

STACKED CIRCULATORS AND METHOD FOR STACKING CIRCULATORS

FIELD OF THE DISCLOSURE

5 This disclosure relates to microwave technology, and more particularly to microwave circulators. This disclosure further concerns the relative orientation of circulators when they are placed next to each other.

BACKGROUND OF THE DISCLOSURE

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Circulators are nonreciprocal devices that route microwave signals in a preferential direction. The essential element of a circulator is a magnet which maintains a preferred direction of propagation in the circulator due to Faraday rotation.

15 Figure 1a illustrates schematically a circulator with three conductors 11, 12 and 13 and a magnet 8. The magnet 8 induces a magnetic bias field which affect a ferrimagnetic material (not shown) located at the junction. The conductors extend beyond the illustrated figure and transmit microwave signals from one component to another. A microwave signal 1 which enters the circulator through conductor 11 exits through conductor 12 due to
20 Faraday rotation in the ferrimagnetic material. It does not exit through conductor 13. Conversely, signal 2, which enters through conductor 12, exits through conductor 13 and signal 3, which enters through 13, exits at 11.

Figure 1b illustrates a configuration where conductor 13 terminates in a microwave-absorbing element 7. In this case the circulator functions as an isolator which allows signal
25 1 to pass from conductor 1 to conductor 2 but prevents microwave signal 2 from entering conductor 1. This feature is particularly useful in applications where signal 1 is a weak signal and the microwave-generating element at the other end (the end which is not illustrated) of conductor 1 is sensitive to external interference.

For example, a qubit or sensor operating at cryogenic temperatures may generate an
30 output signal 1 which comprises just a few microwave photons. The output line has to be connected to preamplifiers when the output signal is read out. These preamplifiers may be located at higher temperatures than the qubit or sensor. The qubit or sensor can be

effectively isolated from thermal noise and back-action noise from the preamplifier input with the kind of circulator which is illustrated in figure 1b. The same principle applies in any application where the microwave element at the other end (the end which is not visible) of conductor 11 is sensitive to external interference, regardless of the temperature.

5 It is possible, and often necessary, to connect multiple circulators in series on the same output line to improve the isolative effect. If multiple microwave output lines are used, then each line requires a dedicated circulator (or several circulators in series). Circulators are therefore often assembled next to each other, and circulator assemblies may be stacked next to each other if a large number of circulators is needed. Figure 1c illustrates
10 schematically a stack with three circulator assemblies 14, 15 and 16. Each assembly comprises three circulators on top of each other: assembly 14 contains circulators 111 – 113, assembly 15 contains circulators 114 – 116 and assembly 16 contains circulators 117 – 119. Each pair of letters N and S signify the north- and south-seeking poles, respectively, of a magnet in the illustrated circulator.

15 A general problem in many microwave applications is that the circulator assembly must be placed relatively close to sensitive microwave elements which lie at the other end of conductor 11 in figure 1a. The magnetic field generated by the magnets in the circulator assembly may disturb the operation of this microwave element. A compromise must therefore often be made between (a) the space needed for circulator assemblies and
20 microwave elements connected to these assemblies (b) the amount of magnetic interference that a microwave element is exposed to and (c) the quality of the isolation (which depends on the number of circulators in the assembly, and therefore on the number of magnets).

25 BRIEF DESCRIPTION OF THE DISCLOSURE

An object of the present disclosure is to relax the constraints of the compromise mentioned above.

30 The object of the disclosure is achieved by an arrangement and a method which is characterized by what is stated in the independent claims. The preferred embodiments of the disclosure are disclosed in the dependent claims.

The disclosure is based on the idea of organizing circulator assemblies next to each other so that north-seeking poles face north-seeking poles and/or south-seeking poles face south-seeking poles.

5 An advantage of this arrangement and method is that magnetic field strength can be reduced in the surroundings of the circulator assembly.

BRIEF DESCRIPTION OF THE DRAWINGS

10 In the following the disclosure will be described in greater detail by means of preferred embodiments with reference to the accompanying drawings, in which

Figures 1a – 1c illustrate circulators and arrangements known from the prior art

Figures 2a – 2e illustrate arrangements with two first circulator assemblies.

