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Laser Machining and Related Control For Additive Manufacturing

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Susan Davis Allen

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(54) LASER MACHINING AND RELATED CONTROL FOR ADDITIVE MANUFACTURING

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B33Y 30/00	(2006.01)
B33Y 50/02	(2006.01)

(52) **U.S. Cl.**

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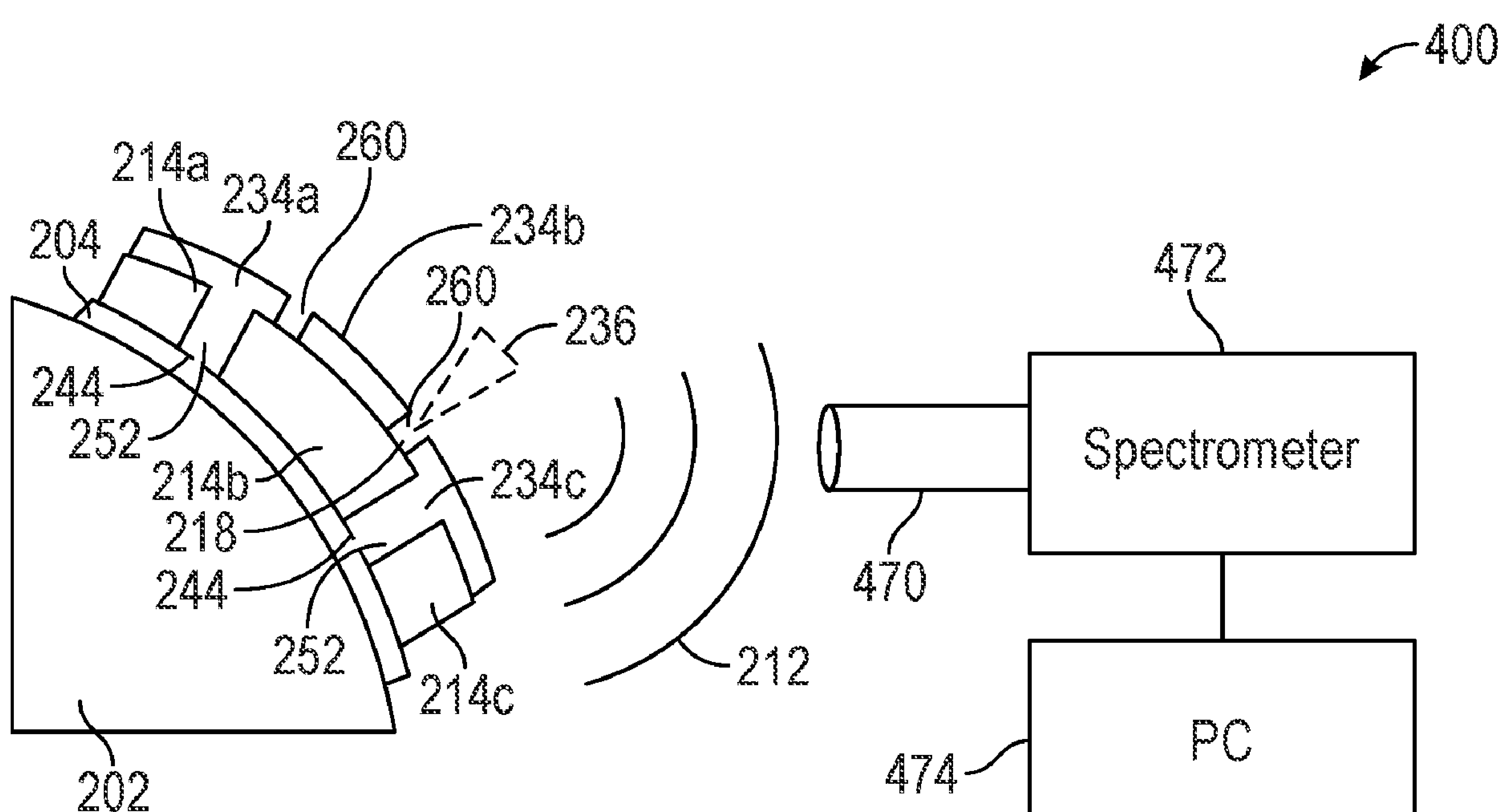
(57) **ABSTRACT**

Additive manufacturing can include use of a laser-machining technique. Laser machining can be used to form cavities, trenches, or other features in an additively-manufactured structure. Spectroscopy can be performed to monitor a laser machining operation. For example, a laser-enhanced additive manufacturing process flow can include depositing a conductive layer on a surface of a dielectric layer, and conductively isolating a first region from a second region of the conductive layer using ablative optical energy, including applying ablative optical energy to the conductive layer, monitoring a spectrum of an ablative plume generated by applying the ablative optical energy, and controlling the ablative optical energy in response to a characteristic of the spectrum of the ablative plume.



