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(54) **Electron beam devices.**

(57) An electron beam device comprises a cold cathode 1, modulation means 2 and an anode 3. The components of the device have a longitudinal configuration and enable an electron beam produced by the cathode 1 to be transversely modulated with a microwave signal transmitted along the modulator waveguide structure 2. The modulated output may be propagated along the elongate anode 3 or may be arranged to propagate through the anode substrate 5 and interface directly with an antenna or other circuit element.

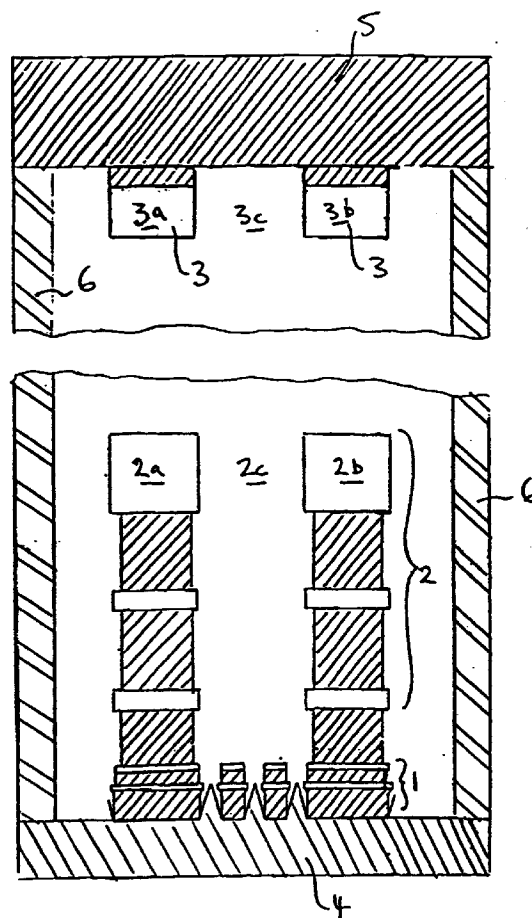


Fig. 1

This invention relates to electronic devices employing cold cathodes, and particularly, but not exclusively, to cathodes of the field emission type.

Most electronic devices operate as the result of longitudinal modulation of the electric current in the direction of the current. This is particularly true of solid state devices but it is also true of many classes of vacuum electronic devices. In these, the modulation of the velocity in the direction of the current produces little immediate modulation of the current unless the electrons of the beam are of very low velocity. For such low velocity beams modulation results in some electrons being returned to the cathode. For higher velocity beam devices the resulting velocity modulation is converted to current modulation only if the beam is permitted to traverse a sufficiently long path. Both of these features are undesirable. In the former case, with a field emission cold cathode in particular, the returned electrons will be collected by extraction grids biased at about 100V and will result in significant energy dissipation. In the latter case, the long drift tube path length results in ungainly device geometries which are difficult to manufacture.

In contrast, transverse modulation does not suffer from either of the above drawbacks. Firstly, the net forward velocity of the electron beam is not reduced by the modulation and there is thus no increased likelihood of electrons being captured by the extraction grid of a cold cathode. Secondly, the conversion of velocity modulation to current modulation is not directly related to the path length of the beam but rather to its width. The longitudinal velocity of the beam is thus not a critical parameter and the size and scale of the device is governed mainly by the degree of control of the beam profile. Indeed higher beam velocities would be an advantage rather than a disadvantage, resulting in lower charge densities, reduced space charge repulsion, more easily controlled beams and higher output power.

A number of vacuum electronic devices do exploit transverse modulation, notably magnetrons and cathode ray tubes (CRTs). Both of these are characterised by high efficiency and relatively compact geometry.

These transverse modulated devices do, however, have limitations. In the case of the magnetron a magnetic field is required to control the beam close to the cathode. The magnetic field is essentially fixed and as a result output power and frequency are not widely tunable within a single device. In the case of the CRT control is obtained either electrostatically or electromagnetically. Although such devices are more easily tuned, accurate current control is precluded as control electrodes are relatively remote from the cathode, and the total beam currents are low. Such CRT devices are therefore applicable to only lower power devices such as those used for display applications.

The present invention seeks to provide an improved device which employs transverse modulation.

According to the invention, there is provided an electron beam device comprising a split anode, a cold cathode arranged to produce a sheet electron beam and waveguide modulation means for applying a modulating signal transversely across the electron beam to modulate the beam deflection whereby current in the split anode is modulated.

By employing the invention, transverse modulation may be used without sacrificing beam control. As the cathode is a cold cathode, control electrodes may be closely spaced next to the electron emissive surface. Furthermore, there is thus no requirement to include magnetic field control. In an advantageous embodiment of the invention, the electrodes are mounted directly on the cathode or on a cathode substrate enabling accurate alignment to be achieved and maintained. In addition, a device in accordance with the invention may be arranged to provide several watts of microwave power.

Preferably, the cathode is a field emission cathode of the type which includes a plurality of sharp tips which are electron emissive and contribute to the electron beam, although other types of cold cathode may be employed. The tips may be surrounded by a common extraction grid or alternatively there may be a plurality of extraction grids associated with different individual, or groups of, tips.

