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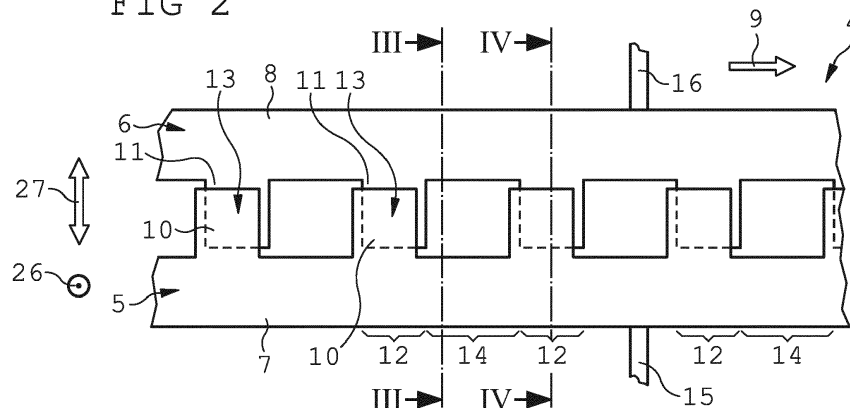
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(54) **RADIO FREQUENCY PHASE SHIFTING DEVICE AND METHOD OF OPERATION FOR THIS PHASE SHIFTING DEVICE**

(57) A phase shifting device with a linear transmission line (4) comprises a first electrode (5) and a second electrode (6) that are spaced at a distance to each other, wherein a tunable dielectric material is arranged between the first electrode (5) and the second electrode (6). The transmission line (4) comprises several overlapping sections (12), wherein an overlapping area (10) of the first electrode (5) overlaps an overlapping area (11) of the second electrode (6) in order to provide for a parallel plate capacitor area (13) that affects the phase of an electromagnetic signal that propagates along the transmission line (4). The first electrode (5) and the second elec-

trode (6) are electrically connected to a bias voltage source, whereby the first electrode (5) is connected to a first bias electrode (15) which is connected to the bias voltage source, and whereby the second electrode (6) is connected to a second bias electrode (16) which is connected to the bias voltage source, whereby the first and second bias electrodes (15, 16) consists of a material with a lower electrical conductivity than that of the first and second electrode (5, 6). Signal transmission along the transmission line (4) of the phase shifting device is performed in differential mode with a quasi-TEM mode signal transmission along the transmission line (4).

FIG 2



## Description

### Technical Field

**[0001]** The invention relates to a radio frequency phase shifting device with a transmission line comprising a first electrode and a second electrode that are spaced at a distance to each other, and which are suitable and used for propagation of a radio frequency electromagnetic signal along the first electrode and the second electrode with a phase difference of  $180^\circ$  between the respective electromagnetic signals, wherein a tunable dielectric material affects a phase shift of the electromagnetic signal that is propagated along the transmission line.

### Background of the invention

**[0002]** Phase shifting devices can be used to modify the relative displacement between two corresponding features like peaks or zero crossings of an electromagnetic wave or signal without changing the frequency of the electromagnetic wave or signal. When two or more electromagnetic signals of the same frequency are superimposed, the result depends on the phase difference between the respective electromagnetic signals. The electromagnetic signals can be reinforced or weakened. Furthermore, by superimposing two or more electromagnetic waves that are radiated by respective antennas, the phase difference between the radiated electromagnetic waves will determine a direction of a reinforced superposition of the electromagnetic waves, resulting in a preferred direction of irradiation originating from the respective antennas.

**[0003]** In order to intensify the reception or emission of electromagnetic irradiation from a given direction, a phased array antenna comprises several antenna elements that are distributed next to each other. The phase difference of electromagnetic signals received or emitted by the respective antennas is predetermined in such a manner that the superposition of the respective signals is maximized for a given direction, resulting in enhanced signal sensitivity or signal emission for said direction.

**[0004]** There are known prior art phase shifting devices that create a pre-set phase difference between the incoming and outgoing signal. A phased array antenna that is equipped with such constant phase shifting devices can be designed to maximize the signal sensitivity or signal emission for a given single direction.

**[0005]** Furthermore, phase shifting devices with a tunable phase difference are known and described e.g. in EP 2 761 693 A1 or EP 2 956 986 B1. These phase shifting devices include a linear transmission line comprising a first electrode and a second electrode that are spaced at a distance to each other, wherein a tunable dielectric material is arranged between the first electrode and the second electrode. The phase difference created by a tunable phase shifting device can be tuned, i.e. it can be operated to produce different phase differences

whereby the respective phase difference can be modified and controlled by a control setting applied to the tunable dielectric material which affects the phase of the signal along the linear transmission line. A phased array antenna with several antennas that are interconnected with such tunable phase shifting devices can be operated in such a manner as to change the direction of enhanced signal sensitivity or signal emission in accordance to the requirements at a given time.

**[0006]** Therefore, one of the key components which are necessary to build phased array antennas with adaptive beam forming is a tunable phase shifting device, meaning a device which dynamically can adjust the phase or the delay of a radiofrequency signal. Usually, there is at least one phase shifting device for each radiating element of the array antenna. Each phase shifter device in turn is fed by a feed network. Due to the usually required large number of radiating elements, an at least equally large number of phase shifting devices must be integrated within a limited area in such a phase array antenna.

**[0007]** Accordingly, there is a need for a phase shifting device that allows for easy manufacturing, requires little space and provides for a large phase difference between the input signal and the output signal. Easy manufacturing is possible if techniques can be used to fabricate a large number of electrodes at high density on an area of e.g.  $0.5 \text{ m}^2$  which is a typical surface area for phased array antennas operating at frequencies of e.g. 20 GHz. The necessary fabrication techniques are in principle known from Liquid Crystal Display (LCD) manufacturing but are usually not applied to building phased array antennas. In order to employ the fabrication techniques of LCD manufacturing suitable tunable phase shifter topologies have to be found which can be both electrically and also mechanically be integrated in a phased array antenna system.

**[0008]** Accordingly, there is a need for a phase shifting device that allows for easy manufacturing, requires little space and provides for a large phase difference between the input signal and the output signal.

### Summary of the invention

**[0009]** The present invention relates to a radio frequency phase shifting device with a transmission line comprising a first electrode and a second electrode that are spaced at a distance in a first direction and/or in a second direction to each other, whereby the first direction is perpendicular to a direction of a signal transmission of a radio frequency electromagnetic signal along the transmission line and whereby the second direction is perpendicular to the first direction and perpendicular to the direction of the signal transmission along the transmission line, whereby the transmission line comprises several overlapping sections, wherein an overlapping area perpendicular the first direction of the first electrode is overlapped by a capacitor electrode area and wherein an

overlapping area perpendicular to the first direction of the second electrode is overlapped by a capacitor electrode area in order to provide for a parallel plate capacitor area within the overlapping section, and whereby the transmission line comprises several non-overlapping sections, wherein the first electrode runs at a distance to the second electrode in the second direction, whereby a tunable dielectric material affects a phase shift of the electromagnetic signal that is propagated along the transmission line, whereby the tunable dielectric material is arranged between the respective capacitor electrode areas and the overlapping area of the first electrode and the overlapping area of the second electrode that affects the phase of a radio frequency electromagnetic signal that propagates along the overlapping section of the transmission line, and whereby the first and second electrode are suitable and used for propagation of a radio frequency electromagnetic signal along the first electrode and the second electrode with a phase difference of 180° between the respective electromagnetic signals of the first and second electrode.

**[0010]** The phase of the electromagnetic signal that propagates along the transmission line will be affected by the parallel plate capacitor areas that are distributed along the transmission line. The electromagnetic signal is preferably a radiofrequency signal with a frequency in the range of 20 kHz to 300 GHz. The phase shifting device is adapted to transmit such a radiofrequency signal and to affect and modify the phase of this signal.

**[0011]** From a topological view the transmission line with non-overlapping sections and with overlapping sections is similar to a periodically loaded differential or balanced transmission line. The resulting phase shift depends inter alia on the number and the area of the parallel plate conductor areas within the overlapping sections that are implemented along the transmission line.

**[0012]** Preferably the tunable dielectric material is a liquid crystal material with a high dependency of the dielectric characteristics on an electric field that is applied to the liquid crystal material. Suitable liquid crystal materials as well as other tunable dielectric materials are known in the art and commercially available. The electric field that is applied to the liquid crystal material superimposes the radio frequency signal that is propagated along the transmission line, but this does not significantly interfere with the signal propagation.

