

A MULTIPLEXER FOR VERY HIGH FREQUENCY APPLICATIONS

TECHNICAL FIELD

[0001] This application relates to a compact multiplexer with minimal components for very high frequency (VHF) applications.

BACKGROUND

[0002] RF multiplexers (MUX) are commonly used in applications requiring multiband or multichannel operations. As a result, many types of RF multiplexer designs and arrangements have been proposed by those skilled in the art, leveraging topologies like resonant star-junction and ring manifold sections. However, designs that comprise of only traditional waveguide- or microstrip-based circuits, while effective, tend to result in larger circuit sizes, typically beyond a few wavelengths in size. This limitation makes them impractical for applications operating in the very high frequency (VHF) electromagnetic range which typically spans from 30 MHz to 300 MHz.

[0003] To address this, those skilled in the art have attempted to utilize High Temperature Superconductors (HTS) for RF multiplexer designs. However, such designs are overly limiting as they require low operating temperatures ($\sim 77^{\circ}\text{K}$) and are inherently bulky when the operating frequencies are in the VHF range. Innovative approaches using Niobium on Sapphire substrate have also been explored by those skilled in the art, particularly for spin qubit readouts. However, these designs typically lack complete multiplexing properties, particularly in terms of achieving passbands at operational frequencies, and are further restricted to operations within a narrow temperature range.

[0004] Despite efforts of those skilled in the art, current techniques are still unable to provide a compact RF multiplexer with minimum components for VHF applications whereby the RF multiplexer is able to operate at both cryogenic and room temperatures.

SUMMARY

[0005] In one aspect, the present application discloses a multiplexer. The multiplexer disclosed in the present application comprises a first bandpass filter having a first passband, and a second bandpass filter having a second passband. The disclosed first bandpass filter

comprises a first multi-stage LC ladder circuit connecting an input terminal to a first output terminal, and a first capacitor connected in series between a series inductor and a parallel capacitor of a final stage of the first multi-stage LC ladder circuit on a path connecting the input terminal and the first output terminal, wherein the first capacitor has a resonant frequency located within the first passband. The disclosed second bandpass filter comprises a second multi-stage LC ladder circuit connecting the common input terminal to a second output terminal, and a second capacitor connected in series between a series inductor and a parallel capacitor of a final stage of the second multi-stage LC ladder circuit on a path connecting the input terminal and the second output terminal, wherein the second capacitor has a resonant frequency located within the second passband.

[0006] In another embodiment of the one aspect, the multiplexer further comprises a third bandpass filter having a third passband, and a fourth bandpass filter having a fourth passband. The disclosed third bandpass filter comprises a third multi-stage LC ladder circuit connecting the common input terminal to a third output terminal, and a third capacitor connected in series between a series inductor and a parallel capacitor of a final stage of the third multi-stage LC ladder circuit on a path connecting the input terminal and the third output terminal, wherein the third capacitor has a resonant frequency located within the third passband. The disclosed fourth bandpass filter comprises a fourth multi-stage LC ladder circuit connecting the input terminal to a fourth output terminal, and a fourth capacitor connected in series between a series inductor and a parallel capacitor of a final stage of the fourth multi-stage LC ladder circuit on a path connecting the input terminal and the fourth output terminal, wherein the fourth capacitor has a resonant frequency located within the fourth passband.

[0007] In another aspect, the present application discloses a method for forming a multiplexer on a microstrip circuit. The disclosed method comprises the steps of forming a first bandpass filter having a first passband on the microstrip circuit and forming a second bandpass filter having a second passband on the microstrip circuit. The formed first bandpass filter comprises a first multi-stage LC ladder circuit formed on the microstrip circuit connecting an input terminal to a first output terminal, and a first capacitor connected in series between a series inductor and a parallel capacitor of a final stage of the first multi-stage LC ladder circuit on a path connecting the input terminal and the first output terminal, wherein the first capacitor has a resonant frequency located within the first passband. The formed second bandpass filter comprises a second multi-stage LC ladder circuit formed on the microstrip circuit connecting

the input terminal to a second output terminal, and a second capacitor connected in series between a series inductor and a parallel capacitor of a final stage of the second multi-stage LC ladder circuit on a path connecting the input terminal and the second output terminal, wherein the second capacitor has a resonant frequency located within the second passband.

[0008] In another embodiment of this another aspect, the disclosed method further comprises the steps of forming a third bandpass filter having a third passband on the microstrip circuit and forming a fourth bandpass filter having a fourth passband on the microstrip circuit. The formed third bandpass filter comprises a third multi-stage LC ladder circuit formed on the microstrip circuit connecting the input terminal to a third output terminal, and a third capacitor connected in series between a series inductor and a parallel capacitor of a final stage of the third multi-stage LC ladder circuit on a path connecting the input terminal and the third output terminal, wherein the third capacitor has a resonant frequency located within the third passband. The formed fourth bandpass filter comprises a fourth multi-stage LC ladder circuit formed on the microstrip circuit connecting the input terminal to a fourth output terminal, and a fourth capacitor connected in series between a series inductor and a parallel capacitor of a final stage of the fourth multi-stage LC ladder circuit on a path connecting the input terminal and the fourth output terminal, wherein the fourth capacitor has a resonant frequency located within the fourth passband.

[0009] In yet another aspect, the present application discloses a multiplexer for very high frequency applications. The disclosed multiplexer has a plurality of arms, wherein each arm comprises a bandpass filter having a passband whereby the bandpass filter comprises a multi-stage LC ladder circuit connecting an input terminal to an output terminal, and a capacitor connected in series between a series inductor and a parallel capacitor of a final stage of the multi-stage LC ladder circuit on a path connecting the input terminal and the output terminal, wherein the capacitor has a resonant frequency located within the passband of the bandpass filter. Each of the plurality of the arms of the multiplexer has a passband with a center frequency that differs from center frequencies of other passbands of other arms.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] Various embodiments of the present disclosure are described below with reference to the following drawings:

Figure 1 illustrates a block diagram of a four-way multiplexer in accordance with embodiments of the present disclosure;

Figure 2 illustrates a circuit diagram of a bandpass filter comprising a 2-stage or 2nd order LC ladder circuit in accordance with embodiments of the present disclosure;

Figure 3a illustrates a circuit diagram of a four-way multiplexer comprising of four bandpass filters whereby each bandpass filter comprises a 2-stage LC ladder circuit in accordance with embodiments of the present disclosure;

