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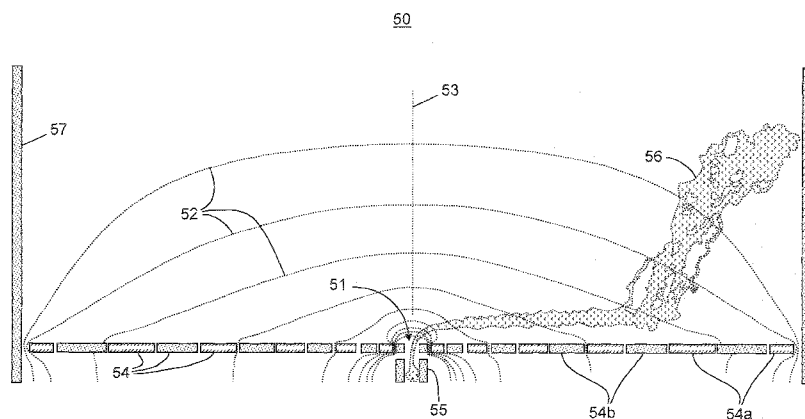


FIG. 2

(57) Abstract: An ion transport apparatus for a mass- or ion-mobility spectrometer comprises: (a) a plurality of strip electrodes disposed in a series on a flat substrate, (b) an ion outlet aperture in the substrate disposed adjacent to a first one of the plurality of strip electrodes, (c) a radio frequency (RF) voltage generator operable to supply an oscillatory RF voltage to each of the plurality of strip electrodes such that an RF phase difference exists between each pair of adjacent electrodes and (d) at least one DC voltage source operable to supply a respective DC bias voltage to each of the plurality of electrodes, the apparatus being characterized in that each strip electrode comprises a respective width such that the electrode strip widths of a series of the plurality of electrodes progressively increase away from the first one of the plurality of electrodes.



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ION CARPET FOR MASS SPECTROMETRY HAVING PROGRESSIVE ELECTRODES

TECHNICAL FIELD

[0001] The present invention relates generally to ion optics for mass spectrometers, and more particularly to a device for confining and focusing ions at atmospheric pressure and at moderate vacuum conditions and to ion source apparatuses using the device.

BACKGROUND ART

[0002] A fundamental challenge faced by designers of mass spectrometers is the efficient transport of ions from the ion source to the mass analyzer, particularly through atmospheric or low vacuum regions where ion motion is substantially influenced by interaction with background gas molecules. While electrostatic optics are commonly employed in these regions of commercially available mass spectrometer instruments for ion focusing, it is known that the effectiveness of such devices is limited due to the large numbers of collisions experienced by the ions. Consequently, ion transport losses tend to be high, which has a significant adverse impact on the instrument's overall sensitivity.

[0003] FIG. 1 is a simplified schematic diagram of a known mass spectrometer system 10. Referring to FIG. 1, an API source 12 housed in an ionization chamber 14 is connected to receive a liquid sample from an associated apparatus such as for instance a liquid chromatograph or syringe pump through a capillary 7. The API source 12 optionally is an electrospray ionization (ESI) source, a heated electrospray ionization (H-ESI) source, an atmospheric pressure chemical ionization (APCI) source, an atmospheric pressure matrix assisted laser desorption (MALDI) source, a photoionization source, or a source employing any other ionization technique that operates at pressures substantially above the operating pressure of mass analyzer 28 (e.g., from about 1 torr to about 2000 torr). The API source 12 forms charged particles 9 (either ions or charged droplets that may be desolvated so as to release ions) representative of the sample, which charged particles are subsequently transported from the API source 12 to the mass analyzer 28 in high-vacuum chamber 26 through at least one intermediate-vacuum chamber 18. In particular, the droplets or ions are entrained in a background gas and transported from the API source 12 through an ion transfer tube 16 that passes through a first partition element or wall 11 into an intermediate-

vacuum chamber **18** which is maintained at a lower pressure than the pressure of the ionization chamber **14** but at a higher pressure than the pressure of the high-vacuum chamber **26**. The ion transfer tube **16** may be physically coupled to a heating element or block **23** that provides heat to the gas and entrained particles in the ion transfer tube so as to aid in desolvation of charged droplets so as to thereby release free ions.

[0004] Due to the differences in pressure between the ionization chamber **14** and the intermediate-vacuum chamber **18** (FIG.1), gases and entrained ions are caused to flow through ion transfer tube **16** into the intermediate-vacuum chamber **18**. A plate or second partition element or wall **15** separates the intermediate-vacuum chamber **18** from either the high-vacuum chamber **26** or possibly a second intermediate-pressure region **25**, which is maintained at a pressure that is lower than that of chamber **18** but higher than that of high-vacuum chamber **26**. Vacuum port **13** is used for evacuation of the intermediate-vacuum chamber **18** by means of a mechanical pump or equivalent. Under typical operating conditions, the pressure within chamber **18** will be in the range of 1-50 Torr.

[0005] The analyte ions exit the outlet end of ion transfer tube **16** as a free jet expansion and travel through an ion channel **41** defined within the interior of ion transport device **40**. As discussed in further detail in US Patent No. 7,781,728, the entire disclosure of which is incorporated herein by reference, radial confinement and focusing of ions within ion channel **41** are achieved by application of oscillatory voltages to apertured electrodes **44** of ion transport device **40**. As is further discussed in US Patent No. 7,781,728, transport of ions along ion channel **41** to the device exit may be facilitated by generating a longitudinal DC field and/or by tailoring the flow of the background gas in which the ions are entrained. Ions leave the ion transport device **40** as a narrowly focused beam and are directed through aperture **22** of extraction lens **29** into the second intermediate pressure chamber **25**.

[0006] Subsequently, the ions pass thereafter through ion optical elements **20**, **31** and **24** and are delivered through aperture **27** to a mass analyzer **28** located within chamber **26**. The ion optical assemblies or lenses **20**, **24** may comprise transfer elements, such as, for instance a multipole ion guide. The mass analyzer **28** comprises one or more detectors **30** whose output can be displayed as a mass spectrum. As depicted in FIG. 1, the mass analyzer may take the form of a conventional two-dimensional quadrupole ion trap having detectors **30**. The mass analyzer **28** could alternatively comprise, a time of flight (TOF) mass analyzer, a Fourier transform mass analyzer, an ion trap, a magnetic sector mass

analyzer or a hybrid mass analyzer. Chambers **25** and **26** may be evacuated to relatively low pressures by means of connection to ports of a turbo pump, as indicated by the arrows adjacent to vacuum port **17** and vacuum port **19**. While ion transport device **40** is depicted as occupying a single chamber, alternative implementations may utilize an ion transport device that bridges two or more chambers or regions of successively reduced pressures.

[0007] The reader is referred to US Patent No. 7,781,728 for more details of the ion transport device **40**. Briefly, the ion transport device **40** is formed from a plurality of generally planar electrodes **44** arranged in longitudinally spaced-apart relation (as used herein, the term “longitudinally” denotes the axis defined by the overall movement of ions along ion channel **41**). Devices of this general construction are sometimes referred to in the mass spectrometry art as “stacked-ring” ion guides. Each electrode **44** is adapted with an aperture through which ions may pass. The apertures collectively define an ion channel **41**, which may be straight or curved, depending on the lateral alignment of the apertures. To improve manufacturability and reduce cost, all of the electrodes **44** may have identically sized apertures. An oscillatory (e.g., radio-frequency) voltage source applies oscillatory voltages to electrodes **44** to thereby generate a field that radially confines ions within ion channel **41**. In order to create a tapered field that focuses ions to a narrow beam near the exit of the ion transport device **40**, the inter-electrode spacing or the oscillatory voltage amplitude is increased in the direction of ion travel.

[0008] The electrodes **44** of the ion transport device **40** may be divided into a plurality of first electrodes interleaved with a plurality of second electrodes, with the first electrodes receiving an oscillatory voltage that is opposite in phase with respect to the oscillatory voltage applied to the second electrodes. Further, a longitudinal DC field may be created within the ion channel **41** by providing a DC voltage source (not illustrated) that applies a set of DC voltages to electrodes **44** in order to assist in propelling ions through the ion transport device **40**.

