114**, and analog circuits **116**.

[**0049**] There are a variety of different detection systems **106** that can be implemented in biosensor device **102**. One such detection system **128** that can be implemented in biosensor **100** is shown in **FIGS. 1***b* and **1***c*. Detection system **128** includes optical components such as mirrors **185**, **186**, diachroic filter **188**, and objective lenses **190**, **192**. Incident light beams (excitation) from laser diode **182** pass through a diachroic filter **188** and are directed at a specific wavelength via a mirror **185** and an objective lens **190** in respective order, to the detection area on the microfluidic system **104**. Reflected (emitted) light beams from the detection area on the microfluidic system **104** are directed via the objective lens **190**, mirror **185**, diachroic filter **188** and mirror **186** at a specific wavelength, in respective order, to the detector **184**, i.e., photomultiplier tube/photodiode. Emitted fluorescence (reflected light) is sensed by the detector **184**, i.e., photomultiplier tube/photodiode. Detector **184** generates data signals representing the emitted (reflected) light and the data signals are input to analog circuits **116** **(FIG. 1)** for signal conditioning and conversion from analog to digital signals.

[**0050**] Microfluidic system **104** is inserted into biosensor device **102** and is guided to the appropriate position by one or more guide members **194** which slides the microfluidic system **104** into position to connect electrical connector **152**. Following insertion of microfluidic system **104**, loading lever **196** is released to allow spring member **198** to place TEC **124** in contact with microfluidic system **104**. Additionally, electromagnetic pump coils **199** are positioned adjacent to the top side of the microfluidic system **104**. One or more of these coils **199** can also be positioned on adjacent other sides of microfluidic system **104** to actuate pump(s) **126**.

[**0051**] Referring now to **FIG. 2**, an embodiment of microfluidic system **104** is shown including a plurality of pumps, valves, filters, mixers, reservoirs, and channels as described below. Connector **152** is also shown in microfluidic system **104**, however the connections between the connector **152** and other components on microfluidic system **104** are not shown for simplicity. The connections between connector **152** and the other components are used to communicate signals such as drive signals and detection signals.

[**0052**] Note that the components shown and their placement with respect to one another in **FIG. 2** depends on the particular processes to be performed using biosensor device **102**. Notably, the number of components and their position with respect to one another, can vary from the configuration shown in **FIG. 2**. Other types of components can be included in addition to those shown in **FIG. 2**. Microfluidic system **104** can be configured with enough components to perform one or more protocols concurrently, or at different times with respect to one another. Further, some applications may not require the use of all the components in a given configuration. For example, a particular configuration of microfluidic system **104** can be used for more than one type of process. In this situation, one or more of the reservoirs may be used in some of the processes, but not in others due to different steps being required to prepare and process the sample. Additionally, the components, operate independently of one another, and can be controlled by an external or an embedded control system.

[**0053**] Components can be included in microfluidic systems **104** to perform processes to detect genes, toxins, viruses, bacteria, and vegetative cells. Microfluidic system **104** is intended to include most, if not all, of the components required to perform the process from start to finish, and thus minimal user handling of the sample and intervention is required. Microfluidic system **104** is also designed to be low-cost and hence disposable. These features advantageously lower the risk of contaminating the sample during testing. Further, microfluidic system **104** yields highly reproducible results while requiring a relatively small sample size. For example, a 2.25 square inch disposable microfluidic system **104** can accommodate a sample volume of 500-1000 microliters (before concentration) and a concentrated sample volume of 10 microliters.

[**0054**] In some situations, a sample can contain a low concentration of molecules to be detected. In some embodi-

ments, the dimensions of microfluidic system **104** can range from one to two inches in length and height, and be less than one millimeter in thickness. Due to the small size of microfluidic system **104**, the sample may need to be filtered and concentrated prior to performing the extraction and detection processes.

[**0055**] Referring to **FIG. 2, a** sample containing varying amounts of targets, i.e., cells, virions, or toxins, can be loaded in sample entry port **202** and subjected to a respective sample preparation procedure, such as concentration. This is accomplished by inputting the sample into filter **204** to remove impurities that are larger in size than the target cells, viruses, or concentrates in the sample.

[**0056**] **FIG. 2***a* shows a flowchart of examples of protocols that may be implemented on microfluidic system **204** (**FIG. 2**), including bacteria protocol **260** for isolating and purifying DNA from bacterial cells, virus protocol **262** for isolating and purifying RNA from animal viruses, and toxin protocol **264** for isolating and purifying toxins. Protocols **260**, **262**, and **264** are representative of the types of assays that can be performed on an appropriately configured microfluidic system **104**.