In a preferred embodiment, electrode means are included for controlling the electron beam profile. An electrode, or electrodes, may be included in the cathode for collimating the electron beam. Alternatively, or in addition, an electrode or electrodes may be included between a waveguide of the modulator means, along which an input signal is propagated, and the cathode to provide a beam forming lens action.

The device is particularly advantageous when used with modulating signals at microwave frequencies but may also be used with signals at other frequencies. The invention enables in one particularly advantageous embodiment a combination to be made of a cold cathode and a CRT type of device geometry fabricated on the cathode to provide an efficient, compact microwave device capable of providing several watts of microwave power.

Some ways in which the invention may be performed are now described with reference to the appended drawings in which:

Figure 1 schematically illustrates an electronic device in accordance with the invention;

Figure 2 is a plan view of part of the device of Figure 1;

Figure 3 illustrates part of a cathode suitable for use in the device of Figure 1;

Figure 4 schematically shows an alternative cathode arrangement which may be employed in the

device of Figure 1;

Figure 5 illustrates a modulator structure used in the device;

Figure 6 illustrates the device of Figure 1 in operation;

Figure 7 shows an output arrangement in accordance with the invention;

Figure 8 schematically illustrates a device in accordance with the invention which includes a plurality of cathodes; and

Figure 9 is a schematic plan view of the device shown in Figure 8.

The Figures are schematic and drawn to different scales in order to clearly show different parts of the device.

A device for modulating an electron beam to produce a microwave output consists of three main parts, as illustrated in Figure 1: a cold cathode 1, split modulator structure 2 and a split anode 3. The first two components are fabricated on a common substrate 4 which may also support auxiliary beam focusing electro-static lenses. The split anode 3 is fabricated on a separate substrate 5 which is preferably a low loss insulating substrate such as quartz enabling the anode 3 to act as a dipolar antenna if desired, for the direct transmission of output microwave power through the substrate directly into an impedance matching feed horn or quasi-optical antenna system (not shown). The whole device is enclosed within an evacuated sealed enclosure, although in other embodiments the enclosure contains deliberately introduced gases at pressures at typically 10^{-5} mbar - 10^{-7} mbar.

The cathode 1, modulator structure 2 and anode 3 are of an elongate geometry. The modulator structure 2 and the split anode 3 each comprise two conductive strips 2a, 2b and 3a, 3b with a gap 2c and 3c between them. The cathode 1 is extensive along the length of the modulator structure 2 and the anode 3 and aligned with the gaps 2c and 3c between them. Figure 2 is a schematic plan view of the cathode 1 and modulator structure 2, the anode 3 being of similar dimensions.

For the intended microwave application of this device, the anode 3 is spaced between approximately 1mm and 10mm from the modulation structure 2 and split anode slot 3c is aligned with the slot 2c in the modulation structure 2. The cathode substrate 4 and the anode substrate 5 respectively form two ends of the vacuum enclosure with an intervening cylindrical wall 6 being sealed by brazing or electrostatic bonding to each of the end substrates 4 and 5 to form the sealed enclosure. This sealing may be carried out under evacuated conditions with passive back filling and results in a completely sealed device.

The detailed structure and operation of the device will now be described by separate reference to its three component parts. Although other cold cathode

structures could be used, this arrangement employs a field emission cathode constructed as an array of sharp tips 7 either on a conducting substrate 8 as shown in Figure 3, which shows only one tip of the array for the sake of clarity, or on a thin conducting layer on an insulating substrate. The fabrication of an array of such tips may be carried out using the process described in our copending application published under serial number GB 2 254 958A. The sharp tips 7 are of silicon, say, and are insulated by approximately $1.5 \mu\text{m}$ of silicon dioxide 9 for example, from a conductive extraction grid 10. Application of approximately +100V to this grid relative to the tips 7 results in a widely diverging beam of electrons, being produced from the tips 7 with a typical average current of $1 \mu\text{A}$ per tip. Such a beam is uncollimated and requires careful design and accurate fabrication to enable it to be guided through the modulation structure 2.

Although the simple cathode structure shown in Figure 3 could be used, in practice it is preferable to include a second focusing grid 12 as shown in Figure 4 biased at approximately the same potential as the tips. This grid 12 is insulated from the first grid 10 by, typically, $1.5 \mu\text{m}$ of silicon dioxide 13 or some other suitable non-outgassing insulator able to withstand the applied fields (about 10^8 V/m). The electrostatic repulsion of the emitted beams from each of the tips 7 by this second grid 12 results in collimation of each separate beam and thus collimation of the whole emitted current.

The overall shape of the beam is determined by the shape of the array of tips 7. In this embodiment of the invention the beam is required to be in the form of a vertical slab rising from cathode surface. Typical cathode dimensions are $100 \mu\text{m}$ x several millimetres so that with the tips 7 spaced $10 \mu\text{m}$ apart or less, the array contains several thousand tips and produces a current of $10 \mu\text{A}$ or more.

