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(54) QUANTUM WAVELENGTH CONVERTER BETWEEN A MICROWAVE SIGNAL AND AN OPTICAL SIGNAL

QUANTENWELLENLÄNGENKONVERTER ZWISCHEN EINEM MIKROWELLENSIGNAL UND EINEM OPTISCHEN SIGNAL

CONVERTISSEUR DE LONGUEUR D'ONDE QUANTIQUE ENTRE UN SIGNAL HYPERFRÉQUENCE ET UN SIGNAL OPTIQUE

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(73) Proprietor: **Qphox B.V.**
2628XG Delft (NL)

(72) Inventors:
- **GROEBLACHER, Simon**
  2628XG Delft (NL)
- **FORSCH, Moritz**
  2628XG Delft (NL)
- **STOCKILL, Robert Hugh James**
  2628XG Delft (NL)

(74) Representative: **Langley, Peter James**
Origin Limited
Twisden Works
Twisden Road
London NW5 1DN (GB)

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Description

FIELD OF THE INVENTION

[0001] The present invention is in the field of a quantum wavelength converter between a microwave signal and an optical signal and vice versa. In the converter a nanoscale cavity optomechanical circuit is used in which optomechanical cavities supporting colocalized infrared photons and microwave phonons are combined with a photonic and a phononic waveguide.

BACKGROUND OF THE INVENTION

[0002] The present invention is in the field of a quantum wavelength converter between a microwave signal and an optical signal and vice versa.

[0003] The microwave signal relates to a form of electromagnetic radiation. Microwaves have wavelengths from about one meter to one millimetre and thus with frequencies between 300 MHz and 300 GHz. Microwaves are often used for communication. However it is limited to a distance of about 64 km. For the high end of the band practical communication distances are however at most about one kilometer. Microwaves are widely used in modern technology and products, such as microwave ovens.

[0004] Infrared radiation (IR) is electromagnetic radiation with longer wavelengths than those of visible light. Typical IR wavelengths are from about 700 nanometers to 1 millimeter. IR behaves both like a wave and like a quantum particle, the photon.

[0005] A resonator provides resonance at some and specific frequencies, called its resonant frequencies. Oscillations in a resonator can be either electromagnetic or mechanical, hence may relate to photons and phonons. Resonators may be used to either generate waves of specific frequencies or to select specific frequencies from a signal. An example is a quartz crystal that produces oscillations of very precise and specific frequency. A cavity resonator is one in which oscillations exist in a hollow space inside the device.

[0006] Piezo-electricity relates to an electric charge that results in a solid material, typically a crystal, in response to applied mechanical stress or force. The piezoelectric effect is considered to result from electromechanical interaction between mechanical and electrical states. In crystalline materials no inversion symmetry may be present. Piezoelectricity is a reversible process. An exemplary material is a lead zirconate titanate crystal. The piezoelectric effect may be used to produce ultrasound and is applied in various applications and products.

[0007] Recently it has been attempted to realize a microwave to optics converter either by directly coupling fields thereof inside a non-linear crystal or by using a mechanical system as a transducer. Therein bi-directional operation, coherent coupling, and efficient conversion have been achieved. However, such conversion has only been achieved at a classical level. Therein input states are submerged in thermal noise from the mechanical oscillators. This added noise renders any converted qubit state useless for further quantum processing. In order to operate a fully functional quantum transducer that could be used to link several superconducting qubit based quantum nodes over long distances, it is crucial to minimize the thermal noise that is added in such a conversion process.

[0008] Some publications recite coupling between radiofrequency, optical and acoustic waves. For instance Balram et al. in Nature Phonics, vol. 10, No. 5, March 18 2016, p. 346-352 recites coupling propagating and localized phononic modes. Andrews et al. in Nature Physics, Vol. 10, No. 4, April 1 2014, p. 321-326 recites conversion between microwave and optical light. In addition, A. P. HIGGINBOTHAM ET AL: "Harnessing electro-optic correlations in an efficient mechanical converter", XU HAN ET AL: "Multimode Strong Coupling in Superconducting Cavity Piezo-electromechanics", BISWARUP GUHA ET AL: "Surface-enhanced gallium arsenide photonic resonator with quality factor of 6x10^6", VAINSENCHER A ET AL: "Using mechanics to convert between microwave and optical frequencies", AMIR H SAFAVI-NAEINI ET AL: "Controlling phonons and photons at the wavelength-scale: silicon photonics meets silicon phononics" provide similar quantum converters.

[0009] The present invention therefore relates to an improved quantum wavelength converter between a microwave signal and an optical signal, which solve one or more of the above problems and drawbacks of the prior art, providing reliable results, without jeopardizing functionality and advantages.

SUMMARY OF THE INVENTION

[0010] It is an object of the invention to overcome one or more limitations of the devices of the prior art and at the very least to provide an alternative thereto. The invention is also subject of a to be published scientific paper entitled "Quantum noise limited microwave to optics conversion" by amongst others Forsch, Stockill and Gröblacher. The present converter is operational on a real quantum level, i.e. below a classical noise level. A microwave quantum signal can be converted into an optical quantum signal, and vice versa. For providing or receiving an optical signal at least one of an optical input 91 and an optical output 92 is provided, and likewise for providing or receiving a microwave signal at least one of a microwave input 93 and a microwave output 94 is provided. Further at least one microwave-to-optical coupler 10 is provided, wherein the coupler comprises at least one of a phonon generator 21 and a phonon detector 22 for generating a photon that is being provided to a resonator or that is received and detected therefrom, and hence mechanically coupled to the phonon generator/detector at least one of an optical high-efficiency photon generator and an

optical photon detector 30 is provided, the photon generator/detector comprising at least one optomechanical resonator 31, wherein the optomechanical resonator is adapted to receive a phonon from the phonon generator or to generate a phonon to the phonon detector. The coupling between phonon generator/detector and optomechanical resonator is preferably coherent coupling and in particular quantum coherent coupling. In order to function at a quantum level the present converter 1 is provided with a cooler 50 for cooling the microwave-to-optical coupler to a temperature below 5K, and wherein the optomechanical resonator 31 comprises on a surface thereof at least one light absorption inhibiting layer 32. It has been found experimentally that both the cooler and light absorption inhibiting layer are considered necessary for operation of the present device at a true quantum level, i.e. such that quantum information can be distinguished (e.g. from background noise). The present coupler is for physical interaction between phonon and photon, to provide conversion of the one into the other, and to provide input/output. A photon may be received, and a phonon can be released, or the reverse, or both. Depending on an application a suitable combination of inputs and outputs can be made.

