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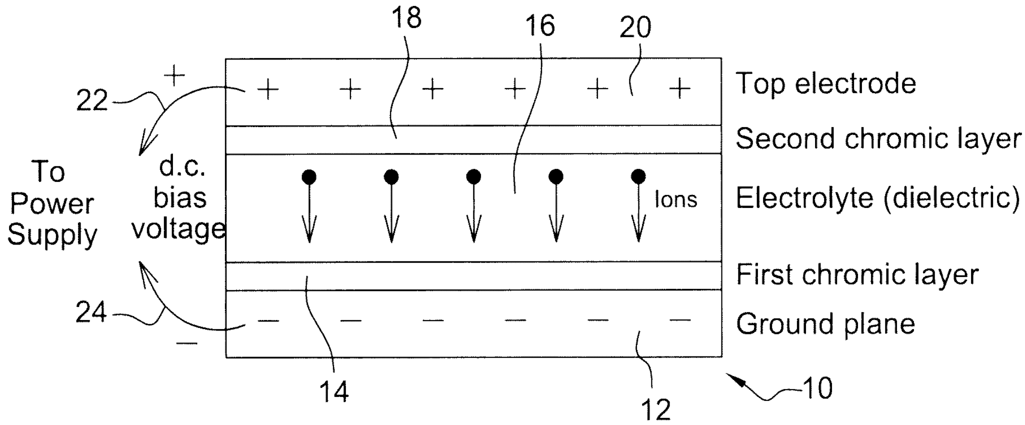
(54) **A RADIO FREQUENCY REFLECTION TYPE PHASE SHIFTER, AND METHOD OF PHASE SHIFTING**

(57) A Radio Frequency reflection type phase shifter is provided comprising a coupler for input and output, and Nvariable capacitors , where N is an integer value of 2 or more, each of the variable capacitors providing radio frequency reflection, each of the variable capacitors being connected to the coupler by at least one impedance transformer, the characteristic impedances of the impedance transformers having been selected so that the phase shifter provides a phase shift at least substantially proportional to the value of N, wherein each of the variable capacitors comprises electrochromic material.

Fig. 6



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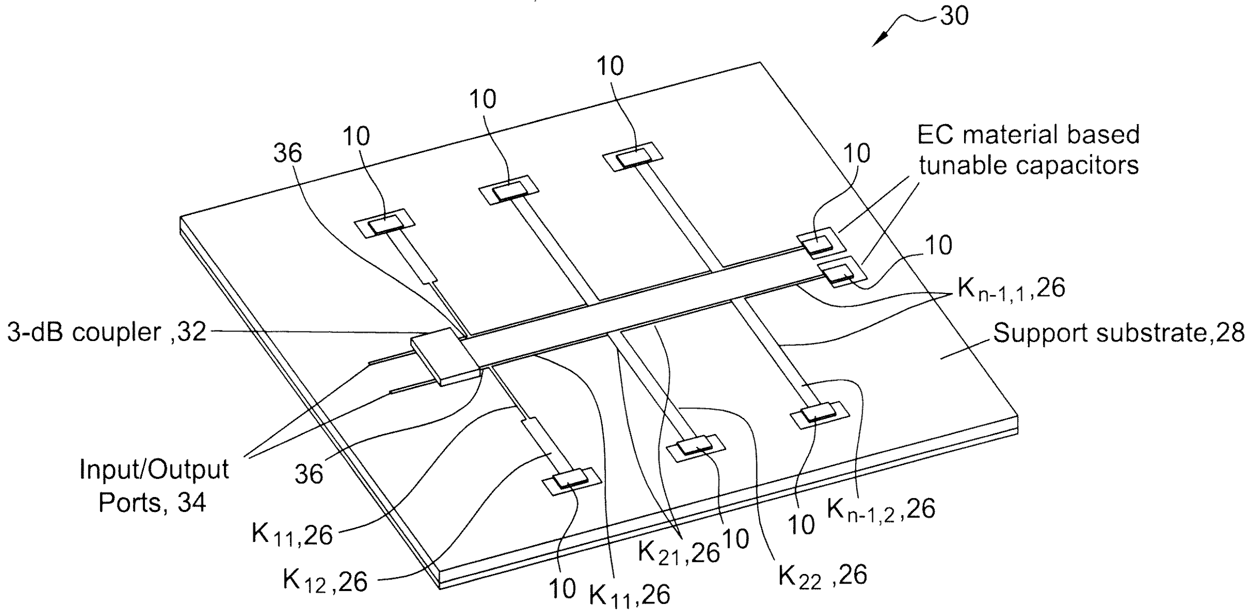
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36
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EC material based
tunable capacitors
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$K_{n-1,1}$,26
3-dB coupler ,32
Support substrate,28
Input/Output
Ports, 34
36
K_{11},26
K_{12},26
10
K_{11},26
K_{21},26
10
10
$K_{n-1,2}$,26
K_{22} ,26

Fig. 7

Description

Field of the Invention

[0001] The present invention relates to a Radio Frequency reflection type phase shifter, and a method of Radio Frequency reflection type phase shifting.

Summary

[0002] The reader is referred to the appended independent claims. Some preferred features are laid out in the dependent claims.

[0003] An example of the present invention is a Radio Frequency reflection type phase shifter, the phase shifter comprising a coupler for input and output, and N variable capacitors, where N is an integer value of 2 or more, each of the variable capacitors providing radio frequency reflection, each of the variable capacitors being connected to the coupler by at least one of the impedance transformers, the characteristic impedances of the impedance transformers having been selected so that the phase shifter provides a phase shift at least substantially proportional to the value of N, wherein each of the variable capacitors comprises electrochromic material.

[0004] The inventors realised that on the one hand capacitors using electrochromic materials were possible, for example as described in United States Patent Publication US2015/00325897A1.

[0005] The inventors realised on the other hand a circuit as described in European Patent Publication EP2996190 A1 was available using capacitors in the form of varactor diodes.

[0006] The inventors realised that the circuit described in EP2996190A1 could be adapted to instead use capacitors using electrochromic materials as described in US2015/00325897A1 in order to provide a useful and improved phase shifter

[0007] As compared to the prior approach described in EP2996190A1, four advantages of using EC based material as opposed to varactor diodes as active elements in the configuration of the proposed phase shifters are: (a) The exact values of the "ON" and "OFF" capacitance of EC based materials can be tailored by the surface area of the electrode end pads (this is not possible with varactor diodes); (b) The capacitance ratio between the "ON" and "OFF" state can be tailored by the appropriate choice of the electrolyte, for which we have in-house experience; (c) Varactor diodes exhibit a significant non-linear behaviour, whereas EC based materials are highly linear; (d) A possibility exists to actuate EC based materials by light, whereas this is not possible with varactor diodes.

[0008] Preferably each of the variable capacitors comprises an electrolyte element and at least one electrochromic element between a first electrode and a second electrode.

[0009] Preferably, the first electrode comprises a ground plate on which lies the first electrochromic element, and the electrolyte element lies on the electrochromic element, the electrochromic element comprising an electrochromic layer, and the electrolyte element comprising an electrolyte layer.

[0010] Preferably each of the variable capacitors further comprises a second electrochromic element between the electrolyte element and second electrode, the second electrochromic element comprising a second electrochromic layer.

[0011] Preferably the coupler is a 3dB-coupler having four ports, N'/2 of the variable capacitors being connected to the coupler via one of two of the ports, and N'/2 of the capacitors being connected to the coupler via a second of said two ports, where N' is an even number integer of 4 or more. Alternatively preferably the coupler is a circulator having three ports, the N variable capacitors being connected to the circulator via one of the ports.

[0012] Preferably the impedance transformers are microstrip lines.

[0013] Preferably the characteristic impedances of the impedance transformers are selected in according with a selected value of a parameter value q determined for a given capacitor as

$$q = \frac{\sqrt{X_{max} X_{min}}}{Z_0}$$

where Z_0 is the characteristic impedance of the impedance transformers, Xmin is the minimum reactance of the capacitor and Xmax is the maximum reactance of the capacitor.

[0014] Preferably the capacitance of each of the variable capacitors is variable by adjusting a d.c. voltage applied across the capacitors. Preferably said phase shift is at least substantially proportional to the value of N when a mid-range value of the capacitance of the variable capacitors is selected so the corresponding reactance at an operating radio frequency is the characteristic impedance Z_0. Preferably the capacitors are variable between a higher capacitance 'fully ON' state when the d.c. voltage is at a first level and a lower capacitance 'OFF' state when the d.c. voltage is at a second level.

[0015] Some preferred embodiments provide, as compared to existing solutions using EC materials, greater amounts of phase shift for lower insertion losses. Some preferred embodiments are suitable for the microwave frequency range.

[0016] Examples of the present invention also relate to corresponding methods.

