



(51) International Patent Classification:

H02M 7/538 (2007.01) *H01J* 7/32 (2006.01)
A61B 18/12 (2006.01)

(21) International Application Number:

PCT/GB2013/053083

(22) International Filing Date:

22 November 2013 (22.11.2013)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

1221012.6 22 November 2012 (22.11.2012) GB

(71) Applicant: **THE UNIVERSITY OF LIVERPOOL**
[GB/GB]; Foundation Building, 765 Brownlow Hill, Liver-
pool, L69 7ZX (GB).

(72) Inventors: **WALSH, James Leon**; c/o The University of
Liverpool, Foundation Building, 765 Brownlow Hill, Liver-
pool, Merseyside L69 7ZX (GB). **BRADLEY, James
William**; c/o The University of Liverpool, Foundation
Building, 765 Brownlow Hill, Liverpool, Merseyside L69
7ZX (GB).

(74) Agents: **HARRISON GODDARD FOOTE LLP** et al.;
4th Floor, Merchant Exchange, 17-19 Whitworth Street
West, Manchester, Greater Manchester, M1 5WG (GB).

(81) Designated States (unless otherwise indicated, for every
kind of national protection available): AE, AG, AL, AM,
AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY,
BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM,
DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT,
HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR,
KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME,
MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ,
OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA,
SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM,
TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM,
ZW.

(84) Designated States (unless otherwise indicated, for every
kind of regional protection available): ARIPO (BW, GH,
GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ,
UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ,
TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK,
EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV,
MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM,
TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW,
KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— of inventorship (Rule 4.17(iv))

Published:

— with international search report (Art. 21(3))

(54) Title: APPARATUS FOR GENERATING A PLASMA

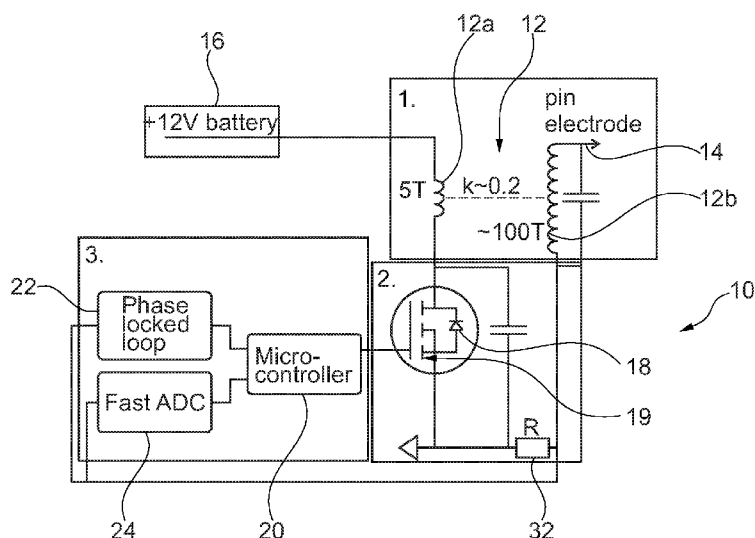


Fig. 1

(57) Abstract: An apparatus for generating a plasma, comprising an air-cored transformer having a primary coil connectable to a power source, and a secondary coil connected to an electrode for generating a plasma, an amplifier connected to the air-cored transformer; and a control system connected to the amplifier, the control system being configured to supply a drive signal to the primary coil via the amplifier. The control system is connected to the secondary coil during operation and adjusts the frequency of the drive signal so as to be supplied to the primary coil at a non-resonant frequency offset from the detected resonant frequency such that the output voltage generates a plasma. The feedback system is further configured to detect the magnitude of the output current of the secondary coil and adjust the non-resonant offset frequency of the drive signal to adjust the output current to compensate for detected changes in the magnitude of the output current so as to maintain a substantially constant output current.

Apparatus for Generating a Plasma

[0001] This invention relates to an apparatus for generating a plasma, and in particular, to an adjustable and controllable apparatus for generating a plasma.

5

BACKGROUND

[0002] According to research by the US Centers for Disease Control and Prevention one out of every 20 persons spending a night in a hospital will acquire an infection, with microbial contaminated surfaces contributing strongly to such healthcare-associated infections (HAI). According to one report (Price Waterhouse Cooper) the annual wastage in the American healthcare system is \$1.2 trillion with HAIs accounting for \$3 billion. In 2006, a prevalence survey in England, Wales, Northern Ireland, and the Republic of Ireland found 7.6% of patients have an infection that was not present at the time of their acute hospital admission. Inclusion of efficient, fast, handheld and economical chemical
10
15
imaging devices in healthcare environment would help to reduce the annual spending on HAIs.

[0003] Some of the methods which are currently used for the detection of biocontamination in healthcare settings include:

- Swab/wipe sampling and subsequent extraction and ex-situ detection using techniques
20 such as High Performance Liquid Chromatography (HPLC) or Enzyme Immunoassay (EIA). These methods for surface contamination analysis suffer from inefficiency and inaccuracy.
- ATP Bioluminescent Meter - this contamination monitoring system works by detecting the presence of adenosine triphosphate (ATP) crucial to conducting energy in all living cells.
25 The presence of ATP on a surgical instrument, light switch or bed rail, for example, indicates the presence of biological contaminants. The testing process involves swabbing the surface in question with sterile water, and then exposing the swab to an enzyme (Luciferase) that reacts to ATP in the bio luminometer. One particular study demonstrates that ATP bioluminescence is not suitable for accurately detecting the number of bacteria
30 on a test surface over a range of concentrations, specifically <103 CFU/cm.
- Other sophisticated and more sensitive surface techniques such as Secondary Ion Mass Spectrometry (SIMS), X-Ray Photoelectron Spectroscopy (XPS), Scanning Electron Microscopy (SEM) are too expensive and complex to handle (high vacuum is often required) for in-situ contamination analysis.