[0011] In the present quantum wavelength converter the optical input 91 and optical output 92 may be independently selected from optical waveguides, such as glass fibers. Therewith a highly efficient optical input 91 and a highly efficient optical output 92 are provided. The optical waveguide may preferably be tapered, widening from the input onwards, and may preferably be of high-efficiency nature, for example through an adiabatic mode conversion of a received optical signal, typically through an input fiber, and the waveguide, and /or adiabatic mode conversion between a waveguide and an output optical signal. The refractive indices of the input (and likewise output) fiber and the waveguide may each be adiabatically adjusted through tapering (going from wide to thin and vice-versa), such that the refractive indices cross and the optical mode gets transferred between the two. Therewith a highly-efficient method of coupling light onto the chip, such as an adiabatic transfer of the optical mode of an optical input fiber (and likewise output fiber), to (and from) an on-chip waveguide.

[0012] In a second aspect the present invention relates to a quantum network or quantum computing nodes comprising at least one present quantum wavelength converter.

[0013] The present invention is made possible by funds of the European Research Council (ERC StG Strong-Q, grant 676842) and Netherlands Organisation for Scientific Research (NWO/OCW) Vidi grant (680-47-541/994).

[0014] The present invention provides a solution to one or more of the above mentioned problems and overcomes drawbacks of the prior art.

[0015] Advantages of the present description are detailed throughout the description.

DETAILED DESCRIPTION OF THE INVENTION

[0016] In an exemplary embodiment of the present quantum wavelength converter the optical signal may have a wavelength of 400 nm-1 mm, preferably 800 nm-15000 nm, more preferably 1000 nm-3000 nm, even more preferably 1200 nm-2000 nm, such as 1400-1700 nm. The wavelengths are particularly suited for transferring signals over long distances, e.g. 10-1000 kms.

[0017] In an exemplary embodiment of the present quantum wavelength converter a microwave may have a frequency in the range of 0.3-300 GHz, preferably 1-100 GHz, more preferably 1.4-20 GHz, such as 2-10 GHz. These frequencies are often used for transfer of information over relative short distances, e.g. less than 10 km, and typically within a few 100 meters.

[0018] In an exemplary embodiment of the present quantum wavelength converter the optical input may provide 10nW-1μW power to the converter, preferably 20-500 nW, such as 30-300 nW. Without a light absorption inhibiting layer, in combination with these powers applied, a quantum ground state energy, or an energy close thereto (see below) could not be reached experimentally.

[0019] In an exemplary embodiment of the present quantum wavelength converter a lensed fibre with a focal length may be used, the focal length being adapted for the wavelength of light used, such as a focal length of 14 μm.

[0020] In an exemplary embodiment of the present quantum wavelength converter the microwave input 93 and microwave output 94 may be independently selected from photon waveguides, such as a crystal waveguides, and a coaxial cable. The microwave input may be attenuated, such as by several dB. The coaxial cable is preferably superconducting at operating temperature, such as an Al cable.

[0021] In an exemplary embodiment of the present quantum wavelength converter the phonon waveguides may be provided with a phononic shield at a side, or sides, of the waveguide. The shield functions as an acoustic insulator.

[0022] In an exemplary embodiment of the present quantum wavelength converter the coupler 10 may be within 1000% of a quantum ground state energy, preferably within 100%, more preferably within 50%, such as within 15%. Albeit the upper range of 1000% may seem high, it is found sufficiently low for many applications; important is that a quantum can still be distinguished as such. It is noted that an energy is preferably as low as possible. Inventors have achieved "close to ground state" levels, such as within (+) 50% thereof, and even within 15% thereof. It is noted that with a typically applied light power GaAs is found unsuited, as experimentally the coupler then is around or above the 1000% above quantum ground state energy (300% at the best).

[0023] In an exemplary embodiment of the present quantum wavelength converter the coupler 10 may be

adapted to generate at least one excitation or at least one photon or at least one (further) quantum state, respectively.

[0024] In an exemplary embodiment of the present quantum wavelength converter the phonon generator/-detector 21,22 may comprise at least one of interdigitated electrically conducting contacts 23. These contacts provide good and reliable generation/detection of single phonons, such as by activating a piezoelectric layer.

[0025] In an exemplary embodiment of the present quantum wavelength converter the phonon generator/-detector 21,22 may comprise a superconducting quantum bit, and the coupler 10 may comprise an external voltage connection 26,27 in electrical contact with the generator/detector and/or quantum bit. A voltage may typically be provided in order to control the present device and operate said device, or parts thereof.

[0026] In an exemplary embodiment of the present quantum wavelength converter the phonon generator 21 and phonon detector 22 may be at least one piezoelectric layer, such as a crystallographic piezoelectric layer. With such as layer good and reliable generation/-detection of single phonons is achieved.

[0027] In an exemplary embodiment of the present quantum wavelength converter the piezoelectric layer may be combined with a light absorption inhibiting layer or may be selected from light absorption inhibiting layers (i.e. may be applied as such, without a further light absorption inhibiting layer, as the layer already functions as such), such as III/V materials, wherein "III" materials are selected from B, Al, Ga, In, and Tl, and wherein "V" materials are selected from N, P, As, and Sb, such as GaN, GaP, AlN, and AlP, with the proviso that GaAs is excluded, and niobates, tantalates, and vanadates, such as monovalent salts thereof, such as Li comprising salts thereof, such as $LiNbO_3$, $LiTaO_3$. As such the light absorption inhibiting layer and at least one piezoelectric layer may be combined.

[0028] In an exemplary embodiment of the present quantum wavelength converter the optical resonator 30 may preferably be a planar resonator, such as a crystal resonator, and may comprise at least one hole 36, each hole having a major axis height (h) and minor axis width (w), wherein a height is from 0.1-2.0 μm, and a width is from 0.1-2.0 μm, and wherein holes have a spacing (a) (heart to heart) of 0.3-2.0 μm, said spacing preferably being constant over the resonator. Such an optical resonator can be mechanically coupled to the present phonon generator/detector and operate at a single photon level.

[0029] In an exemplary embodiment of the present quantum wavelength converter the optical resonator 30 may comprise 10-2000 holes 36, wherein holes are aligned in an array of 1*10 to 20*100.

[0030] In an exemplary embodiment of the present quantum wavelength converter a shape of the holes 36 may be selected from ellipsoid, circular, multigonal, such as hexagonal, multigonal with a protrusion 37 at a side thereof, such as hexagonal with a protrusion.

[0031] In an exemplary embodiment of the present quantum wavelength converter each optical resonator 30 individually may have a thickness (t) of 150 nm-1 mm, preferably 200 nm-10000 nm, even more preferably 250 nm-1000 nm, a total width (w_t)of 1-10000 μm, preferably 5-1000 μm, more preferably 10-500 μm, such as 20-300 μm, and a total depth (d) of 1-10000 μm, preferably 5-1000 μm, more preferably 10-500 μm, such as 20-300 μm,.

[0032] In an exemplary embodiment of the present quantum wavelength converter a material of the optical resonator may be selected from III/V materials, such as GaAs, and $LiNbO_3$, and $LiTaO_3$, dielectric material, such as silicon oxide, such as quartz, silicon nitride, and silicon carbide, and silicon.

