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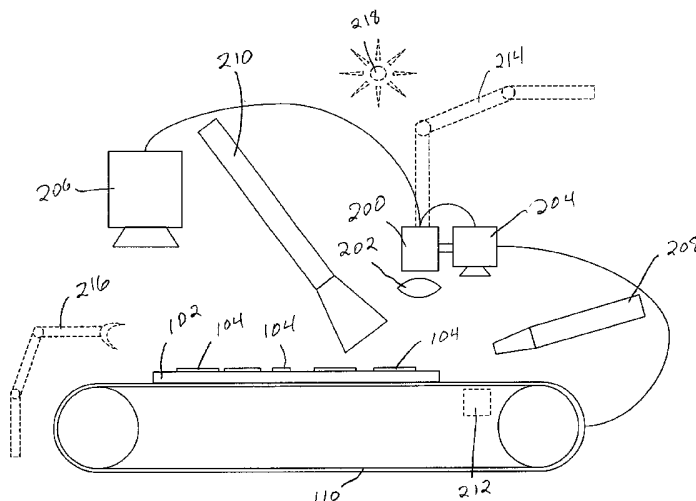
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(54) Title: LOW COST MATERIAL RECYCLING APPARATUS USING LASER STRIPPING OF COATINGS SUCH AS PAINT AND GLUE



(57) Abstract: An apparatus for recycling waste, which includes both recyclable material and non-recyclable material coupled to the recyclable material. The apparatus includes a laser to ablate the non-recyclable material from the recyclable material, a detector to detect the relative position of waste and the laser, a sensor to determine the absorptivity of the non-recyclable material, positioning means to move the laser and/or the waste, and laser control circuitry to control the fluence of the laser source. The laser emits light having a peak wavelength and the sensor determines the absorptivity of the non-recyclable material for light having a wavelength approximately equal to this peak wavelength. The positioning means moves the laser and/or the waste such that the laser light irradiates at least a portion of the waste, and the laser control circuitry controls the fluence of the laser light on the waste based on the absorptivity of the non-recyclable material.

## **LOW COST MATERIAL RECYCLING APPARATUS USING LASER STRIPPING OF COATINGS SUCH AS PAINT AND GLUE**

### **CROSS-REFERENCE TO RELATED APPLICATIONS**

**[0001]** This application claims the benefit of U.S. Provisional Application No. 60/385,950, filed June 5, 2002, the contents of which are incorporated herein by reference.

### **FIELD OF THE INVENTION**

**[0002]** This invention is in the field of recycling waste, and specifically relates to separating recyclable material from non-recyclable material using lasers.

### **BACKGROUND OF THE INVENTION**

**[0003]** Each year millions of units of all types of electronic equipment are manufactured and sold worldwide. This unfortunately leads to an increase in the waste electrical and electronic equipment (WEEE). In 1998, 6 million tons of WEEE was generated. This is 4% of the municipal waste stream and the volume of WEEE is expected to increase to 3-5% per annum. In 12 years, therefore, the amount of WEEE will have doubled. More than 90% of WEEE is landfilled, incinerated, and recovered without any pre-treatment. Large proportions of various pollutants, which can be found in the municipal waste stream, come from WEEE. Some pollutants contain hazardous substances.

**[0004]** Several countries have passed laws for electronic equipment manufacturers to reuse and recycle IT equipment. For example ITVO (IT-Altgerate-Verordnung) in Germany and the Promote Recycling of Resources Act in Japan have

forced an 85% recycling rate for equipment. Therefore, equipment manufacturers have begun designing products that are more recycling friendly.

**[0005]** Magnesium (Mg) alloys have gained popularity amongst electronic equipment manufacturers because they are easily recyclable, sturdy, and lightweight. However, products made from Mg alloys often have aesthetic color coating and glued parts. For example, a housing case for a 13 inch-wide and 8 inch-deep LCD screen, has a ¼ inch lip all the way round and glue on the underside. This color coating and glue must be removed from Mg alloy before recycling since the color coating and glue are non-recyclable or employ a different recycling process than Mg alloy. Therefore, there is a need to remove all non-recyclable, contaminating, material from the Mg alloy prior to recycling the alloy.

**[0006]** There are several known-in-the-art chemical treating techniques (i.e. chemical stripping bath) for cleaning Mg alloy, however these techniques are not efficient due to the toxic chemical waste by-products (i.e. these techniques are not environmentally friendly).

**[0007]** Material ablation by light sources has been studied since the invention of the laser. Reports in 1982 of polymers have been etched by ultraviolet (UV) excimer laser radiation stimulated widespread investigations of the process for micro machining. Since then, scientific and industrial research in this field has proliferated and now lasers can be used to strip an alloy of unwanted coating and glue.

**[0008]** For example, U.S. Patent RE33,777, "Laser removal of poor thermally-conductive materials," assigned to Avco Corporation (Providence, RI), describes a method of removing material of poor thermal conductivity such as paint, grease, ceramics, and the like from a substrate by ablation without damage to the substrate by delivering to the material to be removed pulses or their equivalent of a laser beam

having a wavelength at which the material to be removed is opaque and having a fluence sufficient to ablate or decompose the material without damaging or adversely affecting the substrate or its surface.

**[0009]** It is known that using lasers for stripping alloys can be more environmentally friendly than using chemical treatments, however, the steps mentioned in the above-mentioned prior art take extra precautions in avoiding damage to the underlying substrate material and as a result can make the process of using lasers prohibitively expensive for the recycling application.

**[0010]** What is needed is a low cost and environmentally friendly way of using lasers for recycling in this multi-billion dollar IT and electronic equipment recycling industry.

**[0011]** U.S. Patent No. 5,986,234, "High removal rate laser-based coating removal system," assigned to The Regents of the University of California (Oakland, CA), describes a compact laser system that removes surface coatings (such as paint, dirt, etc.) at a removal rate as high as 1000 ft<sup>2</sup>/hr or more without damaging the surface. A high repetition rate laser with multiple amplification passes propagating through at least one optical amplifier is used, along with a delivery system consisting of a telescoping articulating tube which also contains an evacuation system for simultaneously sweeping up the debris produced in the process. The amplified beam can be converted to an output beam by passively switching the polarization of at least one amplified beam. The system also has a personal safety system, which protects against accidental exposures.

**[0012]** U.S. Patent No. 5,864,114, "Coating removal apparatus using coordinate-controlled laser beam," assigned to Toshiharu Ishikawa (Hyogo, JP), describes how the removal of a coating, especially a thin coating such as a paint, formed on the surface of

various structures, is conducted using a laser beam, based on coordinate data of an area being laser-fired and of a target area to be laser-fired. A projection spot of the laser beam partially and reciprocatingly rotates, and accurate control of removal is conducted in such a way as to match the area being laser-fired and the target area.

**[0013]** U.S. Patent No. 5,782,253, "System for removing a coating from a substrate," assigned to McDonnell Douglas Corporation (St. Louis, MO); and Maxwell Laboratories, Inc. (San Diego, CA), describes a system provided for removing material from a structure having at least one layer of the material formed on a substrate. The system includes a radiant energy source, such as a flash lamp, with an actively cooled reflector for irradiating a target area of a structure with radiant energy, preferably sufficiently intense in at least the visible and ultraviolet, to break or weaken chemical bonds in the material, and an abrasive blaster for impinging the material after irradiation with a cool particle stream, preferably including of CO<sub>2</sub> particles, to remove the irradiated material and cool the substrate. The system may also include light sensors used in a feedback loop to control the removal process by varying the speed at which the radiant energy source is moved along the structure, the repetition rate of the source, the intensity of the source, the pulse width of the source and/or the distance between the source and the structure.

**[0014]** U.S. Patent No. 5,662,762, "Laser-based system and method for stripping coatings from substrates," assigned to Clover Industries, Inc. (Grosse Pointe Woods, MI), describes a laser-based system and method for stripping a coating from a substrate that includes laser apparatus for heating and partially ablating the coating and pressurized gas apparatus for directing a blast of high velocity chilled gas against the heated coating to shatter and strip the coating from the substrate. In one application, the laser-based coating stripping system and method of the present invention is used to strip paint from aluminum aircraft bodies.

### SUMMARY OF THE INVENTION

**[0015]** One embodiment of the present invention is an apparatus for recycling waste, which includes both recyclable material and non-recyclable material that is coupled to the recyclable material. The apparatus includes a laser source that is configured to ablate the non-recyclable material from the recyclable material, a detector to detect a relative position of the waste and the laser source, a sensor to determine absorptivity of the non-recyclable material, positioning means coupled to the laser source and the waste, and laser control circuitry coupled to the sensor and the laser source. The laser source emits a continuous wave (CW) or pulsed light beam having a peak wavelength and the sensor determines absorptivity of the non-recyclable material of the waste for light having a wavelength approximately equal to this peak wavelength. The positioning means moves the laser source and/or the waste such that the light beam irradiates at least a portion of the waste, and the laser control circuitry controls the fluence of the light beam on the waste based on the absorptivity of the non-recyclable material.

**[0016]** Another embodiment of the present invention is a method of recycling waste using a laser source, wherein the waste includes recyclable material and non-recyclable material that is coupled to the recyclable material. The laser source emits a light beam having a peak wavelength. In this method, the absorptivity of the non-recyclable material of the waste is determined for light having a wavelength approximately equal to the peak wavelength of the light beam and the position of the waste relative to the laser source is detected. Then the laser source and/or the waste are positioned, based on the detected position of the waste relative to the laser source, such that the light beam of the laser source irradiates a selected portion of the waste. The fluence of the light beam irradiating the selected portion of the waste is controlled to ablate at least some of non-recyclable material within the selected portion of the

waste based on the determined absorptivity of the non-recyclable material and the detected position of the waste relative to the laser source.