[0004] At present, none of the available methods are ideal and there remains a need for improved means of monitoring biocontamination. A recent study has demonstrated that nearly one-third of high-touch, highrisk objects in hospital patient rooms remain contaminated for the next patient.

- 5 [0005] Perhaps the most promising techniques for providing a convenient method of monitoring biocontamination are those where the sample is ionized or otherwise atomized whilst causing minimal damage. Such techniques include desorption electrospray ionization (DESI), laser induced breakdown spectroscopy (LIBS) and plasma assisted desorption ionization (PADI).
- 10 [0006] Considering plasma based techniques, in order to be convenient for use in healthcare environments, the device for generating the plasma should be small in size and preferably be handheld. Ideally, the device will be capable of operating from a battery or other portable power source, and also be capable of operating at ambient temperature without requiring the presence of an inert gas, such as helium. In order to be versatile, the
- 15 device should be capable of volatilizing the sample from any surface such that the resulting volatilized sample may be detected by a suitable detection means.

- [0007] In Law and Anghel, 2012¹, a compact solid-state self-resonant drive circuit is described that is intended to drive an atmospheric pressure plasma (APP) jet and a parallel-plate dielectric barrier discharge of small volume (0.5 cm³). The resonant
- 20 frequency of the circuit is controlled by the selection of the switching power transistor and means of step-up voltage transformation (ferrite core, flyback transformer, or Tesla coil). In particular, the circuit incorporates a feedback mechanism for controlling the switching frequency to maintain the plasma jet. Despite the advantages of the proposed teachings of Law and Anghel, in common with most other plasma sources, the device may only be
- 25 operated with helium gas, argon gas, or a mixture of both. Additionally, according to the described feedback system, the device is always operated at the resonant frequency of the transformer which means that the plasma jet produced would pose a potential hazard to users and/or thermally sensitive substrates. As such, there still exists a need for a plasma
- 30 source that is small enough so as to be conveniently used in a healthcare environment, and versatile for safe use on a wide range of surfaces.

¹ Law, V.J., and Anghel, S.D. (2012). Compact atmospheric pressure plasma self-resonant drive circuits. *Journal of Physics D: Applied Physics*, **45**, 075202 (14pp)

BRIEF SUMMARY OF THE DISCLOSURE

[0008] In accordance with a first aspect of the present invention there is provided an apparatus for generating a plasma, comprising:

5 an air-cored transformer having a primary coil connectable to a power source, and a secondary coil connected to an electrode for generating a plasma;

an amplifier connected to the air-cored transformer; and

a control system connected to the amplifier, the control system being configured to supply a drive signal to the primary coil via the amplifier;

10 wherein the control system is connected to the secondary coil and includes a feed-back system that detects the resonant frequency of the secondary coil during operation and adjusts the frequency of the drive signal so as to be supplied to the primary coil at a non-resonant frequency offset from the detected resonant frequency such that the output voltage generates a plasma, wherein the feedback system is further configured to detect the magnitude of the output current of the secondary coil
15 and adjust the non-resonant offset frequency of the drive signal to adjust the output current to compensate for detected changes in the magnitude of the output current so as to maintain a substantially constant output current.

[0009] The control system may include a phase locked loop (PLL) for generating the drive signal when power is supplied by the power source, wherein the PLL includes a
20 phase detector connected to the secondary coil to detect the resonant frequency of the secondary coil during operation.

[0010] The drive signal may comprise a periodic envelope function having packets containing a pulsed signal, where the frequency of the pulsed signal determines the frequency of the drive signal. The control system may include a microcontroller for
25 generating the envelope function in the drive signal. The microcontroller may be configured to adjust the frequency of the drive signal as part of said feed-back system. The frequency of the drive signal may be adjusted by the microcontroller to maintain the temperature of the generated plasma below a predetermined threshold temperature. The predetermined threshold temperature may be between 10°C and 30°C, and preferably
30 between 15°C and 25°C.

[0011] In one preferable embodiment, the microcontroller is configured to limit the number of pulses in each packet of the drive signal if the detected magnitude of output current of the secondary coil rises above a predetermined threshold current by a predetermined amount.

[0012] The microcontroller may be configured to limit the number of pulses in each packet of the drive signal if the rate of change of the output current of the secondary coil rises above a predetermined threshold rate by a predetermined amount. The microcontroller may be configured to prevent further pulses of the drive signal if the
5 detected magnitude of output current of the secondary coil rises above the predetermined threshold by 50% of the predetermined threshold.

[0013] In one embodiment, the control system includes an analogue-to-digital converter for converting the current waveform of the secondary coil to a digital signal. The analogue-to-digital converter may be a 10bit ADC.

10 [0014] The apparatus may further comprise an AC to DC converter, wherein the current waveform of the secondary coil passes through the AC to DC converter prior to passing through the analogue-to-digital converter, wherein the amplitude of the DC signal produced by the AC to DC converter represents the magnitude of output current of the secondary coil. The AC to DC converter may comprise a diode bridge rectifier.

15 [0015] In one embodiment, the electrode is a pin electrode.

[0016] In one embodiment, the amplifier is a Class E amplifier. In alternative embodiments, the amplifier is a Zero Voltage Switched (ZVS) or a Zero Current Switched (ZCS) amplifier.