[0009] Ion funnel and stacked ring ion guide apparatuses all perform their intended functions adequately. Nonetheless, the use of these prior apparatuses does present some difficulties. First, it is difficult to completely block the “line-of-sight” through such apparatuses for the purpose of preventing neutral molecules from traveling to down-stream mass spectrometer components (including the detector) where they may cause undesirable contamination and spurious detector noise. Secondly, since such apparatuses comprise

multiple electrodes, proper alignment of all the components is time consuming and subject to later disruption. Thirdly, for the same reason, such apparatuses are difficult to clean once they do become contaminated. Fourthly, the provision of many parallel electrode plates in these conventional apparatuses produces a naturally high capacitance which may draw high RF power.

[0010] Radio Frequency (RF) ion carpets are an alternative type of focusing ion guide. Such RF ion carpets have previously been used in high energy physics experiments, but have not been seen for analytical applications. For example, Takamine et al. ("Space-charge effects in the catcher gas cell of a RF ion guide," *Review of Scientific Instruments*, 76[10], pp. 103503-103503-6, 2005) and Schwarz ("RF ion carpets: The electric field, the effective potential, operational parameters and an analysis of stability," *International Journal of Mass Spectrometry*, 299[2-3], pp. 71-77, 2011) have described the use of ion carpets for the capture of high energy particles in high energy physics experiments.

[0011] The ion carpet apparatuses described in these papers utilize a printed circuit comprising a pattern of concentric strip electrodes that guide ions towards a center hole that channels the ions into high vacuum. The ion carpet apparatus described by Takamine et al. consists of distinct inner and outer regions. The inner region includes 160 concentric ring electrodes to which both RF voltages and DC potentials are applied, the inner-region ring electrodes being included within a diameter of 110 mm and having equal widths of approximately 0.14 mm with 0.14 mm separations between electrodes. The outer region, occupying radii between 55–140 mm, consists of 85 additional equal-width concentric ring electrodes separated by 0.2 mm to which only DC potentials and no RF fields are applied, each such outer-region ring electrode being approximately 0.8 mm wide. Such ion carpet devices should be suitable for use in atmospheric pressure ionization sources used in mass spectrometers and ion mobility spectrometers, but, to date, have not been employed for these analytical applications.

[0012] U.S. Patent No. 5,572,035, in the name of Franzen, describes other ion-carpet-like devices for use as ion guides in mass spectrometer systems. Various embodiments taught by Franzen in the aforementioned U.S. Patent comprise a narrow grid pattern of electrodes, isolated from each other, that forms a surface for reflecting charged particles by creation of strongly inhomogeneous high frequency fields of low penetration range into the space above the surface. The electrode elements of the pattern are regularly repeated in at least

one direction within the surface. The phases of the high frequency voltage are connected alternately to subsequent grid elements. Some embodiments taught by Franzen comprise a plurality of wire tips that form the surface and some other embodiments comprise a plurality of parallel wires parallel to the reflecting surface. Other embodiments taught by Franzen comprise a pattern of wire tips and a wire mesh arranged around the tips. Franzen also teaches embodiments comprising a stack of wire rings that are stacked in the direction of ion transport as well as coiled double-helical structures. U.S. Patent No. 6,683,301, in the name of Whitehouse, describes the use of similar devices for use as either so-called “pusher” electrodes or reflecting electrodes in time-of-flight mass spectrometer instruments.

[0013] The previously-noted RF ion carpets that comprise concentric rings within a plane (i.e., Takamine et al. and Schwarz) have been designed with equally sized and spaced electrodes. Such a design produces a restoring force near the surface of the RF ion carpet that is essentially constant. Such a design presents some problems for mass spectrometry and ion mobility spectrometry applications in that, for spectrometry applications, one would normally like a strong restoring force to initially capture and control the ions, and then a weak restoring force near the center, so that ions can be more easily extracted for transfer to optics further down stream in the instrument. Accordingly, there is a need in the art of analytical ion spectrometry – including mass spectrometry and ion mobility spectrometry – for a new type of ion guide apparatus that it is relatively simple to construct, is easy to clean, can easily provide a complete blockage of line of site, thereby reducing noise at the detector and eliminating contamination concerns, provides a large acceptance aperture than can easily collect ions from multiple sources and that has a lower capacitance and RF usage than an ion funnel or SRIG with an equivalent number of plates. The present invention addresses such a need.

DISCLOSURE OF INVENTION

[0014] The inventors have realized that the variable restoring force required to use an RF ion carpet in analytical applications may be achieved by varying the size and spacing of the electrodes on the surface of the ion carpet. A preferred design may use larger electrodes towards the outer edges, to provide a strong repulsive force and initial capture of ions emerging from the atmospheric pressure expansion. Towards the center of the device, smaller electrodes may be used to allow the ions to approach closer to the surface, which

would ease the eventual extraction. This variable electrode size and spacing also provides a natural way to increase the DC drag force towards the center while still using a linear voltage divider chain. Accordingly, an ion carpet with progressively sized and spaced electrodes is described which provides a natural way to reduce the repulsive forces near the exit orifice.

[0015] In accordance with one aspect of the invention, an ion transport apparatus for a mass spectrometer or an ion mobility spectrometer comprises: (a) a plurality of strip electrodes disposed in a series on a flat substrate, (b) an ion outlet aperture in the substrate disposed adjacent to a first one of the plurality of strip electrodes, (c) a radio frequency (RF) voltage generator operable to supply an oscillatory RF voltage to each of the plurality of strip electrodes such that an RF phase difference exists between each pair of adjacent electrodes and (d) at least one DC voltage source operable to supply a respective DC bias voltage to each of the plurality of electrodes, the apparatus being characterized in that each strip electrode comprises a respective width such that the electrode strip widths of a series of the plurality of electrodes progressively increase away from the first one of the plurality of electrodes.

[0016] Various embodiments may be further characterized by (e) a cage electrode at least partially enclosing the plurality of strip electrodes and the ion outlet aperture; and (f) an extraction electrode disposed adjacent to the ion outlet aperture, wherein the DC voltage source is further operable to supply a first DC voltage to the cage electrode and a second DC voltage to the extraction electrode. The plurality of strip electrodes may comprise a plurality of concentric ring electrodes such that the first one of the plurality of electrodes is the innermost one of the plurality of concentric electrodes. In various embodiments, the plurality of concentric ring electrodes may comprise a plurality of circular rings or may comprise a plurality of rectangular rings. In various embodiments, the cage electrode may comprise a hollow circular cylinder or a hollow rectangular cylinder. In various embodiments: the flat substrate may comprise a printed circuit board comprising electrical connections providing the oscillatory RF voltage and the DC bias voltages to the plurality of strip electrodes; the extraction electrode may comprise an ion transfer tube; or the apparatus may further comprise at least one shield disposed so as to block a direct line of sight between the ion source and the ion outlet aperture.

[0017] In accordance with another aspect of the invention, a multiple ion source system for a mass spectrometer or an ion mobility spectrometer comprises a plurality of ion sources and an ion transport apparatus operable to supply ions from any of the ion sources to the mass spectrometer or ion mobility spectrometer and, the system characterized in that the ion transport apparatus comprises: (a) a plurality of concentrically disposed strip electrodes on a flat substrate, each strip electrode comprising a respective width such that the electrode strip widths of a series of the plurality of strip electrodes progressively increase away from an innermost one of the plurality of electrodes; (b) an ion outlet aperture in the substrate disposed adjacent to an innermost one of the plurality of strip electrodes, the aperture configured so as to direct ions passing therethrough to the mass spectrometer or ion mobility spectrometer; (c) a cage electrode at least partially enclosing the plurality of strip electrodes and the ion outlet aperture; (d) an ion transfer tube comprising an extraction electrode disposed adjacent to the ion outlet aperture; (e) a radio frequency (RF) voltage generator operable to supply an oscillatory RF voltage to each of the plurality of strip electrodes such that an RF phase difference exists between each pair of adjacent electrodes; and (f) at least one DC voltage source operable to supply a first DC voltage to the cage electrode, a second DC voltage to the extraction electrode and a respective DC bias voltage to each of the plurality of electrodes; and further characterized in that the plurality of ion sources is circumferentially disposed about the plurality of concentrically disposed strip electrodes such that, in operation of each respective ion source, ions are emitted in the direction of at least a portion of the plurality of strip electrodes.

