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(54) SUPERCONDUCTING SWITCH SYSTEM

SUPRALEITENDES SCHALTSYSTEM

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Description

[0001] This application claims priority from U.S. Patent Application No. 14/564996, filed 9 December 2014.

TECHNICAL FIELD

[0002] The present invention relates generally to superconducting circuits, and more particularly to a superconducting switch system.

BACKGROUND

[0003] Conventional microwave mechanical, electromechanical, and electronic switches may not be compatible with on-chip integration and cryogenic operation of superconducting electronic circuits, because of incompatible fabrication processes and high power dissipation. Likewise, tunable filters that are commonly realized by use of either active components such as voltage-variable capacitors i.e. varactors, mechanical drivers, or ferroelectric and ferrite materials, are not easily controllable by signal levels that can be generated with single flux quantum (SFQ) technologies, and many are not operable at cryogenic temperatures. While superconducting microwave filters, both fixed and tunable, have been previously realized using both high temperature and low temperature superconductors, their use in switching applications suffered from high return loss, limited usable bandwidth, and poor out-of-band off-state isolation.

[0004] Shimazu, Y., et al. describe in their article "Characteristics of Switchable Superconducting Flux Transformer with DC Superconducting Quantum Interference Device" (Japanese Journal of Applied Physics, Vol. 46, No. 4A, 2007, pp 1478-1481) that they have investigated the flux transfer characteristics of a switchable flux transformer comprising a superconducting loop and a DC superconducting quantum interference device (DC-SQUID). This system can be used to couple multiple flux qubits with a controllable coupling strength, its characteristics were measured using a flux input coil and a DC-SQUID for readout coupled to the transformer loop in a dilution refrigerator. The observed characteristics are consistent with the calculation results. They demonstrated the reversal of the slope of die characteristics and the complete switching off of the transformer, which are useful features for its application as a controllable coupler for flux qubits.

[0005] US 5,912,472 discloses a switchable planar high frequency resonator and filter. A portion of the superconductor in a planar resonator made from that superconductor can be switched into the normally conducting state so that its effective lateral dimensions are changed. The advantage of the planar resonator is that a switchable filter can be constructed very economically based on its planar resonator structure.

[0006] Avenhaus, B., et al. demonstrate in their article "Switched YBa2Cu3O7 lumped element bandstop filter" (Electronic Letters, 8th June 1995, Vol. 31 No.12) the switching capability of a simple high temperature superconducting (HTS) lumped element bandstop filter. A bias current of the order of the critical current of the HTS material is necessary to switch the filter response from high to low attenuation at the stop-band frequency. A simple theoretical model to describe the ON and OFF states is presented.

Martens, J. S., et al describe in their article "HTS-based switched filter banks and delay lines" (IEEE Transactions on Applied Superconductivity, Vol. 3, No. 1, March 1993) that switched filter banks and switched delay lines are useful for a number of communications and other applications. Since YBaCuO and TICaBaCuO filters and delay lines have shown significant performance enhancements over their conventional counterparts, a purely superconducting version of the switched assemblies could result in additional improvements. A thermal switch has been developed that provides good isolation and insertion loss with adequate switching times to allow a monolithic approach to the switched lines and filters banks.

[0007] Huang, F., et al. describe in their article "Lumped-element switchable superconducting filters" (IEE Proceedings: Microwaves, Antennas and Propagation, Vol. 146, No. 3, June 1999) a switchable superconducting band-stop filter consisting of a series of LC resonators. Each resonator can be switched on or off using a bias current to control the superconducting-to-normal resistance transition. The bandwidth of the filter can thus be varied in steps.

SUMMARY

[0008] An apparatus and a method according to the invention are defined in the appended independent claims 1 and 7. Preferred embodiments are defined in the dependent claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009]

FIG. 1 illustrates an example of a superconducting switch system.

FIG. 2 illustrates another example of a superconducting switch system.

FIG. 3 illustrates a graph of transmission and reflection scattering S-parameters versus frequency of the simulated response of the filter of FIG. 2 in the 'ON' state.

FIG. 4 illustrates a graph of transmission and reflection scattering S-parameters versus frequency of the simulated response of the filter of FIG. 2 in the 'OFF' state.

FIG. 5 illustrates a WRSpice simulation that outputs a graph of an output response versus time for the filter switch of FIG. 2.

FIG. 6 illustrates a graph of signal transmission through the switch versus frequency at a drive power of -90 dBm.

FIG. 7 illustrates a graph of power of signal transmission through the switch in the 'ON' state at a single frequency as a function of input power.

FIG. 8 illustrates a schematic diagram of a generic coupled resonator filter using inductive K-inverters.

FIG. 9 illustrates a block schematic diagram of another example of a superconducting switch system.

FIG. 10 illustrates a graph of transmission and reflection scattering S-parameters versus frequency of the simulated response of the filter of FIG. 9 in the 'ON' state.

FIG. 11 illustrates a graph of transmission and reflection scattering S-parameters versus frequency of the simulated response of the filter of FIG. 9 in the 'OFF' state.

FIG. 12 illustrates a schematic of a 3rd order Chebyshev prototype that can be employed in a wide-bandwidth switch.

FIG. 13 illustrates a graph of transmission and reflection S-parameters versus frequency of the simulated response of a filter of FIG. 12 configured as a wide-bandwidth switch in the 'ON' state.

FIG. 14 illustrates a graph of transmission and reflection S-parameters versus frequency of the simulated response of the filter of FIG. 12 configured as a wide-bandwidth switch in the 'OFF' state.

FIG. 15 illustrates a method for providing a superconducting switch system.

DETAILED DESCRIPTION

[0010] The present disclosure relates generally to superconducting circuits, and more particularly to a superconducting switch system. A superconducting switch system can include a variable inductance coupler (also referred to as variable inductance coupling element) that couples and decouples sections of a filter network. In one example, the variable inductance coupler is an element of a Superconducting Quantum Interference Device (SQUID). The SQUID can include a first inductor and a second inductor coupled to opposite sides of a variable inductance coupler all arranged in a superconducting loop. The variable inductance coupler can be, for example, a Josephson junction that has an inductance that can be varied based on a current flowing through the Josephson junction. The current flowing through the Josephson junction can be induced based on a flux applied to the SQUID by, for example, a bias element.

[0011] In one example, the Josephson junction can have a first inductance when no current or a low current is induced in the SQUID, and a second inductance when a current or a higher current is induced in the SQUID that is at a predetermined threshold. The predetermined threshold current induced in the SQUID can be a result of applying a flux to the SQUID from a bias element, for example, greater than about 0.1 Φ_0 and less than about 0.45 Φ_0, where Φ_0 is equal to a flux quantum. The first inductance can be the passive inductance of a Josephson junction (e.g., $\hbar/2e * 1/I_c$, where $\hbar$ is the reduced Planck's constant, e is the elementary charge and I_c is the critical current of the Josephson junction) when no induced current flows through the Josephson junction. This allows for coupling between a first section of a filter network and a second section of the filter network, such that the superconducting switch system is in an 'ON' state allowing passing of a desired bandwidth portion of an input signal. The second inductance (e.g., large inductance value) can provide decoupling between the first and second section of the filter network such that the superconducting switch system is in an 'OFF' state suppressing the input signal.

[0012] FIG. 1 illustrates an example of a superconducting switch system 10. The superconducting switch system 10 can be implemented in any of a variety of superconducting circuit systems to provide switch control of an input signal SIG_{IN}. As an example, the input signal SIG_{IN} can be a microwave signal that is implemented in a control scheme for a quantum circuit, such as performing a gate or a readout operation on a qubit. As another example, the input signal SIG_{IN} can be a signal pulse or another type of signal. The superconducting switch system 10 can provide a band-pass filtered output signal SIG_{OUT} that can corresponds to a desirable portion (e.g., particular frequency bandwidth) of the input signal SIG_{IN} when the superconducting system is an 'ON' state (i.e., pass state). Additionally, all of the spectrum of the input signal SIG_{IN} can be suppressed or blocked such that none of the desired portion of the input signal SIG_{IN} is provided as the output signal when in an 'OFF' state (i.e., suppressed state). The superconducting switch system 10 includes a filter network 12 having one or more impedance components (i.e., capacitors, resistors, inductors) for configuring an input portion of the filter network 12 as one or more input resonators, and an output portion of the filter network 12 as one or more output resonators. At least one of the one or more input resonators and output resonators can be implemented as short-terminated transmission line stubs.

[0013] The filter network 12 also includes a SQUID 18 with a variable inductance coupler (e.g., Josephson junction). The SQUID 18 also includes one or more components that operate both as components of a superconducting loop of the SQUID 18, and impedance components of the one or more input and/or the one or more output resonators. A bias element 16 is inductively coupled to the SQUID 18 to induce current in the SQUID 18. A change in the current induced in the SQUID 18 can result in a change in inductance of the variable inductance coupler.

[0014] For example, the inductance of the variable inductance coupling element can be changed to a first inductance state, for example, when substantially no induced current or a low induced current is induced in the superconducting loop of the SQUID 18, such that the inductance of the variable inductance coupling element is low. When the variable inductance coupling element is in the first inductance state, the first portion of the network is coupled to the second portion of the filter network and the superconducting switch system 10 is in the 'ON' state. Alternatively, the inductance of the variable inductance coupling element can be changed to a second inductance state, for example, when a substantial current (e.g., caused by induction of a substantial fraction of half of a flux quantum in the SQUID) is induced in the superconducting loop of the SQUID 18, such that the inductance of the variable inductance coupling element is high. When the variable inductance coupling element is in a high inductance state, the first portion of the network is decoupled from the second portion of the filter network and the superconducting switch system 10 is in the 'OFF' state. The bias element 16 can be controlled by a switch controller 14 that controls an amount of bias current to the bias element 16, which in turn, controls an amount of flux applied to the SQUID and an amount of current induced in the SQUID 18 and flowing through the variable inductance coupler.

