(19)

SUOMI - FINLAND
(FI)

PATENTTI- JA REKISTERIHALLITUS
PATENT- OCH REGISTERSTYRELSEN
FINNISH PATENT AND REGISTRATION OFFICE

(10) **FI 20195045 A1**

(12) **JULKISEKSI TULLUT PATENTTIHAKEMUS**
PATENTANSÖKAN SOM BLIVIT OFFENTLIG
PATENT APPLICATION MADE AVAILABLE TO THE PUBLIC

(21) Patenttihakemus - Patentansökan - Patent application 20195045

(51) Kansainvälinen patenttiluokitus - Internationell patentklassifikation - International patent classification
H03F 19/00 (2006.01)
H03F 7/00 (2006.01)
H01L 39/22 (2006.01)
H01L 39/24 (2006.01)
H01P 3/00 (2006.01)
H01L 39/02 (2006.01)

(22) Tekemispäivä - Ingivningsdag - Filing date **24.01.2019**

(23) Saapumispäivä - Ankomstdag - Reception date **24.01.2019**

(41) Tullut julkiseksi - Blivit offentlig - Available to the public **25.07.2020**

(43) Julkaisupäivä - Publiceringsdag - Publication date **31.08.2020**

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(54) Keksinnön nimitys - Uppfinningens benämning - Title of the invention

Josephsonin liitoksiin perustuva traveling-wave parametrinen vahvistin

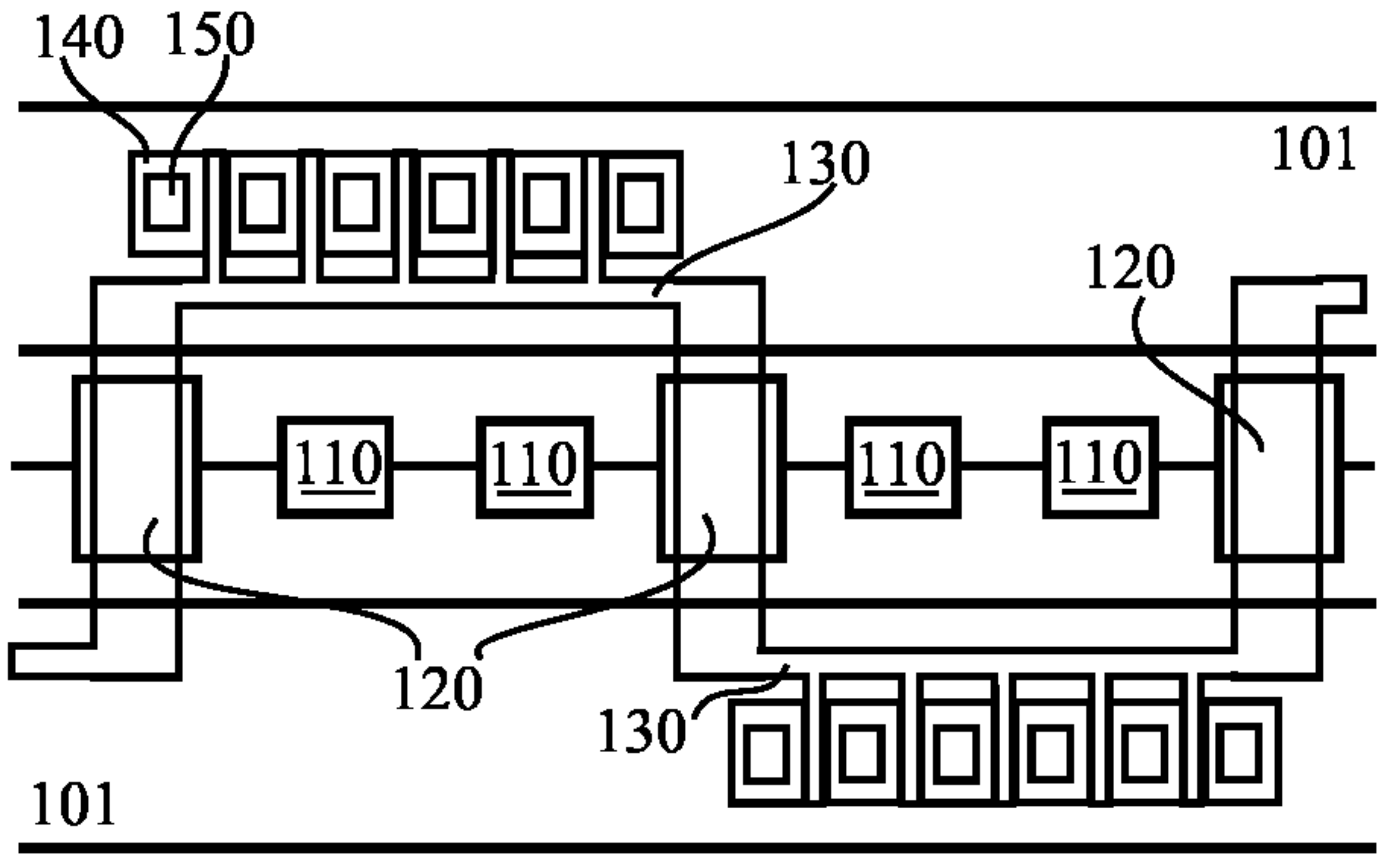
Parametrisk traveling-wave-förstärkare baserad på Josephson-övergångar

JOSEPHSON TRAVELING WAVE PARAMETRIC AMPLIFIER

(57) Tiivistelmä - Sammandrag - Abstract

Esillä olevan keksinnön esimerkinomaisen suoritusmuodon mukaan tuotetaan kulkuaallon parametrinen vahvistin, joka käsittää aalto-ohjaimen siirtolinjan, joka käsittää vähintään kymmenen Josephson-elementtiä (110), jossa kukin vähintään kymmenestä Josephson-elementistä (110) käsittää silmukan ja jossa on tasan yksi ensimmäisen koon Josephson-liitos silmukan toisessa puoliskossa ja vähintään kaksi toisen koon Josephson-liitosta silmukan toisessa puoliskossa, joka toinen koko on suurempi kuin ensimmäinen koko, vuon suuntauslinjan (130), joka on muodostettu tuottamaan magneettinen vuo, joka kulkee kunkin vähintään yhden silmukan läpi, ja joukon resistoreja (140), jotka on yhdistetty vuon suuntauslinjaan (130).

According to an example aspect of the present invention, there is provided a travelling wave parametric amplifier comprising a waveguide transmission line comprising therein at least ten Josephson elements (110), wherein each of the at least ten Josephson element (110) comprises a loop, with exactly one Josephson junction of first size on one half of the loop and at least two Josephson junctions of a second size on a second half of the loop, the second size being larger than the first size, a flux bias line (130) configured to generate a magnetic flux threading each of the at least one loop, and a set of resistors (140) coupled with the flux bias line (130).



JOSEPHSON TRAVELING WAVE PARAMETRIC AMPLIFIER

FIELD

[0001] The present invention relates to superconducting traveling wave parametric amplifiers, TWPAs.

BACKGROUND

[0002] Parametric amplifiers are in effect mixers, wherein a weaker input signal may be amplified by mixing it with stronger pump signal, producing a stronger output signal as a result. Parametric amplifiers rely on a nonlinear response of a physical system to generate amplification. Such amplifiers may comprise standing wave parametric amplifiers or traveling wave parametric amplifiers, wherein a traveling wave parametric amplifier uses a series of nonlinear elements distributed along a transmission line, such as a coplanar waveguide, for example. In case the nonlinear elements comprise Josephson junctions, the amplifier may be referred to as a Josephson traveling wave parametric amplifier, JTWPA. In a JTWPA, the Josephson junctions are maintained in superconducting condition and carry a supercurrent.

[0003] In use, a signal is added to the strong oscillator signal, resulting in a sum signal wherein an amplitude envelope exhibits variance at a frequency which is a difference between the signal and oscillator frequencies. Since in the waveguide transmission line, a phase velocity is dependent on amplitude, a phase of the summed signal at the end of the line will vary in accordance with a difference in the two frequencies. In effect, the nonlinear waveguide transmission line converts amplitude modulation into phase modulation. In case the non-linearity is strong enough, this will result in a gain at the signal frequency.

SUMMARY OF THE INVENTION

[0004] According to some aspects, there is provided the subject-matter of the independent claims. Some embodiments are defined in the dependent claims.