[0017] The apparatus may further comprise a power source, wherein said power source
20 may be a battery, and preferably a 12 V battery.

[0018] In accordance with a second aspect of the present invention, there is provided a chemical detection system comprising:

an apparatus for generating a plasma according to the first aspect of the present invention; and
25 a detector arranged to detect chemicals volatised by the plasma.

[0019] In one preferable embodiment, the detector is a mass spectrometer. In an alternative preferable embodiment, the detector is an optical detector.

[0020] In accordance with a third aspect of the present invention, there is provided a method of operating an apparatus according to the first aspect of the present invention,
30 comprising the steps:

detecting the resonant frequency of the secondary coil during operation;

adjusting the frequency of the drive signal so as to be supplied to the primary coil at a non-resonant frequency offset from the detected resonant frequency such that the output voltage generates a plasma;

detecting the magnitude of the output current of the secondary coil; and

- 5 adjusting the non-resonant offset frequency of the drive signal to adjust the output current to compensate for detected changes in the magnitude of the output current so as to maintain a substantially constant output current.

BRIEF DESCRIPTION OF THE DRAWINGS

- 10 **[0021]** Embodiments of the invention are further described hereinafter with reference to the accompanying drawings, in which:

Figure 1 is a schematic overview of a circuit for generating a plasma source in accordance with an embodiment of the present invention;

Figure 2 shows the current growth during a pulse modulated signal;

- 15 Figure 3 shows the relationship between the frequency of the driving frequency supplied to the transformer and the output voltage of the system accordance with an embodiment of the present invention;

- Figure 4 shows various modes of operation of an embodiment of the present invention, where Figure 4(a) represents a typical operating condition, Figure 4(b)
20 represents an extreme operating condition where the current rises rapidly, and Figure 4(c) represents a fault condition where the current envelope changes abruptly; and

Figure 5 shows a detailed circuit diagram of a plasma source in accordance with an embodiment of the present invention.

25 DETAILED DESCRIPTION

- [0022]** Figure 1 shows an apparatus 10 for generating a plasma in accordance with an embodiment of the present invention. The apparatus 10 comprises a circuit having three main parts indicated by boxes 1, 2 and 3. Box 1 includes an air-cored (Tesla) transformer 12 having a primary coil 12a and a secondary coil 12b connected to an electrode 14 for
30 generating a plasma. The primary coil 12a of the transformer 12 is connectable to a power source 16, which, in the embodiment shown in Figure 1, is a 12V battery.

[0023] Box 2 includes an amplifier 18 that is connected to the air-cored transformer 12. The amplifier 18 may be any suitable amplifier, but is preferably a Class E amplifier , a

Zero Voltage Switched (ZVS) amplifier or a Zero Current Switched (ZCS) amplifier, as these topologies offer improved efficiency.

5 [0024] Box 3 represents a control system that is connected to the amplifier 18 and is configured to supply a drive waveform thereto which in turn provides a drive current to the primary coil 12a.

[0025] The control system 3 is connected to the secondary coil 12b (via the amplifier 18) and includes a feedback system that adjusts the frequency of the drive current supplied to the primary coil 12a to approach the frequency of a current waveform of the secondary coil 12b. The current waveform of the secondary coil 12b will always be at the resonant frequency of the coil in its surroundings where the actual resonant frequency will be determined by the electrical properties of the surroundings and the distance between the electrode 14 and the surroundings. The feedback system allows tracking of the actual resonant frequency and permits the output current to be monitored, and limited where necessary. In preferable embodiments where ZVS or ZCS is used, the feedback system
10 allows ideal operation with very high efficiency.

[0026] Crucially, the actual drive current supplied to the transformer 12 is offset so as to be supplied at a frequency that is a non-resonant frequency of the transformer 12 but still be capable of producing an output voltage at the secondary coil 12b that is sufficient for generating a plasma at the electrode 14.

20 [0027] In the non-limiting embodiment shown in Figure 1, the control system 1 includes a phase locked loop (PLL) component 22, an analogue-to-digital converter (ADC) 24 and a microcontroller 20.

[0028] The secondary coil 12b of the air-cored transformer 12 has an inductance L (due to the large number of turns) and capacitance C (due to both self-capacitance and capacitive coupling to its surroundings). Thus, the transformer 12 forms an LC circuit that resonates at a certain frequency f dependent on L and C, where $f = 1/(2\pi\sqrt{LC})$. The circuit has an extremely high Q value due to it having a large L and a small C. The effect of this is that very high voltages can be generated when the system is driven near the resonant frequency of the circuit. Thus, voltages capable of producing a plasma may be
25 generated from a relatively low voltage power source 16, such as a 12V battery.

[0029] Considering the specific non-limiting embodiment shown in Figure 1, the PLL 22 begins to generate a drive signal (current) at its centre frequency when the 12V potential difference is applied. Initially, the centre frequency of the PLL 22 is set close to the predicted resonant frequency of the transformer 12 (e.g. ~2MHz). This logic level signal, which is a continuous oscillating signal, is passed to the microcontroller 20 which
35

generates an envelope function in the drive current, breaking the continuous signal into periodic packets. In the non-limiting example where the centre frequency is set at 2 MHz, each cycle (or oscillation) has a period of 500 ns, so a packet of 400 oscillations has an envelope that is 200 μ s in duration. The packets are repeated in regular intervals, for example 1 ms intervals. This drive current, which is a relatively low current, is passed to the amplifier 18 via a MOSFET driver IC 19 (e.g. TC4452) to increase the current such that it is sufficient for switching the MOSFET driver 19 at MHz frequencies. This arrangement facilitates particularly efficient operation of the apparatus 10.

