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(54) **FOUR-PORT CIRCULATOR**
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Description**BACKGROUND**

[0001] Some embodiments described in the present disclosure relate to a quadrature circulator and, more specifically, but not exclusively, to a four-port electronic quadrature circulator.

[0002] Electronic Circulator self-interference cancellation (SIC) is done today by coupling the transmit (TX) signal into a finite impulse response (FIR) filter for shaping post power amplifier (PA) and combining the canceling signal pre low noise amplifier (LNA). Such schemes are complex, not scalable to multiple-input and multiple-output (MIMO) systems, where self and mutual interferences are present and create transmit and receive losses, degrading power efficiency and receiver signal to noise ratio.

[0003] Simultaneous Transmit Receive (STR) single transmit/receive antenna wireless communication scenarios (such as Full Duplex (FD) or Frequency Division Duplex (FDD) without a Diplexer) require a Transmit-Receive SIC mechanism. Most implementations of SIC are done between the TX transmit output and the RX receive input, thereby loading both TX and RX channels, reducing the power efficiency and signal to noise ratio.

[0004] The article "Analysis and Design of a Full-Duplex Two-Element MIMO Circulator-Receiver With High TX Power Handling Exploiting MIMO RF and Shared-Delay Baseband Self-Interference Cancellation" by M. B. Dastjerdi et al. (IEEE Journal of Solid-State Circuits, Vol. 54, No. 12, December 2019) describes how full-duplex operation can be integrated with multi-input multi-output operation using RF and baseband self-interference cancellation.

[0005] United States patent application US 2020/0099131 A1 describes a non-reciprocal transceiver array architecture with a single non-reciprocal element.

[0006] The article "Acoustic rat-race coupler and its applications in non-reciprocal systems" by F. Zangeneh-Nejad and R. Fleury (J. Acoust. Soc. Am. 146 (1), July 2019) describes an acoustic four-port circulator based on two rat-race couplers and a non-reciprocal element.

SUMMARY

[0007] It is an object of the present disclosure to describe a four-port circulator, as defined in claim 1 and its dependent claims, and methods of using the four-port circulator for radio frequency (RF) communication, as defined in claim 8 and its dependent claims.

[0008] Embodiments of the present disclosure provide a four-port circulator with lossless receive and SIC transfer functions. The four-port circulator (also denoted herein a quadrature circulator) includes a non-ideal four-point circulator (denoted herein a quasi-circulator) cascaded with a quadrature hybrid. Two ports of the quasi-circulator are respectively connected to two ports of the quadrature hybrid. The quadrature hybrid recovers perfectly the non-ideal characteristics of the quasi-circulator, resulting in a new transfer function of an ideal electronic quadrature circulator.

[0009] Embodiments of the quadrature circulator have the following transfer coefficients:

- **Port 1 to Port 2** transfer coefficient =1;
- **Port 2 to Port 3** transfer coefficient =1;
- **Port 3 to Port 4** transfer coefficient =1; and
- **Port 4 to Port 1** transfer coefficient =1.

All other pairs of ports are isolated from each other. These transfer coefficients are represented in the scattering matrix below:

$$|S_{4-Port_circuit}| = \begin{pmatrix} 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

Benefits of the quadrature circulator presented herein include:

- a) Size and on-chip integration compatibility - An electronic device with a small form factor relative to the bulky magnetic devices currently available;
- b) Full transmission between consecutive ports with no power loss;
- c) Suitable for use in RF Front Ends for full-duplex (FD), half-duplex (HD) and Frequency Division-Duplex (FDD) communication;
- d) Includes a built-in fourth port with no loss into the RX port, enabling SIC for FD and FDD applications;

- e) The fourth port also enables Mutual Interference Cancellation from nearby antennas in MIMO operation; and
 f) Suitable for TX Carrier Aggregation concurrently with FD, HD or FDD.

[0010] The foregoing and other objects are achieved by the features of the independent claims. Further implementation forms are apparent from the dependent claims, the description and the figures.

[0011] A first aspect of the disclosure provides a quadrature circulator device which includes:

a quasi-circulator (100) comprising:

a first port, a second port, a third port, and a fourth port, wherein a scattering matrix S1 of the quasi-circulator is represented as:

$$S1 = \begin{bmatrix} 0 & 0 & -1/\sqrt{2} & -j/\sqrt{2} \\ -j & 0 & 0 & 0 \\ 0 & -j/\sqrt{2} & -1/2 & j/2 \\ 0 & -1/\sqrt{2} & -j/2 & -1/2 \end{bmatrix},$$

wherein each entry $S1_{xy}$ of the scattering matrix S1 represents a portion of a square root of a power of a signal that is directed by the quasi-circulator from the yth port to the xth port, wherein x and y each can be 1, 2, 3, and 4 and x is not equal to y, and each entry $S1_{xx}$ represents a portion of a square root of a power of a signal that is reflected at the xth port; and

a quadrature hybrid comprising a first port, a second port, a third port, and a fourth port, wherein a scattering matrix S2 of the quadrature hybrid is represented as:

$$S2 = \begin{bmatrix} 0 & -j/\sqrt{2} & -1/\sqrt{2} & 0 \\ -j/\sqrt{2} & 0 & 0 & -1/\sqrt{2} \\ -1/\sqrt{2} & 0 & 0 & -j/\sqrt{2} \\ 0 & -1/\sqrt{2} & -j/\sqrt{2} & 0 \end{bmatrix},$$

wherein each entry $S2_{xy}$ of the scattering matrix S2 represents a portion of a square root of a power of a signal that is directed by the quadrature hybrid from the yth port to the xth port, wherein x and y each can be 1, 2, 3, and 4 and x is not equal to y, and each entry $S2_{xx}$ represents a portion of a square root of a power of a signal that is reflected at the xth port,

and wherein the fourth port of the quasi-circulator is connected to the fourth port of the quadrature hybrid and the third port of the quasi-circulator is connected to the first port of the quadrature hybrid.

[0012] A benefit of the first aspect, is that quadrature circulator with an ideal transfer function is obtained with a small form factor.

[0013] In an implementation form of the first aspect, the quasi-circulator includes:

a first 90 degree reciprocal phase shifter, RPS, between the first port of the quasi-circulator and the second port of the quasi-circulator;

a second 90 degree RPS between the second port of the quasi-circulator and the third port of the quasi-circulator;

a 90 degree non-reciprocal phase shifter, NRPS, between the third port of the quasi-circulator and the fourth port of the quasi-circulator; and

a third 90 degree RPS between the fourth port of the quasi-circulator and the first port of the quasi-circulator; wherein a characteristic impedance of the first RPS is a first value that is equal to an impedance of the first port of the quasi-circulator, and a characteristic impedance of the second RPS and the third RPS is a second value, wherein the second

value equals the first value divided by $\sqrt{2}$. In a further implementation form of the first aspect, the NRPS is impedance transparent. In a further implementation form of the first aspect, a phase of a forward signal path from the first port of the quasi-circulator through second port of the quasi-circulator to the third port of the quasi-circulator is 180 degree, and a phase of a forward signal path from the first port of the quasi-circulator through fourth port of the quasi-circulator to the third port of the quasi-circulator is 0 degree.

[0014] A benefit of these implementations is that they provide a four-port device having the desired transfer function of the quasi-circulator.

[0015] In a further implementation form of the first aspect, the quadrature circulator device further includes an antenna connected to the second port of the quasi-circulator. A benefit of this implementation is that a quadrature circulator port may be used in wireless communication devices.

[0016] In a further implementation form of the first aspect, the quadrature circulator device further includes a first reflective element, wherein an output of the first reflective element is connected to the third port of the quadrature hybrid. Thus a self-interference cancellation signal may be input to **Port 3** of the quadrature circulator device, while the signal from **Port 2** is transferred to **Port 4**. A benefit of this implementation is that it is suitable for many communication modes, such as full-duplex, half-duplex and frequency-division-duplex.

[0017] In a further implementation form of the first aspect, the quadrature circulator device further includes a second reflective element, wherein an output of the second reflective element is connected to the first port of the quasi-circulator. Thus transmitted signals may be input both to **Port 1** and **Port 4** of the quadrature circulator. A benefit of this implementation is that it is suitable for carrier-aggregation communication.

[0018] A second aspect of the disclosure provides a method of operating the quadrature circulator device by:

inputting a first radio frequency (RF) signal into one of the first port of the quasi-circulator, the second port of the quasi-circulator, the second port of the quadrature hybrid and the third port of the quadrature hybrid; and
outputting a second radio frequency (RF) signal from one of the first port of the quasi-circulator, the second port of the quasi-circulator, the second port of the quadrature hybrid and the third port of the quadrature hybrid.

[0019] A benefit of this aspect is that the quadrature circulator may be used as part of an RF front end for many forms of RF communications and system architectures.

[0020] In an implementation form of the second aspect, the quadrature circulator device is operated by:

inputting a transmit signal at the first port of the quasi-circulator;
inputting a received signal from an antenna connected to the second port of the quasi-circulator and outputting the transmit signal to the antenna;
inputting a self-interference cancellation (SIC) signal at the third port of the quadrature hybrid via a reflective element;
and
outputting the received signal from the second port of the quadrature hybrid. A benefit of this implementation is that it is suitable for an RF front end for full-duplex communication.

[0021] In further implementation form of the second aspect, the quadrature circulator device is operated by: inputting a transmit signal at the first port of the quasi-circulator;

inputting a received signal from an antenna connected to the second port of the quasi-circulator and outputting the transmit signal to the antenna;
reflecting the received signal at the third port of the quadrature hybrid via a reflective element connected to the third port of the quadrature hybrid; and
outputting the received signal from the second port of the quadrature hybrid. A benefit of this implementation is that it is suitable for an RF front end for half-duplex communication.

[0022] In further implementation form of the second aspect, the quadrature circulator device is operated by: inputting a transmit signal in a first frequency band at the first port of the quasi-circulator;

inputting a received signal at a second frequency band from an antenna connected to the second port of the quasi-circulator and outputting the transmit signal to the antenna;
inputting a self-interference cancellation (SIC) signal at the third port of the quadrature hybrid via a reflective element;
and
outputting the received signal from the second port of the quadrature hybrid. A benefit of this implementation is that it is suitable for an RF front end for frequency-division-duplex communication.

[0023] In further implementation form of the second aspect, the quadrature circulator device is operated by: inputting a first transmit signal in a first frequency band at the first port of the quasi-circulator via a reflective element; inputting a second transmit signal in a second frequency band at the second port of the quadrature hybrid; and outputting the first transmit signal and the second transmit signal from the second port of the quasi-circulator. A benefit of this implementation is that it is suitable for an RF front end for carrier-aggregation communication.

[0024] Other systems, methods, features, and advantages of the present disclosure will be or become apparent to one with skill in the art upon examination of the following drawings and detailed description. It is intended that all such additional

systems, methods, features, and advantages be included within this description, be within the scope of the present disclosure, and be protected by the accompanying claims.

[0025] Unless otherwise defined, all technical and/or scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which embodiments. Although methods and materials similar or equivalent to those described herein can be used in the practice or testing of embodiments, exemplary methods and/or materials are described below. In case of conflict, the patent specification, including definitions, will control. In addition, the materials, methods, and examples are illustrative only and are not intended to be necessarily limiting.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0026] Some embodiments are herein described, by way of example only, with reference to the accompanying drawings. With specific reference now to the drawings in detail, it is stressed that the particulars shown are by way of example and for purposes of illustrative discussion of embodiments. In this regard, the description taken with the drawings makes apparent to those skilled in the art how embodiments may be practiced.