**[0017]** An additional embodiment of the present invention is a low-cost method of removing an electronic component from a circuit board using one or more or continuous wave (CW) or pulsed laser sources. It is contemplated that multiple lasers may be arranged to provide a line of laser beams. In one exemplary embodiment, each beam may be switched between pulsed and CW operational modes. The electronic component includes a body which extends from a first surface of the circuit board and leads which extend from the body and through vias in the circuit board. These leads are mechanically coupled to the second surface of the circuit board by coupling joints. The first side of the circuit board is placed on top of a mesh surface such that the body of the electronic component extends through the mesh surface. The position of the circuit board relative to the laser source is determined. Then the laser source and/or the mesh surface are moved, based on the detected position of the circuit board relative to the laser source, such that a light beam of the laser source irradiates the coupling joints. Material from the plurality of coupling joints is ablated and/or melted, for example, using a laser operating in CW or pulsed mode, to mechanically uncouple the leads of the electronic component from the second surface of the circuit board, such that the leads slip through the vias in the circuit board, thereby removing the electronic component from the circuit board. At the same time, other parts of the circuit board are processed by separately addressed pulsed or CW-mode lasers, for example, to remove paint or glue from the surface of the circuit board.

**[0018]** A further embodiment of the present invention is an electrical device adapted for improved recyclability using a laser which has a predetermined peak wavelength. The electrical device includes a circuit board, an electronic component, coupling joints to couple the electronic device to the circuit board. The circuit board

includes a first surface, a second surface having electrical traces, and vias extending from the first surface to the second surface. The electronic component includes a body which extends from the first surface of the circuit board and leads which extend from the body through the vias in the circuit board. The coupling joints are formed of a solder that is adapted to be melted by application of laser energy. The solder may be a metallic solder or an opaque organic conductor and each coupling joint couples one of the electronic component leads to the one of the electrical traces on the second surface of the circuit board. The opaque organic conductor includes a conductive organic material and a dye selected to have a high absorption of light with a wavelength approximately equal to the predetermined peak wavelength of the laser. The metallic solder also includes elements that make it sensitive to energy at the wavelength of the laser.

#### **BRIEF DESCRIPTION OF THE DRAWINGS**

**[0019]** The invention is best understood from the following detailed description when read in connection with the accompanying drawing. It is emphasized that, according to common practice, the various features of the drawing are not to scale. On the contrary, the dimensions of the various features are arbitrarily expanded or reduced for clarity. Included in the drawing are the following figures:

**[0020]** Figure 1 is a block diagram of an exemplary system for recycling waste including both recyclable and non-recyclable material.

**[0021]** Figure 2 is side plan drawing of an exemplary laser waste recycling apparatus that may be used in the system of Figure 1.

**[0022]** Figure 3 is a front plan drawing of the exemplary laser waste recycling apparatus of Figure 1, illustrating an alternative waste position detector.

**[0023]** Figures 4A and 4B are top plan drawings illustrating exemplary methods of scanning the laser beam over the waste during processing using the exemplary apparatus of Figures 2 and 3.

**[0024]** Figure 5 is a flowchart illustrating an exemplary method of removing non-recyclable material from the recyclable material in waste using the exemplary apparatus of Figures 2 and 3.

**[0025]** Figure 6 is a top plan drawing illustrating an exemplary electrical device adapted for improved recyclability using a laser waste recycling apparatus.

**[0026]** Figure 7 is a side plan drawing illustrating an exemplary laser waste recycling apparatus and an exemplary electrical device adapted for improved recyclability using the exemplary laser waste recycling apparatus.

**[0027]** Figure 8 is a flowchart illustrating an exemplary method of separating an electronic component from a circuit board using the exemplary laser waste recycling apparatus of Figure 7.

#### **DETAILED DESCRIPTION OF THE INVENTION**

**[0028]** One exemplary embodiment of the present invention is a low cost material recycling apparatus using laser stripping. This embodiment desirably includes an apparatus that utilizes a line source that includes multiple laser sources (e.g. multiple laser diodes). In one embodiment of the invention, the multiple laser sources are individually addressable so that some diodes may be operated in pulsed mode while other diodes are operated in CW mode. Alternatively, all of the laser sources in the line source may be operated in one mode (either pulsed or CW). In the present application, the term "laser source" is used to indicate a laser that may be a pulsed laser, a CW

laser or a laser that may be operated either in pulsed mode or CW mode. The line source is used to strip non-recyclable material, including coatings such as paint and glue, from the recyclable material within the waste being processed. The non-recyclable material may be melted or ablated or it may be processed by the laser (e.g. de-polymerized) so that it is easier to remove by conventional mechanical means such as scraping or sandblasting. As described below, the apparatus also desirably includes a simple mechanism that utilizes low-cost components to continuously move and track the waste, while it is being melted or ablated. The use of low-cost components in the exemplary apparatus improves this use of this apparatus for efficient, large scale recycling of electronic equipment.

**[0029]** Figure 1 illustrates an exemplary system for processing waste 100, which may be, for example, waste electrical and electronic equipment (WEEE) that includes both recyclable material 102 and non-recyclable material 104. It is noted that, although non-recyclable material 104 is shown as a number of discreet sections of coating on the surface of a flat substrate of recyclable material 102, other configurations of the recyclable and non-recyclable materials, such as solid chunks of recyclable material included in a matrix of non-recyclable material, may be processed using the exemplary waste processing system of Figure 1. Also, this exemplary waste processing system may be used to separate different types of recyclable material within waste 100.

**[0030]** The exemplary recyclable material 102 shown in Figure 1 is a recyclable substrate that is desirably to be stripped of non-recyclable material 104. For example waste 100 may be a portion of a CD player including a Mg alloy substrate, recyclable material 102, with a coat of paint and fixtures attached with glue, non-recyclable material 104. The paint and glue are desirably stripped from the Mg alloy so that the alloy may be recycled.

**[0031]** Waste 100 may be first processed by mechanical recycling device 106 to separate the waste into smaller waste pieces 108 before the non-recyclable material is processed by laser waste recycling apparatus 114. Mechanical recycling device 106 may crush, flatten, cut, break, or otherwise mechanically process waste 100 into waste pieces 108. This mechanical processing may serve to provide smaller, and/or more uniformly sized, waste pieces for laser processing. Figure 1 illustrates an exemplary embodiment in which mechanical waste processing apparatus 106 processes waste 100 to form waste pieces 108 that have a width less than or equal to the long dimension of line laser source 112. At least one surface of waste objects of this size may be irradiated in a single pass, using conveyor belt 110. As described above, it may be desirable for the line laser source to include multiple, individually addressable laser sources, such that each laser source may be operated in either pulse or CW mode. The laser sources operating in pulse mode may remove paint or glue while the laser sources operating in CW mode may remove solder or other non-recyclable material that is removed using relatively large amounts of energy. By varying the mode of the lasers, which lasers are being used at any given time and the relative speeds of the waste and the line laser source, a wide range of thermal profiles may be applied to the waste. This may reduce the need to sort the waste before it is recycled.

**[0032]** The mechanical processing may also serve loosen, or even remove, a portion of non-recyclable material 104 from the remainder of the waste. This may decrease the amount of laser processing needed to separate the waste, and may increase the efficiency of the exemplary waste processing system.

**[0033]** Following mechanical processing, waste pieces 108 are further processed by laser waste recycling apparatus 114, desirably to produce recyclable material 102 with substantially all of the non-recyclable material 104 removed, as shown in Figure 1.

In the CD player example, this processing desirably results in a bare Mg alloy substrate, which may be recycled as scrap metal.

**[0034]** Figure 2 illustrates an exemplary laser waste recycling apparatus according to the present invention. This exemplary apparatus includes laser source 200, position detector 204, color sensor 206, conveyor belt 110, air blast nozzle 208, and vacuum nozzle 210. Additional alternative elements include detector light source 212 and laser robotic arm 214, both shown in phantom.

**[0035]** As described above, laser source 200 emits a pulsed or CW light beam to ablate non-recyclable material 104, thus separating it from recyclable material 102. To provide high efficiency operation of laser waste recycling apparatus 114, it is desirable for laser source 200 to have a relatively high "plug efficiency" (i.e. power conversion of electricity into optical radiation), preferably greater than 10%. Further, it is desirable for the light beam of the laser source to be mostly absorbed by non-recyclable material 104 to improve the efficiency of the ablation process. It may also be desirable for absorption of the light beam by recyclable material 102 to be significantly lower than by non-recyclable material 104 to reduce possible damage to, or loss of, recyclable material 102. Therefore, the peak wavelength of laser source 200 is desirably chosen to be a wavelength which is substantially absorbed by anticipated non-recyclable materials, but not by anticipated recyclable materials. Alternatively, products may be designed such that non-recyclable materials absorb a particularly advantageous wavelength of laser light. Diode lasers at particular wavelengths are more electrically efficient than others and more readily available (lower cost) this could be a significant factor in the choice of non-recyclable materials.

**[0036]** Exemplary laser waste recycling apparatus 114 may also include lens 202 to focus the laser beam on the surface of the waste. This lens may be a fixed lens within the laser package, an external, adjustable lens (as shown in Figures 2 and 3), or

a combination thereof. It is also noted that a mirror may be used instead of, or in addition to, lens 202 to shape the beam spot size on the waste and depth of focus. Although the lens is shown as spherical, it is contemplated that a cylindrical lens may be used instead. Indeed, for a line laser source, the cylindrical lens may be more desirable.