Figure 3b illustrates a simulated Bode plot showing the magnitude responses of the four bandpass filters of the multiplexer illustrated in Figure 3a;

Figure 4 illustrates a flowchart that sets out the process or method for optimizing the design of the multiplexer illustrated in Figure 3a in accordance with embodiments of the present disclosure;

Figure 5a illustrates a plot showing the simulated input reflection coefficient of the multiplexer illustrated in Figure 3a;

Figure 5b illustrates plots showing the simulated transmission coefficients of the multiplexer illustrated in Figure 3a;

Figure 5c illustrates plots showing the simulated isolation coefficients of the multiplexer illustrated in Figure 3a;

Figure 6 illustrates a circuit diagram of a bandpass filter comprising a 3-stage or 3rd order LC ladder circuit in accordance with embodiments of the present disclosure;

Figure 7a illustrates a circuit diagram of a four-way multiplexer comprising of four bandpass filters whereby each bandpass filter comprises a 3-stage LC ladder circuit in accordance with embodiments of the present disclosure;

Figure 7b illustrates a simulated Bode plot showing the magnitude responses of the four bandpass filters of the multiplexer illustrated in Figure 7a;

Figure 8a illustrates a plot showing the simulated input reflection coefficient of the multiplexer illustrated in Figure 7a;

Figure 8b illustrates plots showing the simulated transmission coefficients of the multiplexer illustrated in Figure 7a;

Figure 9 illustrates a circuit diagram of a bandpass filter comprising a 3-stage or 3rd order LC ladder circuit with a series capacitor provided at the final stage of the 3-stage LC ladder circuit in accordance with embodiments of the present disclosure;

Figure 10a illustrates a circuit diagram of a four-way multiplexer comprising of four bandpass filters whereby each bandpass filter comprises a 3-stage LC ladder circuit as illustrated in Figure 9 in accordance with embodiments of the present disclosure;

Figure 10b illustrates a simulated Bode plot showing the magnitude responses of the four bandpass filters of the multiplexer illustrated in Figure 10a;

Figure 11 illustrates a flowchart that sets out the process or method for optimizing the design of the multiplexer illustrated in Figure 10a in accordance with embodiments of the present disclosure;

Figure 12a illustrates a plot showing the simulated input reflection coefficient of the multiplexer illustrated in Figure 10a;

Figure 12b illustrates plots showing the simulated transmission coefficients of the multiplexer illustrated in Figure 10a;

Figure 12c illustrates plots showing the simulated isolation coefficients of the multiplexer illustrated in Figure 10a;

Figure 13a illustrates a circuit layout of the multiplexer illustrated in Figure 10a in accordance with embodiments of the present disclosure;

Figure 13b illustrates an isometric view of the bottom of the circuit illustrated in Figure 13a in accordance with embodiments of the present disclosure;

Figure 14a illustrates a plot showing the simulated input reflection coefficient of the multiplexer illustrated in Figure 10a when the effects of printed circuit board (PCB) losses are included in the simulation;

Figure 14b illustrates plots showing the simulated transmission coefficients of the multiplexer illustrated in Figure 10a when the effects of PCB losses are included in the simulation;

Figure 14c illustrates plots showing the simulated isolation coefficients of the multiplexer illustrated in Figure 10a when the effects of PCB losses are included in the simulation;

Figure 14d illustrates a plot showing the simulated output reflection coefficient of the multiplexer illustrated in Figure 10a when the effects of PCB losses are included in the simulation;

Figure 15a illustrates a plot showing the simulated input reflection coefficient of the multiplexer illustrated in Figure 10a when the effects of PCB and component losses are included in the simulation;

Figure 15b illustrates plots showing the simulated transmission coefficients of the multiplexer illustrated in Figure 10a when the effects of PCB and component losses are included in the simulation;

Figure 15c illustrates plots showing the simulated isolation coefficients of the multiplexer illustrated in Figure 10a when the effects of PCB and component losses are included in the simulation; and

Figure 15d illustrates a plot showing the simulated output reflection coefficient of the multiplexer illustrated in Figure 10a when the effects of PCB and component losses are included in the simulation.

DETAILED DESCRIPTION

[0011] The following detailed description is made with reference to the accompanying drawings, showing details and embodiments of the present disclosure for the purposes of illustration. Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments, even if not explicitly described in these other embodiments. Additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0012] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

[0013] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance as generally understood in the relevant technical field, e.g., within 10% of the specified value.

[0014] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0015] As used herein, “comprising” means including, but not limited to, whatever follows the word “comprising”. Thus, use of the term “comprising” indicates that the listed elements are required or mandatory, but that other elements are optional and may or may not be present.

[0016] As used herein, “consisting of” means including, and limited to, whatever follows the phrase “consisting of”. Thus, use of the phrase “consisting of” indicates that the listed elements are required or mandatory, and that no other elements may be present.

[0017] As used herein, an “LC ladder circuit” is defined as a type of filter network that comprises an arrangement of inductors (L) and capacitors (C) that are arranged in an alternating pattern in a ladder-like configuration where each stage in the LC ladder circuit comprises an inductor arranged in series with a signal path followed by a capacitor provided in parallel with the signal path, shunting the capacitor to ground. The signal path may be defined as a path that connects an input terminal to an output terminal of the LC ladder circuit.

[0018] A “multi-stage LC ladder circuit”, as used herein, refers to a LC ladder circuit having a plurality of stages where each stage comprises an inductor arranged in series with the signal path and preceded by a capacitor arranged in parallel with the signal path, shunting the capacitor to ground. Further, a “final stage” of a multi-stage LC ladder circuit refers to an arrangement of a serial inductor and a parallel capacitor that is adjacent to an output terminal of the multi-stage LC ladder circuit.

[0019] Lumped inductor and capacitor components, commonly known as surface mount device (SMD) chips may be utilized in the design of multiplexers to address the challenges of designing compact RF multiplexer circuits suitable for VHF applications. These components offer significant size advantages and ease of assembly, making them well-suited for use in multiplexer designs. Moreover, SMD-based circuits may operate effectively across both cryogenic and room temperatures, enhancing their versatility in diverse operational environments.

[0020] The number of SMD components used in the design of the multiplexer should be minimized so that the circuit’s footprint may be optimized without compromising the performance of the multiplexer. This approach not only aids in reducing the overall size of the multiplexer but also facilitates efficient integration of the multiplexer into compact electronic systems, thereby meeting the demands of modern communication and signal processing applications effectively.