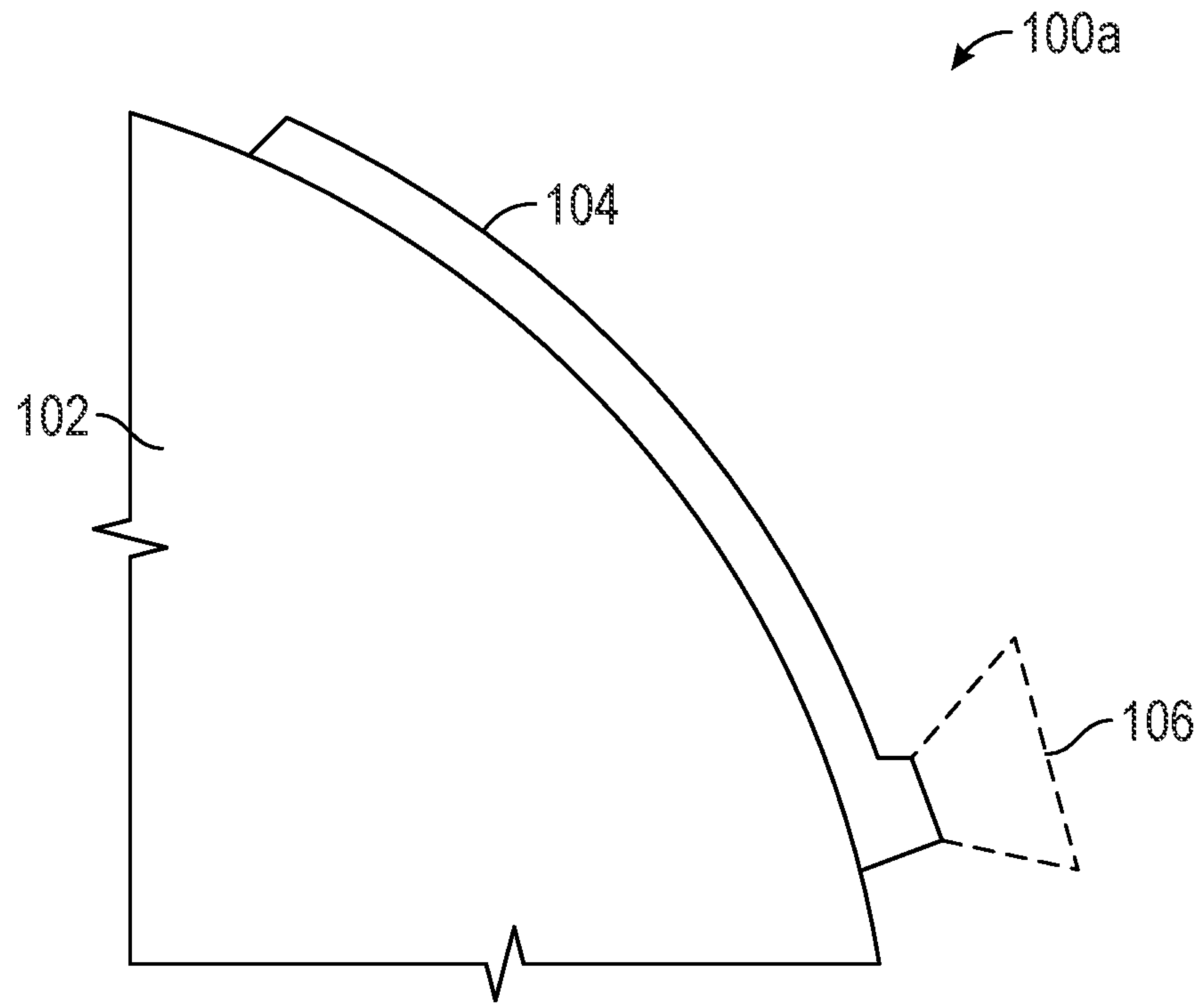


FIG. 1A

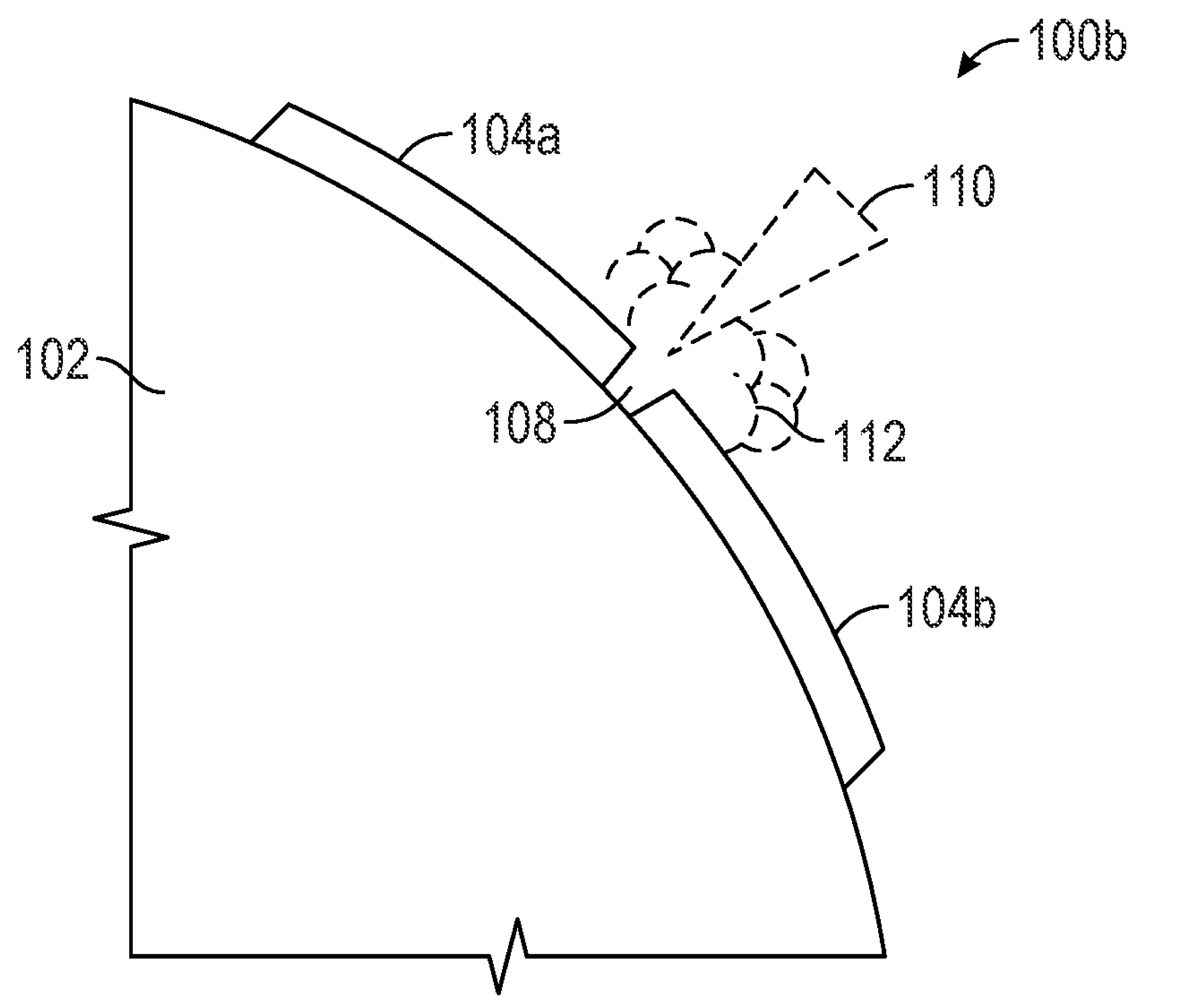


FIG. 1B

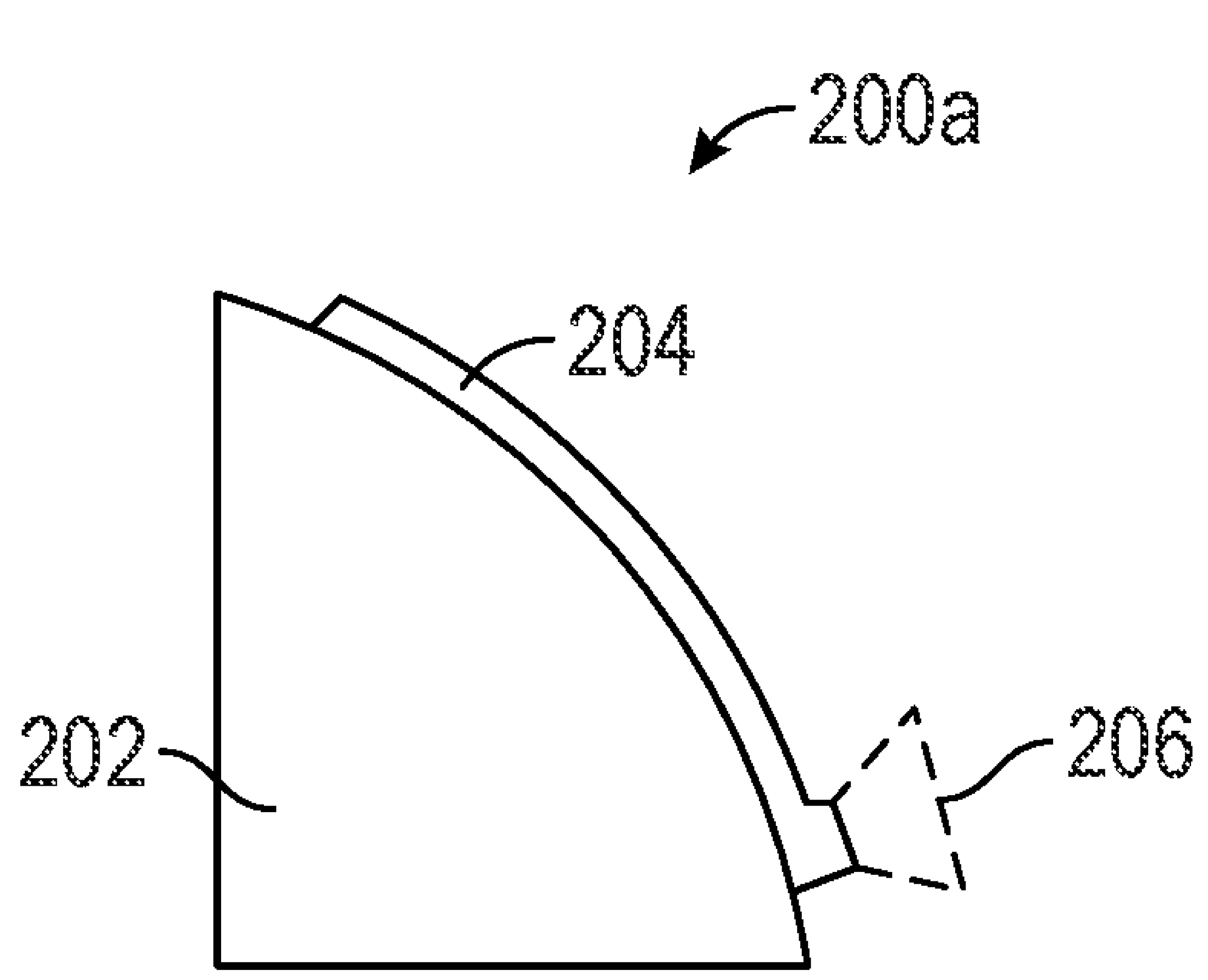


FIG. 2A

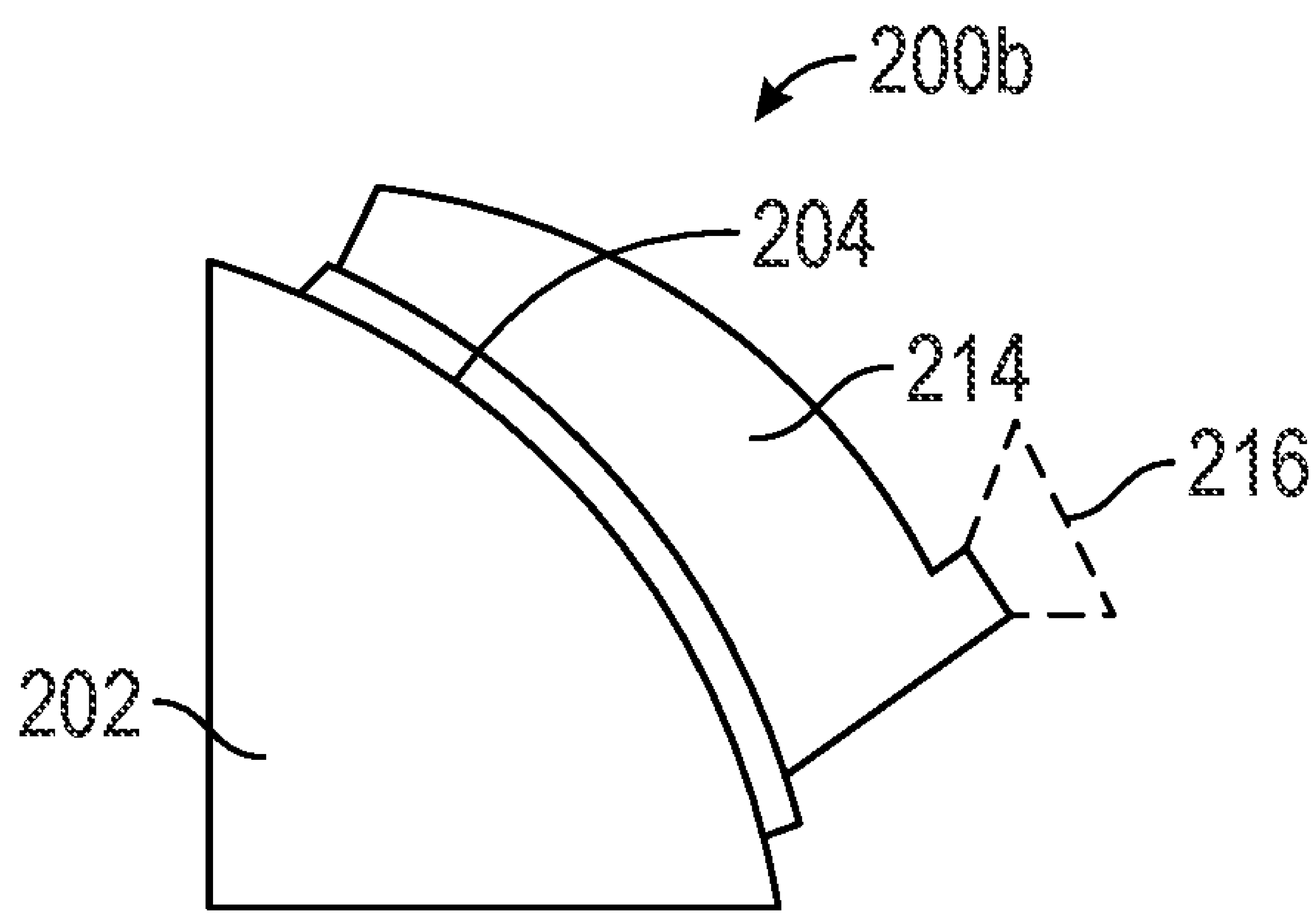


FIG. 2B

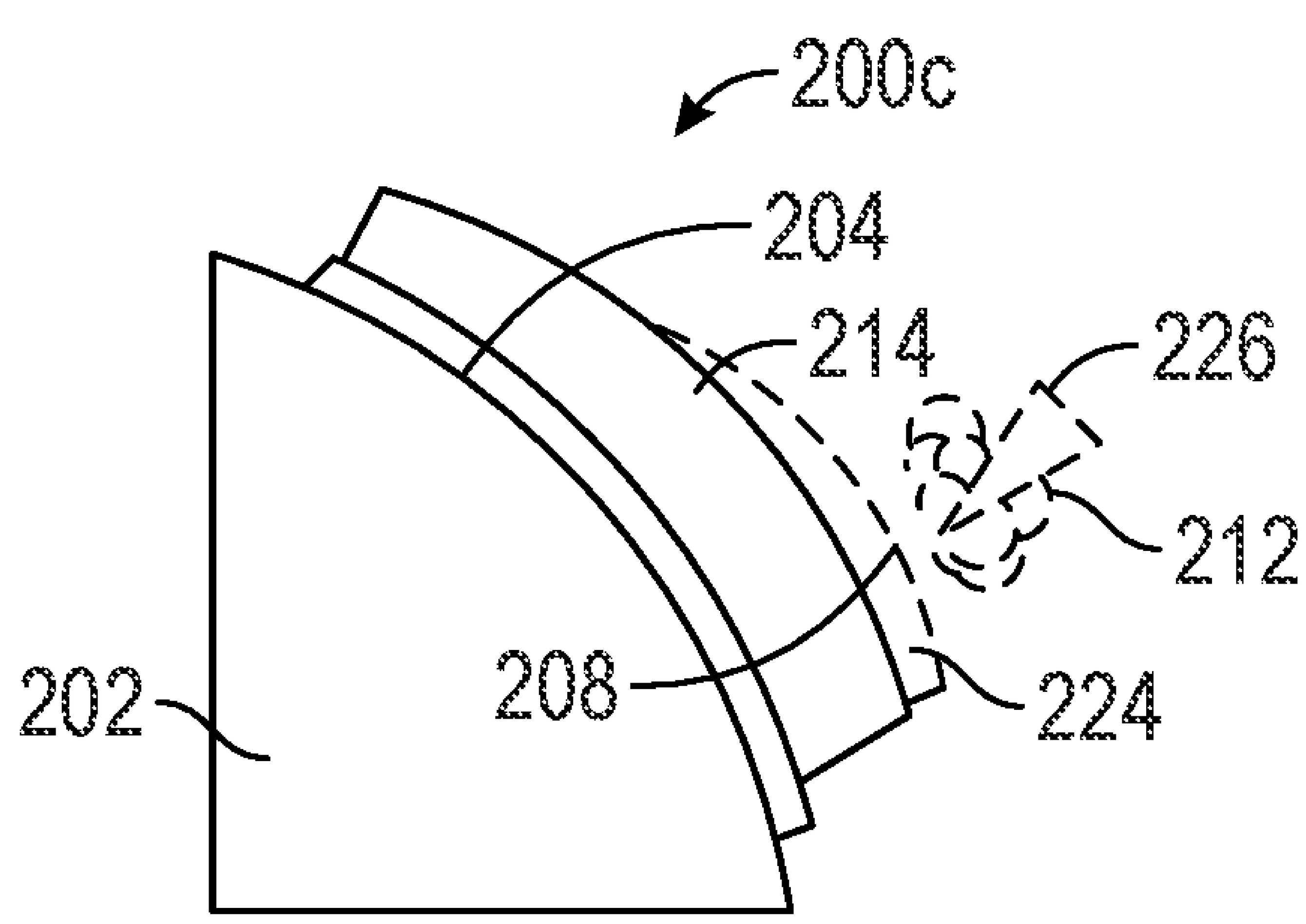


FIG. 2C

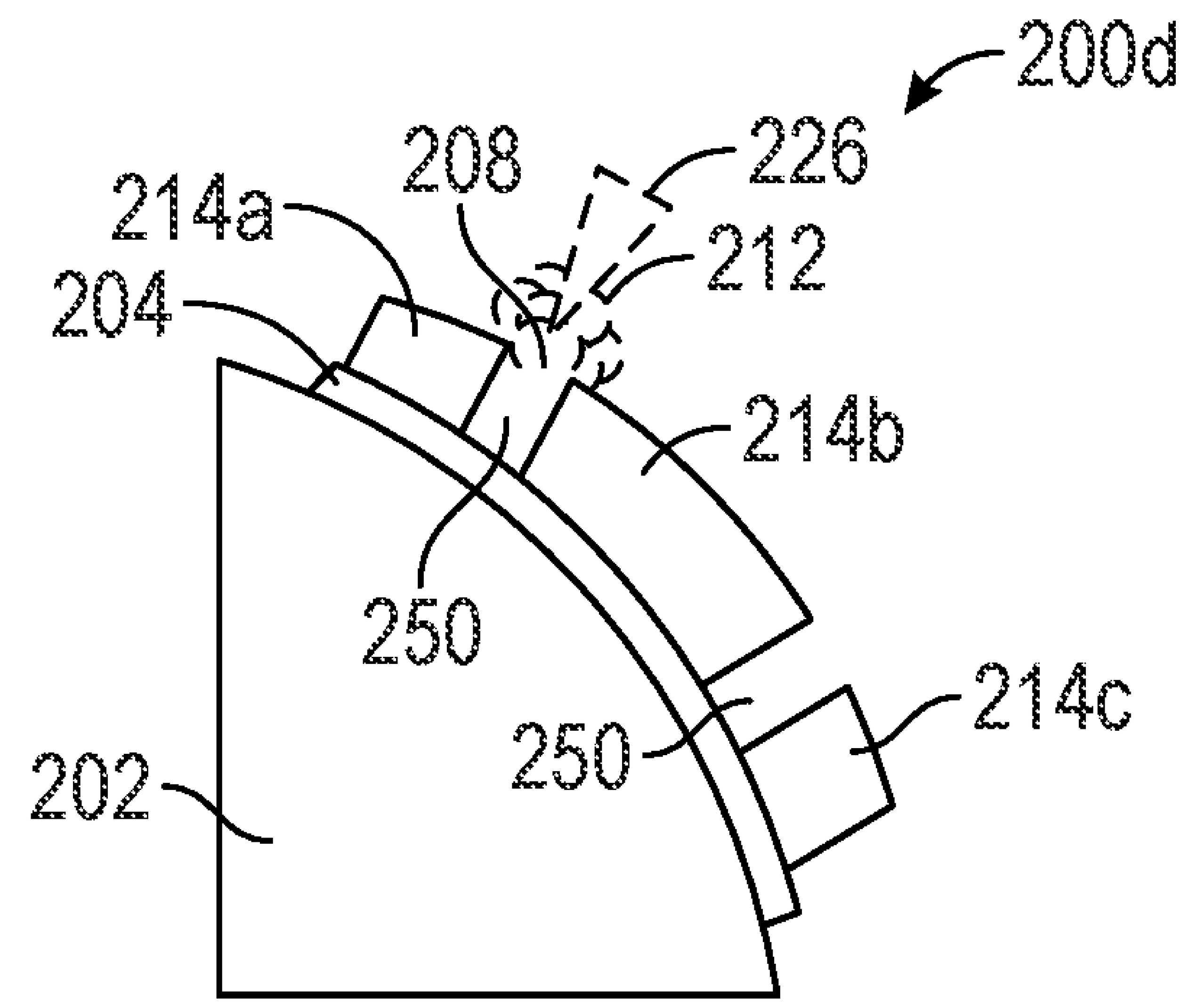


FIG. 2D

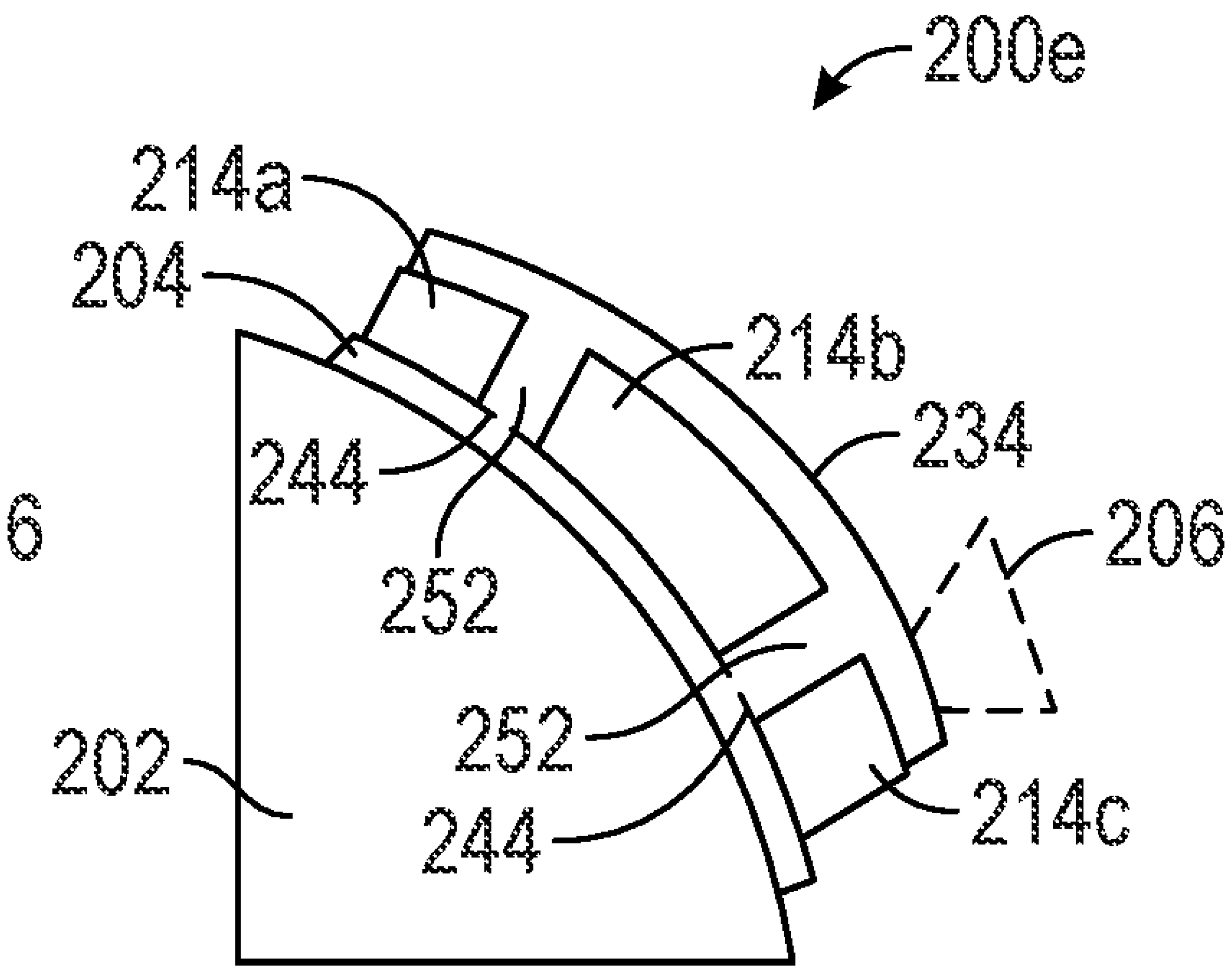


FIG. 2E

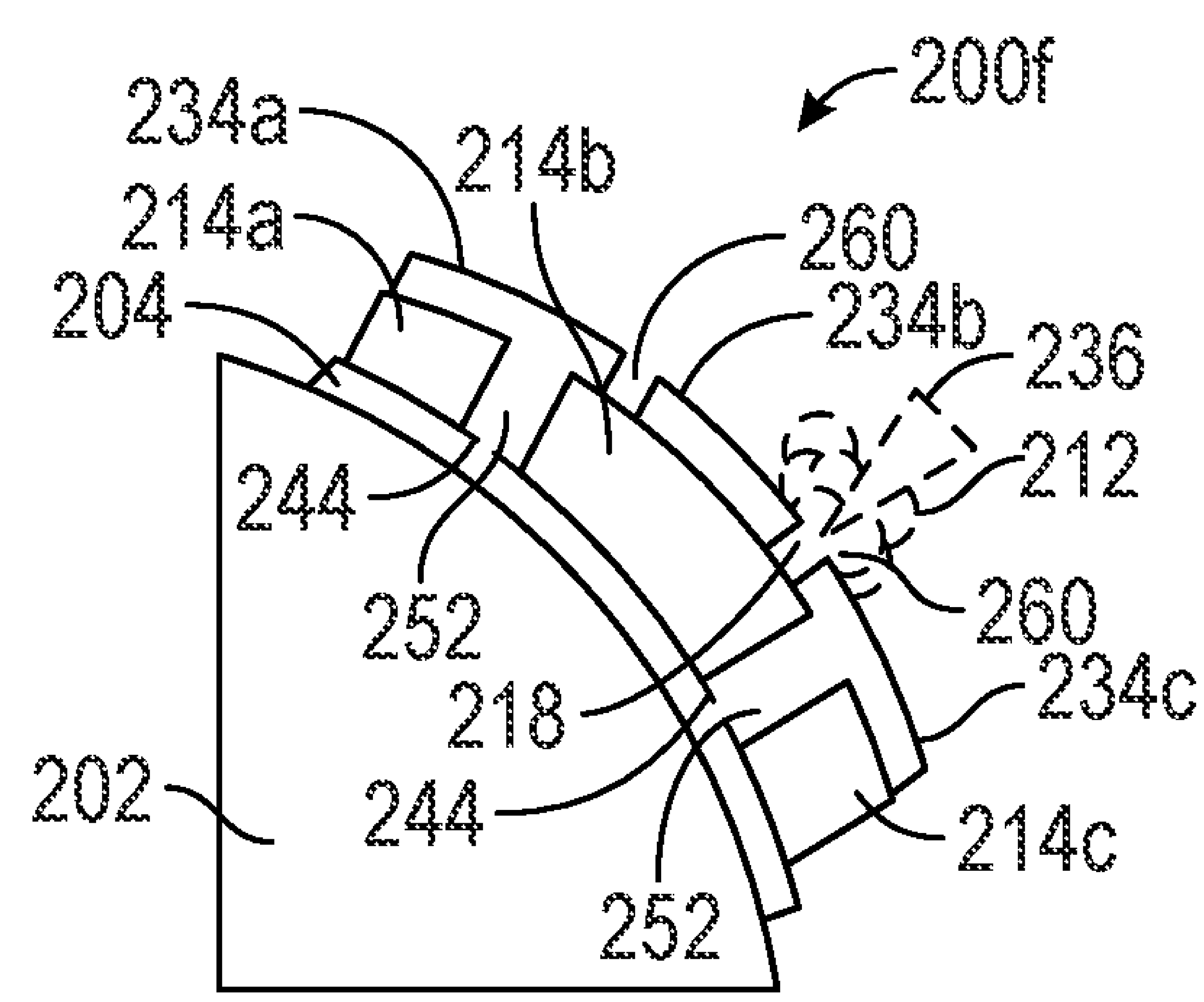