**[0037]** Laser source 200 may be a single direct diode laser, a CO<sub>2</sub> laser or a linear array including multiple individual direct diode laser modules. Alternatively, laser source 200 may be a combination of any of these elements. If a CO<sub>2</sub> laser is used it may be desirable to carefully control the fluence of the laser light on the waste, as described below, to avoid the vaporization of the underlying recyclable substrate.

**[0038]** A wide enough linear array, such as laser source 200 in Figure 3, may produce a line source with a long, narrow rectangular beam cross-section, allowing removal of non-recyclable material from a piece of waste in a single pass, as shown in Figure 4B. In one exemplary embodiment, laser source 200 may be a linear array 12-24 inches wide, including direct diode laser modules approximately 1.25 cm wide, 5 cm long, and 5 cm tall. Desirably, each module creates a rectangle light beam with a spot size of approximately 1 cm wide by 200  $\mu$ m with an output of 1 KW per beam.

**[0039]** Position detector 204, shown in Figure 2, detects a position of the waste relative to the laser source. The position detector may include a light source and measure reflections of this internal light source or overhead light source 218. Alternatively, position detector 204 may respond to light from detector light source 212. It is noted that, if laser source 200 is fixed and the conveyor belt 110 is configured to move the waste in the path of the laser source 200, it may be desirable for the position detector 204 to be located where detector light source 212 is shown in Figure 2. Also if either position detector 204 or detector light source 212 is located in this location within conveyor belt 110, then either conveyor belt 110 is desirably

formed of a material that is substantially transparent to light detected by the position sensor, or an alternative conveyor belt 300 with a gap as shown in Figure 3 is desirably used. The detector may also be located on the same side as the detector light source. In this embodiment, the detector monitors reflections from the conveyor or alternatively the waste stream. The detector can also be a "line detector". If the sensor uses reflections, line source laser may be used as the light source for the detector. If the line laser source uses laser diodes, the individual laser diodes may be set to a lower output power until waste comes into view. This may save power and reduce wear relative to a system that does not modulate the intensity of the laser source.

**[0040]** Position detector 204 may be coupled, as shown in Figure 2, to the control circuitry of conveyor belt 110, laser robotic arm 214, waste robotic arm 216 and/or other positioning means to provide feedback concerning the position of the waste and/or the laser source 200 to allow efficient operation of laser waste recycling apparatus 114. Also as shown in Figure 2, position detector 204 may be coupled to control circuitry of laser source 200.

**[0041]** In one exemplary embodiment, position detector 204 is a photodetector and is coupled to laser source 200, as shown in Figure 2, to maintain a fixed spatial orientation relative to the laser source. This allows the position detector to determine when waste is in position for processing by laser source 200. This allows the exemplary laser waste recycling apparatus 114 to achieve greater efficiency by only activating laser source 200 when a piece of waste is properly positioned to be processed.

**[0042]** Alternatively, position detector 204 may be a CCD camera. The CCD camera may be oriented to detect a pixel image of the waste. Image circuitry in the CCD camera may provide the detected pixel image to image analysis circuitry (not shown). This image analysis circuitry may desirably determine not only the position of

the waste relative to laser source 200, but also the position of non-recyclable material 104 within the waste. Results of this analysis of the pixel image may be provided to position control circuitry included in the positioning means and/or the laser control circuitry included in laser source 200. The position control circuitry may then control the position means to move the laser source 200 and/or the waste so that portions of the waste including non-recyclable material 104 are selectively positioned in the laser beam. The laser control circuitry may also control laser source 200 to emit a light beam only when a portion of waste including non-recyclable material 104 is properly positioned to be processed.

**[0043]** Figure 3 illustrates another type of position detector, a mechanical switch 302. Mechanical switch 302 includes trip lever 304 which protrudes through a gap in alternative conveyor belt 300. When waste passes mechanical switch 302, it pushes the trip lever and is detected as being in a position to be irradiated by the laser beam. In this exemplary embodiment, after the waste passes mechanical switch 302, a spring (not shown) resets trip lever 304.

**[0044]** It is contemplated that a color sensor 206 may be used to determine the absorptivity of non-recyclable material 114 of the waste. In one exemplary embodiment, color sensor 206 includes two emitter laser diodes of the same wavelength as laser source 200 and two detectors located behind a band pass filter (not shown) that allows transmission of the peak wavelength of the laser beam. This color sensor measures light reflected from the area of under observation. The two detectors measure an average the amount of light reflected in different directions. For this embodiment, it is assumed that the waste reflects substantially all of the light and thus, has minimal transmission. Consequently, the absorptivity may be estimated with some confidence from the reflected light alone. Waste that transmits significant amounts of light at the operating wavelength may be accommodated by placing

additional color sensor detectors between the conveyor belts to measure transmission and/or one the sides to measure scattered light may increase the accuracy of the absorptivity of the non-recyclable material measured by the color sensor.

**[0045]** The fluence desired to ablate non-recyclable material 104 depends in part on its absorptivity. Therefore, average absorptivity information may lead to greater efficiency by allowing control of the fluence used to ablate the non-recyclable material, thus increasing the throughput and/or decreasing the energy consumption of exemplary laser waste recycling apparatus 114.

**[0046]** For example, a highly absorptive non-recyclable coating on recyclable material 102 does not need as much laser beam fluence as a highly reflective or highly transmissive coating, and therefore a lower amount of laser beam fluence (power/unit area) may desirably be used for the absorptive surface.

**[0047]** The average absorptivity information provided by the color sensor may desirably be used by the laser control circuitry to adjust the average power (i.e. amount of time that a CW or pulsed laser focused on a spot or line, or the pulse length, pulse rate, and pulse energy of a pulsed laser) of the laser beam emitted by laser source 200, and thereby controlling the laser beam fluence on the waste. This average absorptivity information may also used to control the spot size of the laser beam on the waste, and thus the laser beam fluence, adjusting the distance between laser source 200 and lens 202 and/or laser source 200 and the waste. Additionally, the average absorptivity information may also used to control the scan rate of the laser beam over the waste. One method to alter the scan rate is to alter the speed of conveyor belt 110.

**[0048]** Alternatively, color sensor 206 may include a CCD camera to provide a pixel image of the waste, from which absorptivities of different portions of non-

recyclable material 104 within the waste may be determined. The CCD camera may respond to light from an internal light source or light from overhead light source 218. This absorptivity information may be used to dynamically update the fluence of the laser light on the waste as the waste is scanned to desirably control the ablation rate. An exemplary embodiment of color sensor 206 including a CCD camera may also be able to determine non-coated regions on recyclable material 102 which may not need to be processed.

**[0049]** Alternative or additional known-in-the-art detectors can be added to exemplary laser waste recycling apparatus 114. For example, a contour detector may be used to detect the height and surface contour of recyclable material 102. The surface and contour information can be used to optimally scan the laser beam over the waste to save power. The contour sensor may be, for example, a conventional ultrasonic distance measuring device or a conventional auto-focus system adapted to provide a distance from the lens to the object.

**[0050]** The various control and analysis circuitry included in exemplary laser waste recycling apparatus 114 may be formed as special purpose circuitry elements, which may help to maintain low cost for the apparatus. The functions of this control and analysis circuitry may also be performed by a general purpose computer instructed by software including a database to store information on coating colors, laser power levels desired, conveyer speed, and other information.

**[0051]** Air blast nozzle 208 of exemplary laser waste recycling apparatus 114 provides a fluid and/or particle stream to blow ablated non-recyclable material 104 away from recyclable material 102 and desirably separate these materials. Therefore, it may be desirable to maintain air blast nozzle 208 in a substantially fixed spatial orientation relative to the irradiated portion of the waste. It may also be desirable for air blast nozzle 208 to blow the ablated non-recyclable material 104 away from the

optical components of exemplary laser waste recycling apparatus 114 to help keep these components clean and functioning properly.

**[0052]** If a particle stream is included in the air blast, the particle stream may desirably abrade any remaining non-recyclable material 104 in the irradiated portion of the waste that has not been ablated. This particle stream may desirably include CO<sub>2</sub> particles or particles of some other non-oxygen fluid, which may additionally cool recyclable material 102, to reduce any accidental ablation or undesirable oxidation of the surface of the recyclable material.

**[0053]** Vacuum nozzle 210 may be used to help remove non-recyclable material 104 that has been ablated, or abraded before it can settle onto recyclable material 102 or any of the optical components of exemplary laser waste recycling apparatus 114. Vacuum nozzles 210 may also collect non-recyclable dust and debris generated from the stripping and patterning of the waste for further processing, particularly when non-recyclable material 102 poses a hazard of toxic chemical contamination. Vacuum nozzles 210 are desirably maintained in a substantially fixed spatial orientation relative to the irradiated portion of the waste.

**[0054]** Exemplary laser waste recycling apparatus 114 may further include a laser chamber (not shown) to encase the apparatus. This laser chamber may be used to maintain an appropriate working atmosphere, such as a clean air dust free atmosphere and to provide laser safety for workers. Air blast nozzle 208 and vacuum nozzle 210 may also provide the laser chamber with flowing air stream to remove the ablated non-recyclable material and automatically clean the enclosed optical components.

