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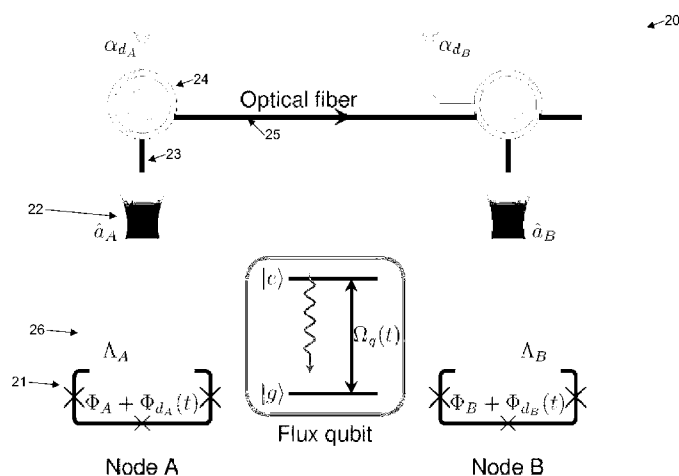


Fig. 2

(57) Abstract: A quantum state transfer device, the device including: a first magnetic state sensor adapted to sense the quantum state of a magnetic flux qubit system; a magnetic state to optical state transfer system, interconnected to the first magnetic state sensor and adapted to transfer the quantum state of the magnetic flux qubit to a corresponding optical quantum state in an output optical signal.

- 1 -

## **An opto-magneto-mechanical quantum interface between distant superconducting qubits**

### **FIELD OF THE INVENTION**

[0001] The present invention relates to the field of quantum coupled systems and in particular, discloses a form of coupling of spatially separated qubits.

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## BACKGROUND

[0036] Any discussion of the background art throughout the specification should in no way be considered as an admission that such art is widely known or forms part of common general knowledge in the field.

[0037] A quantum internet, where widely separated quantum devices are coherently connected, is a desirable requirement for local and global quantum information networks [1–3]. Superconducting quantum devices have developed rapidly and can perform sophisticated manipulations on qubits and microwave photons locally on chip. Developing a quantum internet device using interconnected superconducting devices requires an important element: a device that coherently inter-converts microwave quantum information into optical quantum information, and back again - to effect a coherent optical bus between distant superconducting circuits. Previous proposals to interconvert electromagnetic radiation at different frequencies suggest utilising optomechanical quantum systems [4–12], atomic [13], electro-optic [14–16], and solid-state electronic ensembles [17–21].

[0038] United States Patent 7,889,992 to DiVincenzo et al, discloses one form of superconductor-optical hybrid repeater, interconnecting superconducting qubits, utilising a nonlinear tunnel junction. The operational characteristics of such a device are unknown.

### SUMMARY OF THE INVENTION

[0039] It is an object of the invention, in its preferred form to provide an improved form of quantum coupling of qubits.

[0040] In accordance with a first aspect of the present invention, there is provided a quantum state transfer device, the device including: a first magnetic state sensor adapted to sense the quantum state of a magnetic flux qubit; and a magnetic state to optical state transfer system, interconnected to the first magnetic state sensor and adapted to transfer the quantum state of the magnetic flux qubit to a corresponding optical quantum state in an output optical signal.

[0041] In one embodiment, the magnetic state to optical state transfer system includes a magnetically controlled optical modulator which modulates an optical signal in accordance with a corresponding magnetic signal so as to produce said output optical signal.

[0042] In some embodiments, the magnetic state to optical state transfer system includes an inductive coupling system. In one embodiment, the inductive coupling system includes at least one permanent magnet. In another embodiment, the inductive coupling system includes two or more inductors.

[0043] In some embodiments, the magnetically controlled optical modulator includes an optical cavity in which said output optical signal is modulated. In some embodiments, the optical cavity can comprise a Fabry Perot cavity having dimensions modulated by a magnetically sensitive material. The first magnetic state sensor can comprise a magnetostrictive material. The optical cavity dimensions are preferably modulated by a magnetostrictive material.

[0044] The magnetic flux qubit can comprise a superconducting qubit.

[0045] In accordance with a further aspect of the present invention, there is provided a quantum state transfer device including: an optical cavity modulating an optical input signal, including a first mirror surface for reflection of the optical input signal and a second semi mirrored partially transparent surface for forming an optical input output signal interface; and a magnetically inductive material mechanically coupled to said first mirror surface, and further magnetically coupled to a quantum flux qubit for sensing the quantum state of the quantum flux qubit; wherein the magnetic state

- 5 -

of the quantum flux qubit is inductively transferred to an optical quantum state of the optical input signal and output by the optical cavity device.

