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des brevets



(11)

EP 2 339 689 A1

(12)

EUROPEAN PATENT APPLICATION

(43) Date of publication:

29.06.2011 Bulletin 2011/26

(51) Int Cl.:

H01P 1/26 (2006.01)(21) Application number: **09275130.4**(22) Date of filing: **22.12.2009**

(84) Designated Contracting States:

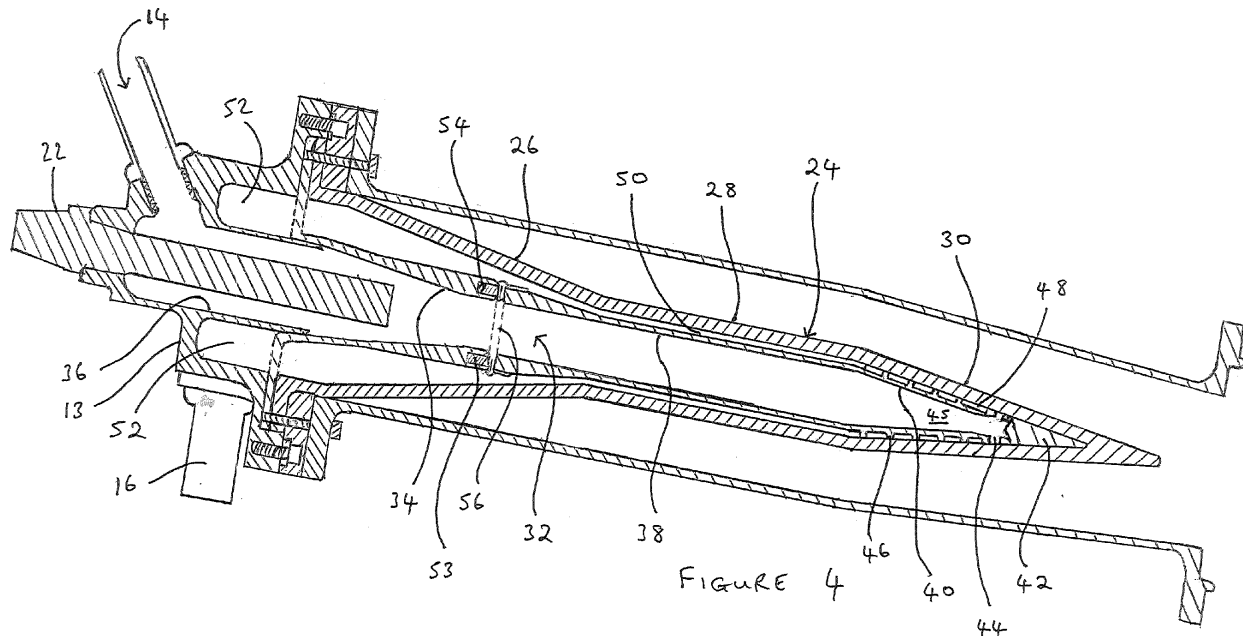
**AT BE BG CH CY CZ DE DK EE ES FI FR GB GR
HR HU IE IS IT LI LT LU LV MC MK MT NL NO PL
PT RO SE SI SK SM TR**

Designated Extension States:

AL BA RS(71) Applicant: **BAE Systems PLC****London SW1Y 5AD (GB)**(72) Inventor: **The designation of the inventor has not yet been filed**(74) Representative: **BAE SYSTEMS plc****Group IP Department****P.O. Box 87****Warwick House****Farnborough Aerospace Centre****Farnborough****Hampshire GU14 6YU (GB)**(54) **Absorptive microwave load**

(57) A method is provided for absorbing microwave energy comprising circulating energy- absorptive fluid along a path which rotates relative to an axis of propagation of the microwaves in a waveguide. Alternatively

or in addition, the method comprises directing micro-waves into a flow of water or other liquid which is not substantially greater in depth than the skin depth of the liquid at the frequency of the microwaves.



Description

[0001] The invention relates to methods and apparatus for absorbing microwave energy.

[0002] It is known to employ water in absorptive microwave loads. For example it may be used as a circulating coolant for removing heat from a lossy dielectric structure which absorbs the microwave energy. Alternatively it may be more directly employed as the energy-absorbing material, by being circulated around a path which exposes it to the microwave radiation.

[0003] The present invention is directed to the efficient use of water or other fluids in absorptive microwave loads, both as a coolant and as an energy absorber. Use of de-ionised or distilled water in particular is preferred to limit contamination of the inside of a load, but a mixture of water and glycol (the loss tangent of the mixture depending upon their relative proportions) or another known type of fluid, selected according to its microwave and heat-absorbing properties, may be used.

