(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 1 235 296 A1

(12) **EUROPEAN PATENT APPLICATION**

(43) Date of publication:
28.08.2002 Bulletin 2002/35

(51) Int Cl.[7]: **H01P 1/18**, H01Q 3/26

(21) Application number: **01301238.0**

(22) Date of filing: **14.02.2001**

(84) Designated Contracting States:
AT BE CH CY DE DK ES FI FR GB GR IE IT LI LU MC NL PT SE TR
Designated Extension States:
AL LT LV MK RO SI

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(54) **Phase shifter tunable via apertures in the ground plane of the waveguide**

(57) A phase shifting element adapted to introduce a variable phase shift to an electromagnetic wave includes a transmission line segment (10), such as a microstrip line segment (1) or a segment of a waveguide, above a ground plane (or waveguide wall) (2). The ground plane or wall (2) includes at least one aperture (3) positioned below the microstrip line or waveguide segment (1). An electrically conductive tuning plate (4) is provided adjacent the ground plane or wall (2) and is movable, toward or away from the ground plane or wall. Movement of the tuning plate (4) provides adjustment of the phase shift introduced to an electromagnetic wave propagated through the waveguide segment.

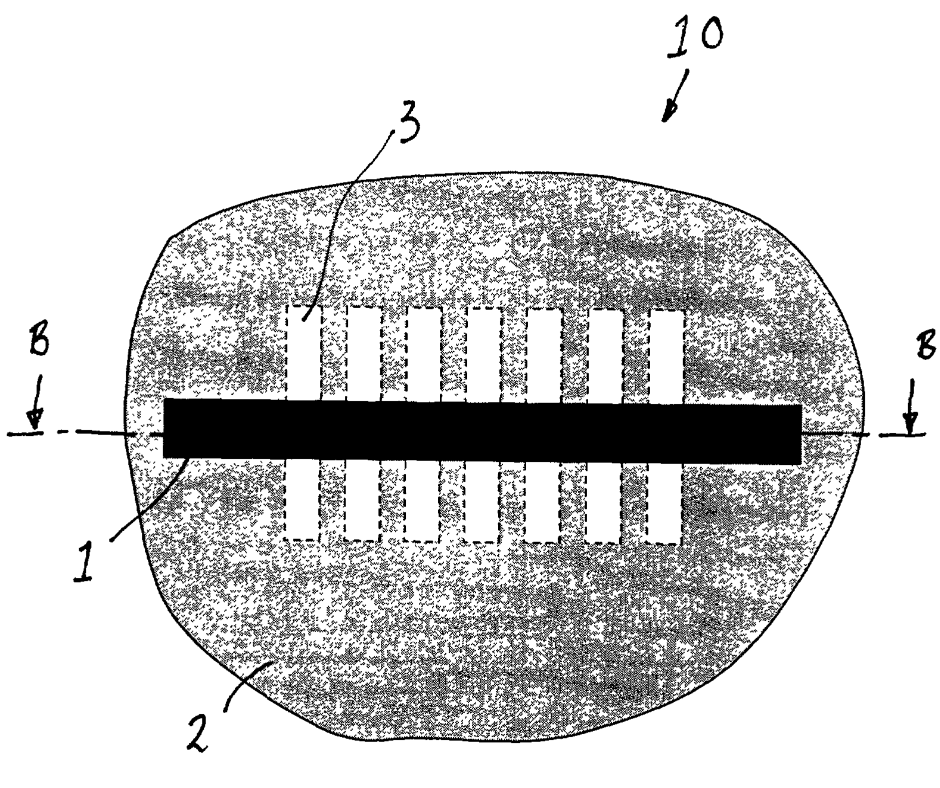

Figure 1A

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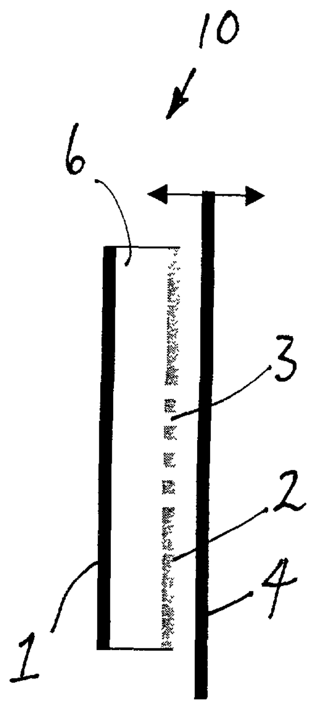

Figure 1B

Description

[0001] This invention relates to a technique for creating a variable phase shift in a transmission line and to the use of such a technique in an antenna array.

[0002] Phase shifters are well know and come in a variety of different types. Ferrite phase shifters use plates, rods and other shapes of ferromagnetic material inside a waveguide or transmission line. The magnetic permeability of the material defines the propagation constant of such lines which can be controlled by an external magnetic field. Ferrite phase shifters can be operated at high speed (in the order of milliseconds for a 360° phase shift) and can be integrated into the feeding network of antennas.

[0003] However, ferrite phase shifters are too expensive for low cost applications such as base station antenna technology, and personal mobile satellite based systems. In addition, ferrite phase shifters require a relatively high level of DC power for operation and introduce typical losses of around 1dB per 360° phase shift. Bandwidth is also limited for these devices to 5-10%.

[0004] Mechanical phase shifters are based on the mechanical displacement of a structure inside a transmission line or waveguide in order to change the propagation constant. The mechanical displacement may be achieved, for example, by using piezoelectric, electrostatic or electrical motor devices. They are potentially low cost, broadband devices, with low DC power consumption and are well suited to mass production. However, these devices have some practical limitations.