[0005] According to a first aspect of the present invention, there is provided a travelling wave parametric amplifier comprising a waveguide transmission line comprising therein at least ten Josephson elements, wherein each of the at least ten Josephson element comprises a loop, with exactly one Josephson junction of first size on one half of the loop and at least two Josephson junctions of a second size on a second half of the loop, the second size being larger than the first size, a flux bias line configured to generate a magnetic flux threading each of the at least one loop, and a set of resistors coupled with the flux bias line.

[0006] According to a second aspect of the present invention, there is provided a method for manufacturing a traveling wave parametric amplifier comprising providing a waveguide transmission line comprising therein at least ten Josephson elements, wherein each of the at least ten Josephson elements comprises a loop, with exactly one junction of first size on one half of the loop and at least two junctions of a second size on a second half of the loop, the second size being larger than the first size, providing a flux bias line configured to generate a magnetic field threading each of the at least one loop, and providing a set of resistors coupled with the flux bias line.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] FIGURE 1 illustrates an example amplifier in accordance with at least some embodiments of the present invention;

[0008] FIGURE 2 illustrates an example Josephson element in accordance with document [2];

[0009] FIGURE 3 illustrates an example Josephson element in accordance with at least some embodiments of the present invention, and

[0010] FIGURE 4 is a flow graph of a method in accordance with at least some embodiments of the present invention.

EMBODIMENTS

[0011] In accordance with solutions disclosed herein, a traveling wave parametric amplifier may be made less sensitive to errors in the size of smaller Josephson junctions in a Josephson element comprising larger and smaller Josephson junctions, by selecting parameters suitably. Further, a gradiometric layout of a Josephson element is disclosed, which renders the element sensitive to a magnetic field gradient only, and a flux bias line in the traveling wave parametric amplifier is provided to generate such a field gradient. Further, the transmission line may be tapered. Overall, using one of more of these enhancements, a traveling wave parametric amplifier may be more suitably used in real-life applications as its operation will be less sensitive to disturbances and manufacturing defects.

[0012] FIGURE 1 illustrates an example amplifier in accordance with at least some embodiments of the present invention. Overall, for example in quantum computation, signals may be attenuated for transmission even to a single-photon or a near-single-photon regime. Detecting such signals presents challenges owing to their low amplitude. Therefore, suitable amplifiers may be employed to increase the amplitudes of received signals prior to their provision to detector elements, where the information encoded into these received signals may be recovered. As another example, a single-photon regime communication may be employed in communicating encryption keys in a secure manner using quantum communication, such that eavesdropping without detection is made very difficult.

[0013] The present disclosure is focuses on a superconductive realization of the TWPA, where the center trace of a transmission line is an array of Josephson junction based elements, known as Josephson elements, that constitute a non-linear inductance. The non-linearity allows for a mixing process that provides power gain for a weak signal that propagates along the same direction as a strong radio frequency, rf, pump tone. The strength of the pump tone is measured with the ratio between the pump current amplitude

Ip and the critical current Ic of the Josephson element. The nature of the non-linearity depends on the arrangement of Josephson junctions within the element. The simplest realization is the use of a single Josephson junction as the non-linear element: the associated Taylor expansion of the inductance is a constant plus a term proportional to (Ip/Ic)^2, that is, a Kerr non-linearity. While the Kerr term results in a desired mixing process, it also changes the wavevector of the pump tone, an effect that has to be compensated with dispersion engineering. The balancing of the wavevectors, also called phase matching, allows an exponential increase of the TWPA gain as a function of the device length. Due to the typically narrowband dispersive features embedded into the transmission line, the center frequency of gain is a fixed quantity in this example of the TWPA.

[0014] There are new solutions that target the realization of a Kerr-free non-linearity by introducing a magnetic flux degree of freedom to the Josephson element. In the Taylor expansion of the inductance, this alternative non-linearity is a term proportional to Ip/Ic. Kerr-free operation is beneficial as no dispersion engineering is necessary to achieve phase matching. The pump frequency, which sets the center frequency of gain, can be freely selected. Main features of a typical Kerr-free element include (i) a superconductive magnetic pick-up loop that can be pictured as two half-loops connected together, (ii) the interruption of the two halves with an unequal number of Josephson junctions, and (iii) a finite magnetic flux bias that makes a screening current flow in the loop according to the principle of flux quantization. Particular weaknesses of the Kerr-free element, in the realizations presented so far, are (i) sensitivity to magnetic interference, and (ii) sensitivity to inhomogeneity of the magnetic bias field, especially in arrays consisting of multiple elements.

[0015] Furthermore, a generic problem in TWPAs is depletion of the pump current. This is due to either dissipation in the transmission line, or transfer of power from the pump to the amplified signal if the TWPA is operated close to saturation. The pump depletion limits the TWPA gain because the mixing process relies on a suitable ratio between Ip and Ic. Another generic problem in TWPAs is the fabrication spread of the Ic, causing inhomogeneity of the electrical parameters of the transmission line.

[0016] The JTWPA of FIGURE 1 comprises a waveguide, which comprises Josephson elements 110 and parallel-plate capacitors 120. The Josephson elements 110 are connected with each other with waveguides capable of conveying electromagnetic waves, as is known in the art. The waveguide, a section of which is illustrated in FIGURE 1, has an input port at the left, arranged to receive the signal to be amplified and a strong oscillator signal, which are mixed in the waveguide in the non-linear Josephson elements 110. At an output port at the right, the phase-modulated amplified signal is obtained as output. Two wiring layer elements 101 may each comprise a superconductor covered with an insulator, for example.

[0017] In general, a Josephson element, such as a single junction, a superconducting quantum interference device (SQUID), an asymmetric SQUID, or a more complex Josephson element such as a flux-qubit-like circuit, can be described using an effective potential energy:

[0018] $U_{eff}(\varphi)/E_j = c_2\varphi^2 + c_3\varphi^3 + c_4\varphi^4 + \ldots$

[0019] here E_j is the Josephson energy, and φ is the superconducting phase. The c_2 term relates to critical current and linear part of Josephson inductance, the c_3 term relates to 3-wave mixing and the c_4 term relates to 4-wave mixing, which is also known as the Kerr nonlinearity.

[0020] Normally single junctions and SQUIDs, including asymmetric SQUIDs, have $c_3 = 0$, whereby 3-wave mixing does not occur, and non-linearity is provided by the Kerr term. 3-wave mixing means the ability to pump at twice the input frequency, which is desirable. 3-wave mixing could be activated by injecting a dc current, but however, the Kerr term would remain non-zero.

[0021] Nonlinearity provided by the Kerr term is associated with the need for resonant phase matching, in practice the pump signal is given a small phase increment at regular intervals along the transmission line. This is due to the pump having a different phase velocity from the signal (at the frequency fP) and the idler (at the frequency fI). This phase mismatch increases with the pump power. Conservation of energy implies the existence of an idler frequency at the output, the frequency of which is located at the "mirror image" of the signal frequency with respect to the pump, $fI=2fP-fS$. In detail, in the Kerr mode, phase mismatch and gain depend on the same parameter, the Kerr nonlinearity. The three frequencies are related by $fS+fI=fP$ in the case of 3-wave mixing.

To minimize the amount of reflections, both ends of the TWPA further need to have good impedance match at each of the frequencies fI, fS and fP.

[0022] Consequently, it would be preferable to operate a TWPA using 3-wave mixing without 4-wave mixing, that is, using the c_3-term with the Kerr nonlinearity suppressed. Thus the amplifier could be constructed without equipment for providing the periodic phase increments which are necessitated by the Kerr mode. In the 3-wave mode, phase mismatch and gain depend on different nonlinear terms.

[0023] In particular, the present invention sets out to solve, or at least alleviate, the following problems: firstly, sensitivity to magnetic interference in a Kerr-free TWPA. The interference may compromise the ultralow-noise performance of the TWPA. Secondly, sensitivity to inhomogeneity of the magnetic bias field in the Kerr-free TWPA. Thirdly, fabrication spread of the Josephson junctions affects the critical current in the TWPA. These effects cause variation of the transmission line impedance, a potential source of reflections. The reflections can cause standing waves that introduce periodicity into the frequency response of the TWPA, or even prevent the mixing process from providing gain. Fourthly, depletion of pump current in the TWPA. This limits the maximum gain of the TWPA.

[0024] A. B. Zorin describes in [1] a solution, wherein the balance between c_3 and c_4 mixing can be controlled by applying a suitable external magnetic field to rf-SQUIDs. Thus predominantly 3-wave mixing may be attained in Zorin's system.