[0027] In the drawings:

FIG. 1 is a schematic block diagram of a quadrature circulator according to embodiments of the invention;

FIG. 2 is a schematic diagram of a simulated quadrature circulator;

FIG. 3 is a schematic diagram of a quasi-circulator reflecting S1 transfer coefficients;

FIG. 4 is a simplified block diagram of a quasi-circulator according to an exemplary embodiment of the invention;

FIG. 5 is a schematic diagram of an exemplary quadrature hybrid, according to an exemplary embodiment of the invention;

FIG. 6 is a schematic block diagram of an RF front end for full-duplex (FD) communication, according to an exemplary embodiment of the invention

FIG. 7 is a schematic block diagram of an RF front end for half-duplex (HD) communication, according to an exemplary embodiment of the invention;

FIG. 8 is a schematic block diagram of an RF front end for Frequency Division-Duplex (FDD) communication, according to an exemplary embodiment of the invention;

FIG. 9 is a schematic block diagram of an RF front end for MIMO communication, according to an exemplary embodiment of the invention;

FIG. 10 is a schematic block diagram of an RF front end for Carrier Aggregation communication, according to exemplary embodiments of the invention; and

FIGS. 11 and 12 are schematic block diagrams of an RF front end for Carrier Aggregation communication and concurrent full-duplex operation, according to respective exemplary embodiments of the invention.

DETAILED DESCRIPTION

[0028] Some embodiments described in the present disclosure relate to a quadrature circulator and, more specifically, but not exclusively, to a four-port quadrature electronic circulator.

[0029] Embodiments of the present disclosure provide a lossless and fully matched quadrature circulator. The quadrature circulator) includes a quasi-circulator cascaded with a quadrature hybrid as described herein.

[0030] Before explaining at least one embodiment in detail, it is to be understood that embodiments are not necessarily limited in its application to the details of construction and the arrangement of the components and/or methods set forth in the following description and/or illustrated in the drawings and/or the Examples. Implementations described herein are capable of other embodiments or of being practiced or carried out in various ways.

[0031] Embodiments may be a system, a method, and/or a computer program product. The computer program product may include a computer readable storage medium (or media) having computer readable program instructions thereon for causing a processor to carry out aspects of the embodiments.

[0032] The computer readable storage medium can be a tangible device that can retain and store instructions for use by an instruction execution device. The computer readable storage medium may be, for example, but is not limited to, an electronic storage device, a magnetic storage device, an optical storage device, an electromagnetic storage device, a semiconductor storage device, or any suitable combination of the foregoing. A non-exhaustive list of more specific examples of the computer readable storage medium includes the following: a portable computer diskette, a hard disk, a random access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or Flash memory), a static random access memory (SRAM), a portable compact disc read-only memory (CD-ROM), a digital versatile disk (DVD), a memory stick, a floppy disk, and any suitable combination of the foregoing. A computer readable storage medium, as used herein, is not to be construed as being transitory signals per se, such as radio waves or other freely propagating electromagnetic waves, electromagnetic waves propagating through a waveguide or other transmis-

sion media (e.g., light pulses passing through a fiber-optic cable), or electrical signals transmitted through a wire.

[0033] Computer readable program instructions described herein can be downloaded to respective computing/processing devices from a computer readable storage medium or to an external computer or external storage device via a network, for example, the Internet, a local area network, a wide area network and/or a wireless network. The network may

comprise copper transmission cables, optical transmission fibers, wireless transmission, routers, firewalls, switches, gateway computers and/or edge servers. A network adapter card or network interface in each computing/processing device receives computer readable program instructions from the network and forwards the computer readable program instructions for storage in a computer readable storage medium within the respective computing/processing device.

[0034] Computer readable program instructions for carrying out operations of embodiments may be assembler instructions, instruction-set-architecture (ISA) instructions, machine instructions, machine dependent instructions, microcode, firmware instructions, state-setting data, or either source code or object code written in any combination of one or more programming languages, including an object oriented programming language such as Smalltalk, C++ or the like, and conventional procedural programming languages, such as the "C" programming language or similar programming languages. The computer readable program instructions may execute entirely on the user's computer, partly on the user's computer, as a stand-alone software package, partly on the user's computer and partly on a remote computer or entirely on the remote computer or server. In the latter scenario, the remote computer may be connected to the user's computer through any type of network, including a local area network (LAN) or a wide area network (WAN), or the connection may be made to an external computer (for example, through the Internet using an Internet Service Provider). In some embodiments, electronic circuitry including, for example, programmable logic circuitry, field-programmable gate arrays (FPGA), or programmable logic arrays (PLA) may execute the computer readable program instructions by utilizing state information of the computer readable program instructions to personalize the electronic circuitry, in order to perform aspects of embodiments.

[0035] Aspects of embodiments are described herein with reference to flowchart illustrations and/or block diagrams of methods, apparatus (systems), and computer program products according to embodiments. It will be understood that each block of the flowchart illustrations and/or block diagrams, and combinations of blocks in the flowchart illustrations and/or block diagrams, can be implemented by computer readable program instructions.

[0036] These computer readable program instructions may be provided to a processor of a general purpose computer, special purpose computer, or other programmable data processing apparatus to produce a machine, such that the instructions, which execute via the processor of the computer or other programmable data processing apparatus, create means for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks. These computer readable program instructions may also be stored in a computer readable storage medium that can direct a computer, a programmable data processing apparatus, and/or other devices to function in a particular manner, such that the computer readable storage medium having instructions stored therein comprises an article of manufacture including instructions which implement aspects of the function/act specified in the flowchart and/or block diagram block or blocks.

[0037] The computer readable program instructions may also be loaded onto a computer, other programmable data processing apparatus, or other device to cause a series of operational steps to be performed on the computer, other programmable apparatus or other device to produce a computer implemented process, such that the instructions which execute on the computer, other programmable apparatus, or other device implement the functions/acts specified in the flowchart and/or block diagram block or blocks.

[0038] The flowchart and block diagrams in the Figures illustrate the architecture, functionality, and operation of possible implementations of systems, methods, and computer program products according to various embodiments. In this regard, each block in the flowchart or block diagrams may represent a module, segment, or portion of instructions, which comprises one or more executable instructions for implementing the specified logical function(s). In some alternative implementations, the functions noted in the block may occur out of the order noted in the figures. For example, two blocks shown in succession may, in fact, be executed substantially concurrently, or the blocks may sometimes be executed in the reverse order, depending upon the functionality involved. It will also be noted that each block of the block diagrams and/or flowchart illustration, and combinations of blocks in the block diagrams and/or flowchart illustration, can be implemented by special purpose hardware-based systems that perform the specified functions or acts or carry out combinations of special purpose hardware and computer instructions.

[0039] Reference is now made to FIG. 1, which is a schematic block diagram of a quadrature circulator according to embodiments of the invention. Quadrature circulator 10 includes quasi-circulator 100 and quadrature hybrid 150, which are connected in cascade. Quasi-circulator 100 and quadrature hybrid 150 have the same characteristic impedance Z_0 .

I. Quadrature Circulator

[0040] Quadrature circulator 10 includes quasi-circulator 100 and quadrature hybrid 150.

[0041] Quasi-circulator 100 has four ports: first port (101), second port (102), third port (103), and fourth port (104). Quadrature hybrid (150) has four ports: first port (151), second port (152), third port (153), and fourth port (154). The quasi-

circulator's fourth port (104) is connected to the quadrature hybrid's fourth port (154) and the quasi-circulator's third port (103) is connected to the quadrature hybrid's first port (151).

[0042] The remaining four ports (ports 101, 102, 152 and 153) serve as the ports of quadrature circulator (10) as follows:

- a) The first port of the quasi-circulator (101) serves as **Port 1** of quadrature circulator (10);
- b) The second port of the quasi-circulator (102) serves as **Port 2** of quadrature circulator (10);
- c) The third port of the quadrature hybrid (153) serves as **Port 3** of quadrature circulator (10); and
- d) The second port of the quadrature hybrid (152) serves as the **Port 4** of quadrature circulator (10).

[0043] As used herein, **Port 1**, **Port 2**, **Port 3** and **Port 4** denote the four ports of the quadrature circulator.

[0044] The scattering matrix (S1) of quasi-circulator 100 is:

$$S1 = \begin{bmatrix} 0 & 0 & -1/\sqrt{2} & -j/\sqrt{2} \\ -j & 0 & 0 & 0 \\ 0 & -j/\sqrt{2} & -1/2 & j/2 \\ 0 & -1/\sqrt{2} & -j/2 & -1/2 \end{bmatrix}.$$

Each entry $S1_{xy}$ of S1 represents a portion of a square root of a power of a signal that is directed by quasi-circulator (100) from the y th port to the x th port, wherein x and y each can be 1, 2, 3, and 4 and x is not equal to y , and each entry $S1_{xx}$ represents a portion of a square root of a power of a signal that is reflected at the x th port.

[0045] The scattering matrix (S2) of quadrature hybrid 150 is:

$$S2 = \begin{bmatrix} 0 & -j/\sqrt{2} & -1/\sqrt{2} & 0 \\ -j/\sqrt{2} & 0 & 0 & -1/\sqrt{2} \\ -1/\sqrt{2} & 0 & 0 & -j/\sqrt{2} \\ 0 & -1/\sqrt{2} & -j/\sqrt{2} & 0 \end{bmatrix}.$$

Similarly to the notation of S1, each entry $S2_{xy}$ of S2 represents a portion of a square root of a power of a signal that is directed by quadrature hybrid (150) from the quadrature hybrid's y th port to the x th port, wherein x and y each can be 1, 2, 3, and 4 and x is not equal to y , and each entry $S2_{xx}$ represents a portion of a square root of a power of a signal that is reflected at the quadrature hybrid's x th port.

[0046] Surprisingly, the inventors have found that a signal entering **Port 3** is fully transmitted to **Port 4** of quadrature circulator (10). This is despite the $-1/2$ reflection coefficients at quasi-circulator ports 103 and 104 and the transfer coefficients of $-j/2$ and $j/2$ between ports 103 to 104 and ports 104 to 103 respectively. While quadrature hybrid 150 divides the signal entering at **Port 3** equally in amplitude, the skilled person would not deduce that these two signal portions will add perfectly at **Port 4**. It is also unexpected that a signal entering **Port 4** will reconstruct at **Port 1**, since quasi-circulator ports 103 and 104 have reflection coefficients of $-1/2$.

[0047] In fact quadrature circulator (10) attains the ideal scattering matrix of:

$$|S_{4-Port_circ}| = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix},$$

where each entry $|S_{4-Port_circ-XY}|$ represents a portion of a square root of a power of a signal that is directed by quadrature circulator (10) from the Port X to Port Y of quadrature circulator (10), wherein X and Y each can be 1, 2, 3, and 4 and X is not equal to Y , and each entry $|S_{4-Port_circ-XX}|$ represents a portion of a square root of a power of a signal that is reflected at Port X of quadrature circulator (10). As can be seen from $|S_{4-Port_circ}|$, quadrature circulator (10) offers "circular" full transmission from port to port in one direction and zero transmission in the reverse direction as well as to non-adjacent ports, with perfect matching at all ports.