[0046] In accordance with a further aspect of the present invention, there is provided a quantum state transfer device including: an optical cavity modulating an optical input signal, including a first mirror surface for reflection of the optical input signal and a second semi mirrored partially transparent surface for forming an optical input output signal interface; and a magnetostrictive material mechanically coupled to the first mirror surface, and further magnetically coupled to a quantum flux qubit for sensing the quantum state of the quantum flux qubit; wherein the magnetic state of the quantum flux qubit is transferred to an optical quantum state of the optical input signal and output by the optical cavity device.

[0047] In accordance with a further aspect of the present invention, there is provided a method of transfer of a magnetic flux qubit quantum state to a corresponding optical quantum state, the method including the steps of: (a) sensing the quantum state of the magnetic flux qubit utilising a magnetostrictive material; (b) utilising the magneto restrictive material to modulate an optical signal so as to impart the corresponding optical quantum state to the optical signal.

[0048] The magneto restrictive material can be utilised to modulate the surface position of one surface of an optical cavity containing the optical signal to thereby impart the corresponding optical quantum state to the optical signal.

### **BRIEF DESCRIPTION OF THE DRAWINGS**

[0049] Embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings in which:

[0050] Fig. 1 illustrates a schematic arrangement of an embodiment showing coupling between Qubit systems;

[0051] Fig. 2 illustrates a schematic of quantum network between two superconducting flux qubits;

[0052] Fig. 3 illustrates a graph of the time evolution of the Rabi oscillation between the optical resonator (OR) and the flux qubit (SQ) within a single node with small excitation of the mechanical resonator (MR);

[0053] Fig. 4 illustrates a graph of the simulated coupling between two Qubits over an optical system; and

[0054] Fig. 5 illustrates one design for one form of magnetic field to optical coupler.

### DETAILED DESCRIPTION

[0055] The preferred embodiment provides a magneto-optomechanical system that can interconvert microwave-to-optical quantum information. The preferred embodiment utilises the effective superconducting-optical coupling strength to coherently transfer quantum information between two spatially separated superconducting qubits via an optical fibre.

[0056] The preferred embodiments make use of the magnetic field generated by the supercurrent in a flux qubit to modulate the motional and optical properties of a high-Q optical cavity and, via this, to coherently transfer quantum information between two spatially separated superconducting qubits. Using currently accessible parameters for the individual components and modelling major sources of loss, the fidelity of transfer is predicted to be as high as  $\sim 0.8$  for a transmission loss of up to 10%.

[0057] The preferred embodiment provides a quantum interface or coupler between superconducting qubits and optical photons and the utilisation of such interfaces to coherently transfer quantum information optically between spatially remote superconducting qubits. This coherent transfer can thus serve as the underlying architecture for a genuine quantum internet. An important element of the preferred embodiment is the utilisation of a magneto-mechanical interaction to provide strong coupling between the quantum state of a superconducting flux qubit (SQ) and a mechanical resonator (MR), which in turn couples via radiation pressure to an optical resonator (OR). By driving the SQ it can be brought into resonance with the magnetomechanically coupled MR. By also optically driving the optomechanical system, it is possible to modulate the optomechanical coupling strength. Using realistic parameters, the configuration can achieve a high fidelity coherent swap between the quantum state of the SQ and the OR in an individual node. By coupling two nodes via an optical fibre, it is possible to create a small quantum network and a protocol to swap the SQ quantum states between the nodes.

[0058] Turning to Fig. 1, there is provided a schematic illustration of one form of the embodiment of the invention 1. In this arrangement, three coupled nodes A, B, C are provided. Each node provides an individual superconducting qubit system e.g. 2, 3, 4. The coupling is provided by a microwave to optical interface 6, 7 which interconnects to a corresponding optical to microwave interface 8, 9. In this manner, the qubit system of a first node is coupled to an adjacent node's qubit system. Depending on requirements, further coupled nodes can be added.

[0059] Turning now to Fig. 2, there is illustrated an arrangement 20 coupling two adjacent nodes A and B. Node A and B are identical and each node consists of a flux qubit e.g. 21 which is

- 7 -

magnetically coupled to a neighbouring optomechanical system 22. Each flux qubit is coherently driven with a Rabi frequency  $\Omega_j$ ,  $j = 1, 2$ , by a time dependent flux bias  $\Phi_j^q(t)$ , while each optical cavity 22 is coherently driven to coherent states with amplitudes  $\alpha_s(\beta_s)$  by input fields. By driving the flux qubit it is possible to control the detuning of its addressed states from the mechanical resonance.

