

(19)



(11)

EP 3 010 083 A1

(12)

EUROPEAN PATENT APPLICATION

(43) Date of publication:
20.04.2016 Bulletin 2016/16

(51) Int Cl.:
H01Q 3/36 (2006.01)

(21) Application number: **14189204.2**

(22) Date of filing: **16.10.2014**

(84) Designated Contracting States:
**AL AT BE BG CH CY CZ DE DK EE ES FI FR GB
GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO
PL PT RO RS SE SI SK SM TR**
Designated Extension States:
BA ME

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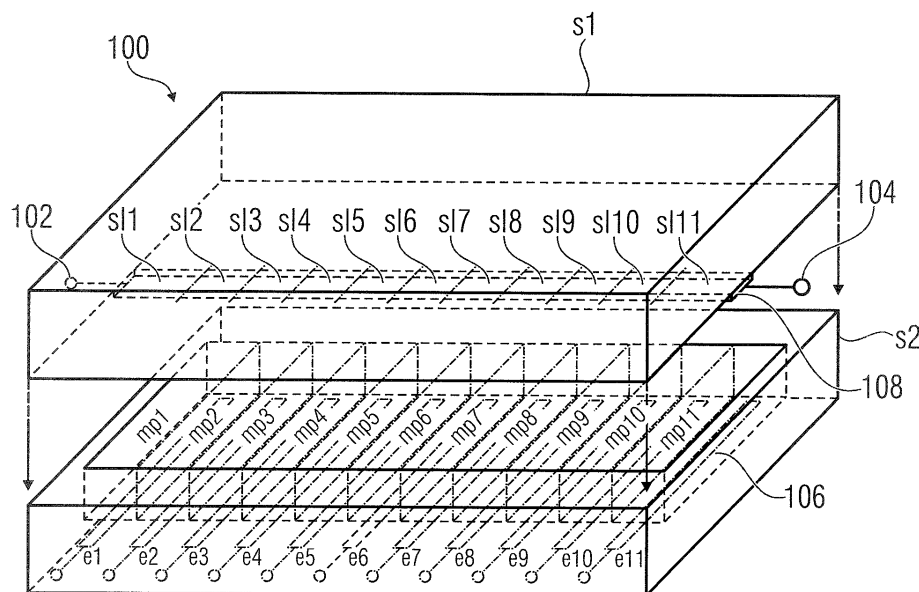
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(54) Phase shifter

(57) A phase shifter comprises a signal input, a signal output, a signal path between the signal input and the signal output, and a plurality of sections. Each section of the plurality of sections comprises a signal line portion and an associated material portion having a characteristic that is tuneable to apply an adjustable phase shift

to a signal transmitted over the signal line portion, wherein the characteristic of the material of each section is tuneable individually, wherein the signal line portions are connected in series in the signal path or wherein the phase shifter is configured to switch the signal line portions in series in the signal path.

**FIG 1**

Description

[0001] The present invention relates to a phase shifter and, in particular, to a phase shifter configured to provide an adjustable phase shift to a signal transmitted via a signal line. In addition, the invention relates to a wireless communication device comprising such a phase shifter.

[0002] In mobile scenarios, wireless communications systems take advantage of phased array antennas that allow for an optimal steering of the radiation characteristics. The phased array is able to adapt its radiation characteristics according to the instantaneous situation. That is, the main beam of radiation can be electronically aligned towards the remote station, independent of the relative orientation between both. This leads to a high signal quality and reliable transmission without any mechanical re-orientation of the antenna. The beam forming in a phased array relies on the phase progression along the radiating aperture. This phase progression is generated by an excitation network, which allows electronic variation of the phase of the signal to be transmitted or the signal received. A key component of phased arrays is therefore a phase shifter. The phase shifter is a two-port device that introduces a tuneable phase lag to the passing signal between the input port and the output port.

[0003] In electronically controlled phase shifters, the phase lag can be tuned via an electrical signal. Depending on the architecture, the tuning can be done continuously or in discrete steps. In continuously tuneable phase shifters, an analogue signal is applied to the phase shifter. While a continuously tuneable phase shifter provides an arbitrary phase shift, it is more sensitive to temperature variations, manufacturing tolerances and alike. Application of continuously tuneable phase shifters therefore needs means for calibration to compensate for phase errors. With a discrete tuneable phase shifter, the phase shift can only be varied within a limited set of steps, restricting the beam forming capabilities in a phased array. Yet discrete tuneable phase shifters are usually less sensitive to environmental variations or manufacturing tolerances and might therefore be easier to implement with lower calibration effort.

[0004] Implementations of electronic phase shifters have been well known for several decades. Early implementations were based on PIN diodes, which served as switching devices. Fig. 4a to 4c show single sections of so-called switched-line phase shifters using series switches and shunt switches, respectively. Fig. 4a shows series switches, Fig. 4b shows shunt switches, and Fig. 4c shows an example implementation using switching shunt diodes D1 to D4. Examples of such phase shifters are described in R. V. Garver, "BroadBand Diode Phase Shifters," IEEE Transactions on Microwave Theory and Techniques, vol. 20, no. 5, pp. 314-323, May 1972; and S. K. Koul and B. Bhat, "Microwave and Millimeter Wave Phase Shifters", Artech House, Boston, 1991, for example. With a cascade of multiple sections each representing another phase shift, the total phase shift can be al-

tered in discrete steps. The phase shift of section n is given by $\psi_n = k(l_n - l)$, with k being the wavenumber and l and l_n being the mechanical length of the respective line. The switched-line phase shifter therefore relies on the length variation of the path, which is passed by the signal. A switched-line phase shifter of N sections with a total phase shift of 360 degrees has a resolution of $360^\circ/2^N$. Suppose a 3-bit phase shifter, i.e., $N = 3$, the resolution amounts 45° .

[0005] Among switching between lines of different mechanical lengths, a phase shift can also be achieved by tuning of material characteristics, i.e., the electrical length of the line is altered rather than the mechanical length thereof. A line section of mechanical length l shows a phase shift of $\psi = k(\mu_r \epsilon_r) l$. The wavenumber k follows

$$\text{from } k(\mu_r \epsilon_r) = 2\pi f \frac{n}{c} = 2\pi f \frac{\sqrt{\mu_r \epsilon_r}}{c} \text{ with } c \text{ the free-}$$

space velocity of light, f the frequency, n the refractive index, μ_r the relative permeability, and ϵ_r the relative permittivity of the substrate supporting the transmission line. A variation of μ_r or ϵ_r causes a variation of k and, therefore, a varying phase.

[0006] This approach was pursued in ferrite-type phase shifters, where the permeability of a ferrite material is varied by an external magnetic field applied to it, as described in S. K. Koul and B. Bhat, "Microwave and Millimeter Wave Phase Shifters", Artech House, Boston, 1991. The drawback of ferrites is their losses, especially occurring at frequency above 1 GHz. Phase shifters using a ferroelectric medium in a microstrip line section are also described in US 5 409 889 A and US 5 451 567 A.