[0021] A multiplexer with a bandpass filter in each arm operates by frequency multiplexing an input signal provided to a common input terminal to the output terminals of each of the arms concurrently. Each bandpass filter is tuned to process the input signal independently from other

bandpass filters, allowing only its designated frequency band to pass through while attenuating other frequency bands. Such a multiplexer may comprise of two or more arms where the number of arms of the multiplexer depends on the application of the multiplexer.

[0022] A simple block diagram of a four-way multiplexer is illustrated in Figure 1. The multiplexer illustrated in Figure 1 comprises four arms, where each arm comprises a bandpass filter. The multiplexer functions by selectively routing signals from common input terminal 101 to the four output terminals, 103, 105, 107 and 109 where terminal 103 is the output terminal for bandpass filter 102, terminal 105 is the output terminal for bandpass filter 104, terminal 107 is the output terminal for bandpass filter 106, and terminal 109 is the output terminal for bandpass filter 108. Each of bandpass filters 102, 104, 106 and 108 comprise a multi-stage LC ladder circuit and each of the LC ladder circuits comprises at least two stages. This ensures that a bandpass filter response may be achieved by each of the multi-stage LC ladder circuits of the bandpass filters. It should be noted that although reference is made throughout the description to a four-way multiplexer, one skilled in the art will recognize that the concepts and features described in this disclosure may be applied to any multiplexer having two or more arms, e.g. a two-way multiplexer, a three-way multiplexer, and etc.

[0023] An exemplary 2-stage LC ladder circuit that may be used as any one of bandpass filters 102, 104, 106 and 108 is illustrated in Figure 2. The 2-stage LC ladder circuit comprises of four LC components (2 serial inductors and 2 parallel capacitors) and connects input terminal 201 to output terminal 202.

[0024] The transfer function $H(s)$ of the 2-stage LC ladder circuit bandpass filter may be defined as:

$$H(s) = \frac{V_{out}}{V_{in}} = \frac{1}{X} = \frac{1}{Z + C_s s^2 (L_1 + L_2 Z)} \quad \dots \text{equation (1)}$$

where $Z = C_1 L_1 s^2 + 1$, and $s = jw$.

[0025] Figure 3a illustrates a circuit diagram of four-way multiplexer 300 in accordance with embodiments of the present disclosure where each arm of four-way multiplexer 300

comprises a bandpass filter that may be implemented using a 2-stage LC ladder circuit. Multiplexer 300 comprises an input terminal-1 that is connected to inputs of bandpass filters 301, 302, 303 and 304 resulting in a star connection, and each of these bandpass filters' outputs are connected to terminal-2, terminal-3, terminal-4 and terminal-5 respectively.

[0026] In embodiments of the disclosure, the initial values of L_1, L_2, C_1, C_2 of a 2-stage LC ladder circuit may be obtained by optimizing a Bode plot magnitude of transfer function $H(s)$ such that the plot has a peak amplitude at the desired centre frequency. When this approach is adopted for each of the bandpass filters of multiplexer 300, the resulting simulated Bode plot showing the magnitude responses of the four bandpass filters may be as illustrated in Figure 3b where plot 311 represents the magnitude response of bandpass filter 301, plot 312 represents the magnitude response of bandpass filter 302, plot 313 represents the magnitude response of bandpass filter 303, and plot 314 represents the magnitude response of bandpass filter 304.

[0027] In a first example, bandpass filter 301 was designed to have a peak amplitude at 110 MHz, bandpass filter 302 was designed to have a peak amplitude at 130 MHz, bandpass filter 303 was designed to have a peak amplitude at 150 MHz, and bandpass filter 304 was designed to have a peak amplitude at 170 MHz. As a result, the values of the LC components of the respective bandpass filters may be as defined in Table 1 below.

Bandpass filter 301	Values	Bandpass filter 302	Values
L_1^1	130 nH	L_1^2	100 nH
C_1^1	45 pF	C_1^2	39 pF
L_2^1	125 nH	L_2^2	105 nH
C_2^1	40 pF	C_2^2	39 pF

Bandpass filter 303	Values	Bandpass filter 304	Values
L_1^3	98 nH	L_1^4	89 nH
C_1^3	31 pF	C_1^4	45 pF
L_2^3	95 nH	L_2^4	125 nH
C_2^3	30 pF	C_2^4	40 pF

TABLE 1

[0028] Figure 4 illustrates a flowchart that sets out a process or a method for optimizing the design of multiplexer 300 in accordance with embodiments of the present disclosure. Process 400 begins at step 402 with process 400 choosing the four operating frequencies or center frequencies for each of the arms of multiplexer 300: $f_1 = 110 \text{ MHz}$, $f_2 = 130 \text{ MHz}$, $f_3 = 150 \text{ MHz}$, $f_4 = 170 \text{ MHz}$ respectively.

[0029] At step 404, process 400 optimizes the transfer function of bandpass filter 301 such that a resonance occurs at center frequency f_1 . Process 400 then obtains the optimized values of L_1^1 , L_2^1 , C_1^1 , C_2^1 in the transfer function of bandpass filter 301 at step 412.

[0030] Process 400 then performs the similar optimization process at step 406 for the transfer function of bandpass filter 302 such that a resonance occurs at center frequency f_2 , at step 408 for the transfer function of bandpass filter 303 such that a resonance occurs at center frequency f_3 , and at step 410 for the transfer function of bandpass filter 304 such that a resonance occurs at center frequency f_4 . The optimized LC values L_j^i , C_j^i ($i=2$ to 4 , $j=1$ to 2) are then obtained for bandpass filter 302 at step 414, for bandpass filter 303 at step 416, and for bandpass filter 304 at step 418.

[0031] Once steps 412 - 418 have been completed, process 400 then proceeds to step 420. At step 420, process 400 will then optimize the performance of multiplexer 300 as a whole to meet the required multiplexer response where the optimized LC values L_j^i , C_j^i ($i=1$ to 4 , $j=1$ to 2) are used as the initial LC values in each of the bandpass filters. In embodiments of the disclosure, the optimization of the multiplexer as a whole may be performed by a large-signal S-Parameter simulation software or any other such similar software.

[0032] Continuing on from the first example described above, after the optimization process was completed, the optimized LC values as shown in Table 2 were obtained for the respective bandpass filters of multiplexer 300.