[0004] In one aspect, the present invention provides a method of absorbing microwave energy comprising circulating energy-absorptive fluid along a path which rotates relative to an axis of propagation of the microwaves in a waveguide.

[0005] The fluid may absorb energy either by thermal transfer, or by direct absorption of microwave energy.

[0006] In a second aspect, the present invention provides an absorptive microwave load comprising a waveguide for receiving microwaves to be absorbed, the waveguide having a propagation axis along which in operation the microwaves propagate, means for absorbing the microwaves and means for circulating a fluid to remove heat generated by said absorption, characterised in that the circulating means are configured to cause the fluid to follow a flow path which rotates around the propagation axis.

[0007] By directing the fluid to flow in a path which rotates around the propagation axis, the risk of hot-spots arising in the load is reduced. Such hot-spots, i.e. regions of the load at which the energy transfer rate per unit area (power density) is abnormally high can arise from the geometry of the load, or from the polarisation of the microwaves.

[0008] By causing the fluid to follow the rotating path, it can systematically sweep the area exposed to the microwaves.

[0009] Preferably the circulating means are configured to cause the fluid to follow a helical path around the propagation axis.

[0010] The helical path may increase in radius along the propagation axis in the direction of microwave propagation.

[0011] As noted, the fluid may be directed to pass over or through the means for absorbing the microwaves, for example a lossy dielectric structure exposed to the microwaves, e.g. a silicon carbide structure.

[0012] Alternatively, the means for absorbing the mi-

crowaves may comprise the circulating fluid itself. Preferably the circulating fluid then is a liquid, for example water or another polar liquid such as ethanol.

[0013] In that event, the flow passage may have a cross-section such that the depth of the fluid therein is not substantially greater than the skin depth of the liquid at the microwave frequency range for which the waveguide is configured to operate.

[0014] Thus in a third aspect, the invention provides a method of absorbing microwave energy comprising directing microwaves into a flow of water or other microwave-absorptive liquid which is not substantially greater in depth than the skin depth of the liquid at the frequency of the microwaves.

[0015] In a fourth aspect, the invention provides an absorptive microwave load comprising a waveguide configured to propagate microwaves in a selected frequency band, and means defining at least one flow path through which in operation water or another microwave-absorptive liquid is passed, the flow path being positioned such that the microwaves are incident on the liquid and being shaped such that the depth of the liquid on which the microwaves are incident is not substantially greater than the skin depth of the liquid at the frequency of the microwaves. If a greater liquid flow rate is required, the liquid depth may be increased to preferably between one and two skin depths, or more preferably to more than two skin depths.

[0016] By "skin depth" is meant the depth at which the current density induced by the microwave has fallen to zero (?), i.e. of its value at the surface of the water [RH - this doesn't make sense at the moment - please correct wording]. Its value at a frequency f is given by

$$\delta^2 = \rho / \pi f \mu_0 \mu_r$$

where

δ = skin depth

ρ = bulk resistivity (ohm-metres)

f = frequency (Hertz)

μ_0 = permeability of free space (Henrys/meter) = $4\pi \times 10^{-7}$

μ_r = relative permeability.

[0017] For pure water, $\delta = 1.25\text{mm}$ approximately for $f = 9.5\text{ GHz}$

[0018] These latter two aspects of the present invention recognise that the majority of the energy absorption takes place within the skin depth, and that a compact and efficient absorptive load can be achieved using shallow cooling channels and a relatively small volume of

water or other energy-absorbing liquid. Of course, the flow rate of the liquid must be sufficient to transport the energy away to a heat exchanger or other heat sink as quickly as it is absorbed from the microwaves.

[0019] Preferably the width of the cross-section of the flow passage is several times its depth, for example at least three and preferably four or five times.

[0020] The circulating means may comprise a structure extending within the waveguide along the propagation axis and containing at least one internal passage defining said flow path.

[0021] The structure may comprise a radially inner portion and a surrounding radially outer portion, the at least one flow passage being defined between the inner and outer portions.

[0022] The inner and outer portions may be of circular cross-section.

[0023] The inner and outer portions may taper towards a microwave-entry end of the waveguide.

[0024] The inner structure may comprise a further flow path for conducting the fluid to or from the first-mentioned flow path.

[0025] The further flow path may communicate with the first-mentioned passage towards the end of the tapered part of the inner structure.

[0026] At least the said end of the tapered part may be moveable relative to the remainder of the inner structure thereby to compensate for differential expansion of the inner and outer portions of the structure.

[0027] The said moveable part may be resiliently biased relative to the remainder of the inner portion of the structure.