[0048] These results were validated by Mason's Flow-Graph analysis and by simulation. FIG. 2 is a schematic diagram of the simulated quadrature circulator. Both the Mason's Flow-Graph analysis and the simulation results show that the cascading the quasi-circulator and quadrature hybrid results in the $|S_{4-Port_circ-XY}|$ represented above. In particular, ideal transmission between **Port 4** and **Port 3** was demonstrated (i.e. $|S_{4-Port_circ-43}| = 1$).

[0049] Technologies for implementation of quadrature circulator (10) include but are not limited to:

- a) Discrete electronic components on printed circuit board (PCB);
- b) Fast electro-mechanical switches integrated with transmission lines;
- c) Gallium arsenide (GaAs);
- d) Gallium nitride (GaN);
- e) Silicon-germanium (SiGe);
- f) Complementary metal-oxide-semiconductor (CMOS); and
- d) Electro-optical and optical devices.

[0050] Optionally, the quadrature circulator is designed to operate in frequency bands ranging from 10 MHz to 100 GHz. Alternately or additionally, the quadrature circulator operates in optical frequencies.

[0051] Quadrature circulator 10 may be integrated into many types of communication system architectures and may be used for many types of communication techniques. Exemplary embodiments of communication techniques utilizing these architectures are presented below.

[0052] Optionally, **Port 2** of the quadrature circulator is configured to be connected to an antenna.

[0053] Optionally, **Port 3** of the quadrature circulator is configured to be connected to a reflective element. Alternately or additionally, **Port 1** of the quadrature circulator is configured to be connected to a reflective element.

[0054] As used herein the term "reflective element" means a circuit element which reflects the signal transferred from the previous port to the following port. Optionally, the reflective element has an input for transferring an input signal (e.g. a SIC signal) to the port it is connected to.

[0055] Examples of reflective elements include but are not limited to:

- 1) Reflective power amplifier;
- 2) Reflective isolator; and
- 3) Reflective buffer.

[0056] Optionally, **Port 4** of the quadrature circulator is configured to be connected to a circuit element which enables carrier aggregation with full-duplex (FD) communication. Examples of this circuit element include but are limited to:

- 1) A Quadrature Balanced Power Amplifier (QBPA); and
- 2) A second quadrature circulator.

Exemplary embodiments are described below with reference to Figs. 11-12.

II. Quasi-circulator

[0057] Reference is now made to FIG. 3, which is a schematic diagram of a quasi-circulator with scattering matrix S1. The quasi-circulator has non-ideal transfer between most pairs of ports 101-104, with reflection at ports 103 and 104.

[0058] Reference is now made to FIG. 4, which is a simplified block diagram of a quasi-circulator according to an exemplary embodiment of the invention. Quasi-circulator 400 comprises a first port 401, a second port 402, a third port 403, and a fourth port 404. The port impedances are all Z_0 .

[0059] A phase shifter is an electronic device that changes the phase of a propagating signal. A reciprocal phase shifter (RPS) introduces the same phase shift into signals propagating in both directions. A non-reciprocal phase shifter (NRPS) introduces different phase shifts into signals propagating in opposite directions.

[0060] In addition, the quadrature quasi-circulator device 400 further comprises a first 90 degree RPS 405 between the first port 401 and the second port 402; a second 90 degree RPS 406 between the second port 402 and the third port 403; a 90 degree NRPS 407 between the third port 403 and the fourth port 404; and a third 90 degree RPS 408 between the fourth port 404 and the first port 401. According to embodiments of this disclosure, the third port 403 and/or the fourth port 404 is isolated from the first port 401. In particular, a characteristic impedance of the first RPS 405 a first value, and a characteristic impedance of the second RPS 406 and the third PRS 408 is a second value, wherein the second value equals the first value divided by $\sqrt{2}$ (square-root of 2). In particular, the first value, i.e., the characteristic impedance of the first RPS 405, is equal to an impedance (i.e., a port impedance) of the first port 401.

[0061] It should be noted that, according to some embodiments, a phase of a forward signal path from the first port 401 through second port 402 to the third port 403 is 180 degrees, resulting from the -90 degree RPS 405 and the -90 degree RPS 406. Similarly, a phase of a forward signal path from the first port 401 through fourth port 404 to the third port 403 is 0 degrees, as a result of the 90 degree NRPS 407 and the -90 degree RPS 408.

[0062] It is noted that NRPS 407 (between the third port 403 and the fourth port 404) is "impedance transparent". Typically, the four ports of quasi-circulator 400 (401-404) have the same impedance value, for instance, a common value of the impedance is 50 ohm. However, other impedance values may also be used.

III. Quadrature hybrid

[0063] A quadrature hybrid is a four port device that splits an input signal at one of the ports equally between two output ports with a 90 degree phase difference between them. When quadrature signals are input to two of the ports, they combine constructively at one of the ports and combine destructively at the other port. The quadrature hybrid is a symmetric device, in which each port may serve as an input and/or output port. Many implementations of quadrature hybrids are known in the art.

[0064] FIG. 5 is a schematic diagram of an exemplary quadrature hybrid. The quadrature hybrid includes two branches with a characteristic impedance Z_0 , and two more branches with a characteristic impedance of $Z_0/\sqrt{2}$. Quadrature hybrid 300 ideally divides the input power equally between two of the other three ports, wherein the remaining port is fully isolated, in accordance with S2 above.

IV. Operation of a quadrature circulator

[0065] In some embodiments of the invention, a radio frequency (RF) signal is input into one of the quadrature circulator ports and an RF signal is output from at least one of the quadrature circulator ports as illustrated in FIGS. 6-11.

[0066] In some of the exemplary embodiments described herein the reflective element is a reflective power amplifier. Other embodiments may use different types of reflective element(s), such as reflective isolator(s).

IV.1. RF front end (RFFE) for full-duplex communication

[0067] Reference is now made to FIG. 6, which is a schematic block diagram of an RF front end for full-duplex (FD) communication according to an exemplary embodiment of the invention. The signal to be transmitted is input to **Port 1**. The received signal is input to **Port 2** and the SIC signal is Input to **Port 3**. **Port 4** is the RX output.

[0068] **Port 2** of quadrature circulator 610 is connected to an antenna. **Port 3** of quadrature circulator 610 is connected to the output of reflective SIC amplifier 620 (or alternately an isolator). **Port 3** is fully reflective and functions as a SIC input that directs its full power to the RX **Port 4** for TX leakage cancellation. Both **Port 3** and **Port 4** are isolated from the TX signal at **Port 1** ($S_{41}=0$, $S_{31}=0$).

IV.2. RF front end for half-duplex communication

[0069] Reference is now made to FIG. 7, which is a schematic block diagram of an RF front end for half-duplex (HD) communication, according to an exemplary embodiment of the invention. **Port 2** of quadrature circulator 710 is connected to an antenna. **Port 3** of quadrature circulator 710 is connected to the output of reflective SIC amplifier 720. In transmit mode, the TX input at **Port 1** is transferred completely to the antenna. In RX mode, all the antenna input signal power is reflected at **Port 3** and directed to **Port 4**.

IV.3. RF front end for Frequency Division-Duplex (FDD) communication

[0070] Reference is now made to FIG. 8, which is a schematic block diagram of an RF front end for Frequency Division-Duplex (FDD) communication, according to an exemplary embodiment of the invention. **Port 2** of quadrature circulator 810 is connected to an antenna. **Port 3** of quadrature circulator 810 is connected to the output of reflective SIC amplifier 820. **Port 3** is fully reflective and functions as a SIC input that directs its full power to the RX **Port 4** for TX leakage cancellation. In TX mode, **Port 1** transmits all the TX power to the antenna at frequency f_1 . In RX mode, all the power of a signal at frequency f_2 input from the antenna is reflected at **Port 3** and directed to **Port 4**. A SIC signal to cancel frequency f_1 at **Port 4** is injected from **Port 3**.

IV.4. RF front end for multiple-input and multiple-output (MIMO) communication

[0071] Reference is now made to FIG. 9, which is a schematic block diagram of an RF front end for MIMO communication, according to an exemplary embodiment of the invention. RFFE 900 is suitable for a MIMO architecture operating in half-duplex, simultaneous transmit-receive FDD and FD modes.

[0072] In FDD and FD, no RF coupling between different antennas is required for cancelling mutual TX leakages because all SIC functionality may be lumped into the **Port 4**. The SIC signal counteracts all the leakages for adjacent MIMO antennas and transmitters.

IV.5. RF front end for Carrier Aggregation (CA) communication

[0073] Reference is now made to FIG. 10, which is a schematic block diagram of an RF front end for Carrier Aggregation communication, according to an exemplary embodiment of the invention. RFFE 1000 is suitable for CA architecture. An RF transmit signal TX₁ with a carrier frequency of f₁ is input to reflective PA₁ 1020. An RF transmit signal TX₂ with a carrier frequency of f₂ is input at **Port 4** of circulator 1010. The aggregated signal is output to an antenna at **Port 2**.

IV.6. RF front ends for Carrier Aggregation (CA) communication

[0074] Reference is now made to FIG. 11, which is a schematic block diagram of an RF front end for Carrier Aggregation communication and concurrent full-duplex operation, according to a first exemplary embodiment. RFFE 1100 is also suitable for HD and STR\FDD communication modes and for MIMO systems.

[0075] In order to support simultaneous transmit-receive for CA FD communications, RFFE 1100 includes two quadrature circulators, 1110 and 1130. **Port 2** of quadrature circulator 1130 is connected to **Port 4** of quadrature circulator 1110.

[0076] RF transmit signal TX₁ with a carrier frequency of f₁ is input via reflective PA₁ 1120 to **Port 1** of quadrature circulator 1110. RF transmit signal TX₂ with a carrier frequency of f₂ is input to **Port 1** of quadrature circulator 1130. Quadrature circulator 1130 also inputs an SIC signal at **Port 3** and outputs an RX signal at **Port 4**. The aggregated signal is output to an antenna at **Port 2** of quadrature circulator 1100.

[0077] RFFE 1100 has a simultaneous transmit/receive operation for **Port 4** of quadrature circulator 1110 and therefore supports CA FD communications.

[0078] RFFE 1100 includes a second reflective power amplifier 1140 for transferring an SIC signal to **Port 3**.

[0079] Reference is now made to FIG. 12, which is a schematic block diagram of an RF front end for Carrier Aggregation communication and concurrent full-duplex operation, according to a second exemplary embodiment of the invention. RFFE 1200 is also suitable for operating in HD and STR\FDD modes and for MIMO communications.

[0080] In order to support simultaneous transmit-receive for CA FD communications, RFFE 1200 includes QBPA 1230.

[0081] An RF transmit signal TX₁ with a carrier frequency of f₁ is input to reflective PA₁ 1220. QBPA 1230 provides a combined SIC signal and RF transmit signal TX₂ with a carrier frequency of f₂ to **Port 4** of circulator 1210. The aggregated signal is output to an antenna at **Port 2** of quadrature circulator 1210.

[0082] The RX output of QBPA 1230 enables a simultaneous transmit/receive operation for **Port 4** of quadrature circulator 1210 and therefore supports CA FD communications.