[0018] In various embodiments, the plurality of concentric electrodes may comprise a plurality of circular rings or a plurality of rectangular rings. In the latter case, the apparatus may be further characterized in that the plurality of ion sources is disposed such that, in operation of each respective ion source, ions are emitted in the direction of a corner section of the plurality of strip electrodes. Various embodiments of the apparatus may further comprise at least one shield disposed so as to block a direct line of sight between each of the plurality of ion sources and the ion outlet aperture. In various embodiments, the flat substrate may comprise a printed circuit board comprising electrical connections providing the oscillatory RF voltage and the DC bias voltages to the plurality of concentrically disposed strip electrodes.

[0019] In accordance with another aspect of the invention, a method of transporting ions generated by an atmospheric pressure ion source to an ion inlet of an evacuated chamber of a mass spectrometer is characterized by: directing the ions from the ion source towards a plurality of mutually concentrically disposed strip electrodes disposed on a flat substrate; applying RF voltages to each of the plurality of strip electrodes such that an RF phase difference exists between each pair of adjacent electrodes; and applying DC voltage differences to each pair of adjacent electrodes, wherein the applied RF and DC voltages are such that the ions are caused to flow past the plurality of electrodes to an aperture of the substrate that directs ions passing therethrough to the ion inlet. The directing of the ions towards the plurality of mutually concentrically disposed strip electrodes may be caused, in part, by a DC voltage difference applied between the plurality of strip electrodes and a cage electrode that at least partially encloses the plurality of strip electrodes. In various embodiments, the ion source may comprise a member of a plurality of ion sources, each of which is disposed so as to direct ions towards the plurality of strip electrodes. In various embodiments, the method may be further characterized by drawing the ions into the aperture by applying a voltage an extraction electrode disposed adjacent to the aperture at a side of the substrate opposite to the plurality of mutually concentrically disposed strip electrodes.

BRIEF DESCRIPTION OF DRAWINGS

[0020] The above noted and various other aspects of the present invention will become apparent from the following description which is given by way of non-limiting example only and with reference to the accompanying drawings, not drawn to scale, in which:

[0021] FIG. 1 is a schematic illustration of a known mass spectrometer system;

[0022] FIG. 2 is a schematic cross-sectional depiction of electrodes of an ion carpet apparatus in accordance with the present teachings, showing calculated electrical equipotential contours and ion trajectories;

[0023] FIG. 3A is a top view of an electrode structure of an ion carpet apparatus in accordance with the present teachings;

[0024] FIG. 3B is a perspective view of an ion carpet apparatus that utilizes the electrode structure of FIG. 3A;

[0025] FIG. 4 is a perspective view of an ion carpet apparatus used as an ion collection lens from multiple atmospheric pressure ion sources;

[0026] FIG. 5 is a perspective view of another ion carpet apparatus in accordance with the present teachings; and

[0027] FIG. 6 is a schematic illustration of a mass spectrometer system using an ion carpet apparatus in accordance with the present teachings.

MODES FOR CARRYING OUT THE INVENTION

[0028] The following description is presented to enable any person skilled in the art to make and use the invention, and is provided in the context of a particular application and its requirements. Various modifications to the described embodiments will be readily apparent to those skilled in the art and the generic principles herein may be applied to other embodiments. Thus, the present invention is not intended to be limited to the embodiments and examples shown but is to be accorded the widest possible scope in accordance with the features and principles shown and described. The particular features and advantages of the invention will become more apparent with reference to the appended FIGS. 1-5, taken in conjunction with the following description.

[0029] FIG. 2 is a schematic cross-sectional depiction of electrodes of an ion carpet apparatus **50** in accordance with the present teachings. The apparatus **50** comprises a plurality of strip electrodes **54**, the width and spacing of which varies from the periphery to the center of the apparatus. As illustrated, the apparatus is symmetrical about a central axis or plane **53**. Generally, wider electrodes are located towards the outer edges – away from the central axis or plane **53** and the electrode width becomes progressively narrower towards the center. A cage electrode **57** partially surrounds the plurality of strip electrodes **54** and an outlet aperture **51** is disposed inward from the innermost electrode or electrodes, preferably along the central axis or plane **53**. An extraction electrode **55** is disposed adjacent to the innermost strip electrode and supplied with a voltage so as to receive ions exiting the apparatus **50** through the outlet aperture **51**. The extraction electrode **55** may comprise, for example, an ion transfer tube or any other form of ion transfer optics or ion optical assembly that serves to transfer ions collected by and from the ion carpet to another portion of an ion spectrometer (e.g., a mass spectrometer or an ion mobility spectrometer) of which the ion carpet apparatus is a part. The extraction electrode may comprise a dedicated

component of the ion carpet apparatus. Alternatively, the extraction electrode may comprise ion transfer optics that would normally be present in a mass spectrometer apparatus, even in the absence of the ion carpet such as, for example, ion optical assembly or lens **20** which may be used in the prior art apparatus (FIG. 1) or in conjunction with the ion carpet apparatus (FIG. 6). In other words, the optical assembly or lens **20** may serve as the extraction electrode or as a portion of the extraction electrode.

[0030] In operation of the RF ion carpet apparatus **50**, an RF voltage generator (not shown in FIG. 2) is electrically coupled to and provides an oscillatory voltage to each of the plurality of strip electrodes **54** such that an RF phase difference $\Delta\phi$ exists between each pair of electrodes. For instance, FIG. 2 illustrates a preferred configuration in which the plurality of strip electrodes **54** consists of two electrode subsets – a first electrode subset **54a** and a second electrode subset **54b** indicated by different shading patterns – such that an RF phase difference of π (180 degrees) occurs between each pair of adjacent electrodes. Further, at least one Direct Current (DC) voltage generator supplies a respective DC bias voltage to each one of the plurality of strip electrodes **54**. A DC voltage is also supplied to the cage electrode **57**.

[0031] FIG. 2 further shows iso-potential lines **52** calculated using a one-dimensional electrostatic model in which the width of the ion carpet apparatus is set to 100 mm, the width of the outlet aperture is set to 2 mm, the voltage in the cage electrode is set to 10 V, the voltage on the extraction electrode **55** is set to -110 V and the difference in bias DC potential between each adjacent pair of electrodes is set at 1 V. The model also employs a 750 kHz RF voltage having a peak amplitude 200V applied to each strip electrode. Ions ranging in mass-to-charge ratio (m/z) from 100 to 1000 are assumed to be generated from an ion source (not shown) located at a point near the top right corner of the apparatus. Ion trajectories through the ion carpet apparatus **50** were simulated using SIMION® charged-particle optics simulation software commercially available from Scientific Instrument Services of 1027 Old York Rd. Ringoes NJ 08551-1054 USA. The simulation was run in conjunction with a collision model in order to account for interactions between ions and gas molecules at a static gas pressure of 2 Torr.

[0032] The overall locus of ion pathways within the apparatus **50**, as calculated according to the SIMION® simulation, as described above, is indicated by ion cloud **56**. The simulations show high efficiency transfer of ions from the edge of the device to the central

outlet aperture **51**. An order of magnitude in mass is easily transferred without any variation in conditions. As can be seen in FIG. 2, the ions move closer and closer to the carpet as they approach the exit outlet aperture, as a result in the gradient in electrostatic potential – as indicated by iso-potential lines **52** – generated by the DC bias-voltage difference between the cage electrode and the strip electrodes. As the ions approach the electrodes, the applied out-of-phase RF voltages maintain the cloud within a confined volume region slightly separated from the surfaces of the strip electrodes. The simulation indicates that the high mass ions travel slightly closer to the surface due to the weaker restoring force that is experienced, but at a distance that should avoid any issues with collisions. This behavior results in optimal positioning for extraction through the outlet aperture **51** to the extraction electrode or ion transfer optics **55**.

[0033] The one-dimensional ion trajectory simulation whose results are indicated in FIG. 2 does not provide ion confinement in a direction outside of the plane of the diagram. As a practical matter, however, ion confinement may be achieved by fabricating the electrode strips as annular rings or annular arcs. The annular ring electrodes **74** illustrated in the ion electrode set **73** of FIG. 3A are an example of how such ring electrodes may be configured. In similar fashion to the strip electrodes **54** shown in FIG. 2, the width of the annular ring electrodes **74** – as measured radially across the apparatus – progressively decreases inwardly through the apparatus. Also similarly to the configuration illustrated in FIG. 2, the annular ring electrodes **74** consist of two electrode subsets – a first electrode subset **74a** and a second electrode subset **74b** indicated by different shading patterns – such that an RF phase difference of π (180 degrees) occurs between each pair of adjacent electrodes. Because of the geometry of the electrode configuration shown in FIG. 3, taken in conjunction with the application of appropriate DC drag field gradients and the out-of-phase RF voltages across adjacent electrodes, ions will be subject to time-averaged force vectors which are directed radially inward and downward towards an outlet aperture **71** disposed centrally within the electrode set **73**.