[0028] The invention now will be described merely by way of example with reference to the accompanying drawings wherein:-

Figure 1 shows an absorptive microwave load according to the present invention;

Figures 2 and 3 show parts of the load of Figure 1; and

Figure 4 is a longitudinal section through the load of Figure 1.

[0029] Referring to Figures 1 and 2, a prototype absorptive load according to the invention comprises a waveguide 10 of circular cross-section and having a longitudinal axis of propagation. Within the waveguide is an absorptive structure 12 forming an axisymmetric termination of the waveguide. Connections 14, 16 in the base 13 of the structure 12 provide for the circulation of water through the interior of the structure as described hereinafter. The base 13 of the absorptive structure 12 is fixed via a flange 18 to a corresponding flange 20 of the waveguide 10. In this prototype example, a heater 22 is provided for calibration purposes; in a production version it would be replaced by a sensor to measure the water

outlet temperature.

[0030] Referring also to Figures 3 and 4, the absorptive structure 12 comprises an outer sleeve 24 of dielectric material, here polytetrafluoroethylene (PTFE), the sleeve wall being 5mm thick. The sleeve comprises a tapered conical end 30, a cylindrical central section 28 and a flared conical base section 26. Within the sleeve 24 is an inner pipe 32 comprising a base portion 34 which connects to an inlet manifold 36 within the base of the structure 12, a central generally cylindrical portion 38, a tapered frusto-conical portion 40 and a solid conical end 42. A four-hole radial port 44 from an internal bore 45 of the pipe is located between the parts 40 and 42.

[0031] The sleeve 24 fits over the inner pipe 32 such that the end 42 of the inner pipe fits snugly within the tapered end 30 of the sleeve. The tapered portion 40 has an external helical band 46, the external diameter of which also fits snugly within the tapering portion 30 of the sleeve 24. There is thereby provided a helical flow path 48 defined by the band 46 and the parallel internal and external conical surfaces of the sleeve 24 and the portion 40. This helical flow path extends from the port 44 to the junction between the portions 38 and 40 of the pipe 32.

[0032] The portions 34, 38 are spaced from the inner wall of the sleeve 24 so as to provide an annular flow path 50. The flow path 50 enlarges radially around the base portion 34 of the pipe 24, due to the outward flare of the sleeve base section 26 relative to the base portion 34 of the pipe 32. The flow path 50 communicates with an annular gallery 52 in the base of the structure 12 and thence with the outlet connection 16.

[0033] In this example the cross-section of the helical flow path 48 is 8mm wide x 2mm deep. The waveguide 10 is dimensioned for use at X-band frequencies (7 to 11 GHz). The skin depth of water at 7 GHz is approximately 2.0mm, and at 11 GHz it is approximately 1.15mm. Thus the depth of the helical flow path 48 is not substantially greater than the skin depth throughout the operating frequency range of the waveguide. The 2mm depth is maintained also in the annular section 50 of the flow path, where bounded by the cylindrical portion 38 of the pipe 32.

[0034] In operation of this prototype apparatus, water passes into it via the connector 14, and through manifold 36 and the bore 45 of pipe 32 to the port 44. Thence it passes around the helical flow path 46, rotating around the propagation axis of the waveguide as it does so, to the annular flow path 50 and then to the outlet connection 16 via the annular gallery 52. Most of the microwave energy is absorbed over the leading tapered portion 30, 40 of the absorptive structure, and the flow rate of the water is chosen so that it is turbulent (Reynolds number >4000) at least in the helical flow path 48. This promotes mixing of the water whilst it is absorbing energy, and reduces the likelihood of local boiling. In experimental use of the apparatus, for an input microwave power of 10kW, a water flow rate of 3 litres/min resulted in a water temperature

rise of 47.6°C without local boiling. The Reynolds number, based on an equivalent hydraulic diameter for the 8x2mm cross section of 4mm was 3.6×10^4 , well into a turbulent flow regime.

[0035] Most of the power in incident microwaves is carried by the linearly polarised TE₁₁-mode electromagnetic wave which, in the preferred annular helical flow path 48 and, to a lesser extent in the annular flow path 50, produces a power density which varies with $\cos^2 \phi$ around the propagation axis, where ϕ is the angular displacement about the propagation axis relative to the plane of polarisation. Standing waves are substantially avoided within the load due to the effective absorption of microwaves by the water. Thus, there is little variation in power density along the propagation axis of the waveguide. Thus, the power density is at its greatest along the E-plane of the load. The advantageous choice of a helical flow path 48 helps not only to avoid localised boiling of the water along that region 30, 40 of the load but also thereby prevents the load reflecting power and damaging the microwave source, as may happen if the water were to boil.