[0083] RFFE 1100 includes a second reflective power amplifier 1240 for transferring an SIC signal to **Port 3**.

[0084] Embodiments of the invention cascade a quasi-circulator and a quadrature hybrid to obtain an ideal quadrature circulator with full transmission and no power loss between consecutive ports. The quadrature circulator has a small form factor and on-chip integration compatibility. The quadrature circulator may be integrated into RF front ends that are suitable for many system architectures and modes of RF communication.

[0085] The descriptions of the various embodiments have been presented for purposes of illustration, but are not intended to be exhaustive or limited to the embodiments disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art without departing from the scope of the described embodiments. The terminology used herein was chosen to best explain the principles of the embodiments, the practical application or technical improvement over technologies found in the marketplace, or to enable others of ordinary skill in the art to understand the embodiments disclosed herein.

[0086] As used herein the term "about" refers to $\pm 10\%$.

[0087] The terms "comprises", "comprising", "includes", "including", "having" and their conjugates mean "including but not limited to". This term encompasses the terms "consisting of" and "consisting essentially of".

[0088] The phrase "consisting essentially of" means that the composition or method may include additional ingredients and/or steps, but only if the additional ingredients and/or steps do not materially alter the basic and novel characteristics of the claimed composition or method.

[0089] As used herein, the singular form "a", "an" and "the" include plural references unless the context clearly dictates otherwise. For example, the term "a compound" or "at least one compound" may include a plurality of compounds, including mixtures thereof.

[0090] The word "exemplary" is used herein to mean "serving as an example, instance or illustration". Any embodiment described as "exemplary" is not necessarily to be construed as preferred or advantageous over other embodiments and/or to exclude the incorporation of features from other embodiments.

[0091] The word "optionally" is used herein to mean "is provided in some embodiments and not provided in other embodiments". Any particular embodiment may include a plurality of "optional" features unless such features conflict.

[0092] Throughout this application, various embodiments may be presented in a range format. It should be understood that the description in range format is merely for convenience and brevity and should not be construed as an inflexible

limitation on the scope of embodiments. Accordingly, the description of a range should be considered to have specifically disclosed all the possible subranges as well as individual numerical values within that range. For example, description of a range such as from 1 to 6 should be considered to have specifically disclosed subranges such as from 1 to 3, from 1 to 4, from 1 to 5, from 2 to 4, from 2 to 6, from 3 to 6 etc., as well as individual numbers within that range, for example, 1, 2, 3, 4, 5, and 6. This applies regardless of the breadth of the range.

[0093] Whenever a numerical range is indicated herein, it is meant to include any cited numeral (fractional or integral) within the indicated range. The phrases "ranging/ranges between" a first indicate number and a second indicate number and "ranging/ranges from" a first indicate number "to" a second indicate number are used herein interchangeably and are meant to include the first and second indicated numbers and all the fractional and integral numerals therebetween.

[0094] It is appreciated that certain features of embodiments, which are, for clarity, described in the context of separate embodiments, may also be provided in combination in a single embodiment. Conversely, various features of embodiments, which are, for brevity, described in the context of a single embodiment, may also be provided separately or in any suitable subcombination or as suitable in any other described embodiment. Certain features described in the context of various embodiments are not to be considered essential features of those embodiments, unless the embodiment is inoperative without those elements.

[0095] Although embodiments have been described in conjunction with specific embodiments thereof, it is evident that many alternatives, modifications and variations will be apparent to those skilled in the art. Accordingly, it is intended to embrace all such alternatives, modifications and variations that fall within the scope of the appended claims.

Claims

1. A four-port circulator device comprising:

a quasi-circulator (100) comprising:

a first port (101), a second port (102), a third port (103), and a fourth port (104), wherein a scattering matrix S1 of said quasi-circulator (100) is represented as:

$$S1 = \begin{bmatrix} 0 & 0 & -1/\sqrt{2} & -j/\sqrt{2} \\ -j & 0 & 0 & 0 \\ 0 & -j/\sqrt{2} & -1/2 & j/2 \\ 0 & -1/\sqrt{2} & -j/2 & -1/2 \end{bmatrix},$$

wherein each entry $S1_{xy}$ of the scattering matrix S1 represents a portion of a square root of a power of a signal that is directed by the quasi-circulator (100) from the yth port to the xth port, wherein x and y each can be 1, 2, 3, and 4 and x is not equal to y, and each entry $S1_{xx}$ represents a portion of a square root of a power of a signal that is reflected at the xth port; and

a quadrature hybrid (150) comprising a first port (151), a second port (152), a third port (153), and a fourth port (154), wherein a scattering matrix S2 of said quadrature hybrid (150) is represented as:

$$S2 = \begin{bmatrix} 0 & -j/\sqrt{2} & -1/\sqrt{2} & 0 \\ -j/\sqrt{2} & 0 & 0 & -1/\sqrt{2} \\ -1/\sqrt{2} & 0 & 0 & -j/\sqrt{2} \\ 0 & -1/\sqrt{2} & -j/\sqrt{2} & 0 \end{bmatrix},$$

wherein each entry $S2_{xy}$ of the scattering matrix S2 represents a portion of a square root of a power of a signal that is directed by the quadrature hybrid (150) from the yth port to the xth port, wherein x and y each can be 1, 2, 3, and 4 and x is not equal to y, and each entry $S2_{xx}$ represents a portion of a square root of a power of a signal that is reflected at the xth port,

and wherein said fourth port of said quasi-circulator (104) is connected to said fourth port of said quadrature hybrid (154) and said third port of said quasi-circulator (103) is connected to said first port of said quadrature hybrid (151).

2. A four-port circulator device according to claim 1, wherein said quasi-circulator (400) comprises:

a first 90 degree reciprocal phase shifter, RPS (405), between said first port (401) of said quasi-circulator and said second port (402) of said quasi-circulator;

a second 90 degree RPS (406) between said second port (402) of said quasi-circulator and said third port (403) of said quasi-circulator;
a 90 degree non-reciprocal phase shifter, NRPS (407), between said third port (403) of said quasi-circulator and said fourth port (404) of said quasi-circulator; and
a third 90 degree RPS (408) between said fourth port (404) of said quasi-circulator and said first port (401) of said quasi-circulator;

wherein a characteristic impedance of said first RPS (405) is a first value that is equal to an impedance of said first port (401) of said quasi-circulator, and a characteristic impedance of said second RPS (406) and said third RPS (408) is a second value, wherein said second value equals said first value divided by $\sqrt{2}$.

3. The four-port circulator device (100) according to claim 2, wherein the NRPS (407) is impedance transparent.

4. The four-port circulator device according to any one of claims 1-3, wherein a phase of a forward signal path from the first port (101) of said quasi-circulator through second port (102) of said quasi-circulator to the third port (103) of said quasi-circulator is 180 degree, and a phase of a forward signal path from the first port (101) of said quasi-circulator through fourth port (104) of said quasi-circulator to the third port (103) of said quasi-circulator is 0 degree.

5. The four-port circulator device (100) according to one of claims 1-4, further comprising an antenna connected to said second port of said quasi-circulator (102).

6. The four-port circulator device (100) according to one of claims 1-5, further comprising a first reflective element, wherein an output of said first reflective element is connected to said third port of said quadrature hybrid (153).

7. The four-port circulator device (100) according to one of claims 1-6, further comprising a second reflective element, wherein an output of said second reflective element is connected to said first port of said quasi-circulator (101).

8. A method for operating a four-port circulator device according to claim 1, comprising:

inputting a first radio frequency, RF, signal into one of said first port of said quasi-circulator (101), said second port of said quasi-circulator (102), said second port of said quadrature hybrid (152) and said third port of said quadrature hybrid (153); and

outputting a second radio frequency, RF, signal from one of said first port of said quasi-circulator (101), said second port of said quasi-circulator (102), said second port of said quadrature hybrid (152) and said third port of said quadrature hybrid (153).

9. A method for operating a four-port circulator device according to claim 8, comprising:

inputting a transmit signal at said first port of said quasi-circulator (101);
inputting a received signal from an antenna connected to said second port of said quasi-circulator (102) and outputting said transmit signal to said antenna;

inputting a self-interference cancellation, SIC, signal at said third port of said quadrature hybrid (153) via a reflective element (620); and

outputting said received signal from said second port of said quadrature hybrid (152).

10. A method for operating a four-port circulator device according to claim 8, comprising:

inputting a transmit signal at said first port of said quasi-circulator (101);
inputting a received signal from an antenna connected to said second port of said quasi-circulator (102) and outputting said transmit signal to said antenna;

reflecting said received signal at said third port of said quadrature hybrid (153) via a reflective element (720) connected to said third port of said quadrature hybrid (153); and

outputting said received signal from said second port of said quadrature hybrid (152).

11. A method for operating a four-port circulator device according to claim 8, comprising:

inputting a transmit signal in a first frequency band at said first port of said quasi-circulator (101);

inputting a received signal at a second frequency band from an antenna connected to said second port of said quasi-circulator (102) and outputting said transmit signal to said antenna;
inputting a self-interference cancellation, SIC, signal at said third port of said quadrature hybrid (153) via a reflective element (820); and
outputting said received signal from said second port of said quadrature hybrid (152).

12. A method for operating a four-port circulator device according to claim 8, comprising:

inputting a first transmit signal in a first frequency band at said first port of said quasi-circulator (101) via a reflective element (1020);
inputting a second transmit signal in a second frequency band at said second port of said quadrature hybrid (152);
and
outputting said first transmit signal and said second transmit signal from said second port of said quasi-circulator (102).

Patentansprüche

1. Viertorige Zirkulatorvorrichtung, umfassend:

einen Quasi-Zirkulator (100), umfassend:
ein erstes Tor (101), ein zweites Tor (102), ein drittes Tor (103) und ein viertes Tor (104), wobei eine Streumatrix S1 des Quasi-Zirkulators (100) folgendermaßen dargestellt wird:

$$S1 = \begin{bmatrix} 0 & 0 & -1/\sqrt{2}-j/\sqrt{2} \\ -j & 0 & 0 & 0 \\ 0 & -j/\sqrt{2} & -1/2 & j/2 \\ 0 & -1/\sqrt{2} & -j/2 & -1/2 \end{bmatrix},$$

wobei jeder Eintrag $S1_{xy}$ der Streumatrix S1 einen Abschnitt einer Quadratwurzel einer Potenz eines Signals darstellt, das durch den Quasi-Zirkulator (100) von dem y-ten Tor zu dem x-ten Tor geleitet wird, wobei x und y jeweils 1, 2, 3 und 4 sein können und x nicht gleich y ist und jeder Eintrag $S1_{xx}$ einen Abschnitt einer Quadratwurzel einer Potenz eines Signals darstellt, das an dem x-ten Tor reflektiert wird; und
ein Quadraturhybrid (150), umfassend ein erstes Tor (151), ein zweites Tor (152), ein drittes Tor (153) und ein viertes Tor (154),

wobei eine Streumatrix S2 des Quadraturhybrids (150) folgendermaßen dargestellt wird:

$$S2 = \begin{bmatrix} 0 & -j/\sqrt{2}-1/\sqrt{2} & 0 \\ -j/\sqrt{2} & 0 & 0 & -1/\sqrt{2} \\ -1/\sqrt{2} & 0 & 0 & -j/\sqrt{2} \\ 0 & -1/\sqrt{2}-j/\sqrt{2} & 0 \end{bmatrix},$$

wobei jeder Eintrag $S2_{xy}$ der Streumatrix S2 einen Abschnitt einer Quadratwurzel einer Potenz eines Signals darstellt, das durch das Quadraturhybrid (150) von dem y-ten Tor zu dem x-ten Tor geleitet wird, wobei x und y jeweils 1, 2, 3 und 4 sein können und x nicht gleich y ist und jeder Eintrag $S2_{xx}$ einen Abschnitt einer Quadratwurzel einer Potenz eines Signals darstellt, das an dem x-ten Tor reflektiert wird,
und wobei das vierte Tor des Quasi-Zirkulators (104) mit dem vierten Tor des Quadraturhybrids (154) verbunden ist und das dritte Tor des Quasi-Zirkulators (103) mit dem ersten Tor des Quadraturhybrids (151) verbunden ist.