[0025] Frattini et al. describe in [2] a flux-qubit-like circuit which simultaneously nulls the Kerr mixing term and maximizes the 3-wave mixing term. This circuit, which the authors of document [2] name "Superconducting Nonlinear Asymmetric Inductive eLement", SNAIL, is modified as described herein to arrive at the Josephson element 110 in the present embodiments. In detail, in [2], a Josephson element has three large Josephson junctions on one half of a loop and one small Josephson junction on the other half of the loop. In the present solution, a Josephson element with at least two large Josephson junctions on one half of a loop and one small Josephson junction on the other half of the loop is used. This will be illustrated later in FIGUREs 2 and 3.

[0026] The JTWPA of FIGURE 1 has, in the waveguide, parallel-plate capacitors 120, interspersed between the Josephson elements 110. Two Josephson elements 110 between every two parallel plate capacitors 120 is one example, to which the invention is not limited, indeed, in various embodiments there may be three or more Josephson elements 110 between every two parallel plate capacitors 120. The parallel plate capacitors 120 form the majority of the shunt capacitance of the transmission line. The JTWPA of FIGURE 1 is a coplanar waveguide.

[0027] The JTWPA of FIGURE 1 is further furnished with a flux bias line, FBL, 130. Flux bias line 130 is a two-port circuit that takes a serpentine path, ranging from one side of the coplanar waveguide to the other. The flux bias line 130 forms an upper electrode of the parallel-plate capacitors 120 in places where it crosses over to another side of the waveguide, as illustrated in FIGURE 1. The flux bias line 130 connects to the ground planes of the transmission line through resistors 140, the value of which is much smaller than the reactive impedance of the capacitors 120, at the relevant frequencies fI, fS and fP. The purpose of the resistors 140 is to provide an rf path to ground from the parallel-plate capacitors 120. At the same time, the resistors 140 and the flux bias line 130 enforce a similar electric potential of the ground planes at the frequencies fI, fS, and fP.

[0028] As illustrated, flux bias line 130 extends on one side of the waveguide, parallel to the waveguide, before ranging over to another side of the waveguide at a place corresponding to one of the parallel-plate capacitors 120, to again extend parallel to the waveguide on said another side of the waveguide. Where flux bias line 130 extends parallel to the waveguide, it may be connected, as illustrated, with the resistors 140, each of which may form a loop surrounding a contact hole 150. Resistors 140 comprise metal layers in the present multi-layer JTWPA. Resistors 140 partly overlay the superconducting material to form a contact, wherein the resistive aspect of resistors 140 is generated where the resistors 140 overlay an insulator, and not the superconductor.

[0029] Operating parameters of the Josephson elements 110 include that these elements have at least two large Josephson junctions on one half of a loop and one small Josephson junction on the other half of the loop is used. In particular, there may be two and only two large Josephson junctions on one half of a loop and one and only one small Josephson junction on the other half of the loop. Further, the critical current of the small junction is smaller than the critical current of the larger junctions by a factor of alpha. In the present Josephson elements 110, alpha may be 0,27. Further, the magnetic flux threading through the loops of elements 110 may in the present solution be 0,40 times the magnetic flux quantum. Thus one parameter combination could be two large Josephson junctions and one smaller one, their relation being 0,27 and the magnetic field amounting to 0,40 times the flux quantum.

[0030] Dissipation of the resistors adds to the dielectric loss of parallel-plate capacitors 120. A dc current in the flux bias line 130 generates the magnetic field gradient for the Josephson elements 110. The resistors 140 prevent the leakage of this current to the ground plane, and they also prevent the formation of superconductive loops from the ground planes and cross-overs. Such superconductive loops could cause the magnetic flux to quantize. A current source floating with respect to the waveguide ground may be provided for generating the dc current in flux bias line 130.

[0031] The amount of dissipation in the transmission line can be expressed through an effective loss tangent of the parallel-plate capacitors 120. Both the pump current and the pump voltage experience an exponential decay due to the dissipation when the characteristic impedance is constant along the transmission line. It would be desirable if a fixed ratio were maintained between Ip and Ic to ensure that the mixing process remains strong in spite of the dissipation. To this end, either position dependent capacitance or position dependent critical current may be applied. , The expression for a position-dependent shunt capacitance, that mainly consists of the parallel-plate capacitors 120, is derivedbelow. . The capacitance variation maintains a fixed pump current magnitude along the transmission line, at the expense of a faster decay of the pump voltage magnitude. From the input to the output to the TWPA, the shunt capacitance 120 will increase. The characteristic impedance will decrease accordingly, and an impedance-matching device may be employed at the output of the device. Examples of an impedance-matching devices are a Klopfenstein taper and exponential taper

[0032] In the following, the following notations are employed:

a: unit cell physical length

G: shunt conductance of the unit cell

V: voltage

C: unit cell capacitance

C_0: line capacitance at the input, i.e., at x=0 tan δ: loss tangent of C

ω: angular frequency

L: unit cell inductance

x: physical coordinate

Z: characteristic impedance

[0033] The power dissipated within an unit cell reads $\mathrm{Re}\{VG^*V^*\}/2$, and the total dissipation from the TWPA input until the position x is an integral:

[0034] $\int_0^x \frac{G|V|^2}{2a} dx'$

[0035] We write V = ZI where the current magnitude |I| is assumed to be constant, and $Z = \sqrt{L/C}$. Further inserting G = omega*C*tan δ,

[0036] $\int_0^x \frac{\omega C(\tan\delta)Z^2|I|^2}{2a} dx' = \frac{x\omega L(\tan\delta)|I|^2}{2a}$

[0037] Importantly, this dissipation does not change with the possible variation of C. On the other hand, we consider the power delivered to position x, that is,

[0038] $\frac{\mathrm{Re}\{VI^*\}}{2} = \frac{Z|I|^2}{2} = \frac{\sqrt{L}|I|^2}{2\sqrt{C}}$

[0039] The self-consistent solution for constant |I| then presents itself as

[0040] $\frac{1}{\sqrt{C}} = \frac{1}{\sqrt{C_0}} - \frac{x\omega\sqrt{L}\tan\delta}{a}$.

[0041] Technical effects enabled by the present embodiments include eliminating a magnetic shield for superconductive circuits, which typically comprises a combination of high-permeability and superconductive layers. The gradiometric design of the Josephson element relaxes the magnetic shielding requirement of the Kerr-free TWPA, allowing savings in the system cost and size. The gradiometric layout of the Kerr-free Josephson element makes the element sensitive to a magnetic field gradient only, as opposed to also being responsive to the magnitude of the magnetic field. Furthermore, the ability to keep the ratio between the pump current and critical current at a fixed value enables higher gain of the TWPA. Parameter selection for the Kerr-free Josephson element render the element first order insensitive to errors in the size of the smallest Josephson junction. Further, the flux bias line 130 produces the necessary magnetic field gradient, and connects to the transmission line ground with low-valued resistors. A gradual modification of the transmission line impedance along the line maintains a constant ratio between Ip and Ic.

[0042] FIGURE 2 illustrates an example Josephson element in accordance with document [2]. In the upper half of the image, a Josephson element is illustrated with three large junctions on one half of a loop and one small Josephson junction on the other half of the loop. The Josephson energies of the junctions relate to each other with the ratio α, as illustrated.

[0043] The lower part of the figure illustrates an example potential for the parameter set $\alpha = 0{,}29$, $\Phi_{ext}/\Phi_0 = 0{,}41$. In other words, here the external magnetic field is 0,41 times the flux quantum. This obtains third-order nonlinearity without fourth-order nonlinearity, in other words, $c_3 \neq 0$ and $c_4 = 0$.

[0044] Where the Josephson element has one small junction and n large junctions, the parameter set may be determined as follows. An inductive energy of the Josephson element may be expressed as

[0045]

$$U_{\mathbf{SNAIL}}(\varphi) = -\alpha E_J \cos(\varphi) - n E_J \cos\left(\frac{\varphi_{\mathrm{ext}} - \varphi}{n}\right)$$

[0046] where φ is a superconducting phase over the small junction, α the ratio of the junction sizes, E_J the Josephson energy of the large junction(s) and φ_{ext} is the reduced external magnetic flux:

[0047] $$\varphi_{\mathrm{ext}} = 2\pi\Phi_{\mathrm{ext}}/\Phi_0$$

[0048] Φ_{ext} is the external magnetic flux and Φ_0 is the magnetic flux quantum, a natural constant h/(2e). Here h is Planck's constant and e the electron charge.