[0015] FIG. 2 illustrates an example of a superconducting switch system 30 having a filter network 32 configured as a single-pole-single-throw (SPST) microwave switch. In the example of FIG. 2, a two-section coupled-resonator band-pass filter is embedded with a radio frequency SQUID 34 having a tunable inductance coupler in the form of a Josephson junction J_1. The SQUID 34 can include a first inductor L_1 and a second inductor L_2 coupled to opposite sides of the Josephson junction J_1 with opposing ends of the first and second inductor coupled to a common potential to form a superconducting loop. The first inductor L_1 can be employed to form an input pole along with other components of an input resonator of the band-pass filter, and the second inductor L_2 can be employed to form an output pole along with other components of an output resonator of the band-pass filter. In the present example, the input resonator is formed of a first capacitor C_1, an inductor L_{S1} and the first inductor L_1.

[0016] An input signal (SIG_{IN}) is provided at an input terminal (IN) to the input resonator through an input coupling capacitor C_{IC}. The output resonator is formed of a second capacitor C_1, an inductor L_{S2} and the second inductor L_2. An output signal (SIG_{OUT}) can be provided at an output terminal (OUT) from the output resonator through an output coupling capacitor C_{OC}. The input coupling capacitor C_{IC} and the output coupling capacitor C_{OC} assure that the current flowing through the superconducting loop of the SQUID 34 is isolated such that it remains in the SQUID 34 and does not flow to other parts of the circuit.

[0017] The Josephson junction J_1 has an inductance that can be varied based on the induced current flowing through the Josephson junction J_1. A bias inductor L_B is inductively coupled to the SQUID 34 to apply flux to the SQUID 34 and to induce current in the SQUID 34. The bias inductor L_B can be controlled by a switch controller 36 that controls an amount of bias current I_B to the bias inductor LB, which in turn, controls an amount of induced current I_{IND} in the SQUID 34 and flowing through the Josephson junction J1. The Josephson junction J_1 can have a first inductive state when no current or a low current is induced in the SQUID, such that the input resonator is coupled to the output resonator of the filter network 32 through the Josephson junction J1. The Josephson junction J1 can have a second inductive state such when a predetermined higher current is flowing through the Josephson junction J1. The second inductive state is a high inductance that essentially decouples the input resonator from the output resonator and suppresses the input signal from being provided as an output signal.

[0018] In the example of FIG. 2, when a first flux is applied to the RF SQUID loop 34 defined by Josephson junction J1 and inductors L_1 and L_2, a first induced current flows through the junction J1 resulting in junction J1 having a first inductance value. This first inductance state can be designed such that the circuit as a whole functions as a band-pass filter with low insertion loss in its pass-band. The superconducting switch system 10 is then said to be in an 'ON' state. When a second flux is applied to the RF SQUID loop, a second higher current is induced in the junction J1 causing its inductance value to increase, driving the inductive coupling between the input and output stages to zero. The two sections of the band-pass filter formed from the input resonator and the output resonator are then decoupled from each other, such that the filter circuit as a whole has a high return loss at all frequencies because the filter becomes reflective. The superconducting switch system 30 is then said to be in an 'OFF' state. In one example, the first applied flux is at or close to zero, and the second applied flux is an appreciable fraction of half a flux quantum (e.g., about .1 Φ_0 to about .45 Φ_0).

[0019] FIGS. 3-4 illustrate graphical responses of simulations of the filter switch 32 of FIG. 2 using Agilent Advanced Design System (ADS). In this simulation, the Josephson junction J1 is treated as a linear inductor corresponding to its Josephson inductance at low drive power. The simulated component values are $L_{S1}=L_{S2}=60$ pH, $L_1=L_2=169$ pH, $C_1=C_2=1.19$ pF, $C_{IC}=C_{OC}=0.659$ pF, and the inductance corresponding to the junction $L_{J1}=375$pH. FIG. 3 illustrates a graph 40 of gain versus frequency showing S_{21} and S_{11} of the filter switch 32 in the 'ON' state, showing a 2 GHz pass-band centered about 10 GHz. The S_{21} parameter is shown in the signal transmission plot 42 and the S_{11} parameter is shown in the signal reflection plot 41. The filter switch 32 is then turned to the 'OFF' state by applying a predetermined flux to the RF SQUID loop, causing the inductance of junction J_1 to increase. The increasing effective inductance of the RF SQUID is modeled in a graph 45 illustrated in FIG. 4, which illustrates gain versus frequency, by raising the value of the junction inductance by a factor of 30. The S_{21} parameter is shown in the signal transmission plot 46 and the S_{11} parameter is shown in the signal reflection plot 47. An overall suppression of the S_{21} parameter, and in particular a 20 dB reduction of the transmission in the pass-band is realized.

[0020] FIG. 5 illustrates a WRSpice simulation that outputs a graph 50 of an output response versus time for the filter switch 32 of FIG. 2. All component values are the same as indicated above. Flux bias is applied to the RF SQUID by the current I_b and the bias component L_B via the switch controller 36. The input waveform is a 10 GHz sinusoid at a power of -120 dBm, the flux bias waveform 54 is piecewise linear in shape, and the voltage at the load termination (filter output) is shown as output waveform 52. As shown, in response to a flux bias sweep from 0 to 0.37 Φ_0, the output voltage changes by a factor of over 80, corresponding to over 30 dB switch ON/OFF ratio.

[0021] A harmonic-balance simulation was also performed in ADS on the circuit of FIG. 2, treating the Josephson junction as a nonlinear inductor. This simulation captures the power dependence of the switch performance expected in circuits containing Josephson junctions. FIG. 6 illustrates a graph 60 of signal transmission through the switch versus frequency at a drive power of -90 dBm. FIG. 7 illustrates a graph 62 of power of signal transmission through the switch in the 'ON' state at a single frequency as a function of input power as well as the large-amplitude S_{21}. The simulation as illustrated in FIG. 6 indicates that the switch can handle input powers up to -90 dBm without degradation to its 'ON' state response. The off state isolation begins to degrade at approximately -80 to -85 dBm according to transient analysis of the circuit model. The applied flux at the 'OFF' state can be adjusted to improve switch performance at these power levels.

[0022] The utilization of an RF SQUID embedded in a filter network to provide a superconducting switch system has been illustrated for one particular example. However, the utilization of an RF SQUID embedded in a filter network to provide a superconducting switch system can be employed in a variety of different filter topologies. For example, a lumped-element, coupled-resonator topology, can be employed where resonators having a frequency that coincides with the center frequency of the filter are coupled via admittance (J) or impedance (K) inverters, and the coupling coefficients of the inverters are related to tabulated filter prototypes to realize a desired response (e.g. Chebyshev, max-flat, etc.). At least one of the inverters can be implemented as an inductive network having a "pi" circuit topology. The series inductor of the pi-section inverter can be replaced with a Josephson junction so that the inverter becomes an RF SQUID.

[0023] For example, FIG. 8 illustrates a schematic diagram of a generic coupled resonator filter 70 using inductive K-inverters. The circuit components can be computed according to tabulated filter prototypes to give a desired response. The circuit 70 of FIG. 8 can be modified by commuting the series inductors and capacitors, forming T-networks of inductors between each capacitor. The T-networks can then be transformed to pi-networks to integrate the RF SQUID design, replacing at least one of the resulting series inductors with a Josephson junction.

[0024] As an example, a circuit schematic of another example of a superconducting switch system 80 is shown in FIG. 9 for the filter type of FIG. 8 with an order of 2, where an RF SQUID loop 84 is formed by junction J_A and inductors L_A and L_B. The inductor L_A can be employed to form an input pole of an input resonator along with inductor L_{H1} and capactitor C_A. The inductor L_B can be employed to form an output pole of an output resonator along with inductor L_{H2} and capactitor C_B. An input signal (SIG_{IN}) is provided at an input terminal (IN) to the input resonator through an input coupling inductor L_{J1}. An output signal (SIG_{OUT}) can be provided at an output terminal (OUT) from the output resonator through an output coupling inductor L_{J2}. The capacitor C_A and the capacitor C_B also act as coupling capacitors to isolate the induced current that runs through the superconducting loop of the RF SQUID 84 from other parts of the circuit.

[0025] A bias inductor L_{B2} is inductively coupled to the SQUID 84 to induce current in the SQUID 84. The bias inductor L_{B2} can be controlled by a switch controller 86 that controls an amount of bias current I_{B2} to the bias inductor L_{B2}, which in turn, controls an amount of induced current I_{IND} in the SQUID 84 and flowing through the Josephson junction J_A. The Josephson junction J_A has an inductance that can be varied based on the induced current flowing through the Josephson junction J_A. The Josephson junction J_A can have a first inductance state when no current or a low current is flowing through the SQUID 84, such that the desired portion of the input signal passes through the filter network 82 through the Josephson junction J_A to be provided as an output signal. The Josephson junction J_A can have a second inductance state that essentially decouples the input portion of the filter network 82 from the output portion of the filter network 82 suppressing the input signal from being provided as an output signal. In this particular example, the circuit parameters are $L_{H1}=L_{H2}=104pH$, $L_{J1}=L_{J2}=46.0pH$, $L_A=L_B=132pH$, $C_A=C_B=1.74pF$, and the junction effective inductance $L_{JA}=566pH$ corresponding to a critical current $I_0=0.58\mu A$. FIG. 10 illustrates a graph 90 of gain versus frequency of the simulated response of this filter in the 'ON' state. The S_{21} parameter is shown in the signal transmission plot 92 and the S_{11} parameter is shown in the signal reflection plot 91. FIG. 11 illustrates a graph 95 of gain versus frequency of the simulated response of this filter in the 'OFF' state. The S_{21} parameter is shown in the signal transmission plot 96 and the S_{11} parameter is shown in the signal reflection plot 97.