[0005] Examples of prior mechanical phase shifters based of the displacement of dielectric slabs inside or in the proximity of transmission lines are described in US-A-5504466, US-A-5940030 and EP-A-0984509. These devices usually require the displacement of large dielectric slabs over a distance of several millimetres. This severely limits the speed at which the phase shifter is able to operate. In addition, low cost, low power piezoelectric and electrostatic technologies, cannot be used, since their movement is typically limited to less than 1mm. Typically, these devices require high dielectric constant materials for a practical, compact design and this also increases the cost of the device and typically also increases losses.

[0006] Examples of prior mechanical phase shifters based on the physical alteration of the length of transmission lines are described in US-A-5440318 and EP-A-1033733. These devices are potentially low cost, use low power and have low power losses. However, movable parts in the transmission line introduce interface problems between these devices and fixed transmission lines to which they are connected thereby adding mechanical complexity to the devices (for example requiring the incorporation of sliding contacts). In addition, because the amount of phase shift introduced is proportional to the length extension amount of the device, speed is also low since large mechanical displacements are required (typically several millimetres at 10GHz).

[0007] It is therefore an object of the present invention to provide a phase shifting element which will go at least some way towards overcoming the above disadvantages.

[0008] Accordingly, in a first aspect, the invention consists in a phase shifting element comprising:

> a transmission line segment adapted to support the propagation of an electromagnetic wave and including a ground plane or wall having at least one aperture,
>
> an electrically conductive plate adjacent the ground plane or wall, and
>
> displacement means connected to the electrically conductive plate and adapted to adjustably alter the distance between the electrically conductive plate and the ground plane or wall thereby adjusting the amount of phase shift introduced to the electromagnetic wave as it passes through the transmission line segment.

[0009] Preferably a plurality of apertures are arranged periodically in the ground plane or wall in a series.

[0010] Preferably the shape, pitch and/or size of individual ones of the periodically arranged aperture series are varied in order to improve the impedance match between the transmission line segment and a connected transmission line.

[0011] Preferably the apertures are rectangular and the lengths of the apertures at either end of the periodically arranged series are reduced as compared to the length of the apertures in the middle of the aperture series.