2. Viertorige Zirkulatorvorrichtung nach Anspruch 1, wobei der Quasi-Zirkulator (400) Folgendes umfasst:

einen ersten reziproken 90-Grad-Phasenschieber, RPS, (405) zwischen dem ersten Tor (401) des Quasi-Zirkulators und dem zweiten Tor (402) des Quasi-Zirkulators;
einen zweiten 90-Grad-RPS (406) zwischen dem zweiten Tor (402) des Quasi-Zirkulators und dem dritten Tor (403) des Quasi-Zirkulators;
einen nichtreziproken 90-Grad-Phasenschieber, NRPS, (407) zwischen dem dritten Tor (403) des Quasi-

Zirkulators und dem vierten Tor (404) des Quasi-Zirkulators; und einen dritten 90-Grad-RPS (408) zwischen dem vierten Tor (404) des Quasi-Zirkulators und dem ersten Tor (401) des Quasi-Zirkulators; wobei eine charakteristische Impedanz des ersten RPS (405) ein erster Wert ist, der gleich einer Impedanz des ersten Tores (401) des Quasi-Zirkulators ist, und eine charakteristische Impedanz des zweiten RPS (406) und des dritten RPS (408) ein zweiter Wert ist, wobei der zweite Wert gleich dem ersten Wert geteilt durch $\sqrt{2}$ ist.

3. Viertorige Zirkulatorvorrichtung (100) nach Anspruch 2, wobei der NRPS (407) impedanztransparent ist.

4. Viertorige Zirkulatorvorrichtung nach einem der Ansprüche 1-3, wobei eine Phase eines Vorwärtssignalfads von dem ersten Tor (101) des Quasi-Zirkulators über das zweite Tor (102) des Quasi-Zirkulators zu dem dritten Tor (103) des Quasi-Zirkulators 180 Grad beträgt und eine Phase eines Vorwärtssignalfads von dem ersten Tor (101) des Quasi-Zirkulators über das vierte Tor (104) des Quasi-Zirkulators zu dem dritten Tor (103) des Quasi-Zirkulators 0 Grad beträgt.

5. Viertorige Zirkulatorvorrichtung (100) nach einem der Ansprüche 1-4, ferner umfassend eine Antenne, die mit dem zweiten Tor des Quasi-Zirkulators (102) verbunden ist.

6. Viertorige Zirkulatorvorrichtung (100) nach einem der Ansprüche 1-5, ferner umfassend ein erstes reflektierendes Element, wobei eine Ausgabe des ersten reflektierenden Elements mit dem dritten Tor des Quadraturhybrids (153) verbunden ist.

7. Viertorige Zirkulatorvorrichtung (100) nach einem der Ansprüche 1-6, ferner umfassend ein zweites reflektierendes Element, wobei eine Ausgabe des zweiten reflektierenden Elements mit dem ersten Tor des Quasi-Zirkulators (101) verbunden ist.

8. Verfahren zum Betreiben einer viertorigen Zirkulatorvorrichtung nach Anspruch 1, umfassend:

Eingeben eines ersten Hochfrequenzsignals, RF-Signals, in eines des ersten Tores des Quasi-Zirkulators (101), des zweiten Tores des Quasi-Zirkulators (102), des zweiten Tores des Quadraturhybrids (152) und des dritten Tores des Quadraturhybrids (153); und Ausgeben eines zweiten Hochfrequenzsignals, RF-Signals, von einem des ersten Tores des Quasi-Zirkulators (101), des zweiten Tores des Quasi-Zirkulators (102), des zweiten Tores des Quadraturhybrids (152) und des dritten Tores des Quadraturhybrids (153).

9. Verfahren zum Betreiben einer viertorigen Zirkulatorvorrichtung nach Anspruch 8, umfassend:

Eingeben eines Übertragungssignals an dem ersten Tor des Quasi-Zirkulators (101); Eingeben eines empfangenen Signals von einer Antenne, die mit dem zweiten Tor des Quasi-Zirkulators (102) verbunden ist, und Ausgeben des Übertragungssignals an die Antenne; Eingeben eines Selbstinterferenzunterdrückungssignals, SIC-Signals, an dem dritten Tor des Quadraturhybrids (153) über ein reflektierendes Element (620); und Ausgeben des empfangenen Signals von dem zweiten Tor des Quadraturhybrids (152).

10. Verfahren zum Betreiben einer viertorigen Zirkulatorvorrichtung nach Anspruch 8, umfassend:

Eingeben eines Übertragungssignals an dem ersten Tor des Quasi-Zirkulators (101); Eingeben eines empfangenen Signals von einer Antenne, die mit dem zweiten Tor des Quasi-Zirkulators (102) verbunden ist, und Ausgeben des Übertragungssignals an die Antenne; Reflektieren des empfangenen Signals an dem dritten Tor des Quadraturhybrids (153) über ein reflektierendes Element (720), das mit dem dritten Tor des Quadraturhybrids (153) verbunden ist; und Ausgeben des empfangenen Signals von dem zweiten Tor des Quadraturhybrids (152).

11. Verfahren zum Betreiben einer viertorigen Zirkulatorvorrichtung nach Anspruch 8, umfassend:

Eingeben eines Übertragungssignals in einem ersten Frequenzband an dem ersten Tor des Quasi-Zirkulators (101);

Eingeben eines empfangenen Signals an einem zweiten Frequenzband von einer Antenne, die mit dem zweiten Tor des Quasi-Zirkulators (102) verbunden ist, und Ausgeben des Übertragungssignals an die Antenne;
 Eingeben eines Selbstinterferenzunterdrückungssignals, SIC-Signals, an dem dritten Tor des Quadraturhybrids (153) über ein reflektierendes Element (820); und
 Ausgeben des empfangenen Signals von dem zweiten Tor des Quadraturhybrids (152).

12. Verfahren zum Betreiben einer viertorigen Zirkulatorvorrichtung nach Anspruch 8, umfassend:

Eingeben eines ersten Übertragungssignals in einem ersten Frequenzband an dem ersten Tor des Quasi-Zirkulators (101) über ein reflektierendes Element (1020);
 Eingeben eines zweiten Übertragungssignals in einem zweiten Frequenzband an dem zweiten Tor des Quadraturhybrids (152); und
 Ausgeben des ersten Übertragungssignals und des zweiten Übertragungssignals von dem zweiten Tor des Quasi-Zirkulators (102).

Revendications

1. Dispositif de circulateur à quatre ports comprenant :

un quasi-circulateur (100) comprenant :

un premier port (101), un deuxième port (102), un troisième port (103) et un quatrième port (104), dans lequel une matrice de diffusion S1 dudit quasi-circulateur (100) est représentée comme suit :

$$S1 = \begin{bmatrix} 0 & 0 & -1/\sqrt{2}-j/\sqrt{2} \\ -j & 0 & 0 & 0 \\ 0 & -j/\sqrt{2} & -1/2 & j/2 \\ 0 & -1/\sqrt{2} & -j/2 & -1/2 \end{bmatrix},$$

dans lequel chaque entrée $S1_{xy}$ de la matrice de diffusion S1 représente une partie d'une racine carrée d'une puissance d'un signal qui est dirigé par le quasi-circulateur (100) du y-ième port au x-ième port, dans lequel x et y peuvent chacun être 1, 2, 3 et 4 et x n'est pas égal à y, et chaque entrée $S1_{xx}$ représente une partie d'une racine carrée d'une puissance d'un signal qui est réfléchi au niveau du x-ième port ; et

un hybride en quadrature (150) comprenant un premier port (151),

un deuxième port (152), un troisième port (153) et un quatrième port (154), dans lequel une matrice de diffusion S2 dudit hybride en quadrature (150) est représentée comme suit :

$$S2 = \begin{bmatrix} 0 & -j/\sqrt{2}-1/\sqrt{2} & 0 \\ -j/\sqrt{2} & 0 & 0 & -1/\sqrt{2} \\ -1/\sqrt{2} & 0 & 0 & -j/\sqrt{2} \\ 0 & -1/\sqrt{2}-j/\sqrt{2} & 0 \end{bmatrix},$$

dans lequel chaque entrée $S2_{xy}$ de la matrice de diffusion S2 représente une partie d'une racine carrée d'une puissance d'un signal qui est dirigé par l'hybride en quadrature (150) du y-ième port au x-ième port, dans lequel x et y peuvent chacun être 1, 2, 3 et 4 et x n'est pas égal à y, et chaque entrée $S2_{xx}$ représente une partie d'une racine carrée d'une puissance d'un signal qui est réfléchi au niveau du x-ième port,

et dans lequel ledit quatrième port dudit quasi-circulateur (104) est connecté audit quatrième port dudit hybride en quadrature (154) et ledit troisième port dudit quasi-circulateur (103) est connecté audit premier port dudit hybride en quadrature (151).

2. Dispositif de circulateur à quatre ports selon la revendication 1, dans lequel ledit quasi-circulateur (400) comprend :

un premier déphaseur réciproque, RPS, à 90 degrés (405) entre ledit premier port (401) dudit quasi-circulateur et ledit deuxième port (402) dudit quasi-circulateur ;

un deuxième RPS à 90 degrés (406) entre ledit deuxième port (402) dudit quasi-circulateur et ledit troisième port (403) dudit quasi-circulateur ;

un déphaseur non réciproque, NRPS, à 90 degrés (407) entre ledit troisième port (403) dudit quasi-circulateur et ledit quatrième port (404) dudit quasi-circulateur ; et
 un troisième RPS à 90 degrés (408) entre ledit quatrième port (404) dudit quasi-circulateur et ledit premier port (401) dudit quasi-circulateur ;
 dans lequel une impédance caractéristique dudit premier RPS (405) est une première valeur qui est égale à une impédance dudit premier port (401) dudit quasi-circulateur, et une impédance caractéristique dudit deuxième RPS (406) et dudit troisième RPS (408) est une seconde valeur, dans lequel ladite seconde valeur est égale à ladite première valeur divisée par $\sqrt{2}$.

3. Dispositif de circulateur à quatre ports (100) selon la revendication 2, dans lequel le NRPS (407) est transparent à l'impédance.