[0049] Phase 1: a minimum of the inductive energy is sought as a function of φ. The φ at the said minimum is denoted φ_{min}. The search may be limited to parameter space $\alpha < 1/n$, to avoid having plural minima. In parameter space $\alpha >= 1/n$ there exists a risk, that for some values of φ_{ext} there exists more than one minimum. The case of the plural minima results in an unwanted hysteresis of the Josephson element.

[0050] Phase 2: a Taylor expansion is developed for the effective potential U_{eff} that describes φ-dependence of the inductive energy near the minimum.

$$\tilde{\varphi} = \varphi - \varphi_{\min}:$$

[0051]
$$U_{\text{eff}}(\tilde{\varphi})/E_J = c_2\tilde{\varphi}^2 + c_3\tilde{\varphi}^3 + c_4\tilde{\varphi}^4 + \cdots$$

[0052] Phase 3: c_2 is investigated as a function of α and Φ_{ext} to establish, where $dc_2/d\alpha = 0$.

[0053] Phase 4: c_4 is investigated as a function of α and Φ_{ext} to establish, where $c_4 = 0$.

[0054] Phase 5: An optimal parameter pair (α, Φ_{ext}) is established, where both $dc_2/d\alpha = 0$ and $c_4 = 0$. Here also $c_3 \neq 0$. Optimal parameters for n=2 and n=3 are presented below:

n	α	Φ_{ext}/ Φ_0	c_3	c_4
2	0.27	0.40	-0.030	0
3	0.12	0.36	-0.016	0

[0055] FIGURE 3 illustrates an example Josephson element in accordance with at least some embodiments of the present invention. In the upper half of the figure, a Josephson element is illustrated, with two large Josephson junctions on one half of a loop, and one smaller Josephson junction on the other half of the loop.

[0056] At the lower part of the figure, a gradiometric Josephson element is illustrated, with n = 2 larger Josephson junctions I_1, and one smaller Josephson junction I_2, as in the upper part of the figure. A superconducting part 301 and tunnel junction 302 are comprised in the Josephson element. Two junctions of critical current I_1 and one junction of critical current I_2 are illustrated, with their Josephson energies relating to each other by α, as in the upper part of the figure.

[0057] The loops are in practice relatively easy to manufacture such that they are symmetric. Example values for the junctions are I_1 = 13,7 µA and I_2 = 3,7 µA. A Josephson inductance series expansion of this element at the optimal Φ_{ext} would amount to 5 µA times [1 + 0,50(Ip/Ic) + 0,00$(Ip/Ic)^2$ +…]. The illustrated element is first-order insensitive to errors in the small junction size, I_2.

[0058] FIGURE 4 is a flow graph of a method in accordance with at least some embodiments of the present invention. The phases of the illustrated method may be performed in a factory apparatus, an auxiliary device or a personal computer, for example, or in a control device configured to control the functioning thereof, when installed therein.

[0059] Phase 410 comprises providing a waveguide transmission line comprising therein at least ten Josephson elements, wherein each of the at least ten Josephson elements comprises a loop, with one junction of first size on one half of the loop and at least two junctions of a second size on a second half of the loop, the second size being larger than the first size. Phase 420 comprises providing a flux bias line configured to generate a magnetic field threading each of the at least one loop. Phase 430 comprises providing a set of resistors coupled with the flux bias line.

[0060] The junctions may comprise Josephson junctions, as described herein above. The flux bias line may generate the magnetic field gradient required once the dc current is applied to traverse it. By exactly one it is meant one and no more than one, and by exactly two it is meant two and no more than two.

[0061] It is to be understood that the embodiments of the invention disclosed are not limited to the particular structures, process steps, or materials disclosed herein, but are extended to equivalents thereof as would be recognized by those ordinarily skilled in the relevant arts. It should also be understood that terminology employed herein is used for the purpose of describing particular embodiments only and is not intended to be limiting.

[0062] Reference throughout this specification to one embodiment or an embodiment means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment of the present invention. Thus, appearances of the phrases “in one embodiment” or “in an embodiment” in various places throughout this specification are not necessarily all referring to the same embodiment. Where reference is made to a numerical value using a term such as, for example, about or substantially, the exact numerical value is also disclosed.

[0063] As used herein, a plurality of items, structural elements, compositional elements, and/or materials may be presented in a common list for convenience. However, these lists should be construed as though each member of the list is individually identified as a separate and unique member. Thus, no individual member of such list should be construed as a de facto equivalent of any other member of the same list solely based on their presentation in a common group without indications to the contrary. In addition, various embodiments and example of the present invention may be referred to herein along with alternatives for the various components thereof. It is understood that such embodiments, examples, and alternatives are not to be construed as de facto equivalents of one another, but are to be considered as separate and autonomous representations of the present invention.

[0064] Furthermore, the described features, structures, or characteristics may be combined in any suitable manner in one or more embodiments. In the preceding description, numerous specific details are provided, such as examples of lengths, widths, shapes, etc., to provide a thorough understanding of embodiments of the invention. One skilled in the relevant art will recognize, however, that the invention can be practiced without one or more of the specific details, or with other methods, components, materials, etc. In other instances, well-known structures, materials, or operations are not shown or described in detail to avoid obscuring aspects of the invention.

[0065] While the forgoing examples are illustrative of the principles of the present invention in one or more particular applications, it will be apparent to those of ordinary skill in the art that numerous modifications in form, usage and details of implementation can be made without the exercise of inventive faculty, and without departing from the principles and concepts of the invention. Accordingly, it is not intended that the invention be limited, except as by the claims set forth below.

[0066] The verbs “to comprise” and “to include” are used in this document as open limitations that neither exclude nor require the existence of also un-recited features. The features recited in depending claims are mutually freely combinable unless otherwise explicitly stated. Furthermore, it is to be understood that the use of "a" or "an", that is, a singular form, throughout this document does not exclude a plurality.

INDUSTRIAL APPLICABILITY

[0067] At least some embodiments of the present invention find industrial application in amplification of low-amplitude signals.

ACRONYMS LIST

f1	Idler frequency
fP	Oscillator/pump frequency
fS	Signal frequency
Ic	Critical current of Josephson junction
Ip	Pump current amplitude
JTWPA	Josephson traveling wave parametric amplifier
SQUID	superconducting quantum interference device
TWPA	traveling wave parametric amplifier

REFERENCE SIGNS LIST

110	Josephson element
120	Shunt capacitor (parallel-plate capacitor)
130	Flux bias line
140	Resistor
150	Contact hole
101	Wiring layer element
301	Superconducting part
302	Tunnel Junction
410 – 420	Phases of the method of FIGURE 4

CITATION LIST

[1] A. B. Zorin: “Josephson traveling-wave parametric amplifier with three-wave mixing”, arXiv:1602.026550v3, 19 Sep 2016.

[2] N.E. Frattini, U. Vool, S. Shankar, A. Narla, K. M. Sliwa and M. H. Devoret, “3-wave mixing Josephson dipole element”, arXiv: 1702.00869v3, 1 Jun 2017.

CLAIMS:

1. A travelling wave parametric amplifier comprising:
   - a waveguide transmission line comprising therein at least ten Josephson elements, wherein each of the at least ten Josephson element comprises a loop, with exactly one Josephson junction of first size on one half of the loop and at least two Josephson junctions of a second size on a second half of the loop, the second size being larger than the first size;
   - a flux bias line configured to generate a magnetic flux threading each of the at least one loop, and
   - a set of resistors coupled with the flux bias line.

2. The travelling wave parametric amplifier according to claim 1, wherein each of the at least ten Josephson elements does not exhibit Kerr nonlinearity at, or exhibits a negligible contribution of Kerr nonlinearity, and wherein each of the at least ten Josephson elements does exhibit three-wave mixing.

3. The travelling wave parametric amplifier according to any of claims 1 - 2, wherein a ratio of a Josephson energy of the junction of the first size to a Josephson energy of the junction of the second size is configured so as to partially or completely eliminate said Kerr nonlinearity.

4. The travelling wave parametric amplifier according to claim 3, wherein the said ratio of the Josephson energies is configured by areas of the junctions.

5. The travelling wave parametric amplifier according to claim 3 where the said ratio of the Josephson energies is configured by the superconducting critical current density of the junctions.

6. The travelling wave parametric amplifier according to any of claims 1 - 5, wherein the travelling wave parametric amplifier is configured to enable generation of a current in the flux bias line so that the magnetic flux threading the said loop corresponds to an operation point minimizing said Kerr nonlinearity.