[0030] Since the resonant frequency of the circuit depends on the electrical properties of its surroundings, it is likely that the chosen default drive frequency will not be at the resonant frequency, and it may be far from the actual resonant frequency. To remedy this, the PLL 22 includes a phase detector connected to the secondary coil 12b to form a feedback system. The phase detector of the PLL 22 detects the current waveform of the secondary coil 12b and the PLL 22 adjusts the drive current supplied to the primary coil 12a to approach the frequency of the detected waveform. This approach ensures that the system always operates close to resonance and the plasma conditions are not strongly dependent on the surroundings (e.g. the proximity to and the composition of the sample material). However, it is not preferable for the system to operate precisely at resonance since this will often create a plasma that is potentially dangerous to the user (or other heat sensitive materials) due to high temperatures. As described in more detail below, the present invention remedies this by incorporating a mechanism for controlling the plasma conditions, whilst still providing an effective and versatile device. The circuit shown in Figure 1 incorporates a current sense resistor 32 for sensing purposes. In alternative embodiments, a secondary winding around the coil 12 could be utilized in place of the current sense resistor.

[0031] During each packet of pulses, the output voltage, and the corresponding current, increase in amplitude over many cycles, eventually reaching an equilibrium condition which is determined by the balance of energy input into the system and energy loss within the generated plasma. This is shown in Figure 2 where a packet of pulses can be seen to initially grow in amplitude before reaching an equilibrium condition where the current envelope is constant with a fixed envelope width.

[0032] In a preferable embodiment, the output current waveform of the secondary coil 12b (such as that shown in Figure 2) is passed through a diode bridge rectifier to provide a DC signal, where the amplitude of the resulting DC signal is representative of the discharge current of the system. This DC signal is then fed through an analogue-to-digital converter (such as a 10bit ADC) that is preferably integrated within the microcontroller 20.

[0033] Under normal operating conditions (for example, for non-conductive samples), the output current signal of the secondary coil 12b initially rises gradually (e.g. as shown in Figure 2). In order to allow a user controllable constant output current (thus achieving predictable plasma conditions), the microcontroller 20 is configured to adjust the frequency of the drive current, either towards resonance or way from it (whilst avoiding the actual resonant frequency) to change the output voltage to maintain control over the discharge (output) current over the entire packet of pulses. Thus, a substantially constant output current can be maintained and the temperature and size of the generated plasma can be controlled.

10 **[0034]** Figure 3 shows the relationship between the frequency of the driving frequency supplied to the transformer 12 and the output voltage of the system 10. The system 10 operates at a fixed input voltage (from the power source 16, e.g. battery). Due to the relationship between frequency of driving current and output voltage (shown in Figure 3), the output voltage may be adjusted by altering the frequency of the driving current. Thus, 15 the output voltage of the system 10 can be changed without varying the input voltage which would require a significantly more complex set-up and would not be particularly efficient or practical.

[0035] Variable output voltage is required because objects coming close to the generated plasma will cause a high electric field and a subsequently intense plasma. In 20 order to maintain constant operating conditions the output voltage should be reduced to compensate.

[0036] Under normal operating conditions, the secondary coil 12b will always oscillate at its resonant frequency regardless of what frequency it is driven at, hence the frequency of the current feedback will always be at the resonant frequency. The peak of the curve 25 shown in Figure 3 represents the resonance condition, where a maximum output voltage is achieved. In order to reduce the output voltage the transformer 12 needs to be driven off resonance. In the present invention, this is achieved using control system 3, which monitors the resonant frequency and the discharge (output) current. As the discharge current increases the control system 3 reduces the frequency of the drive current supplied 30 to the amplifier 18 in an attempt to maintain a constant plasma operating condition.

[0037] The double ended arrow in Figure 3 indicates the operating area of the present invention, i.e. a non-resonant frequency but where a notable output voltage is produced so that a plasma may be generated and maintained. The actual operating range of suitable non-resonant frequencies will depend on the frequency of operation of the system 10 and 35 must be determined experimentally. In the non-limiting example where the resonant frequency of the system 10 is ~2MHz, then a suitable operating range of non-resonant

frequencies could be 1.5 MHz +/- 300 kHz. Equally, the operating range could be on the high side of the resonant frequency and still achieve a reduced output voltage, for example at 2.5 MHz +/- 300 kHz. These ranges avoid the resonant frequency of the system 10 and so avoid the maximum output voltage which may lead to a dangerously hot plasma, especially when an object is brought close to the discharge. However, these ranges of driving frequency are still sufficient for producing and maintaining a plasma at the electrode 14. Since the resonant frequency of the secondary coil 12b will change depending on the electrical properties of the surroundings, the control system 3 will act to adjust the operating ranges accordingly.

10 **[0038]** Figure 4(a) shows an output current signal under normal operating conditions, where the control system 3 of the present invention maintains a constant current envelope with a fixed envelope width where the current remains below a current threshold (indicated by the dotted line).

15 **[0039]** Under extreme operating conditions, e.g. if the plasma generating electrode 14 is used in close proximity to a conductive or partially conductive sample, such as a wet biological material, the output current signal will rise rapidly. In cases such as these, the plasma generated is likely to become unstable within only a few cycles, potentially causing damage to the substrate. Figure 4(b) shows a current output signal where the current signal rises rapidly. The microcontroller 20 is configured to limit the number of pulses in each packet such that the current level is unable to rise far beyond the preset threshold (as indicated by the dotted line). Thus, the microcontroller 20 acts to curtail the pulse width of the output current signal to prevent arcing and/or substrate damage.