[**0057**] Referring to **FIGS. 2 and 2***a*, once the sample is introduced to microfluidic system **104**, DNA/RNA purification that is used in protocols **260** and **262** can be achieved as described in the following steps:

[**0058**] 1. The sample is transferred to chamber **208** by actuating pump **206**, which can be a push button pump or an electronically actuated pump.

[**0059**] 2. The sample is mixed/resuspended in lysozyme solution from reservoir **210**, which is transferred to mixer **208** via actuation of pump **212**.

[**0060**] 3. A chamber in mixer **208** is heated to 95 degrees centigrade for a period of time, for example, 2 minutes.

[**0061**] 4. Protease (e.g. Proteinase K) in reservoir **214** is pumped into mixer **208** via pump **215**.

[**0062**] 5. The lysed sample is pumped through microfilter **216** into mixer **220** via pump **218**. In one implementation, microfilter **216** is a one to two micrometer filter. In other implementations, the size of microfilter **216** is selected based on the size of the target molecule.

[**0063**] 6. A DNA wash solution (for example, Ethanol and salts buffer) is transferred from reservoir **224** to mixer **220** via pump **228**.

[**0064**] 7. The sample+DNA wash solution from mixer **220** is pumped to the wash discard reservoir **232** via pump **234** through a microfilter **230** or a nucleic acid binding agent such as glass milk.

[**0065**] 8. Steps 6 and 7 can be repeated to concentrate DNA/RNA at the microfilter **230** or nucleic acid binding agent, and to discard proteins as well as other contaminants.

[**0066**] 9. Aqueous solution from reservoir **222** is pumped in the reverse direction through the microfilter **230** to the DNA/RNA collection chamber **238** for PCR. At this point, the DNA/RNA is dissolved in the aqueous solution and is no longer bound to microfilter **230**. Collection chamber **238** can either contain magnetic micro-beads or a polynucleotide array with assay-specific primers.

[**0067**] For toxins or antigens (protein) protocol **264** includes the following processes:

[**0068**] 1. The sample is transferred to mixer **208** by actuating pump **206**, which can be a push button pump or an electronically actuated pump.

[**0069**] 3. The toxin sample is mixed/resuspended in lysozyme solution from a reservoir such as **210**, which is transferred to chamber **208** via actuation of pump **212**.

[**0070**] 4. Protease inhibitor from a reservoir such as **214** is pumped into the lysis chamber **208** via pump **215**.

[**0071**] 5. The sample is pumped through microfilter **216** into mixer **220** via pump **218**.

[**0072**] 6. A basic pH wash solution (for example, 0.1M Na_2CO_3 buffer, pH=9.0) is transferred from reservoir **224** to mixer **220** via pump **228**.

[**0073**] 7. The sample+wash solution from mixer **220** is pumped to the wash discard reservoir **232** via pump **234** through a cationic microfilter **230** or a protein binding agent such as cationic beads.

[**0074**] 8. Steps 6 and 7 can be repeated to concentrate the toxin (protein) at the microfilter **230** or protein binding agent, and to discard nucleic acid as well as other contaminants and cell debris.

[**0075**] 9. Neutral pH buffer solution (such as PBS pH=7.4 containing 1M NaCl), from reservoir **222** is pumped through the cationic microfilter **230** to the protein collection chamber **238** for immuno-PCR. At this point, the protein is dissolved in the neutral buffer and is no longer bound to the microfilter **230** or the protein binding agent. In the collection chamber the toxin is mixed with the respective antibodies conjugated with specific primers and allowed to bind at 37 degrees centigrade for a period of time, such as 5 minutes. The treated sample is transferred from the chamber **208** to the collection chamber **238** (PCR area) where a target bound to an antibody is captured for PCR-based signal amplification reaction and waste is discarded in reservoir **232**. The collection chamber **238** can either contain magnetic microbeads or a polynucleotide array with millions of assay-specific primers anchored to the surface.

[**0076**] In one embodiment, millions of copies of the primers can be anchored on magnetic beads, such as those available from Bangs Laboratories, Inc. in Fishers, Ind. The target can be detected using known conjugating methods, such as streptavidin-biotin capture methods. Additionally, for high throughput amplification, an identical set of primers can also be supplied free in solution along with PCR reagents.

[**0077**] After the target is extracted, purified, and captured in the collection chamber **238**, the target is denatured at 95 degrees centigrade, and allowed to anneal (hybridize) at 65° centigrade with the primers anchored to an array or magnetic microbeads. In this step, the two strands of DNA are separated and respective anchored primers, as well as primers free in solution (supplied as reagent), bind to the complimentary target sequences.