**[0055]** Figures 4A and 4B illustrate two exemplary raster patterns 400 and 402, which may desirably be used by the positioning means to scan the light beam spots

112 of the laser source over the waste in a raster pattern. These positioning means may include conveyor belt 110, laser robotic arm 214, and waste robotic arm 216 (shown in Figure 2). In an exemplary embodiment, the row scans of raster patterns 400 and 402 are desirably accomplished using conveyor belt 110 (shown in Figure 2) and the jumps between rows are accomplished using laser robotic arm 214. Exemplary waste robotic arm 216 may be used to reorient the waste on conveyor belt 110 or to flip the waste to expose a new side. It may be desirable for conveyor belt 110 to be formed of a material which is not substantially absorptive to the peak wavelength of the light beam to minimize any possible damage that the laser beam may cause to the conveyor belt. To maintain low cost, it may be desirable for conveyor belt 110 to be a mesh conveyor belt or a set of rails.

**[0056]** It is noted that the raster pattern in Figure 4B includes only one row because the laser beam spot 112 in Figure 4B is at least as wide as the waste being processed. In these exemplary embodiments, the light beam spot 112 has a substantially rectangular shape (i.e. the light beams have a substantially rectangular cross-section) in each of these Figures. Also, the long dimension of these substantially rectangular shapes is desirably perpendicular to the rows of the exemplary raster pattern in each Figure.

**[0057]** Figure 5 illustrates an exemplary method of recycling waste using a laser source. The laser source emits a pulsed or CW light beam having a peak wavelength. The method starts with waste having both recyclable material and non-recyclable material, step 500, where the non-recyclable material is adhering to the recyclable material. For example the non-recyclable material may be a coating, such as paint or glue, on the recyclable material.

**[0058]** The absorptivity of the non-recyclable material of the waste at the peak wavelength of the light beam is determined, step 502. The absorptivity may be

estimated to a reasonable degree of accuracy by measuring the reflectivity and transmission of the non-recyclable material at the peak wavelength. In many cases, the waste has negligible transmission and it is possible to omit measuring the transmission. An average absorptivity of the non-recyclable material in the waste may be determined, or a local absorptivity of the non-recyclable material for each portion of the waste may be determined.

**[0059]** The position of the waste relative to the laser source is detected, step 504. This relative position may be detected mechanically or optically. In one exemplary method, a pixel image of a CCD camera may be used to determine this relative position as well as the positions of the non-recyclable material within the waste.

**[0060]** Based on the determined absorptivity of the non-recyclable material and the detected positions of the non-recyclable material within the waste (if this was detected), step 506 determines whether any non-recyclable material remains in the waste. If a pixel image of the waste was taken in either step 502 or 504, then the pixel image is analyzed to determine if the value of any pixel corresponds to the value expected for a portion of waste including non-recyclable material. If no pixel images of the waste were taken in steps 502 and 504, then the average absorption is compared to the value expected from the recyclable material. If the average absorption of value expected from the recyclable material is unknown, then it is assumed that each portion of the waste is to be irradiated once to remove the non-recyclable material from the waste.

**[0061]** If all of the non-recyclable material is determined to have been removed from the waste, then process is completed, step 512. If any non-recyclable material is determined to be left in the waste at step 506, then the waste and/or the laser source 200 are moved until a selected portion of the waste may be irradiated by the laser

source, step 508, and the relative position of the waste 102 and the laser source 200 is updated. The desired movement of the waste and/or the laser source is determined based on the position of the waste relative to the laser source and the positions of non-recyclable material 104 within the waste 102 (if detected in step 504). If the positions of non-recyclable material 104 within the waste were detected in step 504, then the selected portion of the waste 102 is desirably selected to include a portion of the non-recyclable material 104.

**[0062]** The fluence of the light beam irradiating the selected portion of the waste 102 is controlled to ablate at least some of non-recyclable material within the selected portion of the waste, step 510. The desired level of the fluence is determined based on the absorptivity of the non-recyclable material within the selected portion of the waste, determined in step 502. If the absorptivity of the non-recyclable material in each portion of the waste was determined in step 502, then the value corresponding to the selected portion of the waste may be used; otherwise the average absorptivity value is used.

**[0063]** Additionally, as described above, a fluid and/or particle stream may be used to blow ablated non-recyclable material away, as well as possibly assisting in removal of irradiated non-recyclable material by abrasion, as part of this step. Also, a vacuum may be used to vacuum up ablated and/or abraded non-recyclable material.

**[0064]** Steps 506, 508 and 510 may be repeated until it is determined that substantially all of the non-recyclable material has been removed from the waste. Steps 502 and/or 504 may be repeated to assist with making this determination in step 506. In addition, depending on the cost/utility trade-off from the desired application, several known-in-the-art functional systems may be used with the above-invention. For example, cutting and feeding the waste into the laser waste recycling apparatus may be added as a preparation step to this exemplary recycling method. A multi-step

process of gross laser ablation of non-recyclable material followed by finer and finer removals may be incorporated as well.

**[0065]** Figures 6 and 7 illustrate an exemplary electrical device adapted for improved recyclability using a laser light beam having a predetermined peak wavelength. The electrical device includes circuit board 600 and at least one electronic component 606. Circuit board 600 may be formed of any common rigid circuit board material, such as epoxy resin, fiberglass, glass, ceramic, or a laminate thereof. This exemplary circuit board has vias 604 running from a first surface to a second surface and electrical traces 602 formed on the second surface. Electrical traces 602 may be formed of any conductive material, such as aluminum, aluminum-calcium, gold, silver, copper, nickel, titanium, tungsten, platinum, germanium, polyaniline, polyamide, polysilicon, polyacetylene, polypyrrole, and polyparaphenylene or a combination thereof.

**[0066]** Electronic components 606 are typical electronic components, such as resistors, capacitors, transistor, integrated circuits, etc. The body of each electronic component 606 extends out from the first side of circuit board 600. Leads 608 of the electronic components extend through vias 604 to the second side of circuit board 600. The leads are mechanically, and electrically, coupled to electrical traces 602 by coupling joints 610.

**[0067]** In the exemplary embodiment, coupling joints 610 may be formed of an opaque organic conductor, which includes a conductive organic material and a dye selected to have high absorption light with a wavelength approximately equal to the predetermined peak wavelength. Conductive organic materials include conductive epoxy, conductive thermoplastic, conductive elastomer, polyaniline, polyamide, polyacetylene, polypyrrole, and polyparaphenylene. The conductive organic material provides the mechanical and electrical coupling properties of coupling joints 610. The amount of dye added to the conductive organic material is desirably low enough that it

does not significantly change the electrical and mechanical properties of the conductive organic material, but high enough to significantly increase the susceptibility of the coupling joints to melting and ablation by the laser light beam. It is noted that electrical traces 602 may be formed of the same material as coupling joints 610 so that they may also be readily melted or ablated by light of the predetermined wavelength.

**[0068]** The coupling joints may also be formed from a conventional metallic solder configured for removal by laser light of a particular wavelength. This may be accomplished, for example, by adding material to the solder that increases its absorptivity at the particular wavelength. These may be, for example, particles of a material that readily absorbs light at the particular wavelength. Alternatively, the solder may be made by alloying metals that, in combination, exhibit increased absorption at the particular wavelength.

**[0069]** Figure 7 also illustrates an exemplary laser electrical device recycling apparatus 700, including laser source 200, lens 202, laser robotic arm 214, and mesh conveyor belt 702. The mesh of mesh conveyor belt 702 has openings desirably large enough to accommodate typical electronic components 606. It is noted that mesh conveyor belt 702 may desirably be replaced by a mesh surface. Additionally, this exemplary apparatus also may include any of the various features of laser waste recycling apparatus 114 described above with reference to Figures 2 and 3. In particular, the exemplary laser source 200 may include multiple individually addressable diode lasers that each may operate in pulsed mode or CW mode.

**[0070]** Figure 8 illustrates an exemplary low-cost method of removing electronic components from circuit boards. This method may use exemplary laser electrical device recycling apparatus 700.

**[0071]** The method starts with an electrical device including at least one electronic component 606 mechanically coupled to a circuit board by coupling joints 610, step 800. The electronic component includes a body which extends from a first surface of the circuit board and leads which extend from the body and through vias in the circuit board. These leads are mechanically coupled to the second surface of the circuit board by coupling joints. The coupling joints may be formed of a solder or a conductive organic material. The conductive organic material may be mixed with a dye that is highly absorptive of the peak wavelength of the laser source.

**[0072]** The first side of the circuit board is placed on top of a mesh surface such that the bodies of the electronic components extend through the mesh surface, step 802. This mesh surface may be part of a mesh conveyor as shown in Figure 7, but this is not necessary. The relative position of the circuit board and the laser source is determined, step 804. The positions of the coupling joints on the second surface of the circuit board may desirably also be determined.

**[0073]** At least one of the laser source and the mesh surface are moved, such that a light beam of the laser source irradiates the set of coupling joints corresponding to one of the electronic components, step 806. The desired movements are determined based on the position of the circuit board relative to the laser source detected in step 804. Depending on the spot size of the laser beam on the second surface of the circuit board, it may be desirable to irradiate the selected coupling joints separately or in groups smaller than the full set. As described above, if metallic solder is used for the coupling joint, it may be desirable to operate selected units of the laser diodes in CW mode, applying laser light selectively to the coupling joint over a relatively long period of time to melt the solder and release the component.

**[0074]** The coupling joints are irradiated until they are sufficiently melted and/or ablated to mechanically uncouple the corresponding leads of the electronic component

from the second surface of the circuit board, step 808. In addition, a fluid and/or particle stream from, for example, air blast nozzle 208 (shown in Figure 2) may be used to blow away melted and/or ablated portions of the coupling joints to accelerate the uncoupling process. Also, a vacuum nozzle 210 (shown in Figure 2) may be used to remove ablated or melted portions of the coupling joints.