[0012] Preferably the transmission line segment is a microstrip line or stripline segment on a printed circuit board and the series of apertures are provided in the ground plane, directly beneath and aligned with the microstrip line or stripline.

[0013] Alternatively, the transmission line segment is a segment of ridge, rectangular or circular waveguide and the apertures are provided in one of the walls of the waveguide.

[0014] Preferably the width of the apertures in a direction parallel to the transmission line is less than or equal to about $\lambda/10$, where λ is the wavelength of the electromagnetic wave at the operating frequency.

[0015] Preferably the electrically conducting plate is covered with a dielectric or ferrite layer on the surface of the ground plane or wall of the transmission line segment.

[0016] Preferably the transmission line segment and series of apertures follow the same, meandering path.

[0017] Preferably the meandering path comprises a plurality of straight paths series connected at angles to one another.

[0018] In a further aspect, the invention consists in a control system for an antenna array including a phase shifting element according to the first aspect.

[0019] Preferably the control system incorporates a plurality of phase shifting elements connected together and share a common electrically conductive plate.

[0020] Particular embodiments of the invention will now be described by way of example with reference to the accompanying drawings in which:

Figure 1A is a plan view from above of a phase shifting element in accordance with a first embodiment of the present invention;

Figure 1B is a cross-sectional side elevation of the phase shifting element of Figure 1A though B-B;

Figure 2 is a plan view of an alternative embodiment of the phase shifting element of Figures 1A and 1B in which an integrated impedance matching structure is provided;

Figure 3 is a cross-sectional view through a planar phase shifter incorporating the phase shifting element of Figures 1A and 1B;

Figure 4 is a plan elevation of a series of the phase shifting elements of Figures 1A and 1B coupled together in series; and

Figure 5 is a plan elevation of an alternative embodiment of phase shifting element according to the present invention in which the transmission line follows a meandering path.

[0021] Although the phase shifter according to the present invention will initially be described using a microstrip transmission line, it should be noted that the same principle may be directly implemented using waveguide structures (for example rectangular or ridge) and other transmission line technologies including conventional or suspended stripline or triplate structures.

[0022] With particular reference to Figure 1, a phase shifting element 10 consists of a transmission line segment (or waveguide) 1, the ground plane (or wall) 2 of which is perforated with small apertures 3 (for example, 7 slots are shown in the example of Figure 1). Preferably, the apertures 3 are periodically distributed parallel to the direction of propagation of the wave. An electromagnetic wave is launched from one end of the transmission line 1 and received at the other end with a certain amount of phase shift. In the case the transmission line comprising a microstrip line, the apertures may be rectangular slots on the ground plane of a printed circuit board 6, however other aperture shapes can be used, such as circular or square holes. The ground plane may be a solid metal plate or may be a mesh.

[0023] The apertures 3 are preferably much smaller than the wavelength of the electromagnetic wave at the operating frequencies (for example, having a width of less than or equal to about $\lambda/10$ where λ is the wavelength of the electromagnetic wave at the operating frequency) to avoid leakage of energy by radiation. However, the apertures should be able to store a considerable amount of electromagnetic energy. This is achieved by locating the apertures in regions where the electric and/or magnetic fields have maximum strength. For the microstrip line, maximum field strength occurs just beneath the line conductor 1. When the apertures 3 are introduced, the amount of magnetic and electric energy stored per unit length in the line is altered, resulting in a change in the propagation constant with respect to the original transmission line segment.

[0024] A tuning electrically conductive plate 4, for example a metal plate, is placed adjacent and close to the apertures 3 to control the propagation constant of the line. In theory, when the tuning plate 4 is at zero distance from the apertures, the propagation constant is identical to the propagation constant of the un-slotted transmission line segment. As the tuning plate 4 is separated from the apertures 3, the propagation constant changes gradually towards the propagation constant of the line loaded by the apertures. As a consequence, the phase of the electromagnetic wave at the end of the transmission line segment is controlled by the movement of the tuning plate. As an example, at microwave operating frequencies, it is expected that displacement of the tuning plate will be between 0 to 2mm from the ground plane 2.