FIG. 2F

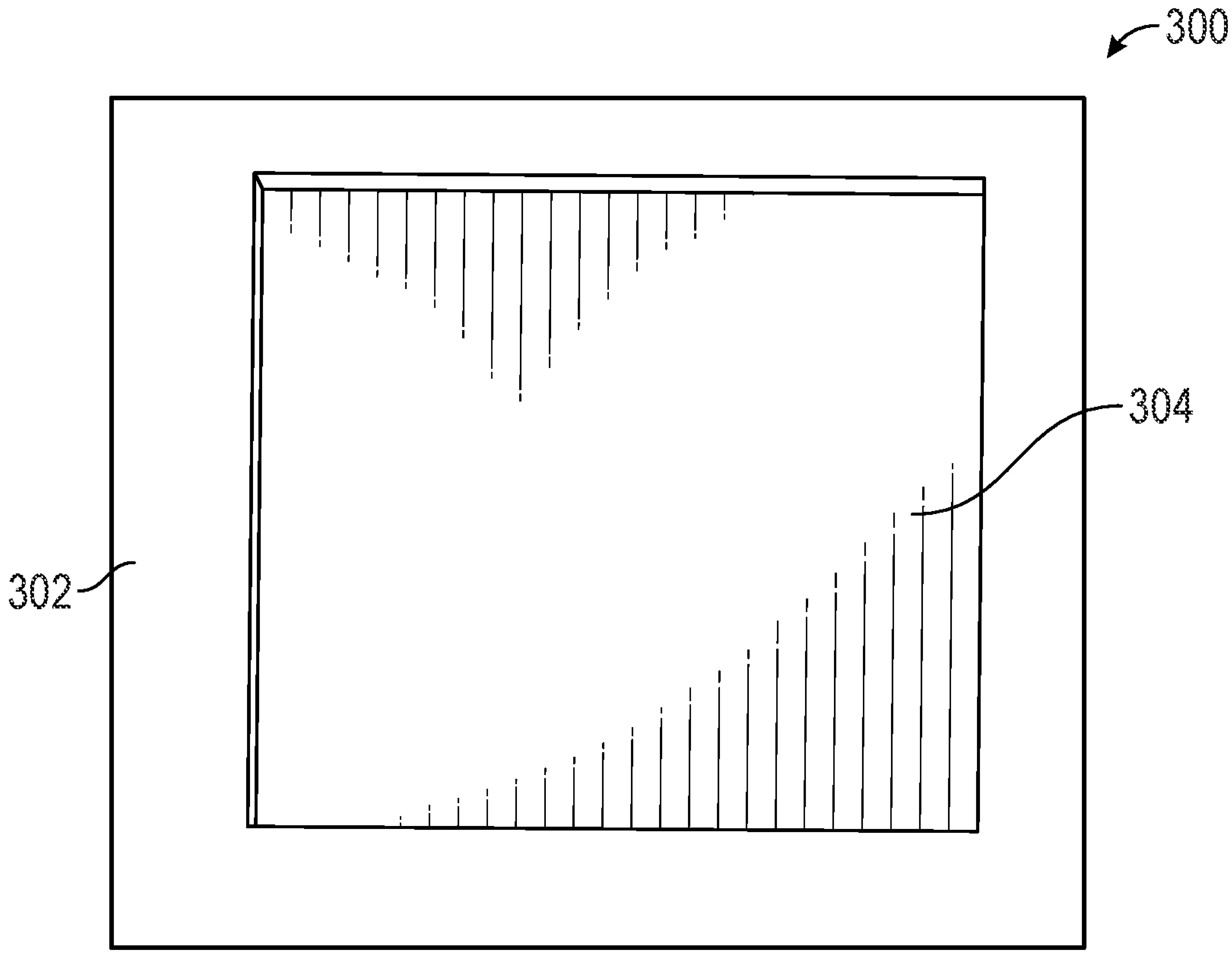

300
304
302

FIG. 3

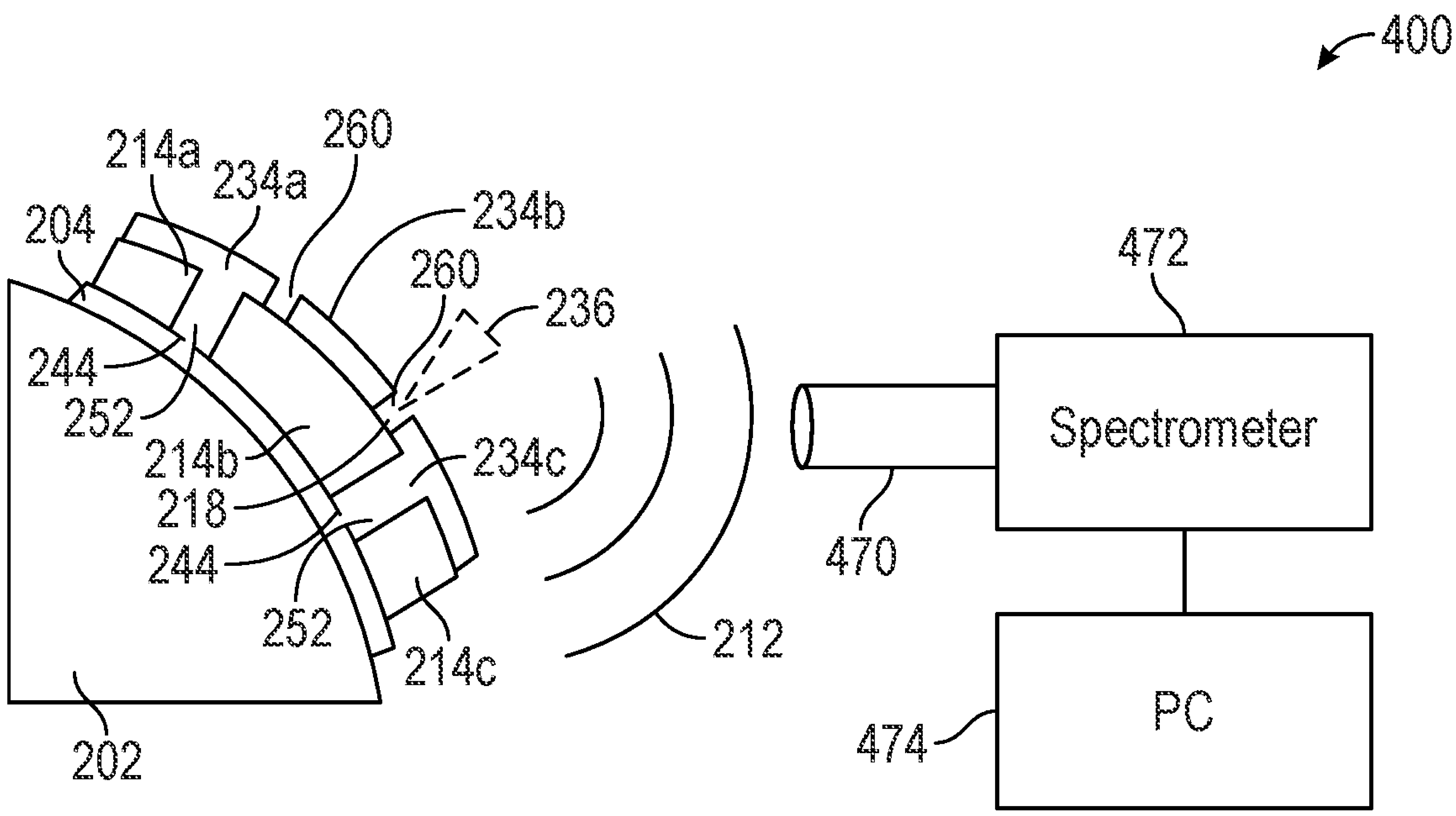

400
214a
260
234a
204
234b
260
236
472
244
252
214b
218
244
252
214c
202
234c
212
470
Spectrometer
PC
474

FIG. 4

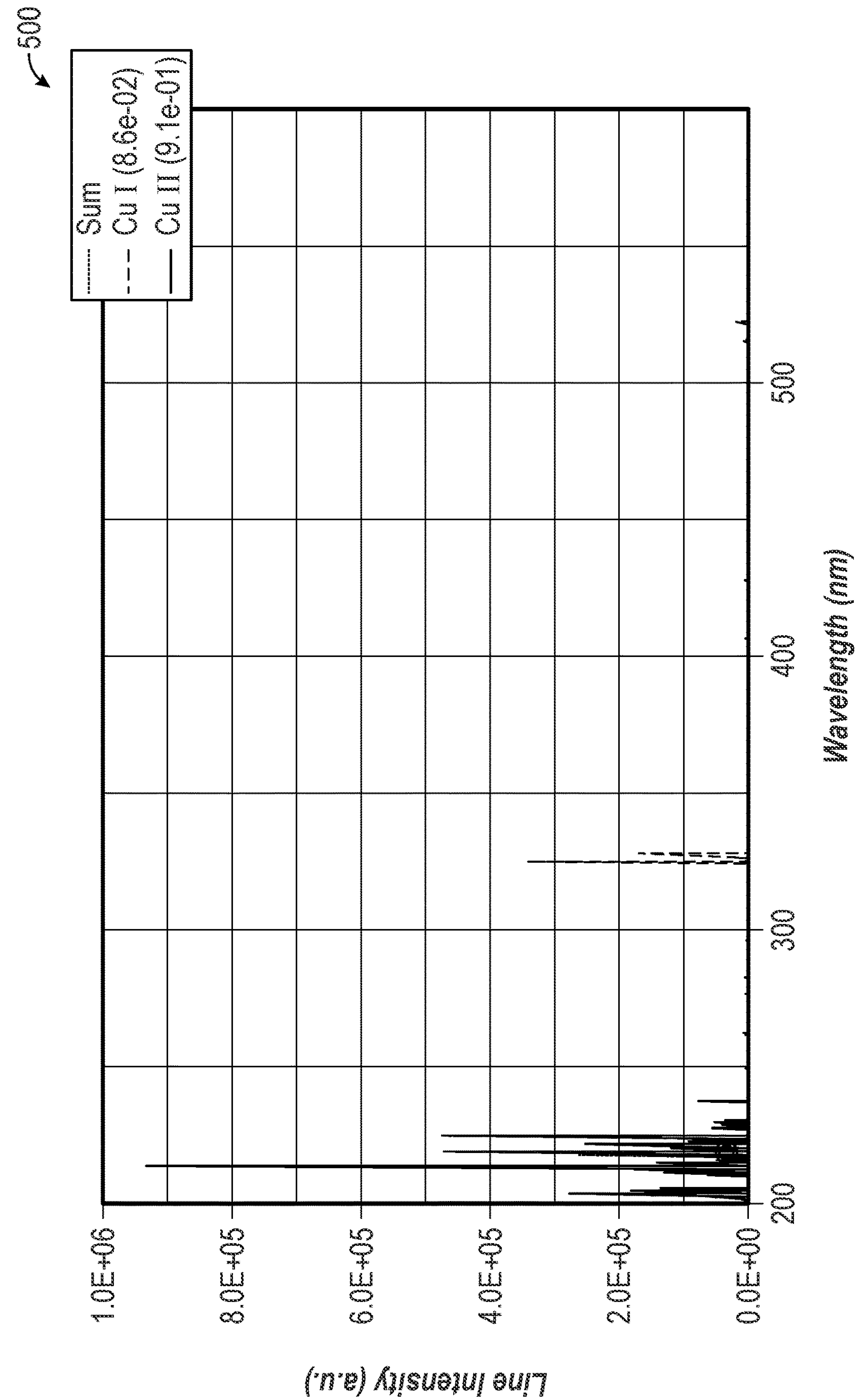

500
Sum
Cu I (8.6e-02)
Cu II (9.1e-01)
Line Intensity (a.u.)
1.0E+06
8.0E+05
6.0E+05
4.0E+05
2.0E+05
0.0E+00
200
300
400
500
Wavelength (nm)