[0017] An example of the present invention relates to a method of Radio Frequency reflection type phase shifting, by: applying an input signal to a phase shifter comprising a coupler for input and output, and N variable capacitors, where N is an integer value of 2 or more, each of the variable capacitors providing radio frequency reflection, each of the variable capacitors being connected to the coupler by at least one impedance transformer, the characteristic impedances of the impedance transformers having been selected so that the phase shifter provides a phase shift at least substantially proportional to the value of N, wherein each of the variable capacitors comprises electrochromic material; and receiving an output signal from the coupler.

[0018] Preferably the capacitance of each of the variable capacitors is variable by adjusting a d.c. voltage applied across the capacitors.

[0019] Preferably said phase shift is at least substantially proportional to the value of N when a mid-range value of the capacitance of the variable capacitors is selected so the corresponding reactance at an operating radio frequency is the characteristic impedance Z_0.

Brief Description of the Drawings

[0020] Embodiments of the present invention will now be described by way of example and with reference to the drawings, in which:

Figure 1 is a diagram illustrating a known Radio Frequency (RF) reflective type phase shifter (PRIOR ART),
Figure 2 is a diagram illustrating a phase shifter which is two of the phase shifters shown in Figure 1 cascaded (PRIOR ART),
Figure 3 is a diagram illustrating phase shifter which is three of the phase shifters shown in Figure 1 cascaded (PRIOR ART),
Figure 4 is a general circuit diagram illustrating a generalised circuit of an RF reflective type phase shifter according to a first embodiment of the invention, generalised in the sense it is n-th order where n is two or more,
Figure 5 is a circuit diagram illustrating part of the reflective loads portion of the circuit shown in Figure 4,
Figure 6 is a cross sectional view of a parallel plate capacitor including electrochromic (EC) material, multiple of which are used in the phase shifter shown in Figures 4,
Figure 7 is a perspective view of the generalised n-th order reflection type phase shifter shown in Figure 4,
Figure 8 is a diagram illustrates the phase shifter shown in Figures 4 and 7 with n selected to be three, and
Figure 9 is a diagram illustrating the phase shifter shown in Figures 4 and 7 with n selected to be two.

Detailed Description

[0021] We will first briefly outline the inventor's understanding of some earlier known approaches then focus in detail on embodiments of the present invention.

Earlier Known Approaches

[0022] A high frequency phase shifter based on EC materials is known from US Patent Publication US 2015/0325897A1. This high frequency phase shifter is based on the use of Electochromic (EC) material as bulk, dc induced tunable media in a circuit.

[0023] The inventors realised that this known high frequency EC material based phase shifter did not exploit the potential of EC materials. In particular, the circuit in that phase shifter only allowed modest values of phase shifts, typically up to 15 -30 degrees at frequencies around 3 GHz. In any particular case, the exact value of the phase shift obtained is, of course, dependent on the frequency of operation and the type and thickness of the EC material used, however, there is always a limitation as to how much phase shift can be obtained. Accordingly, the inventors saw a need for new architectures for high frequency phase shifters based on EC materials.

[0024] This known approach of US 2015/0325897A1 is illustrated in Figure 1. As shown in Figure 1, there is a ground plate on which an electrochromic layer is provided, and input and outputs connected via a 3dB coupler to microstrip contacts contacting the top of the EC layer.

[0025] The inventors realised that a problem with the phase shifter configuration of Figure 1 lies in its inherently low values of achievable phase shifts.

[0026] The inventors realised that the amount of phase shift from the proposed configuration could be increased by cascading several structures of Figure 1 as shown in Figures 2 and 3, but such an arrangements has drawbacks of increased structural size and complexity, and increased losses. As regards increased losses, since the number of 3-dB couplers will be increased, so will its corresponding insertion loss. The increase of the number of 3-dB couplers is particularly detrimental, since the radio frequency signal in any 3-dB coupler travels twice through - first to reach the reflective loads and second, back to reach the input/output ports. A 3-dB coupler is a radio frequency (RF) device which splits an input RF signal into two signals equal in magnitude, but with a 90° phase shift between them.

[0027] From noting these drawbacks, the need for different architectures for high frequency phase shifters based on EC materials became evident to the inventors.

Example Embodiments

[0028] We now turn to describing some preferred embodiments.

[0029] Firstly, a generic circuit for a range of phase shifters will be described. Secondly, the active elements used in the generic circuit will described, namely capacitors using EC material. Thirdly, example reflective type phase shifters will described that are in accordance with the generic circuit.

[0030] As will be seen, in the generic circuit of Figures 4 and 5, parallel plate capacitors are used formed using Electrochromic material as shown in Figure 6.

[0031] After this description, we will present some comparison data comparing some properties of embodiments to examples of known approaches.

Circuit

[0032] The input admittance of the circuit in one of the reflective loads of the proposed circuit of Fig. 4 is represented as

$$Y_{in} = \frac{k_{12}^2}{k_{11}^2} Y + \frac{1}{k_{11}^2 Y_2} \quad (1)$$

[0033] Where,

$$Y_2 = \frac{k_{22}^2}{k_{21}^2} Y + \frac{1}{k_{21}^2 Y_3}, \quad Y_3 = \frac{k_{32}^2}{k_{31}^2} Y + \frac{1}{k_{31}^2 Y_4} \dots \quad (2)$$

[0034] Or, in general,

$$Y_{n-1} = \frac{k_{n-1,2}^2}{k_{n-1,1}^2} Y + \frac{1}{k_{n-1,1}^2 Y_n}, \text{ where } Y_n = Y \quad (3)$$

[0035] Here, $k_{i,j}$, $i = 2 \ldots n$, $j = 1, 2$ represent the impedance transformers, n represents the order of the absorptive filter and $Y=Z^{-1}$. It can be inferred from (2) - (3) that the input admittance, Y_{in}, can be represented in the form of a generalized continued fraction

$$Y_{in} = \frac{k_{12}^2}{k_{11}^2} Y + \cfrac{1}{\cfrac{k_{11}^2 k_{22}^2}{k_{21}^2} Y + \cfrac{k_{11}^2}{\cfrac{k_{21}^2 k_{32}^2}{k_{31}^2} Y + \ldots}} \quad (4)$$

[0036] Or equivalently,

$$Y_{in} = b_0 + \cfrac{a_1}{b_1 + \cfrac{a_2}{b_2 + \ldots}} = b_0 + \mathop{\mathrm{K}}_{0}^{m} \frac{a_k}{b_k}, k = 1 \ldots m, m = n - 1 \quad (5)$$

where $b_0 = \frac{k_{12}^2}{k_{11}^2} Y$, $a_1 = 1$, $b_k = \frac{k_{k,1}^2 k_{k+1,2}^2}{k_{k,1}^2} Y$, $\forall$ n≥2,k=1...n-1 and $a_k = k_{k-1,1}^2$, $\forall$ n≥3, k=2...n-1.

[0037] The input admittance of the n-th order absorptive transmission zero can now be represented as

$$Y_{in,n} = \frac{A_{m-1}}{B_{m-1}} \quad (6)$$

where $A_{m-1} = b_{m-1}A_{m-2}+a_{m-1}A_{m-3}$ and $B_{m-1} = b_{m-1}B_{m-2} +a_{m-1}B_{m-3}$.

[0038] Solving (6), one obtains the n-th order admittance polynomial from which the expression for the n-th order polynomial expression for the transmission coefficient of the notch filter (with the 3-dB coupler included) can be derived

$$S_{21} = -j\frac{Y_0 - Y_{in}}{Y_0 + Y_{in}} \quad (7)$$

where Y_0 is the characteristic admittance of the 3-dB coupler.