Figures 3a – 3c illustrate arrangements with three or four first circulator assemblies.

Figure 4 illustrates a practical implementation.

15 Figure 5 illustrates an arrangement with three first circulator assemblies and three second circulator assemblies.

Figures 6a – 6b illustrate an arrangement comprising a quantum processing unit.

Figures 7a – 7b illustrate methods.

20 DETAILED DESCRIPTION OF THE DISCLOSURE

This disclosure describes an arrangement comprising two or more first circulator assemblies in a first stack where the first circulator assemblies are stacked adjacent to each other so that each pair of adjacent first circulator assemblies form a first assembly pair which comprises two members. Each first circulator assembly comprises one or more
25 first circulators. Each of the one or more first circulators is a microwave circulator. Each of the one or more first circulators comprises one or more first magnets with a north-seeking pole and a south-seeking pole. Each of the one or more first circulators comprises a ferrimagnetic element.

In each first assembly pair, either

- the south-seeking poles of all first magnets in one of the two members of the first assembly pair face toward the south-seeking poles of all first magnets in the other of the two members of the first assembly pair, or
- 5 – the north-seeking poles of all first magnets in one of the two members of the first assembly pair face toward the north-seeking poles of all first magnets in the other of the two members of the first assembly pair.

10 The word “assembly” refers in this disclosure to a set of similar elements, particularly circulators. As explained in the examples above, an assembly of circulators may comprise just a single circulator. Alternatively, a single assembly may comprise more than two, more than five or more than ten circulators. The circulators which are included in a single assembly may, but do not necessarily have to, be connected in series so that a microwave signal can pass through the whole assembly. The circulators which form a single assembly may alternatively not be connected in series, so that a microwave signal can pass through a part of the assembly without passing through the whole assembly.

15 Adjacent assemblies form an assembly pair, as described above. The pair has two members. The two members of an assembly pair may have the same number of circulators, and the assemblies may be positioned so that the magnets of all circulators in the two members are aligned with each other (in the x-direction) and face each other as this disclosure describes. This will be illustrated in the figures below. However, the two
20 members of an assembly pair do not necessarily need to have the same number of circulators. In any embodiment presented in this disclosure, one member of the pair may comprise more circulators than the other. The magnets of some circulators in the two members may then be aligned with each other and face each other in the manner described in this disclosure, while other magnets in one or both members of the pair may
25 not be aligned with magnets from the other member of the pair. But at least some magnets in each member will be aligned with corresponding magnets in the other member as the figures illustrate.

Magnets in the two members which form an assembly pair may also face each other without being perfectly aligned with each other, as figure 3b illustrates.

30 Figure 2a illustrates an arrangement comprising two first circulator assemblies 21 and 22. They have been placed next to each other and together they form a first stack. 21 + 22 is a first assembly pair. 21 is one member of this pair and 22 is the other member of this pair. In the stack illustrated in figure 2a, each first circulator assembly comprises just one first

circulator, illustrated by the letter combination N/S which shows how the north- and south-seeking poles of the magnet in this first circulator are oriented. Figure 2b illustrates a stack where the first circulator assembly 21 comprises three first circulators 211 – 213 on top of each other and first circulator assembly 22 also comprises three first circulators 214 – 216 on top of each other.

Throughout this disclosure, circulator assemblies such as 21 and 22 are illustrated as being separated from each other by a separation plane 29 which lies between each pair of assemblies. The distance between adjacent assemblies is illustrated with a gap with nonzero width for illustrative purposes. In practice, adjacent assemblies may be in physical contact with each other (as figure 4 illustrates) or there may be a gap between adjacent assemblies. In any case, the south/north-seeking poles face each other on opposite sides of the separation plane 29 throughout this disclosure. Separation planes do not necessarily need to be parallel to each other, as figure 3b illustrates.

Figure 2b also illustrates schematically the possible locations of input/output ports 38 and 39 in the first circulator assemblies 21 and 22. All circulators illustrated in this disclosure comprise an input port and output port. When multiple circulators are grouped into one assembly, as for example circulators 211 - 213 in figure 2b, their input/output ports may (but don't have to) be connected to each other in series. The first circulator assembly 21 then has just a single input port (38 or 39) and a single output port (39 or 38).