**[0075]** The mechanically uncoupled leads of the electronic component may then slip through the vias in the circuit board under the force of gravity, thereby removing the electronic component from the circuit board, step 810. Additionally, the mesh surface may be vibrated to help the leads of the electronic component separate from the circuit board and slip through the vias in the circuit board more easily.

**[0076]** The irradiating, melting and/or ablating, and removing processes of steps 806, 808, and 810 may be repeated for each electronic component in turn, or they may be conducted in parallel if the power of laser is sufficient to irradiate the coupling joints corresponding to multiple electronic components at the same time.

**[0077]** Although the invention is illustrated and described herein with reference to specific embodiments, the invention is not intended to be limited to the details shown. Rather, various modifications may be made in the details within the scope and range of equivalents of the claims and without departing from the invention.

## What is Claimed:

1                   1.       An apparatus for recycling waste including recyclable material and  
2 non-recyclable material coupled to the recyclable material, comprising:

3                   a laser source emitting a light beam having a peak wavelength to ablate  
4 the non-recyclable material from the recyclable material;

5                   a detector to detect a position of the waste relative to the laser source;

6                   a sensor to determine absorptivity of the non-recyclable material of the  
7 waste for light having a wavelength approximately equal to the peak wavelength of the  
8 light beam;

9                   positioning means coupled to the laser source and the waste to move at  
10 least one of the laser source and the waste such that the light beam of the laser source  
11 irradiates at least a portion of the waste; and

12                  laser control circuitry coupled to the sensor and the laser source to  
13 control a fluence of the light beam on the waste based on the absorptivity of the non-  
14 recyclable material of the waste determined by the sensor.

1                   2.       The apparatus of claim 1, wherein the laser source is at least one  
2 of a direct diode laser, a linear array of direct diode lasers, and a CO<sub>2</sub> laser.

1                   3.       The apparatus of claim 1, wherein the light beam of the laser  
2 source has a substantially rectangular cross-section.

1                   4.       The apparatus of claim 3, wherein:

2 the substantially rectangular cross-section of the light beam has a long  
3 dimension; and

4 the positioning means is adapted to move the at least one of the laser  
5 source and the waste such that the light beam of the laser source irradiates a plurality  
6 of portions the waste in a raster pattern, a row of the raster pattern being  
7 perpendicular to the long dimension of substantially rectangular cross-section of the  
8 light beam.

1 5. The apparatus of claim 4, wherein the positioning means is further  
2 adapted to move the at least one of the laser source and the waste such that a width  
3 of the waste perpendicular to the row of the raster pattern is shorter than the long  
4 dimension of substantially rectangular cross-section of the light beam.

1 6. The apparatus of claim 1, wherein the detector includes at least  
2 one of a light source, a photodetector, a CCD camera, and a mechanical switch.

1 7. The apparatus of claim 1, wherein the detector is maintained in a  
2 fixed spatial orientation relative to the laser source.

1 8. The apparatus of claim 1, wherein the sensor includes:  
2 a light source adapted to emit light including the peak wavelength of the  
3 light beam; and

4 at least one of a photodetector adapted to detect light in a narrow  
5 bandwidth near the peak wavelength of the light beam, and a CCD camera adapted to  
6 detect light in a bandwidth including the peak wavelength of the light beam.

1                   9.     The apparatus of claim 1, wherein the positioning means includes  
2     at least one of a conveyor belt to move the waste, a waste robotic arm to move the  
3     waste, and a laser robotic arm to move the laser source.

1                   10.    The apparatus of claim 1, wherein the positioning means includes  
2     a conveyor belt formed of a material, which is not substantially absorptive to the peak  
3     wavelength of the light beam, to move the waste.

1                   11.    The apparatus of claim 1, wherein the positioning means is further  
2     coupled to the detector and moves the at least one of the laser source and the waste  
3     based on the position of the waste relative to the laser source detected by the  
4     detector.

1                   12.    The apparatus of claim 1, wherein the laser is a pulse laser which  
2     generates a pulsed light beam and the laser control circuitry controls the fluence of the  
3     pulsed light beam on the waste by controlling at least one of a pulse width of the  
4     pulsed light beam, a pulse energy of the pulsed light beam, and a pulse rate of the  
5     pulsed light beam.

1                   13.    The apparatus of claim 1, wherein the laser source includes at  
2     least one of a lens and a mirror coupled to the laser control circuitry to control a spot  
3     size of the light beam on the waste.

1                   14.    The apparatus of claim 1, wherein the laser control circuitry is  
2     further coupled to the positioning means to control at least one of:

3                   a spot size of the light beam on the waste; and

4                   a scan speed of the laser beam over the waste.

1           15.    The apparatus of claim 1, wherein the laser control circuitry is  
2 further coupled to the detector to control the laser source to emit a laser beam only  
3 when the waste is positioned relative to laser source such that the emitted laser beam  
4 irradiates the waste.

1           16.    The apparatus of claim 1, further comprising a vacuum nozzle  
2 maintained in a substantially fixed spatial orientation relative to the irradiated portion  
3 of the waste to remove portions of the non-recyclable material ablated by the laser  
4 source from the recyclable material of the waste, the laser source, and the sensor.

1           17.    The apparatus of claim 1, further comprising an air blast nozzle  
2 maintained in a substantially fixed spatial orientation relative to the irradiated portion  
3 of the waste to blow portions of the non-recyclable material ablated by the laser source  
4 away from the recyclable material of the waste, the laser source, and the sensor.

1           18.    The apparatus of claim 17, wherein the air blast nozzle is  
2 configured to provide a fluid stream that is substantially free of oxygen onto the  
3 irradiated portion of the waste to accelerate removal of non-recyclable material from  
4 the waste.

1           19.    The apparatus of claim 18, wherein the air blast nozzle is  
2 configured to provide a particle stream including CO<sub>2</sub> particles.

1           20.    The apparatus of claim 1, further comprising a mechanical  
2 recycling device to separate the waste into a plurality of waste pieces before the non-  
3 recyclable material is ablated by the laser source.

1           21.    The apparatus of claim 1, wherein:

the detector includes a CCD camera oriented to detect a pixel image of the waste and image circuitry to provided the detected pixel image to the position means; and

the positioning means includes image analysis circuitry to determine the position of non-recyclable material within the waste and position control circuitry adapted to move the at least one of the laser source and the waste such that the irradiated portion of the waste includes non-recyclable material.

22. A method of recycling waste, including recyclable material and non-recyclable material connected to the recyclable material, using a laser source which emits a light beam having a peak wavelength, the method comprising the steps of:

a) determining absorptivity of the non-recyclable material of the waste for light having a wavelength approximately equal to the peak wavelength of the light beam;

b) detecting a position of the waste relative to the laser source;

c) positioning at least one of the laser source and the waste, based on the position of the waste relative to the laser source detected in step (b), such that the light beam of the laser source irradiates a selected portion of the waste;

d) controlling a fluence of the light beam irradiating the selected portion of the waste to ablate at least some of non-recyclable material within the selected portion of the waste based on;

the absorptivity of the non-recyclable material of the waste determined in step (a); and

17 the position of the waste relative to the laser source detected in  
18 step (b).

1 23. The method of claim 22, wherein step (b) further includes the  
2 step of detecting the position of non-recyclable material within the waste.

1 24. The method of claim 23, further comprising the step of:

2 e) repeating steps (b), (c), and (d) until no non-recyclable material  
3 is detected within the waste in step (b).

1 25. The method of claim 23, wherein step (c) includes the step of  
2 positioning at least one of laser source and the waste, based on the position of the  
3 waste relative to the laser source and the position of the non-recyclable material  
4 detected in step (b), such that the selected portion of the waste includes non-recyclable  
5 material.

1 26. The method of claim 22, further comprising the step of:

2 e) repeating steps (c) and (d) until each portion of the waste has  
3 been selected for irradiation in step (c).

1 27. The method of claim 26, wherein portions of the waste are  
2 selected for irradiation in step (c) in a raster pattern.

1 28. The method of claim 22, further comprising the step of:

2 e) blowing the non-recyclable material ablated in step (d) away from  
3 the recyclable material and the laser source.

1                   29.    The method of claim 22, further comprising the step of:

2                   e)     applying a vacuum to remove the non-recyclable material ablated  
3   in step (d).

1                   30.    A low-cost method of removing an electronic component from a  
2   circuit board using a laser source, the electronic component including a body which  
3   extends from a first surface of the circuit board and a plurality of leads which extend  
4   from the body and through a plurality of vias in the circuit board, the plurality of leads  
5   of the electronic device being mechanically coupled to a second surface of the circuit  
6   board by a plurality of coupling joints, the method comprising the steps of:

7                   a)     placing the first side of the circuit board on top of a mesh surface  
8   such that the body of the electronic component extends through the mesh surface;

9                   b)     detecting a position of the circuit board relative to the laser  
10   source;

11                  c)     moving at least one of the laser source and the mesh surface,  
12   based on the position of the circuit board relative to the laser source detected in step  
13   (b), such that a light beam of the laser source irradiates the plurality of coupling  
14   joints;

15                  d)     at least one of melting and ablating material from the plurality of  
16   coupling joints to mechanically uncouple the plurality of leads of the electronic  
17   component from the second surface of the circuit board so that the plurality of leads of  
18   the electronic component slip through the plurality of vias in the circuit board, thereby  
19   removing the electronic component from the circuit board.

1                   31.    The method of claim 30, further comprising the step of:

2 e) vibrating the mesh surface to cause the plurality of leads of the  
3 electronic component slip through the plurality of vias in the circuit board.

1 32. The method of claim 30, further comprising the step of;

2 e) blowing the material from the plurality coupling joints which is  
3 melted in step (d) away from the leads of the electronic component.