[0039] Substituting (6) into (7) and converting the admittance parameters into their impedance counterparts, i.e. $Y_0 = Z_0^{-1}$ and $Y=Z^{-1}$ one obtains the expression for the transmission coefficient, S_{21}, as a function of impedance parameters

$$S_{21} = -j\frac{Z_{in} - Z_0}{Z_{in} + Z_0} \quad (8)$$

[0040] In order for (8) to offer phase shift increase commensurate with the number of active elements in the reflective loads, (8) needs to be represented in the following form

$$S_{21} = -j\Gamma_{in} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} = \left|\frac{Z - Z_0}{Z + Z_0}\right|^n \cdot e^{jn\left(-\frac{\pi}{2}+arctan\left(\frac{Im(Z)}{real(Z)-Z_0}\right)-arctan\left(\frac{Im(Z)}{real(Z)+Z_0}\right)\right)} \quad (9)$$

where n indicates the number of pairs of active elements in the circuit of the reflective load, Figs. 4 and 5. More generally, (9) can be written as

$$S_{21} = -j\Gamma_{in} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} = \left|\frac{Z - qZ_0}{Z + qZ_0}\right|^n \cdot e^{jn\left(-\frac{\pi}{2}+arctan\left(\frac{Im(Z)}{real(Z)-qZ_0}\right)-arctan\left(\frac{Im(Z)}{real(Z)+qZ_0}\right)\right)} \quad (10)$$

where q indicates the position of the transmission zero on the resistance scale which can be adjusted with a proper selection of the impedance transformers $k_{i,j}$,i = 2...n, j = 1, 2. The phase shift provided by (10) can be written as

$$\Delta\Phi = n\left\{arctan\left(\frac{X_{max}}{R-qZ_0}\right) - arctan\left(\frac{X_{max}}{R+qZ_0}\right)\right\} - \left\{arctan\left(\frac{X_{min}}{R-qZ_0}\right) - arctan\left(\frac{X_{min}}{R+qZ_0}\right)\right\} \quad (11)$$

[0041] For q=1, the phase shift of the proposed structure of Figs. 4 and 5 is increased n-times. Nevertheless, simply setting q=1, does not necessarily result in the optimal phase shift. The optimal phase shift is found by finding the roots of

$$\frac{\partial \Delta\Phi}{\partial q} = 0 \quad (12)$$

yielding the following 6[th] order polynomial

$$P_1 q^6 + P_2 q^4 + P_3 q^2 + P_4 = 0 \quad (13)$$

[0042] Where $P_1 = Z_0^6$, $P_2 = -R^2 Z_0^4 - Z_0^4 X_{max} X_{min} + Z_0^4 X_{max}^2 + Z_0^4 X_{min}^2$, $P_3 = -R^4 Z_0^2 - 6R^2 Z_0^2 X_{min} X_{max} - Z_0^2 X_{max} X_{min}^3 + Z_0^2 X_{max}^2 X_{min}^2 - Z_0^2 X_{max}^3 X_{min} - 2R^2 Z_0^2 X_{max}^2 - 2R^2 Z_0^2 X_{min}^2$ and

$$P_4 = R^6 - R^4 X_{min} X_{max} - R^2 X_{min}^3 X_{max} + R^2 X_{max}^2 X_{min}^2 - R^2 X_{min} X_{max}^3 + R^4 X_{max}^2 + R^4 X_{min}^2 - X_{max}^3 X_{min}^3 \quad (14)$$

[0043] The first four roots of (13) are always complex conjugate, while the remaining two roots are real with equal magnitude, but opposite signs. As such, there is always one solution to (13) that yields the optimum value of the parameter *q*. The expression given by (14) can be simplified if it can be assumed that the parasitic resistance of an active element (i.e. parallel plate capacitor including EC material) can be neglected. This is a valid assumption in most cases, since this resistance is typically of the order of 1- 2 ohms. By setting *R*=0 (14) the optimal value *q* becomes

$$q = \frac{\sqrt{X_{max} X_{min}}}{Z_0} \quad (15)$$

[0044] The insertion loss of the proposed phase shifter (log scale) is

$$|S_{21}| = 20n\,log_{10}\left|\frac{Z - qZ_0}{Z + qZ_0}\right| + \text{insertion loss of 3-dB coupler} \quad (16)$$

[0045] Here, the first term on the right represents the insertion loss of the reflective circuit of the proposed phase shifter. For *q*=1 the insertion loss of the proposed reflective load is n-times higher than the insertion loss of the first order reflective circuit, while if parameter *q* is set in accordance with (13), the insertion loss of the reflective loads is always lower than that achieved with *q*=1. The second term on the right is the insertion loss of a 3-dB coupler.

[0046] For comparison, a known phase shifter having cascade connection of n first order circuits will yield the same phase shift as (11), however, its insertion loss will be

$$|S_{21}| = 20n\,log_{10}\left|\frac{Z - qZ_0}{Z + qZ_0}\right| + n\cdot(\text{insertion loss of 3-dB coupler})$$
$$+(\mathrm{n}-1)\cdot \text{loss due to interconnections} \quad (17)$$

[0047] In quantitative terms, the reduction in the overall insertion loss of the proposed circuit over the known phase shifter having cascade connection is

$$\Delta|S_{21}| = (n-1)\cdot(\text{insertion loss of 3-dB coupler}) + (\mathrm{n}-1)\cdot \text{loss due to interconnections} \quad (18)$$

[0048] In view of (17) and (18), (11) and (16) demonstrate the potential of the proposed circuit - to increase the amount of phase shift of the phase shifter in a linear fashion with respect to the pairs of active elements, without increasing the insertion loss in the same linear fashion. For example, if the insertion loss of a 3-dB coupler is 0.3 dB (2*0.3 dB in the phase shifter configuration), and for n=2, *q*=1 the reduction of the insertion loss using the proposed circuit over the conventional cascade connection is

$$\Delta\left|S_{21}\right| = 0.6\,dB + \text{loss due to interconnections} \quad (19)$$

[0049] In the derivation of the above equations the condition stipulated in the previous section related to the retention of a minimum number of 3-dB couplers in the design of the phase shifter has been fulfilled.

[0050] The active elements are capacitors formed using EC material as will be described next below.

Capacitors using EC material

[0051] Figure 6 shows a parallel plate capacitor 10 in cross-section.

[0052] As shown in Figure 6, there is a ground plate 12 on which lies a first electrochromic layer 14 and a second electrochromic layer 18 separated by an electrolyte layer (in other words a dielectric layer) 16. On top of the second electrochromic layer is a top electrode 20. It may be considered that the ground plate (also known as the ground electrode) 12 and the top electrode 20 effectively "sandwich" the intermediate active layers 14, 16,18.

[0053] An electrochromic material is a material the optical absorption/transmission characteristics of which can be reversibly changed by the application of an external voltage, light source, or electric field. Examples include (i) transition-metal and inorganic oxides such as tungsten oxide, (ii) small organic molecules such as viologens, and (iii) polymers such a poly-viologens and derivatives of polythiophence, polypyrrole and polyaniline.

[0054] The first EC layer 14 comprises a suitable EC material, such as WO_3 in this example. In other examples, the EC material is TiO_2, MoO_3, Ta_2O_5, Nb_2O_5, or another of the above -mentioned electrochromic materials.

[0055] The second EC layer 18 comprises NiO in this example. In other examples this layer is Cr_2O_3, MnO_2, FeO_2, CoO_2, RhO_2, IrO_2, or another suitable material. In this example, the second EC layer 18 acts as an ion-storage layer.

[0056] In operation, the application of a d.c. bias voltage between the ground plate 12 and top electrode 20 induces changes in the dielectric characteristics of the intermediate layers 14,16,18 and hence their capacitance as a function of the applied d.c. voltage. In this example, ground plate 12 is a cathode and the top electrode is an anode.

[0057] The electrolyte layer 16 acts as an ion-conductor layer. The electrolyte layer 16 serves as a reservoir of ions for injection into the first EC layer 14. In this example, the electrolyte layer 16 also receives ions from the second EC layer 18.

[0058] When voltage is applied via electrical leads 22,24, a corresponding electric field is generated between the ground electrode 12 and top electrode 20. This electric field causes ions to be introduced into the first EC layer 14 from electrolyte layer 16. The electric charge caused by this injection of ions into the first EC layer 14 is neutralised by a corresponding charge balancing counter-flow of electrons from ground electrode 12.

[0059] In use the voltage is adjustable to vary the capacitance of the capacitor 10 and is set to provide a capacitance corresponding to an impedance of characteristic impedance Z_0, where Z_0 is the characteristic impedance of the Figure 4 circuit. More specifically, the mid-range capacitance C_{mid} of the capacitor 10 is selected (where $C_{mid} = 0.5*(C_{max} + C_{min})$ so that the reactance of the capacitor, which is a function of radio frequency and capacitance, matches the characteristic impedance Z_0 of the Figure 4 circuit. In other word, the mid-range capacitance C_{mid} of the capacitor 10 is selected so that $Z_{mid} = Z_0$ where $Z_{mid}=1/(\omega C_{mid})$.

[0060] With the EC capacitors set to have this capacitance, the phase shift provided by the phase shifter is at least substantially proportional to N where N is the number of reflective loads, in other words the number of capacitors.

Specific Reflective Type Phase Shifter Examples

[0061] A notional phase shifter 30 of nth order is shown in Figure 7 which is in accordance with the circuit shown in Figure 4 .

[0062] As now shown in Figure 7, and as previously mentioned in relation to Figure 4, $k_{i,j}$,i = 2...n, j =1,2 represent the impedance transformers, and n represents the order of the phase shifter which may be considered an absorptive filter.

[0063] As shown in Figure 7, the impedance transformers $k_{i,j}$, i = 2...n, j =1,2 are formed by microstrip lines 26 over a supporting substrate 28. The capacitors 10 are embedded in the substrate such that, each capacitor 10 has its respective top electrode 20 flush with (in other words in the same plane as) the top surface of the supporting substrate 28 so that the microstrip lines 26 can run flat. The microstrip line 26 has portions of different selected widths, hence different cross-sectional areas, to provide the respective impedance transformers.