7. The travelling wave parametric amplifier according to any of the claims 1 - 6, wherein the magnetic flux threading each of the at least one loop amounts to 0,40 times a magnetic flux quantum, and wherein each of the at least ten Josephson elements comprises exactly two junctions of the second size on a second half of the loop.

8. The traveling wave parametric amplifier according to claim 7, wherein a Josephson energy of a junction of the first size is 0,27 times the Josephson energy of a junction of the second size.

9. The travelling wave parametric amplifier according to any of claims 3 - 5, where the ratio of the Josephson energies and the magnetic flux treading the loops are configured so that the operation is to first order insensitive to the variation of the smaller Josephson energy.

10. The traveling wave parametric amplifier according to any of claims 1 – 9, wherein the waveguide transmission line comprises more than fifteen of the Josephson elements.

11. The traveling wave parametric amplifier according to any of claims 1 – 10, wherein the flux bias line forms an upper or lower electrode of parallel plates which form shunt capacitance of the waveguide transmission line.

12. The traveling wave parametric amplifier according to claim 11, wherein the flux bias line connects to ground planes of the waveguide transmission line through the resistors which have smaller values than a reactive impedance of the shunt capacitors at frequencies which the traveling wave parametric amplifier is configured to amplify.

13. The traveling wave parametric amplifier according to any of claims 11 - 12 , wherein the traveling wave parametric amplifier is configured to apply a dc current in the flux bias line to generate a magnetic field gradient.

14. The traveling wave parametric amplifier according to claim 13, wherein the each of the loops is configured in a gradiometric configuration to be insensitive to homogeneous magnetic fields from the ambient.

15. The traveling wave parametric amplifier according to any of claims 11 – 14, wherein the waveguide transmission line comprises sets of two Josephson elements, the sets separated from each other by the shunt capacitors arranged on the waveguide transmission line.

16. The travelling wave parametric amplifier according to claim 11 - 15 in which the value of the shunt capacitance is not constant along a length of the transmission line to compensate for microwave attenuation along the transmission line.

17. The travelling wave parametric amplifier according to any of claims 11 - 15 in which the value of the critical current is not constant along a length of the transmission line to compensate for microwave attenuation along the transmission line.

18. The traveling wave parametric amplifier according to claim 16 or 17 in which the shunt capacitance value variation or critical current value variation is by design configured so that when exposed to pump microwave signal, corresponding current distribution along the transmission line is constant or nearly constant.

19. The traveling wave parametric amplifier according to any of claims 16, 17 or 18, in which the microwave attenuation is implemented by dielectric loss of the shunt capacitance.

20. The traveling wave parametric amplifier according to any of claims 16, 17, 18 or 19, wherein the microwave attenuation is implemented by losses in said resistors of the waveguide transmission line.

21. The traveling wave parametric amplifier according to any of claims 12 or 20, in which the both the resistor and shunt capacitance values are configured to optimize for the homogenous microwave current distribution along the transmission line.

22. The traveling wave parametric amplifier according to any of claims 1 – 21, further comprising an impedance matching device at at least one end of the waveguide transmission line.

23. The traveling wave parametric amplifier according to claim 22, wherein the impedance matching device comprises a tapered transmission line matching element.

24. The travelling wave parametric amplifier according to claim 23, wherein the tapered transmission line matching element comprises a Klopfenstein taper.

25. The travelling wave parametric amplifier, according to claim 23, wherein the tapered transmission line matching element comprises an exponential taper.

26. A method for manufacturing a traveling wave parametric amplifier comprising:

- providing a waveguide transmission line comprising therein at least ten Josephson elements, wherein each of the at least ten Josephson elements comprises a loop, with exactly one junction of first size on one half of the loop and at least two junctions of a second size on a second half of the loop, the second size being larger than the first size;
- providing a flux bias line configured to generate a magnetic field threading each of the at least one loop, and
- providing a set of resistors coupled with the flux bias line.

PATENTTIVAATIMUKSET:

1. Kulkuaallon parametrinen vahvistin (”travelling wave parametric amplifier”), joka käsittää:

- koplanaarisen aalto-ohjaimen siirtolinjan, joka käsittää vähintään kymmenen Josephson-elementtiä (110), jossa kukin vähintään kymmenestä Josephson-elementistä (110) käsittää silmukan, jossa on tasan yksi ensimmäisen koon Josephson-liitos silmukan toisessa puolikkaassa ja vähintään kaksi toisen koon Josephson-liitosta silmukan toisessa puolikkaassa, joka toinen koko on suurempi kuin ensimmäinen koko;
- vuon suuntauslinjan (130), joka on muodostettu tuottamaan kunkin vähintään yhden silmukan läpi kulkeva magneettinen vuo, joka suuntauslinja käsittää kaksiaukkoisen piirin, joka kulkee reittiä, joka vaihtelee toistuvasti koplanaarisen aalto-ohjaimen siirtolinjan puolelta toiselle ja risteää koplanaarisen aalto-ohjaimen siirtolinjan paikassa, joka vastaa koplanaariselle aalto-ohjaimen siirtolinjalle sovitettua levykondensaattoria (120), ja
- resistorien (140) joukon, joka kytkee vuon suuntauslinjan (130) koplanaarisen aalto-ohjaimen siirtolinjan maadoitustasoihin (101) (”ground planes”).

2. Patenttivaatimuksen 1 mukainen kulkuaallon parametrinen vahvistin, jossa kussakin vähintään kymmenestä Josephson-elementistä (110) ei ole lainkaan Kerrin epälineaarisuutta tai sen havaittava Kerrin epälineaarisuus ei ole merkittävä, ja jossa kussakin vähintään kymmenestä Josephson-elementistä (110) on kolmen aallon sekoitus.

3. Jonkin patenttivaatimuksen 1–2 mukainen kulkuaallon parametrinen vahvistin, jossa ensimmäisen koon liitoksen Josephson-energian suhde toisen koon liitoksen Josephson-energiaan on muodostettu siten, että se poistaa mainitun Kerrin epälineaarisuuden osittain tai kokonaan.

4. Patenttivaatimuksen 3 mukainen kulkuaallon parametrinen vahvistin, jossa mainittu Josephson-energioiden suhde muodostetaan liitosten pinta-aloilla.

5. Patenttivaatimuksen 3 mukainen kulkuaallon parametrinen vahvistin, jossa mainittu Josephson-energioiden suhde muodostetaan liitosten suprajohtavan kriittisen virran tiheydellä.

6. Jonkin patenttivaatimuksen 1–5 mukainen kulkuaallon parametrinen vahvistin, jossa kulkuaallon parametrinen vahvistin on muodostettu mahdollistamaan virran tuottaminen vuon suuntauslinjassa (130) siten, että magneettisen vuon kulkeminen mainitun silmukan läpi vastaa toimintovaihetta, jossa mainittu Kerrin epälineaarisuus minimoidaan.

7. Jonkin patenttivaatimuksen 1–6 mukainen kulkuaallon parametrinen vahvistin, jossa kunkin mainitun vähintään yhden silmukan läpi kulkeva magneettinen vuo on yhtä suuri kuin 0,40 kertaa magneettisen vuon kvantti ja jossa kukin vähintään kymmenestä Josephson-elementistä käsittää tasan kaksi toisen koon liitosta silmukan toisella puoliskolla, jossa ensimmäisen koon liitoksen Josephson-energia on 0,27 kertaa toisen koon liitoksen Josephson-energia.

8. Jonkin patenttivaatimuksen 1–7 mukainen kulkuaallon parametrinen vahvistin, jossa koplanaarinen aalto-ohjaimen siirtolinja käsittää yli viisitoista Josephson-elementtiä (110).

9. Jonkin patenttivaatimuksen 1–8 mukainen kulkuaallon parametrinen vahvistin, jossa vuon suuntauslinja (130) muodostaa koplanaarisen aalto-ohjaimen siirtolinjan shunttikondensaattorit (120) muodostavien samansuuntaisten levyjen ylemmän tai alemman elektrodin, jotka shunttikondensaattorit (120) ovat levykondensaattoreita (120).

10. Patenttivaatimuksen 9 mukainen kulkuaallon parametrinen vahvistin, jossa vuon suuntauslinja (130) kytkeytyy koplanaarisen aalto-ohjaimen siirtolinjan maadoitustasoihin sellaisten resistorien (140) kautta, joiden arvot ovat shunttikondensaattorien (120) reaktiivista impedanssia pienempiä taajuuksilla, joilla kulkuaallon parametrinen vahvistin on muodostettu vahvistamaan.