1 33. The method of claim 30, further comprising the step of:

2 e) blowing the material from the coupling joints which is ablated in  
3 step (d) away from the leads of the electronic component.

1 34. The method of claim 30, further comprising the step of:

2 e) applying a vacuum to the coupling joints to remove the material  
3 which is ablated in step (d).

1 35. An electrical device adapted for improved recyclability using a  
2 laser having a predetermined peak wavelength, comprising:

3 a circuit board including;

4 a first surface;

5 a second surface having a plurality of electrical traces; and

6 a plurality of vias extending from the first surface to the second  
7 surface;

8 an electronic component including;

a body which extends from the first surface of the circuit board;

and

a plurality of leads which extend from the body and through the

plurality of vias in the circuit board; and

a plurality of coupling joints formed of an opaque organic conductor,

each coupling joint coupling one of the plurality of leads of the electronic component to

the one of the electrical traces on the second surface of the circuit board;

wherein the opaque organic conductor includes a conductive organic

material and a dye selected to have high absorption of light with a wavelength

approximately equal to the predetermined peak wavelength of the laser.

36. The electrical device of claim 35, wherein the conductive organic

material includes at least one of conductive epoxy, conductive thermoplastic,

conductive elastomer, polyaniline, polyamide, polyacetylene, polypyrrole, and

polyparaphenylene.

Figure 1

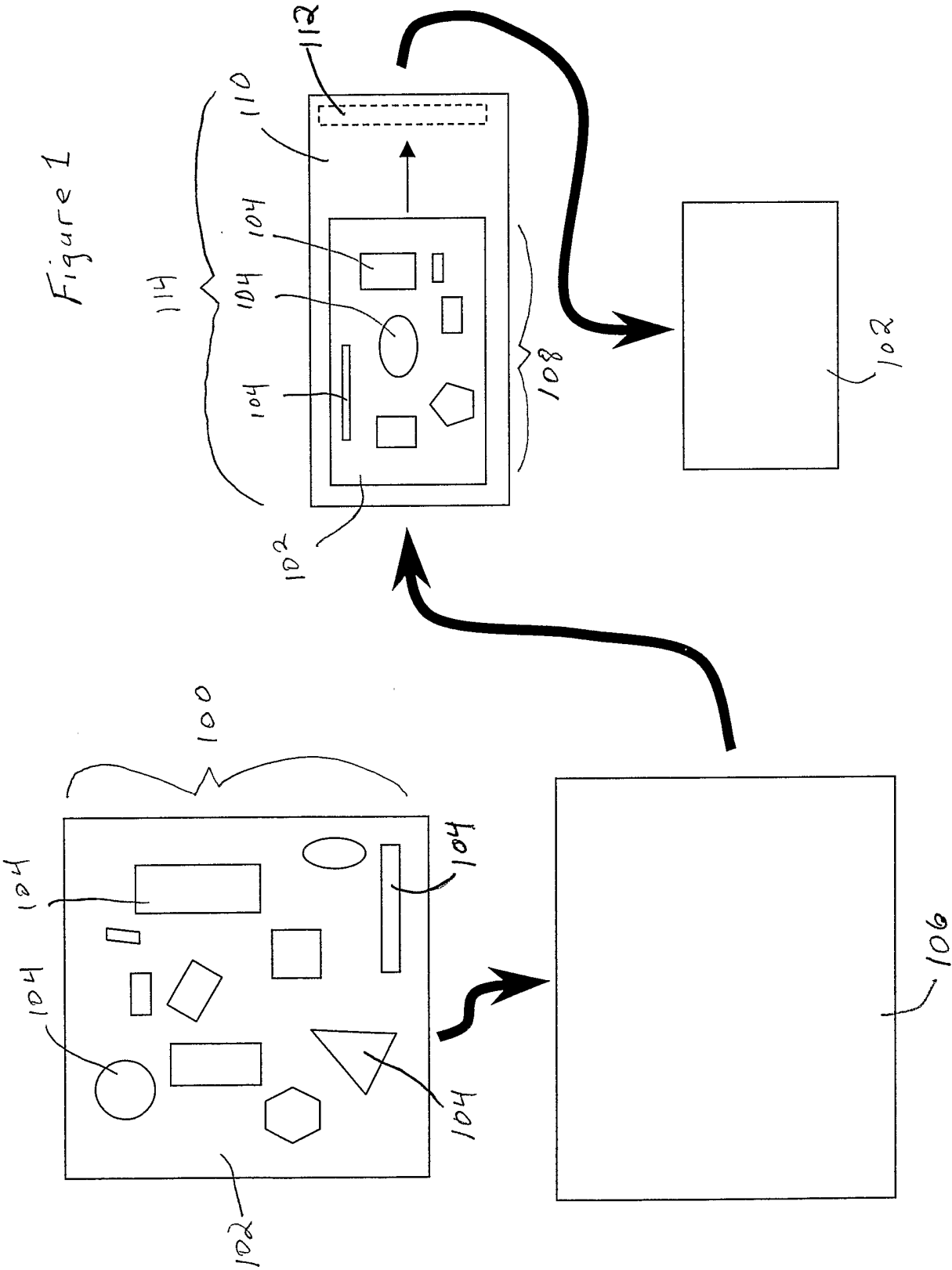


Figure 2

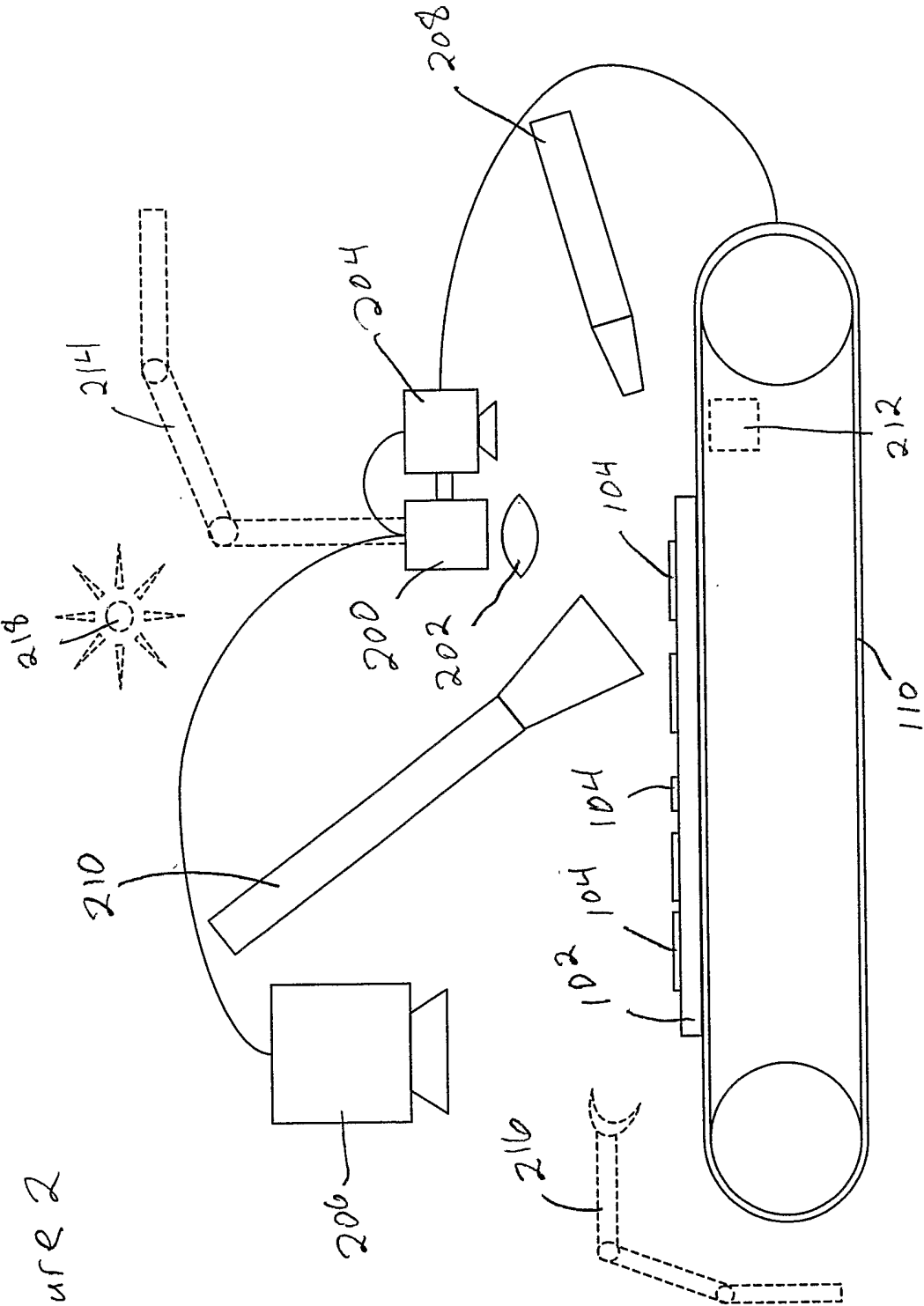
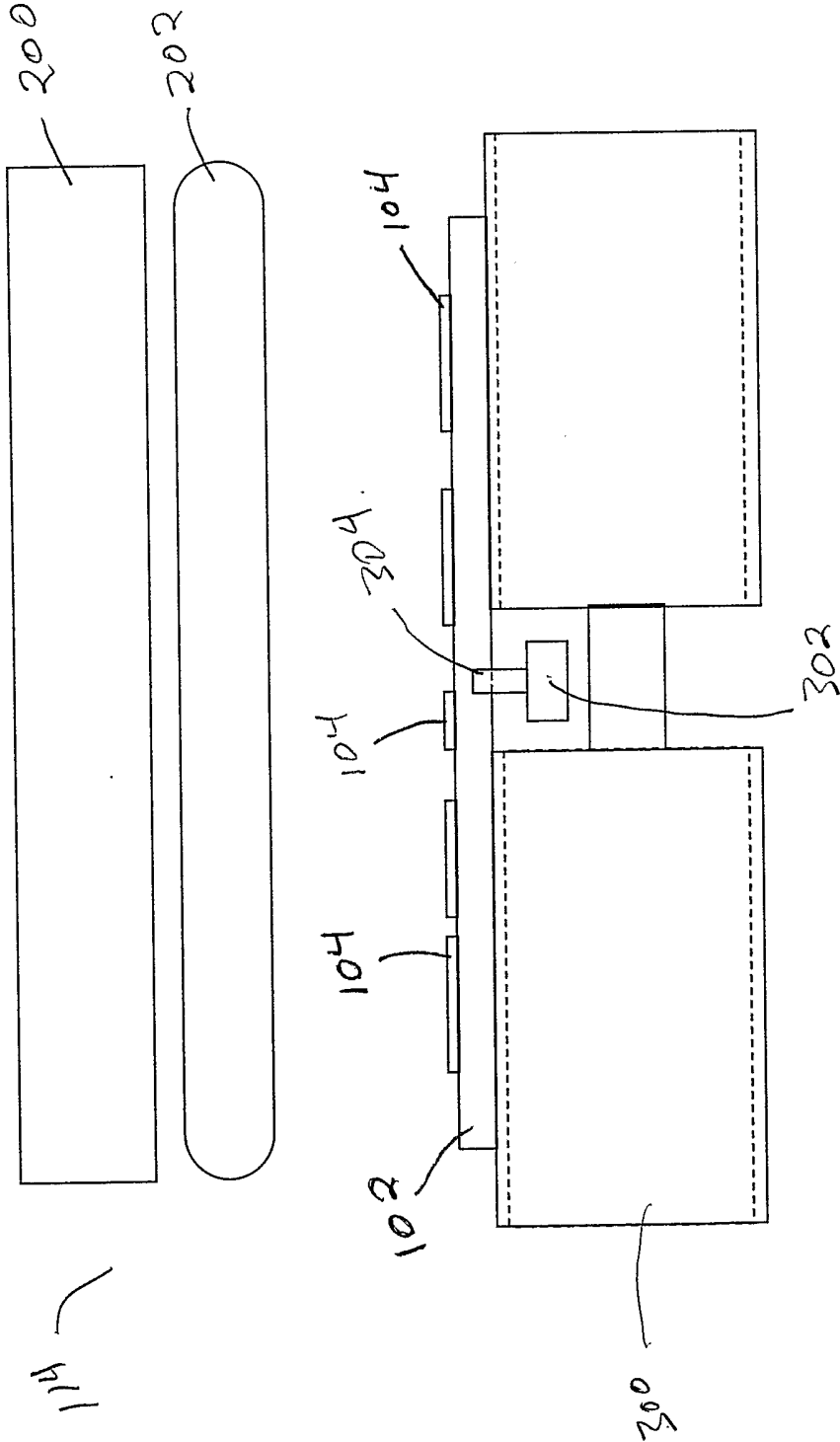