**[0013]** A key difference between phase shifting devices known in prior art and the invention at hand is the design and embodiment of the transmission line as a differential line, i.e. as a transmission line that is suitable and can be used for signal transmission along the transmission line in a differential pair transmission mode. Thus, the arrangement and the design of the first and second electrode of the transmission line must provide for a balanced transmission line. Furthermore, the first electrode and the second electrode are electroconductively isolated from each other. The transmission line must allow for a predominant signal propagation along

the transmission line in transverse electromagnetic mode (TEM-mode) with neither electric nor magnetic field in the direction of propagation, i.e. in the direction along the transmission line.

**[0014]** The phase shift of the electromagnetic signals that are transmitted along the first and second electrode will be affected and controlled by the dielectric characteristics of the overlapping sections, that itself are controlled by the electric field that is applied to the tunable dielectric material arranged within the overlapping sections. The combined radio frequency signal with the appropriate phase shift that has been preset by the phase shifting device can then be used for e.g. signal emission or for signal evaluation of a phased array antenna.

**[0015]** According to an advantageous aspect of the invention the first electrode is arranged at a distance in the first direction to the second electrode, whereby the overlapping area of the first electrode overlaps the overlapping area of the second electrode in order to provide for one parallel plate capacitor area. Thus, no dedicated and separate capacitor electrodes are required. The first electrode and the second electrode are divided into sections that do not overlap each other and into sections that overlap each other. The tunable dielectric material is arranged between the first electrode and the second electrode. The tunable dielectric material may be arranged as a layer that is confined by glass or other material. The surface of the layer may extend over both electrodes and cover overlapping sections and non-overlapping sections of the first electrode and the second electrode. It is also possible to limit the tunable electric material to separate areas that only cover the respective capacitor electrode areas between the first electrode and the second electrode. According to an advantageous embodiment of the invention, the first electrode is arranged at a first surface of a first substrate layer and the second electrode is arranged at a second surface of a second substrate layer, whereby the first surface of the first substrate layer faces the second surface of the second substrate layer and whereby the first surface is arranged at a distance in the first direction to the second surface. The first electrode and the second electrode can be manufactured by deposition of electroconductive material onto a corresponding nonconducting substrate layer. The two substrate layers can be spaced at a distance in the first direction to each other, thereby confining an intermediary layer of the tunable dielectric material. Such a sandwich structure can be manufactured by easily controllable and reliable methods. The space requirement is approximately one millimeter for the thickness of the sandwich structure. Manufacture of the sandwich structure is similar to fabrication of liquid crystal displays and can be integrated into the respective production methods which then include such phase shifting devices. The substrate layers can be made of glass or any other material with non-conductive or sufficiently low conductive characteristics and with sufficient surface smoothness.

**[0016]** According to an advantageous embodiment of

the invention the first surface of the first substrate layer and the second surface of the second substrate layer confine the tunable dielectric material. Thus, no further substrate layers are required for confining the tunable dielectric material, which reduces the size and manufacturing costs for the phase shifting device.

**[0017]** According to an alternative aspect of the invention the first electrode and the second electrode are arranged side by side at a distance towards each other along the second direction on a same surface of a substrate layer, and a capacitor electrode is arranged at a distance in the first direction to this surface of the substrate layer with the first electrode and the second electrode in such a manner that a first capacitor electrode area of the capacitor electrode overlaps the overlapping area of the first electrode and that a second capacitor electrode area of the capacitor electrode overlaps the overlapping area of the second electrode, thus providing for two parallel plate capacitor areas between the capacitor electrode and the respective overlapping areas within the overlapping section. The first electrode and the second electrode may be arranged next to another on the same level of the phase shifting device. In addition to the first and the second electrode at least one or a few, but preferably many capacitor electrodes are arranged at another level in the first direction with respect to the first and second electrodes. The use of separate capacitor electrodes allows for complex shapes of the parallel plate capacitor areas along the transmission line and may simplify the manufacturing of the phase shift device.

**[0018]** In another aspect of the invention the first electrode and the second electrode each comprise an unbranched strip-shaped transmission line segment, whereby both transmission line segments are directed along the transmission line. A strip-shaped transmission line segment usually has a uniform width. Both transmission line segments can be of linear shape, i.e. the strip-shaped transmission line segment extends along a straight line, whereby the respective transmission segments are parallel and at a distance in the second direction to each other.

**[0019]** The strip-shape transmission line segment can also be curved. It is also possible for the strip-shape transmission segment to comprise linear sections in combination with corners or curved sections. Furthermore, the strip-shaped transmission segment may also have a spiral shape or meandering shape. The strip-shape transmission line segment may also have a zig-zag pattern.

**[0020]** According to another aspect of the invention, the strip-shaped transmission segments only comprise non-overlapping sections arranged at a distance towards each other in the second direction, and each of the overlapping areas of the first electrode and/or of the second electrode is protruding in the second direction from the respective strip-shaped transmission line segment of the first electrode and/or of the second electrode. When viewed from a distance in the first direction, the combined

shape of the first electrode and the second electrode can be similar to a ladder, wherein the strip-shaped transmission line segment of the first electrode and of the second electrode are similar to the first and second ladder beams, and wherein the protruding overlapping areas are similar to the rungs of the ladder. Each rung of the ladder comprises one overlapping area that protrudes in the second direction from the strip-shaped transmission line segment of the first electrode, and one overlapping area that protrudes in the second direction from the strip-shaped transmission line segment of the second electrode. Even though the two respective overlapping areas of the first and second electrode do overlap, they are spaced apart in the first direction and separated by the tunable dielectric material that is between the first electrode and the second electrode, or at least between the overlapping areas of the first electrode and the second electrode.

**[0021]** In yet another embodiment of the invention the respective overlapping areas of the first electrode and the second electrode provide for a rectangular or a quadratic parallel plate capacitor area. However, the overlapping areas may have any shape and contour that is advantageous for the desired phase shift or for the design of the electronic component that includes the phase shifting device.

**[0022]** In yet another aspect of the invention, subsequent parallel plate capacitor areas along the transmission line differ in respective distance to each other and/or in size and/or in shape. Thus, the parallel plate capacitor areas may be of identical shape and size and may be arranged in a regular pattern along the transmission line. However, it might be advantageous e.g. for signal propagation or for reduced size or manufacturing costs to arrange for parallel plate capacitor areas that have a different shape or size along the transmission line. Also, the distance in the direction of signal transmission along the transmission line between two adjacent parallel plate capacitor areas may vary according to demands related to size or cost of the phase shifting device, or in order to allow for better signal propagation or enhanced phase shifting properties of the phase shifting device.

**[0023]** According to another aspect of the invention, the first and second electrode can be referenced to one or more ground electrodes located at a distance in the first direction, e.g. on the outward facing surfaces of the substrate layers. However, the phase shifting device does not rely on the presence of a ground electrode. If e.g. for reasons of integrating the sandwich structure with other layers of a phased array antenna one or more ground electrodes are necessary, the size and the distance of the strip shaped transmission line segments can be easily adjusted when compared to a phase shifting device without ground electrodes.

**[0024]** According to an aspect of the invention, the first electrode and the second electrode are electrically connected to a bias voltage source. The bias voltage can be a constant bias voltage or a preferably low frequency

voltage with a frequency of up to several kHz. The bias voltage does not interfere with the signal propagation along the transmission line of the phase shifting device. The bias voltage that is applied to the first and second electrode by the bias voltage affects the dielectric characteristics of the tunable dielectric material that is arranged between the first and the second electrode. By applying a bias voltage to the first and second electrode and thereby affecting and changing the dielectric properties of the tunable dielectric material in between the parallel plate capacitor areas, the phase difference between the input signal and the output signal of the phase shifting device can be easily and reliably controlled and modified according to the respective requirements. According to an advantageous embodiment of the invention, the first electrode is connected to a first bias electrode which is connected to the bias voltage source, and that the second electrode is connected to a second bias electrode which is connected to the bias voltage source. The width of the bias electrode can be small when compared to the width of the first electrode and of the second electrode. The width can be approx. 10 % or less of the width of the first or second electrode. A small width or cross-section area of the first and second bias electrodes contributes to a high impedance of the first and second bias electrode resulting in reduced leakage of the electromagnetic signal from the first and second electrode into the first or second bias electrode.