[0033] In an exemplary embodiment of the present quantum wavelength converter the light absorption inhibiting layer 32 may be selected from a dielectric material, wherein a cation of the dielectric material is selected from Al, Ti, Ta, and Si, and wherein the anion of the dielectric material is selected from O, N, and C, and combinations thereof.

[0034] In an exemplary embodiment of the present quantum wavelength converter the light absorption inhibiting layer 32 may be a conformal layer, that is conforms to the contours of an underlying structure, i.e. the present optical resonator. The layer therefore has approximately a same thickness over the full layer.

[0035] In an exemplary embodiment of the present quantum wavelength converter the light absorption inhibiting layer may have a thickness of 1-10 nm, preferably 2-8 nm, such as 4-6 nm. It is found that a relatively thin layer is sufficient to inhibit light absorption completely or almost completely.

[0036] In an exemplary embodiment of the present quantum wavelength converter the light absorption inhibiting layer 32 may be at least one of an ALD layer, and a chemically oxidized layer. These techniques are found very suited for providing such layers. Also more than one layer may be provided, each layer having a thickness of a fraction of the thickness of the total layer. In addition the (chemical) composition of the layers may be varied.

[0037] In an exemplary embodiment of the present quantum wavelength converter the light absorption inhibiting layer 32 may absorb less than 1 ppm of (the optical signal) photons provided thereon, such as less than 5 ppb. Such a level is sufficiently low as not to interfere with photon and phonon generation on a single level thereof.

[0038] In an exemplary embodiment of the present quantum wavelength converter the cooler 50 may be adapted to cool the microwave-to-optical coupler 10 to a temperature below 1K, preferably below 300 mK, more preferably below 100 mK, even more preferably below 25 mK, such as below 15 mK. It has been found that lower temperatures provide even better quantum behaviour of the present system.

[0039] In an exemplary embodiment of the present quantum wavelength converter the at least one microwave-to-optical coupler 10 may be integrated within one membrane 40. In view of fabrication thereof and in view of operation such is preferred. It is noted however that in an alternative exemplary embodiment a part or all of the at least one microwave-to-optical coupler 10 may in fact not be suspended and may be integrated otherwise, such as in a chip.

[0040] In an exemplary embodiment of the present quantum wavelength converter the membrane 40 may be tethered 70 at corner sections thereof to a frame 71. Tethers and a frame are found to reduce unwanted interference, such as vibrations.

[0041] In an exemplary embodiment the present quantum wavelength converter may comprise at least one of an optical input 91 and at least one microwave output 94, or may comprise at least one optical output 92 and at least one microwave input 93, or may comprise at least one optical input 91 and at least one an optical output 92 and at least one microwave input 93 and at least one microwave output 94. So various configurations are available, e.g. depending on an intended use of the present converter.

[0042] In an exemplary embodiment the present quantum wavelength converter may comprise independently at least one phonon generator 21 and at least one phonon detector 22. Phonon detection and phonon generation may be provided as separate entities, which may be advantageous in certain applications.

[0043] In an exemplary embodiment the present quantum wavelength converter may be adapted to operate in pulsed mode.

[0044] The invention will hereafter be further elucidated through the following examples which are exemplary and explanatory of nature and are not intended to be considered limiting of the invention. To the person skilled in the art it may be clear that many variants, being obvious or not, may be conceivable falling within the scope of protection, defined by the present claims.

SUMMARY OF THE FIGURES

[0045]

Figures 1a-e show schematically details of the present device.

Figs. 2 a-e show an example and results obtained.

DETAILED DESCRIPTION OF FIGURES

[0046] In the figures:

a	heart to heart spacing holes 36-36
d	depth of optical resonator
h	height of a hole 36
t	thickness optical resonator
w	width of a hole 36
w_t	width of optical resonator
1	quantum wavelength converter
10	microwave-to-optical coupler
21	phonon generator
22	phonon detector
23	interdigitated electrically conducting contacts
26	external voltage connection
27	external voltage connection
30	optical photon generator and/or optical photon detector
31	optomechanical resonator
32	light absorption inhibiting layer
36	hole
37	protrusion
40	membrane
50	cooler
70	tether
71	frame
91	optical input
92	optical output
93	microwave input
94	microwave output

[0047] Fig. 1a shows a schematically set-up of the present device 1. Optical and microwave inputs 91,93 and outputs 92,94 are shown. At a right side a phonon generator 21 and phonon detector 21 and 22, such as for instance shown in fig. 2 are shown. A phone is provided to or received from optical photon generator and/or optical photon detector 30. The phonon and photon generator may together be referred to as microwave-to-optical coupler. These may all be provided as one single structure, such as on a membrane 40. The whole system is cooled to very low temperatures, typically well below 5K, and operated as such temperatures. Fig. 1b shows the optical photon generator and/or optical photon detector 30, comprising an optomechanical resonator 31, and provided with a light absorption inhibiting layer 32 covering most or all of the resonator and detector. The generator/detector 30 has a thickness t, w depth d, and a total width w_t. The holes 36 have a width w, a height h, and a spacing (heart to heart) of a, which is constant in the example. Fig. 1c shows various cross-section of holes 36. The second and third example show protrusions 37, thereby providing the third example a snow-flake like form. Fig. 1d shows that the membrane 40 can be attached by tethers 70 to a frame 71. Fig. 1e shows interdigitated electrically conducting contacts 23 on phonon generator 21, provided with external voltage connections 26 and 27. Fig. 2 shows a device layout and room temperature characterization thereof. Fig. 2a shows a microscope image of the transducer device structure. The structures comprise an interdigital transducer (IDT). The IDT spans several optomechanical devices for ease of fabrication. The bottom side of the chip is directly accessible with a lensed fiber, allowing for optical access to the device. Fig. 2b shows a scanning electron microscope image of a pair of optomechanical devices. A

central waveguide is used for evanescently coupling light in and out of the devices using the lensed fiber (which is accessed from the right here). Figure 2b is further provided with an enlargement section, identifying the tapered parts. On a left side the width of the optical wave guide (see arrows) is larger than the width thereof on the right side, indicative of tapering. Fig. 2c shows finite element simulations of the optomechanical device. Fig. 2d shows schematic of a room temperature characterization setup. A laser is used to optically address the device, which is then measured on a high-speed photodiode to resolve the noise spectrum around the mechanical mode of the device, while an RF source is used to drive the IDT. Fig. 2e shows a S11 reflection measurement of the IDT device with a resonance at 2.76 GHz (top). The mechanical noise power spectral density is plotted with (bottom) and without (center) the RF drive tone applied to the IDT, which results in a narrow, coherent peak in the spectrum on top of the thermal peak. The laser in these measurements is blue-detuned from cavity resonance by one mechanical frequency ϖ_m.