[0007] In recent years, non-linear dielectric materials became available and have been used for the implementation of phase shifting devices. In contrast to ferrite-type phase shifters, the permittivity is varied while $\mu_r = 1$. Non-linear dielectrics include so-called ferroelectrics, a solid mixture (e.g. mixtures of Barium, Strontium, and Titanate), and so-called liquid crystals (LC). Applying an electric field of proper strength to a non-linear dielectric causes a variation of the permittivity and, therefore, of the phase.

[0008] An example of a LC-type microstrip-line phase shifter is shown in Fig. 5. The phase shifter comprises a first substrate 10 and a second substrate 12, which are shown separate from each other in Fig. 5. As indicated by arrows 14, in reality, the substrates are attached to each other in the phase shifter. A microstrip line 16 is provided on the surface of the first substrate 10, which is attached to the second substrate 12. A liquid crystal mixture 18 is filled in a recess in the second substrate 12, which extends up to the surface of the second substrate 12, which is attached to the first substrate 10, and the first substrate 10 supporting the microstrip line 16 serves as a cover for the liquid crystal mixture 18. Thus, the liquid crystal mixture 18 is arranged adjacent to the microstrip line 16 and the phase shift provided to a signal transmitted via the microstrip line 16 can be var-

ied by varying the permittivity of the liquid crystal mixture 18.

[0009] Implementations of phase shifters featuring LC mixtures rely on a continuous variation of the permittivity, such as those described in C. Weil, G. Luessem, R. Jacoby, "Tunable Inverted Tunable Inverted-Microstrip Phase Shifter Device Using Nematic Liquid Crystals," Microwave Symposium Digest, 2002 IEEE MTT-S International (Vol. 1), 2-7 June 2002, Seattle, WA, USA, pp. 367-371; and S. Müller et al., "Tunable Passive Phase Shifter for Microwave Application using Highly Anisotropic Liquid Crystals," Microwave Symposium Digest, 2004 IEEE MTT-S International (Vol. 2), 6-11 June 2004. Variations caused by temperature variations, for example, have therefore to be monitored and considered for the biasing of the LC mixture. This holds also for ferroelectric and ferrite-based solutions. Phased arrays comprising tens or hundreds of phase shifters need much effort for calibration.

[0010] Another drawback of available LC mixtures is their little tuning range. With the tuneability t defined by

$$t = 1 - \frac{\sqrt{\varepsilon_{r,\min}}}{\sqrt{\varepsilon_{r,\max}}} \text{ with } \varepsilon_{r,\min} \text{ the minimum permittivity}$$

and $\varepsilon_{r,\max}$ the maximum permittivity of the LC mixture,

the phase shift reads $\psi = 2\pi \frac{f}{c} l \sqrt{\varepsilon_{r,\max}} t$. Usual

LC mixtures have a tuneability of $t = 0.2$ at most. Suppose a maximum permittivity of $\varepsilon_{r,\max} = 3$. To achieve a total phase shift of 2π (or 360°), a transmission line of 2.9 wavelengths is required. Such lengths might be intolerable as it complicates the compact integration of the phase shifter and causes higher losses, leading to a reduced system performance.

[0011] An UHF phase shifter is described in US 5 936 484 A, which comprises a microstrip line deposited on a substrate plate made of insulating material having high permittivity, such as alumina. A second substrate is attached to the substrate by spacers and liquid crystal material is arranged in a sealed space between the substrates, which is adjacent to the microstrip line. A DC voltage is applied to the microstrip line in order to vary the permittivity of the liquid crystal material. Phase shifters including a plurality of microstrip lines in parallel, which constitute independently controllable phase shifters are also disclosed.

[0012] Phase shifters comprising an adjustable phase shift are also disclosed in US 2004/0041664 A1 and US 2001/0017577 A1. Liquid crystal materials usable in phase shifters are disclosed in US 2005/0067605 A1 and US 2014/0022029 A1.

[0013] It is the object underlying the invention to provide a concept permitting implementation of a phase shifter having improved characteristics, in particular a phase shifter which may have at least one of stable characteristics, a wide tuning range and a high resolution.

[0014] This object is achieved by a phase shifter according to claim 1.

[0015] Embodiments provide a phase shifter comprising a signal input, a signal output, a signal path between the signal input and the signal output, and a plurality of sections, each section of the plurality of sections comprising a signal line portion and an associated material portion having a characteristic that is tuneable to apply an adjustable phase shift to a signal transmitted over the signal line portion, wherein the characteristic of the material of each section is tuneable individually, wherein the signal line portions are connected in series in the signal path or wherein the phase shifter is configured to switch the signal line portions in series in the signal path

[0016] Embodiments are based on the recognition that a phase shifter having stable characteristics can be implemented by subdividing the phase shifter into a plurality of serial sections which can be tuned individually. The characteristic of the sections may be tuned continuously, in discrete steps or, as in preferred embodiments, in a binary manner between two values of the characteristic only. Thus, the total phase shift provided between a signal input and a signal output can be adjusted in a flexible manner by controlling each section individually. For example, it is possible to adjust the total phase shift provided by the phase shifter over a wide range.

[0017] In embodiments, the tuneable characteristic of the material portions is the refractive index of the material portions. In embodiments, the refractive index of the material portions is tuneable by varying the permittivity or the permeability of the material portions. In embodiments, the phase shifter comprises, for each section, means for controlling the tuneable characteristic of the material portion, wherein the means for controlling are provided in addition to the signal line portion. The means for controlling may comprise one or two electrodes configured to apply a variable electric field to the corresponding material portion in order to change the permittivity thereof or may comprise an element or a magnet configured to apply a variable magnetic field to the corresponding material portion in order to change the permeability thereof. In embodiments, the material portions comprise a non-linear dielectric selected from the group including at least ferroelectrics, solid mixtures of barium, strontium and titanate, and liquid crystal mixtures. In embodiments, the material portions comprise ferrite materials

[0018] In embodiments, the signal line portions of at least some of the sections have different lengths. In embodiments, the lengths of the signal line portions are dimensioned based on a scheme $b^{n-1}\Delta x$ with b and n being natural numbers and Δx being the length of the section having the shortest signal line portion. Thus, embodiments permit adjusting a desired phase shift provided by the phase shifter in a flexible and appropriate manner.

[0019] In embodiments, the means for controlling are configured to switch the characteristic of the material portion between a respective first value and a respective second value only. Thus, embodiments permit partition-

ing a line of a tuneable electrical signal length into a number of sections, wherein the characteristic (such as the refractive index) of each section is tuned between its minimum and its maximum only. Thus, a number of advantages can be achieved such as usage of a control signal of a binary type, a reduced response time and the usage of mature technologies.

[0020] In embodiments, the signal line portions are arranged on a surface of a first substrate, wherein the material portions are arranged in a second substrate, and wherein the first substrate and the second substrate are attached to each other so that the signal line portions are arranged adjacent to the material portions. Thus, the phase shifter can be implemented in an easy and compact manner. In embodiments, the signal line portions of the plurality of sections form a common signal line coupled between the signal input and the signal output of the phase shifter and wherein the material portions of the sections are arranged side by side along the length of the common signal line.

[0021] In embodiments, the phase shifter comprises at least one non-tuneable signal line portion associated with one of the sections, and switches configured to switch into the signal path either the signal line portion of the one of the sections or the associated non-tuneable signal line portion. In such embodiment, the phase shifter may comprise a respective non-tuneable signal line portion associated with each section and switches configured to switch into the signal path either the signal line portion of the respective section or the associated non-tuneable signal line portion.