**[0025]** In yet another embodiment of the invention the first and second bias electrodes consists of a material with a lower electrical conductivity than the first and second electrode. The resulting higher resistance of the bias electrodes prevents the electromagnetic signal that propagates along the transmission line from leaking from the first and second electrode into the first or second bias electrode. Preferably the first and second electrode are made of or comprise a material with a high conductivity of more than  $40 \cdot 10^6$  S/m like e.g. gold or copper. The first and second bias electrodes preferably has a sheet resistance of more than 20 Ohms/square and can be made of or comprise Indium Tin Oxide (ITO) or Nichrome (NiCr).

**[0026]** According to another aspect of the invention, the width of the first and second electrode in the second direction is between 100  $\mu\text{m}$  and 500  $\mu\text{m}$ , preferably approx. 200  $\mu\text{m}$ . Furthermore, the width of the overlapping area between the first electrode and the second electrode in the second direction is between 100  $\mu\text{m}$  and 500  $\mu\text{m}$ , preferably approx. 200  $\mu\text{m}$ . The width of the first and second electrode should be smaller than  $\Lambda/10$ , i.e. one-tenth of the characteristic wavelength of the electromagnetic signal that propagates along the transmission line. The distance in the second direction between the first electrode and the second electrode can be less than 50  $\mu\text{m}$  or even less than 25  $\mu\text{m}$ . For most applications the distance is between 10  $\mu\text{m}$  and 200  $\mu\text{m}$ . However, it is also possible to provide for a distance of more than 200  $\mu\text{m}$ . In general, it is considered advantageous for

the distance to be smaller than  $\Lambda/10$ .

**[0027]** The invention also relates to a method for operating the radio frequency phase shifting device as described above, whereby a radio frequency signal is fed at a signal entry point into the first electrode and the second electrode of the transmission line, whereby the radio frequency signal is transmitted along the transmission line, and whereby the radio frequency signal exits the transmission line a distance along the transmission line with respect to the signal entry point, characterized in that the radio frequency signal is transformed into a differential mode signal with equal amplitude and opposite polarity that is transmitted along the first electrode and the second electrode respectively, whereby a quasi-transverse electromagnetic mode signal transmission occurs, resulting in a use of the transmission line as differential pair transmission line for signal transmission of the radio frequency signal along the transmission line. Within the meaning of this invention the term quasi-transverse electromagnetic mode denotes a signal transmission mode that is predominantly a transverse electromagnetic mode (TEM-mode), but might also exhibit some less intense longitudinal component of the propagated signal due to the inhomogeneity at the dielectric materials that surround the first and second electrode, e.g. the substrate layers with a limited thickness and the tunable dielectric material in between the substrate layers. However, the transmission line is operated in a manner to support differential mode signal transmission, but not operated in a manner to support slot line mode or microstrip line mode of signal transmission. The space requirements for a pair of electrodes that are suitable for differential mode transmission is significantly smaller than the space requirements for a slot line electrode arrangement. Thus, the method for operating the radio frequency phase shifting device allows for a compact and space-saving design of the phase shifting device, which promotes the use of such a phase shifting device within a phased array antenna.

**[0028]** According to another aspect of the invention related to the method, a phase shift of the radio device signal that is transmitted along the transmission line in a differential pair transmission mode is controlled by controlling a direct current bias voltage that is applied to the first and second electrode of the transmission line. The electric field that is used for controlling the dielectric properties of the tunable dielectric material between the first and second electrode, which results in controlling the phase shift of a radio frequency signal that propagates along the transmission line, is preset by a bias voltage that is applied to the first and second electrode itself. Thus, no additional bias voltage electrodes are required for creating the electric field that is required for dielectric tuning of the tunable dielectric material. The direct current bias voltage that is applied to the first and second electrode does not affect the signal transmission in differential mode of the radio frequency signal that is transmitted along the first and second electrode of the transmission

line.

**[0029]** The invention also relates to a phased array antenna comprising several antenna elements that are arranged at a surface of a substrate layer, a single entry point at which a signal is transmitted to or from the several antenna elements, and for each antenna element a corresponding phase shifting device as described above, whereby a radio frequency signal is transmitted in a differential pair transmission mode along a transmission line within the phase shifting device, whereby the phase of each signal that is transmitted from the single entry point to the respective antenna element or that is transmitted from the respective antenna element to the single entry point is modified in order to adjust the superposition of each signal according to the preferred direction of radiation of the antenna system.

**[0030]** In order to reduce the space requirement and to facilitate the manufacturing, the phased array antenna comprises on top of each other a base layer with an entry point, a first substrate layer with a first electrode, a tunable layer that comprises the tunable dielectric material, a second substrate layer with a second electrode and an antenna layer with a radiating antenna structure. The first and second electrode can be arranged onto the respective surface of the first and second substrate layer by any suitable method, e.g. by printing or vapor deposition or by any method used within the semiconductor industry. The characteristic dimension of the phased array antenna can be some millimeters or up to some centimeters or decimeters. The dimensions are preferably adapted to the frequency of the electromagnetic signal that is received or emitted by the respective antennas. The more antennas that are incorporated into the phased array antenna, the larger the respective dimensions of the phased array antenna will be. The individual antennas are preferably arranged in a regular grid pattern of a rectangular or quadratic shape. However, it is also possible to arrange the antennas of the phased array antenna in a circular shape with several concentric circles of individual antennas.

**[0031]** According to an advantageous embodiment of the invention, the first substrate layer and the second substrate layer consists of a glass material, and the tunable layer comprises a liquid crystal material with tunable dielectric properties.

#### Brief description of the drawings

**[0032]** The present invention will be more fully understood, and further features will become apparent, when reference is made to the following detailed description and the accompanying drawings. The drawings are merely representative and are not intended to limit the scope of the claims. In fact, those of ordinary skill in the art may appreciate upon reading the following specification and viewing the present drawings that various modifications and variations can be made thereto without deviating from the innovative concepts of the invention. Like

parts depicted in the drawings are referred to by the same reference numerals.

Figure 1 illustrates a schematic top view of a phased array antenna that comprises 64 individual antennas arranged in a quadratic grid pattern,

Figure 2 illustrates a schematic top view of a transmission line of a single phase shifting device,

Figure 3 illustrates a sectional view of the transmission line as shown in figure 2 taken along the line III-III,

Figure 4 illustrates a sectional view of the transmission line as shown in figure 2 taken along the line IV-IV,

Figure 5 illustrates a topological representation of the transmission line as shown in figure 2,

Figure 6 illustrates a schematic top view of a transmission line of a single phase shifting device, whereby strip-shaped transmission line segments of the first and second electrode are arranged in a zig-zag pattern,

Figure 7 illustrates a schematic top view of a transmission line of a single phase shifting device, whereby the strip-shaped transmission line segments exhibit a square-wave meandering pattern,

Figure 8 illustrates a schematic top view of a transmission line of a single phase shifting device, whereby parallel plate capacitor areas along the transmission line differ in size and in shape,

Figure 9 illustrates a schematic top view of a transmission line of a single phase shifting device, whereby the first electrode 5 and the second electrode 6 are overlapped by several capacitor electrodes,

Figure 10 illustrates a sectional view of the transmission line as shown in figure 9 taken along the line X-X, and

Figure 11 illustrates a sectional view of the transmission line as shown in figure 9 taken along the line XI-XI.

#### Detailed description of the invention

**[0033]** A phased array antenna 1 that is shown in figure 1 comprises 64 individual antenna elements 2 that are arranged in a quadratic grid pattern with 8 x 8 antenna elements 2. In the center there is a single signal feed point 3 that is located on the back side of the grid pattern. An electromagnetic signal, preferably a radiofrequency

signal, can be introduced into the phased array antenna 1 by the signal feed point 3 and distributed to all of the respective antenna elements 2. In the same manner an electromagnetic signal that is received by the individual antenna elements 2 of the phased array antenna 1 can be transmitted to the signal feed point 3 and extracted from the phased array antenna. All individual antenna elements 2 are connected with the signal feed point 3. The connection comprises a dedicated phase shifting device for each individual antenna element 2, however, the phase shifting devices are not shown in figure 1.

**[0034]** The phase shifting devices can be the electrical connection of the individual antenna elements 2 to the signal feed point 3. Preferably, for each antenna element 2 the corresponding phase shifting device is only a part or section of the electrical connection to the signal feed point 3.