Bandpass filter 301	Values	Bandpass filter 302	Values
L_1^1	192 nH	L_1^2	286.4 nH
C_1^1	73.6 pF	C_1^2	22.7 pF

L_2^1	41.2 nH	L_2^2	95.6 nH
C_2^1	228.7 pF	C_2^2	112.3 pF

Bandpass filter 303	Values	Bandpass filter 304	Values
L_1^3	298 nH	L_1^4	190 nH
C_1^3	15.3 pF	C_1^4	23.8 pF
L_2^3	107 nH	L_2^4	51.7 nH
C_2^3	88.1 pF	C_2^4	115.5 pF

TABLE 2

[0033] The simulated input reflection coefficient of multiplexer 300 based on the optimized LC values listed in Table 2 is plotted in Figure 5a. It can be seen from this plot that the reflection coefficient S_{11} shows four operating frequencies centered at 110 MHz, 130 MHz, 150 MHz, and 170 MHz where each center frequency has a -10 dB impedance bandwidth of approximately 2 MHz. The simulated transmission coefficient for each of the arms of multiplexer 300, i.e., S_{12} , S_{13} , S_{14} , S_{15} , are plotted in Figure 5b and these plots show that the transmission coefficients S_{12} to S_{15} have peaks at their respective operating frequencies. From these plots, it can also be observed that the insertion loss bandwidth at -3 dB is between 5 and 6.5 MHz across all the bands while the maximum side lobe level of the transmission coefficients is around -13.1 dB. The isolation coefficients (S_{23} , S_{24} , S_{25} , S_{34} , S_{35} , S_{45}) between each of the arms of multiplexer 300 are plotted in Figure 5c where it can be seen that the minimum isolation level obtained between the output ports of each of the bandpass filters is about 16.4 dB.

[0034] In another embodiment of the present disclosure, a 3-stage LC ladder circuit that may be used as any one of the bandpass filters of a four-way multiplexer is illustrated in Figure 6. The 3-stage LC ladder circuit comprises of six LC components (3 serial inductors and 3 parallel capacitors) and connects input terminal 601 to output terminal 602.

[0035] The transfer function $H(s)$ of the 3-stage LC ladder circuit bandpass filter may be defined as:

$$H(s) = \frac{V_{out}}{V_{in}} = \frac{1}{A} = \frac{1}{X + s^2 C_3 L_3 X + s C_3 Y}$$

$$X = 1 + s^2 L_1 C_1 + s C_2 (s L_2 + s^3 L_1 L_2 C_1 + s L_1)$$

$$Y = s L_2 + s^3 L_1 L_2 C_1 + s L_1 \quad \dots \text{equation (2)}$$

where $s = j\omega$.

[0036] Figure 7a illustrates a circuit diagram of four-way multiplexer 700 in accordance with embodiments of the present disclosure where each arm of four-way multiplexer 700 comprises a bandpass filter that may be implemented using a 3-stage LC ladder circuit. Multiplexer 700 comprises an input terminal-1 that is connected to inputs of bandpass filters 701, 702, 703 and 704 resulting in a star connection, and each of these bandpass filters' outputs are connected to terminal-2, terminal-3, terminal-4 and terminal-5 respectively.

[0037] A Bode plot showing the simulated magnitude responses of bandpass filters 701 - 704 are illustrated in Figure 7b where plot 711 represents the magnitude response of bandpass filter 701 with a peak amplitude at 110 MHz, plot 712 represents the magnitude response of bandpass filter 702 with a peak amplitude at 130 MHz, plot 713 represents the magnitude response of bandpass filter 703 with a peak amplitude at 150 MHz, and plot 714 represents the magnitude response of bandpass filter 704 with a peak amplitude at 170 MHz.

[0038] In a second example, the values of the LC components of the respective bandpass filters used to generate the Bode plot in Figure 7b are listed in Table 3 below.

Bandpass filter 701	Values	Bandpass filter 702	Values
L_1^1	122 nH	L_1^2	102 nH
C_1^1	62 pF	C_1^2	62 pF
L_2^1	57 nH	L_2^2	57 nH
C_2^1	200 pF	C_2^2	80 pF
L_3^1	128 nH	L_3^2	100 nH
C_3^1	80 pF	C_3^2	80 pF

Bandpass filter 703	Values	Bandpass filter 704	Values
L_1^3	2 nH	L_1^4	20 nH

C_1^3	12 pF	C_1^4	12 pF
L_2^3	100 nH	L_2^4	60 nH
C_2^3	26 pF	C_2^4	26 pF
L_3^3	50 nH	L_3^4	70 nH
C_3^3	100 pF	C_3^4	60 pF

TABLE 3

[0039] Process 400 (as illustrated in Figure 4) is then utilized to optimize the design of multiplexer 700 in accordance with embodiments of the present disclosure based on the initial LC values listed in Table 3. Once optimized, the optimized LC values as shown in Table 4 below were then obtained for the respective bandpass filters of multiplexer 700.

Bandpass filter 701	Values	Bandpass filter 702	Values
L_1^1	61.2 nH	L_1^2	98.8 nH
C_1^1	137.5 pF	C_1^2	40 pF
L_2^1	30.7 nH	L_2^2	58.4 nH
C_2^1	258 pF	C_2^2	394.4 pF
L_3^1	1.7 nH	L_3^2	20.9 nH
C_3^1	25.3 pF	C_3^2	90.6 pF

Bandpass filter 703	Values	Bandpass filter 704	Values
L_1^3	1.7 nH	L_1^4	26.6 nH
C_1^3	70.8 pF	C_1^4	351.5 pF
L_2^3	100 nH	L_2^4	16.3 nH
C_2^3	73.5 pF	C_2^4	101.8 pF
L_3^3	22.6 nH	L_3^4	3 nH
C_3^3	160.1 pF	C_3^4	114.7 pF

TABLE 4

[0040] The simulated input reflection coefficient of multiplexer 700 based on the optimized LC values listed in Table 4 is plotted in Figure 8a. It can be seen from this plot that the reflection coefficient S_{11} shows four operating frequencies centered at 110 MHz, 130 MHz, 150 MHz,

and 170 MHz where each center frequency has a -10 dB impedance bandwidth of approximately 2 MHz. The simulated transmission coefficient for each of the arms of multiplexer 700, i.e., S_{12} , S_{13} , S_{14} , S_{15} , are plotted in Figure 8b and these plots show that the transmission coefficients S_{12} to S_{15} have peaks at their respective operating frequencies. From these plots, it can also be observed that the performance of multiplexer 700 (where the bandpass filters are each based on a 3-stage LC ladder circuit) is comparable or similar with the performance of multiplexer 300 (where the bandpass filters are each based on a 2-stage LC ladder circuit).