[**0078**] Following hybridization, enzyme DNA polymerase, such as Taq DNA polymerase or rTth polymerase provided by, for example, PE Applied Biosystems in Foster City, Calif., elongates or synthesizes new complimentary

strands in 5'→3' incorporating labeled, i.e., fluorogenic dNTPs, at 72° C. In subsequent cycles of denaturation, annealing and elongation, newly synthesized strands (amplicons) serve as templates for exponential amplification of the target sequence. 3' extension of the primers anchored to the surface leads to synthesis of fluorophore labeled target sequences covalently bound to the surface. Fluorophore labeling is accomplished by incorporation of fluorophore-dNTPs such as Cy5 dye-dCTP/dUTP. After removing free dNTPs and other reagents by washing, fluorescence is measured by detection system **128** (**FIG. 1**).

[**0079**] Microfluidic system **104** can be configured and adapted to any of the nucleic acid-based assays, i.e., target amplification and hybridization-based signal amplification methods, as discussed in an article entitled "A Review of Molecular Recognition Technologies for Detection of Biological Threat Agents" by Iqbal, S. S., Michael, M. W., Bruno, J. G., Bronk, B. V., Batt, C. A., Chambers, J. P., Review article (2000). Biosensors and Bioelectronics.

[**0080**] A microfilter that is suitable for use as filter **204** can be fabricated by etching pillars that are spaced as closely as 1 micrometer apart in the substrate that is used as the base for microfluidic system **104**. One or more of a variety of suitable materials can be used for the substrate, such as silicon and/or plastic. The pillars can be created by etching a material such as silicon, or by other processes that depend on the material being used, such as injection molding with plastic materials. The filter pillars can be fabricated along with the pump chambers, valves, and mixers. To create filters with smaller pore sizes, the pillars can be coated with a suitable material. For example, silicon pillars can be coated with a conformal material such as low-pressure-chemical-vapor-deposition (LPCVD) polysilicon, which is a standard material that is well-known in microfabrication art.

[**0081**] **FIG. 3***a* shows filtration/concentration assembly **300** than can be used instead of, or in addition to, filter **204**. Assembly **300** includes a loading chamber **302**, a receiving chamber **304**, and a plunger **306**. Loading chamber includes a funnel portion **308** that mates with another funnel portion **310** on receiving chamber **304** as shown in **FIG. 3***a*. Once loading chamber **302** and receiving chamber **304** are mated, the sample to be concentrated and filtered is introduced in loading chamber **302**. Plunger **306** can be inserted in receiving chamber **304** and pushed downward to force the sample through filter **312**.

[**0082**] Filter **312** is an appropriately sized microfilter, depending on the size of the molecule to be detected. A molecular weight cut off filter or a negatively charged fiber glass filter such as those commercially available from Memtec Limited, Timonium, Md., can be used.

[**0083**] As the sample is pushed through filter **312**, the analytes of interest are retained and concentrated on filter **312** while the excess solution passes through filter **312**. Receiving chamber **304** is open at the end to allow the excess solution to flow out.

[**0084**] Once the runoff of the excess solution is completed, assembly **300** is disassembled, receiving chamber **304** is inverted and a volume of assay reagent is loaded in receiving chamber **304**. The volume of assay reagent can be as low as 5 to 25 microliters, depending on the size of port **202** in the microfluidic system **104**. Plunger **306** is inserted in the top of receiving chamber **304**, and funnel portion **310** is inserted in port **202** (**FIG. 2**) in microfluidic system **104**, as shown in **FIG. 3***b*. Plunger **306** is pushed downward to force the assay reagent though filter **312**. Analytes previously concentrated on filter **312** are dissolved in the assay reagent and transferred into microfluidic system **104** through port **202**.

[**0085**] Any suitable, commercially available thermal cycling device, such as a thermo-electric cooler (TEC) **112** (**FIG. 1**) can be used to heat and cool the sample as described in the steps above. Size and power output of the TEC depends on the application. OptoTEC and ThermaTEC series TEC's by MELCOR Corporation in New Jersey are suitable for use in such in systems. Alternatively, resistive heaters microfabricated on the microfluidic system **104** can be used for heating while the TEC **124** can be used for cooling.