The output port of one circulator assembly can be connected to the input port of the next circulator assembly if the same signal should be routed through multiple assemblies. This has been schematically illustrated with arrows in figure 2c, which indicate one possible way to route a microwave signal 1 through the stack when the assemblies (and the individual circulators) are connected in series. This is possible in any embodiment presented in this disclosure. However, adjacent assemblies do not have to be connected in series in any embodiment presented in this disclosure and signals don't necessarily need to be routed to many assemblies. The circulator assemblies, or even individual circulators, could instead lie on separate signal paths so that a microwave signal which passes through one assembly / circulator does not pass through any other assemblies / circulators. The benefits described in this disclosure can be achieved even if the circulator assemblies are not electrically connected to each other.

An x, y, z coordinate system is used throughout this disclosure to illustrate different orientation options with reference to three perpendicular directions. The circulators can be

stacked in a variety of ways in relation to other structures which surround the circulators. This disclosure is only concerned with how the circulators are stacked in relation to each other. Consequently, some of the previous paragraphs use the expression “on top of”, but it is used only as a simple reference to the order which can be seen in the figures. This expression does not mean that the z-axis necessarily needs to be parallel to the Earth’s gravitational field when the circulators are stacked. These considerations apply throughout this disclosure to similar expressions such as “up”, “down”, “bottom”, “top” etc, which may be utilized for convenient reference to the figures.

It can be seen in figures 2a and 2b that the south-seeking poles of all first magnets in one (21) of the two members of the first assembly pair face toward the south-seeking poles of all first magnets in the other (22) of the two members of the first assembly pair. Figures 2d and 2e illustrate alternative arrangements where the north-seeking poles of all first magnets in one (21) of the two members of the first assembly pair face toward the north-seeking poles of all first magnets in the other (22) of the two members of the first assembly pair.

The first magnets in circulator assemblies 21 and 22 are aligned with each other in the x-direction in figures 2a and 2b. In other words, for each pair of first magnets which face each other, a line parallel to the x-axis can be drawn which passes through both the first magnet in assembly 21 and the first magnet in assembly 22. However, first magnets from the two members of a first assembly pair can face each other even if they are not aligned, or not perfectly aligned, with each other. This is illustrated in figure 3b.

It can be shown that the magnetic field is stronger in the immediate surroundings of the arrangement in the stacking configurations illustrated in figures 2a – 2e than in the configuration shown in figure 1c. However, it can also be shown that, at a distance L from the center of the arrangement and at all distances greater than L, the magnetic field generated in the configuration shown in figures 2a – 2e is weaker than the magnetic field generated in the configuration shown in figure 1c. The limit L is to some extent a function of x, y and z (i.e., direction-dependent), but it is in all directions significantly shorter than typical distances between circulators and devices sensitive to magnetic fields. Consequently, with the arrangement illustrated in figures 2a – 2e, the circulator stack causes less magnetic interference to a device which is sensitive to magnetic fields than a comparable circulator stack (with the same number of circulators) would cause in a stacking order which corresponds to figure 1c. This applies to all embodiments presented in this disclosure.

Any first circulator (and any second circulator, defined below) may be a ferrite junction circulator. The ferrimagnetic element of any first circulator (and any second circulator, defined below) may comprise ferrite material, for example nickel-zinc ferrite, manganese-zinc ferrite or any other ferrite material.

- 5 In any embodiment presented in this disclosure, any of the one or more first magnets (and any second magnet) may comprise at least one of: a permanent magnet, an electromagnet. Any of said magnets which is a permanent magnet may have the shape of a disc magnet, a cylinder magnet, a ring magnet, a horseshoe magnet or a bar magnet. Any of said permanent magnets may be a rare-earth magnet.
- 10 In any embodiment presented in this disclosure, each circulator may comprise a ferrimagnetic element which is adjacent to a first (or second) magnet in said circulator. The magnet creates a magnetic field that biases the ferrimagnetic material of the ferrimagnetic element, i.e. aligns its magnetic dipoles. The biased ferrimagnetic material is electromagnetically anisotropic, giving rise to Faraday rotation of electromagnetic waves.
- 15 The ferrimagnetic element may be in contact with the conductor junction where the propagating microwave modes are located.