Figure 3



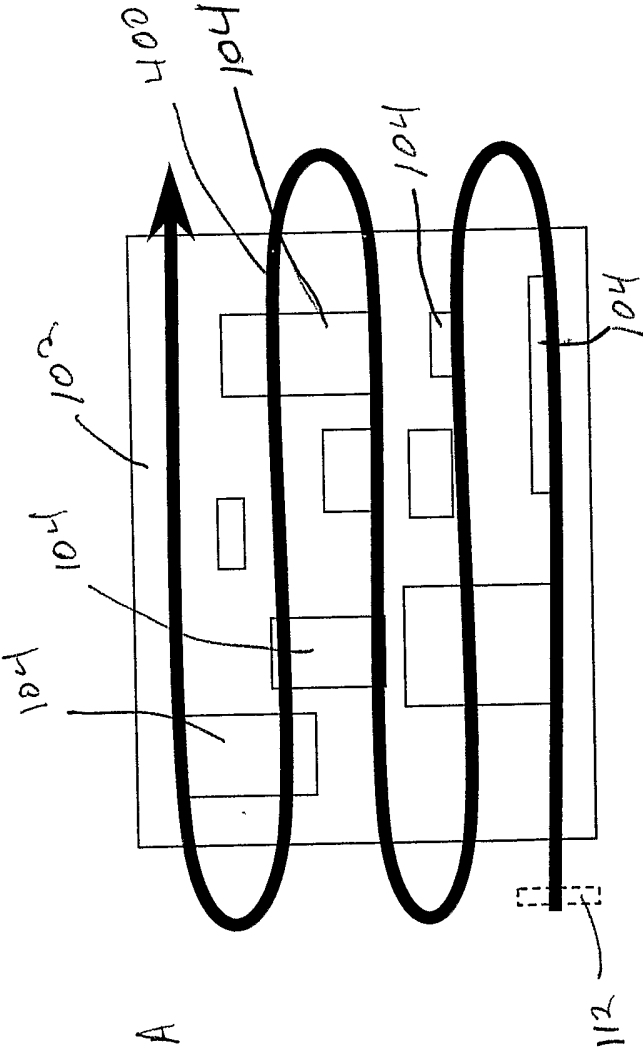


Figure 4A

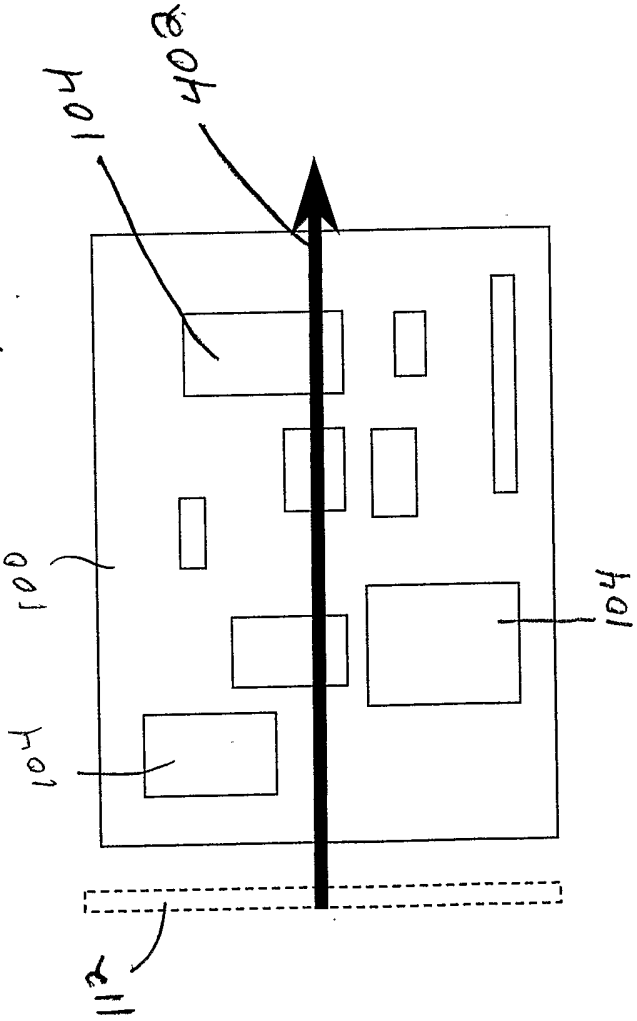
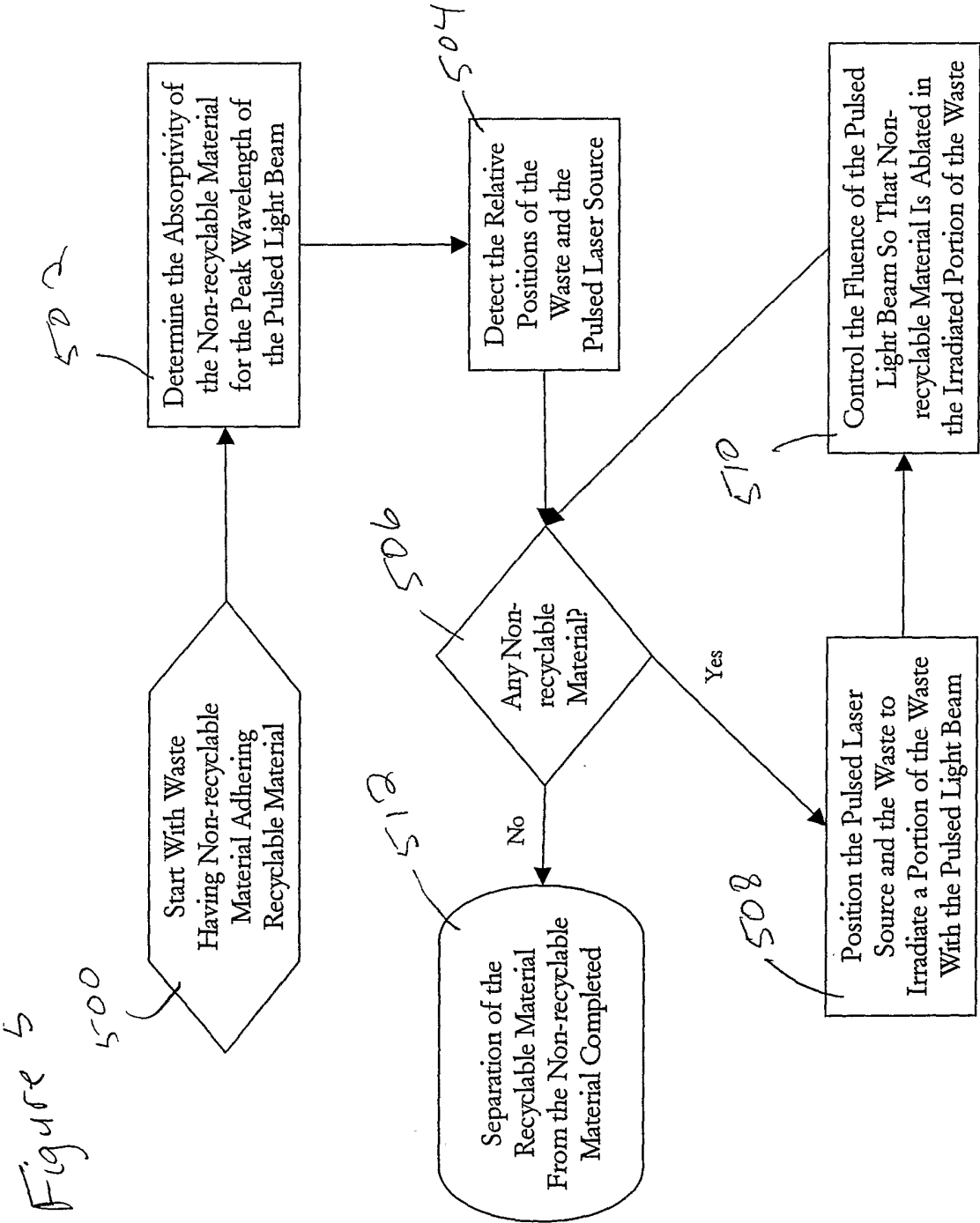