11. Jonkin patenttivaatimuksen 9–10 mukainen kulkuaallon parametrinen vahvistin, jossa kulkuaallon parametrinen vahvistin on muodostettu johtamaan dc-virtaa vuon suuntauslinjaan (130) magneettikentän gradientin tuottamiseksi.

12. Patenttivaatimuksen 11 mukainen kulkuaallon parametrinen vahvistin, jossa kukin silmukoista on muodostettu gradiometrisenä kokoonpanona olemaan epäherkkä ympäristöstä peräisin oleville homogeenisille magneettikentille.

13. Jonkin patenttivaatimuksen 9–12 mukainen kulkuaallon parametrinen vahvistin, jossa koplanaarinen aalto-ohjaimen siirtolinja käsittää kahden Josephson-elementin (110) joukkoja, jotka joukot on erotettu toisistaan koplanaariseen aalto-ohjaimen siirtolinjaan järjestetyillä shunttikondensaattoreilla (120).

14. Jonkin patenttivaatimuksen 9–13 mukainen kulkuaallon parametrinen vahvistin, jossa shunttikondensaattorien (120) arvo siirtolinjan matkalla ei ole vakio mikroaaltojen siirtolinjalla vaimenemisen kompensoimiseksi.

15. Jonkin patenttivaatimuksen 1–14 mukainen kulkuaallon parametrinen vahvistin, joka edelleen käsittää impedanssin sovituslaitteen vähintään koplanaarisen aalto-ohjaimen siirtolinjan toisessa päässä.

16. Patenttivaatimuksen 15 mukainen kulkuaallon parametrinen vahvistin, jossa impedanssin sovituslaite käsittää kapenevan siirtolinjan sovituselementin.

17. Patenttivaatimuksen 16 mukainen kulkuaallon parametrinen vahvistin, jossa kapeneva siirtolinjan sovituselementti käsittää Klopfenstein-kartion.

18. Patenttivaatimuksen 16 mukainen kulkuaallon parametrinen vahvistin, jossa kapeneva siirtolinjan sovituselementti käsittää eksponentiaalisen kartion.

19. Menetelmä kulkuaallon parametrisen vahvistimen (”travelling wave parametric amplifier”) valmistamiseksi, joka menetelmä käsittää:

- koplanaarisen aalto-ohjaimen siirtolinjan järjestämisen, joka siirtolinja käsittää vähintään kymmenen Josephson-elementtiä (110), jossa kukin vähintään kymmenestä Josephson-elementistä (110) käsittää silmukan, jossa on tasan yksi ensimmäisen koon liitos silmukan toisessa puoliskossa ja vähintään kaksi toisen koon liitosta silmukan toisessa puoliskossa, joka toinen koko on suurempi kuin ensimmäinen koko;

- vuon suuntauslinjan (130) järjestämisen, joka suuntauslinja on muodostettu tuottamaan kunkin vähintään yhden silmukan läpi kulkeva magneettikenttä, joka suuntauslinja käsittää kaksiaukkoisen piirin, joka kulkee reittiä, joka vaihtelee toistuvasti koplanaarisen aalto-ohjaimen siirtolinjan puolelta toiselle ja risteää koplanaarisen aalto-ohjaimen siirtolinjan paikassa, joka vastaa koplanaariselle aalto-ohjaimen siirtolinjalle sovitettua levykondensaattoria (120), ja
- resistorien (140) joukon järjestämisen, joka joukko kytkee vuon suuntauslinjan (130) koplanaarisen aalto-ohjaimen siirtolinjan maadoitustasoihin (101) (”ground planes”).