4. Dispositif de circulateur à quatre ports selon l'une quelconque des revendications 1 à 3, dans lequel une phase d'un trajet de signal direct à partir du premier port (101) dudit quasi-circulateur à travers le deuxième port (102) dudit quasi-circulateur jusqu'au troisième port (103) dudit quasi-circulateur est de 180 degrés, et une phase d'un trajet de signal direct à partir du premier port (101) dudit quasi-circulateur à travers le quatrième port (104) dudit quasi-circulateur jusqu'au troisième port (103) dudit quasi-circulateur est de 0 degré.

5. Dispositif de circulateur à quatre ports (100) selon l'une des revendications 1 à 4, comprenant également une antenne connectée audit deuxième port dudit quasi-circulateur (102).

6. Dispositif de circulateur à quatre ports (100) selon l'une des revendications 1 à 5, comprenant également un premier élément réfléchissant, dans lequel une sortie dudit premier élément réfléchissant est connectée audit troisième port dudit hybride en quadrature (153).

7. Dispositif de circulateur à quatre ports (100) selon l'une des revendications 1 à 6, comprenant également un second élément réfléchissant, dans lequel une sortie dudit second élément réfléchissant est connectée audit premier port dudit quasi-circulateur (101).

8. Procédé de fonctionnement d'un dispositif de circulateur à quatre ports selon la revendication 1, comprenant :

l'entrée d'un premier signal de radiofréquence, RF, dans l'un dudit premier port dudit quasi-circulateur (101), dudit deuxième port dudit quasi-circulateur (102), dudit deuxième port dudit hybride en quadrature (152) et dudit troisième port dudit hybride en quadrature (153) ; et
 l'émission d'un second signal de radiofréquence, RF, à partir de l'un dudit premier port dudit quasi-circulateur (101), dudit deuxième port dudit quasi-circulateur (102), dudit deuxième port dudit hybride en quadrature (152) et dudit troisième port dudit hybride en quadrature (153).

9. Procédé de fonctionnement d'un dispositif de circulateur à quatre ports selon la revendication 8, comprenant :

l'entrée d'un signal de transmission au niveau dudit premier port dudit quasi-circulateur (101) ;
 l'entrée d'un signal reçu à partir d'une antenne connectée audit deuxième port dudit quasi-circulateur (102) et l'émission dudit signal de transmission à ladite antenne ;
 l'entrée d'un signal d'annulation d'auto-interférence, SIC, au niveau dudit troisième port dudit hybride en quadrature (153) via un élément réfléchissant (620) ; et
 l'émission dudit signal reçu à partir dudit deuxième port dudit hybride en quadrature (152).

10. Procédé de fonctionnement d'un dispositif de circulateur à quatre ports selon la revendication 8, comprenant :

l'entrée d'un signal de transmission au niveau dudit premier port dudit quasi-circulateur (101) ;
 l'entrée d'un signal reçu à partir d'une antenne connectée audit deuxième port dudit quasi-circulateur (102) et l'émission dudit signal de transmission à ladite antenne ;
 la réflexion dudit signal reçu au niveau dudit troisième port dudit hybride en quadrature (153) via un élément réfléchissant (720) connecté audit troisième port dudit hybride en quadrature (153) ; et
 l'émission dudit signal reçu à partir dudit deuxième port dudit hybride en quadrature (152).

11. Procédé de fonctionnement d'un dispositif de circulateur à quatre ports selon la revendication 8, comprenant :

l'entrée d'un signal de transmission dans une première bande de fréquence au niveau dudit premier port dudit quasi-circulateur (101) ;

l'entrée d'un signal reçu au niveau d'une seconde bande de fréquence à partir d'une antenne connectée audit deuxième port dudit quasi-circulateur (102) et l'émission dudit signal de transmission à ladite antenne ;

l'entrée d'un signal d'annulation d'auto-interférence, SIC, au niveau dudit troisième port dudit hybride en quadrature (153) via un élément réfléchissant (820) ; et

l'émission dudit signal reçu à partir dudit deuxième port dudit hybride en quadrature (152).

12. Procédé de fonctionnement d'un dispositif de circulateur à quatre ports selon la revendication 8, comprenant :

l'entrée d'un premier signal de transmission dans une première bande de fréquence au niveau dudit premier port dudit quasi-circulateur (101) via un élément réfléchissant (1020) ;

l'entrée d'un second signal de transmission dans une seconde bande de fréquence au niveau dudit deuxième port dudit hybride en quadrature (152) ; et

l'émission dudit premier signal de transmission et dudit second signal de transmission à partir dudit deuxième port dudit quasi-circulateur (102).