Examples

[0048] In an example inventors provide a microwave to optics transducer that operates at the quantum limit. A piezoelectric optomechanical crystal is cooled to its quantum ground state. It is coupled to a microwave circuit through surface acoustic waves. A weak-coherent microwave pulse is converted first into a mechanical mode and then into a photon mode at microwave (telecom) wavelength. Less than a single phonon is used on average. The present device operates at the quantum limit. Classical noise is limited. The device consists of a 1D optomechanical crystal (OMC), shown in fig. 2(b), which is mechanically coupled to an interdigital transducer (IDT) through surface acoustic waves. A device comprises a 250 nm thick GaAs layer. A large refractive index and good piezoelectric properties are provided. Fig. 2c shows finite element simulations of the device. The IDT is capable of exciting surface acoustic waves (SAWs) in the GaAs device layer and is designed to operate at the same frequency as the mechanical mode in order to efficiently transfer energy into the mechanical mode. The SAWs are provided close to the surface, such as about 500 nm from the surface. The device comprises 5 nm of AlO_x that reduces unwanted drive-laser absorption. Before deposition inventors stripped native oxide off the GaAs using 7:1 BOE. Then the 5 nm deposition of ALD AlOx at 300 ◦C was performed. A reduction in the initial thermal occupation of the mechanical resonator was obtained. A device with a microwave resonance centered at 2.76 GHz is obtained.

[0049] Conversion from microwave to optical telecom signals at mK temperatures is measured. Red-detuned anti-Stokes optical pulses are sent into the OMC to convert the state of the mechanical mode into photons. The frequency of the RF drive tone is swept across the mechanical resonance. The results show a reliable conversion of a coherent microwave to a coherent optical signal, with only a fixed thermal contribution of the ground-state occupation of the mechanical resonator. Furthermore, these measurements show an ability to detect displacement amplitude of the initial state in the mechanical resonator down to a single phonon. Even at lowest power the conversion of the coherent microwave component is confirmed. The conversion of a coherent GHz microwave to an optical telecom signal at the single quantum level is demonstrated using the present device.

Claims

1. Quantum wavelength converter (1) between a microwave signal and an optical signal, comprising:

   at least one of an optical input (91) and an optical output (92),
   at least one of a microwave input (93) and a microwave output (94), and
   at least one microwave-to-optical coupler (10), wherein the coupler comprises
   at least one of a phonon generator (21) and a phonon detector (22), mechanically coupled to the phonon generator/detector, the converter further comprising at least one of an optical photon generator and an optical photon detector (30), the photon generator/detector comprising at least one optomechanical resonator (31), wherein the optomechanical resonator is adapted to receive a phonon from the phonon generator or to generate a phonon to the phonon detector, wherein
   a cooler (50) for cooling the microwave-to-optical coupler to a temperature below 5K (-268.15 degrees Celsius),
   wherein the optical input (91) and optical output (92) are independently selected from optical waveguides, wherein the optical waveguides are adapted for adiabatic mode conversion between a received optical signal and one of the optical waveguides, and
   the optomechanical resonator comprising on a surface thereof at least one light absorption inhibiting layer (32);
   characterized in that the converter further includes a pulsed drive laser configured to convert between a mechanical mode and a photon mode whilst preserving quantum coherence, in which the drive laser is a red-detuned laser configured to result in anti-Stokes scattering.

2. Quantum wavelength converter according to claim 1, wherein the optical signal has a wavelength of 400 nm-1 mm, preferably 800 nm-15000 nm, more preferably 1000 nm-3000 nm, even more preferably

1200 nm-2000 nm, such as 1400-1700 nm, and/or wherein a microwave has a frequency in the range of 0.3-300 GHz, preferably 1-100 GHz, more preferably 1.4 - 20 GHz, such as 2 - 10 GHz.

3. Quantum wavelength converter according to any of claims 1 - 2, wherein the optical input (91) and optical output (92) are independently selected from glass fibers, and/or wherein the microwave input (93) and microwave output (94) are independently selected from photon waveguides, preferably a superconducting photon waveguide, and a coaxial cable, and optionally comprise at least one phononic shield, and/or wherein the optical waveguide is tapered.

4. Quantum wavelength converter according to any of claims 1 - 3, wherein the coupler (10) is within 1000% of a quantum ground state energy, preferably within 100%, more preferably within 50%, such as within 15%.

5. Quantum wavelength converter according to any of claims 1 - 4, wherein the coupler (10) is adapted to generate at least one excitation or at least one photon or at least one (further) quantum state, respectively.

6. Quantum wavelength converter according to any of claims 1 - 5, wherein the phonon generator/detector (21,22) comprises at least one of interdigitated electrically conducting contacts (23), and/or a superconducting quantum bit, and the coupler (10) comprises an external voltage connection (26,27) in electrical contact with the generator/detector and/or quantum bit.

7. Quantum wavelength converter according to any of claims 1 - 6, wherein the phonon generator (21) and phonon detector (22) is at least one piezoelectric layer, such as a crystallographic piezoelectric layer.

8. Quantum wavelength converter according to any of claims 1 - 7, wherein the piezoelectric layer is selected from light absorption inhibiting layers, such as III/V materials, wherein "III" materials are selected from B, Al, Ga, In, and Tl, and wherein "V" materials are selected from N, P, As, and Sb, such as GaN, GaP, AlN, and AlP, with the proviso that GaAs is excluded, and niobates, tantalates, and vanadates, such as monovalent salts thereof, such as Li comprising salts thereof, such as $LiNbO_3$, and $LiTaO_3$.

9. Quantum wavelength converter according to any of claims 1 - 8, wherein the optical resonator (30) is preferably a planar resonator, such as a crystal resonator, and comprises at least one hole (36), each hole having a major axis height (h) and minor axis width (w), wherein a height is from 0.1-2.0 μm, and a width is from 0.1-2.0 μm, and wherein holes have a spacing (a) (heart to heart) of 0.3-2.0 μm.

10. Quantum wavelength converter according to claim 9, wherein the optical resonator (30) comprises 10-2000 holes (36), wherein holes are aligned in an array of 1*10 to 20*100.

11. Quantum wavelength converter according to any of claims 9-10, wherein a shape of the holes (36) is selected from ellipsoid, circular, polygonal, such as hexagonal, polygonal with a protrusion (37) at a side thereof, such as hexagonal with a protrusion.

12. Quantum wavelength converter according to any of claims 1 - 11, wherein each optical resonator (30) individually has a thickness (t) of 150 nm-1 mm, a total width (wt)of 1-10000 μm, and a total depth (d) of 1-10000 μm, and/or wherein a material of the optical resonator is selected from III/V materials, such as GaAs, and $LiNbO_3$, and $LiTaO_3$, a dielectric material, such as silicon oxide, such as quartz, silicon nitride, and silicon carbide, and silicon.

13. Quantum wavelength converter according to any of claims 1-12, wherein the light absorption inhibiting layer (32) is selected from a dielectric material, wherein a cation of the dielectric material is selected from Al, Ti, Ta, and Si, and wherein the anion of the dielectric material is selected from O, N, and C, and combinations thereof; and wherein the light absorption inhibiting layer (32) is a conformal layer.