- The two or more first circulator assemblies may comprise two end assemblies at opposite ends of the first stack and at least one central assembly between the two end assemblies, so that one of the two members in each assembly pair is a central assembly, and the other
- 20 of the two members in each assembly pair is either a central assembly or an end assembly. The south-seeking poles of all first magnets in each central assembly may then face the south-seeking poles of all first magnets in the first circulator assembly which is adjacent to the central assembly on a first side of said central assembly, and the north-seeking poles of all first magnets in each central assembly may face the north-seeking poles of all first
- 25 magnets in the first circulator assembly which is adjacent to the central assembly on a second side of said central assembly, wherein the second side is opposite to the first side.

- Figure 3a illustrates an arrangement with a single central assembly 22 flanked by two end assemblies 21 and 23. Additional central assemblies could be added between 21 and 22 and/or between 22 and 23. The arrangement in figure 3a comprises a first assembly pair
- 30 with members 21 and 22 and another first assembly pair with members 22 and 23. First assembly pair 21+22 has been oriented so that the south-seeking poles of the first magnets in these circulator assemblies face each other, while first assembly pair 22+23 has been oriented so that the north-seeking poles of the first magnets in these circulator assemblies face each other.

When further central assemblies are added to the arrangement, the alternating north-south pattern illustrated in figure 3a continues throughout the stack. In other words, the first magnets in each central assembly are flanked by south-seeking poles on one side and by north-seeking poles on the other side, and the south-seeking poles of the first magnets in each central assembly face the south-seeking poles of the adjacent assembly, and the north-seeking poles of the first magnets in each central assembly face the north-seeking poles of the adjacent assembly.

In any embodiment presented in this disclosure, the magnetization vectors (which extend from the south-seeking pole toward the north-seeking pole) of all first magnets in a single first circulator assembly may point in the same direction. These magnetization vectors may be parallel to each other. The magnetization vectors of all first magnets in all first circulator assemblies may also be parallel to each other, as they are in figure 3a. Alternatively, the magnetization vectors of the first magnets in adjacent first circulator assemblies may be non-parallel in any embodiment presented in this disclosure. This option has been illustrated in figure 3b which shows first circulator assemblies 21 – 23 that are stacked next to each other but not fully parallel to each other. The magnetization vectors of the first magnets in assembly 22, for example, are not parallel to the magnetization vectors of the first magnets in assemblies 21 or 23. Nevertheless, the south-seeking poles in assembly 22 still face the south-seeking poles in assembly 21 and north-seeking poles in assembly 22 face the north-seeking poles in assembly 23, as they do in figure 3a.

In figure 3a the assembly which is adjacent to the central assembly 22 is an end assembly (21, 23) on both sides, but the adjacent assembly on one or both sides of the central assembly may be another central assembly if the number of assemblies is greater than three. This is illustrated in figure 3c, where the arrangement comprises two end assemblies 21 and 24 and two central assemblies 22 and 23.

Figure 4 illustrates a practical implementation of the arrangement shown in figure 2d. Four first circulator assemblies 21 – 24 are shown, and each assembly comprises three first circulators connected in series. In other words, each circulator assembly is a triple-junction circulator. Each assembly comprises an input port 31 at one end of the assembly and an output port 32 at the opposite end of the assembly. Each assembly could comprise more than three first circulators, and the assemblies themselves can be connected in series according to suitable pattern in order to route a given input signal through an appropriate number of circulators. The S and N letters in figure 4 illustrate the orientation of the first magnets in each first circulator assembly 21 – 24.

In any embodiment presented in this disclosure, each first circulator and each second circulator may comprise a microwave-absorbing element 47, similar to element 7 in figure 1a, which minimizes microwave transfer in the undesired direction (from port 32 toward port 31 in assembly 21, for example). The microwave absorbing element 47 may be a
5 microwave terminator, i.e. a resistive load whose resistance is matched to the characteristic impedance of the circulator output port (e.g. 50 or 75 ohms).