[**0086**] TEC **124** is positioned on or near microfluidic system **104** (**FIG. 1**) in close enough proximity to the chambers to effectively heat or cool the fluid(s). A silver-filled heat resistant adhesive with high thermal conductivity can be used to attach TEC **124** to promote heat transfer. Alternatively, TEC **124** can be included in biosensor device **102** such that it is aligned and spring-loaded to rest in a position to heat or cool the contents of the desired chambers microfluidic system **104** when it is inserted into biosensor device **102**.

[**0087**] Temperature feedback for closed-loop control is provided by a thermocouple which is co-located with the TEC **124**. Thermocouples are a commercially available from numerous companies, for example, Newark Electronics Corporation in Chicago, Ill. and WakeField Engineering, Inc. in Beverly, Mass. Temperature feedback can also be provided by microfabricated temperature sensors that are built in to microfluidic system **104**.

[**0088**] In one embodiment, microfluidic system **104** has a planar design, i.e., all components can be fabricated in one step, which eliminates the need for stacking multiple layers and simplifies fabrication. Reservoirs can be sized according to the amount of substance to be stored in them. Reservoirs, mixers, and pumps can include access holes for loading sample(s) and reagents. The sample(s) and reagents can be introduced using a syringe and the holes can be sealed by laminating a film of a hydrophobic porous material, such as GORE-TEX® by W. L. Gore and Associates, Inc., which will act as a vent for trapped gases.

[**0089**] A variety of materials and fabrication techniques can be used for monolithic fabrication of the pumps and other components of the planar system. In one embodiment, the system can etched out in a silicon substrate using a deep anisotropic silicon etching process known as ICP Multiplex System by Surface Technology Systems in the United Kingdom. A flexible glass cover can then be bonded to cover the channels and also form the diaphragm for the pumps. The flexible cover can also include electrical interconnects for various components in the substrate, and can be transparent to allow optical detection or viewing under a microscope.

[**0090**] In another embodiment, the system can be embossed into a polymer substrate using an embossing tool manufactured by companies such as Jenoptik Microtechnic GmBH in Germany. In this case, a mold or negative replica of the system is first etched into silicon to form an emboss-

ing tool. The tool is then embossed into the polymer substrate at an appropriate softening temperature and then retracted. The tool can be reused to create more replicas reducing the cost per piece. Access holes can be drilled into the embossed polymer substrate. Another thin sheet of polymer can be chemically bonded to cover the channels.

[**0091**] **FIGS. 3***c* and **3***d* show a cross-sectional side view and a top view, respectively, of a pump **320** that is suitable for use in microfluidic system **104** (**FIG. 1**). Pump **320** includes diaphragm **338** that causes alternating volumetric changes in a pump chamber **340** when deflected. When pump chamber **340** contains liquids or gases, they are transferred by the pumping action into another chamber or reservoir (not shown) via channels **342**, **344** in substrate **346**. Check valves **348**, **350** are located in channels **342**, **344**, respectively, to control the flow of fluid into and out of chamber **340**. The diaphragm **338** is actuated electro-magnetically with magnetic member **352** being controlled by magnetic core **354** and alternating current in solenoid **356**.

[**0092**] Techniques known in the art, such as silicon etching, plastic injection molding, and hot embossing can also be used to fabricate microfluidic system **104**. A combination of fabrication methods well-known in the art can be used to fabricate flow channels **342**, **344**, pump chamber **340**, and check valves **348**, **350** in substrate **346**.

[**0093**] In one embodiment, the top side of microfluidic system **104** includes channels **342**, **344**, and pump chamber **340**. The top and bottom sides can include access holes **357**, **367** for loading reagents and other substances into chamber **340**, as required. The sample(s) and reagents can be introduced using a syringe and then access holes **357**, **367** are sealed by chemically bonding layers **360**, **362** to the top and/or bottom sides, respective.

[**0094**] Microfluidic system **104** can also be fabricated out of one or more layers of molded or embossed polymers. In one embodiment, channels, reservoirs, pump chambers, and check valves are embossed in substrate **346**. A flexible layer is chemically bonded to the top of substrate **346**, to form diaphragm **338** and seal the channels, reservoirs, and access holes on the top side. Magnetic members **352** for pumps **320** are positioned on top of the second layer. A top protective layer **360** and/or a bottom protective layer **362** can be included to seal and protect the top and bottom of substrate **346**, as shown in **FIG. 3***c*. The top protective layer **360** is flexible to allow movement of diaphragm **352** during actuation.