[0022] Embodiments provide a phase shifter system comprising a phase shifter having a plurality of sections, a non-tuneable signal line portion, and switches configured to switch into the signal path either the phase shifter or the non-tuneable signal line portion. Embodiments comprise a plurality of phase shifters having a plurality of sections, a respective non-tuneable signal line portion associated with each of the phase shifters, and switches configured to switch into the signal path either the respective phase shifter or the associated non-tuneable signal line portion.

[0023] Thus, embodiments provide a combination of a switched-line phase shifter and a phase shifter based on the tuning of material characteristics. Such embodiments permit for a number of advantages such as a compact implementation and low losses, as well as the possibility of a continuous shifting of the signal phase or a digitally controlled phase shift with high resolution.

[0024] Embodiments provide a wireless communication device comprising a phase shifter as described herein and a phased antenna array, wherein the phase shifter is configured to control the phase shift of a signal sent or received via the phased antenna array.

[0025] Embodiments of the invention are described in the following referring to the drawings, in which:

Fig. 1 shows an embodiment of a phase shifter

comprising a plurality of tunable sections arranged adjoining each other side by side;

5 Fig. 2 shows an embodiment of a phase shifter comprising a plurality of tunable sections switchable into a signal path between a signal input and a signal output of the phase shifter;

10 Fig. 3 shows an embodiment of a phase shifter comprising a plurality of tunable sections of different lengths, which are arranged adjoining each other side by side;

15 Fig. 4a to 4c show embodiments of common phase shifters using switched transmission lines; and

20 Fig. 5 shows a common phase shifter using a non-linear dielectric material.

[0026] An embodiment of a phase shifter 100 is shown in Fig. 1. The phase shifter 100 comprises a signal input 102, a signal output 104, a first substrate s1, a second substrate s2, a material 106 having a tuneable characteristic, and a signal line 108 in the form of a strip line. In the embodiment shown, material 106 is e.g. a liquid crystal material. The substrates s1 and s2 are shown separate from each other for sake of explanation. In reality, the substrates are attached to each other so that the signal line 108 is adjacent to the material 106 and so that the total phase shift of a signal transmitted over the signal line 108 can be adjusted by tuning the characteristic of the material 106.

[0027] Material 106 and signal line 108 are partitioned into a plurality of sections. Each section comprises a signal line portion sl1 to sl11 and an associated material portion mp1 to mp11. The signal line portions sl1 to sl11 form the common signal line 108 between the signal input 102 and the signal output 104. Accordingly, the signal line portions sl1 to sl11 are connected in series between the signal input 102 and the signal output 104. In the embodiment shown in Fig. 1, the partitioning is achieved by respective electrodes e1 to e11, each forming means for controlling the tuneable characteristic of the associated material portion mp1 to mp11. The electrodes may be formed on the lower surface of the second substrate s2 or within the second substrate so as to face the material portions mp1 to mp11. The electrodes e1 to e11 may be formed along the extent of the material portions mp1 to mp11. Alternatively, the electrodes e1 to e11 may be provided in an area facing the respective signal line portion sl1 to sl11 only.

[0028] An electric field applied to each of the material portions mp1 to mp11 is individually controllable by means of the electrodes e1 to e11, such as by applying a corresponding DC voltage between each of the elec-

trodes e1 to e11 and the common signal line 108 or by applying a corresponding DC voltage between each of the electrodes e1 and e11 and a further electrode (not shown) arranged so that the material portions mp1 to mp11 are arranged between the electrodes e1 to e11 and the further electrode. For example, the further electrode may be formed on the top surface of the first substrate s1 or within the first substrate s1.

[0029] Thus, in embodiments of the invention, electrodes configured for the application of voltages in order to change an electric field applied to the material portions are provided. In embodiments of the invention, electrodes or conductors configured for the application of currents in order to change a magnetic field applied to the material portions may be provided. In embodiments, material portions mp1 to mp11 may be formed by magnetically tunable elements and electrodes e1 to e11 may represent conductors allowing a variable current flow in order to apply a variable magnetic field to the respective material portion. Such conductors may be regarded as representing an element or a magnet configured to apply a variable magnetic field to the corresponding material portion in order to change the permeability thereof.

[0030] Thus, the characteristic of the material of each material portion mp1 to mp11 is tuneable individually to apply an adjustable phase shift to a signal transmitted over the associated signal line portion sl1 to sl11. Thus, the total phase shift applied by phase shifter 100 to a signal transmitted from the signal input 102 to the signal output 104 can be adjusted by controlling each section individually.

[0031] In the embodiment shown, the material portions mp1 to mp11 are portions of a continuous volume of material 106 formed in the second substrate s2 so as to extend up to the upper surface thereof. In alternative embodiments, the material portions mp1 to mp11 may be formed by separate volumes of material.

[0032] Accordingly, Fig. 1 shows a phase shifter resembling a strip-line phase shifter based on tuning of material characteristics. Yet, instead of having a continuous substrate and applying a single tuning signal along the line, it is a composite of a number of strip-line sections sl1 to sl11, each can be tuned individually. Each section covers a fractional portion of the total line length, i.e., it measures a fractional part of the guide wavelength. This allows switching only between the maximum and the minimum of the refractive index of the tuneable material in each section. The line is therefore composed of little portions showing either a refractive index $n_{\min}$ or $n_{\max}$. In total, the line can be considered having an effective refractive index n_{eff} that is given by an average value, with $n_{\min} \leq n_{\text{eff}} \leq n_{\max}$.

[0033] While a strip line is shown in Fig. 1, the signal line can be of an arbitrary type, including microstrip lines, tri-plate lines, waveguides, partially filled waveguides, substrate-integrated waveguides among others.

[0034] In the embodiment of Fig. 1, the characteristic, i.e. the refractive index, of the material can be varied by

varying the permittivity of the material by changing an electric field applied. In such embodiments, the tuneable material may comprise a non-linear dielectric, such a non-linear dielectric selected from the group consisting of so-called ferroelectrics, solid mixtures (such as mixtures of Barium, Strontium and Titanate), and so-called liquid crystals. In other embodiments, the characteristic, i.e. the refractive index, of the material can be varied by varying the permeability of the material by changing a magnetic field applied. In such embodiments, the tuneable material may comprise a ferrite material. Generally, the tuneable material can be of any type, provided that the characteristic which changes the phase shift applied to the signal, such as the refractive index, can be varied by any means.

[0035] It goes without saying that embodiments of such phase shifters may comprise at least one controller configured to apply the necessary signals in order to effect the variation of the material characteristics in order to achieve the phase shifts as desired. For example, the phase shifter shown in Fig. 1 may comprise a controller adapted to apply a separate voltage to each of the electrodes e1 to e11. Moreover, it goes without saying that the signal input 102 and the signal output 104 may be connected between a signal generator and a phased array antenna in a wireless communication device so that the radiation characteristic of the phased array antenna can be steered by controlling the phase shift provided by the phase shifter.