[0026] As another example, a 40% bandwidth switch 100 can be provided based on a 3rd order Chebyshev prototype, having the topology shown in FIG. 12. Inductor L1 in FIG. 12 can be replaced with a Josephson junction, and an RF SQUID is then formed by the combination of L1 and the shunt inductances of resonators PLC8 and PLC 9. FIG. 13 shows a graph 110 of the results of an S-parameter simulation of this design in an 'ON' state with the Josephson junction being approximated by a linear inductor. The S_{21} parameter is shown in the signal transmission plot 111 and the S_{11} parameter is shown in the signal reflection plot 112. FIG. 14 shows a graph 120 of the results of an S-parameter simulation of this design in an 'OFF' state with the Josephson junction being approximated by a linear inductor. The S_{21} parameter is shown in the signal transmission plot 121 and the S_{11} parameter is shown in the signal reflection plot 122.

[0027] In summary, an RF SQUID tunable inductance coupler can be embedded in a coupled-resonator band-pass filter to implement a microwave switch, with better than 20 dB on/off ratio, up to 40% bandwidth, and input powers up to -85 dBm. The switch is actuated by application of flux to the RF SQUID in a manner that is compatible with SFQ control.

[0028] In view of the foregoing structural and functional features described above, a methodology in accordance with various aspects of the present invention will be better appreciated with reference to FIG. 15. While, for purposes of simplicity of explanation, the methodology of FIG. 15 is shown and described as executing serially, it is to be understood and appreciated that the present invention is not limited by the illustrated order, as some aspects could, in accordance with the present invention, occur in different orders and/or concurrently with other aspects from that shown and described herein. Moreover, not all illustrated features may be required to implement a methodology in accordance with an aspect of the present invention.

[0029] FIG. 15 illustrates a method 150 for providing a superconducting switch system. The methodology begins at 152, where a desired pass-band output is determined for passing an input signal through a switch as an output signal or suppressing the input signal from passing to the output of the switch. At 154, a desired band-pass filter topology is determined for providing a superconducting switch. As previously discussed, a variety of different filter topologies can be selected from to provide a superconducting switch system based on a desired pass-band output response. At 156, an RF SQUID insertion point is determined based on the selected filter topology. The methodology then proceeds to 158.

[0030] At 158, one or more input resonators and one or more output resonator component values are selected to provide the desired pass-band output based on the determined pass-band filter topology and RF SQUID insertion point. This includes assuring that the resonators include isolation capacitors to ensure that the current flowing through the SQUID does not flow into other parts of the circuit. The SQUID can include a first and second inductor coupled to opposite sides of a variable inductance coupling element (e.g., Josephson junction). At 160, the RF SQUID component values are determined based on the one or more output resonator component values and the desired pass-band output constrained by assuring the SQUID linear inductance does not exceed the inductance of the variable inductance element.

[0031] Assuring that the SQUID linear inductance does not exceed the inductance of the variable inductance element, ensures that the potential of the RF SQUID is monostable. At 162, the superconducting switch system is built including the microwave switch with the above selected components, a bias inductor and a switch controller to drive the bias inductor into inducing a current in the SQUID that can change a value in the variable inductance coupling element between a pass state for passing a desired pass-band of an input signal to a suppressed state for suppressing a the input signal.

[0032] What have been described above are examples of the invention. It is, of course, not possible to describe every conceivable combination of components or methodologies for purposes of describing the invention, but one of ordinary skill in the art will recognize that many further combinations and permutations of the invention are possible. Accordingly, the invention is intended to embrace all such alterations, modifications, and variations that fall within the scope of this application, including the appended claims.

Claims

1. A superconducting switch system (10, 30, 80) for providing switch control of an input signal (SIG_{IN}), comprising:

a filter network (12, 32, 82) having an input portion and an output portion, wherein the input portion comprises one

or more input resonators formed of a first capacitor (C_1, C_A), an inductor (L_{S1}, L_{H1}), and a first inductor (L_1, L_A), and wherein the output portion comprises one

or more output resonators formed of a second capacitor (C_2, C_B), another inductor (L_{S2}, L_{H2}), and a second inductor (L_2, L_B);

a Josephson junction (J_1, J_A) that couples the input portion to the output portion, the Josephson junction (J_1, J_A) having, in an ON state of the superconducting switch system, a first inductance state that allows a desired bandwidth portion of the input signal (SIG_{IN}) to pass from the input portion to the output portion as an output signal (SIG_{OUT}), and in an OFF state of the superconducting switch system, a second inductance state that suppresses the desired bandwidth portion of the input signal (SIG_{IN}) from passing from the input portion to the output portion wherein the Josephson junction (J_1, J_A)

is coupled on a first end to the first inductor (L_1, L_A) and on a second end to the second inductor (L_2, L_B), such that the first inductor (L_1, L_A), the Josephson junction (J_1, J_A) and the second inductor (L_2, L_B) form a Superconducting Quantum Interference Device, SQUID, (34, 84); and a switch controller (14, 36, 86) configured to control the switching of the Josephson junction (J_1, J_A) between the first inductance state and the second inductance state.

2. The system of claim 1, wherein the Josephson junction (J_1, J_A) is configured as a flux-controlled variable inductor that provides the variable inductance based on an amplitude of a current flowing through the flux-controlled variable inductor.

3. The system of claim 2, further comprising a bias element (L_{B1}, L_{B2}) inductively coupled to the SQUID (34, 84) to induce the current that flows through the flux-controlled variable inductor through the SQUID (34, 84) based on a current flowing through the bias element (L_{B1}, L_{B2}).

4. The system of claim 3, wherein the switch controller (36, 86) controls an amount of current (I_{B1}, I_{B2}) through the bias element (L_{B1}, L_{B2}).

5. The system of claim 4, wherein the switch controller (36, 86) can provide either a current or no current to the bias element (L_{B1}, L_{B2}) that substantially induces a low current or no current to the SQUID (34, 84) to provide the first inductance or provide a current to the bias element (L_{B1}, L_{B2}) that substantially induces a second predetermined current due to a flux applied to the SQUID of about 0.1 Φ_0 to about 0.45 Φ_0, where Φ_0 is equal to a flux quantum.

6. The system of claim 1, further comprising an input coupling capacitor (Cic, C_A) coupled between an input of the filter network (32, 82) and the SQUID (34, 84) and an output coupling capacitor (C_{OC}, C_B) coupled between an output of the filter network (32, 82) and the SQUID (34, 84), the input coupling capacitor (Cic, C_A) and the output coupling capacitor (Coc, C_B) ensuring that current that flows through the SQUID (34, 84) is isolated from flowing through other parts of the filter network (32, 82).

7. A method of providing a superconducting switch system (10, 30, 80), the method comprising:

determining a desired pass-band output for passing a desired bandwidth portion of an input signal (SIG_{IN}) to an output of a superconducting switch;
determining a band-pass filter network topology for the superconducting switch;
determining a radio frequency, RF, Superconducting Quantum Interference Device, SQUID, (18, 34, 84) insertion point in the band-pass filter, the RF SQUID (18, 34, 84) comprising a first inductor (L_1, L_A) coupled to a Josephson junction (J_1, J_A) on a first end and a second inductor (L_2, L_B) coupled to the Josephson junction (J_1, J_A) on a second end in a superconducting loop;
determining one or more input resonators and one or more output resonator component values for providing the superconducting switch; and
building a superconductor switch system (10, 30, 80) that includes the superconducting switch comprising the one or more input resonators, the one or more output resonators and the RF SQUID (18, 34, 84), a bias inductor coupled to the RF SQUID (18, 34, 84) and a switch controller (14, 36, 86) that switches an amount of current (I_{B1}, I_{B2}) through the bias inductor and induced in the RF SQUID (18, 34, 84) to change the superconductor switch system (10, 30, 80) between one of an 'ON' state and an 'OFF' state.

8. The method of claim 7, further comprising determining inductor component values for the RF SQUID (18, 34, 84), wherein the determining inductor component values of the RF SQUID (18, 34, 84) comprises assuring that the RF SQUID linear inductance does not exceed the inductance of the Josephson junction (J_1, J_A).

Patentansprüche

1. Ein supraleitendes Schaltsystem (10, 30, 80) zur Bereitstellung einer Schaltsteuerung eines Eingangssignals (SIG_{IN}), umfassend:

ein Filternetzwerk (12, 32, 82) mit einem Eingangsabschnitt und einem Ausgangsabschnitt, wobei der Eingangsabschnitt einen oder mehrere Eingangsresonatoren umfasst, die
aus einem ersten Kondensator (C_1, C_A), einer Induktivität (L_{S1}, L_{H1}) und einer ersten Induktivität (L_1, L_A) gebildet sind, und
wobei der Ausgangsabschnitt einen oder mehrere Ausgangsresonatoren umfasst, die
aus einem zweiten Kondensator (C_2, C_B), einer weiteren Induktivität (L_{S2}, LH2) und einer zweiten Induktivität (L_2, L_B) gebildet sind;
einen Josephson-Übergang (J1, J_A), der den Eingangsabschnitt mit dem Ausgangsabschnitt koppelt, wobei der Josephson-Übergang (J1, J_A) in einem EIN-Zustand des supraleitenden Schaltersystems einen ersten Induktivitätszustand aufweist, der es einem gewünschten Bandbreitenabschnitt des Eingangssignals (SI-

G_{IN}) ermöglicht, von dem Eingangsabschnitt zu dem Ausgangsabschnitt als Ausgangssignal (SIG_{OUT}) zu gelangen, und in einem AUS-Zustand des supraleitenden Schaltersystems einen zweiten Induktivitätszustand, der den gewünschten Bandbreitenanteil des Eingangssignals (SIG_{IN}) daran hindert, von dem Eingangsabschnitt zu dem Ausgangsabschnitt zu gelangen, wobei der Josephson-Übergang (J1, J_A) an einem ersten Ende mit der ersten Induktivität (L_1, L_A) und an einem zweiten Ende mit dem zweiten Induktor (L_2, L_B) gekoppelt ist, so dass der erste Induktor (L_1, L_A), der Josephson-Übergang (J1, J_A) und der zweite Induktor (L_2, L_B) eine supraleitende Quanteninterferenzvorrichtung, SQUID, (34, 84) bilden; und
eine Schaltsteuerung (14, 36, 86), die dazu konfiguriert ist, das Schalten des Josephson-Übergangs (J_1, J_A) zwischen dem ersten Induktivitätszustand und dem zweiten Induktivitätszustand zu steuern.