**[0035]** Figure 2 illustrates a schematic top view of a transmission line 4 of a single phase shifting device. The transmission line 4 comprises a first electrode 5 and a second electrode 6, whereby the first electrode 5 is at a different level in a first direction 26 with respect to the second electrode 6, thus resulting in a distance in the first direction 26 between the first electrode 5 and the second electrode 6. The first direction 26 is perpendicular to the direction of the signal propagation 9, i.e. along the direction of the transmission line 9 and also perpendicular to the drawing plane of figure 2. In figure 2 the first electrode 5 is depicted on top of the second electrode 6. In order to better illustrate the distance in the first direction 26 between the first electrode 5 and the second electrode 6, the first and second electrode 5, 6 are shown slightly displaced with respect to each other within the drawing plane, i.e. along the direction of the transmission line 9 as well as along a second direction 27 that is perpendicular to the direction of the transmission line 9 as well as perpendicular to the first direction 26.

**[0036]** Furthermore, the respective parts of the second electrode 6 that are depicted being below the corresponding parts of the first electrode 5 are shown with a dashed line. For the purpose of this description of the invention, the meaning of the first direction 26 and the second direction 27 is not limited to a single orientation but refers to an alignment along an axis that runs along the first and second direction 26, 27 respectively. Thus, reference to a displacement or a protrusion along the first direction 26 includes a displacement or protrusion in both orientations along the respective direction 26, 27.

**[0037]** Each of the first and second electrode 5, 6 comprises a strip-shaped transmission line segment 7, 8 that runs along a straight line in the direction of a signal propagation direction 9. At regular intervals a rectangular overlapping area 10, 11 protrudes in the second direction 27 from the respective strip-shaped transmission line segment 7, 8 of the first electrode 5 and of the second electrode 6, whereby the rectangular overlapping areas 10, 11 are directed towards each other. Within an overlapping section 12 of the transmission line 4, one over-

lapping area 10 of the first electrode 5 that is perpendicular to the first direction 26 overlaps with one corresponding overlapping area 11 of the second electrode 6 that is also perpendicular to the first direction 26. The two overlapping areas 10, 11 provide for a parallel plate capacitor area 13 of quadratic shape when viewed from the top, i.e. along the first direction 26. The overlapping sections 12 of the transmission line 4 alternate with non-overlapping sections 14 that only comprises the strip-shaped transmission line segments 7, 8 that are at a distance to each other in the second direction 27 and that do not overlap like within the overlapping sections 12 of the transmission line 4.

**[0038]** The non-overlapping sections 14 do not change much of the phase of the electromagnetic signal that propagates along the first and second electrode 5, 6 of the transmission line 4 in the direction of the signal propagation direction 9, as only a small portion of the electromagnetic field penetrates the tunable layer. However, each of the overlapping sections 12 affects the phase of the propagating electromagnetic signal resulting in a significant phase shift of up to  $2\pi$  or more from a phase shifting device that can be easily integrated into the phased array antenna 1 of figure 1.

**[0039]** A first bias electrode 15 is connected to the strip-shaped transmission segment 7 of the first electrode 5 and projects in the second direction 27 in the opposite orientation as the overlapping areas 10 of the first electrode 5. Similarly, a second bias electrode 16 is connected to the strip-shaped transmission segment 8 of the second electrode 6 and projects in the opposite direction of the overlapping areas 11 of the second electrode 6. The first and second bias electrodes 15, 16 are connected to a bias voltage source not shown in figure 2. The bias voltage source provides for a constant, i.e. DC voltage or for a low-frequency AC voltage that is applied to the first and second electrode 5, 6 and creates an electric field in the space between the first electrode 5 and the second electrode 6, thereby superimposing the electromagnetic field of the signal that propagates along the transmission line 4. The electric field between the overlapping areas 10, 11 of the first and second electrode 5, 6 is predominantly perpendicular to the plane of view, i.e. perpendicular to the parallel plate capacitor areas 13 shown in figure 2 and thus along the first direction 26. Due to the material and the small width of the first and second bias electrode 15, 16, the impedance of the first and second bias electrode 15, 16 is significantly higher than the impedance of the strip-shaped transmission segments 7, 8 of the first and second electrode 5, 6 which prevents the propagating electromagnetic signal from leaking from the first and second electrode 5, 6 into the first and second bias electrode 15, 16 and away from the transmission line 4. By choosing a highly resistive bias electrode material the impedance of the bias electrodes can be further increased.

**[0040]** Figures 3 and 4 illustrate two sectional views of a phase shifting device 17 with a transmission line 4 as

shown in figure 2. Figure 3 is a sectional view of a non-overlapping section 14 of the transmission line 4, whereas figure 4 is a sectional view of an overlapping section 12 of the transmission line 4.

**[0041]** The first electrode 5 is on top of a first substrate layer 18 made of glass material. The second electrode 6 is on top of a second substrate layer 19 also made of glass material. The first and second substrate layers 18, 19 are arranged at a distance to each other along the first direction 26 with the first electrode 5 facing the second electrode 6. Between the first and second substrate layer 18, 19 there is a tunable layer 20 that is filled with a liquid crystal material. The dielectric properties of the liquid crystal material can be modified by applying different bias voltages to the first and second electrode 5, 6 resulting in electric fields of different magnitude between the first and second electrode 5, 6. In the overlapping section 12 as shown in figure 3, the overlapping area 10 of the first electrode 5, the corresponding overlapping area 11 of the second electrode 6 and the liquid crystal material in between provide for a parallel plate capacitor with a capacitance that depends on the bias voltage.

**[0042]** The topological representation of the transmission line 4 as illustrated in figure 5 is that of a periodically loaded differential transmission line with the two electrodes 5, 6 and capacitive loads 21 of the overlapping sections 12 that alternate with the non-overlapping sections 14.

**[0043]** Figure 6 illustrates a schematic top view of an alternative embodiment of the transmission line 4, whereby the strip-shaped transmission line segments 7, 8 of the first and second electrode 5, 6 are arranged in a zig-zag pattern. This allows for longer non-overlapping areas 22 of the respective first and second electrodes 5, 6 between the overlapping sections 12 along the transmission line 4 when compared to a straight-line arrangement of the transmission line segments 7, 8 as shown in Figure 2.

**[0044]** Figure 7 illustrates a schematic top view along the first direction 26 of a transmission line 4 of a single phase shifting device, whereby the strip-shaped transmission line segments 7, 8 exhibit a square-wave meandering pattern. The first electrode is separately shown in Figure 7a, the second electrode is separately shown in Figure 7b, and the overlapping arrangement of both first and second electrode 5, 6 is shown in Figure 7c.

**[0045]** Figure 8 illustrates a schematic top view of a transmission line of a single phase shifting device that is similar to the embodiment shown in Figure 2. However, the parallel plate capacitor areas 13 along the transmission line 4 differ in size and in shape. Furthermore, the distance between subsequent parallel plate capacitor areas 13 may also vary along the transmission line 4.

**[0046]** Figure 9 illustrates a schematic top view of a transmission line of a single phase shifting device, whereby the first electrode 5 and the second electrode 6 each consists of a straight-line strip-shaped transmission line segment 7, 8 that are directed along the direction of the transmission line 4 that equals the signal propagation

direction 9. The transmission line segments 7, 8 are overlapped by several rectangular capacitor electrodes 23 that are oriented along the second direction 27 and thus perpendicular to the signal propagation direction 9. The several rectangular capacitor electrodes 23 are arranged at a distance in the first direction 26 with respect to the first and second electrode 5, 6, which are on the same level with respect to the first direction 26. A first capacitor electrode area 24 of each capacitor electrode 23 overlaps with the corresponding overlapping area 10 of the first electrode 5, and a second capacitor electrode area 25 of each capacitor electrode 23 overlaps with the corresponding overlapping area 11 of the second electrode 6. Thus, the first and second capacitor electrode areas 24, 25 and the corresponding overlapping areas 10, 11 of the first and second electrode 5, 6 provide for two separate parallel plate capacitor areas 13 within each overlapping section 12 of the transmission line 4.