[0036] Relatively little microwave energy absorption takes place in the downstream portion 50 of the flow path, so rotation about the propagation axis and a turbulent flow regime are less important. However, should either be required, it is a simple matter to extend the helical band 46 further towards the base 13; indeed if desired it can extend throughout the flow region defined between the sleeve 24 and the pipe 32. The cost of doing so however is a greater pressure drop through the apparatus: consideration would need to be given in each case to the structural integrity of the sleeve 24, and also its tendency to expand under pressure and thereby permit leakage around the helical band 46.

[0037] Thermal expansion of the sleeve may in any event lead to leakage around the band 46 in the tapered portion 30 of the sleeve 24. To counteract this, the portions 38, 40, 42 of the pipe 32 are made axially moveable relative to the portion 34. This is achieved by the portion 38 being slidably received in the end of the portion 34 and biased away from it by a compression spring 53 contained in an axially-facing annular pocket 54 or, preferably, by a ring of eight small axially-facing compression springs 53 held within evenly spaced pockets 54 formed in the end of the portion 34. An o-ring 56 between the sliding surfaces guards against leakage between the portions 34, 38. Expansion of the sleeve 24, both longitudinal and radial, is accommodated by the portions 40, 42 being pushed further into the tapered end 30 of the sleeve. Sealing contact between the band 46 and the inside surface of the sleeve 24 thus is maintained, and even more importantly the solid end 42 remains a snug fit in the end of the sleeve 24. This prevents water entering and being trapped in the tip of the sleeve 24, where microwave energy absorption by the water would be at a maximum (about 4.5MW/kg of water, at 10kW). If water were present it thus would vaporise explosively, and destroy

the end of the sleeve. The contacting surfaces of the sleeve 24 and the tip portion 42 may also be sealed with grease (e.g. silicone grease M494 from ACC Silicones) further to exclude water ingress.

[0038] If some leakage around the band 46 can be tolerated, it is sufficient to make the solid tip 42 of the pipe axially moveable, for example by resiliently mounting it as a separate component on the end of portion 40 of the pipe. In another alternative construction, the resilient mounting can be between the portion 40 and the portion 38 of the pipe 32.

[0039] In the prototype apparatus the sleeve 24 was of PTFE. Other materials may be used: polyether ether ketone (PEEK) for example has good mechanical properties, and is more resistant to the X-rays which are likely to be produced by a high-power electron beam source, such as a travelling wave amplifier. As with a PTFE sleeve, care would be needed to ensure that microwave heating of the water does not take a PEEK sleeve beyond its maximum working temperature. Another possible material is a glass ceramic such as MACOR[®] of Corning Inc. This material has better thermal mechanical and X-ray resistant properties, but has a relatively high dielectric constant, which may necessitate the sleeve wall being made thinner and thus potentially fragile.

[0040] Although it is convenient to use water both as a microwave energy absorber and as a means of transporting-away the absorbed energy, some aspects of the invention can be used with fluids which do not absorb microwave energy to a significant extent. Thus, if the sleeve 24 is made of a microwave absorbing material (for example silicon carbide) the water can be used just for cooling. The need to ensure that absorbed energy is removed from areas of high power density remains however, and consequently the helical flow path, or other method of providing a rotating flow about the waveguide propagation axis, still offers potential advantages.