[0064] As previously mentioned, as now shown in Figure 7, a 3-dB coupler 32 is a radio frequency (RF) device which splits an input RF signal into two signals equal in magnitude, but with a 90° phase shift between them for transmission to the capacitors 10. The 3dB-coupler has two input/output ports 34 and two other ports 36 for connection to the capacitors 10.

[0065] In some otherwise similar embodiments (not shown), the 3-dB coupler is replaced by a circulator (not shown). A circulator has three ports (one port less than the 3-dB coupler). Two ports of the circulator are input/output ports, whereas the last, third port is the port to which two or more reflective loads are connected. Each reflective load comprises a variable capacitor comprising EC materials as described with respect to Figure 6, connected by at least two impedance transformers as described above made up of portions of microstrip line of different widths.

n=3 Example

[0066] Figure 8 shows a phase shifter where its circuit is as shown in Figures 4 and 7 with n selected as three. In other words, Figure 8 shows the 3rd order reflective type phase shifter.

[0067] In one example, let us assume that the capacitance ratio between the "ON" and "OFF" state of the EC material based capacitors 10 is 2 (C_{max}/C_{min} = 2) and that C_{min} = 0.4 pF and that the EC material formed capacitors 10 have an equivalent parasitic resistance of 1 ohm.

Calculation of impedance values for the impedance transformers in this n=3 example

[0068] Setting n = 3 in (5) and substituting (5) into (8), the following expression for the transmission coefficient is obtained

$$S_{21} = -j\Gamma = j\frac{aZ^3 + bZ^2 + cZ + d}{-aZ^3 + bZ^2 - cZ + d} \quad (20)$$

where, $a = -k_{11}^2$, $b = Z_0 k_{12}^2 + Z_0 k_{21}^2$, $c = -k_{11}^2 k_{22}^2$ and $d = Z_0 k_{12}^2 k_{22}^2$. The transmission zero condition is achieved by setting S_{21} =0. In this case, a third order polynomial in Z is obtained and needs to be solved so that it has a multiple and real root. This is accomplished by setting the discriminant, Δ, to be zero.

$$\Delta = 18abcd - 4b^3 d + b^2 c^2 - 4ac^3 - 27a^2 d^2 = 0 \quad (21)$$

[0069] The condition that the discriminant of (21) is zero yields a triple zero at

$$Z = -\frac{b}{3a} = \frac{Z_0 k_{12}^2 + Z_0 k_{21}^2}{3k_{11}^2} \quad (22)$$

[0070] Solving (22) one obtains a quart-quadratic equation in k_{11}^4, given by

$$A k_{11}^8 + B k_{11}^4 + C = 0 \quad (23)$$

where, $A = -4k_{22}^4$, $B = -8Z_0^2 k_{12}^4 k_{22}^2 + 20 Z_0^2 k_{12}^2 k_{22}^2 k_{21}^2 + Z_0^2 k_{22}^2 k_{21}^2$ and $C = -4Z_0^4 k_{12}^8 - 4Z_0^4 k_{12}^2 k_{21}^4 - 12 Z_0^4 k_{12}^6 k_{21}^2 - 12 Z_0^4 k_{12}^4 k_{21}^4$. The double zero in k_{11}^4 is achieved at

$$k_{11}^4 = -\frac{B}{2A} = \frac{-8Z_0^2 k_{12}^4 k_{22}^2 + 20 Z_0^2 k_{12}^2 k_{22}^2 k_{21}^2 + Z_0^2 k_{22}^2 k_{21}^4}{8k_{22}^4} \quad (24)$$

with a condition that the discriminant of (23), $\Delta_1 = B^2 - 4AC$, disappears. This condition yields a third order polynomial in k_{12}^2, given by

$$D k_{12}^6 + E k_{12}^4 + F k_{12}^2 + G = 0 \quad (25)$$

where, D=-512, $E=192k_{21}^2$, $F=-24k_{21}^2$ and $G=k_{21}^6$. The triple zero of (25) is achieved at

$$k_{12}^2=-\frac{E}{3D}=\frac{1}{8}k_{21}^2 \quad (26)$$

provided that the discriminant of (25) disappears. It can be shown that the discriminant of (32) is always equal to zero, regardless of the value assigned to k_{21}^2. This infers that the triple and identical zero of the polynomial given by (25) is always achieved and that k_{21}^2 can be used as a parameter. Substituting (26) into (24), one finds the expression for k_{11}^2 where k_{22} and k_{21}^2 are used as parameters

$$k_{11}^2=\sqrt{\frac{27}{64}}\frac{Z_0k_{21}^2}{k_{22}} \quad (27)$$

[0071] The relationship between k_{22} and the rest of impedance transformers is found from (29). Imposing that the triple zero of (20) occurs at $q \cdot Z_0$, where q is a parameter that dictates the position of the transmission zero on the resistance scale, one obtains the following relationship for k_{22}

$$k_{22}=\frac{\sqrt{27}}{3}q\cdot Z_0 \quad (28)$$

[0072] Substituting (28) into (27), the expression for k_{11}^2 now becomes

$$k_{11}^2=\frac{3}{8\cdot q}k_{21}^2 \quad (29)$$

[0073] The following conditions for the characteristic impedances, k_{12}, k_{11} and k_{22} can now be expressed as

$$k_{12}^2=\frac{1}{8}k_{21}^2\,;\; k_{11}^2=\frac{3}{8\cdot q}k_{21}^2 \text{ and } k_{22}=\frac{\sqrt{27}}{3}q\cdot Z_0 \quad (30)$$

where Z_0, q and k_{21} are used as parameters. Since, Z_0 is usually, but not necessarily, 50Ω, only k_{21} and q can be used in the adjustment of the rest of the impedances of the quarter-wave transformers, k_{12}, k_{11} and k_{22}.

n=2 Example

[0074] Figure 9 shows a phase shifter where its circuit is as shown in Figures 4 and 7 with n selected as two. In other words, Figure 9 shows the 2nd order reflective type phase shifter.

[0075] In one example, let us assume that the capacitance ratio between the "ON" and "OFF" state of the EC material based capacitors 10 is 2 (C_{max}/C_{min} = 2) and that C_{min} = 0.4 pF and that the EC material formed capacitors 10 have an equivalent parasitic resistance of 1 ohm.

Calculation of impedance values for the impedance transformers in this n=2 example

[0076] Setting n = 2 in (5) and substituting (5) into (8), the following expression for the transmission coefficient is obtained

$$S_{21}=-j\Gamma=j\frac{-Zk_{11}^2+Z_0k_{12}^2+Z_0Z^2}{Zk_{11}^2+Z_0k_{12}^2+Z_0Z^2} \quad (31)$$

(30) assumes that the 3-dB coupler is ideal. The zeroes of (30) yield the following values for the transformers k_{11} and k_{12}

$$k_{11} = Z_0\sqrt{2q} \text{ and } k_{12} = Z_0 q \quad (32)$$

[0077] Upon which (32) becomes

$$S_{21} = -j\Gamma_{in} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} = \left|\frac{Z - qZ_0}{Z + qZ_0}\right|^2 \cdot e^{j2\left(-\frac{\pi}{2} + arctan\left(\frac{Im(Z)}{real(Z) - qZ_0}\right) - arctan\left(\frac{Im(Z)}{real(Z) + qZ_0}\right)\right)} \quad (33)$$

[0078] By setting q=1 it follows $k_{11} = Z_0\sqrt{2}$ and $k_{12} = Z_0$.

Comparison

[0079] For this comparison, with prior art approaches involving capacitors using EC materials, it is assumed that the capacitance ratio between the "ON" and "OFF" state of the EC material based capacitors 10 is 2 (C_{max}/C_{min} = 2) and that C_{min} = 0.4 pF and that the EC material formed capacitors 10 have an equivalent parasitic resistance of 1 ohm.

[0080] Based on the information on the variable EC material based variable capacitors, the two phase shifters (one second order and one third order) shown in Figures 8 and 9 were compared against prior art phase shifters involving capacitors using EC materials. In the design of all these phase shifters, a 3-dB coupler with an insertion loss of 0.3 dB is used. This is a realistic assumption and is evidenced in many practical designs. All three phase shifters are designed to operate at a centre frequency of 2. 5 GHz. Their performance is summarized in table 1 below.