25 **[0040]** Figure 4(c) shows an output current signal where the current envelope changes abruptly, for example in the case of a fault such as the electrode 14 becoming grounded. In this case, the microcontroller 20 acts to terminate the pulse immediately such that only one pulse is applied during each packet. The short duration of the packets prevent the amplifier 18 being damaged.

30 **[0041]** Figure 5 shows a detailed schematic of a circuit 100 according to an alternative embodiment of the present invention. The circuit 100 shown in Figure 5 may be considered to be a preferable variation of the circuit described above in relation to Figure 1 and includes the same basic components. In the circuit 100 of Figure 5, the return path from the secondary coil 12b to the ADC 24 features a bridge rectifier 26 for converting the AC voltage which is representative of the current of the secondary coil 12b into DC. Additionally, the return path from the secondary coil 12b to the PPL 22 includes a diode clamp 28 for preventing overvoltage, and a Schmitt trigger 30. In Figure 5, the sample is indicated by numeral 15.

- [0042]** The apparatus for generating a plasma in accordance with the present invention can operate at ambient temperature in air (i.e. not requiring an inert gas). The electronic set-up of the invention permits a very small plasma source device to be made such that it may be in the form of a hand-held device, making it particularly suitable for use in healthcare environments such as hospital wards. In particular, in the case where a ZVS amplifier 18 is used, the primary coil 12a may be incorporated into the ZVS amplifier in the place of the usually present RF choke. This reduces the number of required components further permitting a compact device. Additionally, since the secondary coil 12b is resonant, the secondary coil 12b acts to filter the harmonics of the non-sinusoidal drive waveform, so no filtering or matching components are necessary. Furthermore, due to the voltages produced by the air-cored transformer, the device may operate with a removable, small power source such as a battery (e.g. a 12V battery). The resulting device is a compact, controllable pulse width modulated, air operable RF plasma source that is suitable for use on a range of surfaces (being capable of being used non-destructively).
- [0043]** Whilst preferable, the PLL 22 need not necessarily be included in the control system 3 within the scope of the present invention. In such embodiments, the detected output current of the secondary coil may be inputted into the microcontroller 20 (via an ADC or Schmitt trigger), and the initial start-up frequency of the drive signal could be programmed into the microcontroller 20.
- [0044]** In a further embodiment of the present invention, the plasma source may be used with a suitable detection means so that particles volatilized by the plasma may be detected. A particularly suitable detector is a mass spectrometer. Given that "miniature" mass spectrometers are now established, the small plasma source of the present invention may be combined with a similarly small mass spectrometer to create a convenient and effective detection system for analyzing a wide variety of surfaces. Alternatively, an optical detector may be used to detect light emitted from the plasma which contains information regarding the chemical makeup of the gas and any excited sample fragments. Suitable optical detectors may include a monochromator, a spectrometer, or a wavelength filtered photo diode.
- [0045]** In certain embodiments of the present invention, the plasma source may be used for decontamination. For example, the electrode 14 may be arranged in a liquid such that the plasma gives rise to ionised gas bubbles in the liquid, where the ionization has a decontaminating effect.
- [0046]** Throughout the description and claims of this specification, the words "comprise" and "contain" and variations of them mean "including but not limited to", and they are not intended to (and do not) exclude other moieties, additives, components, integers or steps.

Throughout the description and claims of this specification, the singular encompasses the plural unless the context otherwise requires. In particular, where the indefinite article is used, the specification is to be understood as contemplating plurality as well as singularity, unless the context requires otherwise.

5 **[0047]** Features, integers, characteristics, compounds, chemical moieties or groups described in conjunction with a particular aspect, embodiment or example of the invention are to be understood to be applicable to any other aspect, embodiment or example described herein unless incompatible therewith. All of the features disclosed in this specification (including any accompanying claims, abstract and drawings), and/or all of the
10 steps of any method or process so disclosed, may be combined in any combination, except combinations where at least some of such features and/or steps are mutually exclusive. The invention is not restricted to the details of any foregoing embodiments. The invention extends to any novel one, or any novel combination, of the features disclosed in this specification (including any accompanying claims, abstract and drawings),
15 or to any novel one, or any novel combination, of the steps of any method or process so disclosed.

[0048] The reader's attention is directed to all papers and documents which are filed concurrently with or previous to this specification in connection with this application and which are open to public inspection with this specification, and the contents of all such
20 papers and documents are incorporated herein by reference.

CLAIMS

1. An apparatus for generating a plasma, comprising:
 - an air-cored transformer having a primary coil connectable to a power source, and
 - 5 a secondary coil connected to an electrode for generating a plasma;
 - an amplifier connected to the air-cored transformer; and
 - a control system connected to the amplifier, the control system being configured to supply a drive signal to the primary coil via the amplifier;
 - 10 wherein the control system is connected to the secondary coil and includes a feed-back system that detects the resonant frequency of the secondary coil during operation and adjusts the frequency of the drive signal so as to be supplied to the primary coil at a non-resonant frequency offset from the detected resonant frequency such that the output voltage generates a plasma, wherein the feedback system is
 - 15 further configured to detect the magnitude of the output current of the secondary coil and adjust the non-resonant offset frequency of the drive signal to adjust the output current to compensate for detected changes in the magnitude of the output current so as to maintain a substantially constant output current..
2. An apparatus according to any preceding claim, wherein the control system includes a
- 20 phase locked loop (PLL) for generating the drive signal when power is supplied by the power source, wherein the PLL includes a phase detector connected to the secondary coil to detect the resonant frequency of the secondary coil during operation.
3. An apparatus according to claim 1 or 2, wherein the drive signal comprises a periodic
- 25 envelope function having packets containing a pulsed signal, where the frequency of the pulsed signal determines the frequency of the drive signal.
4. An apparatus according to claim 3, wherein the control system includes a
- 30 microcontroller for generating the envelope function in the drive signal.
5. An apparatus according to claim 4, wherein the microcontroller is configured to adjust the frequency of the drive signal as part of said feed-back system.