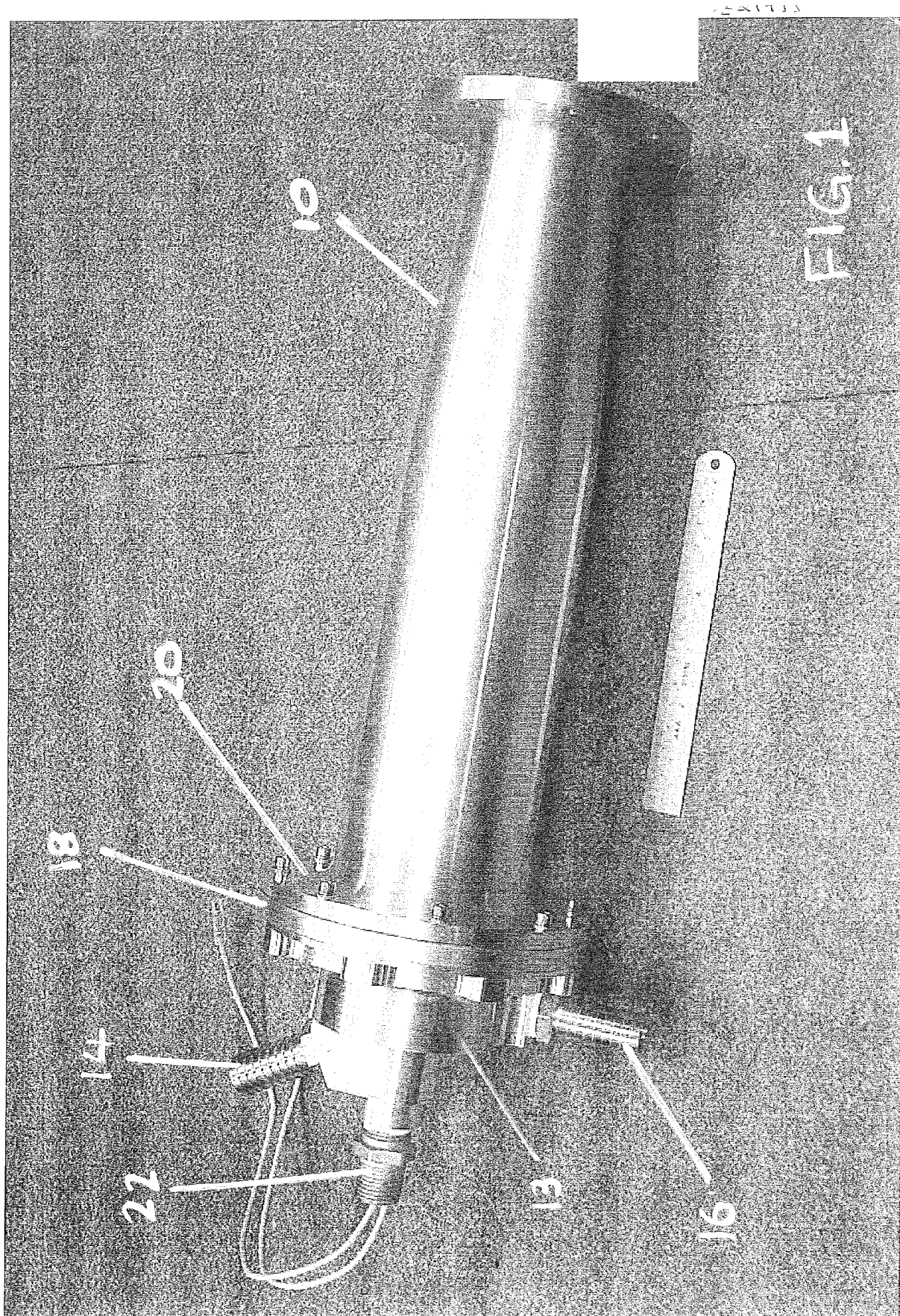
[0041] The direction of flow through the apparatus may be reversed, so that the fluid enters via the connection 16 and leaves via the connection 14. In embodiments where the fluid acts as a coolant rather than microwave energy absorber, this may result in somewhat higher heat transfer efficiency because the coolest fluid entering via the connection 16 flows first in contact with the coolest parts of the sleeve 24, namely the conical base section 26 and the cylindrical central section 28.