FIG. 5

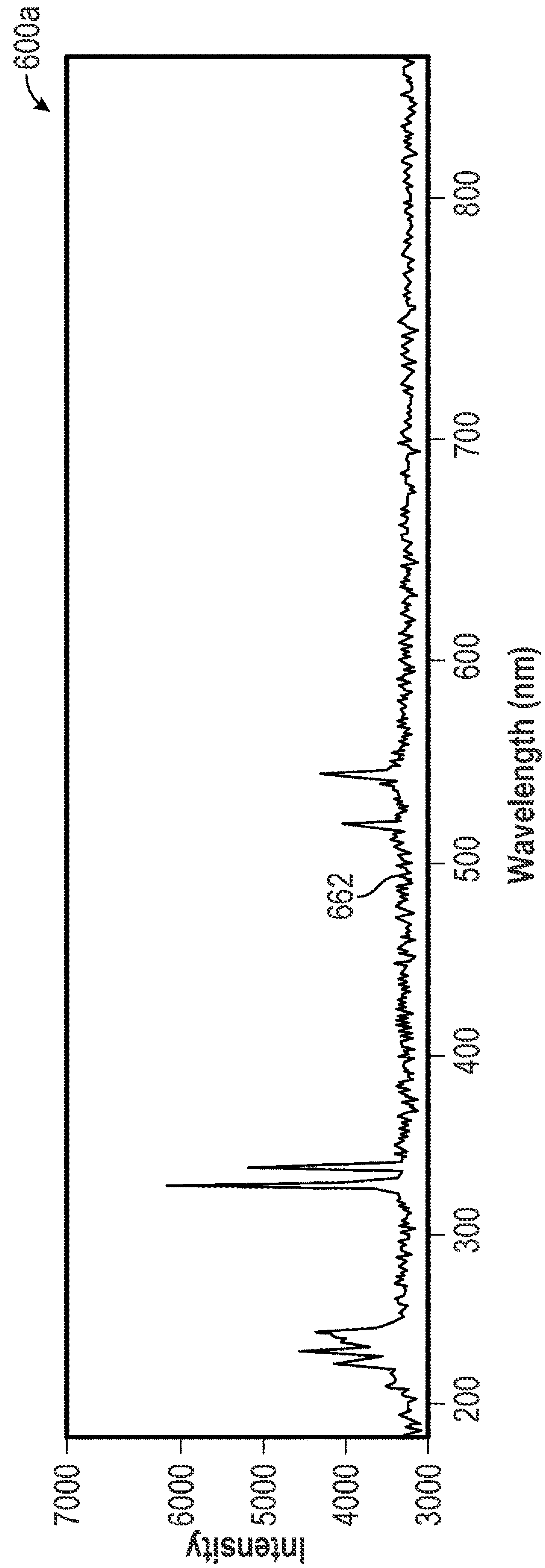

600a
662
Wavelength (nm)
Intensity
7000
6000
5000
4000
3000
200
300
400
500
600
700
800

FIG. 6A

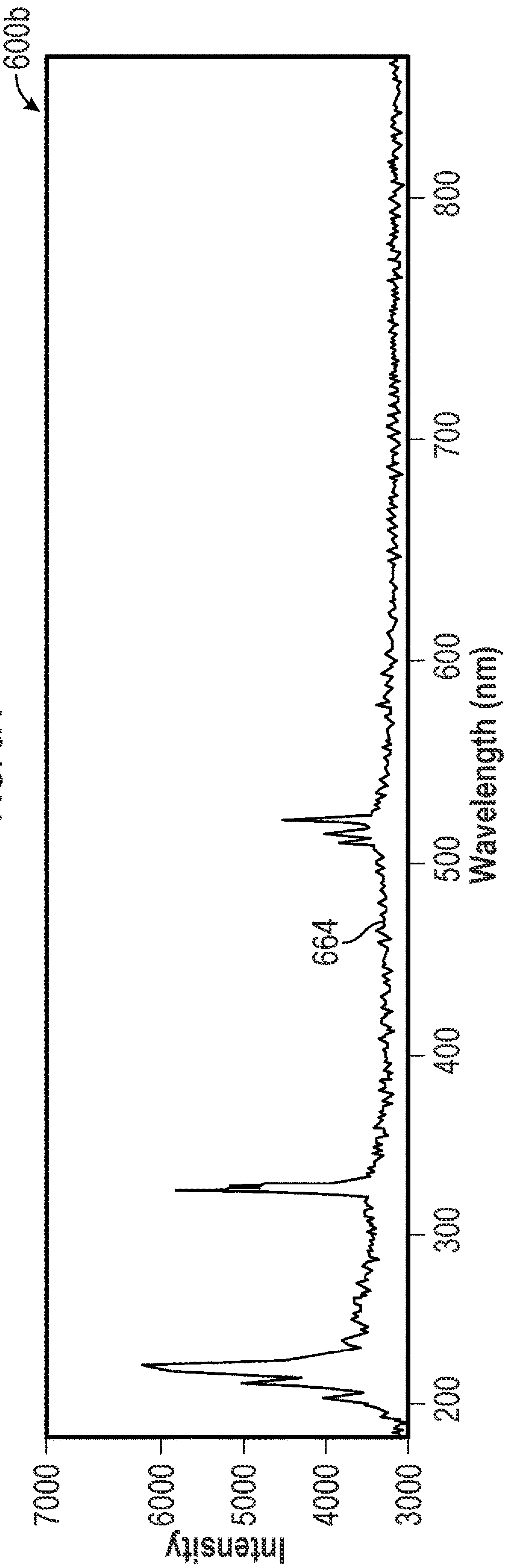

600b
664
Wavelength (nm)
Intensity
7000
6000
5000
4000
3000
200
300
400
500
600
700
800