14. Quantum wavelength converter according to any of claims 1 - 13, wherein the cooler (50) is adapted to cool the microwave-to-optical coupler (10) to a temperature below 1K (-272.15 degrees Celsius), preferably below 300 mK, more preferably below 100 mK, even more preferably below 25 mK, such as below 15 mK.

15. Quantum wavelength converter according to any of claims 1 - 14, comprising at least one of an optical input (91) and at least one microwave output (94), or comprising at least one optical output (92) and at least one microwave input (93), or comprising at least one optical input (91) and at least one an optical output (92) and at least one microwave input (93) and at least one microwave output (94).

16. Quantum wavelength converter according to any of claims 1 - 15, adapted to operate in pulsed mode.

17. Quantum network or quantum computing nodes comprising at least one quantum wavelength converter according to any of claims 1 - 16.

Patentansprüche

1. Quantenwellenlängenkonverter (1) zwischen einem Mikrowellensignal und einem optischen Signal, umfassend:

   mindestens eines von einem optischen Eingang (91) und einem optischen Ausgang (92),
   mindestens eines von einem Mikrowelleneingang (93) und einem Mikrowellenausgang (94) und
   mindestens einen Mikrowelle-zu-optisch-Koppler (10), wobei der Koppler Folgendes umfasst:
   mindestens eines von einem Phononengenerator (21) und einem Phononendetektor (22), der mechanisch an den Phononengenerator/-detektor gekoppelt ist, wobei der Konverter ferner mindestens einen von einem optischen Photonengenerator und einem optischen Photonendetektor (30) umfasst, wobei der Photonengenerator/-detektor mindestens einen optomechanischen Resonator (31) umfasst, wobei der optomechanische Resonator dazu ausgelegt ist, ein Phonon von dem Phononengenerator zu empfangen oder ein Phonon für den Phononendetektor zu erzeugen, wobei
   einen Kühler (50) zum Kühlen des Mikrowelle-zu-optisch-Kopplers auf eine Temperatur unter 5 K (-268,15 Grad Celsius),
   wobei der optische Eingang (91) und der optische Ausgang (92) unabhängig ausgewählt sind aus optischen Wellenleitern, wobei die optischen Wellenleiter zur adiabatischen Modusumwandlung zwischen einem empfangenen optischen Signal und einem der optischen Wellenleiter ausgelegt sind, und
   den optomechanischen Resonator, der auf einer Oberfläche davon mindestens eine die Lichtabsorption hemmende Schicht (32) umfasst;
   dadurch gekennzeichnet, dass der Konverter ferner einen gepulsten Erregungslaser beinhaltet, der dazu konfiguriert ist, zwischen einem mechanischen Modus und einem Photonenmodus umzuwandeln, während die Quantenkohärenz beibehalten wird, in dem der Erregungslaser ein rotverstimmter Laser ist, der dazu konfiguriert ist, zu Anti-Stokes-Streuung zu führen.

2. Quantenwellenlängenkonverter nach Anspruch 1, wobei das optische Signal eine Wellenlänge von 400 nm-1 mm, vorzugsweise 800 nm-15000 nm, weiter bevorzugt 1000 nm-3000 nm, noch weiter bevorzugt 1200 nm-2000 nm, wie etwa 1400-1700 nm, aufweist und/oder wobei eine Mikrowelle eine Frequenz im Bereich von 0,3-300 GHz, vorzugsweise 1-100 GHz, weiter bevorzugt 1,4-20 GHz, wie etwa 2-10 GHz, aufweist.

3. Quantenwellenlängenkonverter nach einem der Ansprüche 1-2, wobei der optische Eingang (91) und der optische Ausgang (92) unabhängig ausgewählt sind aus Glasfasern und/oder wobei der Mikrowelleneingang (93) und der Mikrowellenausgang (94) unabhängig ausgewählt sind aus Photonenwellenleitern, vorzugsweise einem supraleitenden Photonenwellenleiter, und einem Koaxialkabel und gegebenenfalls mindestens einen phononischen Schild umfassen und/oder wobei der optische Wellenleiter konisch ist.

4. Quantenwellenlängenkonverter nach einem der Ansprüche 1-3, wobei der Koppler (10) innerhalb von 1000 % einer Quantengrundzustandsenergie, vorzugsweise innerhalb von 100 %, weiter bevorzugt innerhalb von 50 %, wie etwa innerhalb von 15 %, liegt.

5. Quantenwellenlängenkonverter nach einem der Ansprüche 1-4, wobei der Koppler (10) dazu ausgelegt ist, mindestens eine Erregung oder mindestens ein Photon oder mindestens einen (weiteren) Quantenzustand zu erzeugen.

6. Quantenwellenlängenkonverter nach einem der Ansprüche 1-5, wobei der Phononengenerator/-detektor (21, 22) mindestens eines von ineinandergreifenden elektrisch leitenden Kontakten (23) und/oder einem supraleitenden Quantenbit umfasst und der Koppler (10) eine externe Spannungsverbindung (26, 27) in elektrischem Kontakt mit dem Generator/Detektor und/oder dem Quantenbit umfasst.

7. Quantenwellenlängenkonverter nach einem der Ansprüche 1-6, wobei der Phononengenerator (21) und der Phononendetektor (22) mindestens eine piezoelektrische Schicht sind, wie etwa eine kristallographische piezoelektrische Schicht.

8. Quantenwellenlängenkonverter nach einem der Ansprüche 1-7, wobei die piezoelektrische Schicht ausgewählt ist aus die Lichtabsorption hemmenden Schichten, wie etwa III/V-Materialien, wobei "III"-Materialien ausgewählt sind aus B, Al, Ga, In und Tl und wobei "V"-Materialien ausgewählt sind aus N, P, As und Sb, wie etwa GaN, GaP, AlN und AlP, mit der Maßgabe, dass GaAs ausgeschlossen ist, und Niobaten, Tantalaten und Vanadaten, wie etwa monovalenten Salzen davon, wie etwa Li umfassenden Salzen davon, wie etwa $LiNbO_3$ und $LiTaO_3$.

9. Quantenwellenlängenkonverter nach einem der Ansprüche 1-8, wobei der optische Resonator (30) vorzugsweise ein planarer Resonator, wie etwa ein Kristallresonator, ist und mindestens ein Loch (36) umfasst, wobei jedes Loch eine Hauptachsenhöhe (h) und eine Nebenachsenbreite (w) aufweist,

wobei eine Höhe 0,1-2,0 μm beträgt und eine Breite 0,1-2,0 μm beträgt und wobei Löcher enen Abstand (a) (Herz zu Herz) von 0,3-2,0 μm aufweisen.

10. Quantenwellenlängenkonverter nach Anspruch 9, wobei der optische Resonator (30) 10-2000 Löcher (36) umfasst, wobei Löcher in einer Anordnung von 1*10 bis 20*100 ausgerichtet sind.