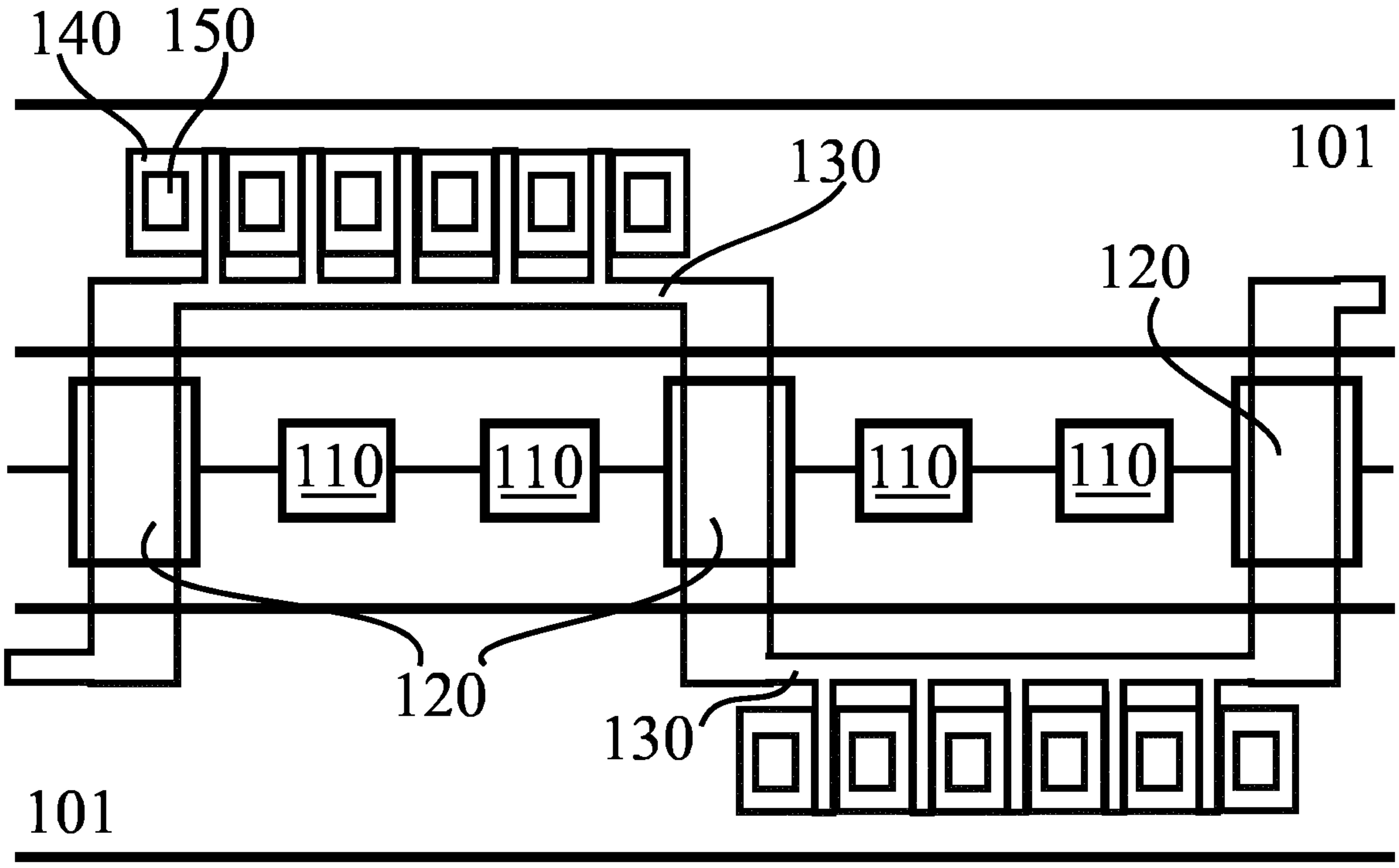


FIGURE 1

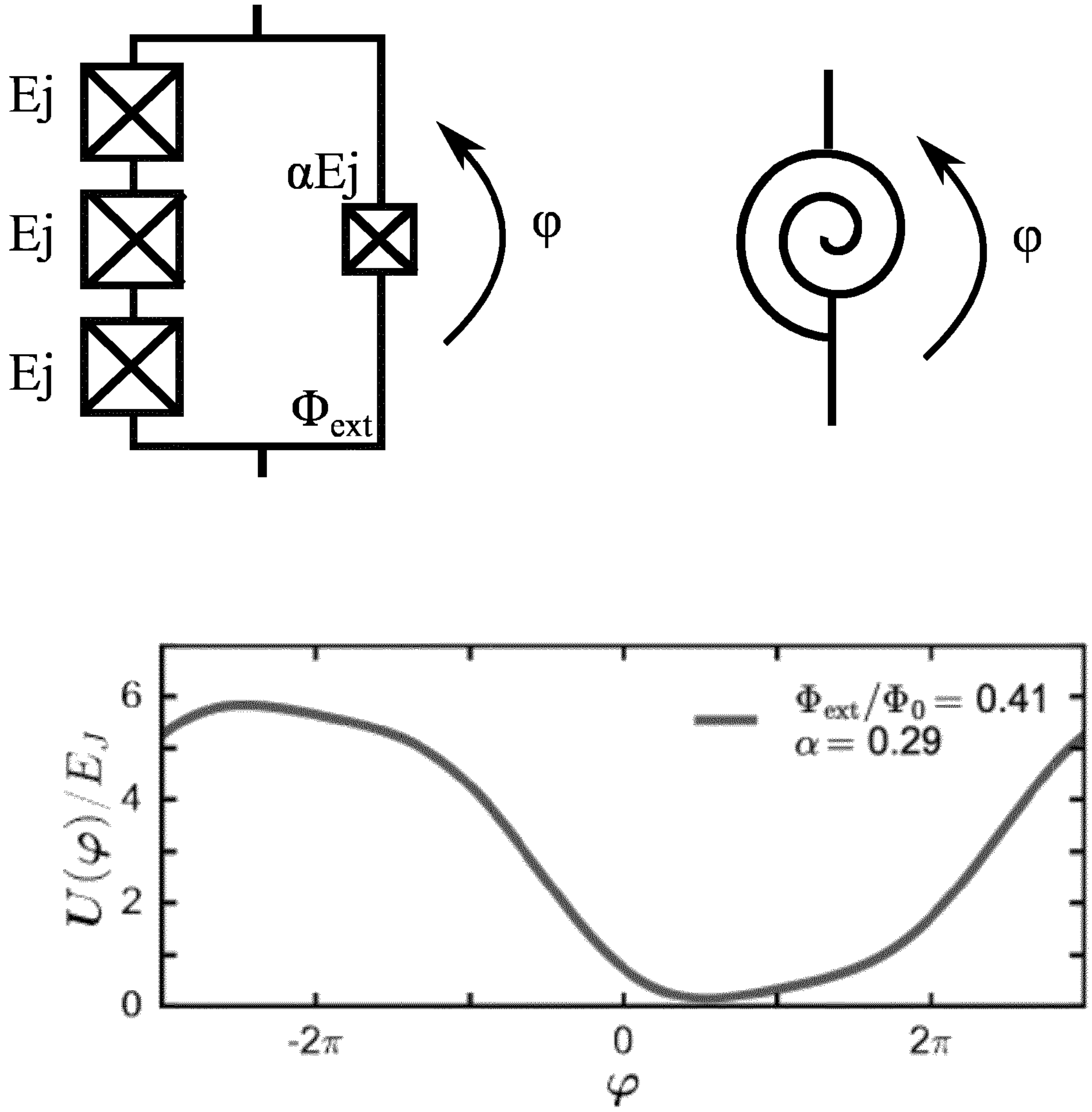

Ej
Ej
Ej
αEj
Φ_{ext}
φ
φ
$\Phi_{ext}/\Phi_0 = 0.41$
$\alpha = 0.29$
$U(\varphi)/E_J$
6
4
2
0
-2π
0
2π
φ

FIGURE 2

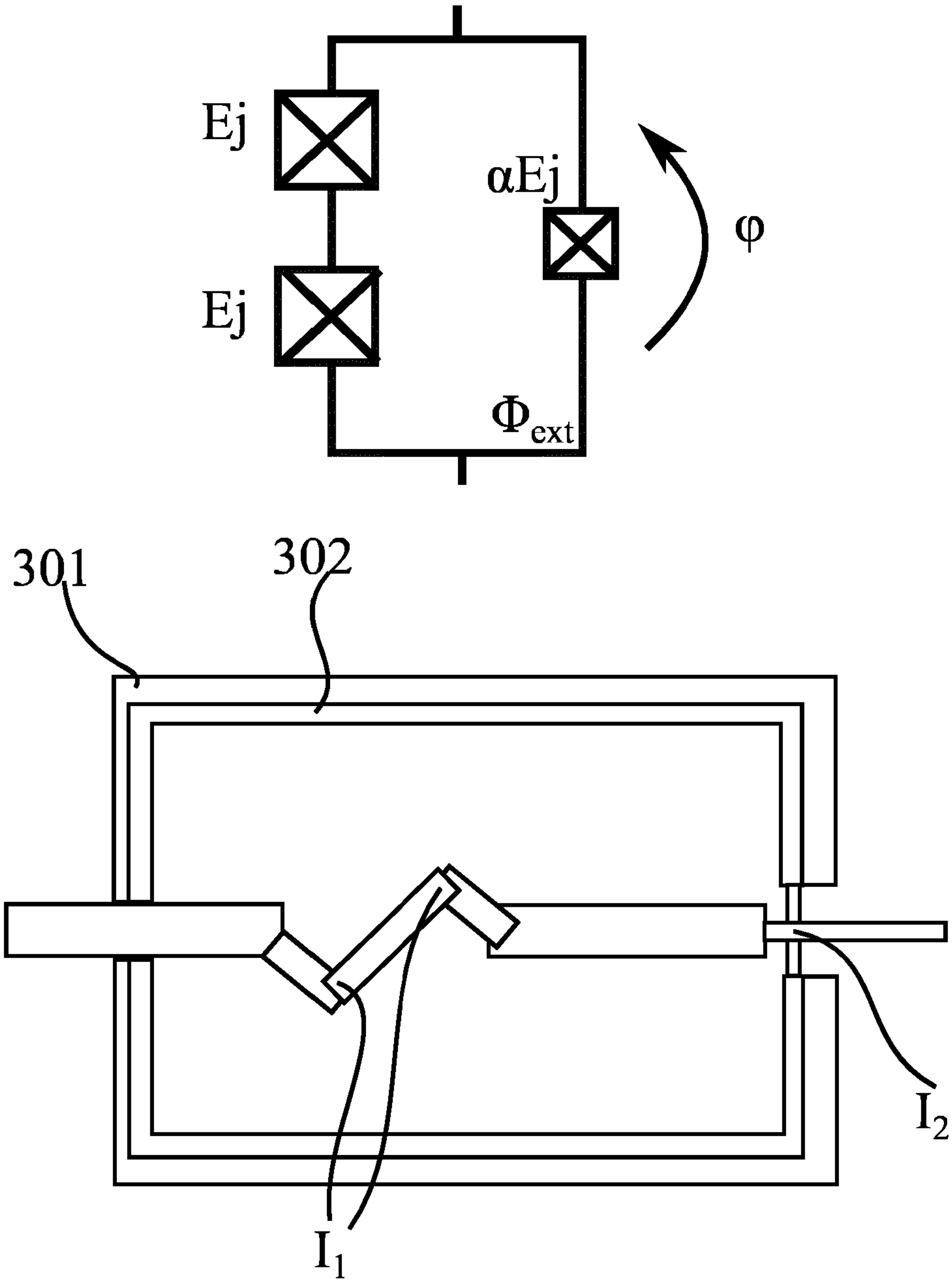
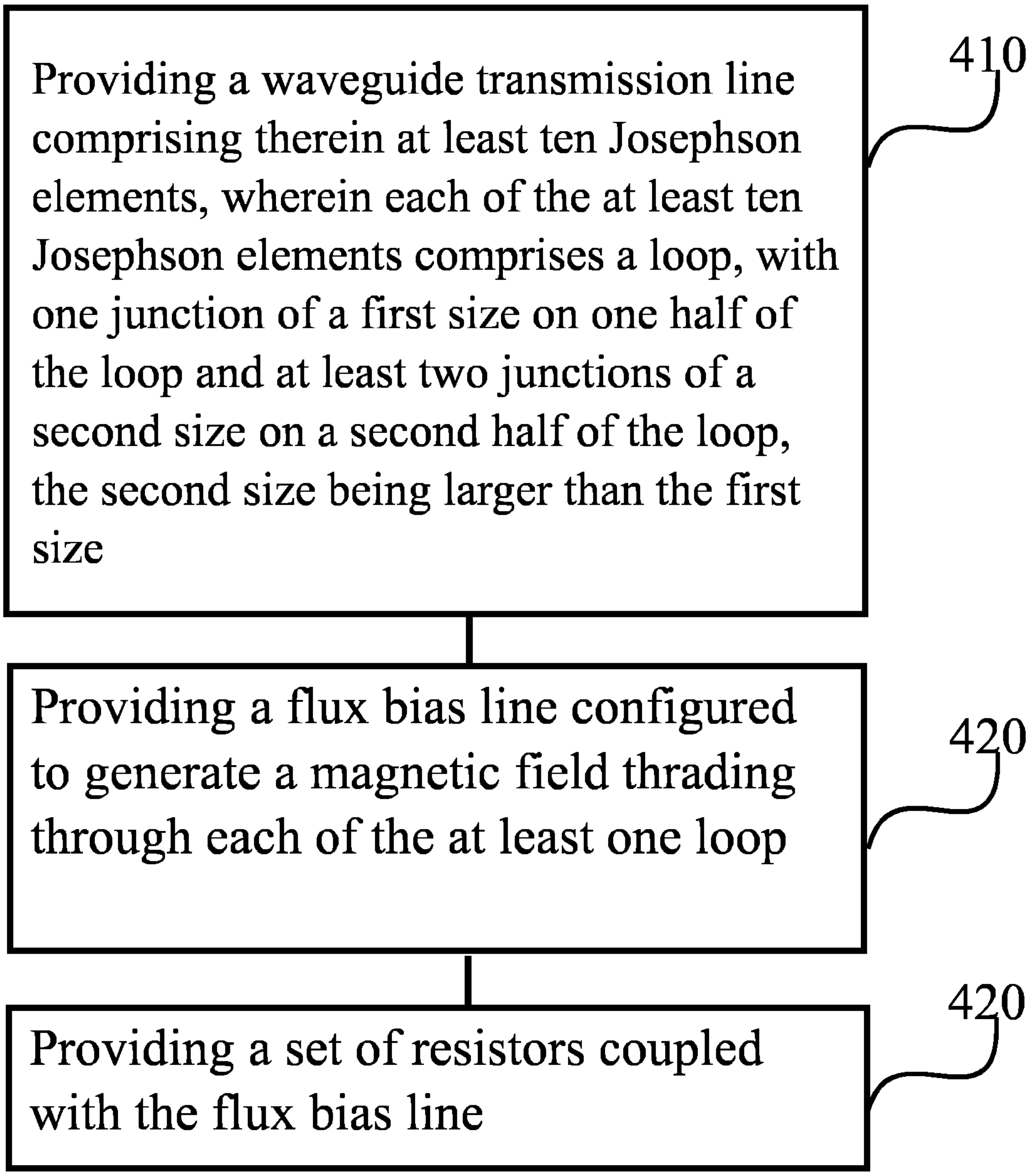