[0036] Fig. 2 shows a phase shifter 200 comprising a plurality of sections. Each section represents a tunable portion and comprises a tunable signal line portion 202, 204, 206. Each signal line portion 202, 204, 206 has associated therewith a material portion having a tuneable characteristic so that the phase shift applied to a signal transmitted over the associated signal line portion 202, 204, 206 can be adjusted. Thus, the electrical length of line portions 202, 204 and 206, which have fixed mechanical lengths, can be adjusted by tuning the characteristic of the material portion. Moreover, each signal line portion 202, 204, 206 has associated therewith a non-tunable signal line portion 212, 214, 216. Switches 220 to 230 are provided. Switches 220 to 230 can be controlled by control signals c1 to c6. The switches 220 to 230 are configured to switch into a signal path between a signal input 232 and a signal output 234 of the phase shifter 200 either the tunable signal line portion 202, 204, 206 or the associated non-tunable signal line portion 212, 214, 216. That is, depending on the control signals applied, switches 220 to 230 are configured to switch the tunable signal line portions 202, 204, 206 in series between the signal input 232 and the signal output 234.

[0037] The characteristic of the tunable signal line portions may be controlled continuously, in discrete steps or, in preferred embodiments, in a binary manner between two values only. The phase shift provided by each of the non-tunable signal line portions may be different from the phase shifts which the associated tuneable sig-

nal line portions may be tuned to. Thus, an additional increase of the range of the overall phase shift of the phase shifter can be achieved by the provision of the non-tuneable signal line portions. Accordingly, Fig. 2 shows a phase shifter comprising a combination of a switched-line phase shifter with each section being individually tuneable by variation of material characteristics. This approach allows implementation of a phase shifter composed of a few switched-line sections with a high phase resolution. The total achievable phase shift is composed of two terms: the phase shift corresponding with the difference of the mechanical lengths, i.e., the switched-line portion $\psi_{s,max}$, and the phase shift corresponding with the difference of the electrical lengths, i.e., the tuneable portion $\psi_{t,max}$. The switched-line portion is given by $\psi_{s,max} = 2\pi(1 - 2^{-N})$ with N being the number of switched-line sections. The tuneable portion reads $\psi_{t,max} = \psi_{s,max}(n_{max} - n_{min}) = 2\pi(1 - 2^{-N})(n_{max} - n_{min})$. The number of switched-line sections required follows from the condition $\psi_{t,max} \geq \pi/2^{N-1}$, assuming a maximum total phase shift of 2π (or 360 degrees).

[0038] In embodiments, the tuneable portions of the phase shifter shown in Fig. 2 can be implemented using a continuously tuneable phase shifter. In other embodiments, the tunable portions of the phase shifter shown in Fig. 2 can be implemented using a phase shifter as shown in Fig. 1 or Fig. 3. Such embodiments may be regarded as a phase shifter system comprising at least one phase shifter having a plurality of individually tuneable sections as described herein and a non-tunable signal line portion, wherein the switches 220 to 230 are configured to switch into the signal path between the signal input 232 and the signal output 234 either the phase shifter or the non-tunable signal line portion.

[0039] As for the embodiment shown in Fig. 1, the signal line of the tunable line portion can be of an arbitrary type, including microstrip lines, tri-plate lines, waveguides, partially filled waveguides, substrate-integrated waveguides among others. The tuneable material can be of any type, provided that the refractive index can be varied by any means. Again, this includes ferrites, ferroelectrics, ferromagnetics, dielectrics, and LC mixtures. The switches can be of any type, including semiconductor switches (e.g. diodes, transistors), micromechanical switches (MEMS), among others.

[0040] As indicated in Fig. 2, the line lengths of the tunable line portions may be different from each other. In embodiments of the invention, the tunable line portions may have equal lengths.

[0041] In the embodiment shown in Fig. 2, each tunable line portion 202, 204, 206 has associated therewith a non-tunable line portion 212, 214, 216. In other embodiments, only some or only one of the tunable line portions may have associated therewith a non-tunable line portion.

[0042] Fig. 3 shows an embodiment of a phase shifter 300 similar to the embodiment shown in Fig. 1, wherein the plurality of sections has different line lengths. To be

more specific, signal line 108 is partitioned into a plurality of signal line portions sl12 to sl16 of different length and material 106 is partitioned into a plurality of material portions mp12 to mp16 of different length. The partitioning is achieved by electrodes e12 to e16. Except for the different partitioning, aspects of the embodiment shown in Fig. 3 may be identical to aspects of the embodiment shown in Fig. 1 and, therefore, repeated description of such aspects is omitted.

[0043] Phase shifter 300 shown in Fig. 3 combines aspects of the embodiments shown in Figs. 1 and 2. It adopts the composite shown Fig. 1 with differently sized portions. In the embodiment shown in Fig. 3, partitioning may be done based on a binary scheme, i.e., the first and shortest section sl12 measures a given length, say Δx , the second section sl13 measures a length of $2\Delta x$, the third sl14 of $4\Delta x$ and so on. In general, the n th section measures a length of $2^{n-1}\Delta x$ with $n = 1, 2, \dots$. Other schemes, including schemes of other bases are also possible. Let b be the base with b a natural number and $b > 0$. Then the length of the n th section reads $b^{n-1}\Delta x$ with $n = 1, 2, \dots$. In addition, any permutation of the order of the different length sections may be considered. The composite of differently sized portions allows reducing the number of steering signals.

[0044] Phase shifters according to the invention provide numeral advantages when compared to prior solutions.

[0045] The partitioning of a line of tuneable electrical length into a number of sections of a tuneable material permits tuning each either to its minimum or to its maximum refractive index, which has the following advantages:

a) The shifting of the signal's phase is less sensitive to temperature variations or manufacturing tolerances. The control signal applied can be of binary type, i.e., it needs to adopt only two values. If the upper value exceeds the highest possible threshold and the lower value is below the lowest possible threshold occurring over the possible environmental conditions during operation, the control signals do not need to be adjusted for calibration purposes. Thus, in embodiments, the controller is configured to apply control signals to switch the characteristics of the material portions between a respective first value and a respective second value only, wherein these values are beyond thresholds expected to occur over the possible environmental conditions during operation of the phase shifter.

b) The response time of tuneable materials can be reduced by the binary control of the phase shift, provided that the amplitude of the control signals is chosen large enough. This circumvents the tuning delay occurring in LC mixtures, for example.

c) The control of multiple sections or portions of tune-

able materials is well known in optics; the liquid-crystal display devices rely on this technique. That is, the proposed phase shifter can be manufactured by means of a mature technology.

[0046] The combination of a switched-line phase shifter and a phase shifter based on tuning of material characteristics (as shown in Fig. 2, for example) has the following advantages:

d) The phase shifter may measure a mechanical length of approximately one guide wavelength, even for materials of low tuneability.

i) This allows for a compact implementation and therefore eases the integration into a phased array.

ii) This causes lower losses compared to a phase shifter based on tuning of the electrical length using a material of low tuneability such as an LC mixture and therefore leads to an enhanced system performance.

e) The phase shifter allows continuous shifting of the signals phase. The switched-line part can be composed of a few sections providing coarse resolution, e.g., 2 or 3 bit, but covering a large maximum phase shift. The tuneable refractive index of the transmission lines enables arbitrary steering of the phase with a little maximum phase shift.

f) The lines of tuneable refractive index can be implemented each with a plurality of individually tuneable sections. This results in a digitally controlled phase shifter with high resolution.