[**0095**] Diaphragm **338** is attached to the top of substrate **346** and is made out of a thin sheet of flexible material such as plastic, glass, silicon, elastomer, or any other suitable, flexible material. The flexibility or stiffness required of diaphragm **338** depends on the desired deflection of the diaphragm. Typically the stiffness is selected to achieve a total upward and downward deflection of approximately five to fifteen microns. Any suitable attachment mechanism, such as chemical bonding, can be used to attach diaphragm **338** to substrate **346**. The bonding technique utilized should be capable of maintaining the seal while the pump **320** is operating.

[**0096**] Magnetic member **352** is made out of magnetic material which is attracted and repelled by a magnetic force from magnetic core **354**. Magnetic member **352** can be adhesively bonded to diaphragm **338**, or electroplated onto the diaphragm **338** during manufacturing. Substrate **346** can be made of plastic, silicon, or other suitable material that is capable of substantially retaining the shape of pump chamber **340** during operation.

[**0097**] An electrically conductive wire is coiled around magnetic core **354** to form solenoid **356**. When an electric current passes through solenoid **356**, a magnetic field is created in magnetic core **354**. The polarity of the current can be alternated to change the direction of force of the magnetic field, thus alternately repelling and attracting magnetic member **352**. The repelling and attracting forces cause diaphragm **338** to move, changing the volume of chamber **340**. An increase in volume draws fluid or gas into chamber **340** via channel **342**, and a decrease in volume forces the fluid or gas into channel **344**. Applying a periodic excitation voltage to solenoid **356**, such as provided by current source **364**, causes diaphragm **338** to oscillate, producing a pumping action. The flow rate is thus directly controlled by the frequency of the alternating current to solenoid **356**.

[**0098**] Note that the current through solenoid **356** can have a positive or negative sign that produces a magnetic field in magnetic core **354**. One end of the magnetic core **354** becomes positively charged, and the other end becomes negatively charged. When the sign of the current through solenoid **356** is reversed, the charge at the ends of magnetic core **354** also reverse. When the current is shut off, magnetic core **354** loses its magnetism. Further, magnetic member **352** has a positively charged end, and a negatively charged end. Magnetic member **352** is attracted to magnetic core **354** when the ends closest to each other are oppositely charged. Similarly, magnetic member **352** is repelled by magnetic core **354** when the ends closest to each other have the same charge. The strength of the attraction or repulsion depends on the number of windings in solenoid **356**, and the strength of the electric current.

[**0099**] Check valve **348** controls the inflow of fluid or gas into chamber **340**, and check valve **350** controls flow out of chamber **340**. Check valve **348** allows fluid to flow into chamber **340** when the volume of chamber **340** is increased, and prevents backflow of the fluid or gas when the volume of chamber **340** is decreased. Flow through channel **344** is controlled by check valve **350**, which allows flow into channel **344** when the volume of chamber **340** is decreased, and prevents backflow from channel **344** when the volume of chamber **340** is increased.

[**0100**] Pump **337** is well-suited for use with a variety of devices, in addition to microfluidic system **104**, because the components associated with actuating pump **337**, namely, magnetic member **352**, magnetic core **354**, and coil **356**, can be fabricated to a wide range of dimensions, including micro-scale dimensions. Flow rates can be adjusted by varying the frequency and amplitude of the alternating current through solenoid **356**. Additionally, an electronic, microprocessor-based control system **366**, as known in the art and shown in **FIG. 3***e*, can be implemented to receive sensor input from flow sensors **368** that measure the flow into and/or out of pump **337**. For example, a Digital Signal Processor such as model number ADSP-2181 by Analog Devices, Inc. of Norwood, Mass., can be used as the controller. Logic associated with control system **366** compares the actual flow rate to the desired flow rate, and

provides a drive signal to current source **364** to adjust the frequency and amplitude of the current source **364** accordingly to achieve the desired flow rate from pump **337**.

[**0101**] Referring again to **FIGS. 3***c* and **3***d*, magnetic member **352** is located on diaphragm **338**. Magnetic core **354** is positioned close enough for its magnetic field to actuate diaphragm **338**. Magnetic core **354** with solenoid **356** can be positioned above magnetic member **352** or below chamber **340**, depending on the strength of the magnetic field developed by the magnetic core. Instead of a single electromagnet, two magnets placed on opposite sides of the magnetic member **352** can also be used in a push-pull configuration to maximize deflection. Further, magnetic core **354**, solenoid **356**, and current source **364** can be built into a structure surrounding substrate **346**, diaphragm **338**, and magnetic member **352**.