[0025] The tuning plate 4 is suspended parallel to the slotted ground plane 2 and does not require any electrical connection to the transmission line. As a result, the geometry of the phase shifting element is identical to a conventional transmission line or waveguide, ensuring simple interfacing to other transmission lines.

[0026] The apertures 3 on the ground plane 2 are tunable impedance loads on the transmission line 1. If the apertures are periodically distributed (as shown in Figures 1a and 1b), the line can be seen as periodically loaded. Typically, the pitch between the apertures is smaller than about a quarter wavelength. In this case, the loaded line behaves as a new transmission line, with a new effective characteristic impedance and propagation constant. The amount of impedance loading is modified by the proximity of the ground plane 2.

[0027] The effect of the apertures in the transmission line segment may alternatively be explained using the concept of artificial dielectric. Small apertures in a metallic wall have an associated magnetic dipolar moment. If the apertures are much smaller than the wavelength (typically around $\lambda/10$) they produce an average magnetic moment per surface unit that contributes to the effective magnetic polarisability of the substrate 2 in a similar way to the magnetic dipolar moment from atoms and molecules of the substrate. As a result, the apparent magnetic permeability of the substrate 2 is increased by the magnetic field induced into the apertures.

[0028] To produce a variable phase shift, the metallic tuning plate 4 is placed close to the apertures 3 on the transmission line. The tuning plate 4 alters the induced magnetic dipolar moment of the apertures and therefore the propagation constant of the transmission line segment. If the distance between the tuning plate 4 and the apertures 3 is varied, the propagation constant of the line is also changed accordingly and, as a consequence, the phase of the electromagnetic wave is also changed.

[0029] With reference now to Figure 2, the phase shifting element 10 may be provided with an integrated impedance matching structure wherein the size, pitch and/or shape of the apertures can be varied to match the aperture-loaded line to the connected input/output standard lines. Typically, a gradual change of the aperture sizes (taper) can provide a good broadband impedance match, provided that the phase shifting element is at least one wavelength long. In the phase shifting element example of Figure 2, tapered apertures 5 having varying, shorter lengths are provided at either end of a series of uniform length apertures.

[0030] A particular advantage of this integrated matching structure is that the return loss is low for all displacements of the tuning plate 4 (and therefore all phase shift settings within the range of the device). This happens because when the ground plane is at zero distance from the apertures the transmission line appears unloaded and the return loss is extremely low. As the tuning plate 4 is separated from the apertures 3, a relative phase shift is produced, but the taper of the apertures always ensures a smooth transition from the input lines. As a result, the phase shifting element 10 is matched in an adaptable way. This flexible behaviour saves space and increases performance in comparison to rigid matching structures designed to cope with a broad range of propagation constant.

[0031] The taper of the apertures can, for example, be linear (as shown in Figure 2), parabolic or any other custom profile to obtain the lowest reflection. Preferably, the taper will be optimised for the maximum separation of the tuning plate 4 from the apertures 3 since very low reflection is expected for the minimum (zero) separation. The apertures can form blocks of different sizes rather than a continuous taper. These blocks are typically $\lambda/4$ sections that can match the device over a narrowband.

[0032] Examples of devices including the phase shifting element 10 according to the present invention will now be described with reference to Figures 3 and 4. A planar phase shifter may be implemented using simple manufacturing procedures, typically in a physically planar form (for example microstrip line). An example is shown in Figure 3 which is suitable for mass production of low cost phase shifting devices.