2. Das System nach Anspruch 1, wobei der Josephson-Übergang (J_1, J_A) als flussgesteuerte variable Induktivität konfiguriert ist, die die variable Induktivität basierend auf einer Amplitude eines Stroms bereitstellt, der durch die flussgesteuerte variable Induktivität fließt.

3. Das System nach Anspruch 2, das ferner ein Vorspannungselement (L_{B1}, L_{B2}) umfasst, das induktiv mit dem SQUID (34, 84) gekoppelt ist, um den Strom, der durch den flussgesteuerten variablen Induktor fließt, durch das SQUID (34, 84) auf der Grundlage eines durch das Vorspannungselement (L_{B1}, L_{B2}) fließenden Stroms zu induzieren.

4. Das System nach Anspruch 3, wobei die Schaltsteuerung (36, 86) eine Strommenge ($_{IB1}$, $_{IB2}$) durch das Vorspannungselement (L_{B1}, L_{B2}) steuert.

5. Das System nach Anspruch 4, wobei die Schaltsteuerung (36, 86) entweder einen Strom oder keinen Strom an das Vorspannungselement (L_{B1}, L_{B2}) liefern kann, der im Wesentlichen einen niedrigen Strom oder keinen Strom in das SQUID (34, 84) induziert, um die erste Induktivität bereitzustellen, oder einen Strom an das Vorspannungselement (L_{B1}, L_{B2}) liefern kann, der im Wesentlichen einen zweiten vorbestimmten Strom aufgrund eines an das SQUID angelegten Flusses von etwa $0{,}1\Phi_0$ bis etwa $0{,}45\Phi_0$ induziert, wobei Φ_0 gleich einem Flussquantum ist.

6. Das System nach Anspruch 1, das ferner einen Eingangskopplungskondensator (C_{IC}, C_A), der zwischen einen Eingang des Filternetzwerks (32, 82) und den SQUID (34, 84) gekoppelt ist, und einen Ausgangskopplungskondensator (Coc, C_B) umfasst, der zwischen einen Ausgang des Filternetzwerks (32, 82) und den SQUID (34, 84) gekoppelt ist, wobei der Eingangskopplungskondensator (C_{IC},C_A) und der Ausgangskopplungskondensator (Coc, C_B) sicherstellen, dass Strom, der durch den SQUID (34, 84) fließt, vom Fließen durch andere Teile des Filternetzwerks (32, 82) isoliert ist.

7. Ein Verfahren zum Bereitstellen eines supraleitenden Schaltersystems (10, 30, 80), wobei das Verfahren umfasst:

Bestimmen eines gewünschten Durchlassband-Ausgangs zur Weiterleitung eines gewünschten Bandbreitenanteils eines Eingangssignals (SIG_{IN}) an einen Ausgang eines supraleitenden Schalters;
Bestimmen einer Bandpassfilter-Netzwerk-Topologie für den supraleitenden Schalter;
Bestimmen eines Hochfrequenz-, RF-, supraleitenden Quanteninterferenzaordnung, SQUID, (18, 34, 84) -Einfügungspunktes in dem Bandpassfilter, wobei das RF-SQUID (18, 34, 84) einen ersten Induktor (L_1, L_A), der mit einem Josephson-Übergang (J1, J_A) an einem ersten Ende gekoppelt ist, und einen zweiten Induktor (L_2, L_B), der mit dem Josephson-Übergang (J_1, J_A) an einem zweiten Ende in einer supraleitenden Schleife gekoppelt ist, umfasst;
Bestimmen eines oder mehrerer Eingangsresonatoren und eines oder mehrerer Ausgangsresonator-Komponentenwerte zur Bereitstellung des supraleitenden Schalters; und
Aufbauen eines supraleitenden Schaltersystems (10, 30, 80), das den supraleitenden Schalter mit dem einen oder den mehreren Eingangsresonatoren, dem einen oder den mehreren Ausgangsresonatoren und dem RF-SQUID (18, 34, 84), eine mit dem RF-SQUID (18, 34, 84) gekoppelte Vorspannungsinduktivität 84) und eine Schaltsteuerung (14, 36, 86), die eine Strommenge ($_{IB1}$, $_{IB2}$) durch die Vorspannungsinduktivität und induziert in dem RF-SQUID (18, 34, 84) schaltet, um das supraleitende Schaltersystem (10, 30, 80) zwischen einem "EIN"-Zustand und einem "AUS"-Zustand zu ändern.

8. Das Verfahren nach Anspruch 7, das ferner das Bestimmen von Induktionskomponentenwerten für das HF-SQUID (18, 34, 84) umfasst, wobei das Bestimmen von Induktionskomponentenwerten des HF-SQUID (18, 34, 84) das Sicherstellen umfasst, dass die lineare Induktivität des HF-SQUID die Induktivität des Josephson-Übergangs (J1, J_A) nicht überschreitet.

Revendications

1. Un système de commutation supraconducteur (10, 30, 80) pour fournir une commande de commutation d'un signal d'entrée (SIG_{IN}), comprenant :

   un réseau de filtres (12, 32, 82) ayant une partie d'entrée et une partie de sortie,
   dans lequel la partie d'entrée comprend un ou plusieurs résonateurs d'entrée formés d'un premier condensateur (C_1, CA), une inductance (L_{S1}, L_{H1}), et une première inductance (L_1, L_A), et
   dans lequel la partie de sortie comprend un ou plusieurs résonateurs de sortie formés d'un deuxième condensateur (C_2, C_B), une autre inductance (L_{S2}, L_{H2}), et une deuxième inductance (L_2, L_B);
   une jonction Josephson (J1, J_A) qui couple la partie d'entrée à la partie de sortie, la jonction Josephson (J1, J_A) ayant, dans un état ON du système de commutation supraconducteur, un premier état d'inductance qui permet à une partie de largeur de bande souhaitée du signal d'entrée (SIG_{IN}) de passer de la partie d'entrée à la partie de sortie comme un signal de sortie (SIG_{OUT}), et dans un état OFF du système de commutation supraconducteur, un deuxième état d'inductance qui supprime la partie de largeur de bande souhaitée du signal d'entrée (SIG_{IN}) pour qu'elle passe de la partie d'entrée à la partie de sortie, dans lequel la jonction Josephson (J1, J_A) est couplée sur une première extrémité à la première inductance (L_1, L_A) et sur une seconde extrémité à la seconde inductance (L_2, L_B), de sorte que la première inductance (L_1, L_A), la jonction Josephson (J1, J_A) et la seconde inductance (L_2, LB) forment un dispositif d'interférence quantique supraconducteur, SQUID, (34, 84) ; et
   un contrôleur de commutation (14, 36, 86) configuré pour commander la commutation de la jonction Josephson (J1, J_A) entre le premier état d'inductance et le second état d'inductance.

2. Le système de la revendication 1, dans lequel la jonction Josephson (J1, J_A) est configurée comme une inductance variable commandée par flux qui fournit l'inductance variable sur la base d'une amplitude d'un courant circulant à travers l'inductance variable commandée par flux.

3. Le système de la revendication 2, comprenant en outre un élément de polarisation (L_{B1}, L_{B2}) couplé de manière inductive au SQUID (34, 84) pour induire le courant qui circule à travers l'inducteur variable à flux contrôlé à travers le SQUID (34, 84) sur la base d'un courant circulant à travers l'élément de polarisation (L_{B1}, L_{B2}).

4. Le système de la revendication 3, dans lequel le contrôleur de commutateur (36, 86) commande une quantité de courant (I_{B1}, I_{B2}) à travers l'élément de polarisation (LB1, L_{B2}).

5. Le système selon la revendication 4, dans lequel le contrôleur de commutation (36, 86) peut fournir un courant ou aucun courant à l'élément de polarisation (LB1, LB2) qui induit sensiblement un faible courant ou aucun courant au SQUID (34, 84) pour fournir la première inductance ou fournir un courant à l'élément de polarisation (L_{B1}, L_{B2}) qui induit sensiblement un second courant prédéterminé dû à un flux appliqué au SQUID d'environ 0,1 Φ_0 à environ 0,45Φ_0, où Φ_0 est égal à un quantum de flux.

6. Le système de la revendication 1, comprenant en outre un condensateur de couplage d'entrée (C_{IC},C_A) couplé entre une entrée du réseau de filtrage (32, 82) et le SQUID (34, 84) et un condensateur de couplage de sortie (Coc, C_B) couplé entre une sortie du réseau de filtrage (32, 82) et le SQUID (34, 84), le condensateur de couplage d'entrée (C_{IC},C_A) et le condensateur de couplage de sortie (Coc, C_B) assurant que le courant qui circule à travers le SQUID (34, 84) est isolé de la circulation à travers d'autres parties du réseau de filtrage (32, 82).

7. Un procédé pour fournir un système de commutation supraconducteur (10, 30, 80), le procédé comprenant les étapes suivantes

   déterminer une sortie de bande passante souhaitée pour faire passer une partie de bande passante souhaitée d'un signal d'entrée (SIG_{IN}) à une sortie d'un commutateur supraconducteur ;
   déterminer une topologie de réseau de filtre passe-bande pour le commutateur supraconducteur ;
   déterminer un point d'insertion de dispositif d'interférence quantique supraconducteur RF, SQUID (18, 34, 84) dans le filtre passe-bande, le SQUID RF (18, 34, 84) comprenant une première inductance (L_1, L_A) couplée à une jonction Josephson (J1, $_{JA}$) sur une première extrémité et une seconde inductance (L_2, LB) couplée à la jonction Josephson (J1, J_A) sur une seconde extrémité dans une boucle supraconductrice ;
   déterminer un ou plusieurs résonateurs d'entrée et une ou plusieurs valeurs de composants de résonateurs de sortie pour fournir le commutateur supraconducteur ; et
   construire un système de commutation supraconducteur (10, 30, 80) qui comprend le commutateur supraconducteur comprenant le ou les

résonateurs d'entrée, le ou les résonateurs de sortie et le SQUID RF (18, 34, 84), une inductance de polarisation couplée au SQUID RF (18, 34, (18, 34, 84), une inductance de polarisation couplée au SQUID RF (18, 34, 84) et un contrôleur de commutateur (14, 36, 86) qui commute une quantité de courant (I_{B1}, I_{B2}) à travers l'inductance de polarisation et induit dans le SQUID RF (18, 34, 84) pour changer le système de commutateur supraconducteur (10, 30, 80) entre un état "ON" et un état "OFF".