[**0102**] Other types of devices for creating magnetic fields for actuating the magnetic member **352** can also be utilized with the present invention, instead of, or in addition to an electromagnet. For example, permanent magnets with opposing charges can be mounted on a structure that moves toward and away from the magnetic member **352** at a periodic, variable rate, thereby actuating diaphragm **338**. The magnet having a like charge to the magnetic member **352** would be used to repel the magnetic member **352**, while the magnet having the opposite charge would be used to attract the magnetic member **352**. Other alternatives known in the art for attracting and repelling a magnetic member **352** can also be utilized.

[**0103**] Various types of check valves are suitable for use with the pump **320** to control the flow of fluid, gas, or other substance in the desired direction. In one embodiment, as shown in **FIG. 3***d*, check valves **348** and **350** are passive flaps etched or molded in the substrate **346**. As shown in **FIG. 3***d*, check valves **348**, **350** are a substantially straight flap having a length that is longer than the width of channels **342**, **344**. The flap is angularly positioned across the width of the channel, with the end that is closer to the start of the flow being anchored to a sidewall of the channels **342**, **344**, while the other end of the flap is free-floating. This type of construction can be achieved by cutting or etching around the substrate material to leave it attached to one sidewall, while cutting or etching through the material to free it from the other sidewall. If an injection molding process is used, the mold is continuous between the sidewall and the flap to leave it attached to the sidewall, while a space is left between the other end of the flap and the sidewall.

[**0104**] The force of a substance, such as a fluid or gas, being pumped through channels **342**, **344** tries to align the flap with the direction of the flow. The substance passes through channel **342** as the free-floating end of the flap moves away from the sidewall with the direction of the flow caused by the vacuum that is created when diaphragm **338** is raised. The vacuum created by upward movement of diaphragm **338** also forces the free end of check valve **350** into the sidewall of channel **344**, thereby preventing backflow from channel **344**. The reverse happens when the diaphragm moves downward and the fluid is propelled in one direction.

[**0105**] It is anticipated that some embodiments of biosensor device **102** would include one or more bi-directional valves. Further, the operation of both unidirectional and bi-directional valves could be controlled by the force of the flow created by actuating diaphragm **338**, or electronically using logic in valve controller **164** (**FIG. 1***a*) to open and close valves **348**, **350**, in **FIG. 3***d*.

[**0106**] It is important to note that one or more channels, such as channel **342** in **FIG. 3***d*, can feed into pump chamber **340**. Likewise, one or more channels, such as channel **344**, can be used to transport a substance out of pump chamber **340**.

[**0107**] **FIG. 3***f* shows a diagram of a typical piezoelectric micropump **380** found in the art that is suitable for use with the present invention in addition to, or instead of, pump **320** (**FIG. 3***e*). Pump **380** includes a pump chamber **382** which is capped by heat-resistant glass layer **388** which also forms the diaphragm. Piezoelectric element **390** is bonded to diaphragm **388**. Applying a voltage from voltage source **386** to the piezoelectric element **390** induces either an upward or downward deflection depending upon the polarity of the applied voltage. This changes the volume of the pump chamber **382**, causing it to draw fluid through an inlet valve, and to pump fluid through an outlet valve, on opposite strokes of the cycle. Applying a periodic excitation voltage causes diaphragm **388** to oscillate, producing a pumping action. The flow rate is thus directly controlled by the frequency of the electrical drive signal to the piezoelectric element **390**.

[**0108**] Substrate **392** can be fabricated from polymer or silicon material. The glass layer **384** is bonded onto substrate **392** using a suitable bonding method, such as anodic or epoxy bonding, to prevent leakage. Polyimides and thermal laminants can also be used for bonding and have the advantage of a lower bonding temperature.

[**0109**] One way to mix very small amounts of two or more substances in microfluidic system **104** is to feed the flow streams into one channel as they are directed to a reservoir or pump chamber. An alternative way includes injecting one substance into another using micro-nozzles. Referring now to **FIG. 3***g*, one embodiment of mixer **394** with micro-nozzles is shown that is suitable for use with the present invention microfluidic system **104**. Mixer **394** includes a mixing chamber **396** with nozzles **398** on one side. During operation, the mixing chamber **396** is filled with one or more substances, and another substance is injected through the nozzles **398**, thereby generating a plurality of micro-plumes. The plumes effectively mix the substances without requiring any additional processing. Mixing time depends on injection flow rate, size of nozzles, distance between each nozzle and size of the mixing chamber. Nozzles with orifices as small as one (1) micrometer can be provided using known fabrication processes.