[0034] The cage electrode **77** (FIG. 3B) of the ion carpet apparatus **70** may comprise a hollow cylinder at least partially enclosing the electrode set **73** comprising the annular ring electrodes **74**. The annular ring electrodes **74** may be formed from any suitable conductive material but, advantageously, may be fabricated as thin metal straps attached to a substrate **72**. The substrate **72** may advantageously be provided as a printed circuit board which

provides all the appropriate electrical connections required to provide DC and RF voltages to the annular ring electrodes **74**. With the application of appropriate DC bias voltages to the annular ring electrodes **74** and the cage electrode **72**, an appropriate extraction voltage to the extraction electrode or ion transfer optics **55** and appropriate out-of-phase RF voltages across adjacent electrodes **74**, ions will be caused to migrate radially inward and downward above the surface of the surface of the electrode set **73** so as to be collected by the outlet aperture **71** and directed into the extraction electrode or ion transfer optics **55**. The substrate may include a heater so as to heat the electrode set to prevent condensation of materials introduced from ion sources.

[0035] FIG. 4 illustrates one example of usage of an ion carpet apparatus in accordance with the present teachings. In FIG. 4, the ion carpet apparatus is shown utilized at atmospheric pressure as an ion collection lens from multiple atmospheric pressure ion sources **12**. Accordingly, the ion carpet apparatus may be used within an ionization chamber **14** as shown in FIG. 1. Each atmospheric pressure ion source **12** is capable of producing a plume of charged particles **9**, including ions, generally directed inward into the cage electrode (not shown) towards the electrode plate **73** of the ion carpet apparatus. Oftentimes, the ion plume **9** will include charged solvent droplets in addition to free ions. Therefore, a shield **79** may be deployed so as to block any direct line of sight between any of the ion sources **12** and the outlet aperture (at the center of the electrode set **73**) so as to prevent any droplets from entering the outlet aperture. Although the shield **79** is illustrated as a plate disposed above the electrode set **73** in FIG. 4, the shield may be formed in any suitable shape and configuration, such as a cylindrical part disposed within the inner diameter of the cage electrode (not shown). The relative configuration of the ion sources **12**, the cage electrode and the shield **79** should allow the ions to be able to migrate downwards towards the electrode set and to hover above the electrodes (under the application of appropriate DC and RF fields) as described previously in reference to FIG. 2.

[0036] The configuration shown in FIG. 4 may permit “multiplexing” of analyses of several samples – each sample introduced to a different one of the ion sources – using a single ion spectrometer. Because of the radial symmetry of the apparatus, ions derived from the multiple ion sources **12** may be captured and directed into the extraction electrode or ion optics **55** with the same efficiency. The various ion sources **12** need not produce ions by the

same process; for example some of the ion sources may be electrospray ion sources whereas others of the sources comprise atmospheric pressure chemical ionization sources.

[0037] FIG. 5 illustrates an alternative ion carpet apparatus **80** in accordance with the present teachings and provides a second example of how ring electrodes of the apparatus may be configured. In the configuration shown, the ion carpet apparatus may be used within an ionization chamber **14** as shown in FIG. 1 so as to collect ions emitted by one or more ion sources **12**. In the ion carpet apparatus **80** (FIG. 5) the electrode set **83** comprises a set of concentric rectangular rings **84** disposed on a substrate **82** which may also be rectangular so as to match the shape of the rectangular rings **84**. A cage electrode (not shown) may be formed as a hollow 4-sided rectangular “box” partially surrounding the electrodes **84**. Because of the straight sides of the electrodes **84**, it may be advantageous to dispose ion sources **12** so as direct the charged-particle plumes **9** towards the electrode corners so as to confine ions within a narrow region. A shield (not shown) of any suitable form may be employed to prevent ingestion of charged droplets into the outlet aperture and extraction electrode or ion optics **55**, as previously described with reference to FIG. 4. Other aspects of the apparatus **80** are similar to the descriptions already provided.

[0038] FIG. 6 illustrates another example of usage of an ion carpet apparatus in accordance with the present teachings. The mass spectrometer system **210** illustrated in FIG. 5 is similar to the known mass spectrometer system **10** shown in FIG. 1 except that the ion transport device **40** of the known system is replaced by the ion carpet apparatus **250**. In FIG. 6, the ion carpet apparatus **250** is shown utilized as an ion collection and focusing apparatus for collecting a plume **217** of ions that emerges from an ion transfer tube **16** into an intermediate vacuum chamber **18** of a mass spectrometer system **210**. Generally, there is a differential pressure of 750 to 760 Torr across the length of the ion transfer tube (e.g., ion transfer tube **16** of FIGS. 1 and 6) which leads to a rapid expansion at the outlet end. This expansion is characterized by a rapid increase of the velocity of the ionized analyte containing gas that flows into the first vacuum stage **18** of the mass spectrometer. Thus, a device with a high aspect ratio (ratio to width to height), such as an ion carpet apparatus in accordance with the present teachings, is useful for collecting and focusing the ions emerging from the ion transfer tube **16**.

[0039] The ion carpet apparatus **250**, which may comprise, for example, the apparatus **70** shown in FIG. 3, serves to transfer the collected and focused ions into the second

intermediate-pressure chamber **25** or, in the absence of a second intermediate-pressure chamber, into the high-vacuum chamber **26**. The shape of the electrode set of the ion carpet apparatus could be circular as shown in FIG. 3 or could comprise some other shape, possibly chosen so as to match a cross sectional shape of the ion plume **217** that emerges from the ion transfer tube **16**. For example, the electrode set and the electrodes therein could be rectangular in shape as illustrated in FIG. 5 or could be comprise an oval shape or some other shape. As shown, the ion carpet apparatus includes a shield **279** to block direct flow of neutral gas molecules or any residual droplets into the second intermediate-pressure or high-vacuum chamber. In other embodiments, the center of the ion carpet apparatus **250** could be positioned so as to be non-coaxial with the ion transfer tube, thereby eliminating a direct line of sight between the ion transfer tube and the outlet aperture of the ion carpet apparatus.

[0040] The ion carpet apparatuses as described herein are expected to have several benefits over current high pressure RF devices like the SRIG and ion funnel. First, it is very simple to provide a complete blockage of line of site, thus reducing noise at the detector and eliminating concern about contamination of the instrument further down stream. Second, since the design is typically flat, apparatuses in accordance with the present teachings are relatively simple to construct. Third, the larger acceptance aperture of apparatuses in accordance with the present teachings can easily collect ions from multiple sources. Fourth, these apparatuses are very easy to clean. Fifth, the capacitance should be lower than a SRIG with an equivalent number of plates, and therefore should these novel apparatuses should use less RF power.

[0041] Improved ion collection, focusing, and transfer devices for ion spectrometers used in analytical applications have been described. The novel devices are based on the concept of an ion carpet having concentric electrodes comprising electrode widths which progressively decrease from edge to center. The discussion included in this application is intended to serve as a basic description. Although the present invention has been described in accordance with the various embodiments shown and described, one of ordinary skill in the art will readily recognize that there could be variations to the embodiments or combinations of features in the various illustrated embodiments and those variations or combinations of features would be within the scope of the claims. The reader should thus be aware that the specific discussion may not explicitly describe all embodiments possible;

many alternatives are implicit. Accordingly, many modifications may be made by one of ordinary skill in the art without departing from the scope of the invention. Neither the description nor the terminology is intended to limit the scope of the invention – the invention is defined only by the claims.