8. Le procédé de la revendication 7, comprenant en outre la détermination de valeurs de composants d'inductance pour le SQUID RF (18, 34, 84), dans lequel la détermination de valeurs de composants d'inductance du SQUID RF (18, 34, 84) comprend l'assurance que l'inductance linéaire du SQUID RF ne dépasse pas l'inductance de la jonction Josephson (J_1, J_A).

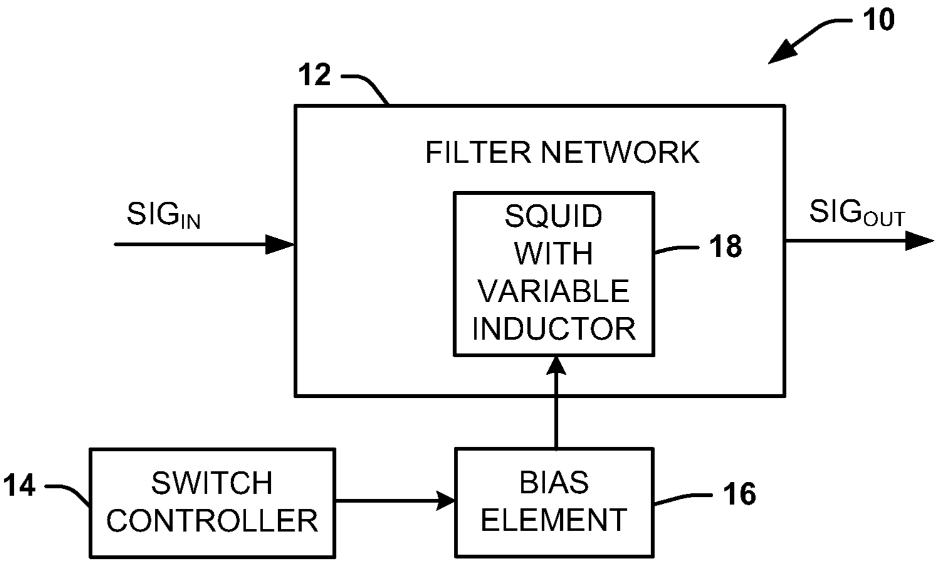
10
12
FILTER NETWORK
SIG_{IN}
SQUID WITH VARIABLE INDUCTOR
18
SIG_{OUT}
14
SWITCH CONTROLLER
BIAS ELEMENT
16

FIG. 1

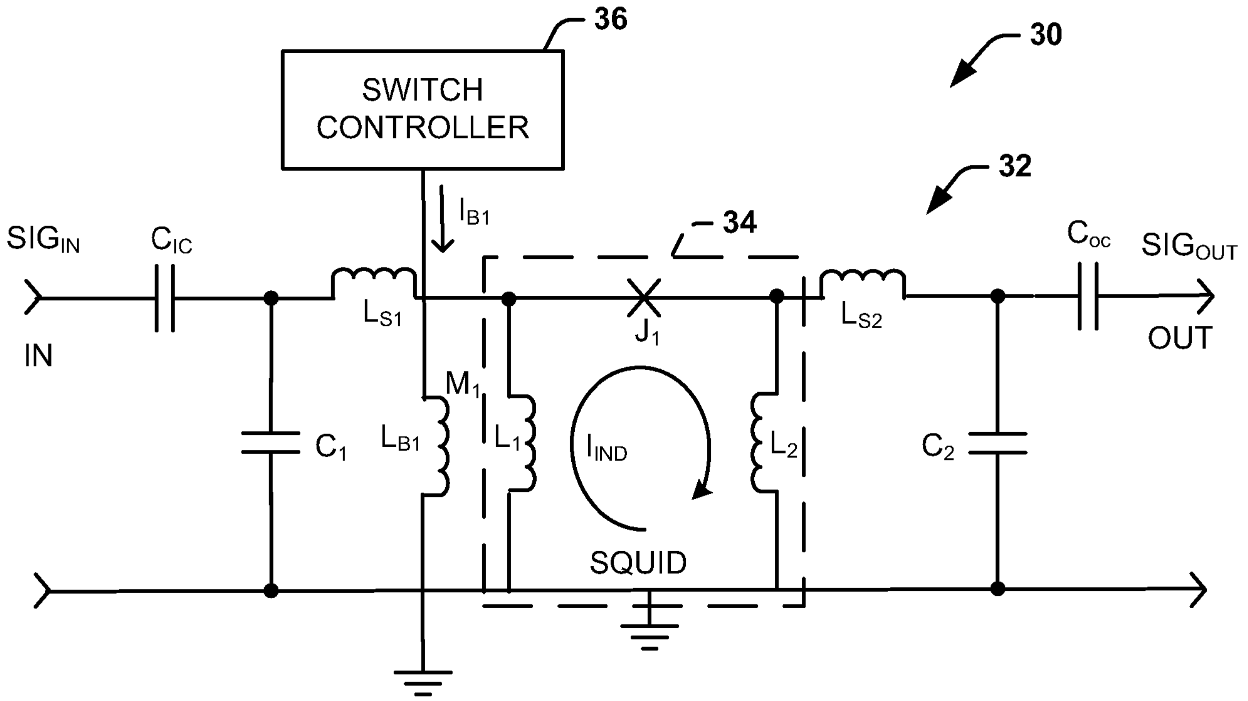
36
SWITCH CONTROLLER
30
32
I_{B1}
34
SIG_{IN}
C_{IC}
IN
L_{S1}
J_1
L_{S2}
C_{OC}
SIG_{OUT}
OUT
M_1
C_1
L_{B1}
L_1
I_{IND}
L_2
C_2
SQUID

FIG. 2

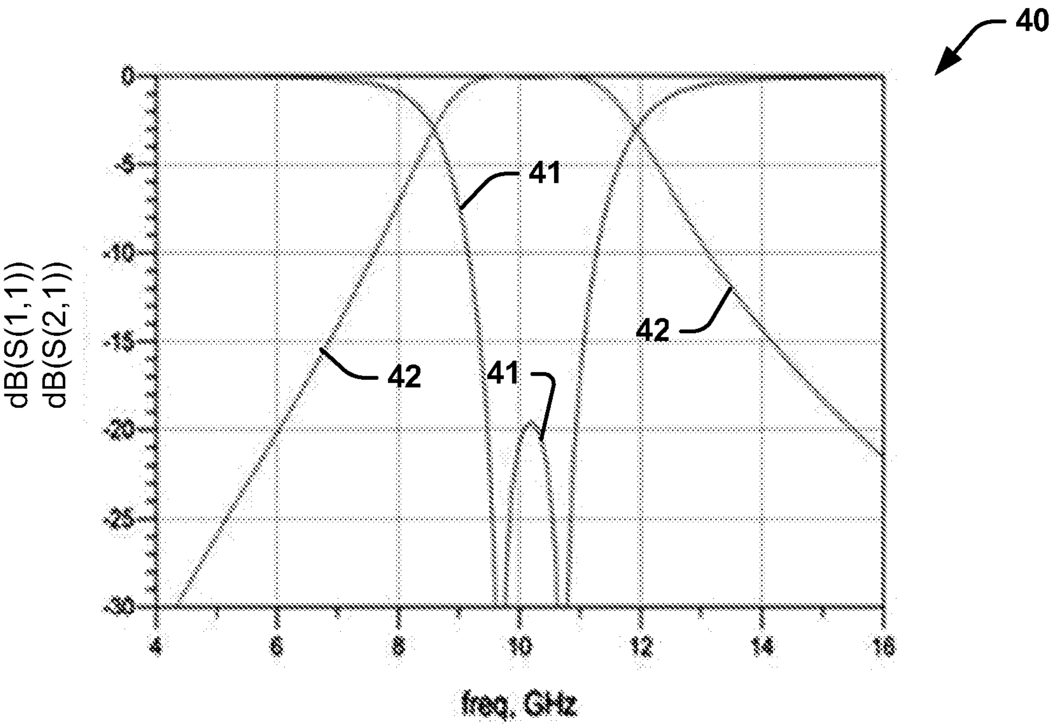
40
41
41
42
42
0
-5
-10
-15
-20
-25
-30
4
6
8
10
12
14
16
dB(S(1,1))
dB(S(2,1))
freq, GHz