The beam is modulated by means of a planar waveguide structure 14 immediately in front of, and preferably supported on, the cathode substrate 4. The structure and action of the modulator 2 is illustrated in greater detail in Figure 5. Because of space charge repulsion, and also in order to increase the current density through the modulator 2, this structure also contains lens structures 15 consisting of two electrodes lying perpendicularly to the beam direction and co-parallel with the substrate 4 and planar waveguide 14. These structures 14 and 15 are supported by underlying insulator layers 16 preferably composed of silicon dioxide or high temperature organic polymer materials such as polyamide for example. These electrodes 15 are a few microns thick equally spaced (typically $30 \mu\text{m}$) from the cathode substrate 4 and the modulation structure 2. With these spacings the modulator 2 is some $100 \mu\text{m}$ above the cathode 1. This spacing minimises capacitance between the planar modulation waveguide 14 and the cathode substrate

4. As some modulation field penetrates down through the lens structure 15, these electrodes, and also the modulator 2 are advantageously constructed of a high electrical conductivity material, such as copper or gold, to minimise microwave losses.

In other embodiments of the invention, the lens structure may be omitted, or only one electrode or more than two electrodes could be included, depending on the application of the device and the desired performance characteristics.

With the first grid lens biased at close to tip potential and the second at close to extraction grid potential the collimated beam is compressed to increase the current density through the modulator waveguide 14 and minimise the current intercepted by the waveguide.

During operation of the device, microwave radiation is arranged to propagate down the planar modulation waveguide 14. This results in an oscillating electric field substantially perpendicular to the beam. To minimise non-perpendicular components of this field, and also to ensure that the field acts on the beam along a long path length of the beam, the modulation waveguide 14 is some many tens of microns thick.

A few tenths of a watt of microwave power results in sufficient oscillating angular beam deflection that complete charge modulation is achieved on the split anode 3 planar waveguide mounted some few millimetres above the modulator as illustrated in Figure 6. The split anode waveguide may be matched to the modulator waveguide so that the distributed amplification of the input signal occurring along the length of the device constructively interferes on the anode waveguide. In particular this would require the microwave phase velocities to be the same on the two waveguides. With both modulator and anode structures being at the same bias of approximately + 100V relative to the tips 3 electrons have approximately 100 eV of energy at the split anode and with complete charge density modulation, shown in Figure 6, several watts of output power may be generated.

Complete beam modulation as shown in Figure 6 need not be necessary for device operation. It may be advantageous to have a relatively larger gap between the two halves of the anode waveguide such that the beam does not impact on the split anode. In such a case the output power is induced in the waveguide by the oscillating charge density in the gap. In this mode of operation lower gain is obtained but the efficiency can remain high by retarding the electrons after they pass the split anode to be collected on an additional electrode on the anode substrate 5 between the two halves of the split anode and biased negatively with respect to the split anode. For such operation the substrate might be electrically conducting and itself be the final depressed collector of the electrons. In practice the depressed collector is likely to have a more

complicated structure than a simple metal sheet and may consist of several electrodes 17, as schematically shown in Figure 7, following the well known design criteria for depressed collectors in other devices. In addition, because of the lower gain in this configuration the split anode structure may consist of several such anode structures 18 along the beam so that after passing one, the beam then enters the next split anode segment and so on. The outputs of these separate anode segments 18 are then combined onto a single waveguide 19 in such a way as to compensate for the phase delay caused by the finite transit time between the segments. Such a multistage output is common to other microwave devices such as the travelling wave tube and klystron.

Although generated anode power could be simply propagated via the anode planar waveguide to some distant antenna or other circuit element, in an advantageous implementation of the device the split anode is structured to be directly microwave compatible with the output antenna itself within which it then constitutes a simple dipole source. In such an implementation DC current return is provided by a high microwave impedance (inductive) link.

In practice, the device is operated with the extraction grid and both planar waveguides at near ground potential for easy integration with other microwave components.

Although the device has been described by reference to a single microwave output unit it is also envisaged that multiple units of the type described could be mounted within the same vacuum enclosure and preferably interfaced to the same output antenna or other circuit element. In addition to simply providing greater output power, such an arrangement would also allow the possibility of variable phasing between the separate units and thus provide an electronically steerable output microwave beam.

In such a multiple beam device, electrostatic interactions between the beams may lead to beam distortion. At high current, this could be sufficient to displace the beams from an end position centred on the split anode structure. Such space-charge distortions may be minimised by segmenting the drift space between the split modulator and the split anode structures with screening electrode means. The screening electrode may advantageously consist of an electrically conductive support structure 20 which spaces the anode substrate 21 from the cathode/modulator substrate 22, as shown in Figure 8. The screening electrode, anode structure and waveguide modulator are maintained at a common dc potential. As shown in Figure 9, which is a plan view through a transparent anode substrate of the arrangement shown in Figure 8, the screening electrode 20 may also be configured to provide a sealed enclosure enclosing the beam electrodes but need not divide the individual beam regions into separate sealed enclosures. In this em-

bodiment, screening electrode 20 encloses the active part of the device within a single cylindrical enclosure 20a and also includes a portion 20b which separates two beam regions 23 and 24, which address the same anode transmission line 25. In other arrangements separate screening members may be used.