CLAIMS

What is claimed is:

1. An ion transport apparatus for directing ions generated by an ion source to an ion inlet aperture of a mass spectrometer or an ion mobility spectrometer, the apparatus comprising (a) a plurality of strip electrodes disposed in a series on a flat substrate, (b) an ion outlet aperture in the substrate disposed adjacent to a first one of the plurality of strip electrodes, (c) a radio frequency (RF) voltage generator operable to supply an oscillatory RF voltage to each of the plurality of strip electrodes such that an RF phase difference exists between each pair of adjacent electrodes and (d) at least one DC voltage source operable to supply a respective DC bias voltage to each of the plurality of electrodes, the apparatus characterized in that:

each strip electrode comprises a respective width such that the electrode strip widths of a series of the plurality of electrodes progressively increase away from the first one of the plurality of electrodes.
2. An ion transport apparatus as recited in claim 1, further characterized by:

(e) a cage electrode at least partially enclosing the plurality of strip electrodes and the ion outlet aperture; and

(f) an extraction electrode disposed adjacent to the ion outlet aperture,

wherein the at least one DC voltage source is further operable to supply a first DC voltage to the cage electrode and a second DC voltage to the extraction electrode.
3. An ion transport apparatus as recited in either one of claims 1-2, wherein the plurality of strip electrodes comprise a plurality of concentric ring electrodes such that the first one of the plurality of electrodes is the innermost one of the plurality of concentric electrodes.
4. An ion transport apparatus as recited in claim 3, wherein the plurality of concentric ring electrodes comprise a plurality of circular rings.
5. An ion transport apparatus as recited in claim 4, further characterized in that the cage electrode comprises a hollow circular cylinder.

6. An ion transport apparatus as recited in claim 3, further characterized in that the plurality of concentric ring electrodes comprises a plurality of rectangular rings.
7. An ion transport apparatus as recited in claim 6, wherein the cage electrode comprises a hollow rectangular cylinder.
8. An ion transport apparatus as recited in claim 1, wherein the flat substrate comprises a printed circuit board comprising electrical connections providing the oscillatory RF voltage and the DC bias voltages to the plurality of strip electrodes.
9. An ion transport apparatus as recited in claim 2, wherein the extraction electrode comprises an ion transfer tube.
10. An ion transport apparatus as recited in either of claims 1-2, further comprising at least one shield disposed so as to block a direct line of sight between the ion source and the ion outlet aperture.
11. A multiple ion source system for a mass spectrometer or an ion mobility spectrometer comprising a plurality of ion sources and an ion transport apparatus operable to supply ions from any of the ion sources to the mass spectrometer or ion mobility spectrometer and, the system characterized in that:
 - the ion transport apparatus comprises:
 - (a) a plurality of concentrically disposed strip electrodes on a flat substrate, each strip electrode comprising a respective width such that the electrode strip widths of a series of the plurality of strip electrodes progressively increase away from an innermost one of the plurality of electrodes;
 - (b) an ion outlet aperture in the substrate disposed adjacent to an innermost one of the plurality of strip electrodes, the aperture configured so as to direct ions passing therethrough to the mass spectrometer or ion mobility spectrometer;
 - (c) a cage electrode at least partially enclosing the plurality of strip electrodes and the ion outlet aperture;
 - (d) an ion transfer tube comprising an extraction electrode disposed adjacent to the ion outlet aperture;

(e) a radio frequency (RF) voltage generator operable to supply an oscillatory RF voltage to each of the plurality of strip electrodes such that an RF phase difference exists between each pair of adjacent electrodes; and

(f) at least one DC voltage source operable to supply a first DC voltage to the cage electrode, a second DC voltage to the extraction electrode and a respective DC bias voltage to each of the plurality of electrodes; and

the plurality of ion sources is circumferentially disposed about the plurality of concentrically disposed strip electrodes such that, in operation of each respective ion source, ions are emitted in the direction of at least a portion of the plurality of strip electrodes.

12. A multiple ion source system as recited in claim 11, wherein the plurality of concentric electrodes comprises a plurality of circular rings.
13. A multiple ion source system as recited in claim 11, wherein the plurality of concentric electrodes comprises a plurality of rectangular rings.
14. A multiple ion source system as recited in claim 13, further characterized in that the plurality of ion sources are disposed such that, in operation of each respective ion source, ions are emitted in the direction of a corner section of the plurality of strip electrodes.
15. A multiple ion source system as recited in claim 11, further comprising at least one shield disposed so as to block a direct line of sight between each of the plurality of ion sources and the ion outlet aperture.
16. A multiple ion source system as recited in claim 11, wherein the flat substrate comprises a printed circuit board comprising electrical connections providing the oscillatory RF voltage and the DC bias voltages to the plurality of concentrically disposed strip electrodes.
17. A method of transporting ions generated by an atmospheric pressure ion source to an ion inlet of an evacuated chamber of a mass spectrometer, the method characterized by:

directing the ions from the ion source towards a plurality of mutually concentrically disposed strip electrodes disposed on a flat substrate;
applying RF voltages to each of the plurality of strip electrodes such that an RF phase difference exists between each pair of adjacent electrodes; and
applying DC voltage differences to each pair of adjacent electrodes,
wherein the applied RF and DC voltages are such that the ions are caused to flow past the plurality of electrodes to an aperture of the substrate that directs ions passing therethrough to the ion inlet.

18. A method of transporting ions as recited in claim 17, wherein the ion source comprises a member of a plurality of ion sources, each of which is disposed so as to direct ions towards the plurality of strip electrodes.
19. A method of transporting ions as recited in claim 17, wherein the directing of the ions towards the plurality of mutually concentrically disposed strip electrodes is caused, in part, by a DC voltage difference applied between the plurality of strip electrodes and a cage electrode that at least partially encloses the plurality of strip electrodes.
20. A method of transporting ions as recited in claim 17, further characterized by:
drawing the ions into the aperture by applying a voltage an extraction electrode disposed adjacent to the aperture at a side of the substrate opposite to the plurality of mutually concentrically disposed strip electrodes.

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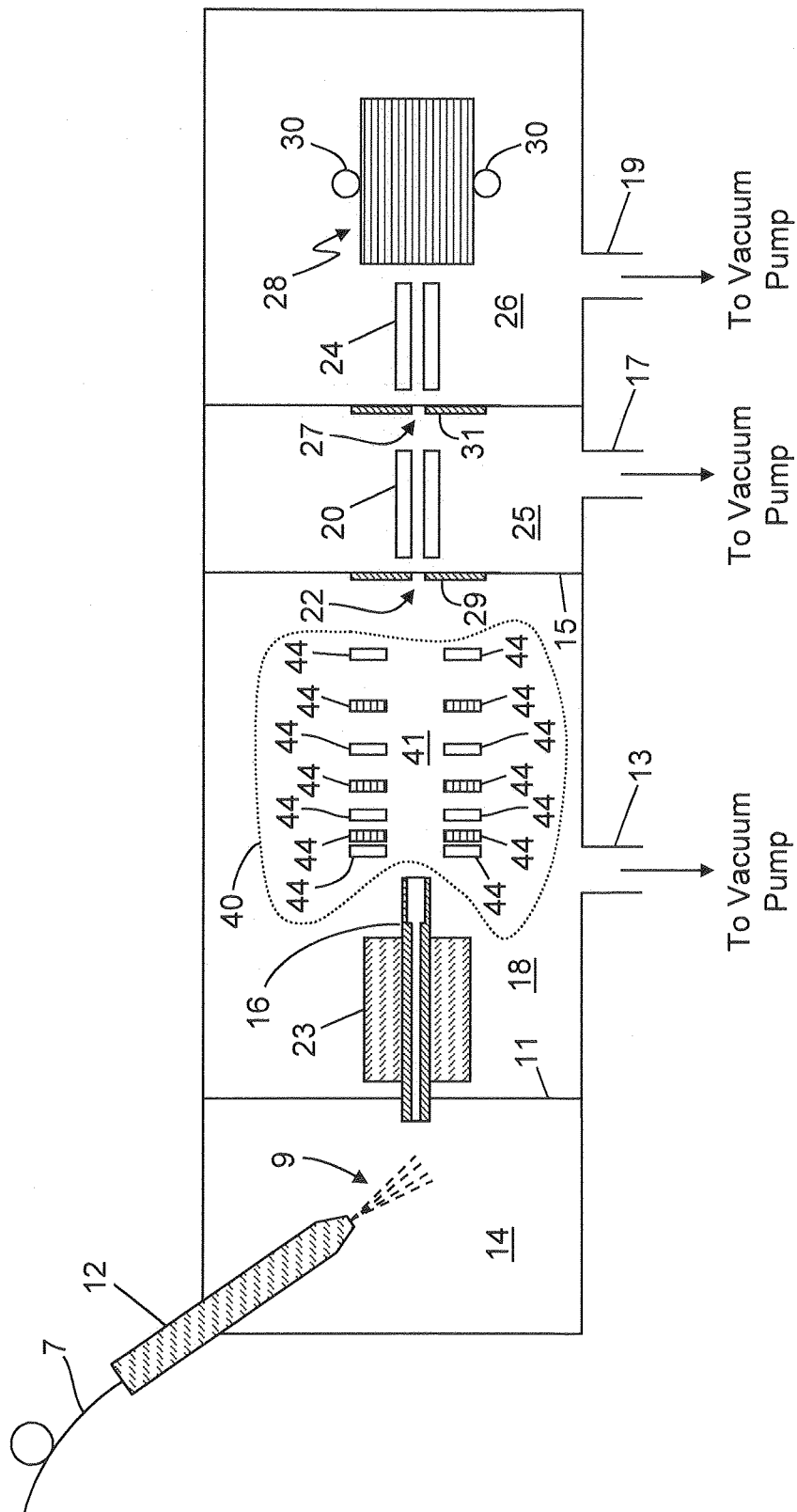