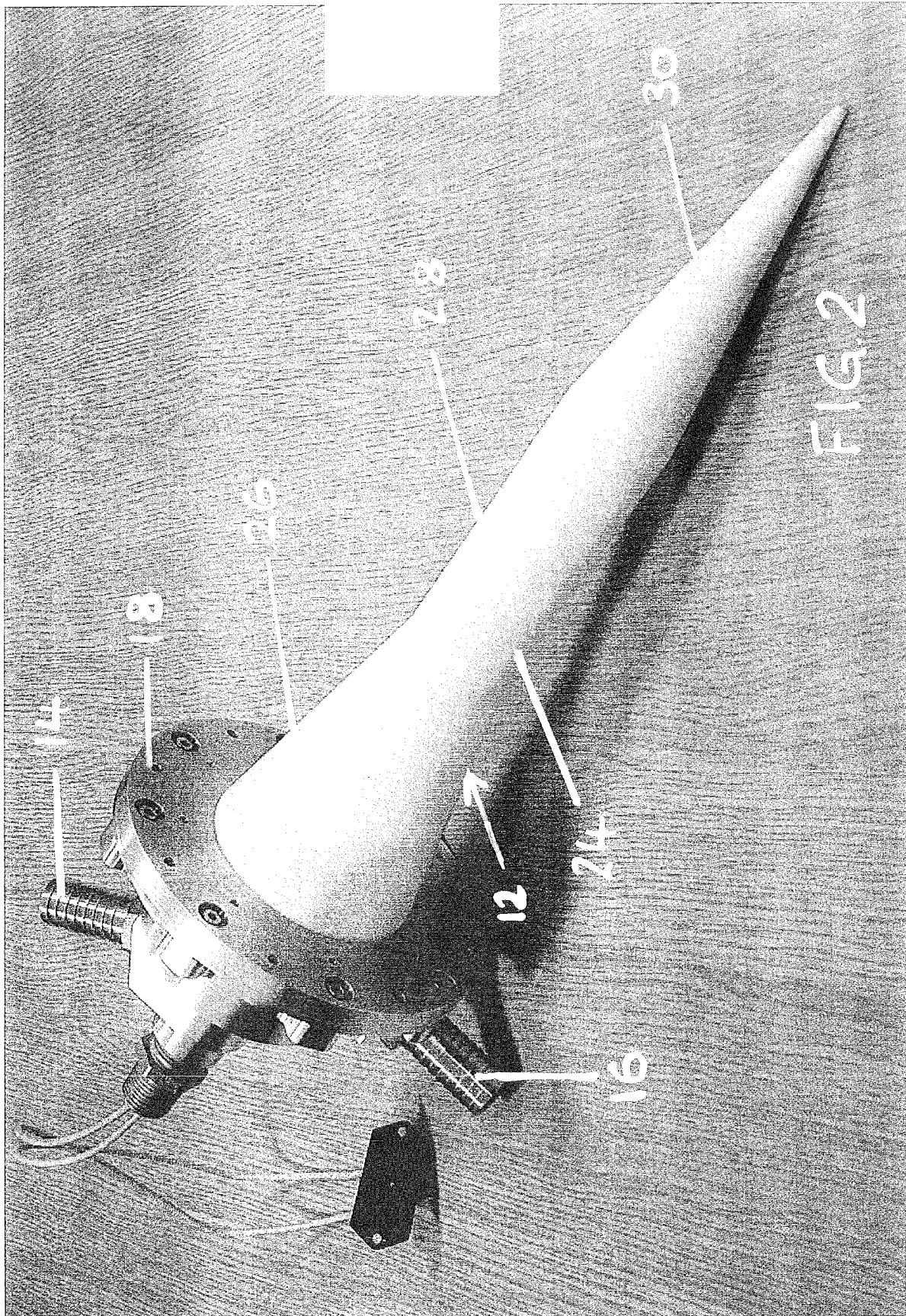
[0042] The invention also includes any novel feature or combination of features herein disclosed, whether or not specifically claimed.