[**0110**] Information from biosensor device **102** can be accessed by authorized users when biosensor device **102** is connected to an information network. One embodiment of components and connections between components in information network **410** that can be used with the present invention is shown in **FIG. 4**. Users access information and interface with information network **410** through workstations **412**. Workstations **412** execute application programs for presenting information from, and entering data and selections as input to interface with information network **410**. Workstations **412** also execute one or more application programs to establish a connection with server **416** through

network **420**. Various communication links can be utilized, such as a dial-up wired connection with a modem, a direct link such as a T1, ISDN, or cable line, a wireless connection through a cellular or satellite network, or a local data transport system such as Ethernet or token ring over a local area network. Accordingly, network **420** includes networking equipment that is suitable to support the communication link being utilized.

[**0111**] Those skilled in the art will appreciate that workstations **412** can be one of a variety of stationary and/or portable devices that are capable of receiving input from a user and transmitting data to the user. The devices can include visual display, audio output, tactile input capability, and/or audio input/output capability. Such devices can include, for example, biosensor system **100**, desktop, notebook, laptop, and palmtop devices, television set-top boxes and interactive or web-enabled televisions, telephones, and other stationary or portable devices that include information processing, storage, and networking components. Additionally, each workstation **412** can be one of many workstations connected to information network **410** as well as to other types of networks such as a local area network (LAN), a wide area network (WAN), or other information network.

[**0112**] Server **416** is implemented on one or more computer systems, as are known in the art and commercially available. Such computer systems can provide load balancing, task management, and backup capacity in the event of failure of one or more computer systems in server **416**, to improve the availability of server **416**. Server **416** can also be implemented on a distributed network of storage and processor units, as known in the art, wherein the modules and databases associated with the present invention reside on workstations **412**, thereby eliminating the need for server **416**.

[**0113**] Server **416** includes database **422** and system processes **424**. Database **422** can reside within server **416**, or it can reside on another server system that is accessible to server **416**. Database **422** contains information regarding users as well as results from tests performed using biosensor device **102**. Consequently, to protect the confidentiality of such information, a security system can be implemented that prevents unauthorized users from gaining access to database **422**. Users can be authorized to transmit and/or receive information from database **422**. User interface **114 (FIG. 1)** can allow the user to download and/or retrieve results from one or more tests to database **422**.

[**0114**] System processes **424** include program instructions for performing analysis of data from biosensor device **102** and other information provided by the user. The type of analysis performed is based on the type of data being analyzed, and the type of information to be provided to the user.

[**0115**] One application of biosensor system **100** is generating and sharing information for medical diagnosis. A user can introduce a sample to be analyzed, such as a drop of blood or other bodily fluid, into microfluidic system **104**. As discussed above, a variety of different configurations can be implemented on microfluidic system **104**, depending on the specific test to be performed. Accordingly, microfluidic system **104** includes the components, and the type and amount of reagents required to perform one or more assays on the sample.

[**0116**] Biosensor system **100** can screen for known pathogens for infectious diseases and/or markers for genetic disorders. After the sample is analyzed, the presence of a pathogen or a disease marker (gene/protein) above a specific level can be indicated. Data from each assay can be transmitted to server **416** directly from biosensor system **100** or via workstation **412**. The data is stored in server **416** using a personal, secured account that is generated for each user. A subscriber, such as a physician and/or other authorized individual, can be granted remote access to the user's account via information network **420**.

[**0117**] Advantageously, the electromagnetic pumps **100** do not require electrical interconnects to operate.

[**0118**] Another advantage is that microfluidic system **400** may be used to perform a variety of microfluidic and bio-analytical functions, and can have varying levels of complexity depending on the number of components included, and the functions to be performed.

[**0119**] The foregoing detailed description has set forth various embodiments of the present invention via the use of block diagrams, flowcharts, and examples. It will be understood by those within the art that each block diagram component, flowchart step, and operations and/or components illustrated by the use of examples can be implemented, individually and/or collectively, by a wide range of hardware, software, firmware, or any combination thereof.

[**0120**] The above description is intended to be illustrative of the invention and should not be taken to be limiting. Other embodiments within the scope of the present invention are possible. Those skilled in the art will readily implement the steps necessary to provide the structures and the methods disclosed herein, and will understand that the process parameters and sequence of steps are given by way of example only and can be varied to achieve the desired structure as well as modifications that are within the scope of the invention. Variations and modifications of the embodiments disclosed herein can be made based on the description set forth herein, without departing from the spirit and scope of the invention as set forth in the following claims.

What is claimed is:

1. A microfluidic pump comprising:

a substrate including a chamber;

at least one channel in communication with the chamber;

a flexible diaphragm forming a wall of the chamber; and

a magnetic member attached to the diaphragm.