FIG. 1
(Prior Art)

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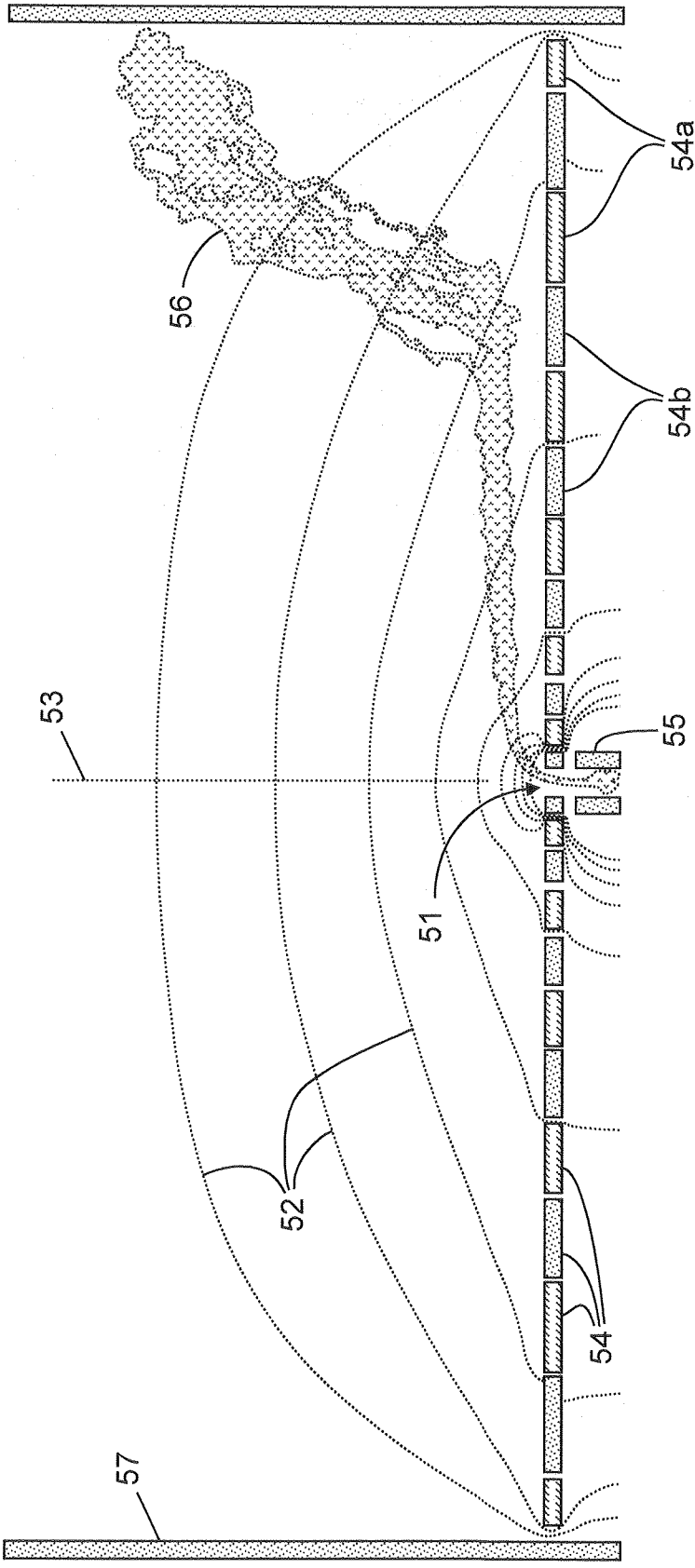
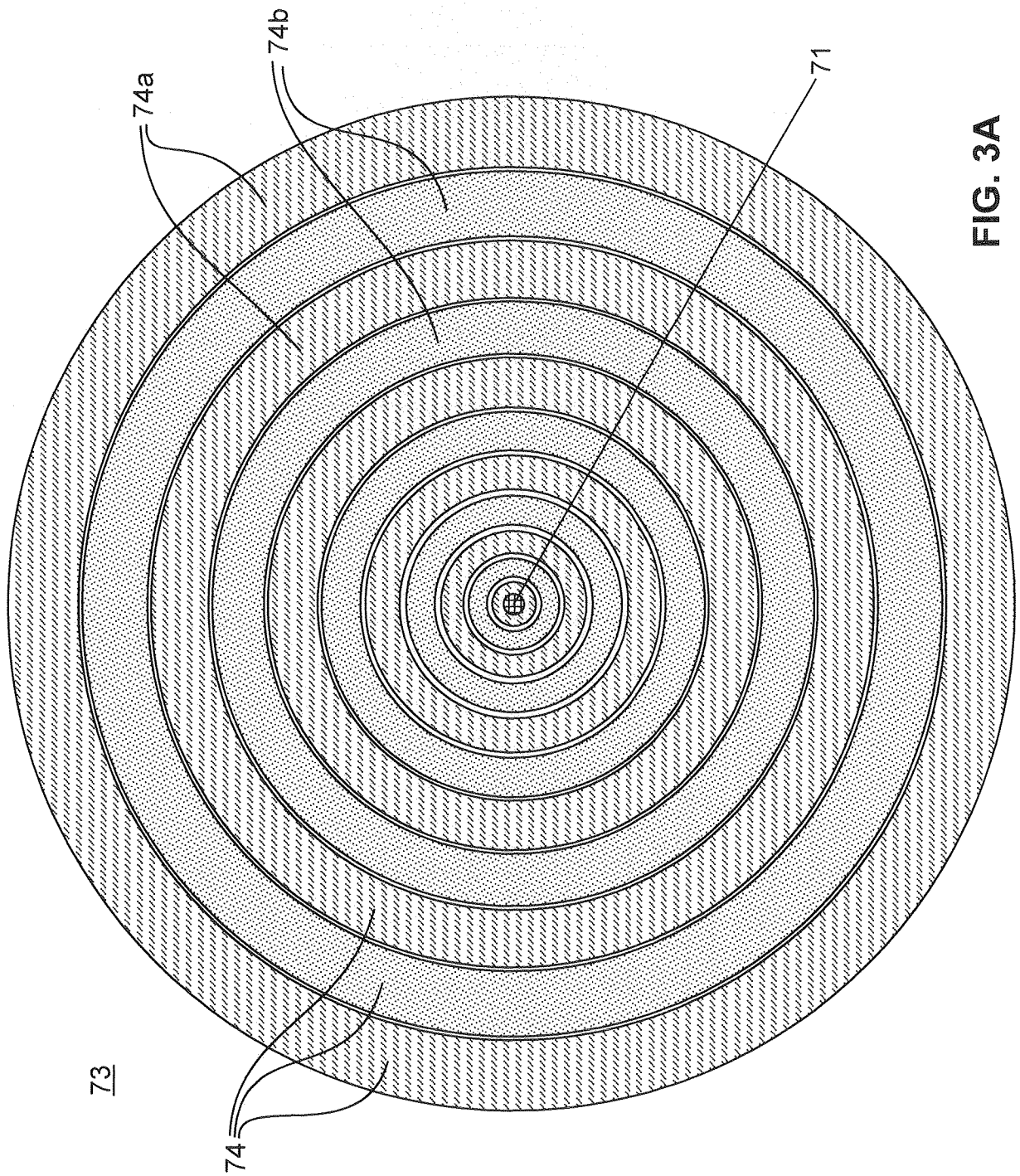