Table 1 Performance comparison of first, second and third order reflective type phase shifters

Type of Phase Shifter	Insertion phase (deg.)	Insertion loss (dB)
First order reflective type EC material based phase shifter (Fig. 1 PRIOR ART)	29.4	0.7
Second order reflective type EC material based phase shifter (Fig. 9)	58.6	0.8
Third order reflective type EC material based phase shifter (Fig. 8)	88.9	0.9
Second order reflective type EC material based phase shifter obtained by cascade connection of two first order phase shifters (Fig. 2 PRIOR ART)	58.8	1.4
Third order reflective type EC material based phase shifter obtained by cascade connection of three first order phase shifters(Fig. 3 PRIOR ART)	88.2	2.1

[0081] As shown in this table the proposed reflective type EC material based phase shifters of order two or more (n=2,3,4..) offer the benefits of lower loss and increased phase shift compared to an earlier approach. This can be seen, for example, in comparing the "second order" data, namely second and fourth rows of data in Table 1. This can also be seen, for example by comparing the "third order" data, namely the third and fifth row of data in Table 1.

Some advantages and further details

[0082] As compared to the prior approach described in EP2996190A1, some advantages of using EC based material as opposed to varactor diodes as the active elements in the configuration of the proposed phase shifters are as follows.

[0083] First, the exact values of the "ON" and "OFF" capacitance of EC based materials can be tailored by the surface area of the top electrodes- this is not possible with varactor diodes.

[0084] Secondly, the capacitance ratio between the "ON" and "OFF" state can be tailored by the appropriate choice of the electrolyte, for which we have in-house experience.

[0085] Thirdly, varactor diodes exhibit significant non-linear behaviour, whereas EC based materials are highly linear.

[0086] Fourthly, a possibility exists in some other embodiments to actuate EC based materials by light, whereas this is not possible with varactor diodes.

[0087] The present invention may be embodied in other specific forms without departing from its essential characteristics. The described embodiments are to be considered in all respects only as illustrative and not restrictive. The scope of the invention is, therefore, indicated by the appended claims rather than by the foregoing description. All changes that come within the meaning and range of equivalency of the claims are to be embraced within their scope.

[0088] A person skilled in the art would readily recognize that steps of various above-described methods can be performed by programmed computers. Some embodiments relate to program storage devices, e.g., digital data storage media, which are machine or computer readable and encode machine-executable or computer-executable programs of instructions, wherein said instructions perform some or all of the steps of said above-described methods. The program storage devices may be, e.g., digital memories, magnetic storage media such as a magnetic disks and magnetic tapes, hard drives, or optically readable digital data storage media. Some embodiments involve computers programmed to perform said steps of the above-described methods.

Claims

1. A Radio Frequency reflection type phase shifter,

   the phase shifter comprising a coupler for input and output, and N variable capacitors, where N is an integer value of 2 or more, each of the variable capacitors providing in use radio frequency reflection,
   each of the variable capacitors being connected to the coupler by at least one impedance transformer, the characteristic impedances of the impedance transformers having been selected so that the phase shifter provides a phase shift at least substantially proportional to the value of N, wherein each of the variable capacitors comprises electrochromic material.

2. A Radio Frequency reflection type phase shifter according to claim 1, in which each of the variable capacitors comprises an electrolyte element and at least one electrochromic element between a first electrode and a second electrode.

3. A Radio Frequency reflection type phase shifter according to claim 2, in which the first electrode comprises a ground plate on which lies the first electrochromic element, and the electrolyte element lies on the electrochromic element, the electrochromic element comprising an electrochromic layer, and the electrolyte element comprising an electrolyte layer.
   A Radio Frequency reflection type phase shifter according to claim 2 or claim 3, in which each of the variable capacitors further comprises a second electrochromic element between the electrolyte element and second electrode, the second electrochromic element comprising a second electrochromic layer.

4. A Radio Frequency reflection type phase shifter according to any preceding claim, in which the coupler is a 3dB-coupler having four ports, N'/2 of the variable capacitors being connected to the coupler via one of two of the ports, and N'/2 of the capacitors being connected to the coupler via a second of said two ports, where N' is an even number integer of 4 or more.

5. A Radio Frequency reflection type phase shifter according to any of claims 1 to 4, in which the coupler is a circulator having three ports, the N variable capacitors being connected to the circulator via one of the ports.

6. A Radio Frequency reflection type phase shifter according to any preceding claim, in which the impedance transformers are microstrip lines.

7. A Radio Frequency reflection type phase shifter according to any preceding claim, in which the characteristic impedances of the impedance transformers are selected in accordance with a selected value of a parameter value q determined for a given capacitor as

$$q=\frac{\sqrt{X_{max}X_{min}}}{Z_0}$$

where Z_0 is the characteristic impedance of the impedance transformers, Xmin is the minimum reactance of the capacitor and Xmax is the maximum reactance of the capacitor.

8. A Radio Frequency reflection type phase shifter according to any preceding claim, in which the capacitance of each of the variable capacitors is variable by adjusting a d.c. voltage applied across the capacitors.

9. A Radio Frequency reflection type phase shifter according to claim 9, in which said phase shift is at least substantially proportional to the value of N when a mid-range value of the capacitance of the variable capacitors is selected so the corresponding reactance at an operating radio frequency is the characteristic impedance Z_0.

10. A Radio Frequency reflection type phase shifter according to claim 10, in which the capacitors are variable between a higher capacitance 'fully ON' state when the d.c. voltage is at a first level and a lower capacitance 'OFF' state when the d.c. voltage is at a second level.

11. A method of Radio Frequency reflection type phase shifting, by:

applying an input signal to a phase shifter comprising a coupler for input and output, and N variable capacitors, where N is an integer value of 2 or more, each of the variable capacitors providing radio frequency reflection, each of the variable capacitors being connected to the coupler by at least one impedance transformer, the characteristic impedances of the impedance transformers having been selected so that the phase shifter provides a phase shift at least substantially proportional to the value of N, wherein each of the variable capacitors comprises electrochromic material; and
receiving an output signal from the coupler.

12. A method of Radio Frequency reflection type phase shifting according to claim 12, in which the capacitance of each of the variable capacitors is variable by adjusting a d.c. voltage applied across the capacitors.

13. A method of Radio Frequency reflection type phase shifting according to claim 13, in which said phase shift is at least substantially proportional to the value of N when a mid-range value of the capacitance of the variable capacitors is selected so the corresponding reactance at an operating radio frequency is the characteristic impedance Z_0.

Amended claims in accordance with Rule 137(2) EPC.

1. A Radio Frequency reflection type phase shifter (30),

the phase shifter comprising a coupler (32) for input and output (34), and N variable capacitors (10), where N is an integer value of 2 or more, each of the variable capacitors providing in use radio frequency reflection, each of the variable capacitors being connected to the coupler by at least one impedance transformer (K, 26), the characteristic impedances of the impedance transformers having been selected so that the phase shifter provides a phase shift at least substantially proportional to the value of N, wherein each of the variable capacitors comprises electrochromic material.

2. A Radio Frequency reflection type phase shifter according to claim 1, in which each of the variable capacitors (10) comprises an electrolyte element (16) and at least one electrochromic element (14, 18) between a first electrode (12) and a second electrode (20)

3. A Radio Frequency reflection type phase shifter according to claim 2, in which the first electrode (12) comprises a ground plate on which lies the first electrochromic element (14), and the electrolyte element (16) lies on the electrochromic element (14), the electrochromic element comprising an electrochromic layer, and the electrolyte element comprising an electrolyte layer.

4. A Radio Frequency reflection type phase shifter according to claim 2 or claim 3, in which each of the variable capacitors further comprises a second electrochromic element (18) between the electrolyte element and second electrode, the second electrochromic element comprising a second electrochromic layer.

5. A Radio Frequency reflection type phase shifter according to any preceding claim, in which the coupler (32) is a 3dB-coupler having four ports, N'/2 of the variable capacitors being connected to the coupler via one of two of the ports, and N'/2 of the capacitors being connected to the coupler via a second of said two ports, where N' is an even number integer of 4 or more.

6. A Radio Frequency reflection type phase shifter according to any of claims 1 to 4, in which the coupler is a circulator having three ports, the N variable capacitors being connected to the circulator via one of the ports.

7. A Radio Frequency reflection type phase shifter according to any preceding claim, in which the impedance transformers (K, 26) are microstrip lines.

8. A Radio Frequency reflection type phase shifter according to any preceding claim, in which the characteristic impedances of the impedance transformers are selected in accordance with a selected value of a parameter value q determined for a given capacitor as

$$q = \frac{\sqrt{X_{max} X_{min}}}{Z_0}$$

where Zo is the characteristic impedance of the impedance transformers, Xmin is the minimum reactance of the capacitor and Xmax is the maximum reactance of the capacitor.

9. A Radio Frequency reflection type phase shifter according to any preceding claim, in which the capacitance of each of the variable capacitors (10) is variable by adjusting a d.c. voltage applied across the capacitors.

10. A Radio Frequency reflection type phase shifter according to claim 9, in which said phase shift is at least substantially proportional to the value of N when a mid-range value of the capacitance of the variable capacitors (10) is selected so the corresponding reactance at an operating radio frequency is the characteristic impedance Z_0.