[0060] It can be seen that each node consists of an OR supporting one optical cavity mode and one mechanical vibrational mode, and a SQ. The optical cavity mode  $\hat{a}_j$  in the  $j$ th node ( $j \in \{A, B\}$ ) has a resonance frequency  $\omega_j$  and an intrinsic decay rate  $\kappa_i^{(j)}$ . It couples to a nearby optical fiber 23 with a coupling  $\kappa_{ex}^{(j)}$  and connects with the other node via circulator 24 and the fiber 25. Thus the total decay rate becomes  $\kappa_j = \kappa_i^{(j)} + \kappa_{ex}^{(j)}$ , assuming  $\kappa_{ex}^{(j)} = \xi_j \kappa_j$  with  $0 \leq \xi_j \leq 1$ .

[0061] The  $\kappa_{ex}^{(j)}$  denote the couplings into the waveguide connecting the two distant nodes. The resonance frequency and relaxation rate of mechanical motion mode  $\hat{b}_j$  of the  $j$ th OR are  $\omega_m^{(j)}$  and  $\gamma_m^{(j)}$  respectively. To achieve the magnetomechanical coupling between the SQ and MR, the MR can be bonded to a magnetostrictive material like Terfenol-D, which, in the presence of a magnetic field expands and thus can be used to drive the mechanical motion. This kind of magnetomechanical coupling has been used for magnetic field sensing and can be quite substantial [22]. Each SQ can be modelled as a two-level system (TLS) with the transition frequency  $\omega_q^{(j)}$  driven by a classical microwave field. The frequency  $\omega_q^{(j)}$  can be tuned via a biased magnetic field. The two nodes are connected by an optical fiber to form a quantum network.

[0062] Modelling first the interaction between the OR and the SQ within each node, in the  $j^{\text{th}}$  node, the optomechanical coupling can be described by the interaction Hamiltonian:  $H_{OM}^{(j)} = \hbar g_0^{(j)} \hat{a}_j^\dagger \hat{a}_j (\hat{b}_j^\dagger + \hat{b}_j)$ , where  $\hat{a}_j^\dagger(\hat{a}_j)$  and  $\hat{b}_j^\dagger(\hat{b}_j)$  are the photon and phonon annihilation (creation) operators for the optical and mechanical modes respectively and  $g_0^{(j)}$  is the optomechanical coupling rate.

[0063] In the frame rotating at the frequency of driving field (on resonance with the SQ), the flux qubit with excited (ground) states  $|e_j\rangle(|g_j\rangle)$  can be modelled as  $H_Q^{(j)} = \hbar \Delta_q^{(j)} / 2 \hat{\sigma}_z^{(j)} + \hbar \Omega_j / 2 \hat{\sigma}_x^{(j)}$ , where the Pauli operators are defined as  $\hat{\sigma}_z^{(j)} = |e_j\rangle\langle e_j| - |g_j\rangle\langle g_j|$  and  $\hat{\sigma}_x^{(j)} = |e_j\rangle\langle g_j| + |g_j\rangle\langle e_j|$ . It is assumed the flux qubit is driven by a classical field detuned by  $\Delta_q^{(j)}$  from each SQ's transition frequency and with Rabi frequencies  $\Omega_j$ .

[0064] The macroscopic persistent current  $I(j)$  circulating within each flux qubit induces a magnetic field  $B_j \propto I^{(j)}$  dependent on the quantum state of each flux qubit. This magnetic field actuates the motion of the nearby mechanical resonator 26. The interaction Hamiltonian is given by

- 8 -

$H_{MQ} = \hbar \Lambda (\hat{b}_j^\dagger + \hat{b}_j) \hat{\sigma}_z^{(j)}$  where  $\Lambda \propto I_p^{(j)} x_{zp}$  is the magnetomechanical qubit coupling rate,  $x_{zp} = (\hbar / 2m\omega_m)^{1/2}$  is the zero-point width of the mechanical fluctuations with effective mass m.

[0065] When the flux qubit is put close to a magneto-optomechanical system (coupled MR+OR), they form a three-body quantum system whose total Hamiltonian is:

$$\begin{aligned} H_f / \hbar = & \Delta_c' \hat{a}^\dagger \hat{a} + g_0 \hat{a}^\dagger \hat{a} (\hat{b}^\dagger + \hat{b}) + (\varepsilon \hat{a} + \varepsilon^* \hat{a}^\dagger) \\ & + \omega_m \hat{b}^\dagger \hat{b} + \frac{1}{2} \omega_0 \hat{\sigma}_z + \Lambda (\hat{b}^\dagger + \hat{b}) \hat{\sigma}_z + \frac{1}{2} \Omega \hat{\sigma}_x. \end{aligned} \quad (1)$$