11. Quantenwellenlängenkonverter nach einem der Ansprüche 9-10, wobei eine Form der Löcher (36) ausgewählt ist aus ellipsoid, kreisförmig, polygonal, wie etwa hexagonal, polygonal mit einem Vorsprung (37) an einer Seite davon, wie etwa hexagonal mit einem Vorsprung.

12. Quantenwellenlängenkonverter nach einem der Ansprüche 1-11, wobei jeder optische Resonator (30) jeweils eine Dicke (t) von 150 nm-1 mm, eine Gesamtbreite (w_t) von 1-10000 μm und eine Gesamttiefe (d) von 1-10000 μm aufweist und/oder wobei ein Material des optischen Resonators ausgewählt ist aus III/V-Materialien, wie etwa GaAs, und $LiNbO_3$ und $LiTaO_3$ einem dielektrischen Materialien, wie etwa Siliciumoxid, wie etwa Quartz, Siliciumnitrid und Siliciumcarbid und Silicium.

13. Quantenwellenlängenkonverter nach einem der Ansprüche 1-12, wobei die die Lichtabsorption hemmende Schicht (32) ausgewählt ist aus einem dielektrischen Material, wobei ein Kation des dielektrischen Materials ausgewählt ist aus Al, Ti, Ta und Si und wobei das Anion des dielektrischen Materials ausgewählt ist aus O, N und C und Kombinationen davon; und wobei die die Lichtabsorption hemmende Schicht (32) eine konforme Schicht ist.

14. Quantenwellenlängenkonverter nach einem der Ansprüche 1-13, wobei der Kühler (50) dazu ausgelegt ist, den Mikrowelle-zu-optisch-Koppler (10) auf eine Temperatur unter 1 K (-272,15 Grad Celsius), vorzugsweise unter 300 mK, weiter bevorzugt unter 100 mK, noch weiter bevorzugt unter 25 mK, wie etwa unter 15 mK, zu kühlen.

15. Quantenwellenlängenkonverter nach einem der Ansprüche 1-14, umfassend mindestens eines von einem optischen Eingang (91) und mindestens einem Mikrowellenausgang (94) oder umfassend mindestens einen optischen Ausgang (92) und mindestens einen Mikrowelleneingang (93) oder umfassend mindestens einen optischen Eingang (91) und mindestens einen optischen Ausgang (92) und mindestens einen Mikrowelleneingang (93) und mindestens einen Mikrowellenausgang (94).

16. Quantenwellenlängenkonverter nach einem der Ansprüche 1-15, der dazu ausgelegt ist, in einem gepulsten Modus betrieben zu werden.

17. Quantennetzwerk oder Quantenrechnerknoten, umfassend mindestens einen Quantenwellenlängenkonverter nach einem der Ansprüche 1-16.

Revendications

1. Convertisseur de longueur d'onde quantique (1) entre un signal micro-onde et un signal optique, comprenant :

au moins une parmi une entrée optique (91) et une sortie optique (92),
au moins une parmi une entrée micro-onde (93) et une sortie micro-onde (94), et
au moins un coupleur micro-onde-optique (10), le coupleur comprenant
au moins un générateur de phonons (21) et un détecteur de phonons (22), couplés mécaniquement au générateur/détecteur de phonons, le convertisseur comprenant en outre au moins un parmi un générateur de photons optiques et un détecteur de photons optiques (30), le générateur/détecteur de photons comprenant au moins un résonateur optomécanique (31), le résonateur optomécanique étant adapté pour recevoir un phonon à partir du générateur de phonons ou pour générer un phonon vers le détecteur de phonons, dans lequel
un refroidisseur (50) pour refroidir le coupleur micro-onde-optique à une température inférieure à 5K (-268,15 degrés Celsius),
dans lequel l'entrée optique (91) et la sortie optique (92) sont sélectionnées indépendamment parmi des guides d'ondes optiques, dans lequel les guides d'ondes optiques sont adaptés à la conversion de mode adiabatique entre un signal optique reçu et l'un des guides d'ondes optiques, et
le résonateur optomécanique comprenant sur une surface de celui-ci au moins une couche inhibant l'absorption de la lumière (32) ;
caractérisé en ce que le convertisseur comprend en outre un laser à entraînement pulsé configuré à convertir entre un mode mécanique et un mode photonique tout en préservant la cohérence quantique, dans laquelle le laser d'entraînement est un laser désaccordé vers le rouge configuré à résulter en une diffusion anti-Stokes.

2. Convertisseur de longueur d'onde quantique selon la revendication 1, dans lequel le signal optique a une longueur d'onde de 400 nm à 1 mm, préférablement de 800 nm à 15000 nm, plus préférablement de 1000 nm à 3000 nm, encore plus préférablement

de 1200 nm à 2000 nm, telle que 1400 à 1700 nm, et/ou dans lequel une micro-onde a une fréquence dans la plage de 0,3 à 300 GHz, préférablement de 1 à 100 GHz, plus préférablement de 1,4 à 20 GHz, telle que 2 à 10 GHz.

3. Convertisseur de longueur d'onde quantique selon l'une quelconque des revendications 1 à 2, dans lequel l'entrée optique (91) et la sortie optique (92) sont indépendamment sélectionnées parmi des fibres de verre, et/ou dans lequel l'entrée micro-onde (93) et la sortie micro-onde (94) sont indépendamment sélectionnées parmi des guides d'ondes photoniques, préférablement un guide d'ondes photoniques supraconducteur, et un câble coaxial, et comprennent éventuellement au moins un blindage phononique, et/ou dans lequel le guide d'ondes optique est conique.

4. Convertisseur de longueur d'onde quantique selon l'une quelconque des revendications 1 à 3, dans lequel le coupleur (10) est à 1000 % d'une énergie d'état fondamental quantique, préférablement à 100 %, plus préférablement à 50 %, tel qu'à 15 %.

5. Convertisseur de longueur d'onde quantique selon l'une quelconque des revendications 1 à 4, dans lequel le coupleur (10) est adapté pour générer au moins une excitation ou au moins un photon ou au moins un (autre) état quantique, respectivement.

6. Convertisseur de longueur d'onde quantique selon l'une quelconque des revendications 1 à 5, dans lequel le générateur/détecteur de phonons (21, 22) comprend au moins l'un parmi des contacts électriquement conducteurs interdigités (23) et/ou un bit quantique supraconducteur, et le coupleur (10) comprend une connexion de tension externe (26, 27) en contact électrique avec le générateur/détecteur et/ou le bit quantique.

7. Convertisseur de longueur d'onde quantique selon l'une quelconque des revendications 1 à 6, dans lequel le générateur de phonons (21) et le détecteur de phonons (22) sont au moins une couche piézoélectrique, telle qu'une couche piézoélectrique cristallographique.