FIGURE 3



Providing a waveguide transmission line comprising therein at least ten Josephson elements, wherein each of the at least ten Josephson elements comprises a loop, with one junction of a first size on one half of the loop and at least two junctions of a second size on a second half of the loop, the second size being larger than the first size

Providing a flux bias line configured to generate a magnetic field thrading through each of the at least one loop

Providing a set of resistors coupled with the flux bias line

FIGURE 4

FINNISH PATENT AND REGISTRATION OFFICE **SEARCH REPORT**

Finnish Patent and Registration Office
FI-00091 PRH

PATENT APPLICATION No.	**CLASSIFICATION**	
20195045	IPC ***H03F 19/00*** (2006.01) ***H03F 7/00*** (2006.01) ***H01L 39/22*** (2006.01) ***H01L 39/24*** (2006.01) ***H01P 3/00*** (2006.01) *H01L 39/02* (2006.01)	CPC **H03F 19/00** **H03F 7/00** **H01L 39/223** **H01L 39/2493** **H01P 3/003** H01L 39/025

PATENT CLASSES SEARCHED (classification systems and classes)

IPC: H03F, H01L, H03P

DATABASES CONSULTED DURING THE SEARCH

EPODOC, EPO-Internal full-text databases, Full-text translation databases from Asian languages, WPIAP, COMPDX, INSPEC, TDB, NPL, XPAIP, XPCPVO, XPESP, XPETSI, XPI3E, XPIEE, XPIETF, XPIOP, XPIPCOM, XPMISC, XPOAC, XPRD, XPTK, Google, arXiv.org

DOCUMENTS CONSIDERED TO BE RELEVANT

Category*)	**Bibliographic data on the document and relevant passages**	**Relevant to claims**
X	FRATTINI, N.E. et al. Optimizing the nonlinearity and dissipation of a SNAIL Parametric Amplifier for dynamic range. In: arXiv.org, Cornell University Library [online], 2018-12-20, pages 1-17, [retrieved on 2019-08-05]. Retrieved from <https://arxiv.org/abs/1806.06093v2> abstract; page 3, left column, first paragraph; page 6, right column, second paragraph; Fig. 1; Table I; Appendix A.1	1-11, 13-14, 22-26

Continued on the next sheet ☒

*) X Document indicating that the invention is not novel or does not involve an inventive step with respect to the state of the art.
Y Document indicating that the invention does not involve an inventive step with respect to the state of the art if combined with one or more other documents in the same category.
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T Document published after the filing date or priority date and illustrating the principle or theory underlying the invention.
E Earlier patent or utility model application that either is Finnish or designates Finland published on or after the filing date (priority date).
D Document that is mentioned in the application.
L Document which may throw doubts on priority claim(s), is cited to establish the publication date of another citation or is referred to for some other reason.

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Date
21.08.2019

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PATENT APPLICATION No.
20195045

DOCUMENTS CONSIDERED TO BE RELEVANT, CONTINUED

Category*)	Bibliographic data on the document and relevant passages	Relevant to claims
X	ZORIN, A.B. et al. Traveling-wave parametric amplifier based on three-wave mixing in a Josephson metamaterial. In: arXiv.org, Cornell University Library [online], 2017-05-08, pages 1-3, [retrieved on 2019-08-08]. Retrieved from <https://arxiv.org/abs/1705.02859v1> abstract; sections II-IV; Figs. 1-2	1-11, 13-26
X	BELL, M.T. et al. Traveling wave parametric amplifier based on a chain of coupled asymmetric SQUIDs. In: arXiv.org, Cornell University Library [online], 2015-09-15, pages 1-9, [retrieved on 2019-07-17]. Retrieved from <https://arxiv.org/abs/1509.04573v1> abstract; section II; Fig. 1	1, 26
A, D	FRATTINI, N.E. et al. 3-Wave Mixing Josephson Dipole Element. In: arXiv.org, Cornell University Library [online], 2017-06-01, pages 1-5, [retrieved on 2019-07-17]. Retrieved from <https://arxiv.org/abs/1702.00869v3> abstract; page 1, right column; page 4, left column; Figs. 1, 4	1-26
A	REHAK, M. et al. Parametric amplification by coupled flux qubits. In: arXiv.org, Cornell University Library [online], 2013-12-27, pages 1-4, [retrieved on 2019-08-12]. Retrieved from <https://arxiv.org/abs/1312.7237v1> abstract; page 2, left column; page 3, left column, first paragraph; Fig. 1	1-26
A	TAN, B.-K. et al. Design of a uniplanar resonance phase-matched Josephson traveling-wave parametric amplifier. In: 10th UK-Europe-China Workshop on Millimetre Waves and Terahertz Technologies (UCMMT). IEEE Xplore Digital Library Liverpool, UK: IEEE [online], 2017-09-11, pages 1-4, [retrieved on 2019-08-15]. Retrieved from <https://ieeexplore.ieee.org/document/8068511>, <DOI:10.1109/UCMMT.2017.8068511> abstract; Figs. 1, 3	1-26
A	SCHWARZ, M.J. et al. Gradiometric flux qubits with a tunable gap. In: arXiv.org, Cornell University Library [online], 2013-04-06, pages 1-23, [retrieved on 2019-08-07]. Retrieved from <https://arxiv.org/abs/1210.3982v2> abstract; Fig. 1	1-26

FINNISH PATENT AND REGISTRATION OFFICE **SEARCH REPORT**

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PATENT APPLICATION No.
20195045

DOCUMENTS CONSIDERED TO BE RELEVANT, CONTINUED		
Category*)	**Bibliographic data on the document and relevant passages**	**Relevant to claims**
A	SIMBIEROWICZ, S. et al. Flux-driven Josephson parametric amplifier for sub-GHz frequencies fabricated with side-wall passivated spacer junction technology. In: arXiv.org, Cornell University Library [online], 2018-05-18, pages 1-23, [retrieved on 2019-08-07]. Retrieved from <https://arxiv.org/abs/1805.07307v1> abstract; section 2, second paragraph; Fig. 1	1-26
A	WO 2017149319 A1 (UNIV OXFORD INNOVATION LTD [GB]) 08 September 2017 (08.09.2017) abstract; page 9, line 27 – page 10, line 6; page 32, lines 1-14; Fig. 9c	1-26