[0047] Embodiments of phase shifters of the invention may be applied in wireless communication devices and systems, for example in satellite communications, especially beam forming and tracking for moving receivers or transmitters, or other communication systems or devices including mobile phones, wireless local area networks, etc., that benefit from improved antenna gain and/or directivity. It is however, clear for those skilled in the art that the invention may find application in any field where adjustable phase shifters are needed.

[0048] The above described embodiments are merely illustrative for the principles of the present invention. It is understood that modifications and variations of the arrangements and the details described herein will be apparent to others skilled in the art. It is the intent, therefore, to be limited only by the scope of the impending patent claims and not by the specific details presented by way of description and explanation of the embodiments herein.

Claims

1. A phase shifter (100, 200, 300) comprising:

5 a signal input (102, 232),
a signal output (104, 234),
a signal path between the signal input (102, 232) and the signal output (104, 234), and
10 a plurality of sections, each section of the plurality of sections comprising a signal line portion (sl1 to sl16, 202, 204, 206) and an associated material portion (mp1 to mp16) having a characteristic that is tuneable to apply an adjustable phase shift to a signal transmitted over the signal line portion (sl1 to sl16, 202, 204, 206),
15 wherein the characteristic of the material of each section is tuneable individually,
wherein the signal line portions (sl1 to sl16, 202, 204, 206) are connected in series in the signal path or wherein the phase shifter (100, 200, 300) is configured to switch the signal line portions (sl1 to sl16, 202, 204, 206) in series in the signal path.

25 2. The phase shifter (200, 300) of claim 1, wherein the signal line portions (sl12 to sl16, 202, 204, 206) of at least some of the sections have different lengths.

30 3. The phase shifter (200, 300) of claim 2, wherein the lengths of the signal line portions (sl12 to sl16, 202, 204, 206) are dimensioned based on a scheme $b^{n-1}\Delta x$ with b and n being natural numbers and Δx being the length of the section having the shortest signal line portion (sl12, 202).

35 4. The phase shifter (100, 200, 300) of one of claims 1 to 3, wherein the tunable characteristic of the material portions (mp1 to mp16) is the refractive index thereof.

40 5. The phase shifter (100, 200, 300) of one of claims 1 to 4, comprising, for each section, means (e1 to e16) for controlling the tunable characteristic of the material portion (mp1 to mp16), wherein the means (e1 to e16) for controlling are provided in addition to the signal line portion (sl1 to sl16, 202, 204, 206).

45 6. The phase shifter (100, 200, 300) of claim 5, wherein the means (e1 to e16) for controlling comprise one or two electrodes configured to apply a variable electric field to the corresponding material portion (mp1 to mp16) in order to change the permittivity thereof.

50 7. The phase shifter (100, 200, 300) of claim 6, wherein the material portions (mp1 to mp16) comprise a non-linear dielectric selected from the group including at least ferroelectrics, solid mixtures of barium, strontium and titanate, and liquid crystal mixtures.

8. The phase shifter of claim 5, wherein the means for controlling comprise an element configured to apply a variable magnetic field to the corresponding material portion in order to change the permeability thereof. 5
9. The phase shifter of claim 8, wherein the material portions comprise ferrite materials.
10. The phase shifter (100, 200, 300) of one of claims 5 to 9, wherein the means (e1 to e16) for controlling are configured to binary switch the characteristic of the material portion between a respective first value and a respective second value only. 10
11. The phase shifter (100, 300) of one of claims 1 to 10, wherein the signal line portions (sl1 to sl16) are arranged on a surface of a first substrate (s1), wherein the material portions (mp1 to mp16) are arranged in a second substrate (s2), and wherein the first substrate (s1) and the second substrate (s2) are attached to each other so that the signal line portions (sl1 to sl16) are arranged adjacent to the material portions (mp1 to mp16). 15 20
12. The phase shifter (100, 300) of one of claims 1 to 11, wherein the signal line portions (sl1 to sl16) of the plurality of sections form a common signal line (108) coupled between the signal input (102) and the signal output (104) of the phase shifter (100, 300) and wherein the material portions (mp1 to mp16) of the sections are arranged side by side along the length of the common signal line (108). 25 30
13. The phase shifter (200) of one of claims 1 to 11, comprising at least one non-tuneable signal line portion (212, 214, 216) associated with one of the sections, and switches (220 to 230) configured to switch into the signal path either the signal line portion (202, 204, 206) of the one of the sections or the associated non-tuneable signal line portion (212, 214, 216). 35 40
14. The phase shifter (200) of claim 13, comprising a respective non-tuneable signal line portion (212, 214, 216) associated with each section and switches configured to switch into the signal path either the signal line portion (202, 204, 206) of the respective section or the associated non-tuneable signal line portion (212, 214, 216). 45 50
15. A phase shifter system comprising a phase shifter (100, 300) of one of claims 1 to 11, a non-tuneable signal line portion (212, 214, 216), and switches (220 to 230) configured to switch into the signal path either the phase shifter (100, 300) or the non-tuneable signal line portion (212, 214, 216). 55
16. The phase shifter system of claim 15, comprising a plurality of phase shifters (100, 300) of one of claims 1 to 11, a respective non-tuneable signal line portion (212, 214, 216) associated with each of the phase shifters (100, 300), and switches (220 to 230) configured to switch into the signal path either the respective phase shifter (100, 300) or the associated non-tuneable signal line portion (212, 214, 216).
17. Wireless communication device comprising a phase shifter (100, 200, 300) according to one of claims 1 to 16 and a phased antenna array, wherein the phase shifter (100, 200, 300) is configured to control the phase shift of a signal sent or received via the phased antenna array.