In any embodiment presented in this disclosure, the circulator assemblies may be attached to a mechanical support structure that is rigid enough to overcome the repulsive magnetic force between adjacent circulator assemblies. The mechanical support then holds together
10 the circulator stack.

In addition to organizing adjacent first circulator assemblies in one row as the preceding figures illustrate, additional circulators can be organized in additional rows in the same arrangement. If a second row is implemented, these additional circulators may be called second circulators.

15 In other words, the arrangement may comprise two or more second circulator assemblies in a second stack where the second circulator assemblies are stacked adjacent to each other. The first and second stacks may be adjacent to each other so that each second circulator assembly is adjacent to one of the two or more first circulator assemblies. Furthermore, each second circulator assembly comprises one or more second circulators.
20 Each of the one or more second circulators may be a microwave circulator. Each of the one or more second circulators may comprise a second magnet with a north-seeking pole and a south-seeking pole. Each of the one or more second magnets may comprise a ferrimagnetic element.

Each second circulator assembly may be oriented so that the south-seeking poles of all
25 second magnets in the second circulator assembly face the north-seeking poles of the first magnets in the adjacent first circulator assembly, and the north-seeking poles of all second magnets in the second circulator assembly face the south-seeking poles of the first magnets in the adjacent first circulator assembly.

This option is illustrated in figure 5, where reference numbers 51 – 53 and 59 correspond
30 to reference numbers 21 – 23 and 29, respectively, in the preceding figures. Unlike figures 2a – 3c, figure 5 illustrate an xy cross-section. That is, if the perspective in figures 2a – 3c is called a “side view” of the arrangement, then the perspective in figure 5 may be called a “top view”.

In figure 5 the arrangement comprises three first circulator assemblies 51 – 53 and three second circulator assemblies 54 – 56. The two members of each pair of adjacent first circulator assemblies are separated from each other by a separation plane 59 which is parallel to the illustrated yz-plane. The two members of each pair of adjacent second circulator assemblies are separated from each other by the same separation planes 59. Furthermore, the first stack (containing first circulator assemblies 51 – 53) is separated from the second stack (containing second circulator assemblies 54 – 56) by the additional separation plane 58 which is parallel to the illustrated xz-plane. The first and second stack may be separated by a nonzero distance in the y-direction, or they may be in direct contact with each other.

Each second circulator assembly 54 – 56 is in figure 5 oriented and positioned so that the south-seeking poles of all second magnets in the second circulator assemblies are aligned in the y-direction with the north-seeking poles of the corresponding first magnets in the first circulator assemblies 51 – 53. In other words, there is a line which extends in the y-direction and passes through the south-seeking pole of a first magnet and the north-seeking pole of a second magnet. These poles therefore face each other across the additional separation plane 58. The north-seeking poles in the first circulator assemblies and the south-seeking poles of the second circulator assemblies are correspondingly aligned with each other in the y-direction, as figure 5 illustrates.

The arrangement may be located in a room temperature environment. Alternatively, the arrangement may be located in a cryogenic environment.

In any embodiment presented in this disclosure, the cryogenic environment may be generated by a 3-He/4-He dilution refrigerator, and the arrangement may be thermally coupled to the mixing chamber stage of the 3-He/4-He dilution refrigerator. Thermal coupling between the arrangement and the mixing chamber stage of the refrigerator may be achieved by a mechanical contact, possibly with additional support structures made of a thermally conductive material, such as copper, in between. Alternatively, the arrangement may be coupled to any other stage of the 3-He/4-He dilution refrigerator, such as still stage, an intermediate stage between the mixing chamber stage and the still stage, or any stage of a pulse tube cooler.

Instead of a 3-He/4-He dilution refrigerator, the cryogenic environment may alternatively be generated by any other refrigerator type, such as a 3-He refrigerator, adiabatic demagnetization refrigerator, Pomeranchuk cooling, Cliford-McMahon cryocooler, Joule-

Thomson cooler, Stirling cryocooler, liquid helium, or liquid nitrogen. The arrangement may be thermally coupled to any temperature stage of such refrigerators, e.g. to the lowest temperature stage or to some intermediate temperature stage.