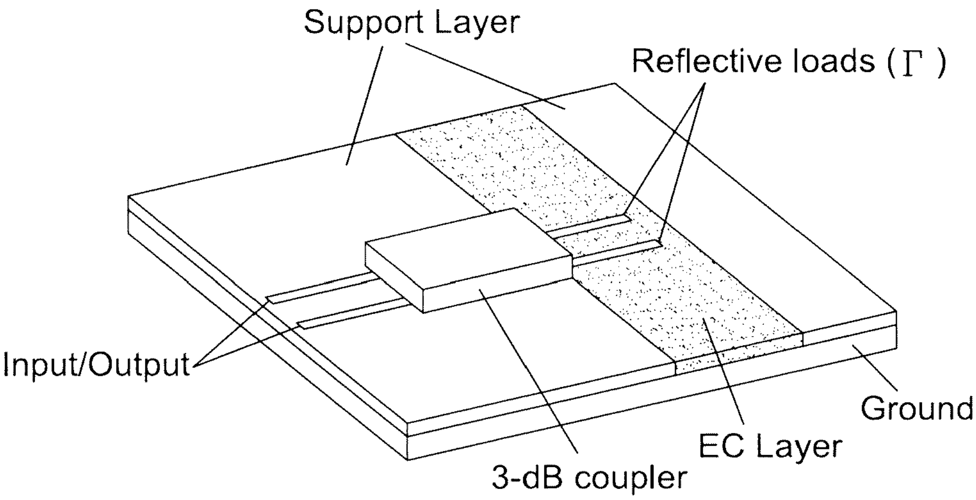
11. A Radio Frequency reflection type phase shifter according to claim 10, in which the capacitors are variable between a higher capacitance 'fully ON' state when the d.c. voltage is at a first level and a lower capacitance 'OFF' state when the d.c. voltage is at a second level.

12. A method of Radio Frequency reflection type phase shifting, by:

applying an input signal to a phase shifter (30) comprising a coupler (32) for input and output, and N variable capacitors (10), where N is an integer value of 2 or more, each of the variable capacitors providing radio frequency reflection, each of the variable capacitors being connected to the coupler by at least one impedance transformer, the characteristic impedances of the impedance transformers (K, 26) having been selected so that the phase shifter provides a phase shift at least substantially proportional to the value of N, wherein each of the variable capacitors comprises electrochromic material; and
receiving an output signal from the coupler.

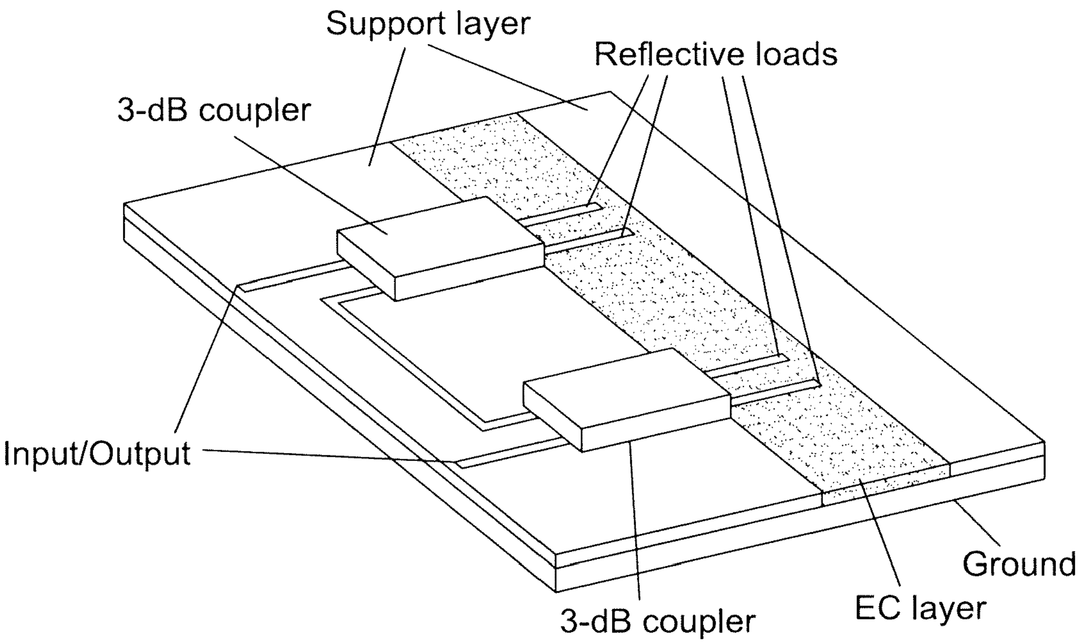
13. A method of Radio Frequency reflection type phase shifting according to claim 12, in which the capacitance of each of the variable capacitors (10) is variable by adjusting a d.c. voltage applied across the capacitors.

14. A method of Radio Frequency reflection type phase shifting according to claim 13, in which said phase shift is at least substantially proportional to the value of N when a mid-range value of the capacitance of the variable capacitors (10) is selected so the corresponding reactance at an operating radio frequency is the characteristic impedance Z_0.