Claims

1. An electron beam device comprising a split anode (3), a cold cathode (1) arranged to produce a sheet electron beam and waveguide modulation means (2, 14) for applying a modulating signal transversely across the electron beam to modulate the beam deflection whereby current in the split anode is modulated.
2. A device as claimed in claim 1 wherein the cathode (1) is of the field emission type and comprises an array of sharp tips (7) which are electron emissive and contribute to the electron beam.
3. A device as claimed in any preceding claim and including electrode means (12, 15) arranged to control the electron beam profile.
4. A device as claimed in claim 1, 2 or 3 wherein the modulation means (14) and the cathode (1) are supported on a common substrate (4).
5. A device as claimed in any preceding claim wherein the waveguide modulation means comprises an elongate waveguide structure (14) along which the modulation signal is arranged to propagate and the cathode (1) is of an elongate configuration and aligned with the waveguide structure (14).
6. A device as claimed in any preceding claim wherein the anode comprises two elongate conductors (3a, 3b) which act as waveguide means via which an output signal is extracted.
7. A device as claimed in claim 6 wherein the anode (3) is aligned substantially parallel with the waveguide modulation means (14).
8. A device as claimed in any preceding claim wherein the modulating signal is at microwave frequency.
9. A device as claimed in any preceding claim wherein the phase velocities of the split anode (3) and the modulation means (14) are matched.
10. A device as claimed in any preceding claim wherein the output signal is arranged to propa-

gate through the substrate (5) on which the anode (3) is mounted.

11. A device as claimed in claim 10 wherein a circuit element or antenna is mounted on the anode substrate to receive the output signal.
12. A device as claimed in any preceding claim wherein the split anode comprises a plurality of anode members (18) spaced apart in the direction of the electron beam.
13. A device as claimed in any preceding claim wherein the maximum deflection of the electron beam at the anode is less than the gap (3c) defined by the split anode (3a, 3b).
14. A device as claimed in any preceding claim and including electrically conductive multistage collector means (17) on which the electron beam is arranged to be incident, the collector means being arranged to operate in a depressed mode.
15. A device as claimed in any preceding claim wherein the split anode (3) is arranged to act as a dipolar microwave source.
16. A device as claimed in any preceding claim and comprising a plurality of cold cathodes arranged to produce a plurality of sheet electron beams (Figure 8).
17. A device as claimed in claim 16 wherein the cathodes are associated with respective modulation means whereby respective sheet electron beams are individually controllable.
18. A device as claimed in claim 16 or 17 and including screening means (20) arranged to screen one electron beam (23) from an adjacent electron beam (24).
19. A device as claimed in claim 18 wherein the screening means (20) comprises an electrically conductive member extensive between the anode and the cathode substrate (21).
20. A device as claimed in claim 18 or 19 wherein the screening means (20) is integral with an enclosure defining wall (20a) within which electrodes of the device are located.
21. A device as claimed in any one of claims 16 to 20 wherein different electron beams are arranged to modulate current in a common split anode (25).