5 In any embodiment described above, the arrangement may also comprise a quantum processing unit (QPU) 60 and a readout circuit 69. This has been illustrated in figure 6a. The quantum processing unit 60 may comprise a QPU output port 600. The two or more first circulator assemblies 61 (only one assembly is illustrated in this figure, but others are next to it) in the first stack may comprise a circulator input port 601 and a circulator output port 602. The QPU output port 600 may be coupled to the circulator input port 601. The
10 circulator output port 602 may be coupled to the readout circuit 69. The two or more first circulator assemblies 61 may be configured to transfer output signals from the quantum processing unit 60 to the readout circuit 69.

The coupling between ports described in the previous paragraph may comprise a direct electrical connection formed by an electrical wire or cable, for example by a coaxial cable
15 which extends from the QPU output port 600 to the circulator input port 601. The input port 601 may then be a coaxial port. Alternatively or additionally, the direct electrical connection may comprise rectangular waveguides, circular waveguides, coplanar waveguides, microstrip lines, or striplines. The direct electrical connection may extend from the QPU output port 600 to the circulator input port 601. It may transfer microwaves between the
20 two ports. The circulator output port 602 may be coupled to an input port 603 in the readout circuit 69 may be implemented in the same manner. The optimal configuration will depend on the application. In general, any signal line coupled to the arrangement described in this disclosure may be formed by any of cables, waveguides and lines mentioned above.

There may be additional microwave components placed between the QPU output port 600 and the circulator input port 601 and/or between the circulator output port 602 and the
25 input port 603 in the readout circuit 69. These additional microwave components may comprise filters (such as bandpass, low-pass, high-pass, or band stop filters), directional couplers, microwave splitters, microwave combiners, or bias-tees.

Figure 6b illustrates an alternative arrangement where reference numbers 61 – 63 correspond to reference numbers 21 – 23 and 51 – 53 in the preceding figures,
30 respectively. In this case the circulator input port 601 and circulator output port 602 are on different first circulator assemblies and the assemblies 61 – 63 have been connected in series. The coupling between ports (also from one circulator assembly to next in series

connection) may be implemented as described in the previous paragraphs in any embodiment presented in this disclosure.

A quantum computing system may comprise an arrangement described in any embodiment of this disclosure.

5 This disclosure also describes a method a method for stacking circulator assemblies adjacent to each other. The stacked circulator assemblies comprise two or more first circulator assemblies in a first stack. Each pair of adjacent first circulator assemblies form a first assembly pair which comprises two members. Each first circulator assembly comprises one or more first circulators. Each of the one or more first circulators is a
10 microwave circulator. Each of the one or more first circulators comprises one or more first magnets with a north-seeking pole and a south-seeking pole. Each of the one or more first circulators comprises a ferrimagnetic element.

The method comprises providing to or more first circulator assemblies, and placing the two or more first circulator assemblies adjacent to each other so that either

- 15 – the south-seeking poles of all first magnets in one of the two members of the first assembly pair face toward the south-seeking poles of all first magnets in the other of the two members of the first assembly pair, or
- the north-seeking poles of all first magnets in one of the two members of the first assembly pair face toward the north-seeking poles of all first magnets in the other of
20 the two members of the first assembly pair.

This method has been illustrated in figure 7a. Figure 7b illustrates a method for stacking circulator assemblies next to each other. In this method the stacked circulator assemblies also comprise two or more second circulator assemblies in a second stack, and the first and second stacks are adjacent to each other so that each second circulator assembly is
25 adjacent to one of the two or more first circulator assemblies.

Each second circulator assembly comprises one or more second circulators. Each of the one or more second circulators is a microwave circulator. Each of the one or more second circulators comprise a second magnet with a north-seeking pole and a south-seeking pole. Each of the one or more second circulators comprises a ferrimagnetic element.