6. An apparatus according to claim 5, wherein the frequency of the drive signal is adjusted by the microcontroller to maintain the temperature of the generated plasma below a predetermined threshold temperature.
- 5 7. An apparatus according to claim 6, wherein the predetermined threshold temperature is between 10°C and 30°C, and preferably between 15°C and 25°C.
8. An apparatus according to any of claims 4 to 7, wherein the microcontroller is
10 configured to limit the number of pulses in each packet of the drive signal if the detected magnitude of output current of the secondary coil rises above a predetermined threshold current by a predetermined amount.
9. An apparatus according to any of claims 4 to 8, wherein the microcontroller is
15 configured to limit the number of pulses in each packet of the drive signal if the rate of change of the output current of the secondary coil rises above a predetermined threshold rate by a predetermined amount.
10. An apparatus according to claim 8, wherein the microcontroller is configured to
20 prevent further pulses of the drive signal if the detected magnitude of output current of the secondary coil rises above the predetermined threshold by 50% of the predetermined threshold.
11. An apparatus according to any preceding claim, wherein the control system includes
25 an analogue-to-digital converter for converting the current waveform of the secondary coil to a digital signal.
12. An apparatus according to claim 11, wherein the analogue-to-digital converter is a 10bit ADC.
- 30 13. An apparatus according to claim 11 or 12, further comprising an AC to DC converter, wherein the current waveform of the secondary coil passes through the AC to DC

converter prior to passing through the analogue-to-digital converter, wherein the amplitude of the DC signal produced by the AC to DC converter represents the magnitude of output current of the secondary coil.

- 5 14. An apparatus according to claim 13, wherein the AC to DC converter comprises a diode bridge rectifier.

15. An apparatus according to any preceding claim, wherein the electrode is a pin electrode.

10

16. An apparatus according to any preceding claim, wherein the amplifier is a Class E amplifier.

- 15 17. An apparatus according to any of claims 1 to 15, wherein the amplifier is a Zero Voltage Switched (ZVS) or a Zero Current Switched (ZCS) amplifier.

18. An apparatus according to any preceding claim, further comprising a power source.

19. An apparatus according to claim 18, wherein said power source is a battery.

20

20. An apparatus according to claim 19, wherein said battery is a 12 V battery.

21. A chemical detection system comprising:

- 25 an apparatus for generating a plasma according to any preceding claim; and
a detector arranged to detect chemicals volatilised by the plasma.

22. A chemical detection system according to claim 21, wherein the detector is a mass spectrometer.

- 30 23. A chemical detection system according to claim 21, wherein the detector is an optical detector.

24. A method of operating an apparatus according to any of claims 1 to 20, comprising the steps:

detecting the resonant frequency of the secondary coil during operation;

5 adjusting the frequency of the drive signal so as to be supplied to the primary coil at a non-resonant frequency offset from the detected resonant frequency such that the output voltage generates a plasma;

detecting the magnitude of the output current of the secondary coil; and

10 adjusting the non-resonant offset frequency of the drive signal to adjust the output current to compensate for detected changes in the magnitude of the output current so as to maintain a substantially constant output current.

25. An apparatus for generating a plasma substantially as hereinbefore described with reference to the accompanying drawings.

15

26. A chemical detection system substantially as hereinbefore described with reference to the accompanying drawings.

27. A method of operating an apparatus substantially as hereinbefore described with
20 reference to the accompanying drawings.