FIG. 3

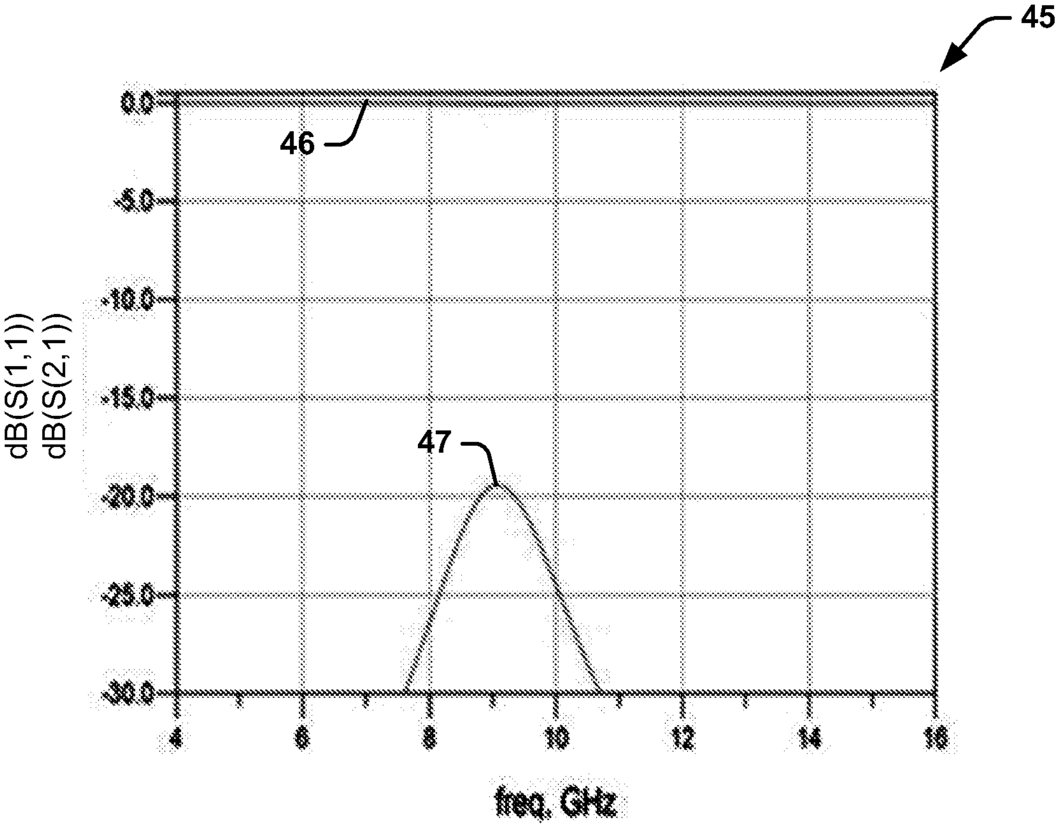
45
46
47
0.0
-5.0
-10.0
-15.0
-20.0
-25.0
-30.0
4
6
8
10
12
14
16
dB(S(1,1))
dB(S(2,1))
freq, GHz

FIG. 4

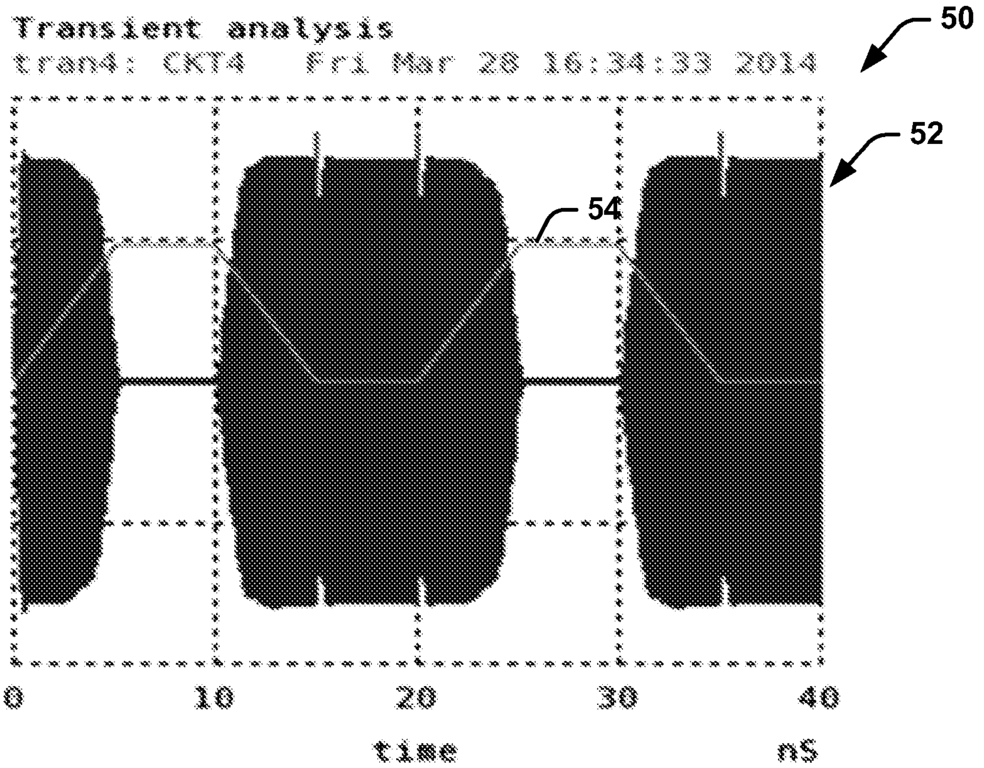
50
Transient analysis
tran4: CKT4 Fri Mar 28 16:34:33 2014
52
54
0
10
20
30
40
time
nS

FIG. 5

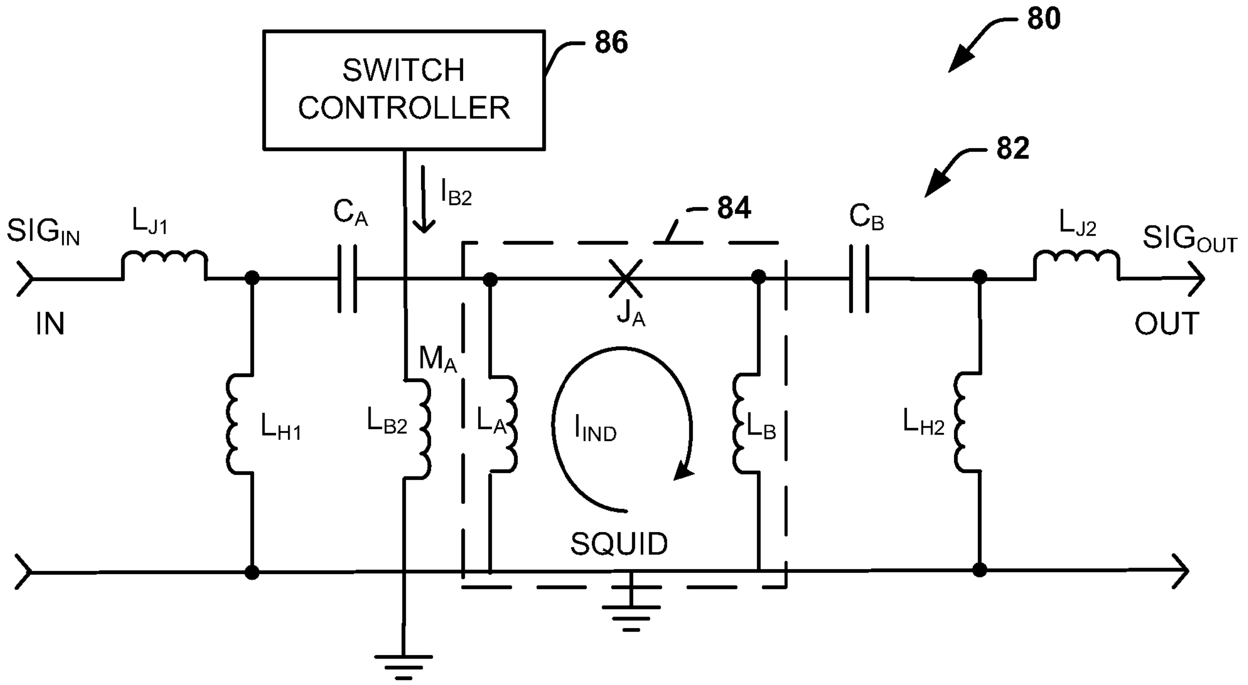
80
SWITCH CONTROLLER
86
82
I_{B2}
84
SIG_{IN}
L_{J1}
C_A
C_B
L_{J2}
SIG_{OUT}
IN
J_A
OUT
M_A
L_{H1}
L_{B2}
L_A
I_{IND}
L_B
L_{H2}
SQUID