**[0047]** Figures 10 and 11 illustrate two sectional views of a phase shifting device 17 with a transmission line 4 as shown in figure 9. Figure 10 is a sectional view of a non-overlapping section 12 of the transmission line 4, whereas figure 11 is a sectional view of an overlapping section 14 of the transmission line 4. Both first and second electrode 5, 6 are on the same level and on top of a first substrate layer 18 made of glass material. The rectangular capacitor electrodes 23 are on top of a second substrate layer 19 also made of glass material. The first and second substrate layers 18, 19 are arranged at a distance along the first direction 26 to each other, with the first and second electrode 5, 6 facing the capacitor electrodes 23. Between the first and second substrate layer 18, 19 there is a tunable layer 20 that is filled with a liquid crystal material. The dielectric properties of the liquid crystal material can be modified by applying different bias voltages to the first and second electrode 5, 6 and to the capacitor electrodes 23, resulting in electric fields of different magnitude between the first and second electrode 5, 6 and the respective overlapping areas 24, 25 of the capacitor electrodes 23. In the overlapping section 12 as shown in figure 3, the overlapping area 10 of the first electrode 5 and the corresponding overlapping area 24 of the capacitor electrode 23 as well as the overlapping area 11 of the second electrode 6 and the corresponding overlapping area 25 of the capacitor electrode 23 in combination with the liquid crystal material in between each provide for a parallel plate capacitor area 13 with a capacitance that depends on the bias voltage. The bias electrode 16 that is connected to all capacitor electrodes 23 is a strip-shaped linear bias electrode 16 that runs parallel to the first and second electrode 5, 6, but on the same level as the capacitor electrodes 23 and provides for electrical connection of all the capacitor electrodes 23 with the bias voltage source that is not shown in the figures.



## Claims

1. Radio frequency phase shifting device (17) with a transmission line (4) comprising a first electrode (5) and a second electrode (6) that are spaced at a distance in a first direction (26) and/or in a second direction (27) to each other, whereby the first direction (26) is perpendicular to a direction of a signal transmission (9) of a radio frequency electromagnetic signal along the transmission line (4) and whereby the second direction (27) is perpendicular to the first direction (26) and perpendicular to the direction of the signal transmission (9) along the transmission line (4), whereby the transmission line (4) comprises several overlapping sections (12), wherein an overlapping area (10) perpendicular to the first direction (26) of the first electrode (5) is overlapped by a capacitor electrode area (11, 24) and wherein an overlapping area (11) perpendicular to the first direction (26) of the second electrode (6) is overlapped by a capacitor electrode area (10, 25) in order to provide for a parallel plate capacitor area (13) within the overlapping section (12), and whereby the transmission line (4) comprises several non-overlapping sections (14), wherein the first electrode (5) runs at a distance to the second electrode (6) in the second direction (27), whereby a tunable dielectric material affects a phase shift of the electromagnetic signal that is propagated along the transmission line (4), whereby the tunable dielectric material is arranged between the respective capacitor electrode areas (24, 25) and the overlapping area (10) of the first electrode (5) and the overlapping area (11) of the second electrode (6) that affects the phase of an radio frequency electromagnetic signal that propagates along the overlapping section (12) of the transmission line (4), and whereby the first and second electrode (5, 6) are suitable and used for propagation of a radio frequency electromagnetic signal along the first electrode (5) and the second electrode (6) with a phase difference of  $180^\circ$  between the respective electromagnetic signals of the first and second electrode (5, 6).
2. Radio frequency phase shifting device (17) according to claim 1, wherein the first electrode (5) is arranged at a distance in the first direction (26) to the second electrode (6), whereby the overlapping area (10) of the first electrode (5) overlaps the overlapping area (11) of the second electrode (6) in order to provide for one parallel plate capacitor area (13).
3. Radio frequency phase shifting device (17) according to claim 2, **characterized in that** the first electrode (5) is arranged at a first surface of a first substrate layer (18), **in that** the second electrode (6) is arranged at a second surface of a second substrate layer (19), whereby the first surface of the first substrate layer (18) faces the second surface of the second substrate layer (19) and whereby the first surface is arranged at a distance in the first direction (26) to the second surface (26) to the second surface.
4. Radio frequency phase shifting device (17) according to claim 3, **characterized in that** the first surface of the first substrate layer (18) and the second surface of the second substrate layer (19) confine the tunable dielectric material.
5. Radio frequency phase shifting device (17) according to claim 1, wherein the first electrode (5) and the second electrode (6) are arranged side by side at a distance along the second direction (27) on a same surface of a substrate layer, and wherein a capacitor electrode (23) is arranged at a distance in the first direction (26) to this surface of a substrate layer with the first electrode (5) and the second electrode (6) in such a manner that a first capacitor electrode area (24) of the capacitor electrode (23) overlaps the overlapping area (10) perpendicular to the first direction (26) of the first electrode (5) and that a second capacitor electrode area (25) of the capacitor electrode (23) overlaps the overlapping area (11) perpendicular to the first direction (26) of the second electrode (6), thus providing for two parallel plate capacitor areas (13) between the capacitor electrode (23) and the respective overlapping areas (10, 11) within the overlapping section (10).
6. Radio frequency phase shifting device (17) according to one or more of the preceding claims, **characterized in that** the first electrode (5) and the second electrode (6) each comprise an unbranched strip-shaped transmission line segment (7, 8), whereby both strip-shaped transmission line segments (7, 8) are directed along the transmission line (4).
7. Radio frequency phase shifting device (17) according to claim 6, **characterized in that** the strip-shaped transmission segments (7, 8) only comprise non-overlapping sections (14) arranged at a distance towards each other in the second direction (27), and that each of the overlapping areas (10, 11) of the first electrode (5) and/or of the second electrode (6) are protruding in the second direction (27) from the respective strip-shaped transmission segment (7, 8) of the first electrode (5) and/or of the second electrode (6).
8. Radio frequency phase shifting device (17) according to one or more of the preceding claims, **characterized in that** the respective overlapping areas (10, 11) of the first electrode (5) and the second electrode (6) provide for a rectangular or a quadratic parallel plate capacitor area (13), whereby subsequent parallel plate capacitor areas (13) along the transmission line (4) differ in respective distance to each other

along the direction of signal propagation (9) and/or in size and/or in shape.

9. Radio frequency phase shifting device (17) according to one or more of the preceding claims, **characterized in that** the first electrode (5) and the second electrode (6) are electrically connected to at least one bias voltage source. 5
10. Radio frequency phase shifting device (17) according to claim 9, **characterized in that** the width of the first and second bias electrodes (15, 16) is smaller than the width of the first and second electrode (5, 6) in the second direction (27). 10
11. Radio frequency phase shifting device (17) according to one or more of the preceding claims, **characterized in that** the width of the first and second electrode (5, 6) in the second direction (27) is between 100  $\mu\text{m}$  and 500  $\mu\text{m}$ , preferably approx. 200  $\mu\text{m}$ . 15 20
12. Method for operating the radio frequency phase shifting device (17) according to one or more preceding claims 1 to 11, whereby a radio frequency signal is fed at a signal entry point into the first electrode (5) and the second electrode (6) of the transmission line (4), whereby the radio frequency signal is transmitted along the transmission line (4), and whereby the radio frequency signal exits the transmission line (4) a distance along the transmission line (4) with respect to the signal entry point, **characterized in that** the radio frequency signal is transformed into a differential mode signal with equal amplitude and opposite polarity that is transmitted along the first electrode (5) and the second electrode (6) respectively, whereby a quasi-transverse electromagnetic mode signal transmission occurs, resulting in a use of the transmission line (4) as differential pair transmission line for signal transmission of the radio frequency signal along the transmission line (4). 25 30 35 40
13. Method for operating the radio frequency phase shifting device (17) according to claim 12, whereby a phase shift of the radio device signal that is transmitted along the transmission line (4) in a differential pair transmission mode is controlled by controlling a direct current bias voltage that is applied to the first and second electrode (5, 6) of the transmission line (4). 45 50
14. Phased array antenna (1) comprising several antenna elements (2) that are arranged at a surface of a substrate layer (23), a signal feed network from or to which a radio frequency signal is transmitted to or from the several antenna elements (2), and for each antenna element (2) a corresponding phase shifting device (17) according to one or more of the preceding claims 1 to 11, whereby a radio frequency signal is 55

transmitted in a differential pair transmission mode along a transmission line (4) within the phase shifting device (17), and whereby the phase of each radio frequency signal that is transmitted from the single signal feed point (3) to the respective antenna element (2) or that is transmitted from the respective antenna element (2) to the single signal feed point (3) is modified in order to adjust the superposition of each radio frequency signal according to the preferred direction of radiation of the phased array antenna (1).