Figure 4B



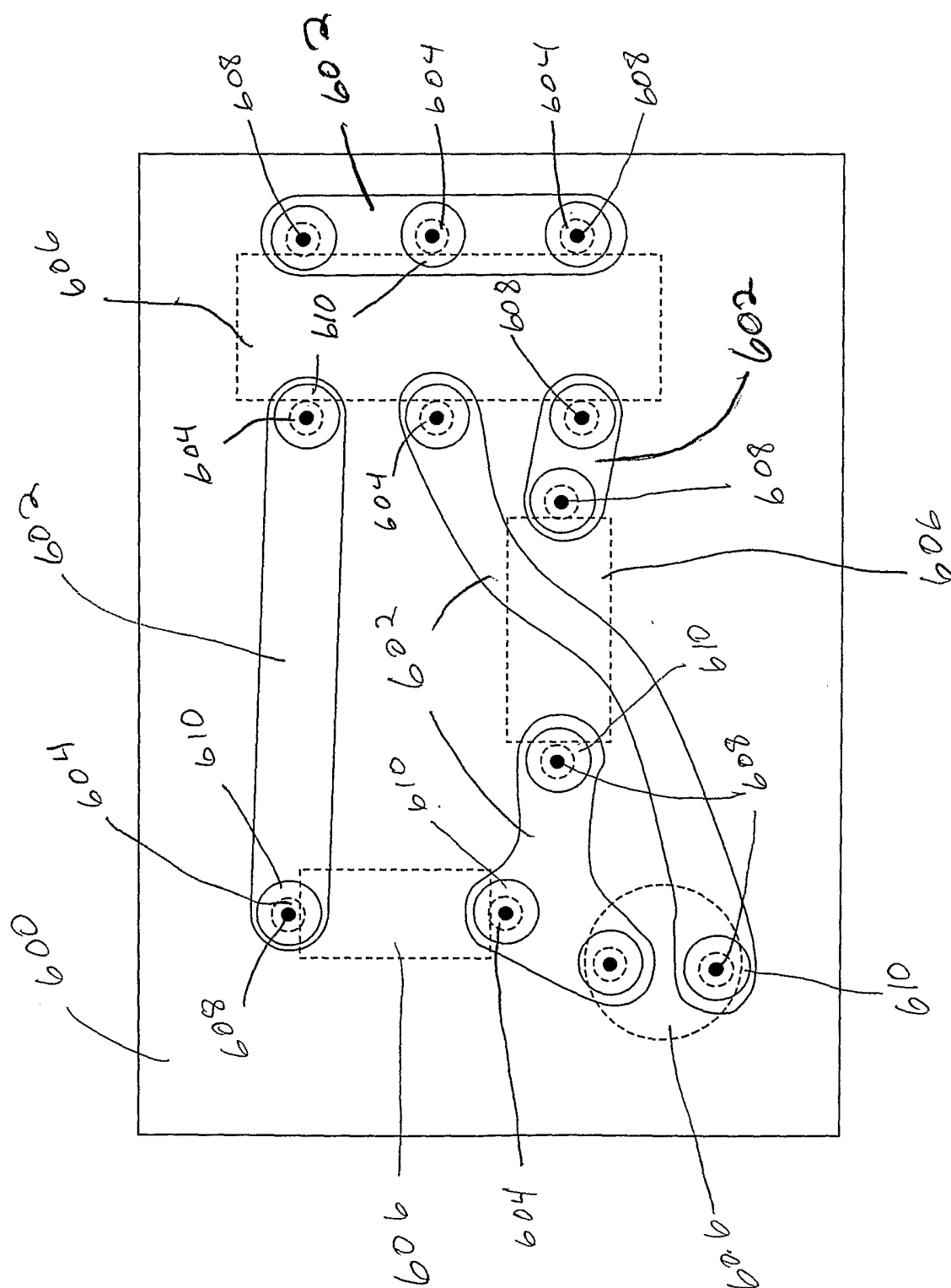


Fig 2

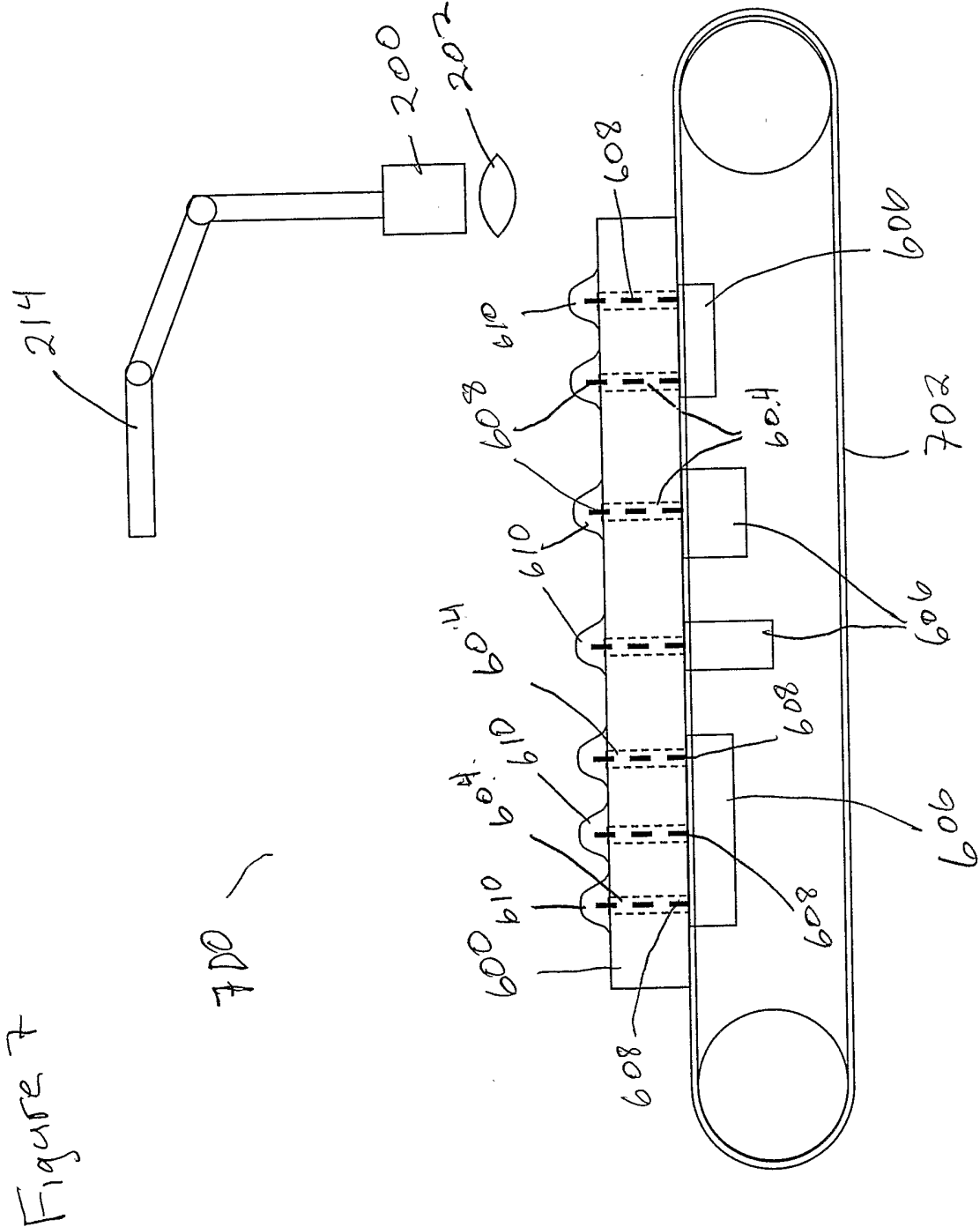


Figure 8