FIG. 6B

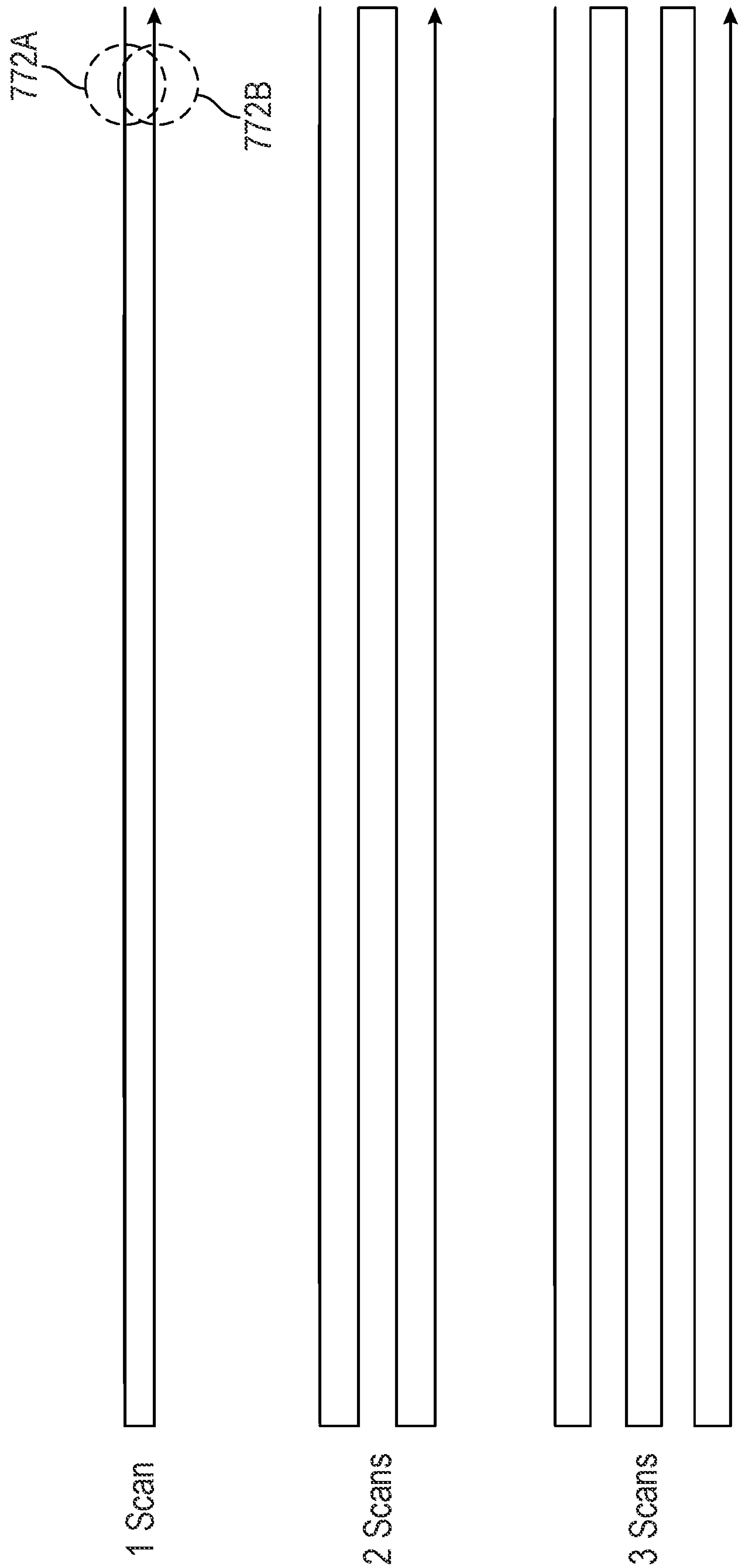


FIG. 7

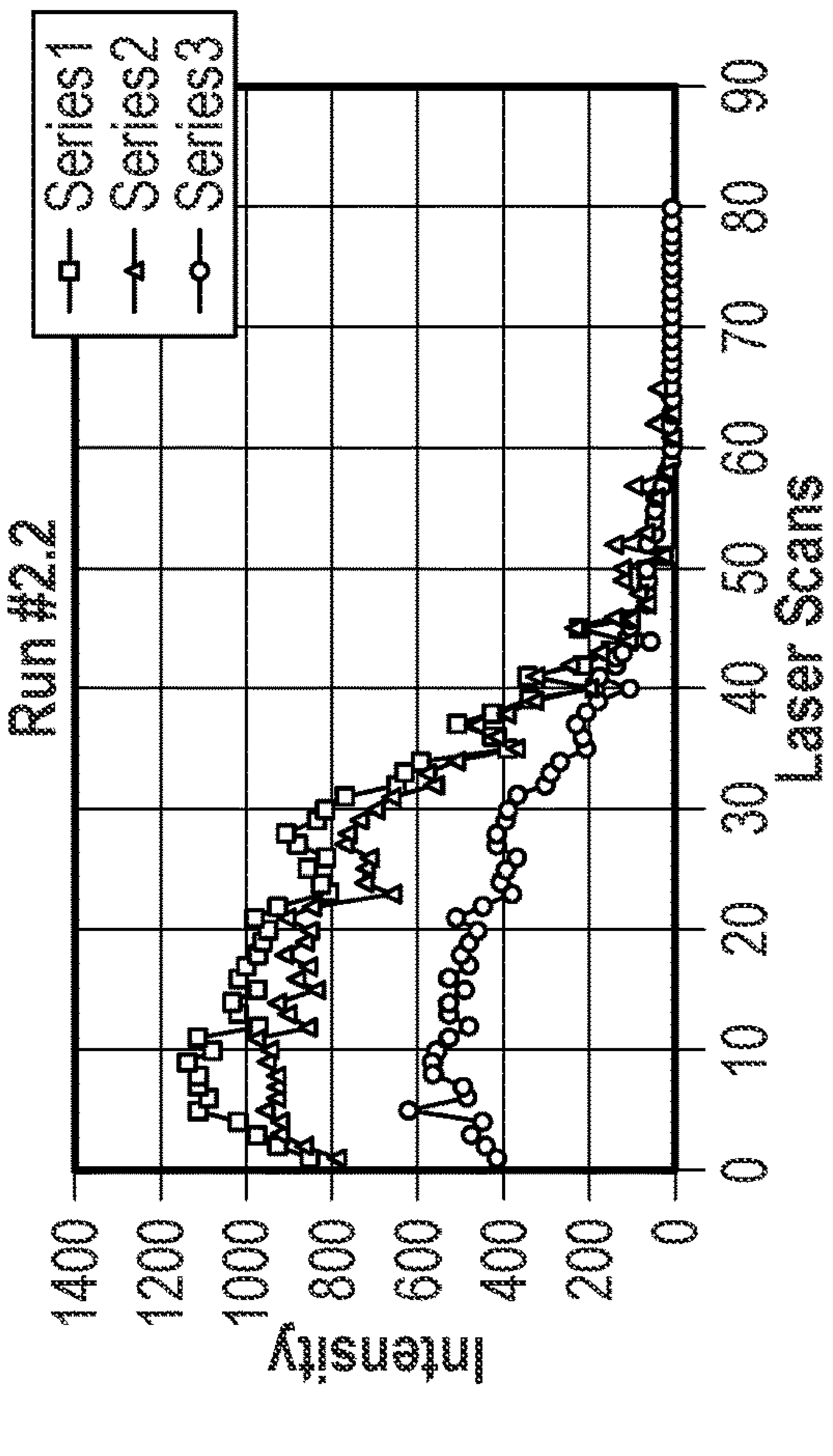


FIG. 8A

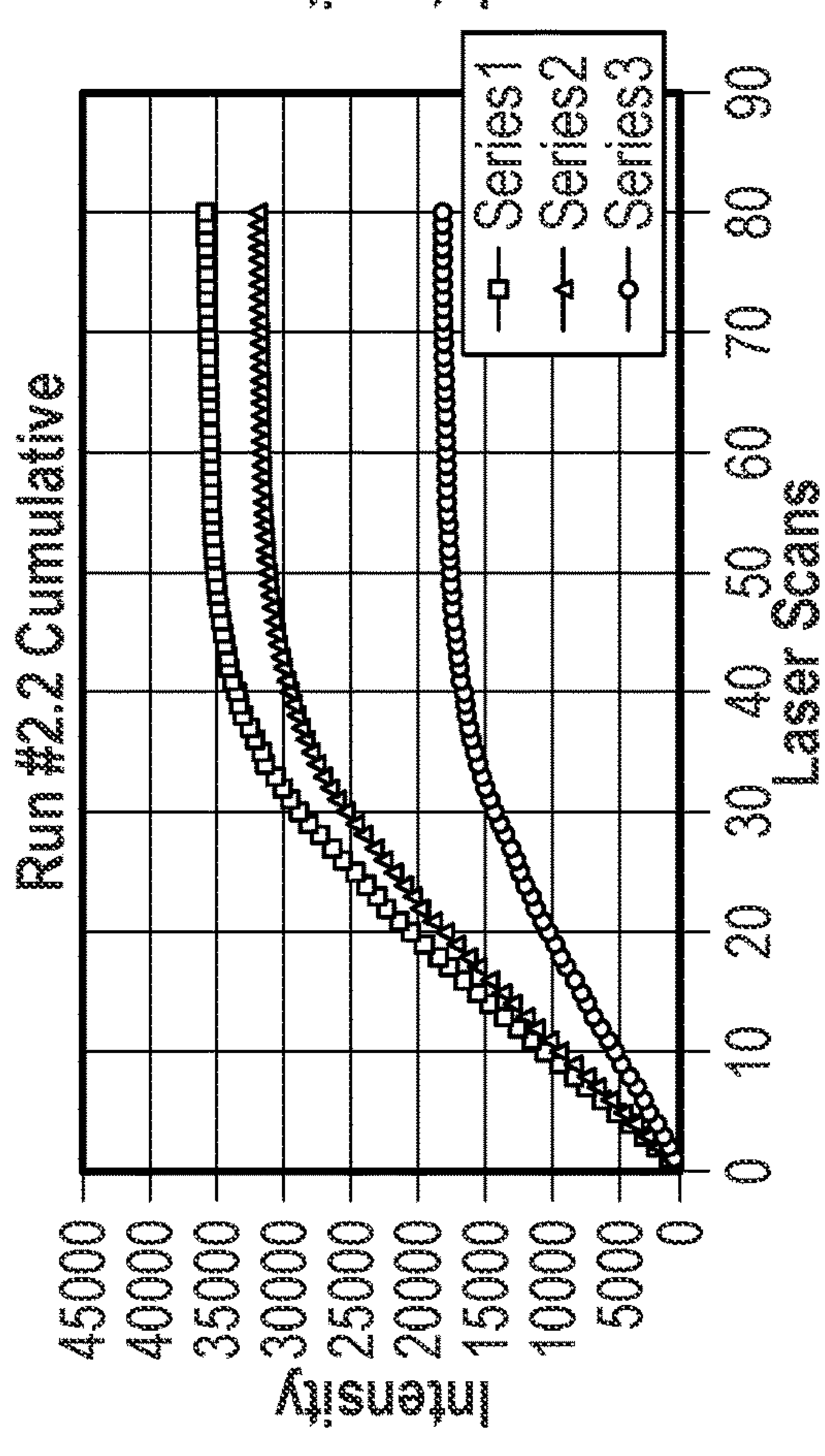


FIG. 8B

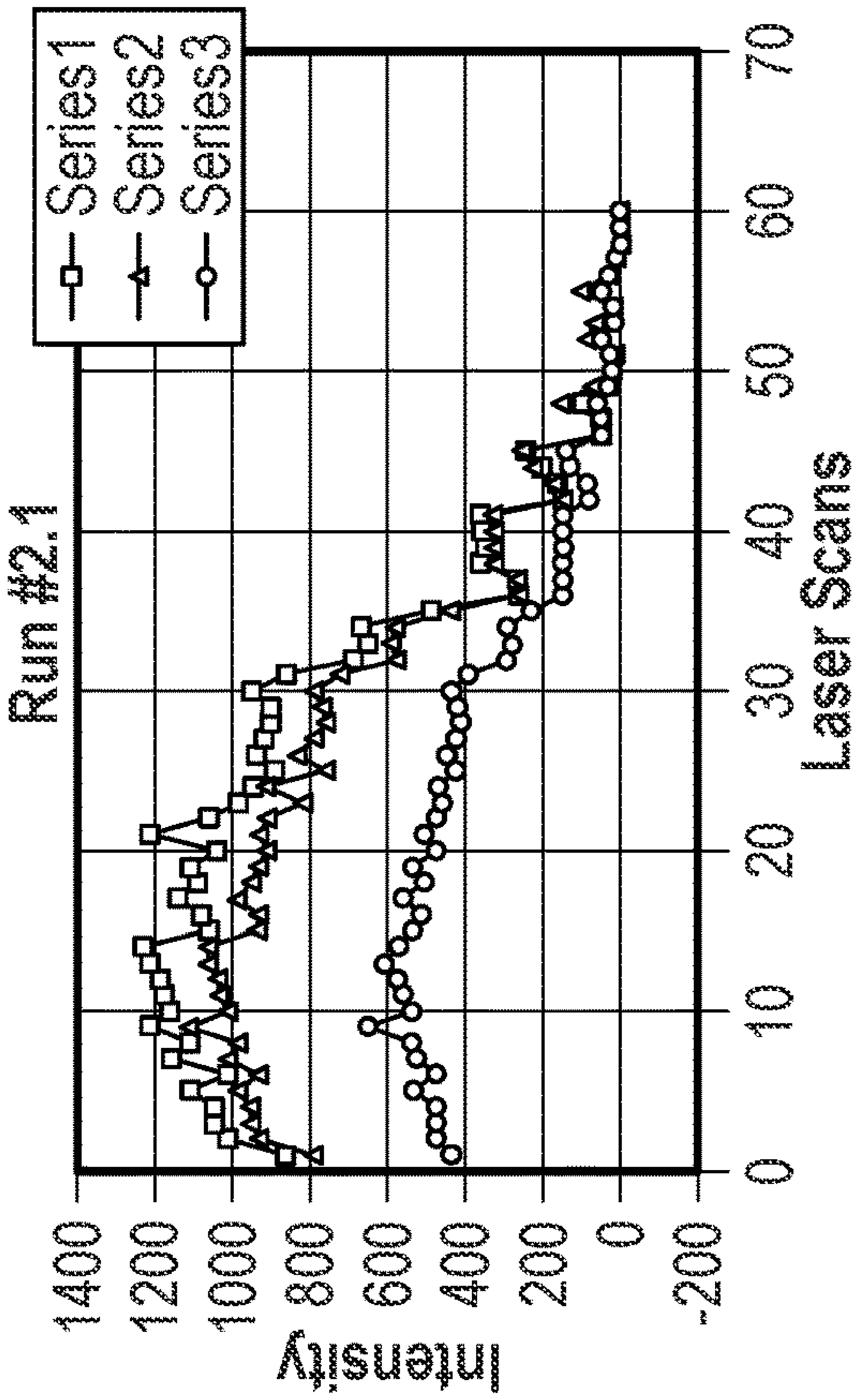


FIG. 8C

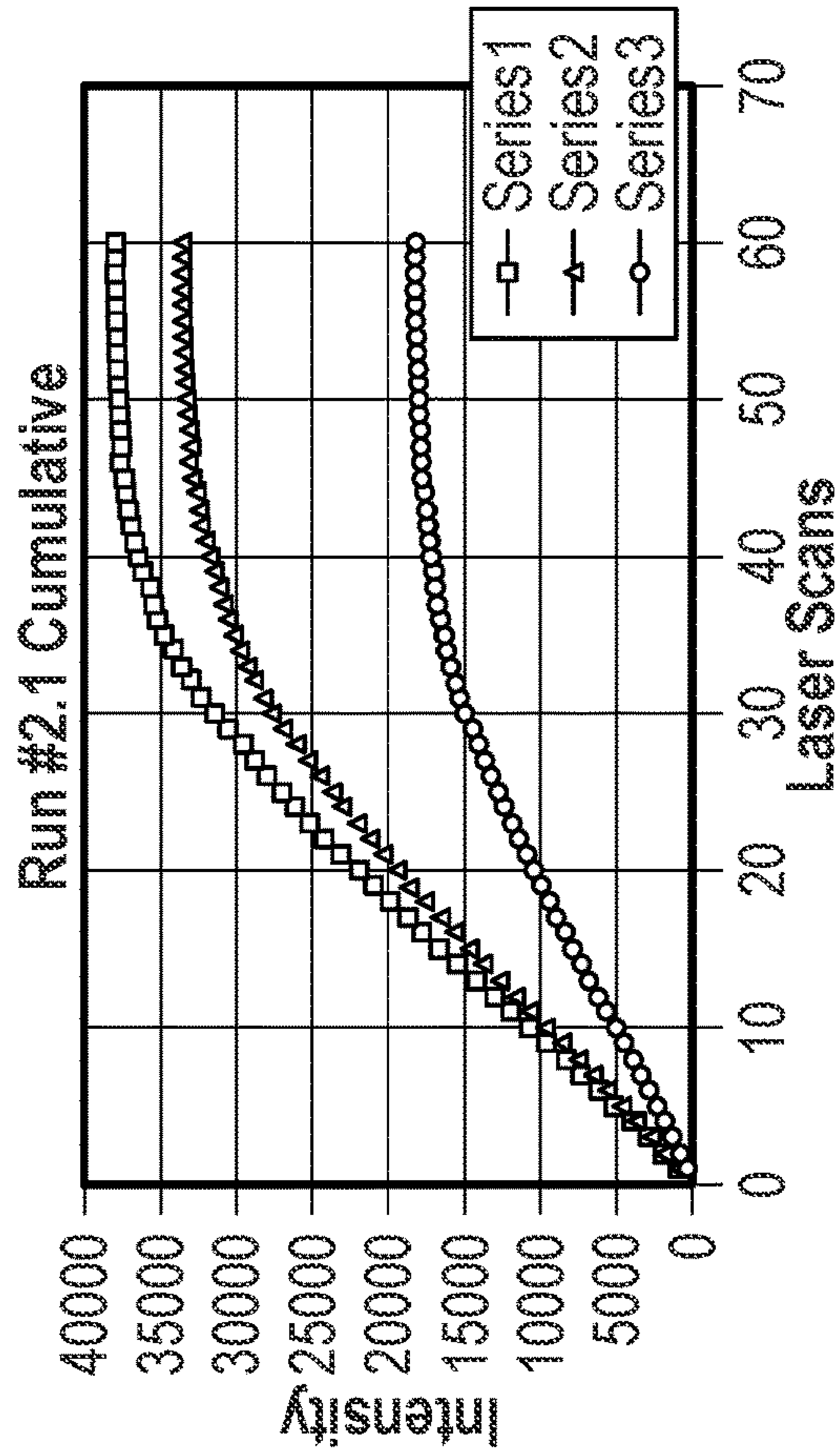


FIG. 8D

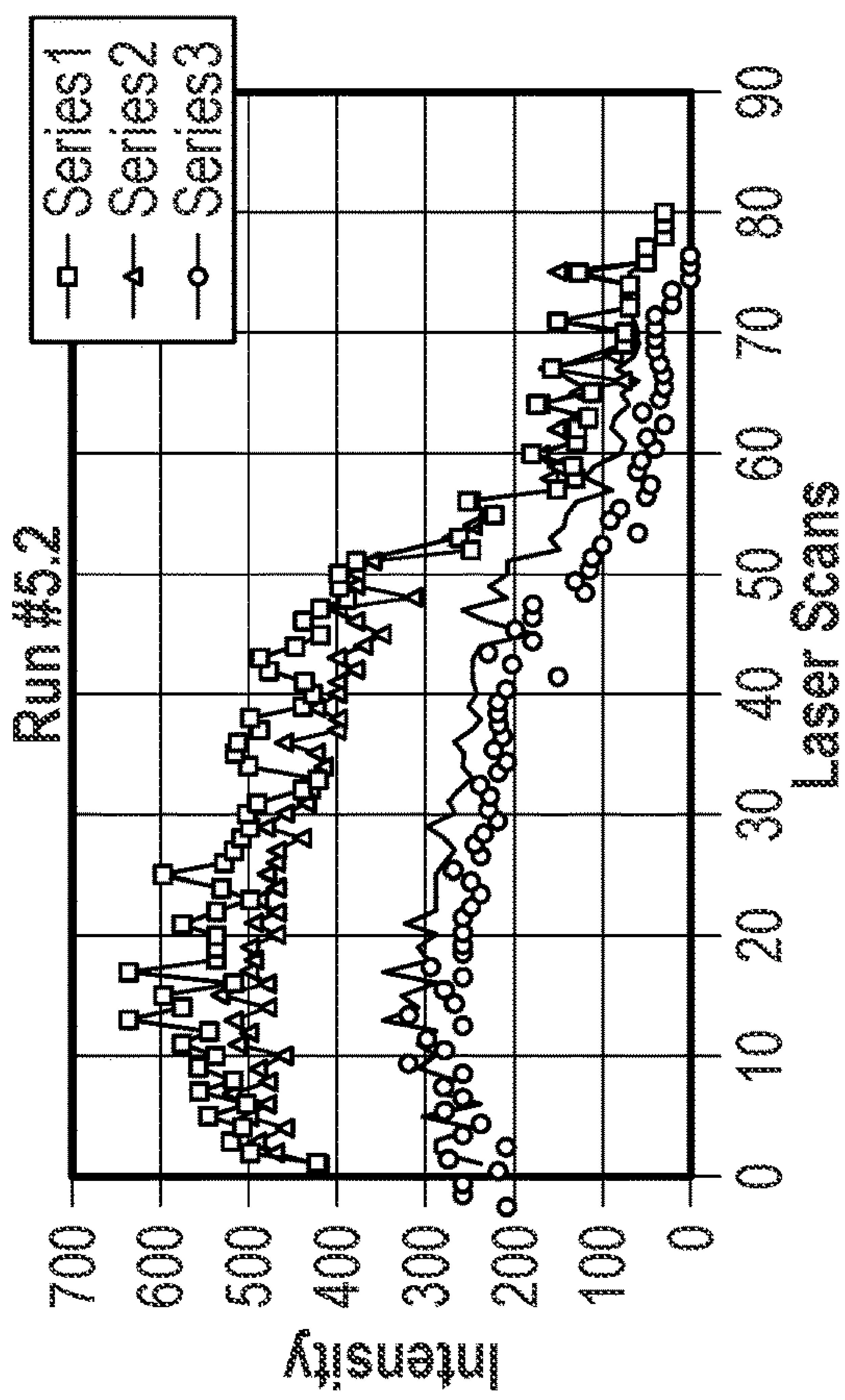


FIG. 9A

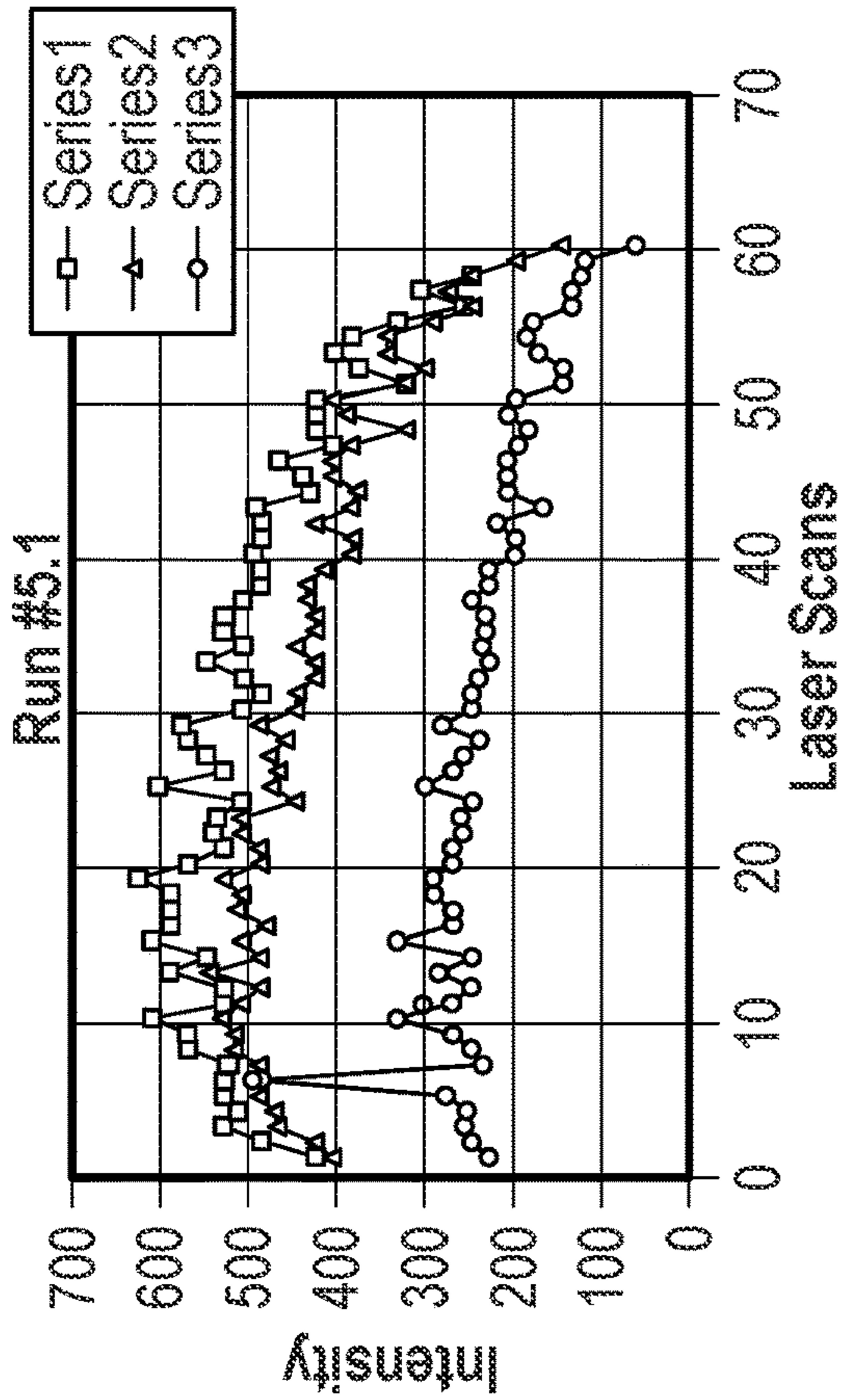


FIG. 9C

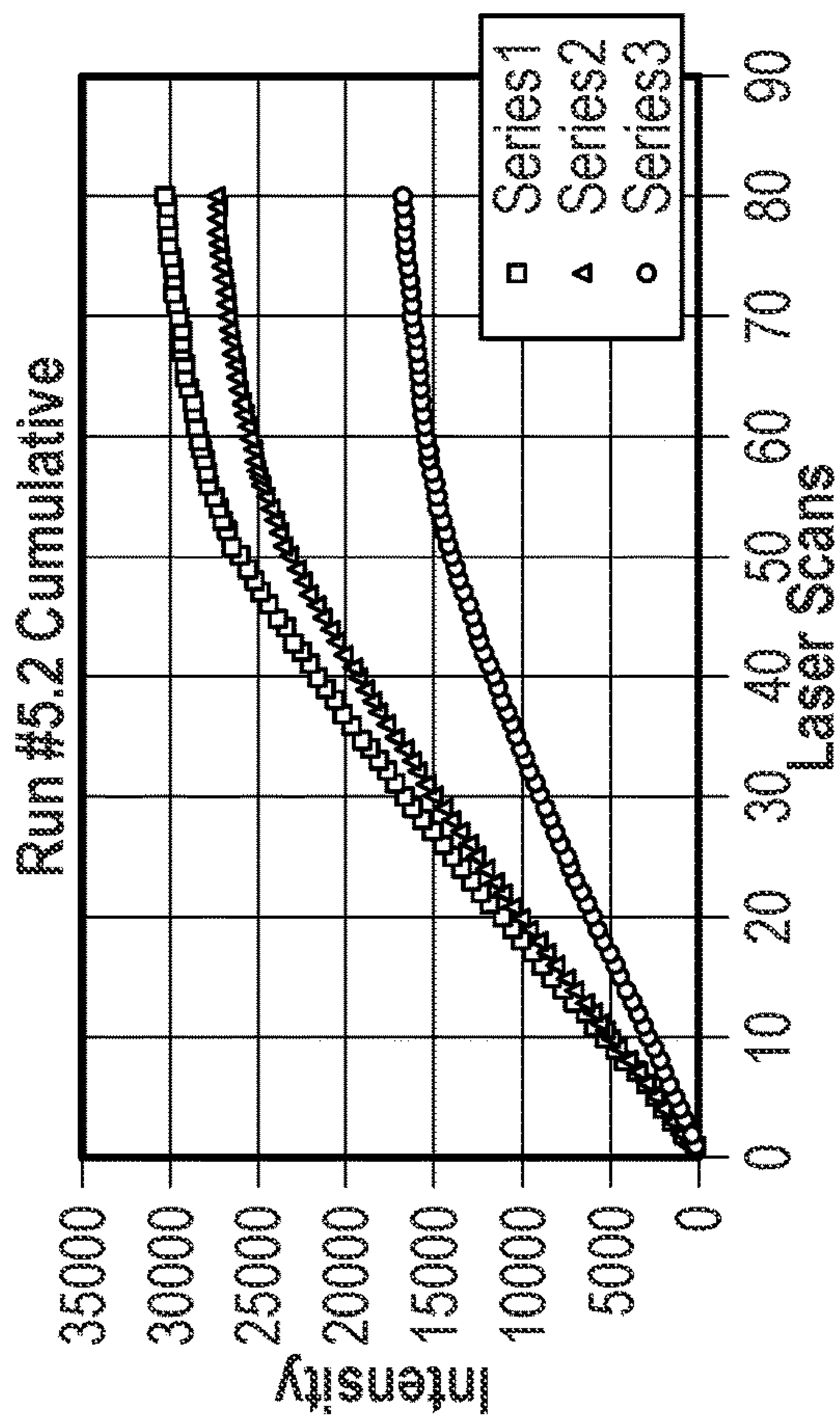


FIG. 9B

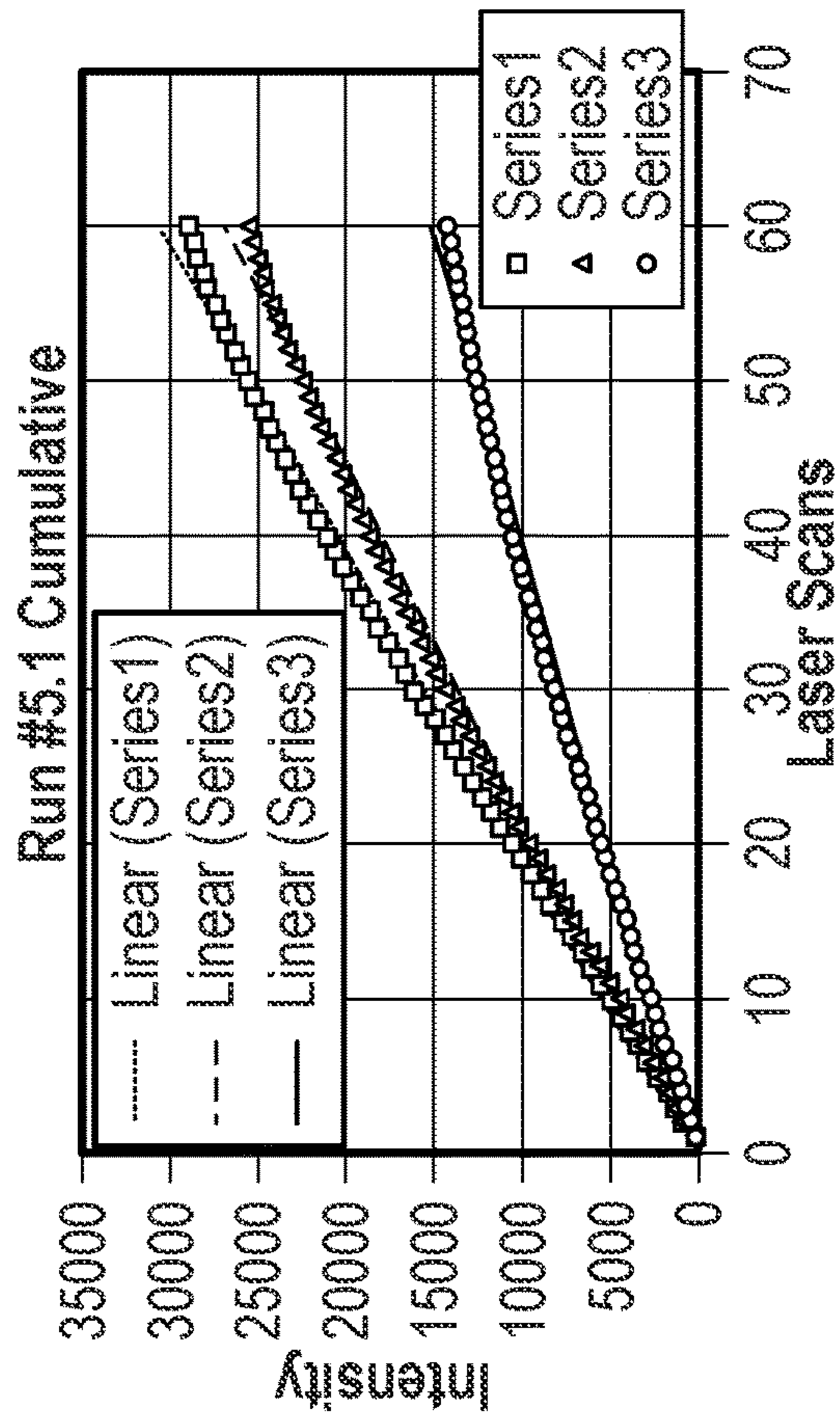


FIG. 9D

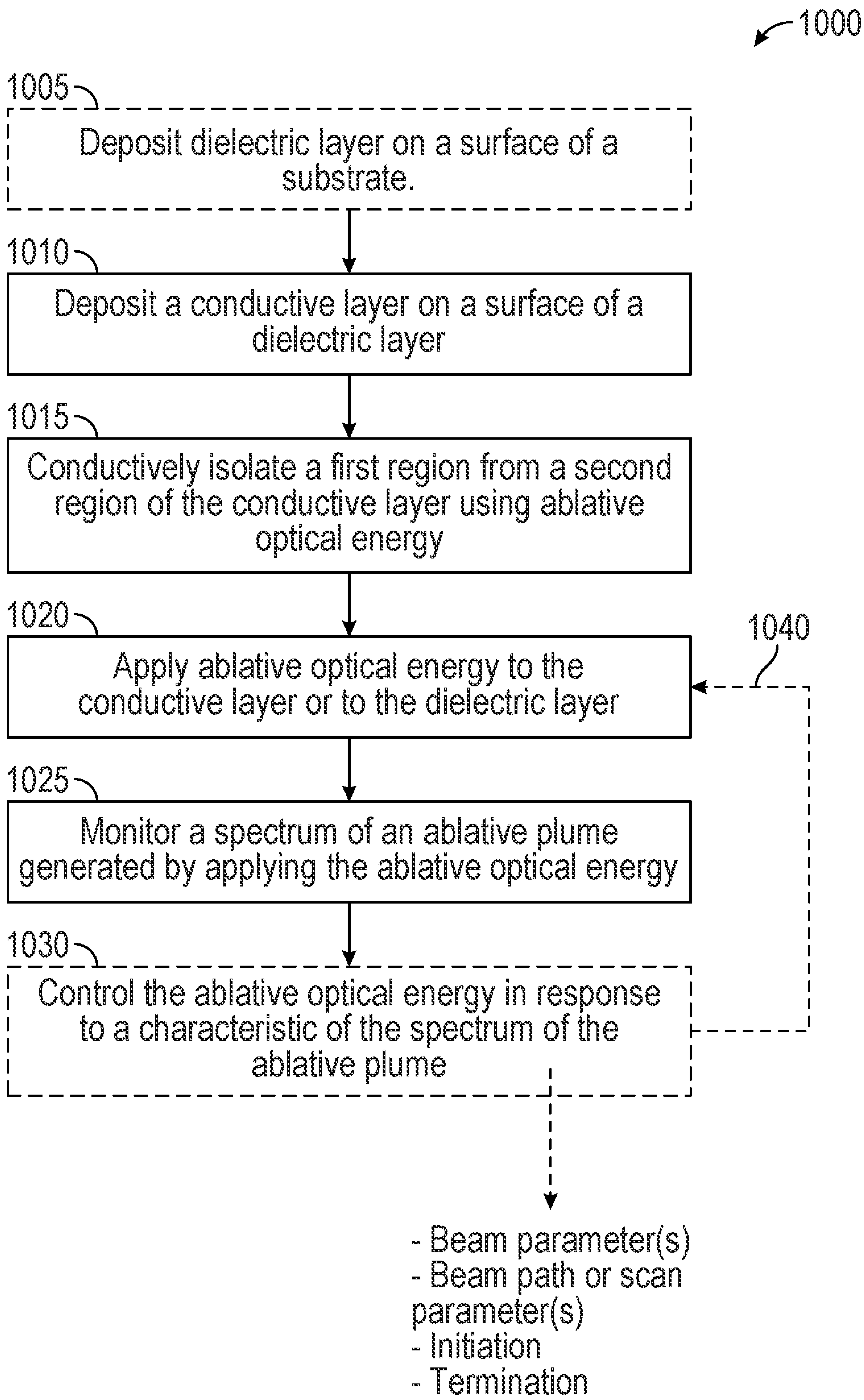

1000
1005
Deposit dielectric layer on a surface of a substrate.
1010
Deposit a conductive layer on a surface of a dielectric layer
1015
Conductively isolate a first region from a second region of the conductive layer using ablative optical energy
1020
Apply ablative optical energy to the conductive layer or to the dielectric layer
1040
1025
Monitor a spectrum of an ablative plume generated by applying the ablative optical energy
1030
Control the ablative optical energy in response to a characteristic of the spectrum of the ablative plume
- Beam parameter(s)
- Beam path or scan parameter(s)
- Initiation
- Termination

FIG. 10

LASER MACHINING AND RELATED CONTROL FOR ADDITIVE MANUFACTURING

CLAIM OF PRIORITY

[0001] This patent application claims the benefit of priority of Rojas et al., U.S. Provisional Patent Application Ser. No. 63/270,903, titled "LASER MACHINING AND RELATED CONTROL FOR ADDITIVE MANUFACTURING," filed on Oct. 22, 2021 (Attorney Docket No. 4568.013PRV), which is hereby incorporated by reference herein in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] This invention was made with government support under award number 1944599 awarded by the National Science Foundation. The government has certain rights in the invention.

FIELD OF THE DISCLOSURE

[0003] This document pertains generally, but not by way of limitation, to additive manufacturing of electrical structures, and more particularly to techniques for performing and monitoring laser machining of portions of structures including additively-manufactured elements.

BACKGROUND

[0004] Additive manufacturing generally refers to techniques involving deposition of material, such as via spraying, dispensing, or extrusion, for example, to form mechanical or electrical structures in an additive manner. Examples of generally-available additive manufacturing approaches include polymer jetting (e.g., involving depositing a polymer material which is then cured), fused deposition molding, or dispensing of paste materials such as comprising a paste composition having a conductive species. Additive manufacturing facilitates fabrication of structures such as extending along or protruding from non-planar surfaces, such as conforming to curved or irregular surfaces. Additive manufacturing also permits flexibility in manufactured structures, such as permitting variation, iteration, or fabrication of entirely different structural configurations with minimal re-tooling.

SUMMARY OF THE DISCLOSURE