[0033] The sensitivity of the device with respect to displacements of the tuning plate is very high (typically enabling phase shifts of up to 250° per mm of displacement in the microstrip implementation) depending upon design. As a result, piezoelectric and electrostatic or other low cost displacement mechanisms 7 can be employed to produce accurate vertical displacement of the tuning plate 7, keeping a low profile and low power consumption. However, conventional electrical motors can also be used as a low cost displacement mechanism in some cases.

[0034] The apertures 3 may be etched or mould cut in the ground plane 2 (or a flat electrically conductive wall of the transmission line or waveguide in alternative implementations). The amount of phase shift achieved per unit of length can be enhanced by coating the tuning plate 4 with a dielectric of ferrite material.

[0035] A single control compact scanning array antenna is possible by coupling together a plurality of phase shifting elements according to the present invention.

[0036] Figure 4 shows an example layout of four series coupled phase shifting elements, each of which share a single tuning plate 4 and which combine to form a microstrip array. Because each of the phase shifting elements 10 share a common tuning plate 4, all of the phase shifting elements are electromagnetically coupled. This arrangement can be used to implement a scanning array that requires a single control for all of the phase shifters of a corporate or series feeding network having multiple input/output ports 8.

[0037] The tuning plate 4 can be slightly inclined or shaped (for example curved) to produce an initial phase distribution in the array, which may then be varied globally as the plate displacement is altered. The array can be configured to scan a beam of a linear, planar or conformal array for example, in a single plane and, if appropriately configured, in arbitrary scan directions.

[0038] Figure 5 shows a further embodiment of a phase shifting element 10 wherein the microstrip line 1 follows a meandering path over selected apertures 3 in a ground plane 2. The apertures shown in Figure 5 are square shaped and include tapered apertures 5 having gradually reduced sizes to achieve the above described impedance matching benefits. This embodiment allows a relatively long length of transmission line segment to be used in a reduced space and therefore improves the compactness of the device incorporating the phase shifter. The apertures could of course be other shapes, such as rectangular or circular, and the microstrip line 1 could be replaced with other transmission line types such as waveguide structures.

Claims

1. A phase shifting element comprising:

a transmission line segment adapted to support the propagation of an electromagnetic wave and including a ground plane or wall having at least one aperture,
an electrically conductive plate adjacent the ground plane or wall, and
displacement means connected to the electrically conductive plate and adapted to adjustably alter the distance between the electrically conductive plate and the ground plane or wall thereby adjusting the amount of phase shift in-

troduced to the electromagnetic wave as it passes through the transmission line segment.

2. A phase shifting element as claimed in claim 1, wherein a plurality of apertures are arranged periodically in the ground plane or wall in a series.

3. A phase shifting element as claimed in claim 1 or claim 2, wherein the shape, pitch and/or size of individual ones of the periodically arranged aperture series are varied in order to improve the impedance match between the transmission line segment and a connected transmission line.

4. A phase shifting element as claimed in any one of the preceding claims, wherein the apertures are rectangular and the lengths of the apertures at either end of the periodically arranged series are reduced as compared to the length of the apertures in the middle of the aperture series.

5. A phase shifting element as claimed in any one of the preceding claims, wherein the transmission line segment is a microstrip line or stripline segment on a printed circuit board and the series of apertures are provided in the ground plane, directly beneath and aligned with the microstrip line or stripline.

6. A phase shifting element as claimed in any one of claims 1 to 4, wherein the transmission line segment is a segment of ridge, rectangular or circular waveguide and the apertures are provided in one of the walls of the waveguide.

7. A phase shifting element as claimed in any one of the preceding claims, wherein the width of the apertures in a direction parallel to the transmission line is about $\lambda/10$, where λ is the wavelength of the electromagnetic wave at the operating frequency.

8. A phase shifting element as claimed in any one of the preceding claims, wherein the electrically conducting plate is covered with a dielectric or ferrite layer on the surface of the ground plane or wall of the transmission line segment.

9. A phase shifting element as claimed in any one of the preceding claims, wherein the transmission line segment and series of apertures follow the same, meandering path.