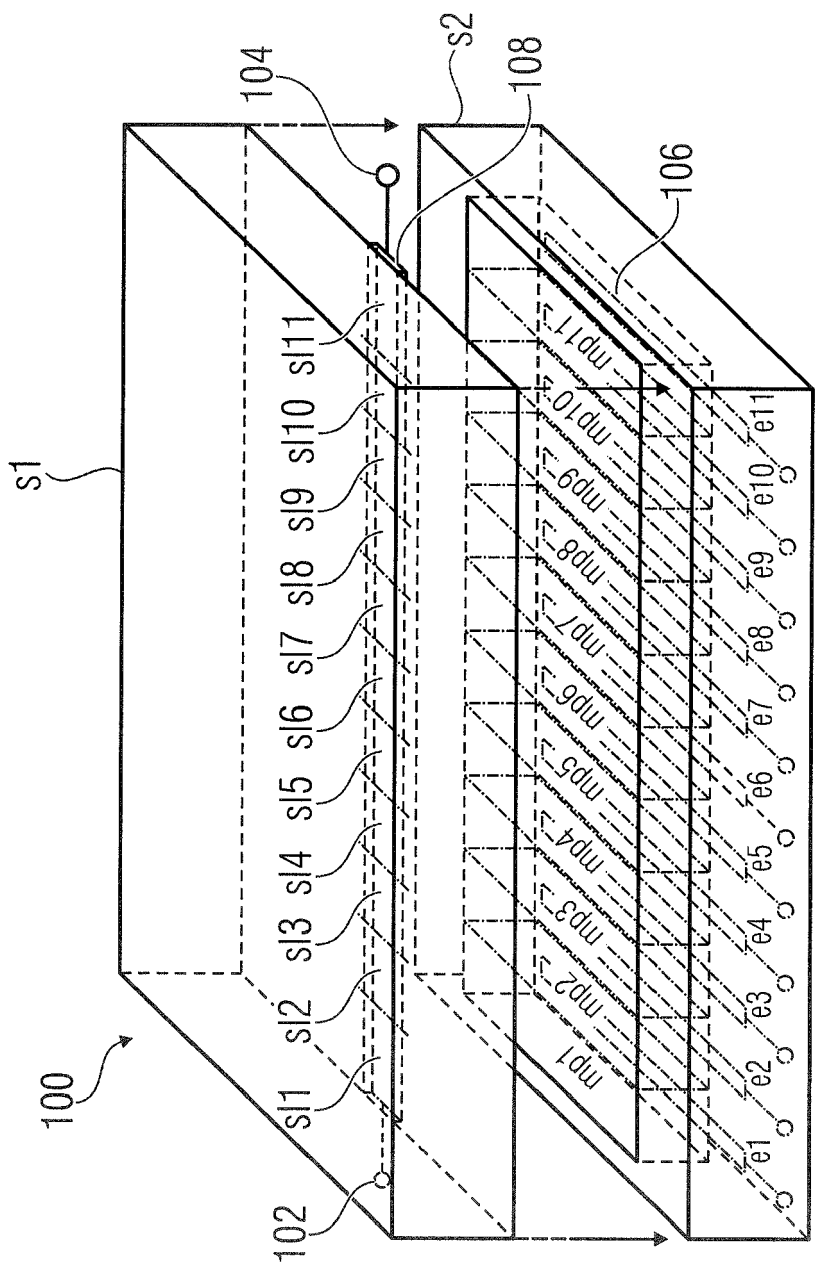


FIG 1

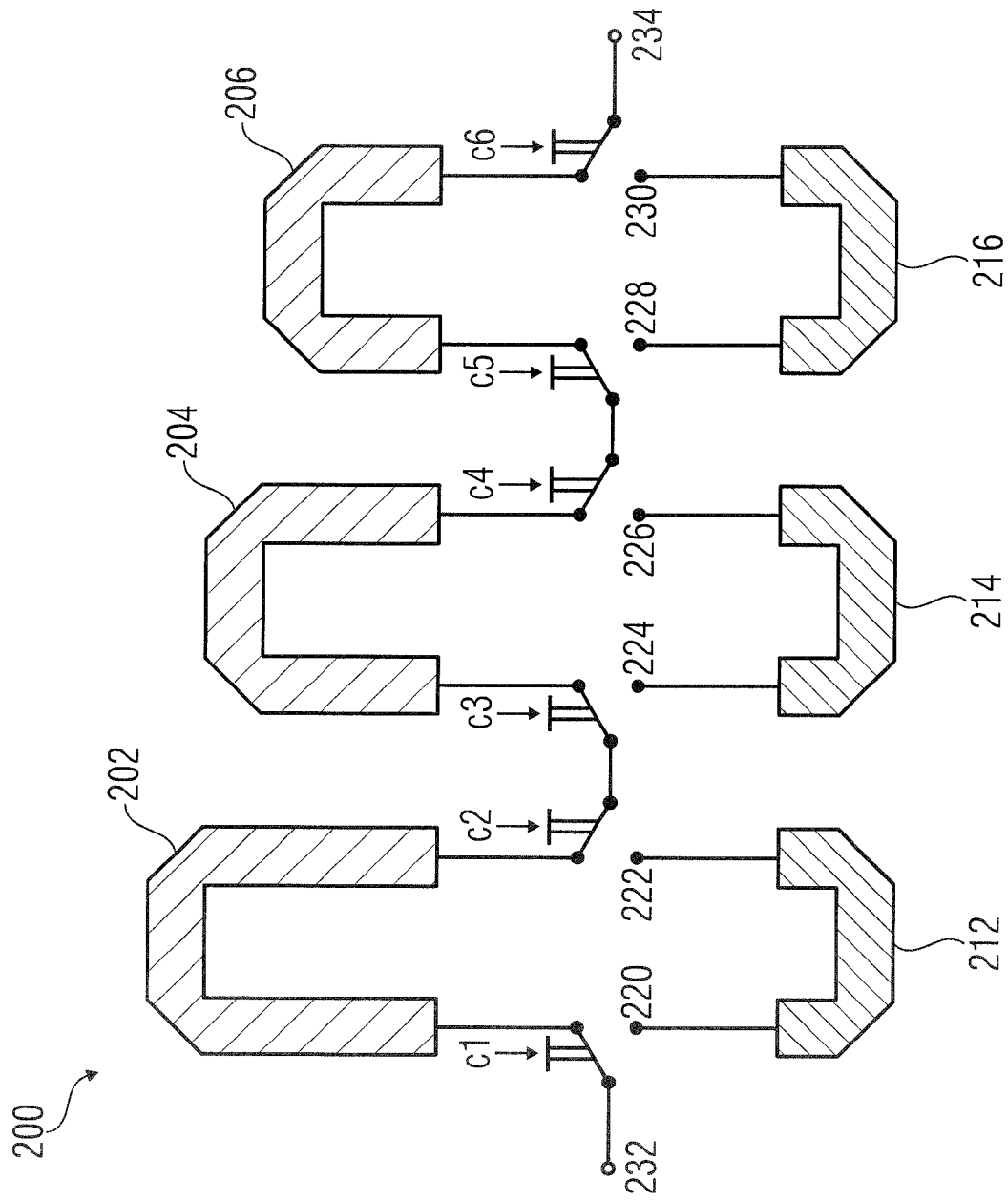


FIG 2

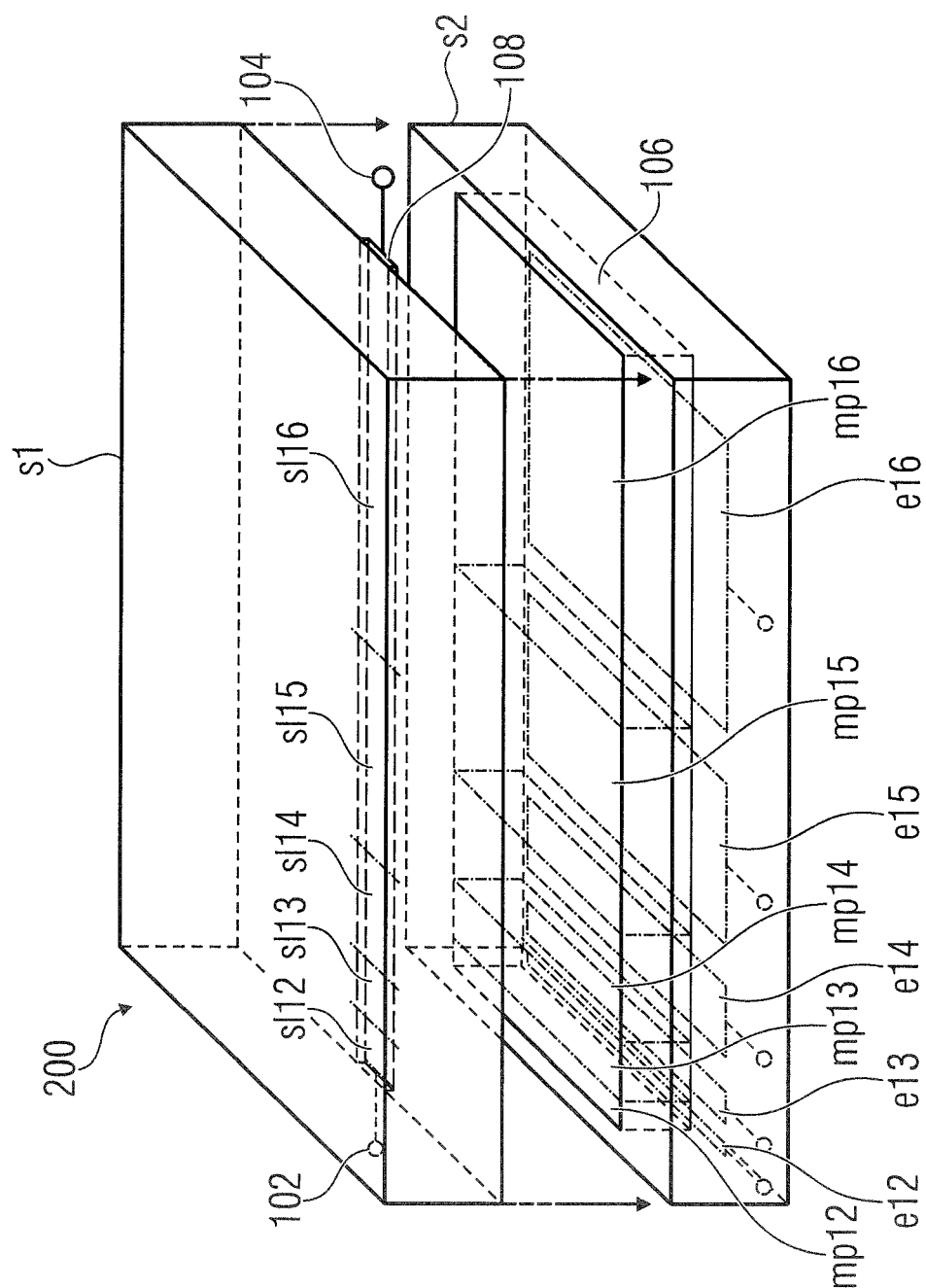


FIG 3

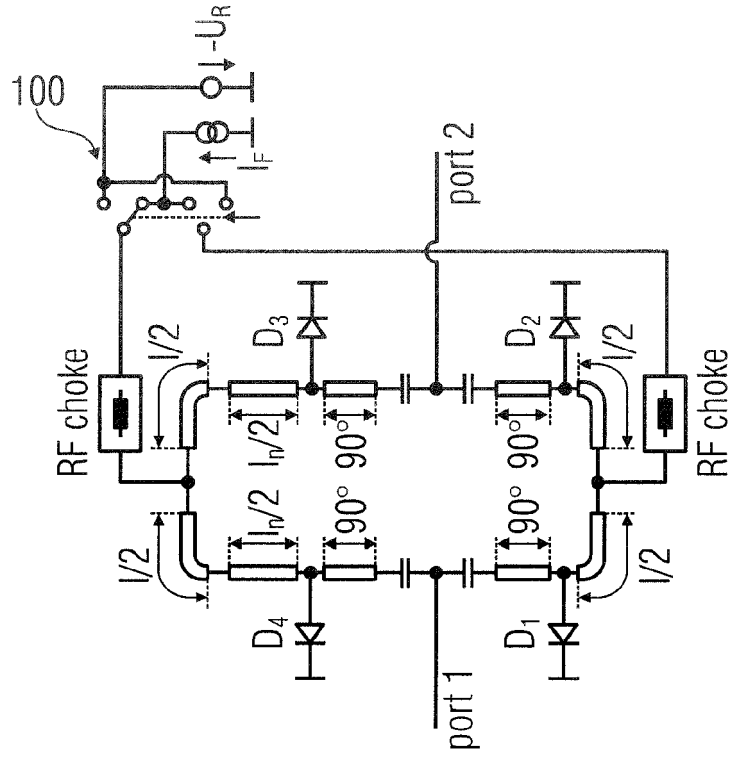


FIG 4C

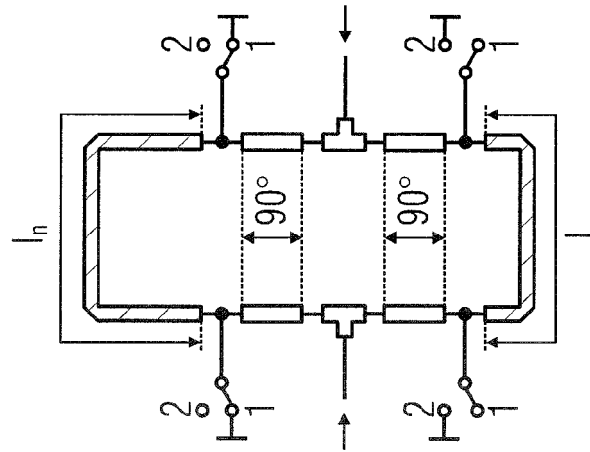


FIG 4B

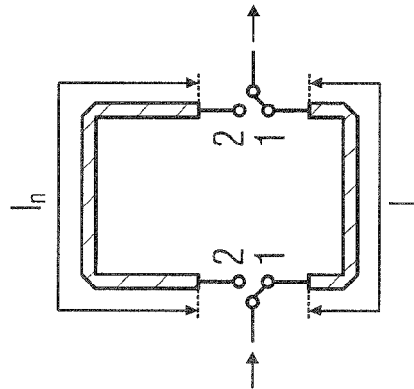


FIG 4A

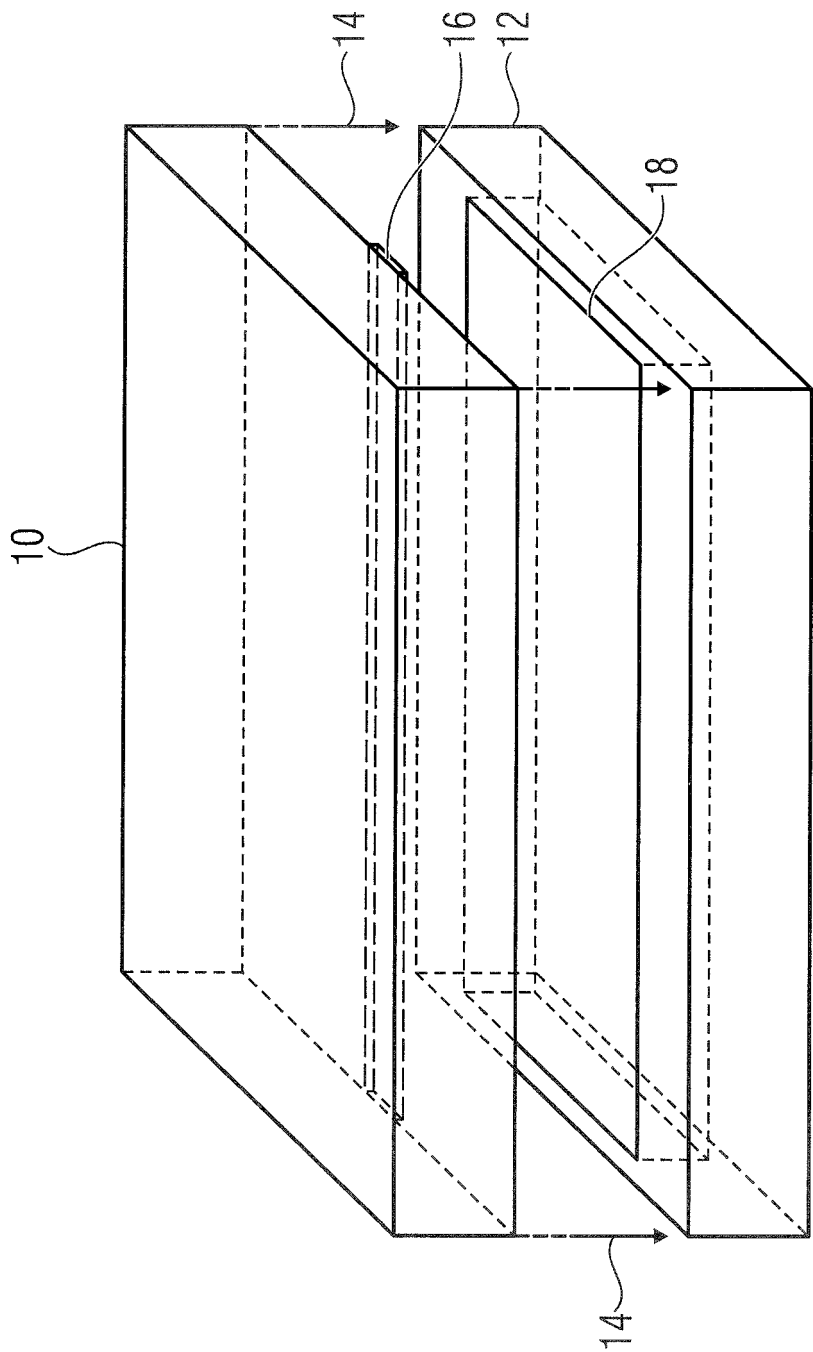


FIG 5



EUROPEAN SEARCH REPORT

 Application Number
 EP 14 18 9204

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DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	US 5 237 629 A (HIETALA VINCENT M [US] ET AL) 17 August 1993 (1993-08-17)	1-5, 8-11,17 1,13-16	INV. H01Q3/36
Y	* column 1, lines 10-15 * * column 2, line 43 - column 4, line 47 * * column 6, line 19 - column 7, line 24 * * figures 1b, 1c, 4 *		
X	----- US 2009/073332 A1 (IRIE YASUYUKI [JP]) 19 March 2009 (2009-03-19) * paragraphs [0004] - [0008], [0059] - [0080] * * figures 4-8 *	1,4-7	
X	----- PARK J ET AL: "Distributed phase shifter with pyrochlore bismuth zinc niobate thin films", IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS, IEEE SERVICE CENTER, NEW YORK, NY, US, vol. 16, no. 5, 1 May 2006 (2006-05-01), pages 264-266, XP001548908, ISSN: 1531-1309, DOI: 10.1109/LMWC.2006.873528 * the whole document *	1,4-7,12	TECHNICAL FIELDS SEARCHED (IPC) H01Q H01P
Y	----- US 2005/242993 A1 (HEIN PAUL W [US]) 3 November 2005 (2005-11-03) * paragraphs [0036] - [0041] * * figure 3 *	1,13-16	
Y	----- DE 36 35 740 C1 (DASSAULT ELECTRONIQUE [FR]) 8 January 1998 (1998-01-08) * column 2, line 25 - column 5, line 27 * * figures 1,2 *	1,13-16	
	----- -/--		
The present search report has been drawn up for all claims			
Place of search Munich		Date of completion of the search 7 July 2015	Examiner Kruck, Peter
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document			

EPO FORM 1503 03.02 (P04C01)



EUROPEAN SEARCH REPORT

Application Number
EP 14 18 9204