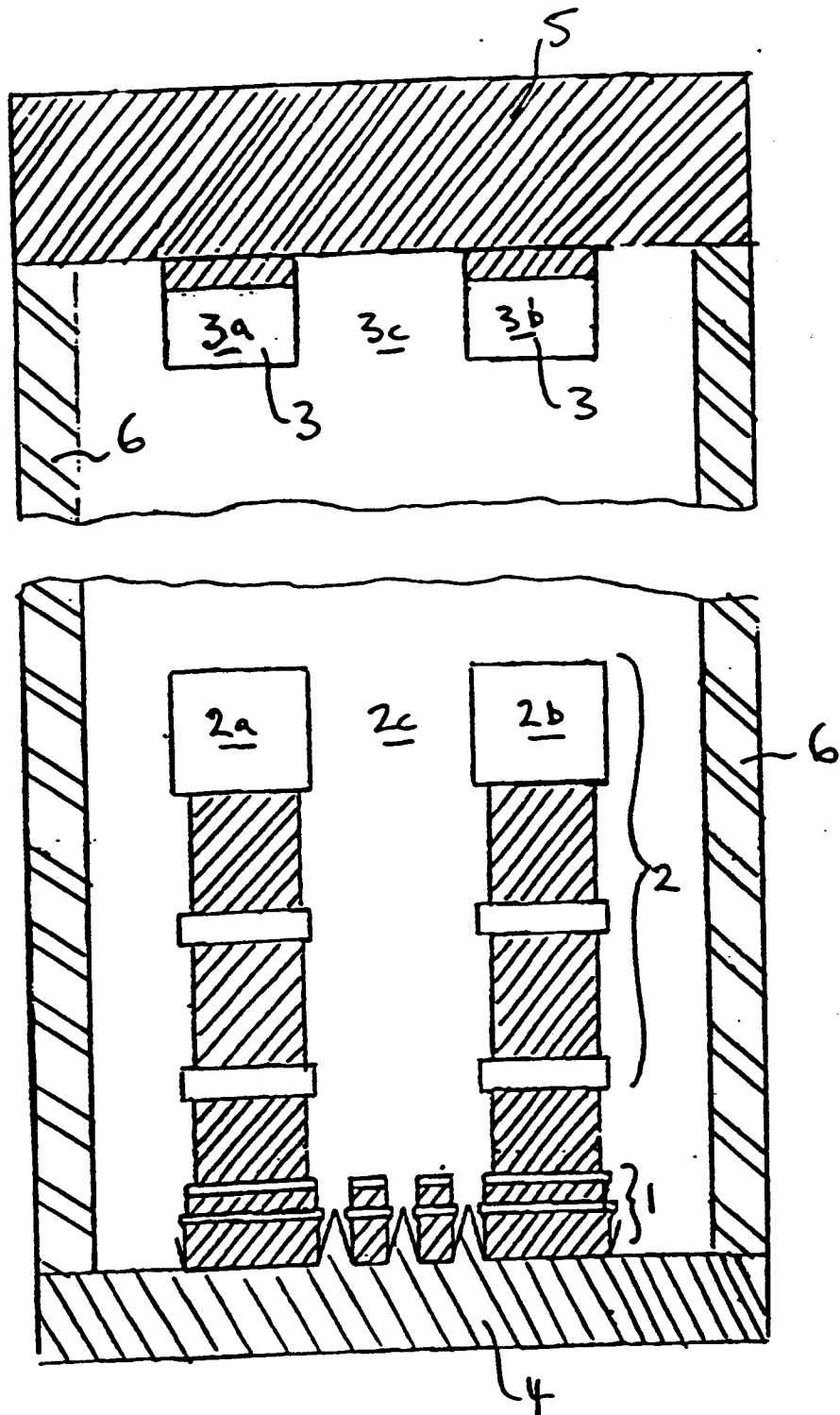


Fig. 1

Fig. 2

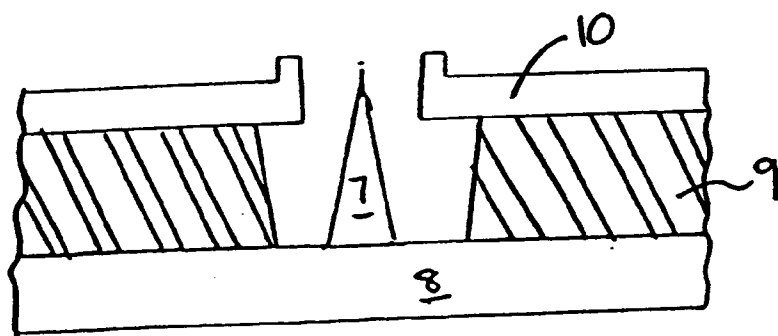