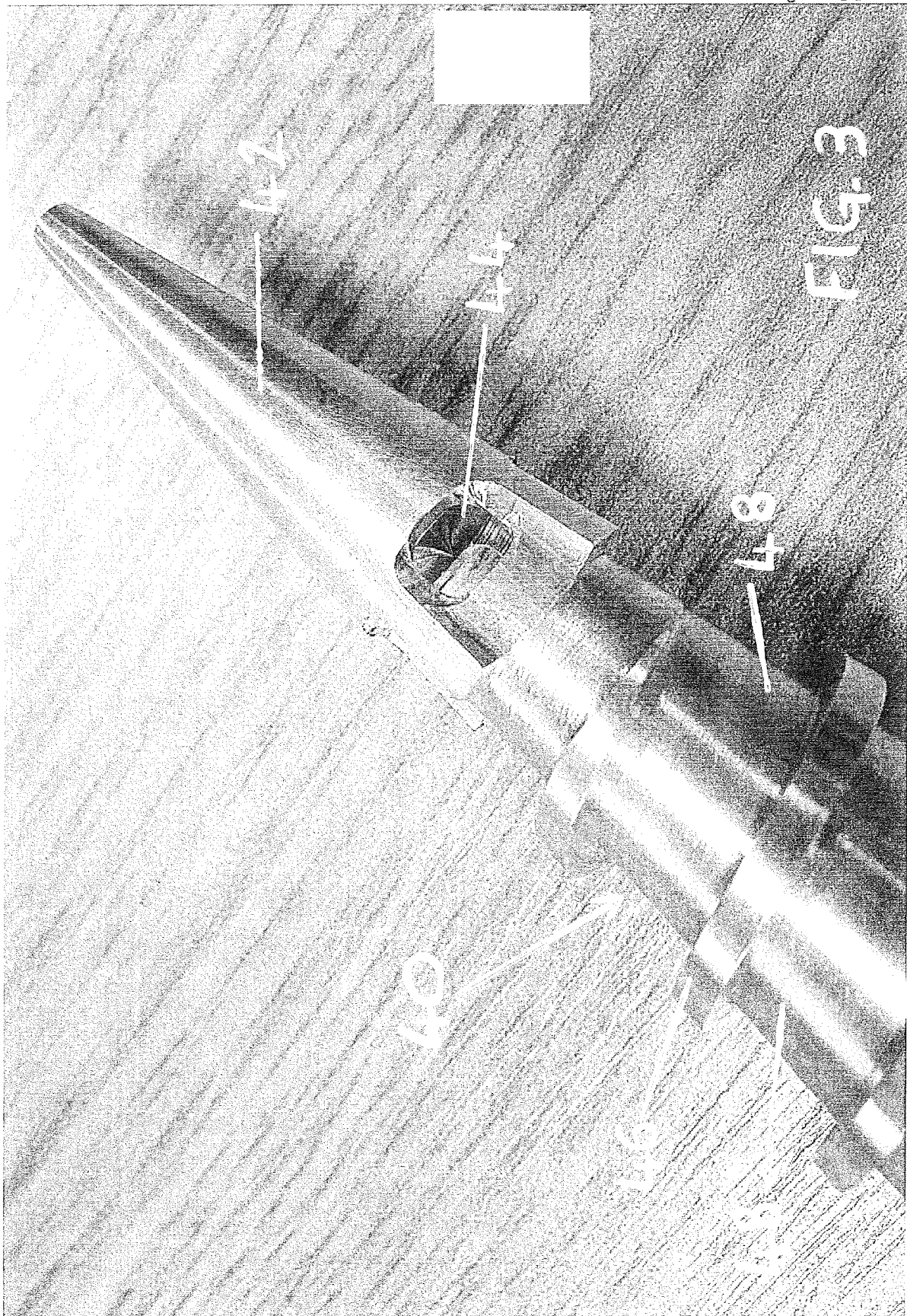
Claims

1. A method of absorbing microwave energy comprising directing microwaves into a flow of water or other microwave-absorptive liquid which is not substantially greater in depth than the skin depth of the liquid at the frequency of the microwaves.

2. The method of claim 1 comprising circulating the flow of liquid in a path which rotates about an axis of propagation of the microwaves in a waveguide.
3. An absorptive microwave load comprising a waveguide configured to propagate microwaves in a selected frequency band, and means defining at least one flow path through which in operation water or another microwave-absorptive liquid is passed, the flow path being positioned such that the microwaves are incident on the liquid and being shaped such that the depth of the liquid on which the microwaves are incident is not substantially greater than the skin depth of the liquid at the frequency of the microwaves. 5 10 15
4. The load of claim 3 wherein the means defining at least one flow path comprises circulating means for circulating the flow of liquid in a path which rotates about an axis of propagation of the microwaves in a waveguide. 20
5. The load of claim 4 wherein the circulating means is configured to cause the liquid to follow a helical path around the propagation axis. 25
6. The load of claim 5 wherein the helical path increases in radius along the propagation axis in the direction of microwave propagation. 30
7. The load of claim 4, 5 or 6 wherein the circulating means comprise a structure extending within the waveguide along the propagation axis and containing at least one internal passage defining said flow path. 35
8. The load of claim 7 wherein the structure comprises a radially inner portion and a surrounding radially outer portion, the at least one flow passage being defined between the inner and outer positions. 40
9. The load of claim 8 wherein the inner and outer portions are of circular cross-section.
10. The load of claim 8 when dependent from claim 6, wherein the inner and outer portions of the structure taper towards a microwave-entry end of the waveguide. 45
11. The load of claim 8, 9 or 10 wherein the inner portion of the structure comprises a further flow path for conducting the fluid to or from the first-mentioned flow path. 50
12. The load of claims 10 and 11 wherein the further flow path communicates with the first-mentioned path towards the end of the tapered part of the inner structure. 55
13. The load of claim 12 wherein at least the said end of the tapered part is moveable relative to the remainder of the inner structure thereby to compensate for differential expansion of the inner and outer structure.
14. The load of claim 13 wherein the said moveable part is resiliently biased relative to the remainder of the inner structure.