30 The method in figure 7b comprises providing the two or more second circulator assemblies and placing the two or more second circulator assemblies adjacent to the two or more first

circulator assemblies so that the south-seeking poles of all second magnets in the second circulator assembly face the north-seeking poles of the first magnets in the adjacent first circulator assembly, and the north-seeking poles of all second magnets in the second assembly face the south-seeking poles of the first magnets in the adjacent first assembly.

- 5 The method steps illustrated in figure 7b may be performed together with the steps illustrated in figure 7a.

CLAIMS

1. An arrangement comprising two or more first circulator assemblies (21, 22, 23, 24, 51, 52, 53, 61, 62, 63) in a first stack where the first circulator assemblies are stacked adjacent to each other so that each pair of adjacent first circulator assemblies form a first assembly pair (21-22, 22-23, 23-24, 51-52, 52-53, 61-62, 62-63) which comprises two members, and
- each first circulator assembly comprises one or more first circulators (211, 212, 213, 214, 215, 216),
 - each of the one or more first circulators (211, 212, 213, 214, 215, 216) is a microwave circulator,
 - each of the one or more first circulators (211, 212, 213, 214, 215, 216) comprises one or more first magnets with a north-seeking pole and a south-seeking pole, and
 - each of the one or more first circulators (211, 212, 213, 214, 215, 216) comprises a ferrimagnetic element,
- characterized** in that, in each first assembly pair, either
- the south-seeking poles of all first magnets in one of the two members of the first assembly pair (21-22, 22-23, 23-24, 51-52, 52-53, 61-62, 62-63) face toward the south-seeking poles of all first magnets in the other of the two members of the first assembly pair (21-22, 22-23, 23-24, 51-52, 52-53, 61-62, 62-63), or
 - the north-seeking poles of all first magnets in one of the two members of the first assembly pair (21-22, 22-23, 23-24, 51-52, 52-53, 61-62, 62-63) face toward the north-seeking poles of all first magnets in the other of the two members of the first assembly pair (21-22, 22-23, 23-24, 51-52, 52-53, 61-62, 62-63).
2. An arrangement according to claim 1, wherein the two or more first circulator assemblies (21, 22, 23, 24, 51, 52, 53, 61, 62, 63) comprise two end assemblies (21, 24, 51, 53, 61, 63) at opposite ends of the first stack and at least one central assembly (22, 23, 52, 62) between the two end assemblies, so that one of the two members in each assembly pair (21-22, 22-23, 23-24, 51-52, 52-53, 61-62, 62-63) is a central

assembly, and the other of the two members in each assembly pair (21-22, 22-23, 23-24, 51-52, 52-53, 61-62, 62-63) is either a central assembly or an end assembly, and

5 – the south-seeking poles of all first magnets in each central assembly (22, 23, 52, 62) face the south-seeking poles of all first magnets in the first circulator assembly (21, 22, 51, 61) which is adjacent to the central assembly (22, 23, 52, 62) on a first side of said central assembly (22, 23, 52, 62), and

10 – the north-seeking poles of all first magnets in each central assembly (22, 23, 52, 62) face the north-seeking poles of all first magnets in the first circulator assembly (23, 24, 53, 63) which is adjacent to the central assembly (22, 23, 52, 62) on a second side of said central assembly (22, 23, 52, 62), wherein the second side is opposite to the first side.

3. An arrangement according to any of claims 1-2, wherein each of the one or more first magnets comprises at least one of: a permanent magnet, an electromagnet.

15 4. An arrangement according to any of claims 1-3, wherein the arrangement also comprises two or more second circulator assemblies (54, 55, 56) in a second stack where the second circulator assemblies are stacked adjacent to each other, and the first and second stacks are adjacent to each other so that each second circulator assembly (54, 55, 56) is adjacent to one of the two or more first circulator assemblies (51, 52, 53), and

20 – each second circulator assembly (54, 55, 56) comprises one or more second circulators,

 – each of the one or more second circulators is a microwave circulator,

 – each of the one or more second circulators comprises a second magnet with a north-seeking pole and a south-seeking pole, and

25 – each of the one or more second circulators comprises a ferrimagnetic element, and

 – each second circulator assembly (54, 55, 56) is oriented so that the south-seeking poles of all second magnets in the second circulator assembly (54, 55, 56) face the north-seeking poles of the first magnets in the adjacent first circulator assembly (51, 52, 53), and the north-seeking poles of all second magnets in the second

circulator assembly (54, 55, 56) face the south-seeking poles of the first magnets in the adjacent first circulator assembly (51, 52, 53).