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DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
A	WO 2005/099086 A1 (XCOM WIRELESS INC [US]; 1 KURODA ROGER [US]; HYMAN DANIEL J [US]) 20 October 2005 (2005-10-20) * paragraphs [0079] - [0081] * * figure 6 * -----	1	
			TECHNICAL FIELDS SEARCHED (IPC)
The present search report has been drawn up for all claims			
Place of search Munich		Date of completion of the search 7 July 2015	Examiner Kruck, Peter
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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EPO FORM 1503 03.02 (P04C01)



Application Number

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CLAIMS INCURRING FEES

The present European patent application comprised at the time of filing claims for which payment was due.

☐ Only part of the claims have been paid within the prescribed time limit. The present European search report has been drawn up for those claims for which no payment was due and for those claims for which claims fees have been paid, namely claim(s):

☐ No claims fees have been paid within the prescribed time limit. The present European search report has been drawn up for those claims for which no payment was due.

LACK OF UNITY OF INVENTION

The Search Division considers that the present European patent application does not comply with the requirements of unity of invention and relates to several inventions or groups of inventions, namely:

see sheet B

☒ All further search fees have been paid within the fixed time limit. The present European search report has been drawn up for all claims.

☐ As all searchable claims could be searched without effort justifying an additional fee, the Search Division did not invite payment of any additional fee.

☐ Only part of the further search fees have been paid within the fixed time limit. The present European search report has been drawn up for those parts of the European patent application which relate to the inventions in respect of which search fees have been paid, namely claims:

☐ None of the further search fees have been paid within the fixed time limit. The present European search report has been drawn up for those parts of the European patent application which relate to the invention first mentioned in the claims, namely claims:

☐ The present supplementary European search report has been drawn up for those parts of the European patent application which relate to the invention first mentioned in the claims (Rule 164 (1) EPC).



LACK OF UNITY OF INVENTION
SHEET B

Application Number

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The Search Division considers that the present European patent application does not comply with the requirements of unity of invention and relates to several inventions or groups of inventions, namely:

1. claims: 2-12, 17(completely); 1(partially)

Claim 1 in part (last paragraph, 1st alternative: "signal line portions...connected in series") relating to a distributed phase shifter comprising a signal path formed by a plurality of signal line portions and claims 2-12 and 17 being dependent on claim 1;

2. claims: 13-16(completely); 1(partially)

Claim 1 in part (last paragraph, 2nd alternative: "configured to switch the signal line portions in series in the signal path") relating to a phase shifter comprising switched signal line portions and claims 13-16 being dependent on that part of claim 1.

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

EP 14 18 9204

5 This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report.
The members are as contained in the European Patent Office EDP file on
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07-07-2015

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- **S. MÜLLER et al.** Tunable Passive Phase Shifter for Microwave Application using Highly Anisotropic Liquid Crystals. *Microwave Symposium Digest, 2004 IEEE*, 06 June 2004, vol. 2 [0009]