1/3

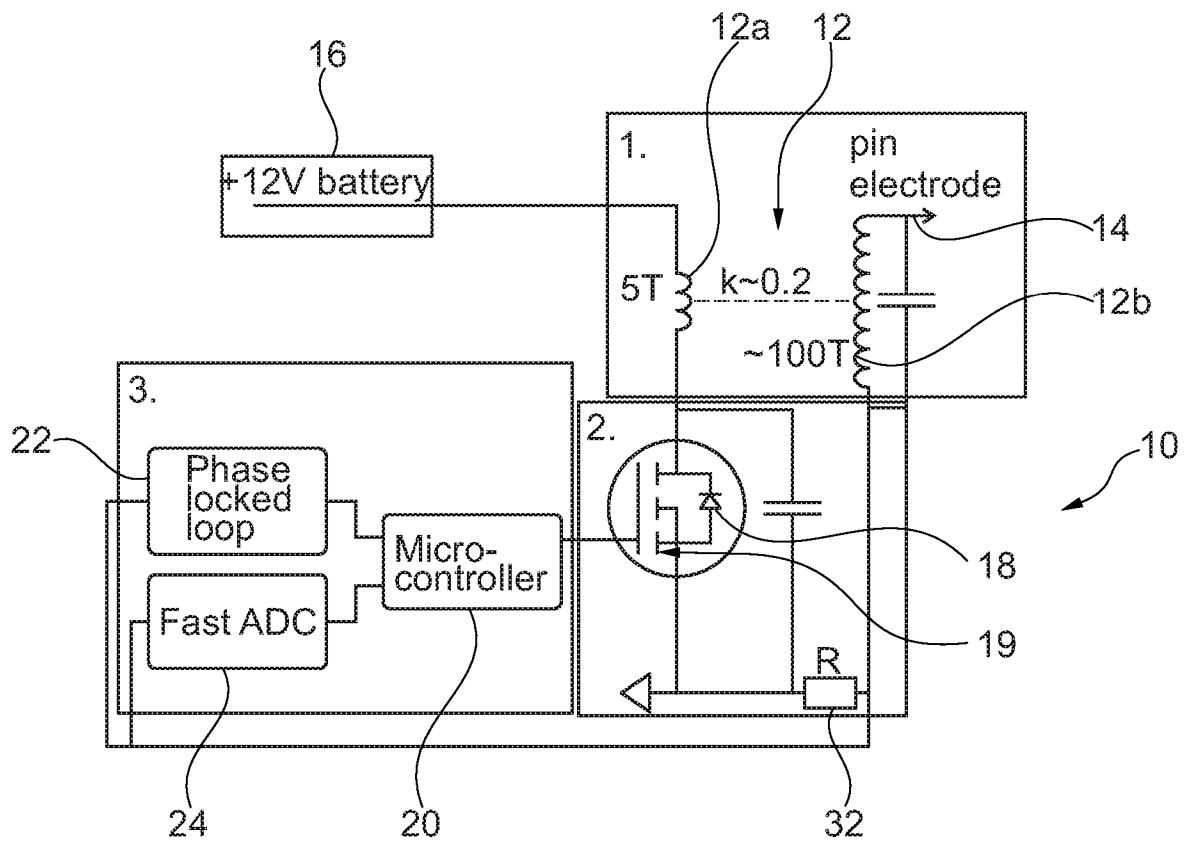


Fig. 1

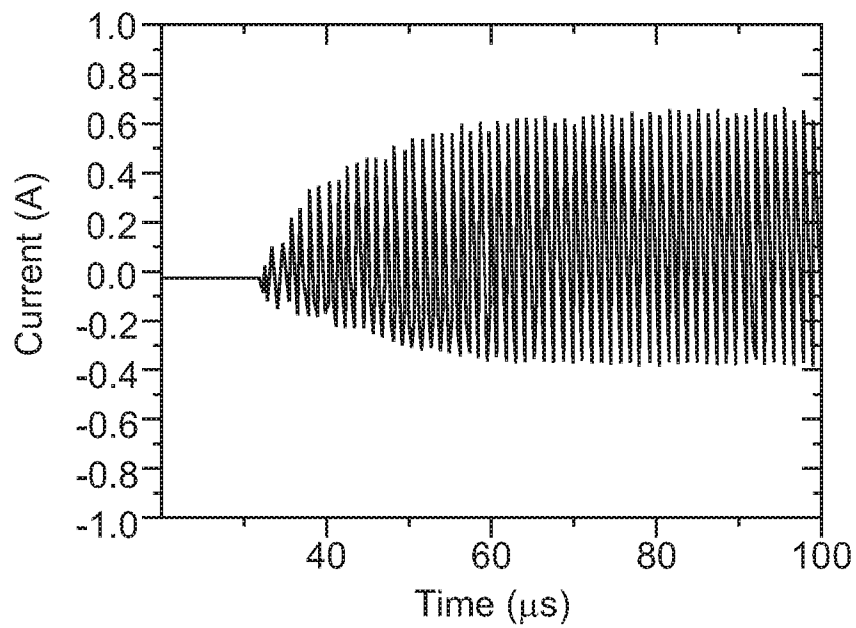


Fig. 2

2/3

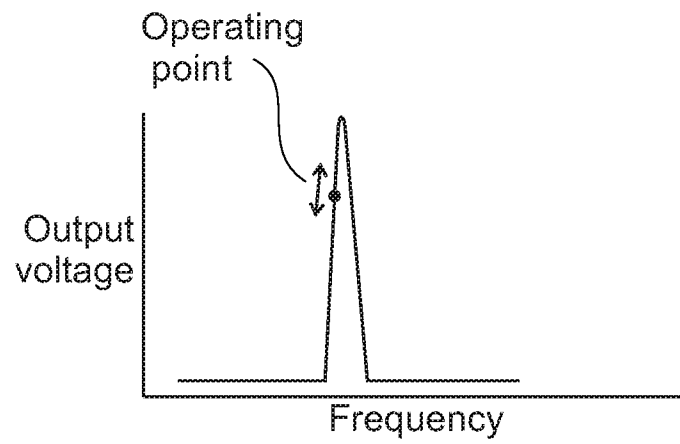


Fig. 3

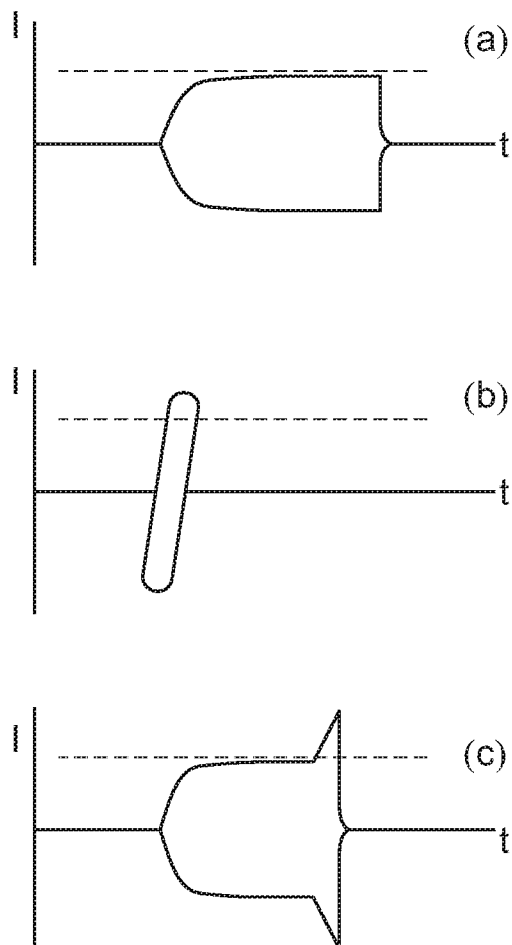


Fig. 4

3/3

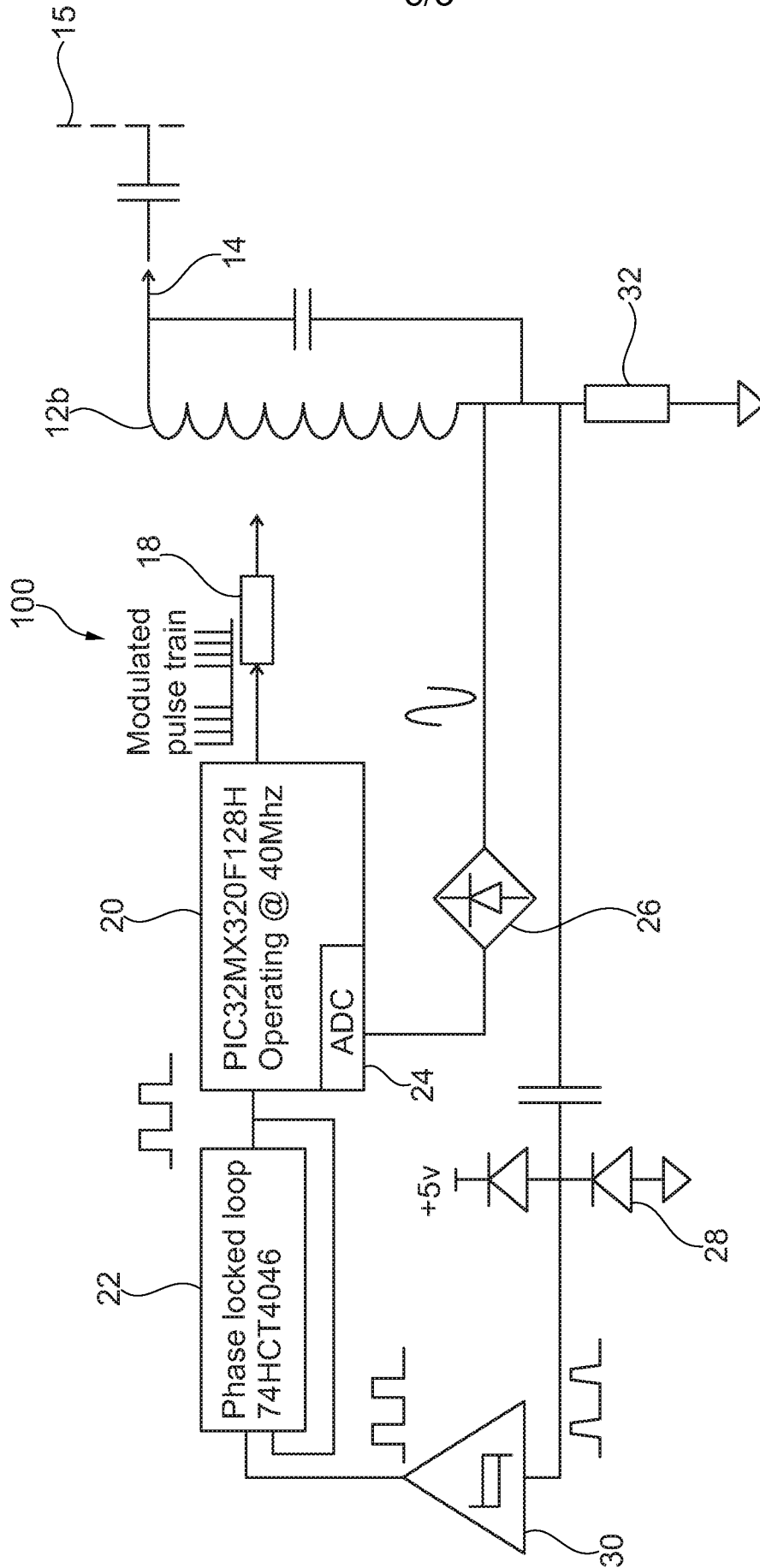


Fig. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2013/053083

A. CLASSIFICATION OF SUBJECT MATTER

INV. H02M7/538 A61B18/12 H01J7/32
ADD.

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)

H02M H01J A61B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 2 469 699 A2 (FRIEDRICH DANIEL [US]; ERICKSON ROBERT [US]; GILBERT JAMES [US]) 27 June 2012 (2012-06-27) paragraphs [0034], [0035], [0061], [0062]; figures 1,4 -----	1,24



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"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

26 February 2014

Date of mailing of the international search report

07/03/2014

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Taccoen, J

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2013/053083

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 2469699	A2	27-06-2012	
		AU 2011265566 A1	12-07-2012
		CA 2762649 A1	23-06-2012
		EP 2469699 A2	27-06-2012
		JP 2012135203 A	12-07-2012
		US 2012215216 A1	23-08-2012