10. A phase shifting element as claimed in claim 9, wherein the meandering path comprises a plurality of straight paths series connected at angles to one another.

11. A control system for an antenna array including a phase shifting element according to any one of the preceding claims.

12. A control system for an antenna array as claimed in claim 11, wherein a plurality of phase shifting elements are connected together and share a common electrically conductive plate.

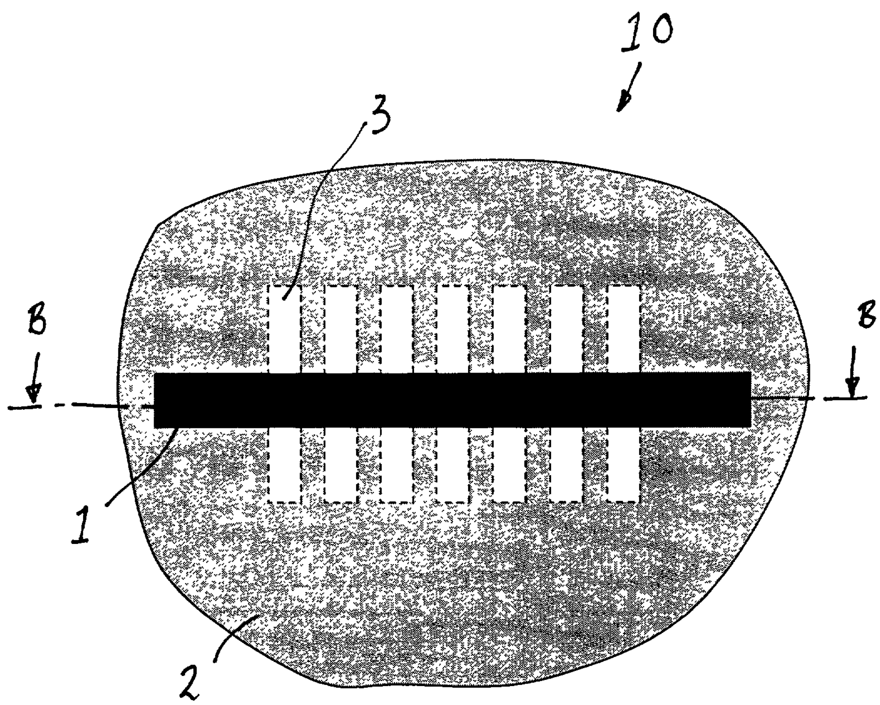

Figure 1A