8. Convertisseur de longueur d'onde quantique selon l'une quelconque des revendications 1 à 7, dans lequel la couche piézoélectrique est choisie parmi les couches inhibant l'absorption de lumière, telles que les matériaux III/V, dans lequel les matériaux « III » sont choisis parmi B, Al, Ga, In et Tl, et dans lequel les matériaux « V » sont choisis parmi N, P, As et Sb, tels que GaN, GaP, AlN et AlP, à condition que GaAs soit exclu, et les niobates, tantalates et vanadates, tels que leurs sels monovalents, tel que Li comprenant des sels de ceuxci, tels que $LiNbO_3$ et $LiTaO_3$.

9. Convertisseur de longueur d'onde quantique selon l'une quelconque des revendications 1 à 8, dans lequel le résonateur optique (30) est préférablement un résonateur plan, tel qu'un résonateur à cristal, et comprend au moins un trou (36), chaque trou ayant une hauteur d'axe majeur (h) et une largeur d'axe mineur (w), dans lequel une hauteur est de 0,1 à 2,0 μm, et une largeur est de 0,1 à 2,0 μm, et dans lequel les trous ont un espacement (a) (cœur à cœur) de 0,3 à 2,0 μm.

10. Convertisseur de longueur d'onde quantique selon la revendication 9, dans lequel le résonateur optique (30) comprend 10 à 2000 trous (36), les trous étant alignés dans un réseau de 1*10 à 20*100.

11. Convertisseur de longueur d'onde quantique selon l'une quelconque des revendications 9 à 10, dans lequel une forme des trous (36) est sélectionnée parmi ellipsoïde, circulaire, polygonale, telle qu'hexagonale, polygonale avec une saillie (37) sur un côté de celle-ci, telle qu'hexagonale avec une saillie.

12. Convertisseur de longueur d'onde quantique selon l'une quelconque des revendications 1 à 11, dans lequel chaque résonateur optique (30) a individuellement une épaisseur (t) de 150 nm à 1 mm, une largeur totale (wt) de 1 à 10000 μm et une profondeur totale (d) de 1 à 10000 μm, et/ou dans lequel un matériau du résonateur optique est choisi parmi des matériaux III/V, tels que GaAs, et $LiNbO_3$, et $LiTaO_3$, un matériau diélectrique, tel que l'oxyde de silicium, tel que le quartz, le nitrure de silicium et le carbure de silicium, et le silicium.

13. Convertisseur de longueur d'onde quantique selon l'une quelconque des revendications 1 à 12, dans lequel la couche inhibant l'absorption de lumière (32) est choisie parmi un matériau diélectrique, un cation du matériau diélectrique étant choisi parmi Al, Ti, Ta et Si, et l'anion du matériau diélectrique étant choisi parmi O, N, et C, et leurs combinaisons ; et dans lequel la couche inhibant l'absorption de lumière (32) est une couche conforme.

14. Convertisseur de longueur d'onde quantique selon l'une quelconque des revendications 1 à 13, dans lequel le refroidisseur (50) est adapté pour refroidir le coupleur micro-onde-optique (10) à une température inférieure à 1K (-272,15 degrés Celsius), préférablement inférieure à 300 mK, plus préférablement inférieure à 100 mK, encore plus préférablement inférieure à 25 mK, tel qu'inférieure à 15 mK.

15. Convertisseur de longueur d'onde quantique selon

l'une quelconque des revendications 1 à 14, comprenant au moins une parmi une entrée optique (91) et au moins une sortie micro-onde (94), ou comprenant au moins une sortie optique (92) et au moins une entrée micro-onde (93), ou comprenant au moins une entrée optique (91) et au moins une sortie optique (92) et au moins une entrée micro-onde (93) et au moins une sortie micro-onde (94).

16. Convertisseur de longueur d'onde quantique selon l'une quelconque des revendications 1 à 15, adapté pour fonctionner en mode pulsé.

17. Réseau quantique ou nœuds de calcul quantique comprenant au moins un convertisseur de longueur d'onde quantique selon l'une quelconque des revendications 1 à 16.

Fig. 1a

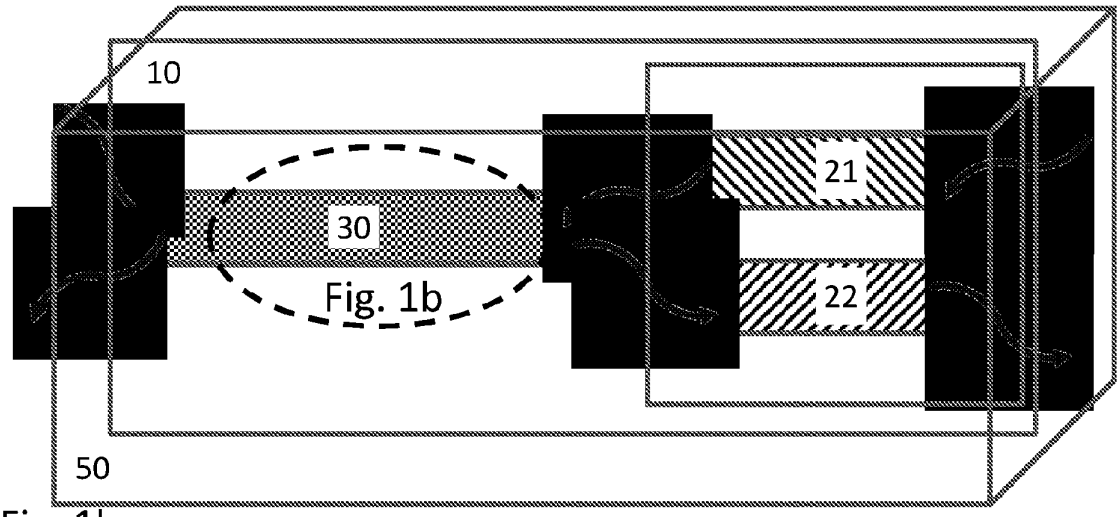


Fig. 1b

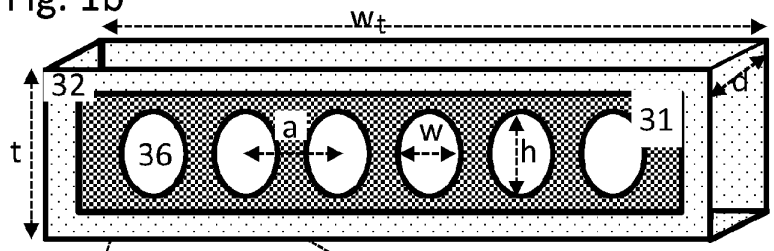


Fig. 1d

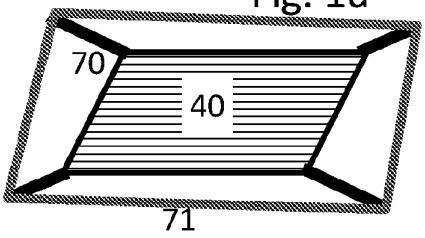
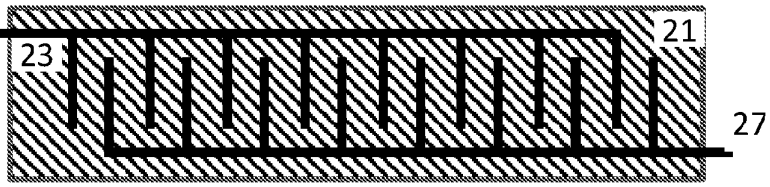