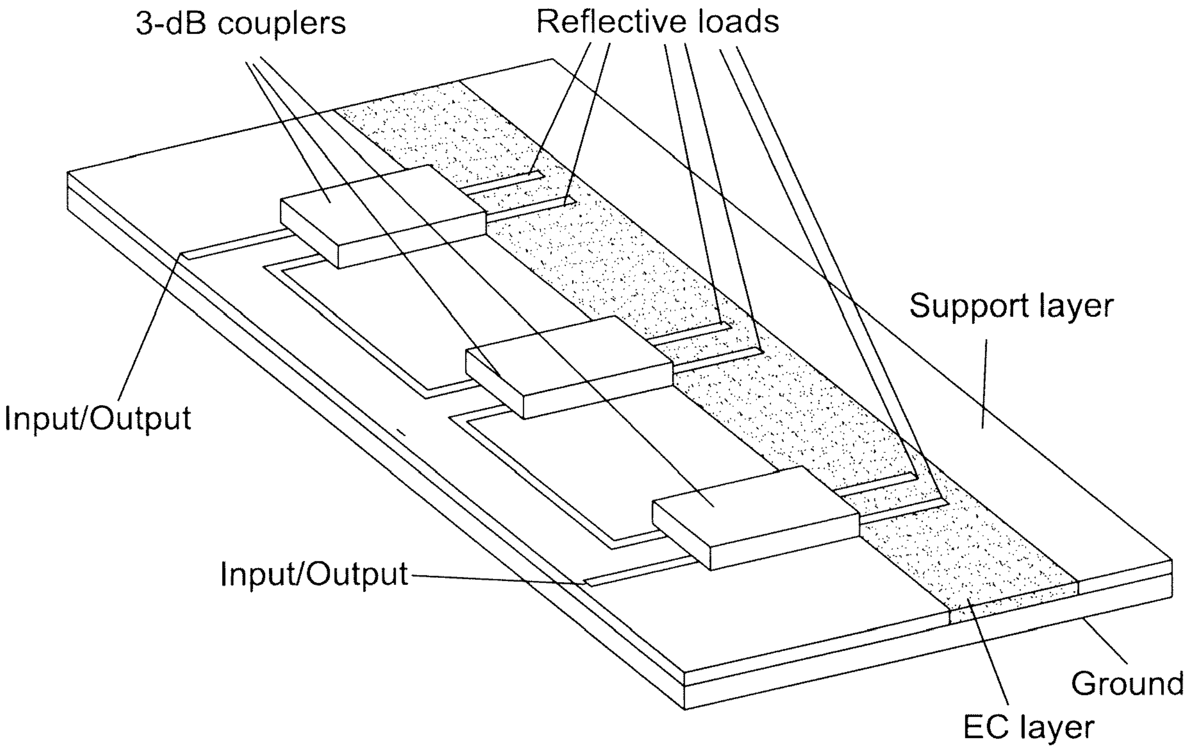
PRIOR ART

Fig. 1



PRIOR ART

Fig. 2



PRIOR ART

Fig. 3

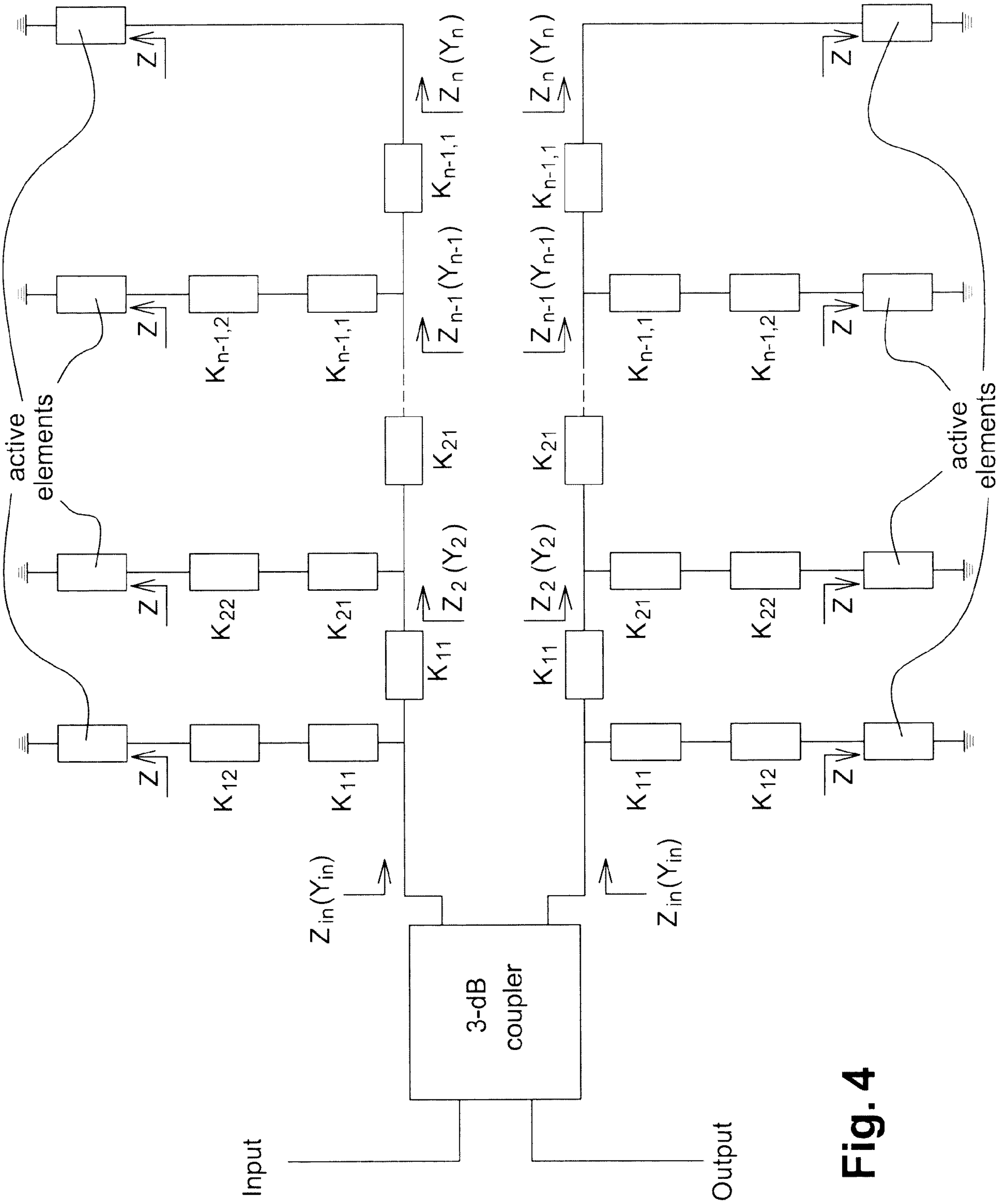

Input
Output
3-dB coupler
Z in(Y in)
Z in(Y in)
K 11
K 12
K 11
K 21
K 22
K 21
K n-1,1
K n-1,2
K n-1,1
K n-1,1
Z 2 (Y 2)
Z n-1 (Y n-1)
Z n (Y n)
Z
active elements

Fig. 4

Fig. 5

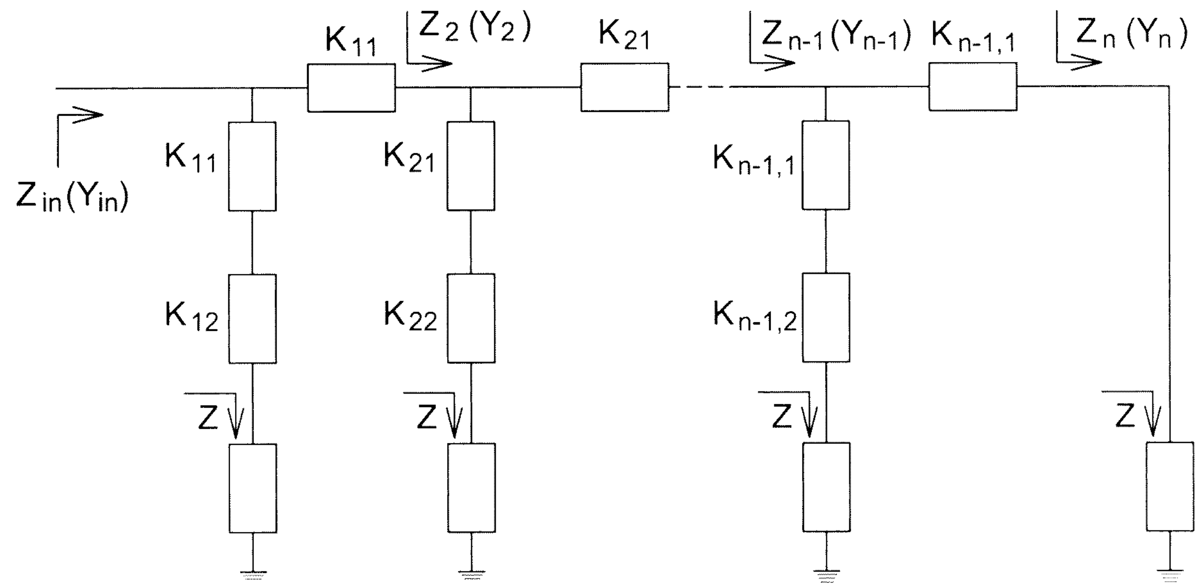
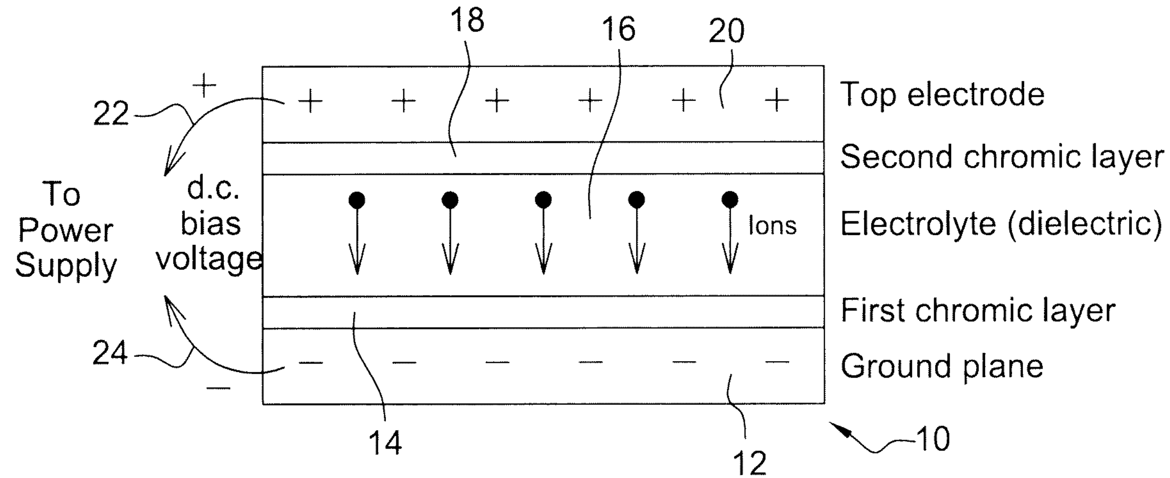

K11
Z2 (Y2)
K21
Zn-1 (Yn-1)
Kn-1,1
Zn (Yn)
Zin (Yin)
K11
K21
Kn-1,1
K12
K22
Kn-1,2
Z
Z
Z
Z

Fig. 6


18
16
20
+
22
24
−
To
Power
Supply
d.c.
bias
voltage
Ions
Top electrode
Second chromic layer
Electrolyte (dielectric)
First chromic layer
Ground plane
14
12
10