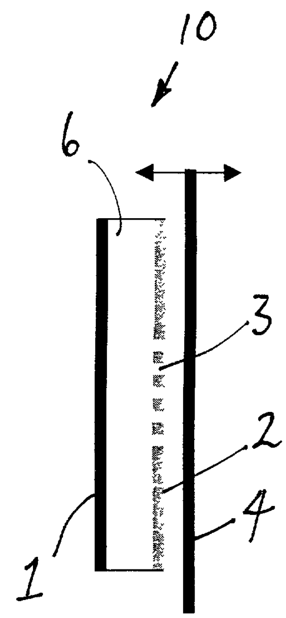

Figure 1B

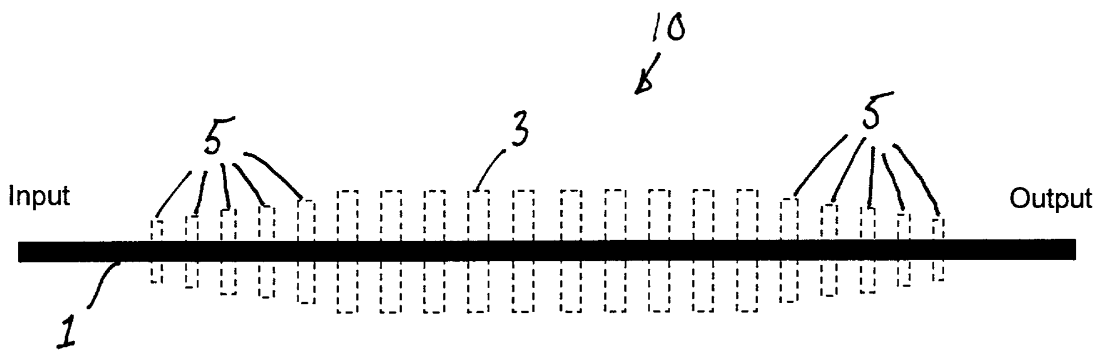

Figure 2

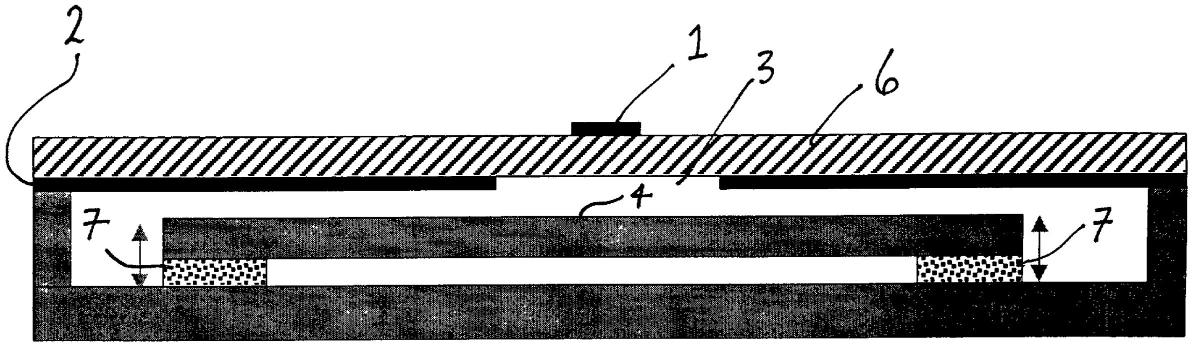

Figure 3

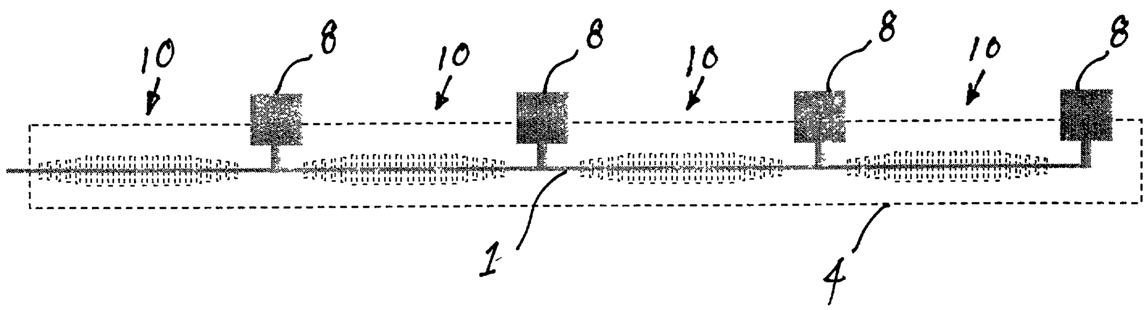

Figure 4

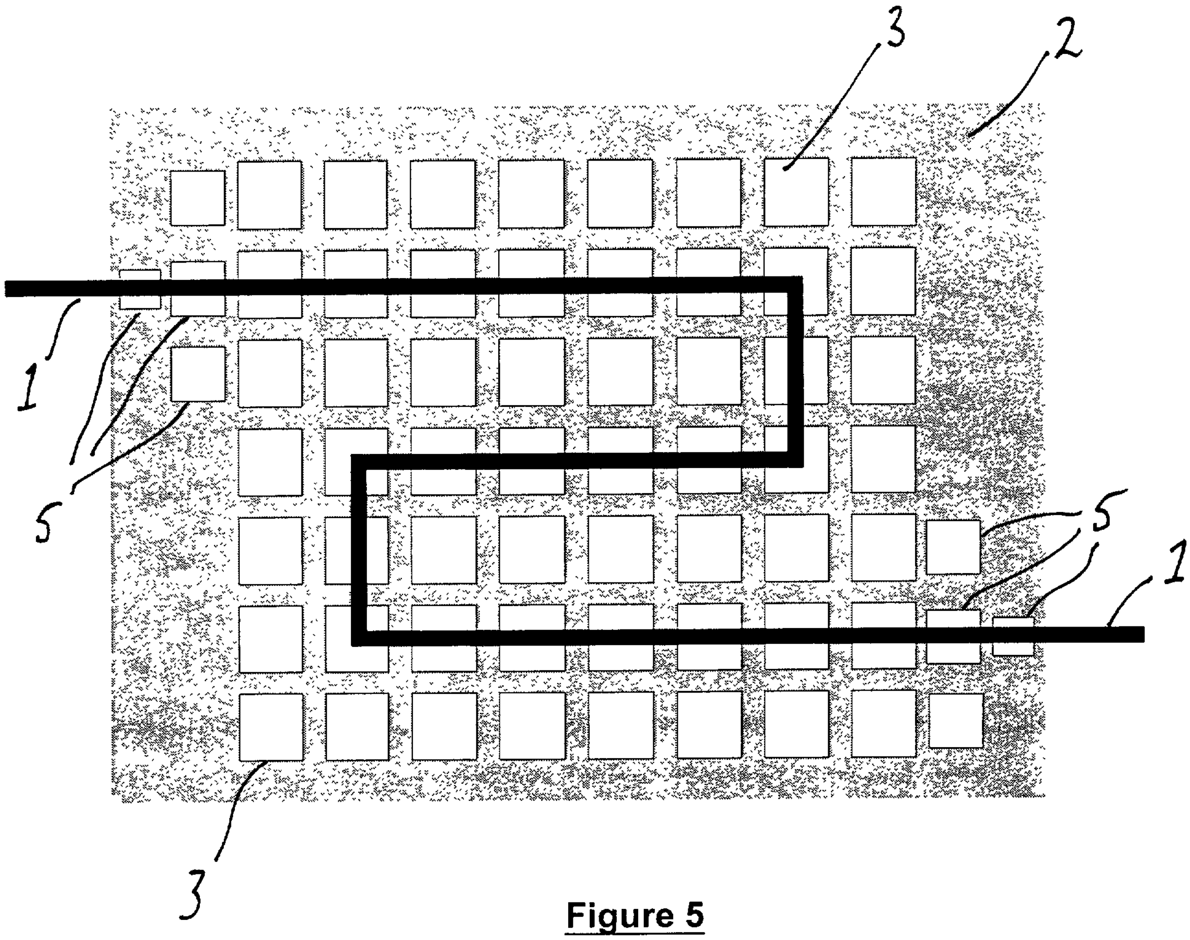

Figure 5

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EUROPEAN SEARCH REPORT

Application Number
EP 01 30 1238

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.7)
X	FR 2 581 255 A (ONERA (FR)) 31 October 1986 (1986-10-31) * abstract * * page 1, line 8-11 * * page 7, line 5-11; figures 3,6 * ---	1,2,6,11	H01P1/18 H01Q3/26
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A	US 3 789 330 A (DIXON E ET AL) 29 January 1974 (1974-01-29) * abstract; figure 1 * ---	1-10	
A,D	US 5 940 030 A (HAMPEL KARL GEORG ET AL) 17 August 1999 (1999-08-17) * abstract; figure 3A * ---	1-12	
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TECHNICAL FIELDS SEARCHED (Int.Cl.7)

H01P
H01Q

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
MUNICH	7 August 2001	Schmelz, C

CATEGORY OF CITED DOCUMENTS

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