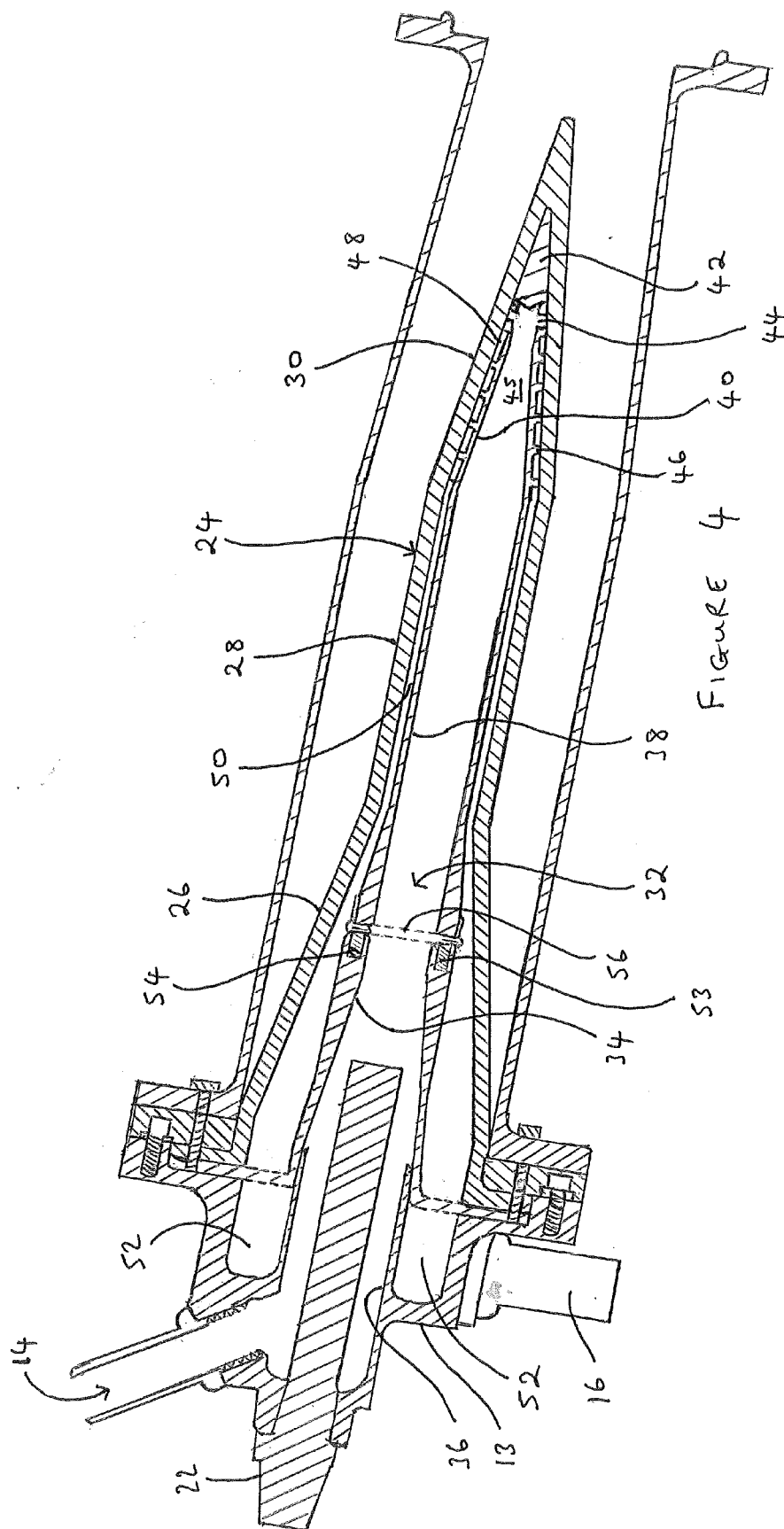


FIGURE 4



EUROPEAN SEARCH REPORT

Application Number
EP 09 27 5130

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	US 2006/087381 A1 (JOHNSON RAY M [US]) 27 April 2006 (2006-04-27) * paragraph [0002] - paragraph [0003] * * paragraph [0007] - paragraph [0008] * * paragraph [0013] - paragraph [0018] * * paragraph [0026]; figures 1-3 * * paragraph [0032] - paragraph [0041]; figure 4 *	1-14	INV. H01P1/26
X	JP 63 250902 A (TOSHIBA CORP) 18 October 1988 (1988-10-18) * abstract; figures 1,2 *	1,3	
A	US 3 369 198 A (CAMPBELL RICHARD A ET AL) 13 February 1968 (1968-02-13) * column 1, line 53 - column 2, line 16; figures 1-4 *	1,3	
A	US 3 904 993 A (JAMES BERTRAM G) 9 September 1975 (1975-09-09) * column 2, line 57 - column 3, line 25; figure 3 *	1,3	TECHNICAL FIELDS SEARCHED (IPC)
A	US 4 638 268 A (WATANABE MASAKAZU [JP] ET AL) 20 January 1987 (1987-01-20) * column 1, line 8 - line 55 * * column 2, line 12 - line 29; figures 4,5 *	1,3	H01P
The present search report has been drawn up for all claims			
Place of search The Hague		Date of completion of the search 18 May 2010	Examiner Pastor Jiménez, J
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document			

EPO FORM 1503 03.82 (P04-C01)

**ANNEX TO THE EUROPEAN SEARCH REPORT
ON EUROPEAN PATENT APPLICATION NO.**

EP 09 27 5130

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report.
The members are as contained in the European Patent Office EDP file on
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18-05-2010

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