[0041] In yet another embodiment of the present disclosure, a 3-stage LC ladder circuit with a capacitor C_3 connected in series between a series inductor and a parallel capacitor of a final stage of the 3-stage LC ladder circuit is illustrated in Figure 9 whereby this 3-stage LC ladder circuit may be used as any one of the bandpass filters of a four-way multiplexer. For the avoidance of doubt, the final stage of the 3-stage LC ladder circuit illustrated in Figure 9 comprises serial inductor L_3 and parallel capacitor C_3 whereby a node of parallel capacitor C_3 is electrically connected to output terminal 902. As shown, it can be seen that the 3-stage LC ladder circuit comprises of seven LC components (3 serial inductors, 1 serial capacitor and 3 parallel capacitors) and connects input terminal 901 to output terminal 902.

[0042] The transfer function $H(s)$ of the 3-stage LC ladder circuit bandpass filter shown in Figure 9 may then be defined as:

$$H(s) = \frac{V_{out}}{V_{in}} = \frac{1}{A} = \frac{1}{X(1 + C_3/C_S) + s^2 C_3 L_3 X + s C_3 Y}$$

$$X = 1 + s^2 L_1 C_1 + s C_2 (s L_2 + s^3 L_1 L_2 C_1 + s L_1)$$

$$Y = s L_2 + s^3 L_1 L_2 C_1 + s L_1 \quad \dots \text{equation (3)}$$

where $s = j\omega$.

[0043] When equation (2) is compared with equation (3), it can be noted that the only difference between these two equations is the term $(1 + C_3/C_S)$ that is found in equation (3). By introducing the serial capacitor C_S between the series inductor L_3 and the parallel capacitor C_3 of a final stage of the multi-stage LC ladder circuit, on a path connecting the input terminal and the first output terminal, this causes an additional resonant frequency to be introduced in

the passband of the bandpass filter of the multi-stage LC ladder circuit shown in Figure 9. In embodiments of the disclosure, this additional resonant frequency is tuned to be around the desired original frequency by tuning the serial capacitor C_s along with other inductor and capacitor components.

[0044] In other embodiments of the disclosure, the capacitor C_s may be connected in series between a series inductor and a parallel capacitor of a final stage of any multi-stage LC ladder circuit which comprises 3 or more stages. The objective of the capacitor C_s would similarly be to cause an additional resonant frequency to be introduced in the passband of the bandpass filter formed by the multi-stage LC ladder circuit.

[0045] With reference to Figure 10a, this figure illustrates a circuit diagram of four-way multiplexer 1000 in accordance with embodiments of the present disclosure where each arm of four-way multiplexer 1000 comprises a bandpass filter that may be implemented using a 3-stage LC ladder circuit. Multiplexer 1000 comprises an input terminal-1 that is connected to inputs of bandpass filters 1001, 1002, 1003 and 1004 resulting in a star connection, and each of these bandpass filters' outputs are connected to terminal-2, terminal-3, terminal-4 and terminal-5 respectively.

[0046] A Bode plot showing the simulated magnitude responses of bandpass filters 1001 - 1004 are illustrated in Figure 10b where plot 1011 represents the magnitude response of bandpass filter 1001 with a peak amplitude at 110 MHz, plot 1012 represents the magnitude response of bandpass filter 1002 with a peak amplitude at 130 MHz, plot 1013 represents the magnitude response of bandpass filter 1003 with a peak amplitude at 150 MHz, and plot 1014 represents the magnitude response of bandpass filter 1004 with a peak amplitude at 170 MHz. It can be seen from these plots that the introduction of the serial capacitor C_s to the final stage of each of the 3-stage LC ladder circuits has caused a second pole to be introduced adjacent to each of the poles of the respective bandpass filters 1001 – 1004. These plots show that a second peak occurs in the Bode plot magnitude of each of the bandpass filters with the center frequency of the bandpass filters being located between the two peaks. These two peaks are formed by the two resonant frequencies that occur closer to each other and they help in slightly increasing the bandwidth of the operating bands of the multiplexer.

[0047] Figure 11 illustrates a flowchart that sets out a process or a method for optimizing the design of multiplexer 1000 in accordance with embodiments of the present disclosure. Process 1100 begins at step 1102 with process 1100 choosing the four operating frequencies or center frequencies for each of the arms of multiplexer 1000: $f_1 = 110 \text{ MHz}$, $f_2 = 130 \text{ MHz}$, $f_3 = 150 \text{ MHz}$, $f_4 = 170 \text{ MHz}$ respectively.

[0048] At step 1104, process 1100 optimizes the transfer function of bandpass filter 301 such that a resonance occurs at center frequency f_1 . Process 1100 then obtains the optimized values of $L_1^1, L_2^1, L_3^1, C_1^1, C_2^1, C_3^1, C_5^1$ in the transfer function of bandpass filter 1001 at step 1112.

[0049] Process 1100 then performs the similar optimization process at step 1106 for the transfer function of bandpass filter 1002 such that a resonance occurs at center frequency f_2 , at step 1108 for the transfer function of bandpass filter 1003 such that a resonance occurs at center frequency f_3 , and at step 1110 for the transfer function of bandpass filter 1004 such that a resonance occurs at center frequency f_4 . The optimized LC values L_j^i, C_j^i ($i=2$ to 4 , $j=1, 2, 3$, s where the superscript 'i' denotes the arm number and subscript 'j' denote that position of the component in the bandpass filter) are then obtained for bandpass filter 1002 at step 1114, for bandpass filter 1003 at step 1116, and for bandpass filter 1004 at step 1118.

[0050] Once steps 1112 - 1118 have been completed, process 1100 then proceeds to step 1120. At step 1120, process 1100 will then optimize the performance of multiplexer 1000 as a whole to meet the required multiplexer response where the optimized LC values L_j^i, C_j^i ($i=1$ to 4 , $j=1, 2, 3$, s) are used as the initial LC values in each of the bandpass filters. Once step 1120 has been completed, process 1100 would have obtained the optimized LC values for multiplexer 1000 as a whole.