FIG. 2

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70

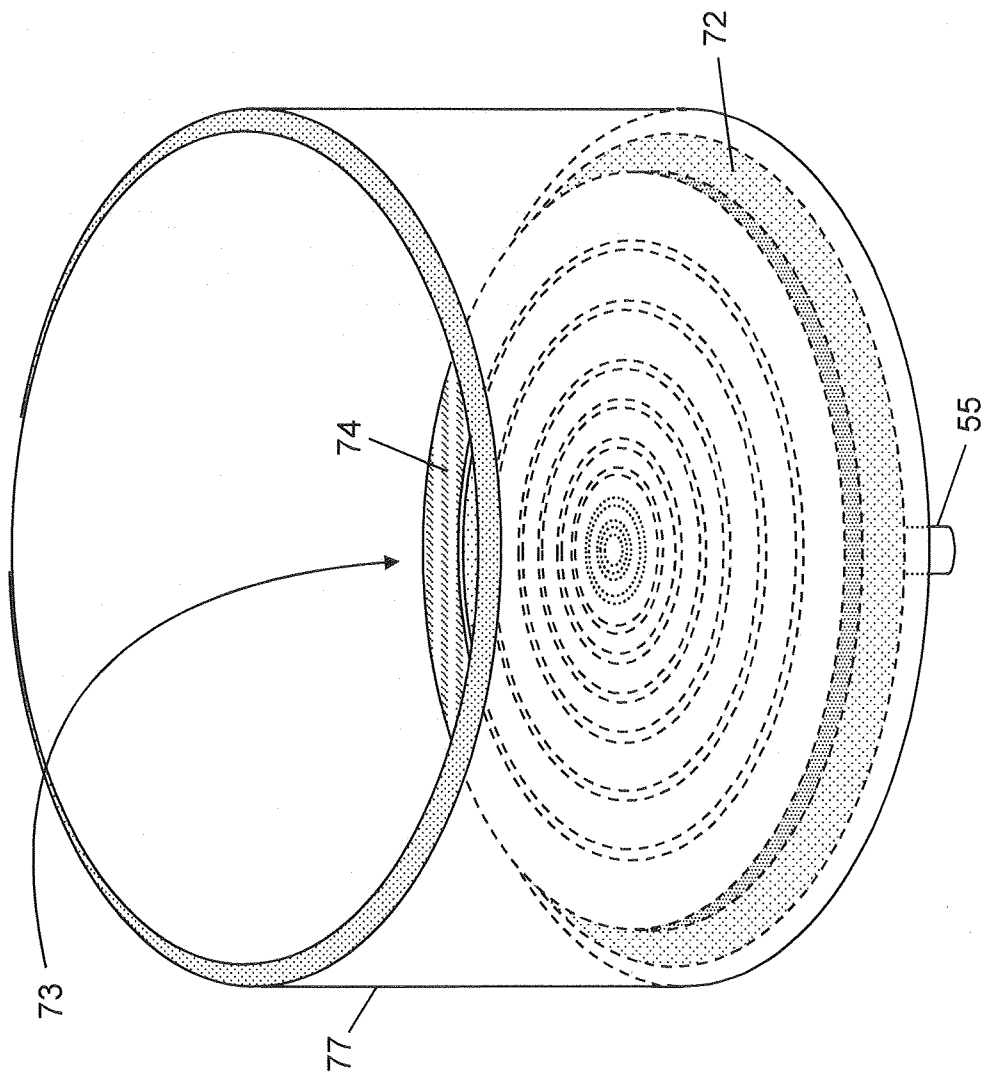


FIG. 3B

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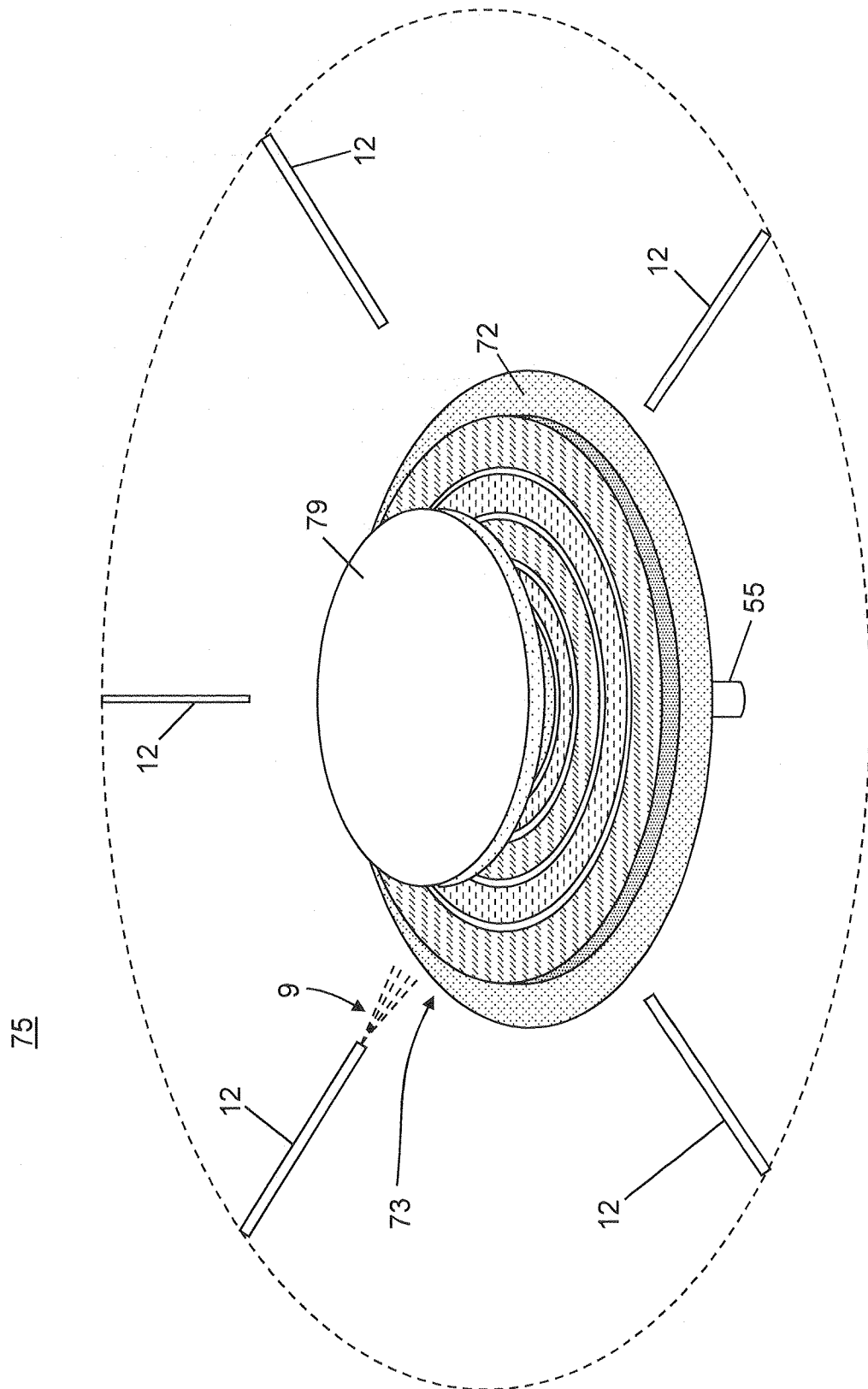