15. Phased array antenna (1) according to claim 14, **characterized in that** the phased array antenna (1) comprises on top of each other a base layer (22), a first substrate layer (18) with a first electrode (5), a tunable layer (20), a second substrate layer (19) with a second electrode (6) and an antenna layer (23) with a radiating antenna structure for each of the antenna elements (2).
16. Phased array antenna (1) according to claim 14 or 15, **characterized in that** the first substrate layer (18) and the second substrate layer (19) consists of a glass material, and that the tunable layer (20) comprises a liquid crystal material with tunable dielectric properties.

FIG 1

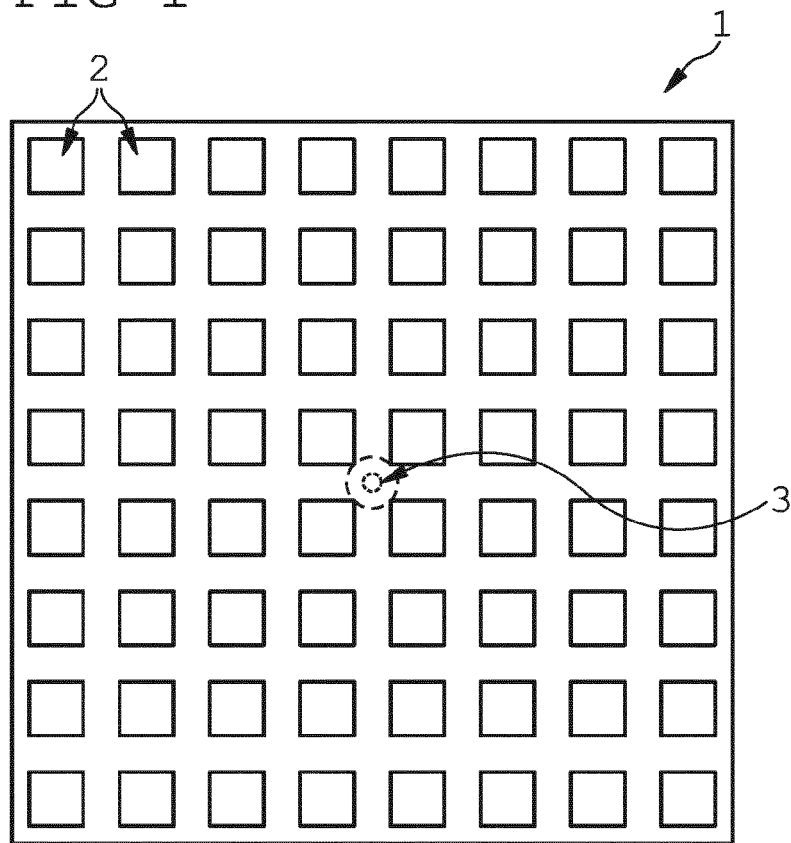


FIG 2

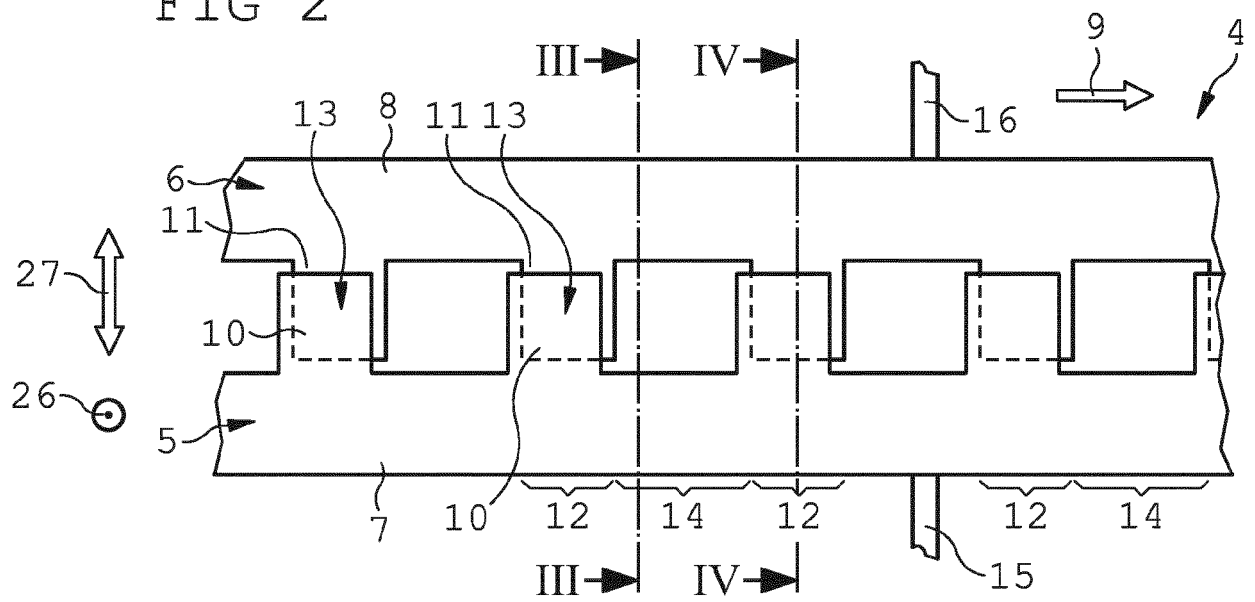


FIG 3

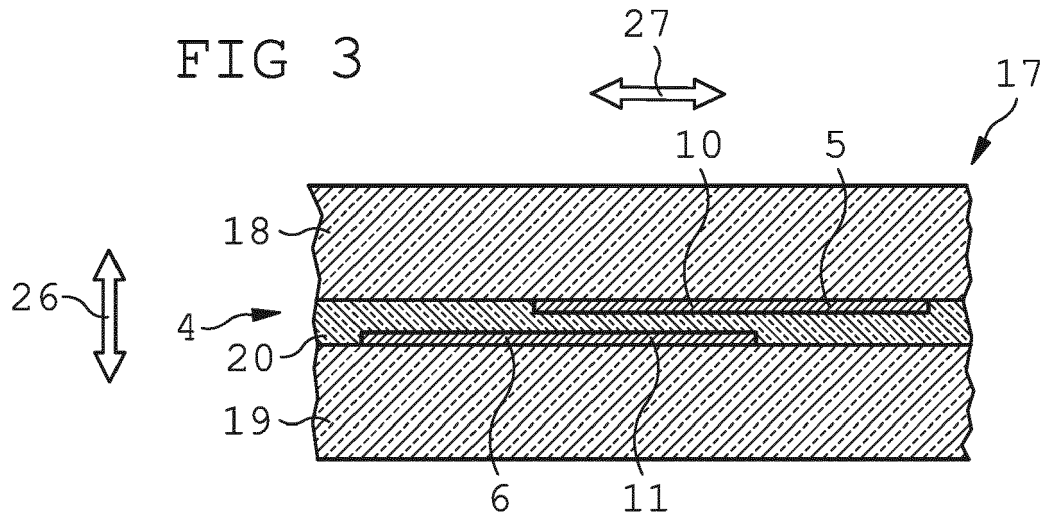


FIG 4