[0051] Process 1100 then proceeds to step 1122. At this step, process 1100 utilizes the optimized LC values obtained from step 1120 as the initial values for the optimization process that takes place at step 1122. In this optimization process, the ideal LC component values as obtained from step 1120 are laid out on a printed circuit board (PCB) and the PCB's layout losses are then taken into consideration during the optimization process that takes place at this step.

[0052] Process 1100 then proceeds to step 1142. At this step, process 1100 replaces the LC values obtained from step 1122 with corresponding s-parameters for each of the LC components and uses these s-parameter files for each of the LC components as the initial values for the optimization process that takes place at step 1124. In this optimization process, the s-parameter files of the LC components are used together with the PCB's layout losses to perform the final optimization process at this step to obtain the final optimized set of LC values for multiplexer 1000.

[0053] In a third example, for multiplexer 1000, bandpass filter 1001 was designed to have a peak amplitude at 110 MHz, bandpass filter 1002 was designed to have a peak amplitude at 130 MHz, bandpass filter 1003 was designed to have a peak amplitude at 150 MHz, and bandpass filter 1004 was designed to have a peak amplitude at 170 MHz. As a result, the values of the LC components of the respective bandpass filters was found to be as defined in Table 5 below.

Bandpass filter 1001	Values	Bandpass filter 1002	Values
L_1^1	101.8 nH	L_1^2	58.8 nH
C_1^1	58.4 pF	C_1^2	58.4 pF
L_2^1	66.5 nH	L_2^2	55.5 nH
C_2^1	300 pF	C_2^2	320 pF
L_3^1	148.5 nH	L_3^2	98.5 nH
C_3^1	81.6 pF	C_3^2	81.6 pF
C_S^1	19.4 pF	C_S^2	19.4 pF

Bandpass filter 1003	Values	Bandpass filter 1004	Values
L_1^3	40.8 nH	L_1^4	32.8 nH
C_1^3	58.4 pF	C_1^4	58.4 pF
L_2^3	40.5 nH	L_2^4	30.5 nH
C_2^3	280 pF	C_2^4	260 pF
L_3^3	88.5 nH	L_3^4	88.5 nH
C_3^3	81.6 pF	C_3^4	81.6 pF
C_S^3	16.4 pF	C_S^4	11.4 pF

TABLE 5

[0054] After an optimization process was performed on the multiplexer as whole (i.e., step 1120 of Figure 11), the LC values as shown in Table 6 were obtained for the respective bandpass filters of multiplexer 1000.

Bandpass filter 1001	Values	Bandpass filter 1002	Values
L_1^1	121.8 nH	L_1^2	150 nH
C_1^1	58.4 pF	C_1^2	24.3 pF
L_2^1	46.5 nH	L_2^2	102.5 nH
C_2^1	300 pF	C_2^2	11.1 pF
L_3^1	148.5 nH	L_3^2	28 nH
C_3^1	81.6 pF	C_3^2	66.4 pF
C_S^1	16.4 pF	C_S^2	50.2 pF

Bandpass filter 1003	Values	Bandpass filter 1004	Values
L_1^3	1.12 nH	L_1^4	68.3 nH
C_1^3	12.3 pF	C_1^4	48 pF
L_2^3	106.8 nH	L_2^4	20.2 nH
C_2^3	26.5 pF	C_2^4	258 pF
L_3^3	28 nH	L_3^4	24.2 nH
C_3^3	64.4 pF	C_3^4	93 pF
C_S^3	15.4 pF	C_S^4	48.2 pF

TABLE 6

[0055] The simulated input reflection coefficient of multiplexer 1000 based on the optimized LC values listed in Table 6 is plotted in Figure 12a. It can be seen from this plot that the reflection coefficient S_{11} shows four operating frequencies centered at 110 MHz, 130 MHz, 150 MHz, and 170 MHz where each center frequency has a -10 dB impedance bandwidth of approximately 4 MHz. Hence, it can be seen that the passbands of multiplexer 1000 has a larger bandwidth than the passbands of multiplexer 700. It should be noted that two valley points can be observed for each passband indicating that two resonance frequencies are

introduced closer to each other due to the introduction of C_s . Additionally, the -3 dB bandwidth of the transmission bands are at least 5.5 MHz which is higher than the passbands of multiplexer 300.

[0056] The simulated transmission coefficient for each of the arms of multiplexer 1000, i.e., S_{12} , S_{13} , S_{14} , S_{15} , are plotted in Figure 12b and these plots show that the transmission coefficients S_{12} to S_{15} have two peaks at their respective operating frequencies. From these plots, it can be observed that the first side lobe levels of the transmission coefficients are lower than -15 dB for all bands with the roll-off factor for the passbands being more than 2 dB/MHz.

[0057] The isolation coefficients for each of the arms of multiplexer 1000 (i.e., S_{23} , S_{24} , S_{25} , S_{34} , S_{35} , S_{45}) are plotted in Figure 12c where it can be seen that the minimum isolation level obtained between the output ports of each of the bandpass filters is about 17.8 dB at 150 MHz.

[0058] Figure 13a illustrates a top view of a circuit layout of multiplexer 1000 without a ring manifold feed in accordance with embodiments of the present disclosure. The substrate used in the design comprises an FR4 substrate having a height of 1.6 mm and $\epsilon_r = 4.4$ and $\tan\delta = 0.02$. The metal layer of the PCB, the surface mount inductors and capacitors, inner conductor pins of coaxial SMAs (Sub-Miniature version A) and ground vias are all indicated in the circuit layout. In this circuit layout, the total size of the circuit is 27mm x 27mm and the diameter of the vias are each 0.6mm. An isometric view of the bottom of multiplexer 1000 is illustrated in Figure 13b.

[0059] In order to include the effect of PCB substrate and metal losses, the circuit layout illustrated in Figures 13a and 13b are simulated using three-dimensional electromagnetic simulation software. The resulting S-parameter files are then included into a S-parameter circuit simulation software together with the optimized ideal LC values for each of the bandpass filters and all these values then taken into consideration during a further optimization process (i.e., step 1122 of Figure 11).

[0060] The simulated input reflection coefficient of multiplexer 1000 based on the effects of PCB loss and the further optimized LC values are plotted in Figure 14a. It can be seen from this plot that the input reflection coefficient shows a slight change in the bandwidth of the 2nd and 3rd bandpass filters which have center frequencies at 130 MHz and 150 MHz respectively. The simulated transmission coefficient for each of the arms of multiplexer 1000, i.e., S_{12} , S_{13} , S_{14} , S_{15} , are plotted in Figure 14b and these plots show that there is a drop in the peak values due to the losses introduced by the PCB's substrate and metal layers. It can be seen that the insertion loss observed across the bands are 0.6 dB, 0.37 dB, 0.24 dB, and 0.38 dB for the bandpass filters centered at 110 MHz, 130 MHz, 150 MHz and 170 MHz respectively.