FIG. 9

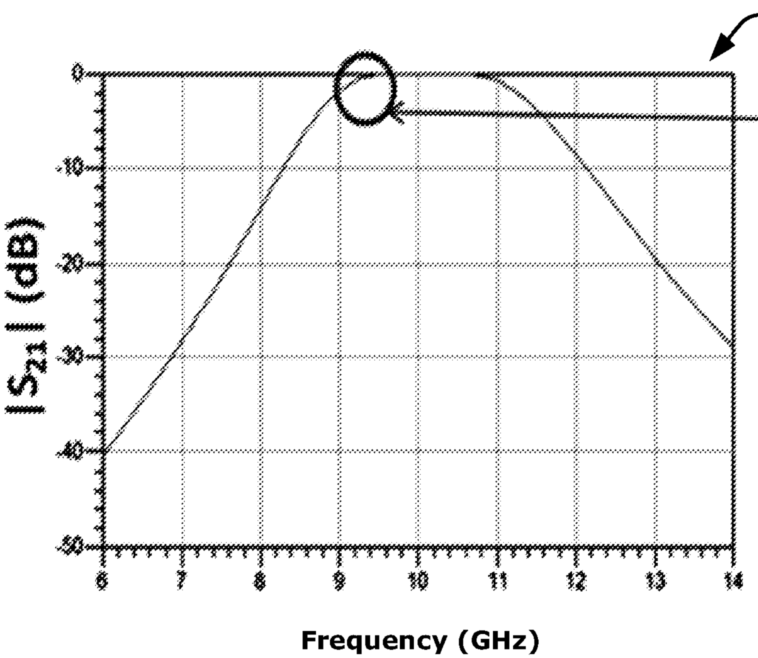

FIG. 6

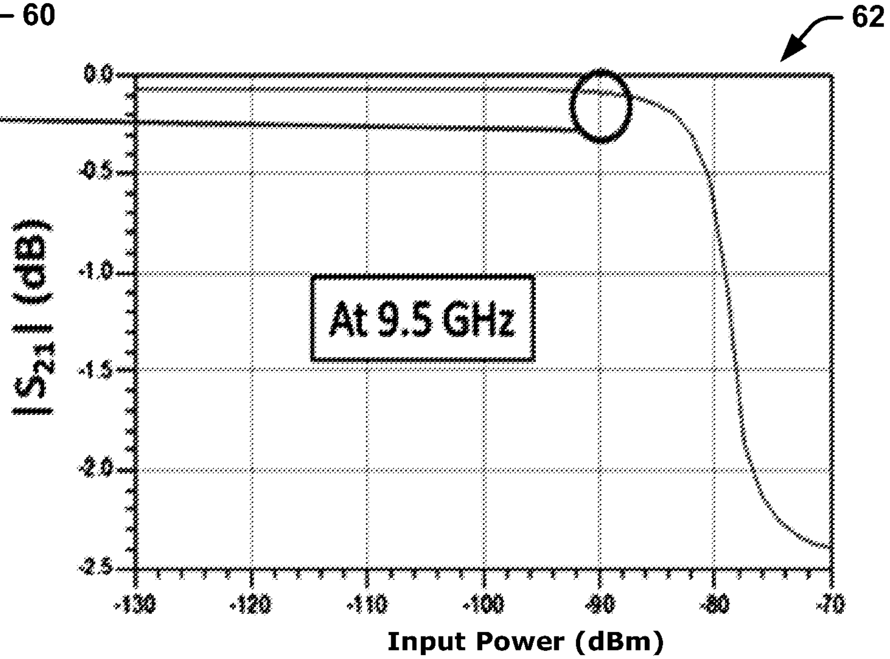

FIG. 7

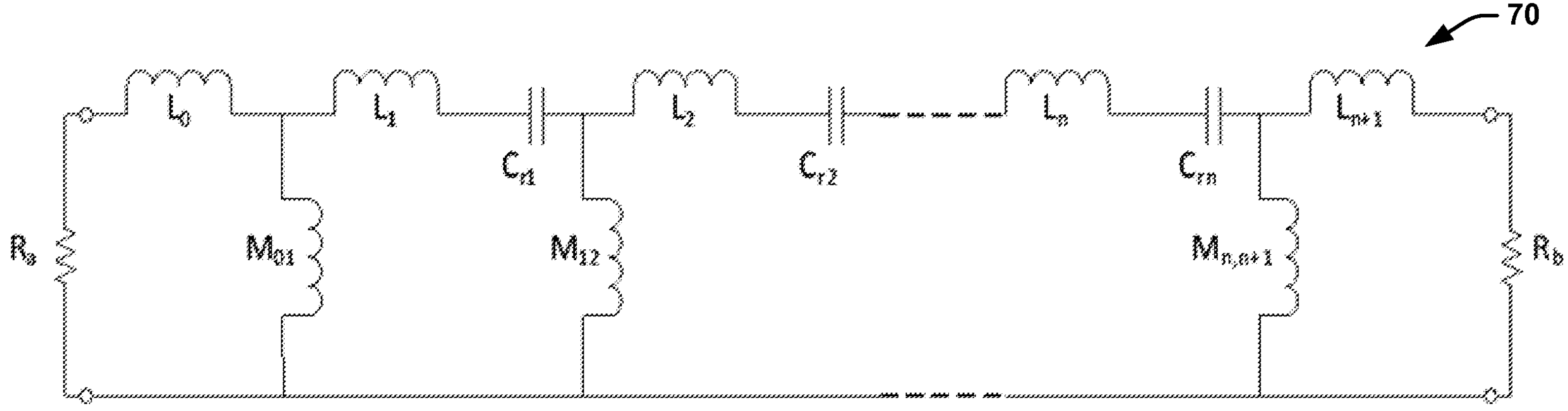

FIG. 8

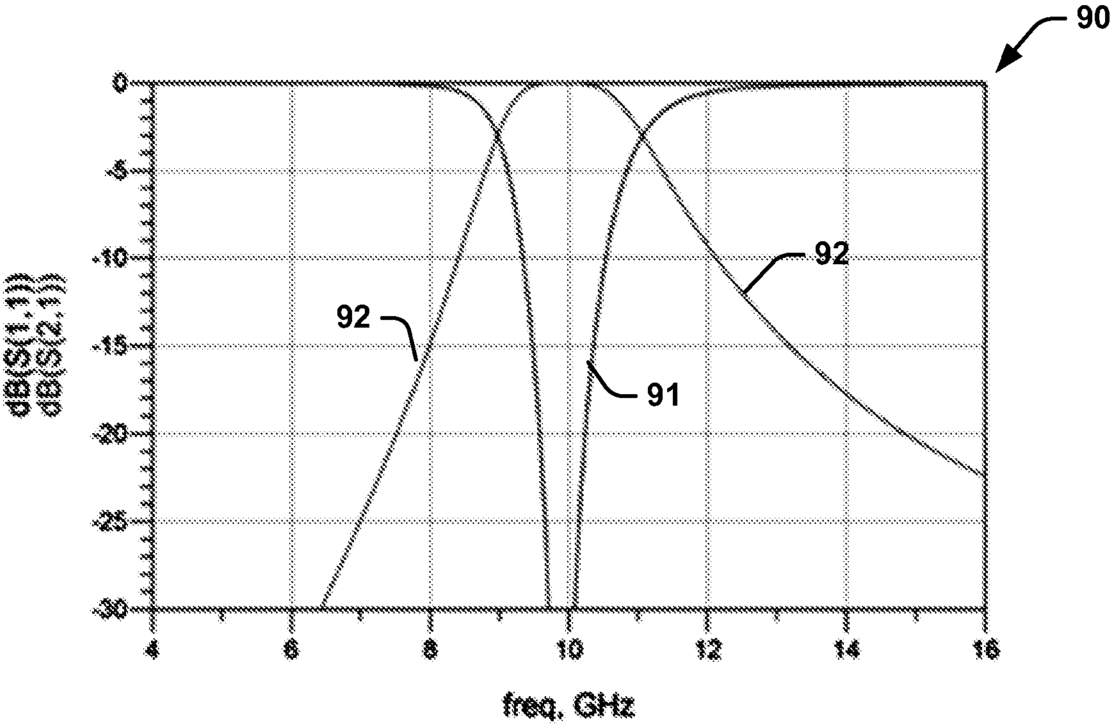
90
0
-5
-10
-15
-20
-25
-30
4
6
8
10
12
14
16
dB(S(1,1))
dB(S(2,1))
freq, GHz
92
92
91

FIG. 10

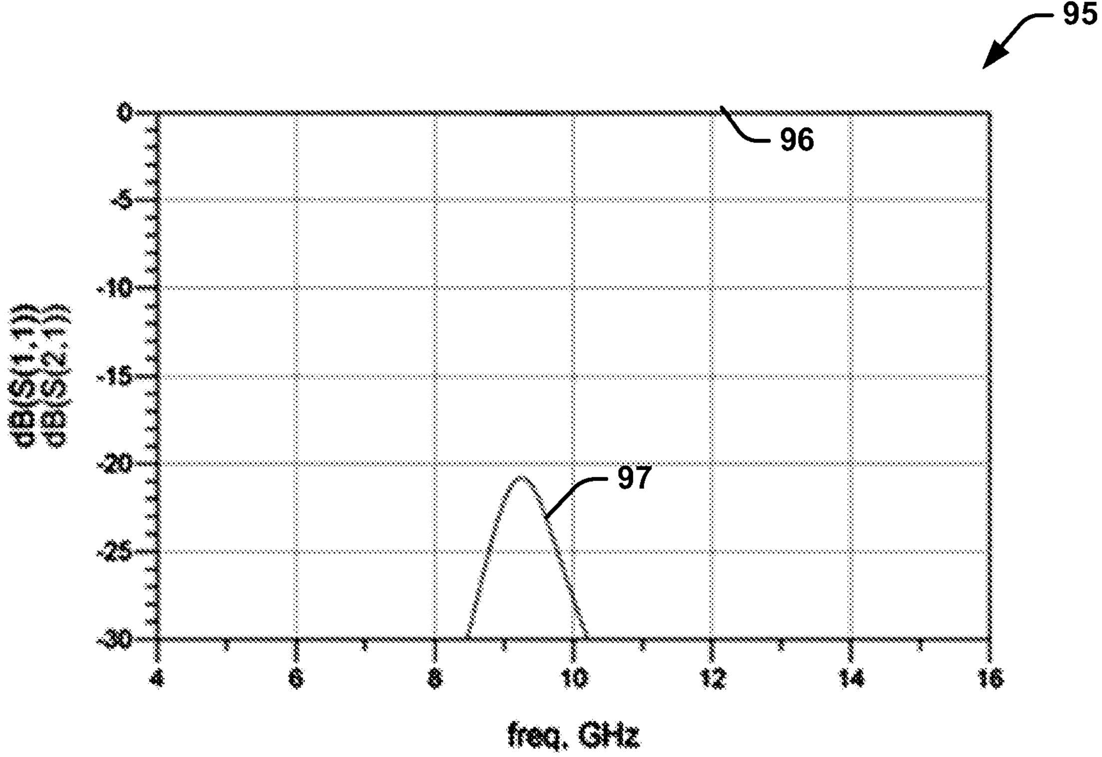
95
0
-5
-10
-15
-20
-25
-30
4
6
8
10
12
14
16
dB(S(1,1))
dB(S(2,1))
freq, GHz
96
97