FIG. 4

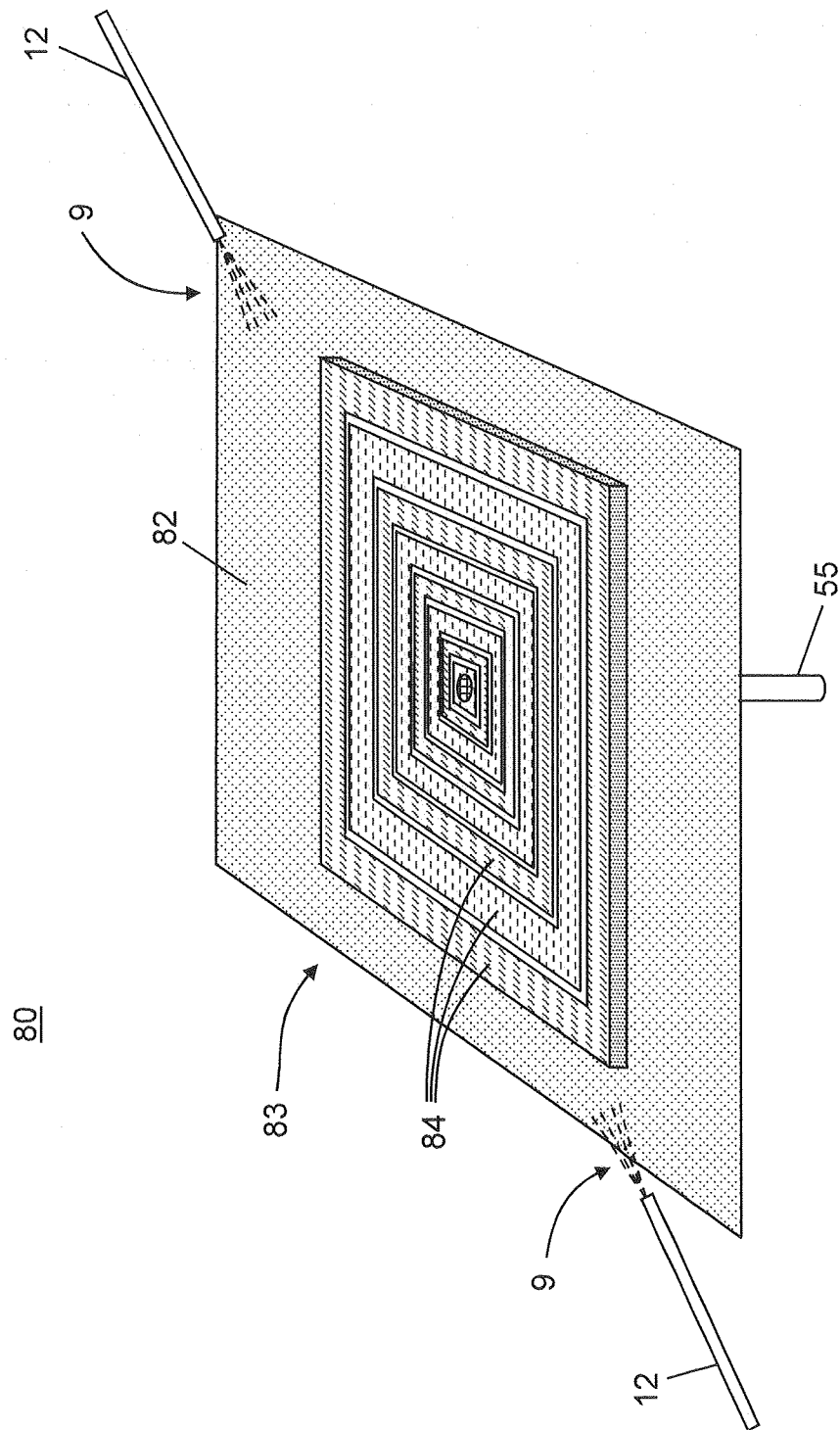


FIG. 5

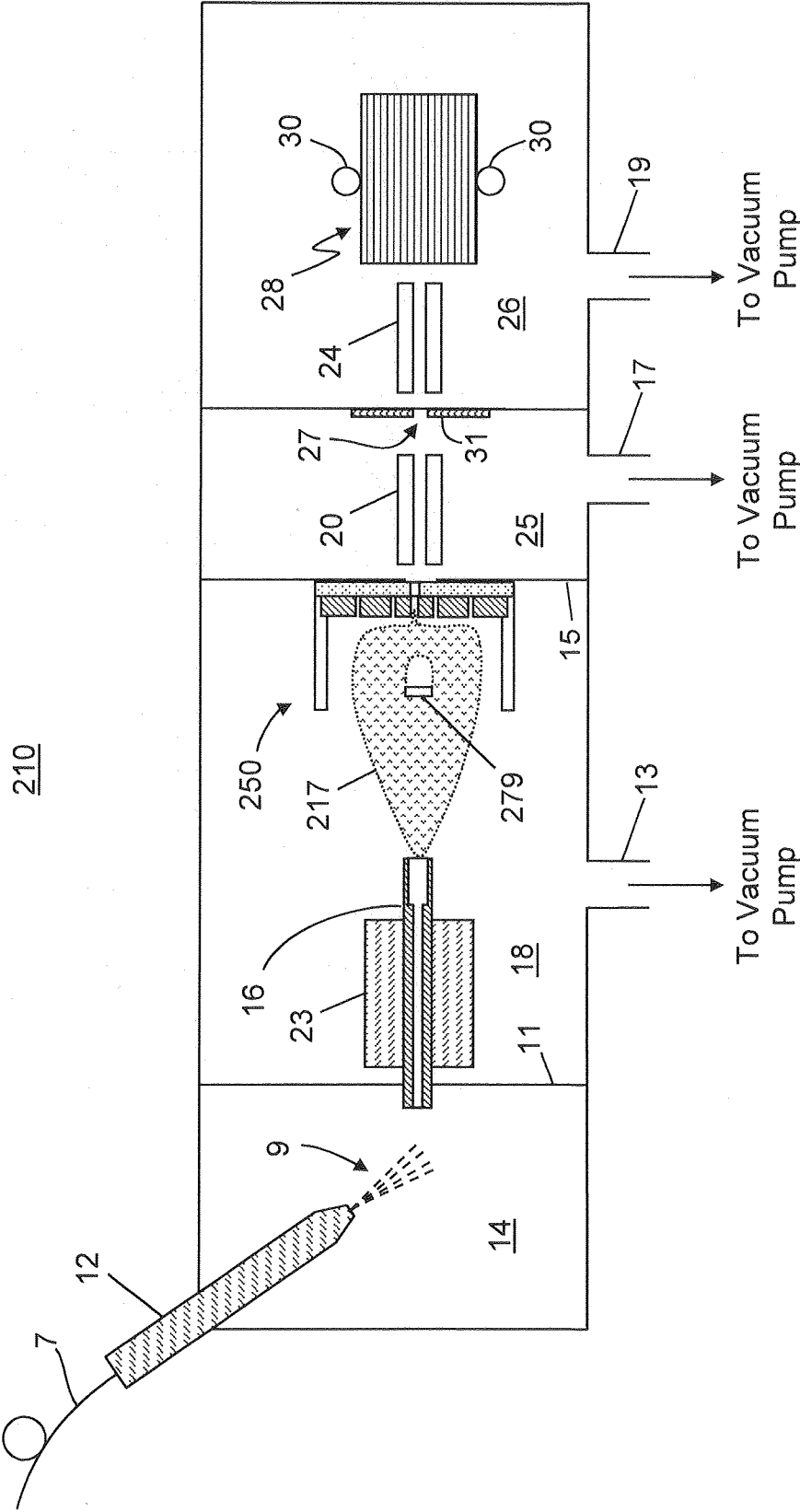


FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 13/52552

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - H01J 49/06; B01D 59/44 (2013.01)

USPC - 250/281

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
USPC: 250/281Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
IPC(8): H01J 49/06; B01D 59/44 (2013.01)
USPC: 250/281-285,290-298; 313/359.1,360.1,361.1Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PatBase (PatBase); PubWEST(USPT,PGPB,EPAB,JPAB); Google Scholar, Science Direct, Google Patents
Search Terms: ion, transport, strip, circular, rf, radio, oscillator, electrode, cage, ring, flat, substrate, DC, cylinder, hollow, concentric, plane, spectrometer.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2010/0148062 A1 (WOLLNIK et al.) 17 June 2010 (17.06.2010), entire document, especially; FIG 1-18, para [0001], [0011], [0032], [0066], [0072]-[0074], [0078], [0079], [0082]-[0086], [0091]	1, 3/(1), 4/(1), 6/(1), 8, 10/(1), 17, 20

Y		2, 3/(2), 4/(2), 5/(1-2), 6/(2), 7/(1-2), 9, 10/(2), 11-16, 18, 19
Y	US 5,302,827 A (FOLEY) 12 April 1994 (12.04.1994), entire document, especially; FIG 2, col 3, ln 6-30, col 4, ln 54 to col 5, ln 33	2, 3/(2), 4/(2), 5/(1-2), 6/(2), 7/(1-2), 9, 10/(2), 11-16, 18, 19
A	US 3,081,020 A (ROSTAS) 12 March 1963 (12.03.1963), entire document	1-20
A	US 5,248,883 A (BREWER et al.) 28 September 1993 (28.09.1993), entire document	1-20
A	US 6,180,942 B1 (TRACY et al.) 30 January 2001 (30.01.2001), entire document	1-20

☐ Further documents are listed in the continuation of Box C.

* Special categories of cited documents:

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

30 November 2013 (30.11.2013).

Date of mailing of the international search report

20 DEC 2013

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