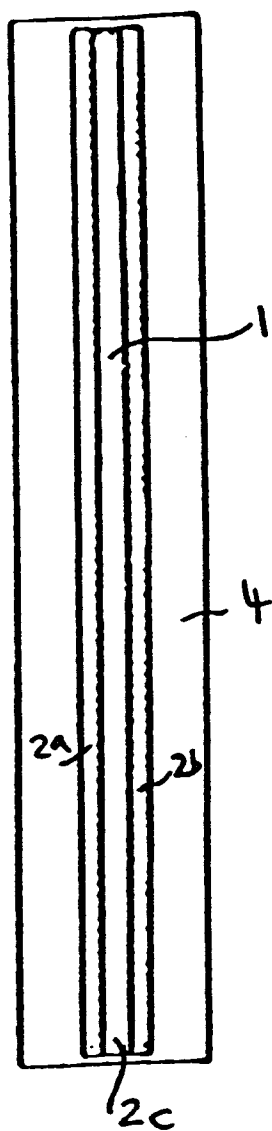
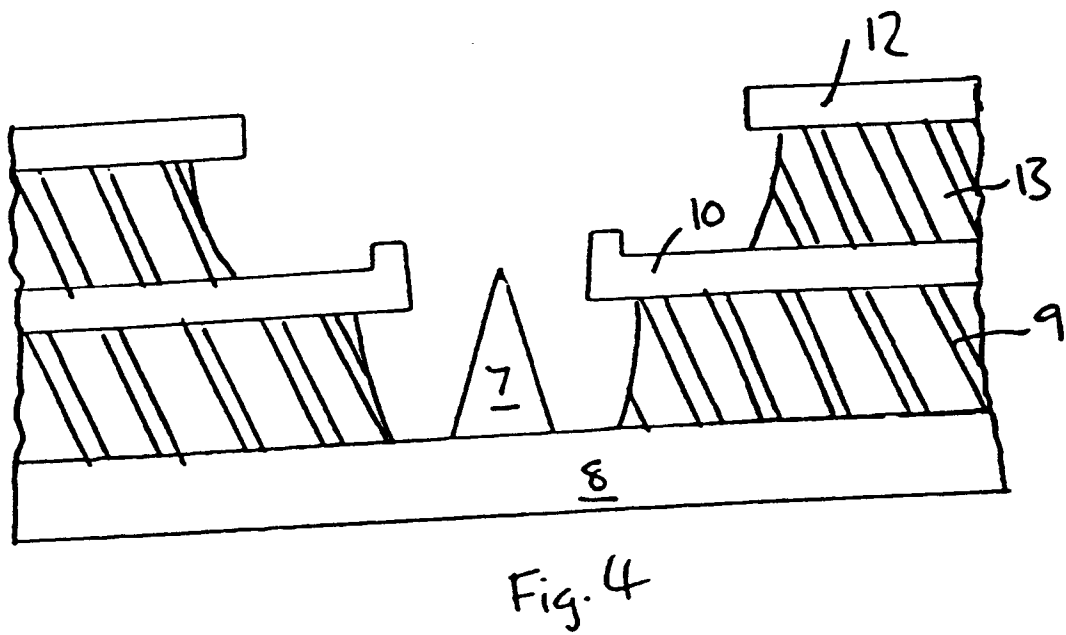
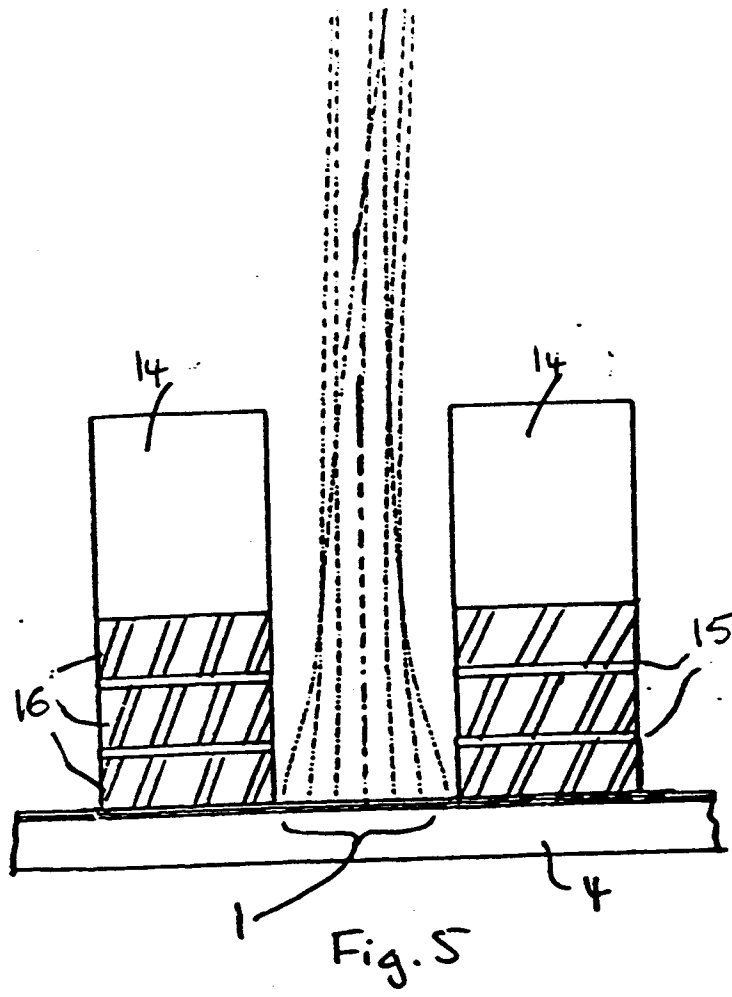