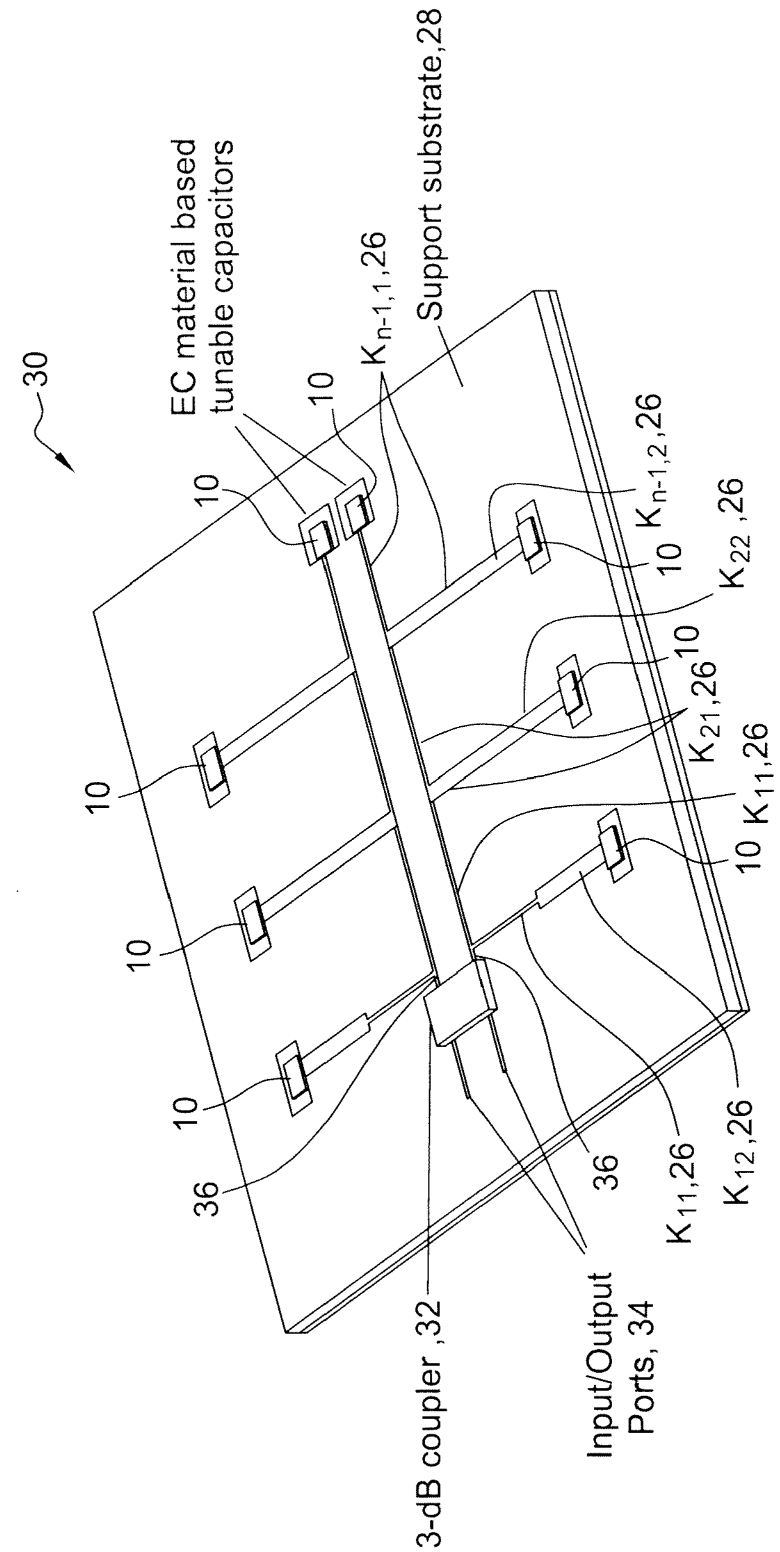

30
EC material based tunable capacitors
10
10
$K_{n-1,1}$,26
Support substrate,28
$K_{n-1,2}$,26
10
K_{22} ,26
10
K_{21},26
K_{11},26
10
10
10
10
36
3-dB coupler ,32
Input/Output Ports, 34
36
K_{11},26
K_{12},26

Fig. 7

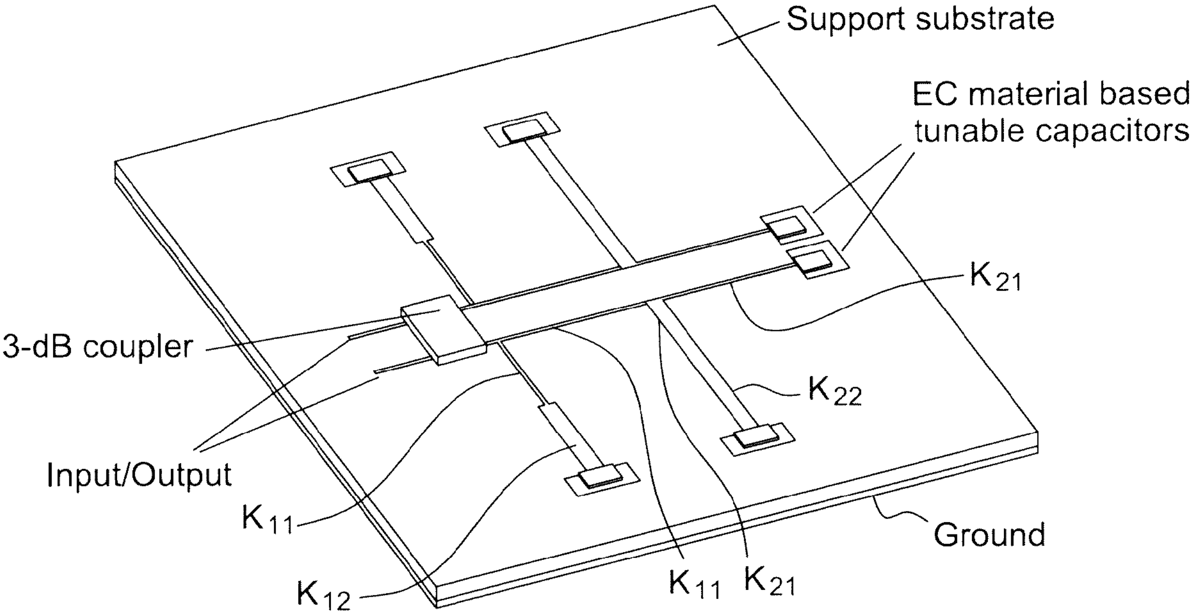

Support substrate
EC material based tunable capacitors
K_{21}
3-dB coupler
K_{22}
Input/Output
K_{11}
Ground
K_{12}
K_{11}
K_{21}

Fig. 8

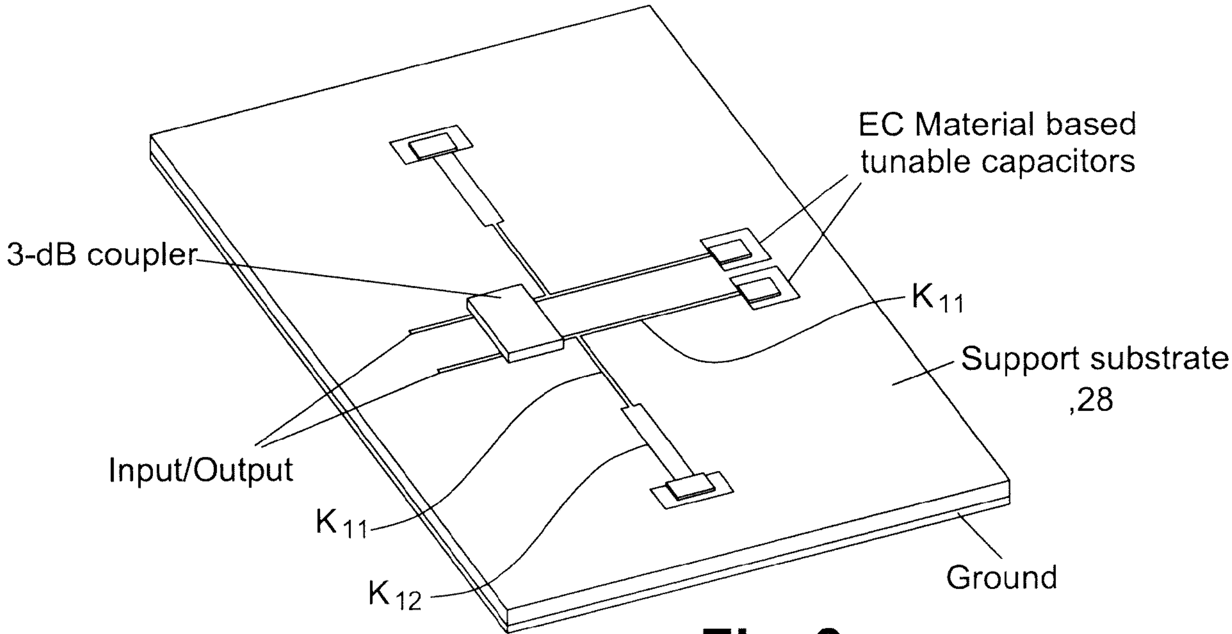

EC Material based tunable capacitors
3-dB coupler
K_{11}
Support substrate ,28
Input/Output
K_{11}
K_{12}
Ground

Fig. 9

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EUROPEAN SEARCH REPORT

Application Number
EP 16 30 6453

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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
The Hague	20 April 2017	La Casta Muñoa, S

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EUROPEAN SEARCH REPORT

Application Number
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E : earlier patent document, but published on, or after the filing date
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20-04-2017

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