2. The pump of claim 1 further comprising:

a check valve positioned in the channel.

3. The pump of claim 2 wherein the check valve is unidirectional.

4. The pump of claim 2 wherein the check valve includes a flap having one end movably attached to one sidewall of the channel.

5. The pump of claim 1 further comprising an electromagnet positioned to attract and repel the magnetic member.

6. The pump of claim 5 further comprising:

a current source coupled to supply electric current to the electromagnet.

7. The pump of claim 6 further comprising:

a control system coupled to adjust the current output by the current source.

8. The pump of claim 1 further comprising a protective layer covering the top of the diaphragm.

9. The pump of claim 1 further comprising a protective layer covering the bottom of the substrate.

10. The pump of claim 5 wherein the electromagnet is positioned adjacent the magnetic member.

11. The pump of claim 5 wherein the electromagnet is positioned separate from the magnetic member.

12. A microfluidic pump comprising:

a substrate including a pump chamber;

at least one channel in communication with the pump chamber;

a flexible diaphragm overlying the pump chamber; and

means for actuating the flexible diaphragm.

13. The pump of claim 12 wherein the means for actuating the flexible diaphragm includes an electromagnet.

14. The pump of claim 12 wherein the means for actuating the flexible diaphragm includes a permanent magnet.

15. The pump of claim 13 further comprising:

a current source coupled to supply electric current to the electromagnet.

16. The pump of claim 15 further comprising:

a control system coupled to adjust the current output by the current source.

17. The pump of claim 12 further comprising:

a check valve positioned in the channel.

18. The pump of claim 12 wherein the substrate is a polymer material.

19. The pump of claim 12 wherein the substrate is injection molded.

20. The pump of claim 12 wherein the channel and the pump chamber are embossed in the substrate.

21. A system for transporting a substance, the system comprising:

a substrate including a pump chamber;

at least one channel in communication with the pump chamber;

a flexible diaphragm forming a wall of the pump chamber;

means for actuating the flexible diaphragm; and

a control system coupled to control the means for actuating the flexible diaphragm.

22. The system of claim 21 wherein the means for actuating the flexible diaphragm includes an electromagnet.

23. The system of claim 21 wherein the means for actuating the flexible diaphragm includes a permanent magnet.

24. The system of claim 22 further comprising:

a current source coupled to supply electric current to the electromagnet.

25. The system of claim 21 further comprising:

a check valve positioned in the at least one channel.

26. The system of claim 21 wherein the substrate is a polymer material.

27. The system of claim 21 wherein the substrate is injection molded.

28. The system of claim 21 wherein the channel and the pump chamber are embossed in the substrate.

29. A method for transporting a substance using a pump system, wherein the pump system includes a chamber, at least one channel in communication with the chamber, a flexible diaphragm forming a wall of the chamber, and a magnetic member attached to the diaphragm, the method comprising:

attracting the magnetic member to cause the substance to flow into the chamber; and

repelling the magnetic member to cause the substance in the chamber to flow out of the chamber.

30. The method of claim 29, wherein the pump system further includes a check valve positioned in the channel, the method further comprising:

opening the check valve while attracting the magnetic member; and

closing the check valve while repelling the magnetic member.

31. The method of claim 30 wherein the check valve is unidirectional.

32. The method of claim 30 wherein the check valve includes a flap having one end movably attached to one sidewall of the channel.

33. The method of claim 29, wherein the pump system further includes an electromagnet positioned to attract and repel the magnetic member, the method further comprising:

adjusting current supplied to the electromagnet to control attracting and repelling the magnetic member.

34. A method of fabricating a pump system for transporting a substance, the method comprising:

forming a pump chamber in a substrate;

positioning at least one channel in communication with the pump chamber;

forming at least a portion of a wall of the pump chamber with a flexible diaphragm; and

attaching a magnetic member on the flexible diaphragm.

35. The method of claim 34 further comprising:

positioning a magnet to attract and repel the magnetic member.

36. The method of claim 34, wherein the magnet is an electromagnet, the method further comprising

coupling a control system to control current to the electromagnet.

37. The method of claim 34 further comprising:

positioning a check valve in the at least one channel.

38. The method of claim 34 further comprising:

using a polymer material for the substrate.

39. The method of claim 34 further comprising:

injection molding the substrate.

40. The method of claim 34 further comprising:

embossing the pump chamber in the substrate.

41. The method of claim 34 further comprising:

positioning a protective layer over the pump system.

42. The pump of claim 34 further comprising:

positioning a protective layer under the pump system.

* * * * *