Fig. 3



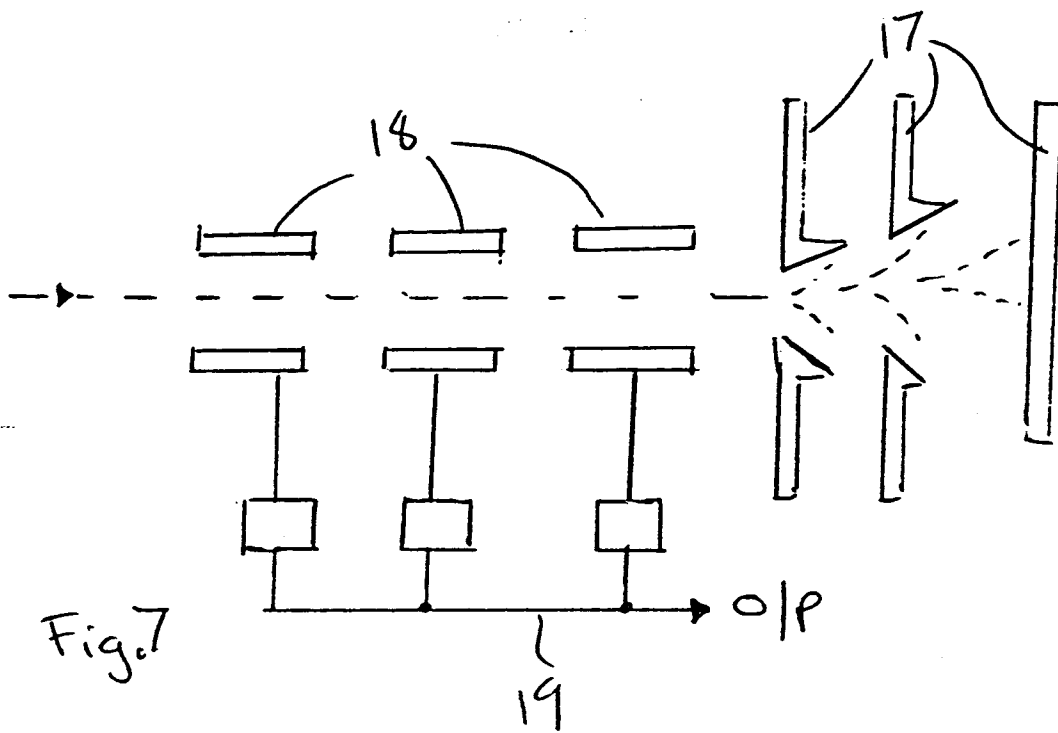
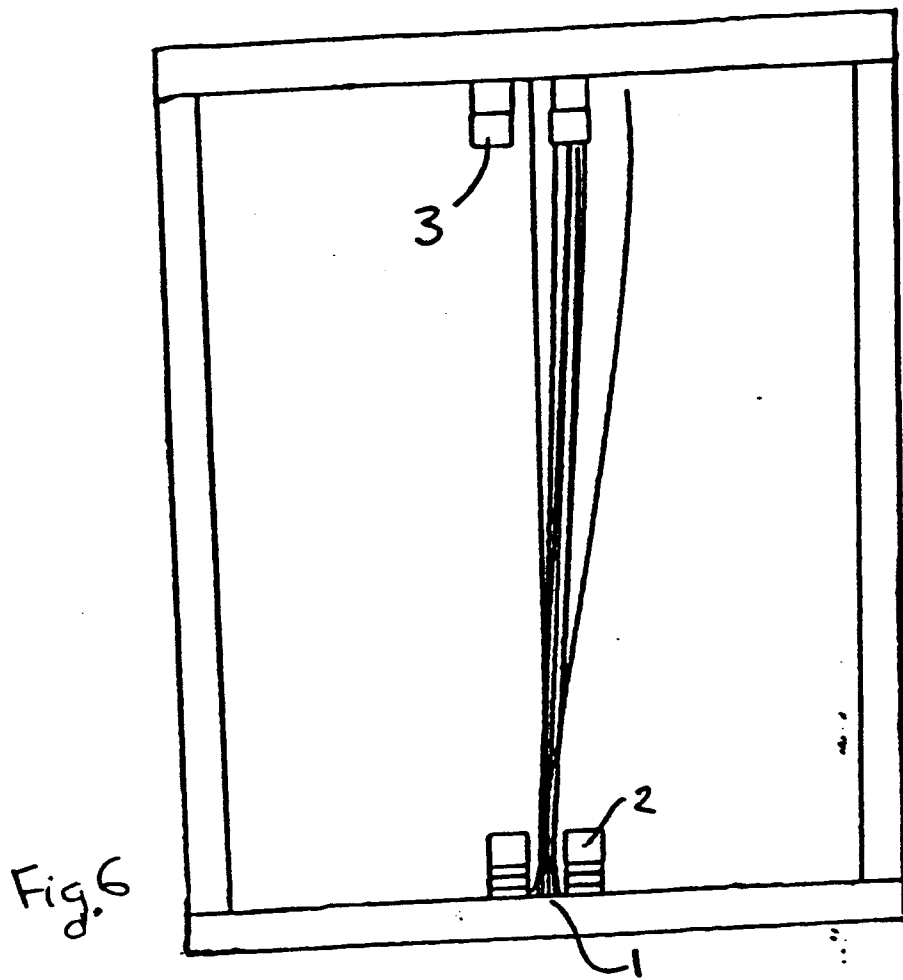