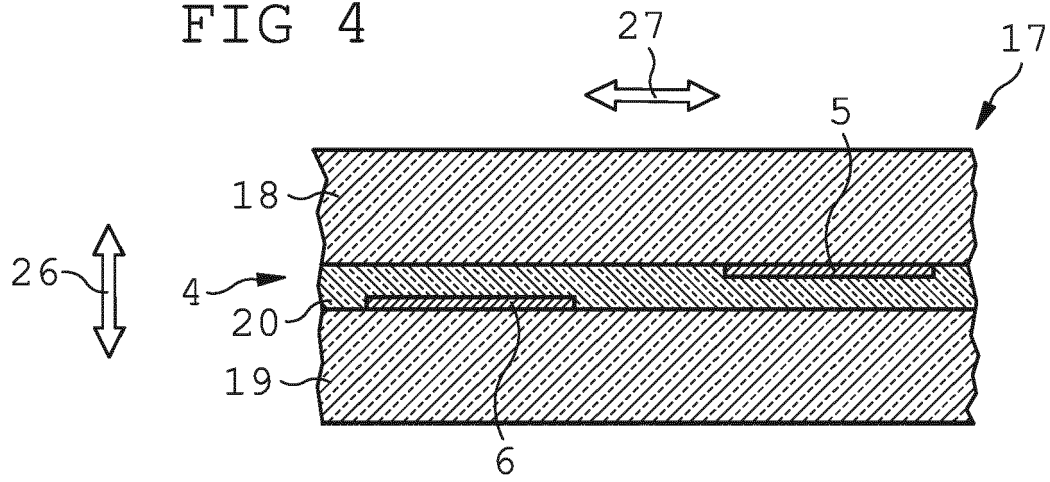


FIG 5

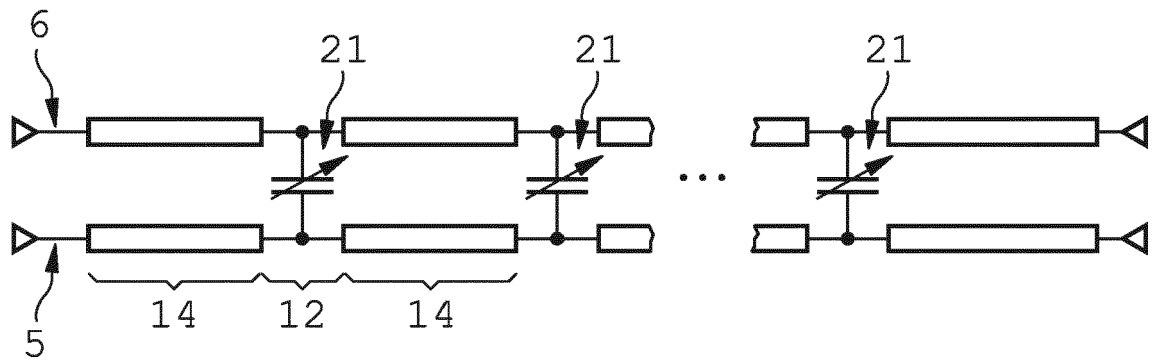


FIG 6

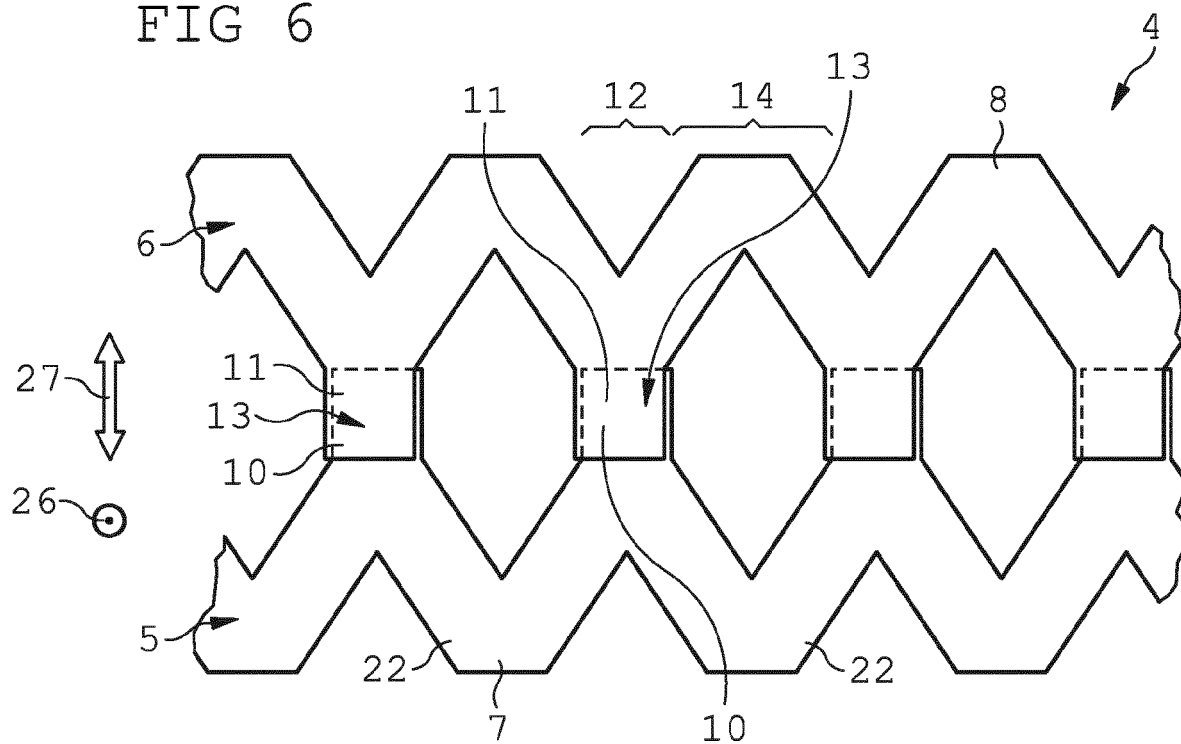


FIG 7

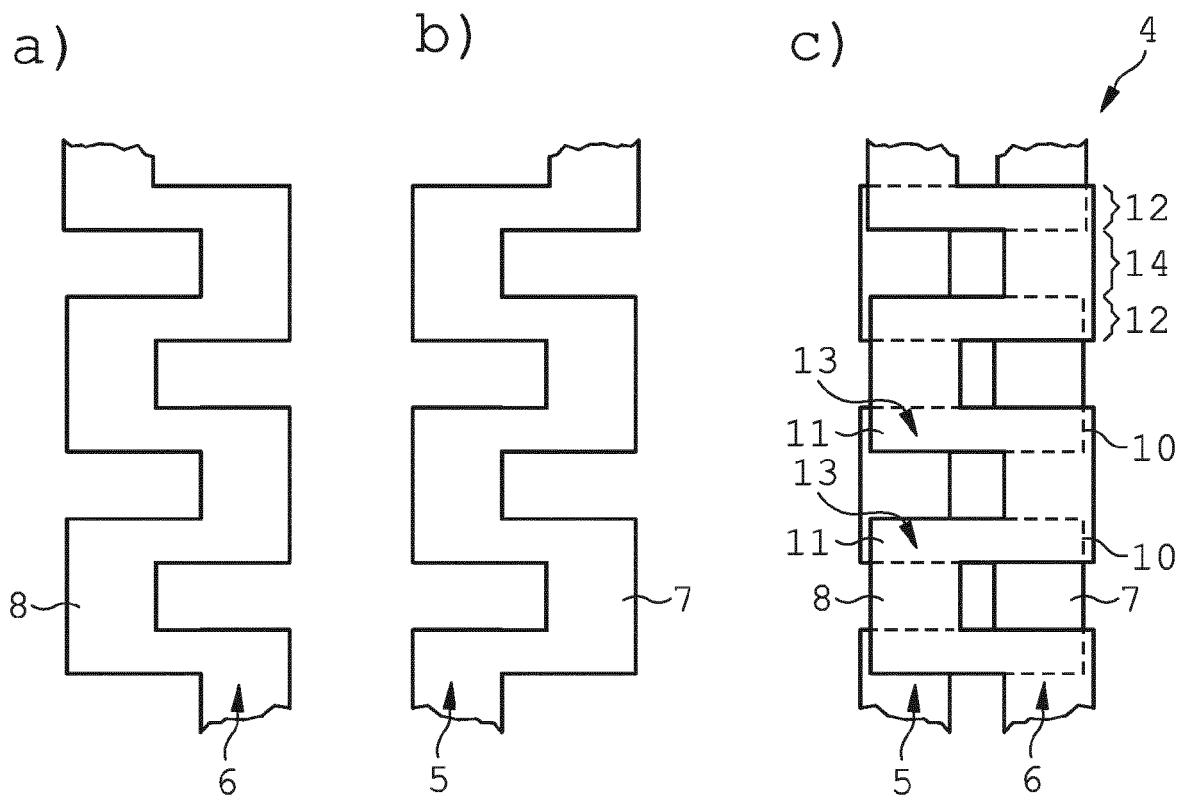


FIG 8

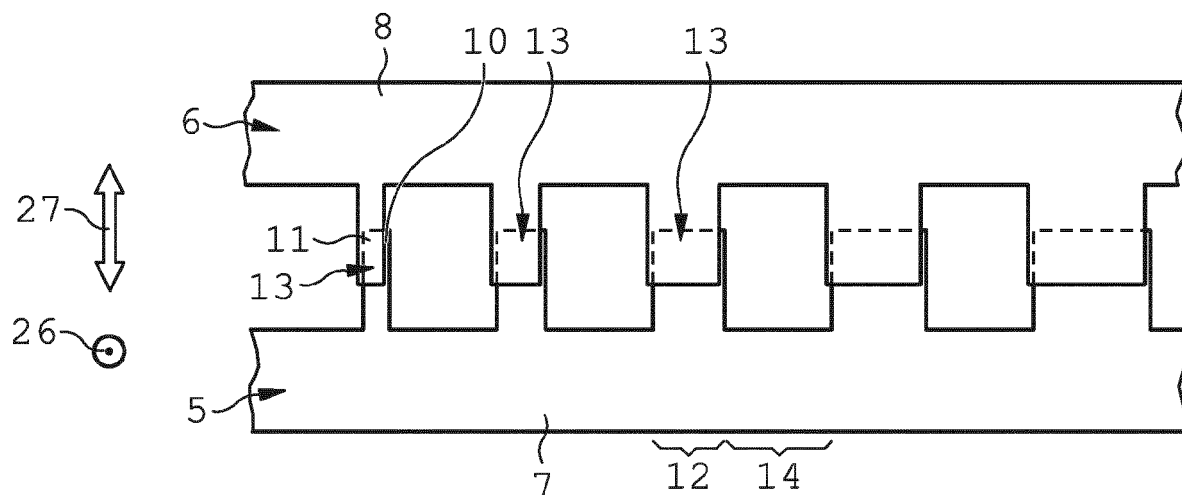
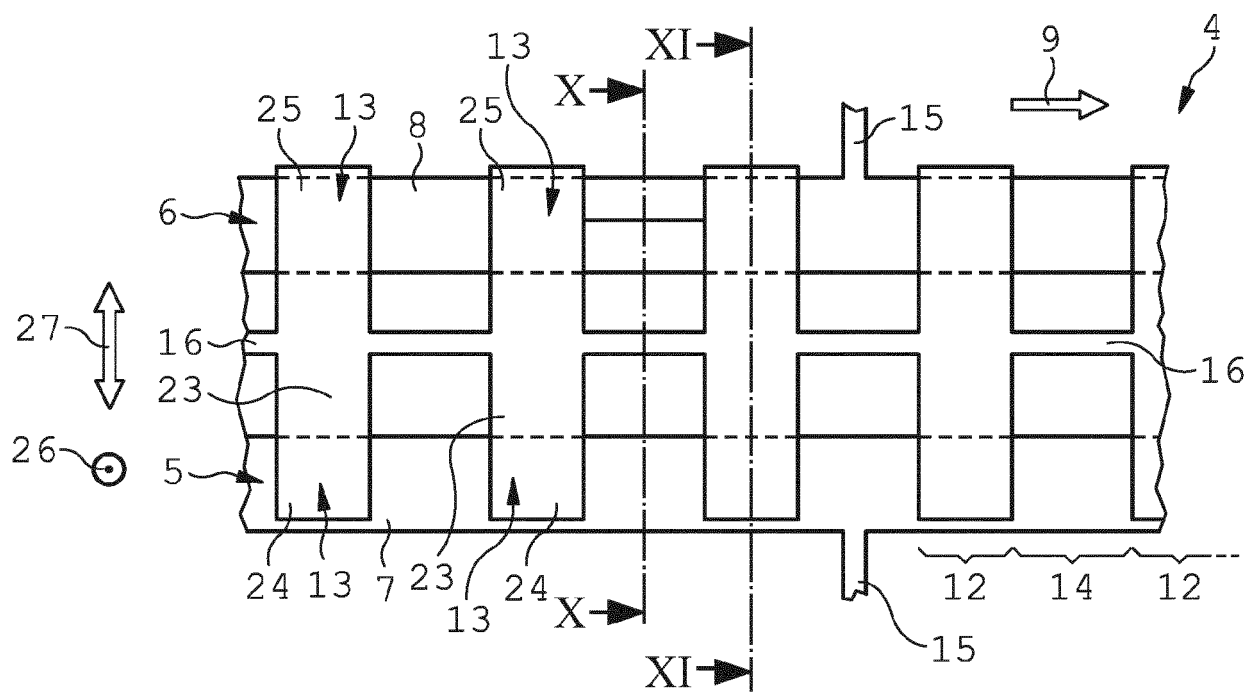
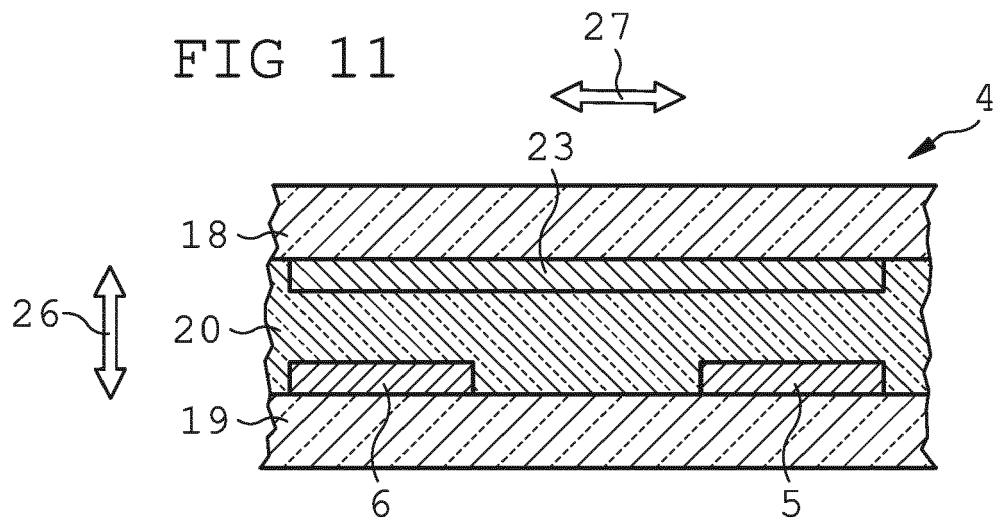
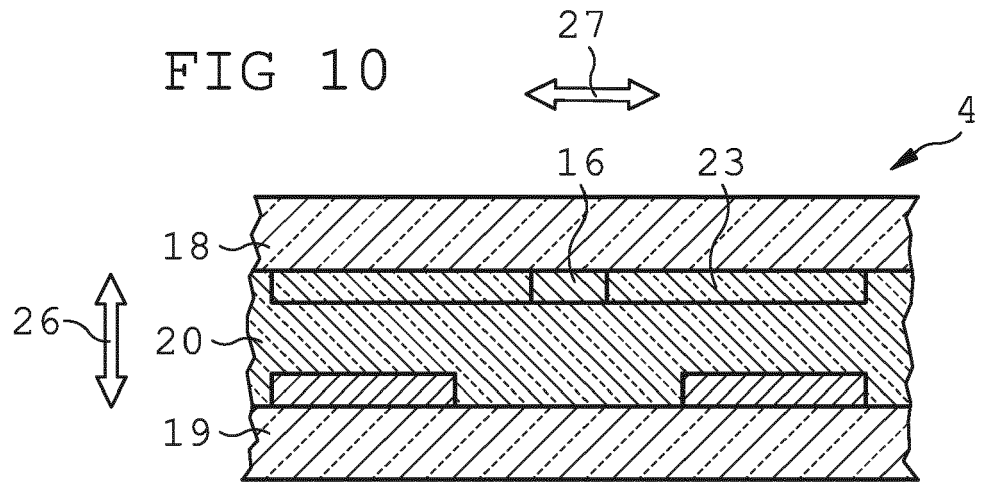


FIG 9







## EUROPEAN SEARCH REPORT

Application Number  
EP 19 19 0405

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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
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Y A	* page 1, left-hand column, paragraph section I - page 1, right-hand column, paragraph section II; figure 4 * * page 3, left-hand column, line 6 - page 4, right-hand column, line 6; figure 4 * * section III.A; page 3, left-hand column, paragraphs 1,2 *	14-16 5-7	
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Y	* section I, lines 1-3 of second paragraph; page 1, right-hand column; figures 3-5 * * section IV; page 2, right-hand column, paragraph 1 * * section V; page 3, left-hand column, lines 1-7, paragraph 1 *	14-16	
The present search report has been drawn up for all claims			
Place of search The Hague		Date of completion of the search 12 December 2019	Examiner Georgiadis, A
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			

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			TECHNICAL FIELDS SEARCHED (IPC)
The present search report has been drawn up for all claims			
Place of search		Date of completion of the search	Examiner
The Hague		12 December 2019	Georgiadis, A
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			

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