FIG. 11

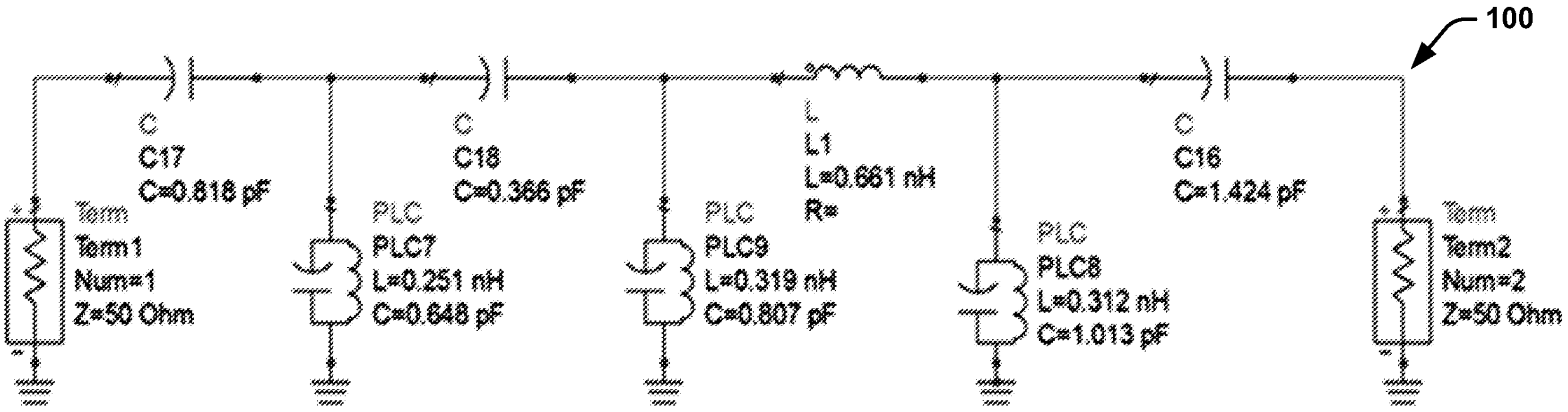

FIG. 12

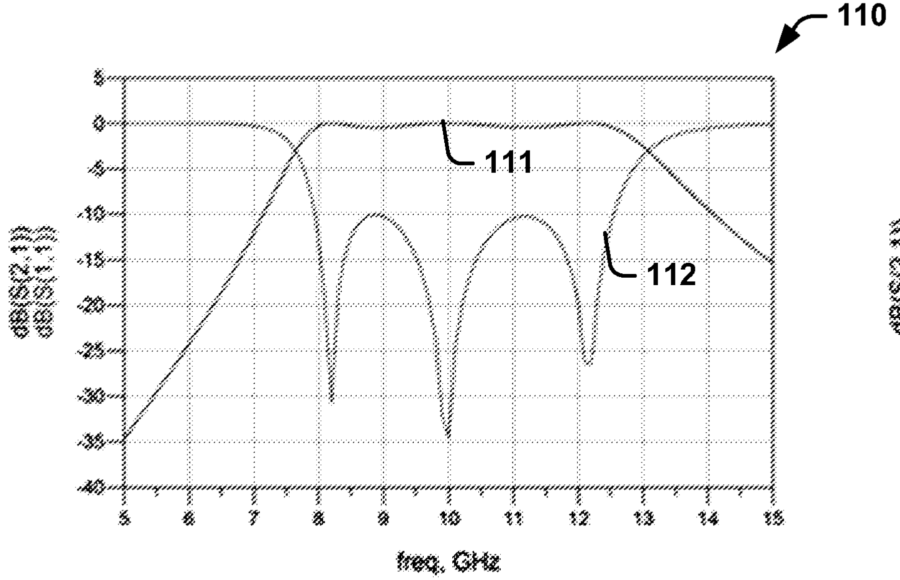

FIG. 13

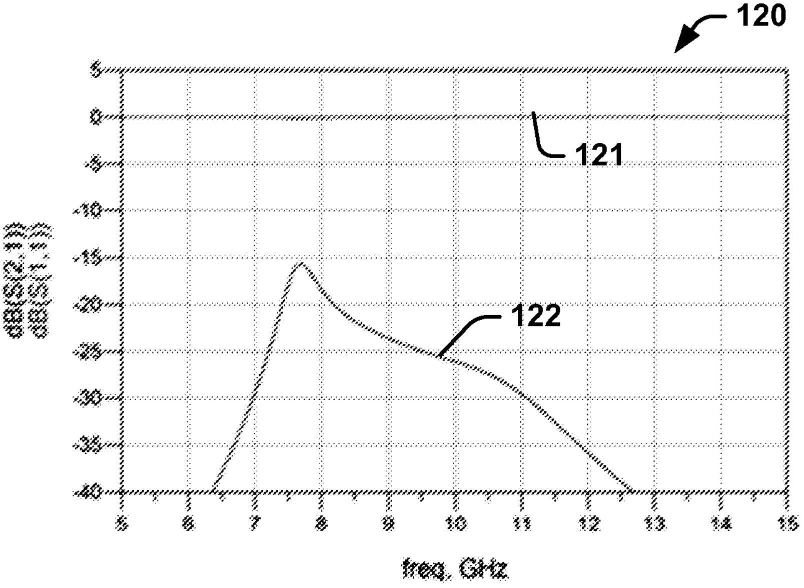

FIG. 14

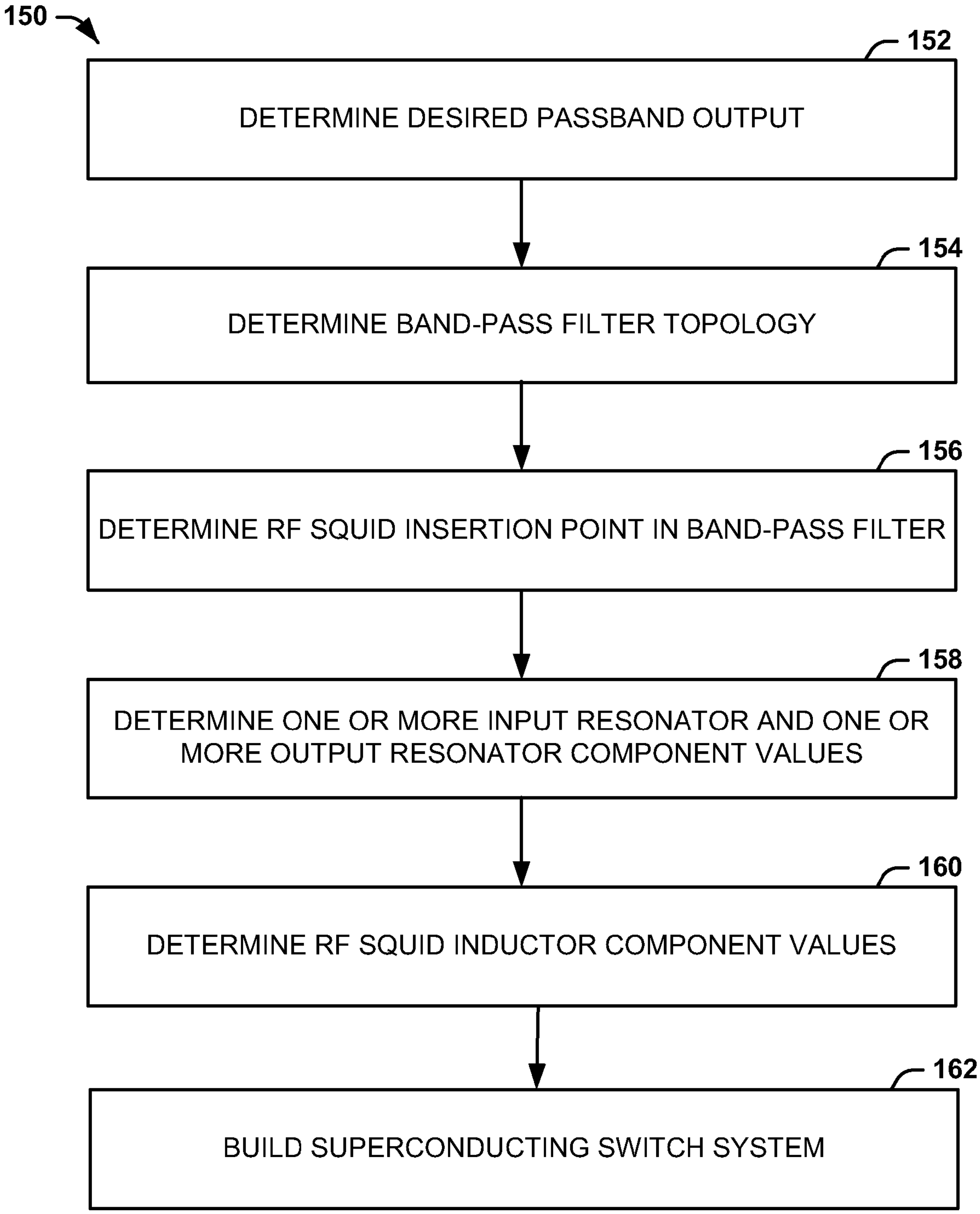
150
152
DETERMINE DESIRED PASSBAND OUTPUT
154
DETERMINE BAND-PASS FILTER TOPOLOGY
156
DETERMINE RF SQUID INSERTION POINT IN BAND-PASS FILTER
158
DETERMINE ONE OR MORE INPUT RESONATOR AND ONE OR MORE OUTPUT RESONATOR COMPONENT VALUES
160
DETERMINE RF SQUID INDUCTOR COMPONENT VALUES
162
BUILD SUPERCONDUCTING SWITCH SYSTEM

FIG. 15

REFERENCES CITED IN THE DESCRIPTION

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- US 56499614 **[0001]**
- US 5912472 A **[0005]**

Non-patent literature cited in the description

- **SHIMAZU, Y. et al.** Characteristics of Switchable Superconducting Flux Transformer with DC Superconducting Quantum Interference Device. *Japanese Journal of Applied Physics,* 2007, vol. 46 (4A), 1478-1481 **[0004]**
- **AVENHAUS, B. et al.** Switched YBa2Cu3O7 lumped element bandstop filter. *Electronic Letters,* 08 June 1995, vol. 31 (12 **[0006]**
- **MARTENS, J. S. et al.** HTS-based switched filter banks and delay lines. *IEEE Transactions on Applied Superconductivity,* March 1993, vol. 3 (1 **[0006]**
- **HUANG, F. et al.** Lumped-element switchable superconducting filters. *IEE Proceedings: Microwaves, Antennas and Propagation,* June 1999, vol. 146 (3 **[0007]**