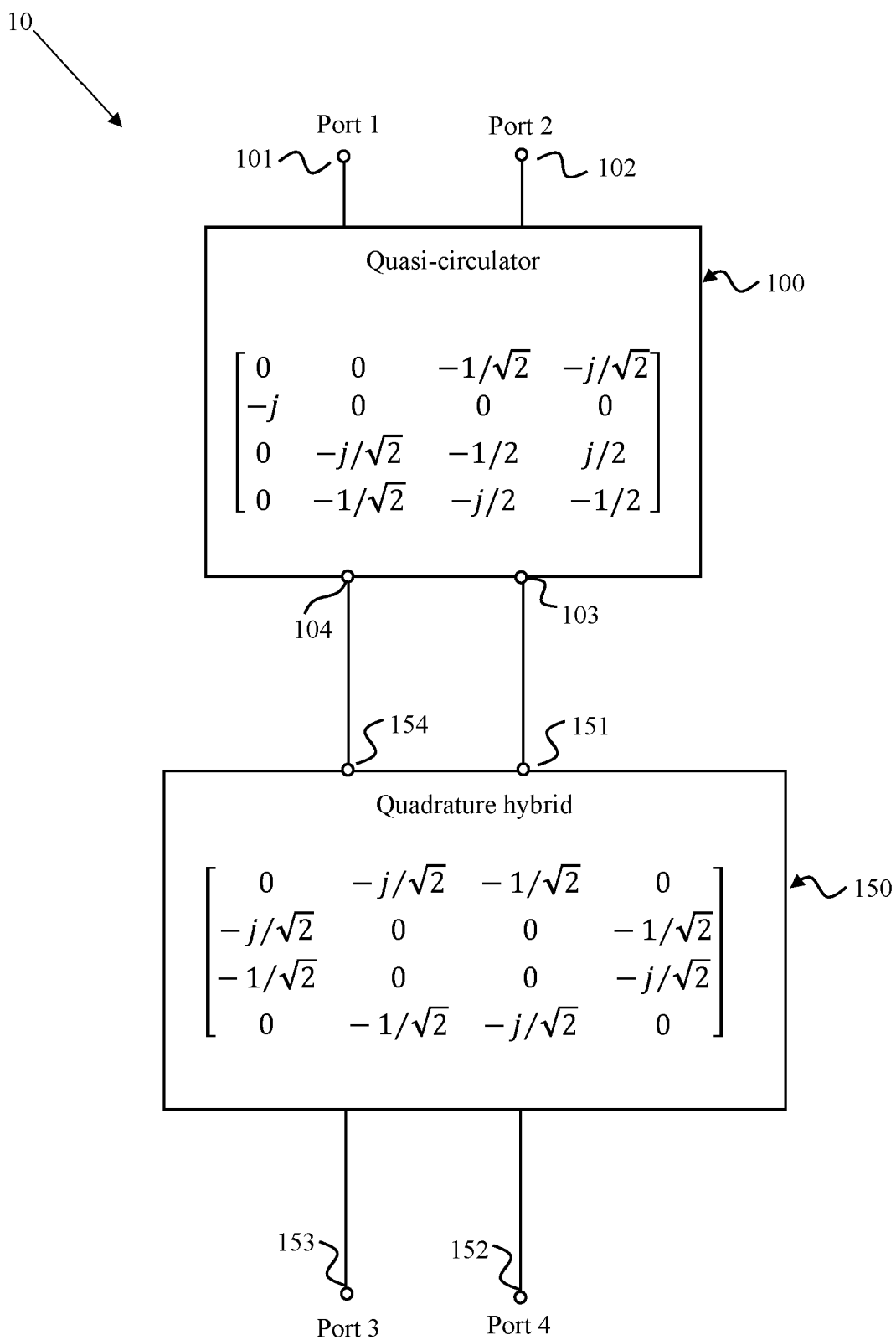


FIG. 1

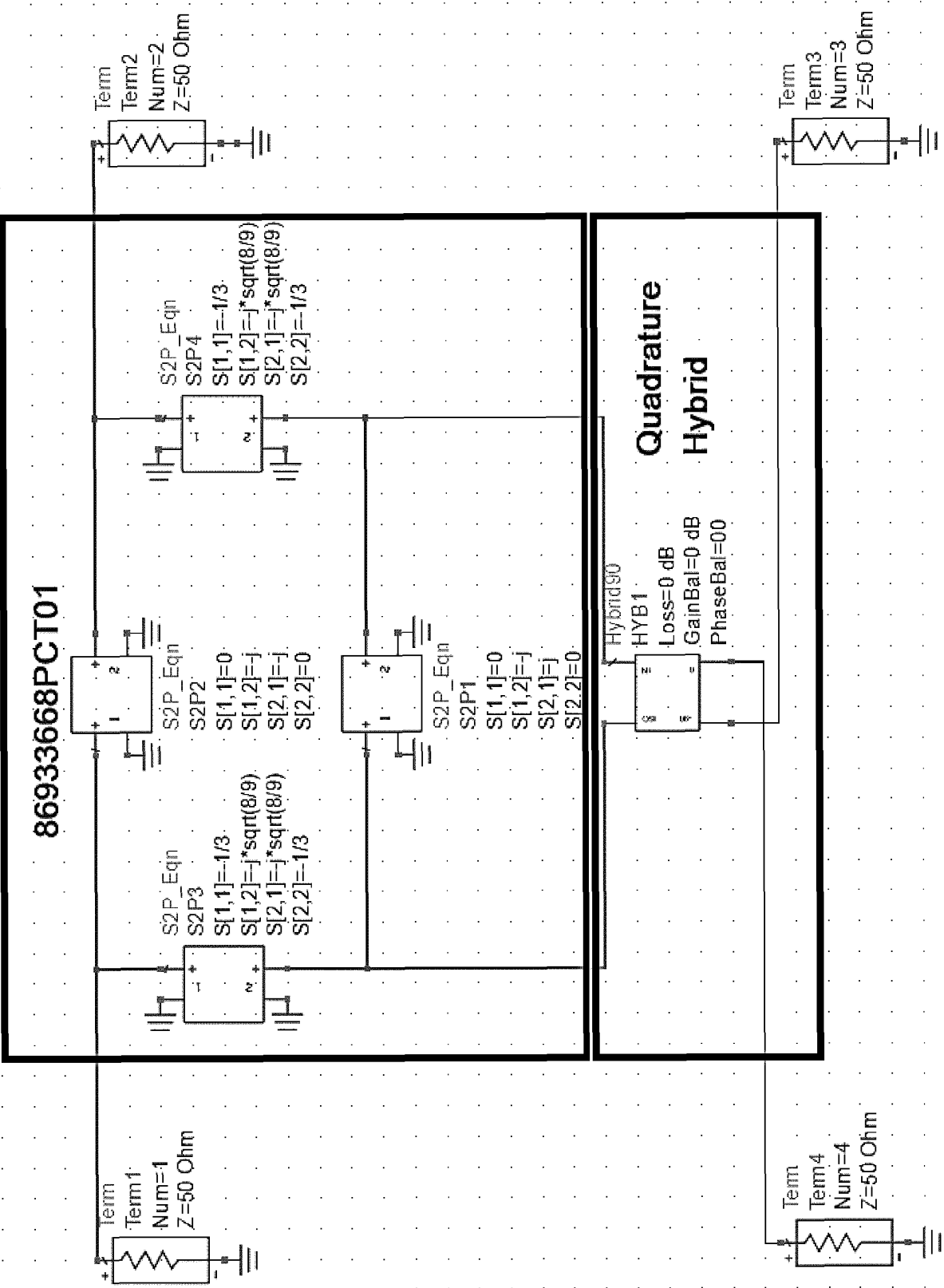


FIG. 2

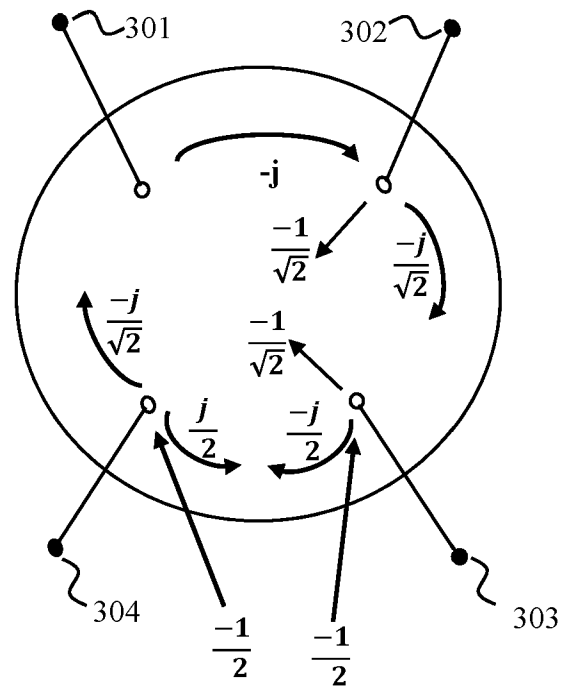


FIG. 3

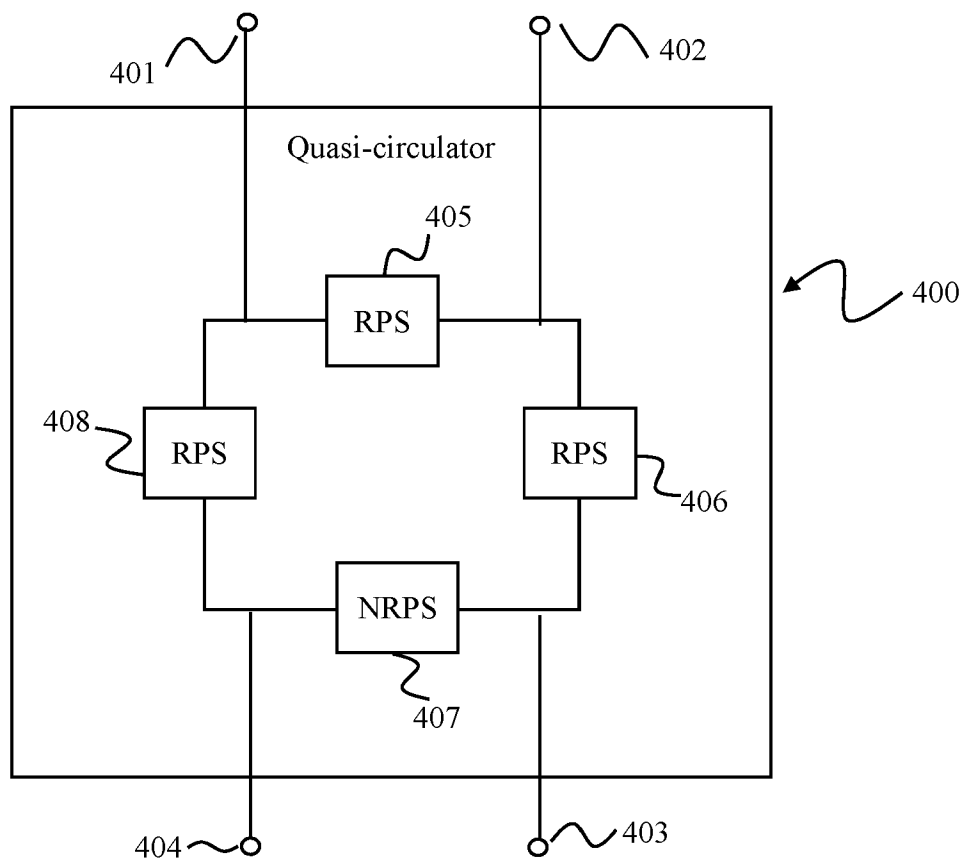


FIG. 4

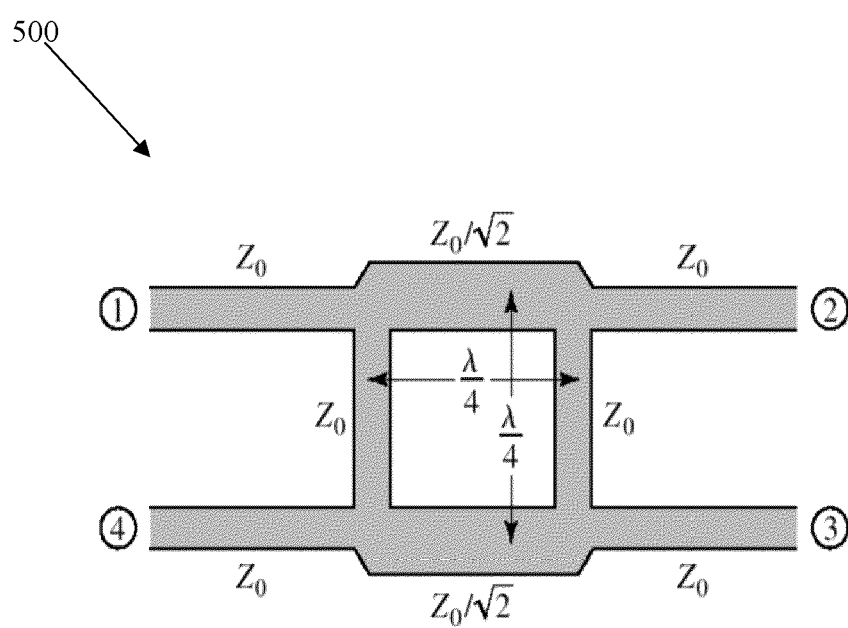


FIG. 5

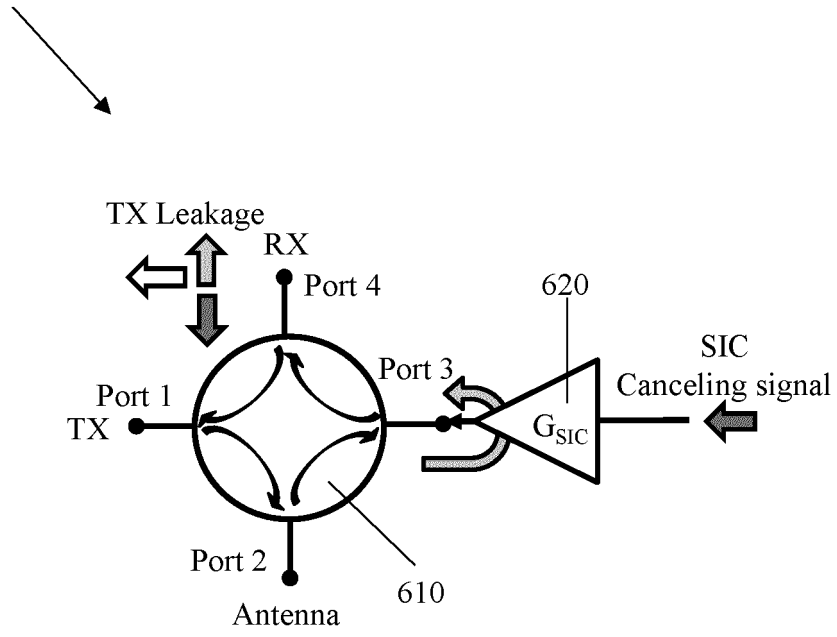


FIG. 6

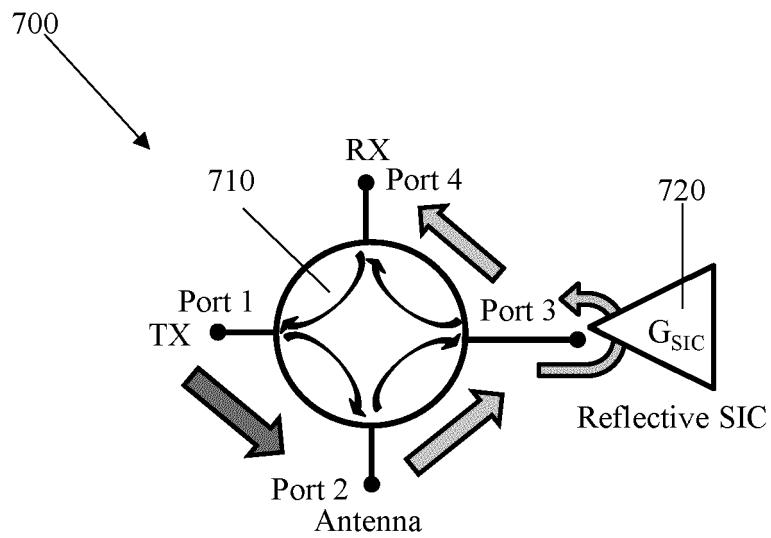