[0061] The isolation coefficients for each of the arms of multiplexer 1000 (i.e., S_{23} , S_{24} , S_{25} , S_{34} , S_{35} , S_{45}) are plotted in Figure 14c where it can be seen that the minimum isolation level obtained between the output ports of each of the bandpass filters is about 12.6 dB. The simulated output reflection coefficient for each of the arms of multiplexer 1000, i.e., S_{22} , S_{33} , S_{44} , S_{55} , are plotted in Figure 14d and it can be seen that the output reflection coefficients for the respective passbands are low.

[0062] Based on the further optimized ideal LC values obtained for each of the bandpass filters, corresponding SMD component values are then selected accordingly whereby if components with exact values are not available, then component values with relatively closer values are selected (i.e., step 1124 of Figure 11). SMD inductor components are also selected such that they have low DC resistance so that the amount of insertion loss introduced by these components will be minimal. The selected SMD components values are as set out in Table 7 below.

Bandpass filter 1001	Values	Bandpass filter 1002	Values
L_1^1	130 nH	L_1^2	31 nH
C_1^1	43 pF	C_1^2	33 pF
L_2^1	68 nH	L_2^2	62 nH
C_2^1	300 pF	C_2^2	75 pF
L_3^1	130 nH	L_3^2	56 nH
C_3^1	100 pF	C_3^2	120 pF
C_S^1	18 pF	C_S^2	47 pF

Bandpass filter 1003	Values	Bandpass filter 1004	Values
L_1^3	43 nH	L_1^4	120 nH
C_1^3	10 pF	C_1^4	16 pF
L_2^3	10 nH	L_2^4	115 nH
C_2^3	100 pF	C_2^4	130 pF
L_3^3	47 nH	L_3^4	23 nH
C_3^3	110 pF	C_3^4	120 pF
C_s^3	36 pF	C_s^4	56 pF

TABLE 7

[0063] The simulated input reflection coefficient of multiplexer 1000 based on simulated S parameter data of the layout and measured S2P files of the commercially available LC components are plotted in Figure 15a. It can be seen from this plot that there are four operating passbands centered at 110 MHz, 130 MHz, 150 MHz and 170 MHz. The simulated transmission coefficient for each of the arms of multiplexer 1000, i.e., S_{12} , S_{13} , S_{14} , S_{15} , are plotted in Figure 15b and these plots show that the insertion loss observed across the bands are 5.9 dB, 3.5 dB, 5.2 dB, and 6.8 dB for the bandpass filters centered at 110 MHz, 130 MHz, 150 MHz and 170 MHz respectively.

[0064] The isolation coefficients for each of the arms of multiplexer 1000 (i.e., S_{23} , S_{24} , S_{25} , S_{34} , S_{35} , S_{45}) are plotted in Figure 15c where it can be seen that the minimum isolation level obtained between the output ports of each of the bandpass filters is about 18.2 dB over the frequency range of 100-200 MHz. The simulated output reflection coefficient for each of the arms of multiplexer 1000, i.e., S_{22} , S_{33} , S_{44} , S_{55} , are plotted in Figure 15d and it can be seen that the output reflection coefficients for the respective passbands are low.

[0065] In yet another embodiment of the disclosure, a two-way multiplexer comprising of a first bandpass filter having a first passband and a second bandpass filter having a second passband is described in this disclosure. In this embodiment, the first bandpass filter has a multi-stage LC ladder circuit connecting an input terminal to a first output terminal and a first capacitor connected in series between a series inductor and a parallel capacitor of a final stage of the first multi-stage LC ladder circuit on a path connecting the input terminal and the first

output terminal, wherein the first capacitor has a resonant frequency located within the first passband. As for the second bandpass filter, this filter has a second multi-stage LC ladder circuit connecting the input terminal to a second output terminal, and a second capacitor connected in series between a series inductor and a parallel capacitor of a final stage of the second multi-stage LC ladder circuit on a path connecting the input terminal and the second output terminal, wherein the second capacitor has a resonant frequency located within the second passband. The circuit diagram of the first and second bandpass filters are similar to the 3-stage LC ladder circuit illustrated in Figure 9. It should also be noted that the resonant frequency of the first capacitor may introduce an additional pole in the first passband, and the resonant frequency of the second capacitor may introduce an additional pole in the second passband and the introduction of these additional poles in the respective passbands causes the size of the passbands to increase accordingly.

[0066] In yet another embodiment of the disclosure, a method for forming a multiplexer on a microstrip circuit is disclosed. The method comprises the steps of forming a first and a second bandpass filter on the microstrip circuit where the first bandpass filter has a first passband, and the second bandpass filter has a second passband. The formed first bandpass filter comprises a first multi-stage LC ladder circuit formed on the microstrip circuit connecting an input terminal to a first output terminal, and a first capacitor connected in series between a series inductor and a parallel capacitor of a final stage of the first multi-stage LC ladder circuit on a path connecting the input terminal and the first output terminal, wherein the first capacitor has a resonant frequency located within the first passband. The formed second bandpass filter has a second multi-stage LC ladder circuit formed on the microstrip circuit connecting the input terminal to a second output terminal and a second capacitor connected in series between a series inductor and a parallel capacitor of a final stage of the second multi-stage LC ladder circuit on a path connecting the input terminal and the second output terminal, wherein the second capacitor has a resonant frequency located within the second passband.

[0067] In a further embodiment, a third bandpass filter having a third passband is formed on the microstrip circuit. The formed third bandpass filter has a third multi-stage LC ladder circuit formed on the microstrip circuit connecting the input terminal to a third output terminal, and a third capacitor connected in series between a series inductor and a parallel capacitor of a final stage of the third multi-stage LC ladder circuit on a path connecting the input terminal

and the third output terminal, wherein the third capacitor has a resonant frequency located within the third passband.

[0068] In a further embodiment, a fourth bandpass filter having a fourth passband is formed on the microstrip circuit, the fourth bandpass filter having a fourth multi-stage LC ladder circuit formed on the microstrip circuit connecting the input terminal to a fourth output terminal, and a fourth capacitor connected in series between a series inductor and a parallel capacitor of a final stage of the fourth multi-stage LC ladder circuit on a path connecting the input terminal and the fourth output terminal, wherein the fourth capacitor has a resonant frequency located within the fourth passband.