[0005] Additive manufacturing (AM) techniques such as aerosol jet printing (AJP), laser-enhanced direct print (LE-DPAM), and inkjet printing can be used at least in part for fabrication of flexible, high-performance, electronics and structures, e.g., RF circuits, antennas, sensors, or metamaterials, such as structures having tailored mechanical, electrical, or optical properties. As an illustrative example, using RF circuits and antennas as a case study, additively manufactured (AM) antennas can be made by fused deposition modeling (FDM) or polymer jetting to achieve complex geometries. However, generally available techniques such as FDM to perform such fabrication may be restricted to either flat (e.g., planar structures) or reproduction of simple structures such as horn antennas, waveguides, or reflectors. By contrast, the apparatus and techniques described herein (e.g., laser-enhanced techniques with monitoring, such as laser-enhanced direct-print techniques) allow fabrication of structures conforming to curved or irregular surfaces. For example, the techniques described herein facilitate fabrication of antenna structures suitable for aviation or aerospace environments, such as conforming to curved (e.g., compound curved) surfaces, or possessing shapes or material configurations to provide desired antenna performance characteristics that would otherwise be difficult or impossible to achieve with a flat structure, for example.

[0006] As mentioned above, laser machining can be used in combination with additive manufacturing, such as to remove material from a deposited layer. The present inventors have recognized, among other things, that laser machining can present various challenges. One such challenge is a lack of feedback for closed-loop control of the laser machining process, such as to enhance one or more of consistency, efficiency, or reliability of material processing. In particular, generally-available approaches to laser-trimming of AM structures are performed without closed-loop monitoring of structures being ablated. Such open-loop approaches can fail to account for variations in material properties or material geometry (e.g., dimensional or shape variation).

[0007] To help remedy such challenges, the present inventors have developed, among other things, techniques for monitoring of laser ablation using an observed spectrum of a laser plasma during processing. Laser induced breakdown spectroscopy (LIBS) is a technique that can be used for trace analysis of items such as steel and other alloy composition, analysis of artworks, and tracing of archeological materials, among other applications. The present inventors have recognized that LIBS can be used to provide monitoring of laser machining in an additive manufacturing context. Such monitoring can be used for control of a laser machining operation, or even to gather data concerning the fabrication of AM structures (e.g., to observe structural characteristics indicative of a quality or process variation in the AM fabrication flow).