FIG. 7

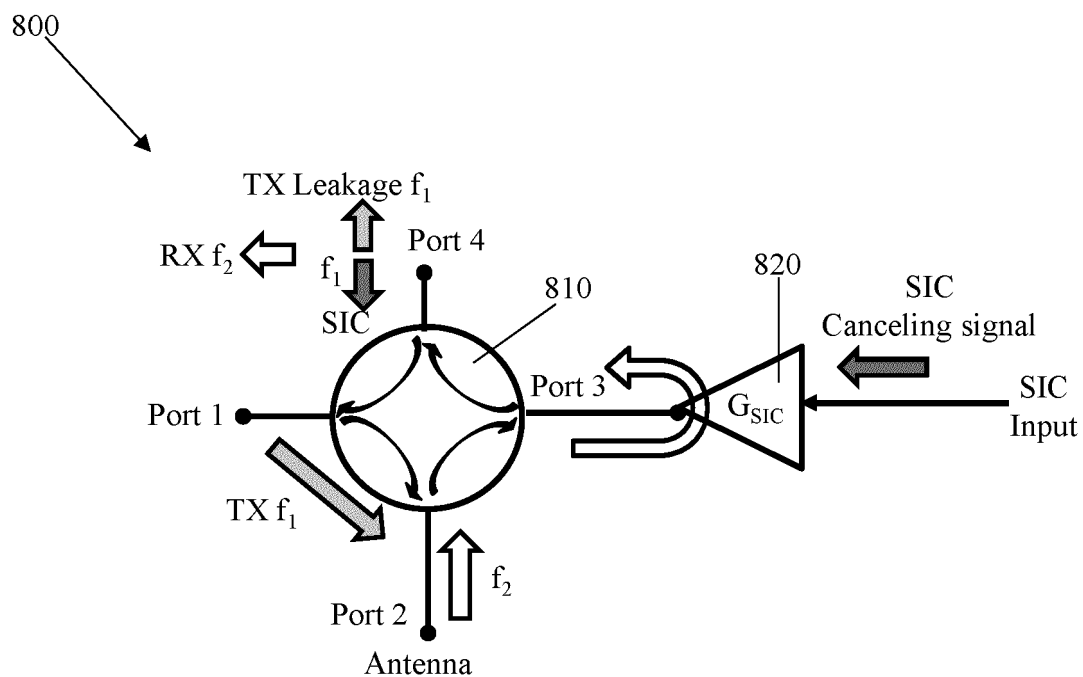


FIG. 8

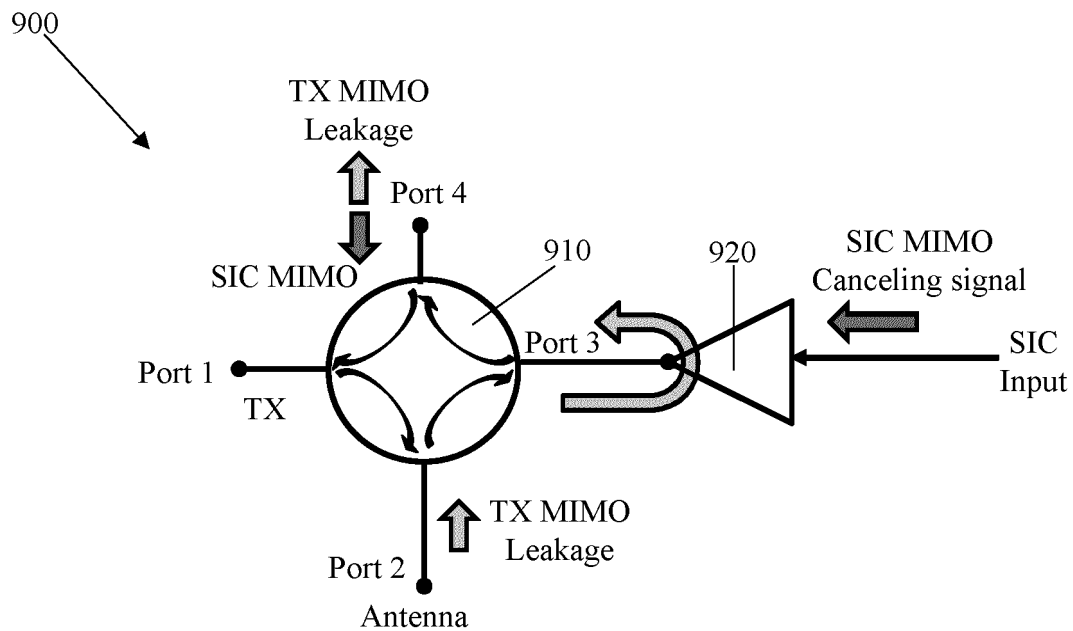


FIG. 9

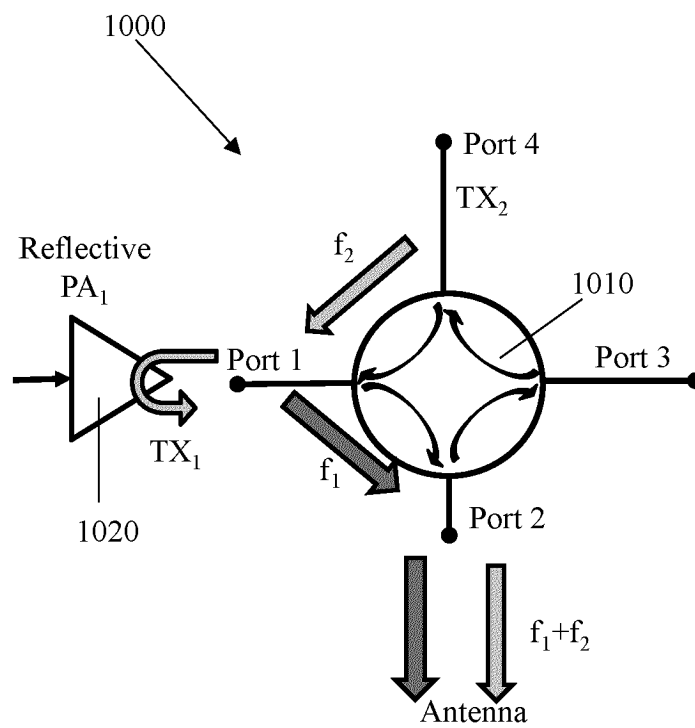


FIG. 10

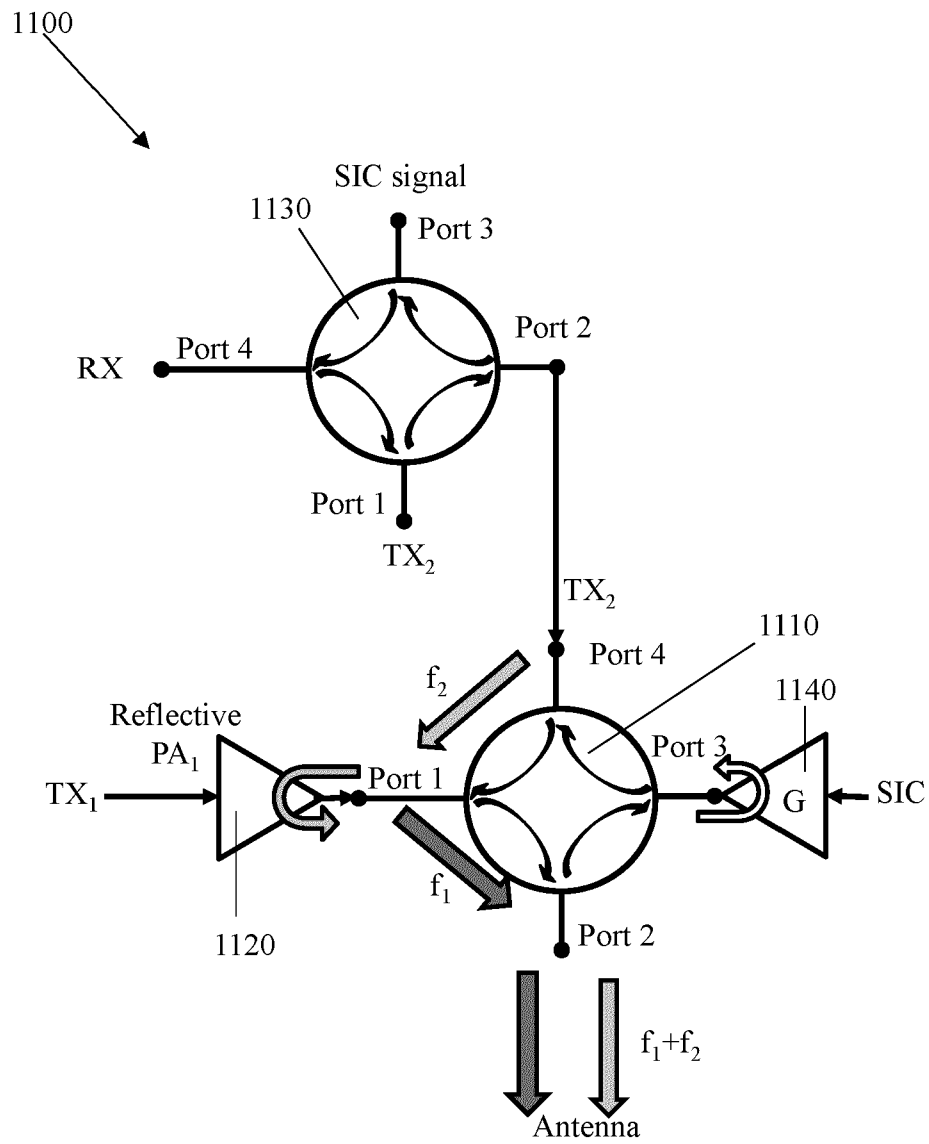


FIG. 11

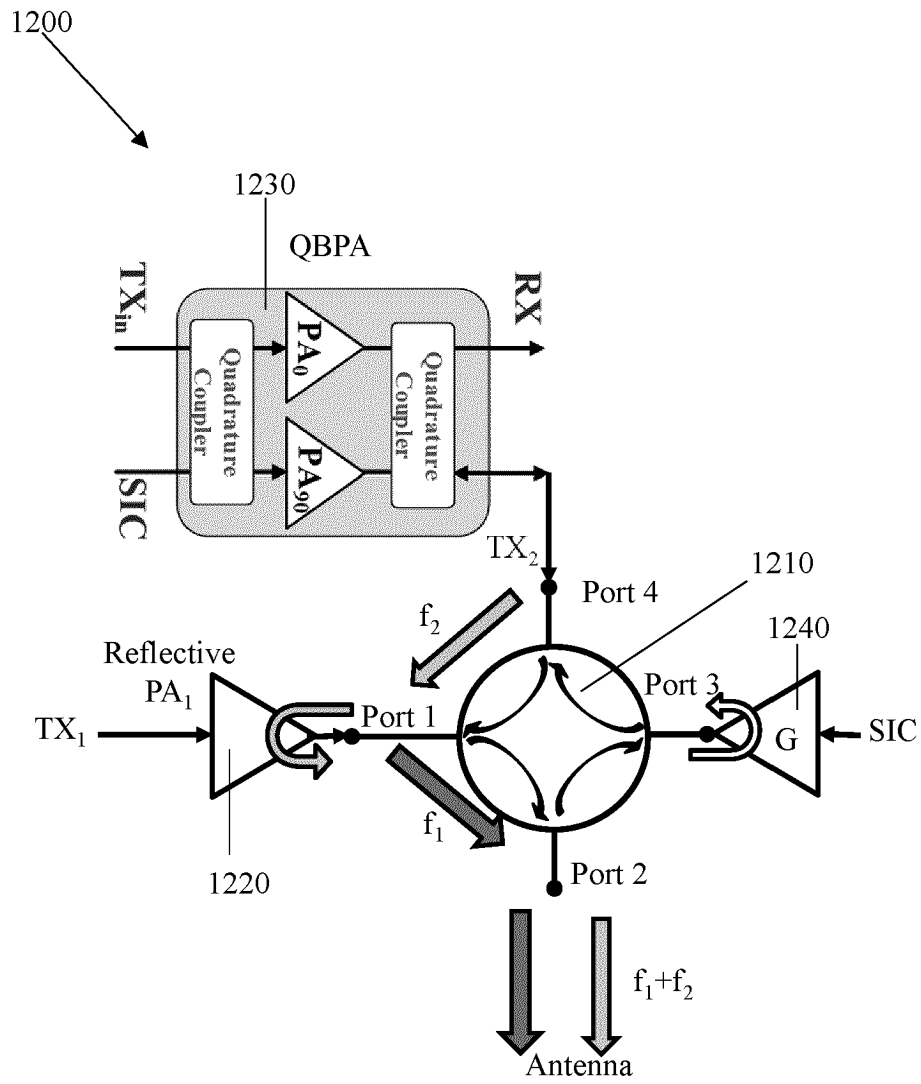


FIG. 12

REFERENCES CITED IN THE DESCRIPTION

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