5. An arrangement according to any preceding claim, wherein the arrangement is located in a cryogenic environment.
- 5 6. An arrangement according to any preceding claim, wherein
 - the arrangement also comprises a quantum processing unit (QPU) (60) and a readout circuit (69),
 - the QPU comprises a QPU output port (600),
 - the two or more first circulator assemblies (61, 62, 63) in the first stack comprise a circulator input port (601) and a circulator output port (602),
 - 10 – the QPU output port (600) is coupled to the circulator input port (601),
 - the circulator output port (602) is coupled to the readout circuit (69), and
 - the two or more first circulator assemblies (61, 62, 63) are configured to transfer output signals from the QPU (60) to the readout circuit (69).
- 15 7. A method for stacking circulator assemblies adjacent to each other, wherein the stacked circulator assemblies comprise two or more first circulator assemblies (21, 22, 23, 24, 51, 52, 53, 61, 62, 63) in a first stack, and each pair of adjacent first circulator assemblies form a first assembly pair (21-22, 22-23, 23-24, 51-52, 52-53, 61-62, 62-63) which comprises two members, wherein
 - 20 – each first circulator assembly (21, 22, 23, 24, 51, 52, 53, 61, 62, 63) comprises one or more first circulators,
 - each of the one or more first circulators (211, 212, 213, 214, 215, 216) is a microwave circulator,
 - each of the one or more first circulators (211, 212, 213, 214, 215, 216) comprises one or more first magnets with a north-seeking pole and a south-seeking pole, and
 - 25 – each of the one or more first circulators (211, 212, 213, 214, 215, 216) comprises a ferrimagnetic element,

characterized in that the method comprises providing the two or more first circulator assemblies (21, 22, 23, 24, 51, 52, 53, 61, 62, 63), and placing the two or more first circulator assemblies (21, 22, 23, 24, 51, 52, 53, 61, 62, 63) adjacent to each other so that either

5 – the south-seeking poles of all first magnets in one of the two members of the first assembly pair (21-22, 22-23, 23-24, 51-52, 52-53, 61-62, 62-63) face toward the south-seeking poles of all first magnets in the other of the two members of the first assembly pair (21-22, 22-23, 23-24, 51-52, 52-53, 61-62, 62-63), or

10 – the north-seeking poles of all first magnets in one of the two members of the first assembly pair (21-22, 22-23, 23-24, 51-52, 52-53, 61-62, 62-63) face toward the north-seeking poles of all first magnets in the other of the two members of the (21-22, 22-23, 23-24, 51-52, 52-53, 61-62, 62-63) first assembly pair.

8. A method according to claim 7, wherein the stacked circulator assemblies also comprise two or more second circulator assemblies (54, 55, 56) in a second stack, and the first and second stacks are adjacent to each other so that each second circulator assembly (54, 55, 56) is adjacent to one of the two or more first circulator assemblies (51, 52, 53), and

15 – each second circulator assembly (54, 55, 56) comprises one or more second circulators,

20 – each of the one or more second circulators is a microwave circulator,

 – each of the one or more second circulators comprises a second magnet with a north-seeking pole and a south-seeking pole, and

 – each of the one or more second circulators comprises a ferrimagnetic element, and

25 the method comprises providing the two or more second circulator assemblies (54, 55, 56) and placing the two or more second circulator assemblies (54, 55, 56) adjacent to the two or more first circulator assemblies (51, 52, 53) so that the south-seeking poles of all second magnets in the second circulator assembly (54, 55, 56) face the north-seeking poles of the first magnets in the adjacent first circulator assembly (51, 52, 53), and the north-seeking poles of all second magnets in the second circulator assembly (54, 55, 56) face the south-seeking poles of the first magnets in the adjacent first circulator assembly (51, 52, 53).

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9. A quantum computing system comprising the arrangement according to any of claims 1-6.