Fig. 1e



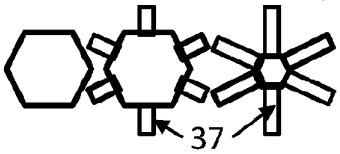


Fig. 1c

Fig. 2a

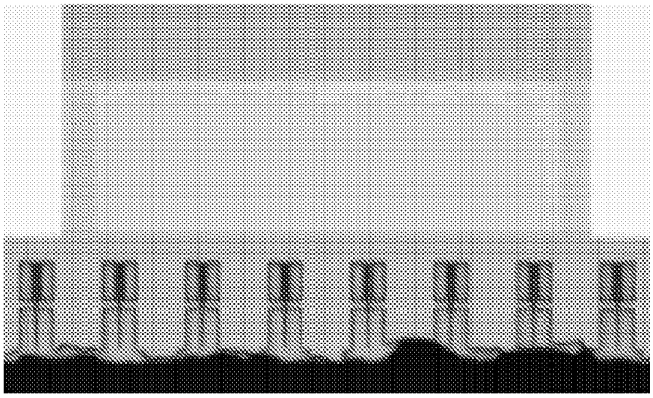


Fig. 2b

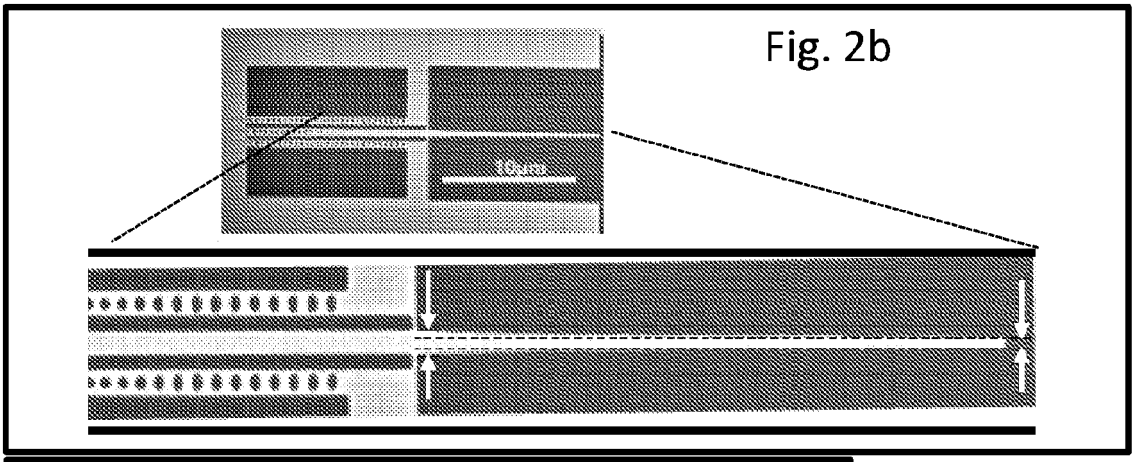


Fig. 2c

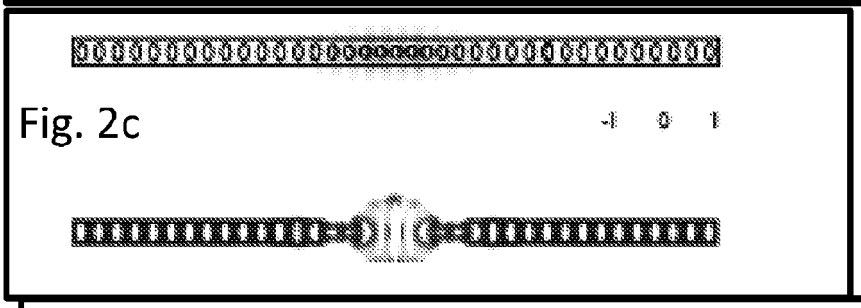


Fig. 2d

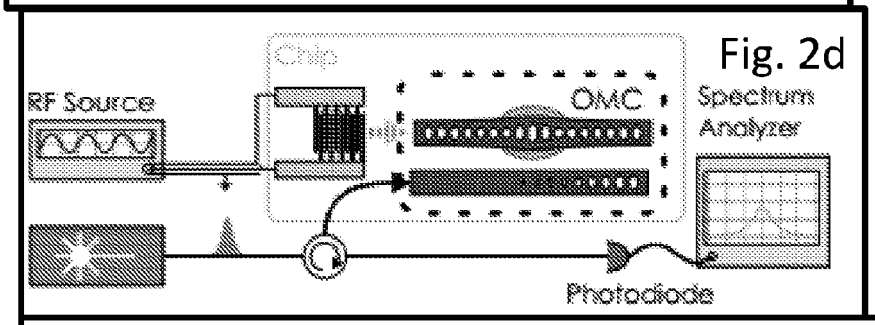
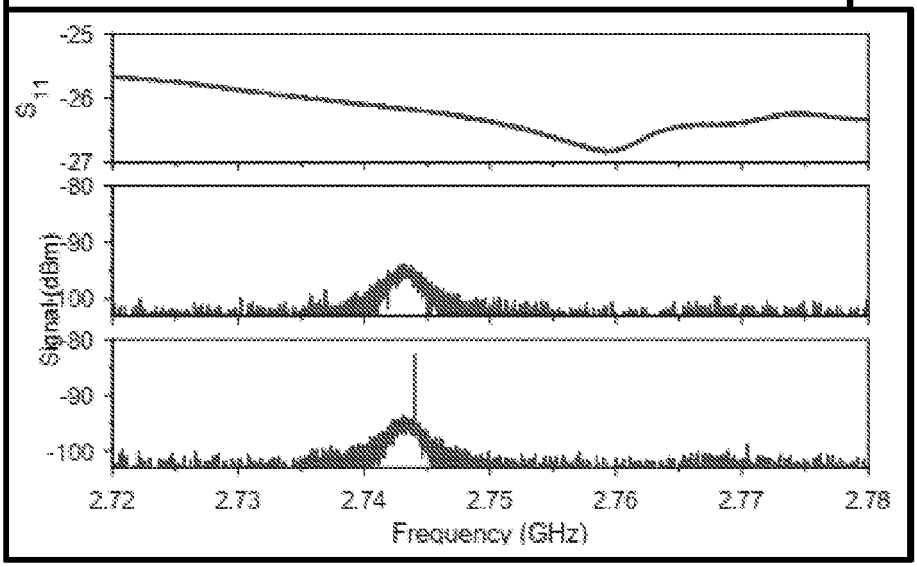


Fig. 2e



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