[0008] In an example, a technique such as an automated or semi-automated method can include depositing a conductive layer on a surface of a dielectric layer, and conductively isolating a first region from a second region of the conductive layer using ablative optical energy. Conductively isolating the regions can be performed by applying ablative optical energy to the conductive layer, monitoring a spectrum of an ablative plume generated by applying the ablative optical energy, and controlling the ablative optical energy in response to a characteristic of the spectrum of the ablative plume. In another example, a technique such as an automated or semi-automated method can include depositing a first conductive layer, depositing a dielectric layer on a surface of the first conductive layer, forming apertures or holes in the dielectric layer using ablative optical energy, depositing a second conductive layer on a surface of the dielectric layer opposite the first conductive layer, the depositing the second conductive layer including filling at least some of the apertures or holes in the dielectric layer with conductive material, and conductively isolating a first region from a second region of the second conductive layer using ablative optical energy. The conductively isolating the first region from the second region can include applying ablative optical energy to the second conductive layer, monitoring a spectrum of an ablative plume generated by applying the ablative optical energy, and controlling the ablative optical energy in response to a characteristic of the spectrum of the ablative plume.

[0009] In an example, one or more methods or techniques shown and described herein can performed at least in part using a system, comprising a dispenser configured to deposit a conductive material to form a conductive layer on a surface of a dielectric layer, a source of ablative optical energy to direct the ablative optical energy to a specified region of the conductive layer, a spectrometer optically coupled with the specified region of the conductive layer to monitor a spectrum of an ablative plume generated in response to application of the ablative optical energy from the source, and a controller coupled to the source of ablative optical energy and the spectrometer, the controller configured to monitor a characteristic of the ablative plume and, in response, control the source of ablative optical energy.

[0010] This summary is intended to provide an overview of subject matter of the present patent application. It is not intended to provide an exclusive or exhaustive explanation of the invention. The detailed description is included to provide further information about the present patent application.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] In the drawings, which are not necessarily drawn to scale, like numerals may describe similar components in different views. Like numerals having different letter suffixes may represent different instances of similar components. The drawings illustrate generally, by way of example, but not by way of limitation, various embodiments discussed in the present document.

[0012] FIG. **1**A and FIG. **1**B illustrate respective operations that can be included in a laser-enhanced additive manufacturing process.

[0013] FIG. **2**A, FIG. **2**B, FIG. **2**C, FIG. **2**D, FIG. **2**E, and FIG. **2**F illustrate respective operations that can be included in a laser-enhanced additive manufacturing process, such as can include depositing two conductive layers and, optionally, forming conductive structures (e.g., via structures) to provide an electrical interconnection between conductive layers.

[0014] FIG. **3** shows an illustrative example comprising a dielectric layer formed from a dielectric ink, and a laser-machined cavity.

[0015] FIG. **4** shows an illustrative example comprising a system that can be used to implement a laser-enhanced additive manufacturing process.

[0016] FIG. **5** shows an illustrative example comprising laser-induced breakdown spectroscopy (LIBS) spectra for respective copper species.

[0017] FIG. **6**A and FIG. **6**B show an illustrative example comprising laser-induced breakdown spectroscopy (LIBS) spectra for silver and copper

[0018] FIG. **7** shows illustrative examples of laser machining scan patterns for one round-trip scan (top), two round-trip scans (middle), and three round-trip scans (bottom).

[0019] FIG. **8**A, FIG. **8**B, FIG. **8**C, and FIG. **8**D show illustrative examples comprising experimentally obtained data corresponding to three different regions of an emission spectrum (FIG. **8**A and FIG. **8**C), and corresponding cumulative laser-induced breakdown spectroscopy (LIBS) intensity (FIG. **8**B and FIG. **8**C), with all plots shown versus a count of laser scans.

[0020] FIG. **9**A, FIG. **9**B, FIG. **9**C, and FIG. **9**D show illustrative examples comprising experimentally obtained data corresponding to three different regions of an emission spectrum (FIG. **9**A and FIG. **9**C), and corresponding cumulative laser-induced breakdown spectroscopy (LIBS) intensity (FIG. **9**B and FIG. **9**D), with all plots shown versus a count of laser scans.

[0021] FIG. **10** illustrate generally a technique, such as a method, for performing laser-enhanced additive manufacturing.

DETAILED DESCRIPTION

[0022] The apparatus and techniques described herein are applicable to a broad range of additive manufacturing approaches where laser machining is used. For example, Laser Enhanced DPAM (LE-DPAM) is a process that can achieve higher resolution than other additive manufacturing approaches. LE-DPAM generally includes use of thick-film deposition (e.g., microdispensing) such as to provide, as an illustrative example, 100 micrometer (μm)-thick layers. LE-DPAM can use ablative pulsed laser machining to achieve feature sizes of 10 μm by, using the laser, removing previously deposited material. Generally, LE-DPAM also enables manufacturing of high-frequency vertical interconnects (e.g., via structures). Laser processing need not be restricted to removal of material to entirely isolate different regions of a DPAM-fabricated structure. For example, picosecond laser processing of conductive ink solidifies conductive flakes (e.g., silver flakes) in slot structures. As an illustrative example, such processing can increase an effective RF conductivity of coplanar waveguides (CPW) by a factor of 100× from 0.3 MS/m to 30 MS/m up to 40 GHz.

[0023] FIG. **1**A and FIG. **1**B illustrate respective operations that can be included in a laser-enhanced additive manufacturing process. A substrate **102**, such as a dielectric material can be provided. The substrate can include a structure such as a skin, window, radome, or other portion of a vehicle, as an illustrative example. A conductive layer **104** can be deposited on a surface of the substrate **102**, such as using a dispenser **106**, or other similar approach (e.g., extrusion, ink-jet printing). The material forming the conductive layer **104** can include a conductive ink (e.g., a paste or liquid including a conductive medium). The conductive layer **104** can be dried or cured to form a portion of an electrical structure **100***a*. In FIG. **1**B, optical energy can be applied to the conductive layer, such as an output **110** from a laser. As the conductive layer is ablated, a plume **112** may be generated. The spectrum of emission generated by the plume **112** may be indicative of constituents of material in the region **108** being ablated by the output **110** of the laser. Monitoring of the plume **112** can be used to control application of ablative optical energy, such as to terminate or otherwise tailor application of such energy when constituents of the substrate **102** are detected in the plume **112**, or when constituents of the substrate **102** are detected in the plume **112** in a quantity exceeding a specified abundance. In an example, a parameter associated with application of ablative optical energy can be adjusted in response to monitoring of the plume **112**. Application of the ablative optical energy output **110** from the laser can conductively isolate regions of the conductive layer into a first region **104***a* and a second region **104***b*, forming a portion of an electrical structure **100***b*, as an illustrative example. As shown below, laser-enhanced DPAM can be used for fabrication of multi-layer structures, such as to provide a conformal stack of dielectric and conductive layers.

[0024] FIG. **2**A, FIG. **2**B, FIG. **2**C, FIG. **2**E, and FIG. **2**F illustrate respective operations that can be included in a laser-enhanced additive manufacturing process, such as can include depositing two conductive layers and, optionally, forming conductive structures (e.g., via structures) to provide an electrical interconnection between conductive layers. The process shown in FIG. **2**A through FIG. **2**F can include use of 5-axis printing such as including micro-dispensing, and femtosecond pulsed laser machining. As an illustration, the process flow can include scanning a 3D object **202** (e.g., substrate) to extract a profile. The 3D object **202** may be planar such as having a generally flat contour, non-planar such as having a generally curved contour, or have some other 3D shape or configuration. As an illustrative example, a micro-epsilon IDL1750 scanner (MICRO-EPSILON MESSTECHNIK GmbH & Co. KG, Ortenburg, Germany) can be used along with an nScrypt-configured tabletop printer (Nscrypt, Orlando, Fla., U.S.A.). The 3D object **202** can be heated using a heating bed, which is set to 80° C. Then, a micro-dispensing pump **206** can be loaded with a conductive ink such as DuPont CB028 (DuPont, Wilmington, Del., U.S.A), to dispense a first conductive ink layer **204** on the 3D object **202**, with a thickness after curing of ~50 μm, as shown illustratively in FIG. **2**A The first conductive ink layer **204** may be conformal to the 3D object **202**. Note that the 3D object **202** is shown as fixed for illustration but scanning for dispensing or other operations can be accomplished by rotation, translation, or elevation of the substrate while the dispenser or laser output remains stationary, or vice versa (or each could be actuated in specified degrees of freedom to provide relative motion between the dispenser or laser, and the substrate). In this illustrative example, the ink dries for 20 minutes while the part **200***a* is kept in the system.

[0025] In the example of FIG. **2**B showing part **200***b*, a micro-dispensing pump **216** (either the same micro-dispensing pump **206** shown in FIG. **2**A or a different pump) can be loaded with a dielectric material (e.g., DuPont 8153), and dispensed over the dried first conductive ink layer **204** with a thickness of about 100 μm. In this illustrative example, the dielectric ink layer **214** is dried for 20 minutes, and more layers can be deposited to achieve a target total thickness. The thickness uniformity of the dielectric layer **214** can be controlled by a flow of the ink through the pump tip, which can be controlled by a valve opening and a printing height. Ink height variations can be around 10 μm/layer while using the apparatus mentioned here (e.g., nScrypt system and the DuPont 8153 ink on a layer that is 100 μm thick).

[0026] Pulsed laser machining can be used (as shown at FIG. **2**C) to attempt to reduce layer thickness variation for prints that may require tight thickness tolerances. In the example of FIG. **2**C showing part **200***c*, an optical energy source **226** (e.g., a laser) can be used to ablate or remove a portion **224** of the dielectric ink layer **214**. The ablation process may produce an ablative plume **212** near the point of operation **208**.

[0027] Pulsed laser machining can also be used to create cavities, apertures, or holes for inter-layer interconnects (e.g., via structures), as shown illustratively in FIG. **2**D showing part **200***d*. In the example of FIG. **2**D, an optical energy source **226** (e.g., a laser) can be used to ablate or remove a portion of the dielectric ink layer **214** to create machined cavities **250**. The optical energy source **226** may be the same as the optical energy source **226** shown in FIG. **2**C, or it may differ in one or more ways. The optical energy source **226** may produce an ablative plume **212** near the point of operation **208**. The machined cavities **250** may separate the dielectric ink layer **214** into a first region **214***a*, a second region **214***b*, and a third region **214***c*.

[0028] These machined cavities **250** can be filled with conductive ink as shown in FIG. **2**E showing part **200***e*, and second conductive layer **234** can be deposited. The second conductive layer **234** may fill the machined cavities **250** creating a via structure **252** as a result of a continuous printing pattern, or the micro-dispensing pump **206** may adjust its printing pattern or properties to fill the machined cavities **250**. For example, filling of cavities and deposition of another conductive layer can be performed with the same micro-dispensing pump **206** shown in FIG. **2**A. The adjoining portion or portions **244** of the first conductive ink layer **204** and the second conductive ink layer **234** may be conductive to electricity. In an example, the first conductive ink layer **204** may be cleaned or otherwise prepared before the second conductive layer **234** is applied in an attempt to improve electrical conduction between layers.

[0029] Features in the outward-facing conductive layer can also be established by laser machining, such as shown at FIG. **2**F showing part **200***f*. For example, traces, lands, patches, or other features can be defined by laser machining of the second conductive layer **234** as shown in FIG. **2**F. In the example of FIG. **2**F, an optical energy source **236** can be used to ablate or remove a portion of the second conductive layer **234** to create machined cavities **260**. The machined cavities **260** may separate the second conductive layer **234** into a first region **234***a*, a second region **234***b*, and a third region **234***c*. The first region **234***a*, second region **234***b*, and third region **234***c* may be electrically isolated from each other due to the machine cavities **260**. In an example, the first region **234***a* and the third region **234***c* may be electrically coupled by the first conductive ink layer **204**. The optical energy source **236** may be the same as the optical energy source **226** shown in FIG. **2**C or it may differ in one or more ways from the optical energy source **226**.

[0030] The optical energy source **236** may produce an ablative plume **212** near the point of operation **218**. The constituents and properties of the ablative plume **212** in FIG. **2**F may differ from the constituents and properties of the ablative plume **212** in FIG. **2**C. The conductive ink used in the second conductive layer **234** may contain a metallic element, a metallic compound, or a substance with metallic properties such that the ablative plume **212** produced by ablating the second conductive layer **234** may have a unique and identifiable laser-induced breakdown spectroscopy (LIBS) spectrum. The dielectric ink layer **214** may not contain metallic elements, compounds, or substances with metallic properties, or may contain small or trace amounts of metallic elements, compounds, or substances with metallic properties, such that the ablative plume **212** produced by the dielectric ink layer **214** may be distinct and discernable from the ablative plume **212** produced by the second conductive layer **234**. In an example, one or more constituents or components of the dielectric ink layer **214** or the second conductive layer **234** may be selected such that the LIBS spectra of the layers are different.

[0031] In one or more of the examples above, such as at FIG. **2**C, FIG. **2**D, or FIG. **2**F, monitoring of a plume of ablated material can be performed such as for use in controlling laser machining. Such monitoring can include use of laser-induced breakdown spectroscopy (LIBS), as discussed elsewhere herein.

[0032] FIG. **3** shows an illustrative example **300** comprising a dielectric layer **302** formed from a dielectric ink, and a laser-machined cavity **304**. Such a cavity **304** can be a feature as mentioned above in relation to laser machining of deposited layers, and such machining need not be restricted to removal of material from a conductive layer. In the illustrative example of FIG. **3**, a 1 mm×1 mm cavity **304** in a dielectric layer **302** comprising cured DuPont 8153 ink was formed using laser ablation having a 360 femtosecond (fs) pulse width, 2 W average power, 100 kilohertz (kHz) repetition rate, and a scan rate of 20 millimeters per second.

[0033] FIG. **4** shows an illustrative example comprising a system **400** that can be used to implement a laser-enhanced additive manufacturing process. Generally, pulsed laser machining (PLM) is a highly energetic process that generates atoms and ionic species, or small molecular species and ionic species, in an ablative plume. Constituents in the plume generally produce a distinctive emission spectrum. The experimental results described below were obtained using a system as shown illustratively in FIG. **4**. The system can include an optical energy source **236**, such as a laser, with an output to direct ablative optical energy to a target, such as a conductive or dielectric layer that has been previously deposited. An ablative plume **212** (e.g., plasma emissions) from application of the ablative optical energy can be observed using an optical structure such as an optical fiber **470**, coupled to a spectrometer **472** or other optical detector. Emission lines or other features of an emission spectrum can be determined, and a controller such as a personal computer **474** or embedded system can be used to control the optical energy source **236** (e.g., laser) or other parameters related to application of ablative optical energy (such as scan path, scan configuration, beam power, pulse width, pulse repetition rate, overall duration of application of optical energy, termination of application of optical energy, or the like).

[0034] FIG. **5** shows an illustrative example comprising laser-induced breakdown spectroscopy (LIBS) spectra **500** for respective copper species published by the National institute of Standards and Technology (NIST). In the illustrative example of FIG. **5**, there are three distinct spectral emission peak clusters, two in the ultraviolet range (around 200 nm and 300 nm) and one in the visible (e.g., a green Cu emission around 500 nm). In some laser machining contexts encountered by the inventors, the 500 nm peaks were of roughly the same magnitude as the 200 and 300 nm peaks.

[0035] An illustrative example given below is for removal of a copper (Cu) conductive layer from a dielectric substrate (alumina—Al_2O_3). This approach can be used, for example, to provide electrical isolation (open circuit) of regions of a conductive layer on each side, laterally, of a PLM trench. Because ablated material tends to fall back into the PLM-fabricated trench, challenges can exist to determine when electrical isolation has been achieved. In one approach, over-machining of the trench into the dielectric base is used. But such an approach can unnecessarily erode or ablate the dielectric underlayer. The present inventors have developed techniques, among other things, to ablate only the Cu conductive layer, leaving the dielectric substrate substantially undamaged. For example, by monitoring LIBS emission during PLM, completion of ablation of the Cu overlayer can be detected.