Fig 8

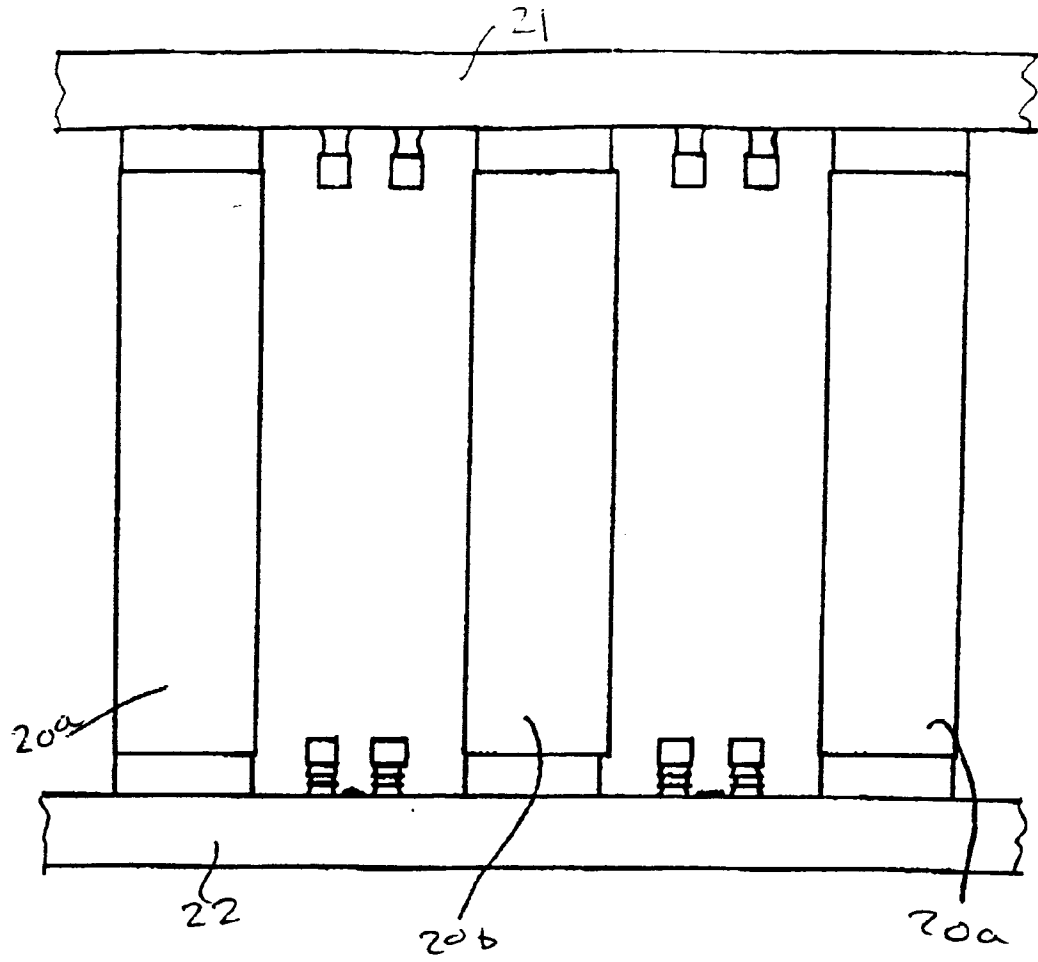
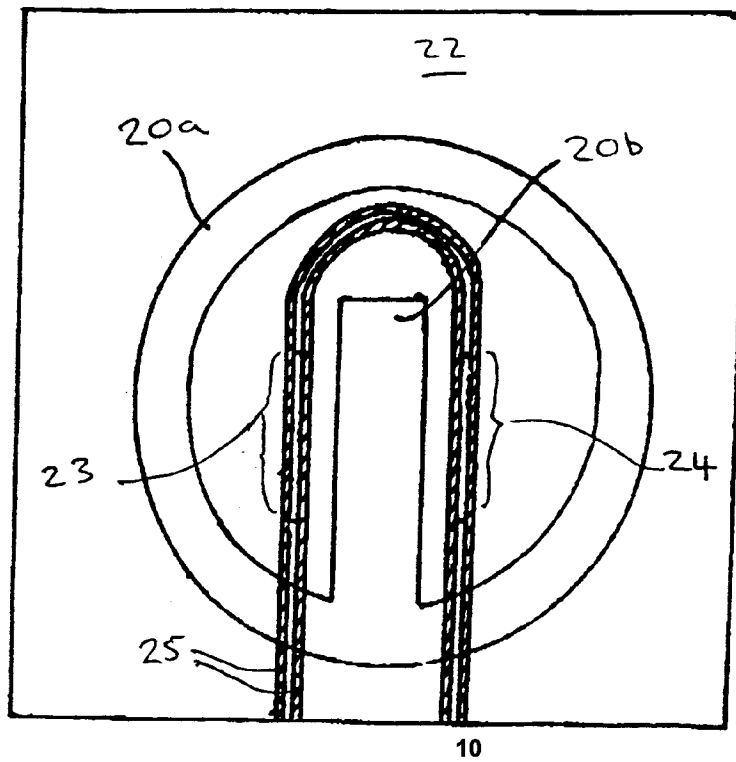


Fig 9





European Patent
Office

EUROPEAN SEARCH REPORT

Application Number
EP 94 30 5852

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
Y A	US-E-21 739 (LLEWELLYN) * page 1, left column, line 18 - line 21 * * page 1, left column, line 49 - line 54 * * page 2, left column, line 46 - line 54 * * page 2, left column, line 65 - right column, line 17; figure 2 * ---	1-3,5,8, 10,11,15 4	H01J25/78
Y A	US-A-2 650 956 (HEISING) * column 1, line 43 - column 2, line 5 * * column 2, line 28 - line 43 * * column 3, line 2 - line 16; figure 1 * ---	1-3,5,8, 10,11,15 4	
Y A	US-A-2 223 851 (HERRIGER) * page 1, left column - page 1, right column, line 6 * * page 1, right column, line 30 - page 2, left column, line 8; figure * ---	1-3,5,8, 10,11,15 18	TECHNICAL FIELDS SEARCHED (Int.Cl.6) H01J
D,Y	EP-A-0 497 509 (GEC-MARCONI LIMITED) * column 1, line 1 - line 13; figures 1-3 * ---	1-3,5,8, 10,11,15	
Y	US-A-2 758 210 (ADLER) * column 2, line 9 - line 13 * -----	1-3,5,8, 10,11,15	
The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 24 October 1994	Examiner Martín Vicente, M
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