[0069] Numerous other changes, substitutions, variations, and modifications may be ascertained by the skilled in the art and it is intended that the present application encompass all such changes, substitutions, variations, and modifications as falling within the scope of the appended claims.

CLAIMS:

1. A multiplexer for very high frequency applications comprising:
 - a first bandpass filter having a first passband, the first bandpass filter comprising:
 - a first multi-stage LC ladder circuit connecting an input terminal to a first output terminal;
 - a first capacitor connected in series between a series inductor and a parallel capacitor of a final stage of the first multi-stage LC ladder circuit on a path connecting the input terminal and the first output terminal, wherein the first capacitor has a resonant frequency located within the first passband; and
 - a second bandpass filter having a second passband, the second bandpass filter comprising:
 - a second multi-stage LC ladder circuit connecting the input terminal to a second output terminal;
 - a second capacitor connected in series between a series inductor and a parallel capacitor of a final stage of the second multi-stage LC ladder circuit on a path connecting the input terminal and the second output terminal, wherein the second capacitor has a resonant frequency located within the second passband.
2. The multiplexer according to claim 1 wherein the resonant frequency of the first capacitor introduces an additional pole in the first passband, and the resonant frequency of the second capacitor introduces an additional pole in the second passband.
3. The multiplexer according to claims 1 or 2, further comprising:
 - a third bandpass filter having a third passband, the third bandpass filter comprising:
 - a third multi-stage LC ladder circuit connecting the input terminal to a third output terminal;
 - a third capacitor connected in series between a series inductor and a parallel capacitor of a final stage of the third multi-stage LC ladder circuit on a path connecting the input terminal and the third output terminal, wherein the third capacitor has a resonant frequency located within the third passband; and
 - a fourth bandpass filter having a fourth passband, the fourth bandpass filter comprising:
 - a fourth multi-stage LC ladder circuit connecting the input terminal to a fourth output terminal;

a fourth capacitor connected in series between a series inductor and a parallel capacitor of a final stage of the fourth multi-stage LC ladder circuit on a path connecting the input terminal and the fourth output terminal, wherein the fourth capacitor has a resonant frequency located within the fourth passband.

4. The multiplexer according to claim 3 wherein the resonant frequency of the third capacitor introduces an additional pole in the third passband, and the resonant frequency of the fourth capacitor introduces an additional pole in the fourth passband.
5. The multiplexer according to any one of claims 1 to 4 wherein each multi-stage LC ladder circuit comprises a 3-stage LC ladder circuit.
6. The multiplexer according to claim 3 wherein the final stage of each of the multi-stage LC ladder circuits comprises a 3rd stage of each of the multi-stage LC ladder circuits.
7. The multiplexer according to any one of claims 1 to 6, wherein all the passbands of all the bandpass filters are within a very high frequency range (VHF).
8. The multiplexer according to any one of claims 1 to 7, wherein all the inductors and capacitors comprise surface mount devices.
9. The multiplexer according to any one of claims 1 to 8, wherein the first passband has a centre frequency of 110 MHz, the second passband has a centre frequency of 130 MHz, the third passband has a centre frequency of 150 MHz, and the fourth passband has a centre frequency of 170 MHz.
10. A method for forming a multiplexer for very high frequency applications on a microstrip circuit, the method comprising the steps of:
forming a first bandpass filter having a first passband on the microstrip circuit, the first bandpass filter comprising:
a first multi-stage LC ladder circuit formed on the microstrip circuit connecting an input terminal to a first output terminal,
a first capacitor connected in series between a series inductor and a parallel capacitor of a final stage of the first multi-stage LC ladder circuit on a path connecting the input

terminal and the first output terminal, wherein the first capacitor has a resonant frequency located within the first passband; and
forming a second bandpass filter having a second passband on the microstrip circuit, the second bandpass filter comprising:

a second multi-stage LC ladder circuit formed on the microstrip circuit connecting the input terminal to a second output terminal;

a second capacitor connected in series between a series inductor and a parallel capacitor of a final stage of the second multi-stage LC ladder circuit on a path connecting the input terminal and the second output terminal, wherein the second capacitor has a resonant frequency located within the second passband.

11. The method according to claim 10 wherein the resonant frequency of the first capacitor introduces an additional pole in the first passband, and the resonant frequency of the second capacitor introduces an additional pole in the second passband.

12. The method according to claims 10 or 11, further comprising the steps of:

forming a third bandpass filter having a third passband on the microstrip circuit, the third bandpass filter comprising:

a third multi-stage LC ladder circuit formed on the microstrip circuit connecting the input terminal to a third output terminal;

a third capacitor connected in series between a series inductor and a parallel capacitor of a final stage of the third multi-stage LC ladder circuit on a path connecting the input terminal and the third output terminal, wherein the third capacitor has a resonant frequency located within the third passband; and

forming a fourth bandpass filter having a fourth passband on the microstrip circuit, the fourth bandpass filter comprising:

a fourth multi-stage LC ladder circuit formed on the microstrip circuit connecting the input terminal to a fourth output terminal;

a fourth capacitor connected in series between a series inductor and a parallel capacitor of a final stage of the fourth multi-stage LC ladder circuit on a path connecting the input terminal and the fourth output terminal, wherein the fourth capacitor has a resonant frequency located within the fourth passband.

13. The method according to claim 12 wherein the resonant frequency of the third capacitor introduces an additional pole in the third passband, and the resonant frequency of the fourth capacitor introduces an additional pole in the fourth passband.
14. The method according to any one of claims 10 to 13 wherein each multi-stage LC ladder circuit comprises a 3-stage LC ladder circuit.
15. The method according to claim 12 wherein the final stage of each of the multi-stage LC ladder circuits comprises a 3rd stage of each of the multi-stage LC ladder circuits.
16. The method according to any one of claims 10 to 15, wherein all the passbands of all the bandpass filters are within a very high frequency range (VHF).
17. The method according to any one of claims 10 to 16, wherein all the inductors and capacitors comprise surface mount devices.
18. The method according to any one of claims 10 to 17, wherein the first passband has a centre frequency of 110 MHz, the second passband has a centre frequency of 130 MHz, the third passband has a centre frequency of 150 MHz and the fourth passband has a centre frequency of 170 MHz.