[0036] For the experimental data obtained herein, different counts of PLM scans were conducted and the maximum emission intensity for the 200, 300, and 500 nm LIBS peaks were plotted as a function of the count of scans. Accordingly, a closed-loop approach could be implemented where a magnitude of specified emission peaks (or a presence or absence of such peaks) could be used to control application of ablative optical energy in a contemporaneous manner (e.g., in real-time or near-real-time in the machining operation). The experimental data shown herein were obtained using a StellarNet fiber-optic coupler (StellarNet Inc., Tampa, Fla., U.S.A.) and spectrometer with spectra collected as a function of time from the PLM samples using video capture in Canvas Studio (Infrastructure, Salt Lake City, Utah, U.S.A.).

[0037] While the examples herein are predominantly related to LIBS spectroscopy of copper-layer ablation, the techniques are believed applicable to a variety of other materials where such materials exhibit distinct spectra. For example, FIG. **6**A and FIG. **6**B show an illustrative example comprising laser-induced breakdown spectroscopy (LIBS) spectra for silver **662** in graph **600*a*** in FIG. **6**A, and copper **664** in graph **600*b*** in FIG. **6**B. These graphs show that the two spectra can be distinct (and can be discernable from each other). Both spectra show emission peaks in the 200, 300, and 500 nm regions, and the two spectra can be distinguishable from each other. These spectra were recorded in a laboratory setting.

[0038] For the experimental results below, six circuit board samples were run with four cuts made on each board. Boards were cut with single 80% overlapping scans, two 80% overlapping scans, and three 80% overlapping scans, as shown illustratively in FIG. **7**.

[0039] FIG. **7** shows illustrative examples of laser machining scan patterns for one round-trip scan (top), two round-trip scans (middle), and three round-trip scans (bottom). Beam overlap refers to the beam footprint from one direction of the pass **772**A overlapping with the beam footprint on the adjacent pass **772**B. For example, if the beam width is approximately 0.1 mm, an 80% overlap pass would be conducted approximately 0.02 mm from the original pass which may result in an overlap of approximately 80%. In the example of Table 1, a pass is equivalent to one unidirectional movement of the laser. For example, a round-trip for the 2-scan pattern shown in FIG. **7** would require 4 passes, whereas a round-trip for the 3-scan pattern would require 6 passes.

TABLE 1

Board 2	2 Scans	Scan Overlap	Electrical Conductivity Across PLM Cut
2.1 CU 35 micrometer plate, 2 centimeter line, 100 mm/s 80% 50 KHz 10 ps 15 passes		80%	Open
2.2 CU 35 micrometer plate, 2 centimeter line, 100 mm/s 80% 50 KHz 10 ps 15 passes		80%	Open
2.3 CU 35 micrometer plate, 2 centimeter line, 100 mm/s 80% 50 KHz 10 ps 15 passes		80%	Open

TABLE 1-continued

2.4 CU 35 micrometer plate, 2 centimeter line, 100 mm/s 80% 50 KHz 10 ps 15 passes		80%	Open

Board 5	2 Scans	Scan Overlap	Electrical Conductivity Across PLM Cut
5.1 CU 35 micrometer plate, 2 centimeter line, 50 mm/s 80% 25 KHz 10 ps 15 passes		80%	Short
5.2 CU 35 micrometer plate, 2 centimeter line, 50 mm/s 80% 25 KHz 10 ps 20 passes		80%	Open
5.3 CU 35 micrometer plate, 2 centimeter line, 50 mm/s 80% 25 KHz 10 ps 25 passes		80%	Open
5.4 CU 35 micrometer plate, 2 centimeter line, 50 mm/s 80% 25 KHz 10 ps 30 passes		80%	Open

[0040] TABLE 1 shows a subset of the laboratory tests performed on the six circuit board samples, including the four cuts made with the 2-scan pattern on Board 2 and Board 5. The laser machining scan parameters are shown above in TABLE 1, and such parameters include the scan length, scan speed, power (80% of maximum), pulse repetition rate, pulse duration, and count of number of passes. FIG. **8**A, FIG. **8**B, FIG. **8**C, and FIG. **8**D show illustrative examples comprising experimentally obtained data corresponding to emission intensities in three different regions of an emission spectrum (FIG. **8**A and FIG. **8**C), and corresponding cumulative laser-induced breakdown spectroscopy (LIBS) intensity (FIG. **8**B and FIG. **8**D), with all plots shown versus a count of laser scans. Series1 shows peaks in the 200 nm region, Series2 shows peaks in the 300 nm region, and Series3 shows peaks in the 500 nm region with the vertical axis representing arbitrary units of intensity. FIG. **8**B and FIG. **8**D were obtained by cumulatively summing (e.g., discrete integration) the results of FIG. **8**A and FIG. **8**C respectively. FIG. **8**A and FIG. **8**B show data for Cut #2 in Board 2 and FIG. **8**C and FIG. **8**D. show data for Cut #1 in Board 2.

[0041] FIG. **9**A, FIG. **9**B, FIG. **9**C, and FIG. **9**D show illustrative examples comprising experimentally obtained data corresponding to emissions intensities in three different regions of an emission spectrum (FIG. **9**A and FIG. **9**C), and corresponding cumulative laser-induced breakdown spectroscopy (LIBS) intensity (FIG. **9**B and FIG. **9**D), with all plots shown versus a count of laser scans. Series1 shows peaks in the 200 nm region, Series2 shows peaks in the 300 nm region, and Series3 shows peaks in the 500 nm region with the vertical axis representing arbitrary units of intensity. FIG. **9**B and FIG. **9**D were obtained by cumulatively summing (e.g., discrete integration) the results of FIG. **9**A and FIG. **9**C respectively. FIG. **9**A and FIG. **9**B show data for Cut #2 in Board 5 and FIG. **9**C and FIG. **9**D. show data for Cut #1 in Board 5.

[0042] Generally, in the laboratory experiments, debris accumulation in the PLM trench is harder to remove with a single overlapping scan than for two or three scans overlapping by 80% such as following paths as shown illustratively in FIG. **7**. For this reason, a series of two-three overlapping scans appeared more effective in establishing electrical isolation of the PLM machined pattern in a conductive layer. As noted in TABLE 1, all but one of the experimentally obtained data resulted in desired electrical isolation of the PLM machined pattern.

[0043] Referring to FIG. **8**B, FIG. **8**D, FIG. **9**B, and FIG. **9**D, simple accumulative intensities were determined as a function of scan count. Differential (first derivative) and second derivative plots were considered as a method of measuring for a desired endpoint (e.g., the complete removal of conductive material from the PLM trench and electrical isolation of an PLM-defined conductive pad). The cumulative plots show behavior that can be modeled piece-wise as two straight lines with different slopes. The initial slope is steeper than the second with a gradual transition from one to the other. It is believed, without being bound by theory, that the second straight line would be basically flat if the baseline of the measurements were zero. Again, without being bound by theory, a closed-loop monitoring scheme could include determining where the slope of the cumulative plot begins to flatten, as an illustrative example, and a machining operation could be deemed completed upon observation of such flattening, or other parameters could be varied to achieve such flattening. For example, in Scan 5.1, corresponding to the first row in TABLE 1 and FIG. **9**D, a short remained across the PLM trench, and the flattening has not yet occurred or is less distinct in the corresponding cumulative plot shown in FIG. **9**B, at the upper end of the scan count.

[0044] FIG. **10** illustrates generally a technique **1000**, such as a method, for performing laser-enhanced additive manufacturing. For example, at **1010**, a conductive layer can be deposited on a surface of a dielectric layer. The dielectric layer can be a substrate, or another deposited layer. For example, at **1005**, a dielectric layer can be deposited upon which the conductive layer is deposited at **1010**. The dielectric layer can be formed by additive manufacturing or other techniques. At **1015**, one or more features can be formed in the conductive layer using ablative optical energy. For example, a first region in the conductive layer deposited at **1010** can be isolated from a second conductive region of the conductive layer, such as using pulsed laser machining by applying ablative optical energy to the conductive layer at **1020** (or to another layer such as a dielectric layer for establishing cavities or other features, planarizing, or making a uniform thickness, for example) and monitoring a spectrum of an ablative plume generated by applying the ablative optical energy at **1025**.

[0045] Optionally, the ablative optical energy can be controlled at **1030**, such as in response to such monitoring, such as including adjusting one or more beam parameters (e.g., pulse width, repetition rate, power), or beam path (e.g., scan) parameters, such as beam overlap, count of scans, or scan rate. Such control can include one or more of continuing application of ablative optical energy in response to a characteristic of a detected spectrum remaining above or below a specified threshold or terminating application of ablative optical energy in response to a characteristic of a detected spectrum remaining above or below a specified threshold. As mentioned elsewhere herein, monitoring of the ablative plume can be performed in a closed-loop manner, such as providing feedback **1040** to continue application of ablative optical energy at **1020**, such as using adjusted or modified parameters established at **1030**.

[0046] Generally, the technique **1000** of FIG. **10** can be implemented using apparatus or techniques as shown and described elsewhere herein, such as including use of LIBS to monitor the spectrum of the ablative plume at **1025**.

[0047] Each of the non-limiting aspects above can stand on its own or can be combined in various permutations or combinations with one or more of the other aspects or other subject matter described in this document.

[0048] The above detailed description includes references to the accompanying drawings, which form a part of the detailed description. The drawings show, by way of illustration, specific embodiments in which the invention can be practiced. These embodiments are also referred to generally as "examples." Such examples can include elements in addition to those shown or described. However, the present inventors also contemplate examples in which only those elements shown or described are provided. Moreover, the present inventors also contemplate examples using any combination or permutation of those elements shown or described (or one or more aspects thereof), either with respect to a particular example (or one or more aspects thereof), or with respect to other examples (or one or more aspects thereof) shown or described herein.

[0049] In the event of inconsistent usages between this document and any documents so incorporated by reference, the usage in this document controls.

[0050] In this document, the terms "a" or "an" are used, as is common in patent documents, to include one or more than one, independent of any other instances or usages of "at least one" or "one or more." In this document, the term "or" is used to refer to a nonexclusive or, such that "A or B" includes "A but not B," "B but not A," and "A and B," unless otherwise indicated. In this document, the terms "including" and "in which" are used as the plain-English equivalents of the respective terms "comprising" and "wherein." Also, in the following claims, the terms "including" and "comprising" are open-ended, that is, a system, device, article, composition, formulation, or process that includes elements in addition to those listed after such a term in a claim are still deemed to fall within the scope of that claim. Moreover, in the following claims, the terms "first," "second," and "third," etc., are used merely as labels, and are not intended to impose numerical requirements on their objects.

[0051] Method examples described herein can be machine or computer-implemented at least in part. Some examples can include a computer-readable medium or machine-readable medium encoded with instructions operable to configure an electronic device to perform methods as described in the above examples. An implementation of such methods can include code, such as microcode, assembly language code, a higher-level language code, or the like. Such code can include computer readable instructions for performing various methods. The code may form portions of computer program products. Such instructions can be read and executed by one or more processors to enable performance of operations comprising a method, for example. The instructions are in any suitable form, such as but not limited to source code, compiled code, interpreted code, executable code, static code, dynamic code, and the like.

[0052] Further, in an example, the code can be tangibly stored on one or more volatile, non-transitory, or non-volatile tangible computer-readable media, such as during execution or at other times. Examples of these tangible computer-readable media can include, but are not limited to, hard disks, removable magnetic disks, removable optical disks (e.g., compact disks and digital video disks), magnetic cassettes, memory cards or sticks, random access memories (RAMs), read only memories (ROMs), and the like.

[0053] The above description is intended to be illustrative, and not restrictive. For example, the above-described examples (or one or more aspects thereof) may be used in combination with each other. Other embodiments can be used, such as by one of ordinary skill in the art upon reviewing the above description. The Abstract is provided to allow the reader to quickly ascertain the nature of the technical disclosure. It is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the claims. Also, in the above Detailed Description, various features may be grouped together to streamline the disclosure. This should not be interpreted as intending that an unclaimed disclosed feature is essential to any claim. Rather, inventive subject matter may lie in less than all features of a particular disclosed embodiment. Thus, the following claims are hereby incorporated into the Detailed Description as examples or embodiments, with each claim standing on its own as a separate embodiment, and it is contemplated that such embodiments can be combined with each other in various combinations or permutations. The scope of the invention should be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled.

The claimed invention is:

1. A method, comprising:

depositing a conductive layer on a surface of a dielectric layer; and

conductively isolating a first region from a second region of the conductive layer using ablative optical energy, including:

applying ablative optical energy to the conductive layer;

monitoring a spectrum of an ablative plume generated by applying the ablative optical energy; and

controlling the ablative optical energy in response to a characteristic of the spectrum of the ablative plume.

2. The method of claim **1**, wherein depositing the conductive layer comprises dispensing or printing a conductive species.

3. The method of claim **2**, wherein the conductive layer comprises at least one of a dried conductive ink or a cured conductive ink.

4. The method of claim **1**, comprising depositing the dielectric layer on a surface of a substrate.

5. The method of claim **4**, wherein depositing the dielectric layer comprises dispensing or printing a dielectric material.

6. The method of claim **5**, wherein the substrate is non-planar.

7. The method of claim **1**, wherein the characteristic of the spectrum includes a feature corresponding to ablation of a constituent of the conductive layer.

8. The method of claim **7**, wherein controlling the ablative optical energy comprises continuing applying ablative optical energy when the characteristic of the spectrum indicates a presence of the constituent of the conductive layer above a specified abundance.

9. The method of claim **7**, wherein the constituent comprises a metallic species, and wherein the characteristic of the spectrum includes a peak corresponding to the metallic species.

10. The method of claim **9**, wherein the constituent comprises copper or silver.

11. The method of claim **1**, wherein the characteristic of the spectrum includes a feature corresponding to ablation of a constituent of the dielectric layer.

12. The method of claim **11**, wherein controlling the ablative optical energy comprises reducing or terminating the application of ablative optical energy to a specified region when the characteristic of the spectrum indicates a presence of the constituent of the dielectric layer above a specified abundance.

13. The method of claim **11**, wherein the controlling the ablative optical energy comprises reducing or terminating the application of ablative optical energy to a specified region when the characteristic of the spectrum indicates at least one of (1) a presence of the constituent of the dielectric layer above a specified abundance or (2) the constituent of the conductive layer below a specified abundance.

14. The method of claim **1**, wherein the spectrum comprises an emission spectrum; and

wherein the ablative optical energy is provided using a laser.

15. A method, comprising:

depositing a first conductive layer;

depositing a dielectric layer on a surface of the first conductive layer;

forming apertures or holes in the dielectric layer using ablative optical energy;

depositing a second conductive layer on a surface of the dielectric layer opposite the first conductive layer, depositing the second conductive layer including filling at least some of the apertures or holes in the dielectric layer with conductive material; and

conductively isolating a first region from a second region of the second conductive layer using ablative optical energy, including:

applying ablative optical energy to the second conductive layer;

monitoring a spectrum of an ablative plume generated by applying the ablative optical energy; and

controlling the ablative optical energy in response to a characteristic of the spectrum of the ablative plume.

16. The method of claim **15**, wherein at least one of the first conductive layer, the second conductive layer, or the dielectric layer are dispensed or printed in liquid or paste form.

17. The method of claim **15**, comprising removing a portion of the dielectric layer to establish a specified dielectric layer profile or thickness using ablative optical energy.

18. The method of claim **15**, wherein the spectrum comprises an emission spectrum; and

wherein the ablative optical energy is provided using a laser.

19. The method of claim **15**, wherein the first conductive layer follows a contour of a non-planar substrate.

20. A system, comprising:

a dispenser configured to deposit a conductive material to form a conductive layer on a surface of a dielectric layer;

a source of ablative optical energy to direct the ablative optical energy to a specified region of the conductive layer;

a spectrometer optically coupled with the specified region of the conductive layer to monitor a spectrum of an ablative plume generated in response to application of the ablative optical energy from the source; and

a controller coupled to the source of ablative optical energy and the spectrometer, the controller configured to monitor a characteristic of the ablative plume and, in response, control the source of ablative optical energy.

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