[0066] where the external coherent field  $\varepsilon$  drives the optical cavity mode  $\hat{a}$  and  $\Delta_c'$  is the detuning of this driving from  $\hat{a}$ . After linearizing  $H_{OM}$  by setting  $\hat{a} = \alpha_s + \hat{a}$ , and  $\hat{b} = \beta_s + \hat{b}$ , and rotating the frame of the flux qubit by  $\hat{\sigma}_z \rightarrow \hat{S}_x$ ,  $\hat{\sigma}_x \rightarrow \hat{S}_z$ , the reduced effective Hamiltonian or the node takes the form:

$$\begin{aligned} H_{eff} / \hbar = & \Delta_c \hat{a}^\dagger \hat{a} + \omega_m \hat{b}^\dagger \hat{b} + (G \hat{a}^\dagger + G^* \hat{a}) (\hat{b}^\dagger + \hat{b}) \\ & + \frac{1}{2} \Omega \hat{S}_z + \Lambda (\hat{b}^\dagger + \hat{b}) \hat{S}_x. \end{aligned} \quad (2)$$

[0067] with  $G = \alpha_s g_0$ , and  $\alpha_s(\beta_s)$  are the steady-state values of  $\langle \hat{a} \rangle (\langle \hat{b} \rangle)$ , while  $\Delta_c = \Delta_c' - 2\eta^2 \omega_m |\alpha_s|^2$ , with the Lamb-Dicke parameter  $\eta = g_0 / \omega_m$ ,  $\alpha_s \approx \varepsilon^* / (\Delta_c + i\kappa)$  and  $\beta_s \approx -\eta |\alpha_s|^2$  and  $\kappa$  is the optical cavity damping rate (the mechanical damping is much smaller). The parameters  $\Delta_c$ ,  $\Omega$  and coupling  $G$  are tunable while  $\omega_m$ , and  $\Lambda$  are not. Using this effective full Hamiltonian (2), it is possible to reversibly swap a quantum state between the flux qubit and the optical cavity. For simplicity it is assumed the nodes are identical and hence the super/subscript j will be removed from future discussion to aid clarity.

[0068] It is therefore possible to perform a coherent quantum transfer between the flux qubits in two distant nodes connected by an optical fibre. The master equation (ME) describing the cascaded two-node network capturing all forms of dissipation is [4, 23–28]:

$$\begin{aligned} \dot{\rho} = & -i \left( \sum_j H_{eff}^{(j)} \rho - \rho \sum_j H_{eff}^{(j)\dagger} \right) + \mathcal{L}_{noise} \rho \\ & \sum_{i < j} \sqrt{\xi_i \xi_j} \sqrt{\kappa_i \kappa_j} ([\hat{a}_j^\dagger, \hat{a}_i \rho] + [\rho \hat{a}_i^\dagger, \hat{a}_j]). \end{aligned} \quad (3)$$

- 9 -

[0069] where the Lindblad term  $\mathcal{L}_{noise}\rho$  describes the open system dynamics of the optomechanical resonators and flux qubits. The second line breaks time-reversal symmetry and models the quantum transfer from the node  $i$  to the node  $j$  or reversely, while  $\kappa_j$  is the  $j^{th}$  optical cavity decay rate and  $\xi_j$  represents photon loss in the transfer (initially taking  $\xi_j \approx 1$ ).

[0070] Initially, numerical results showed the coherent swapping of the quantum state between the flux qubit and the photon within a single node and then the coherent transfer of a flux qubit's quantum state between nodes. In much of the literature in optomechanics the radiation pressure interaction is linearised, similar to that shown in Eq. (2), where, via the large optical drive, strong optomechanical coupling can be achieved [29]. We have numerically verified that this linearisation is accurate for the above three-body system.

[0071] The SQ is initially prepared in the excited state  $|\psi_q\rangle_i = |e\rangle$ , and the OR in the photonic vacuum state  $|\psi_o\rangle_i = |0\rangle$ , while the mechanical resonator is subject to a thermal bath at a temperature  $T \sim 10\text{mK}$ , with  $\bar{n}_{th} = 0.2$ . The photon, mechanical mode and flux qubit interact resonantly.

[0072] Fig. 3 illustrates a graph 30 of the time evolution of the Rabi oscillation between the optical resonator (OR) and the flux qubit (SQ) within a single node with small excitation of the mechanical resonator (MR). After a half Rabi oscillation, at  $\kappa t_1 = 0.39$  (31), the occupation of the SQ is transferred to the photon with a fidelity about  $\mathcal{F} = 85\%$  (corresponding to  $n_a = 0.92$ ) evaluated by  $\mathcal{F} = \sqrt{\langle \psi_t | \rho | \psi_t \rangle}$ , where  $|\psi_t\rangle$  is the target state. Here  $|\psi_t\rangle = |1\rangle$ . If we continue the evolution the quantum state swaps back to the SQ with  $\mathcal{F} = 76\%$  at  $\kappa t_2 = 0.85$ . If we initially cool the mechanical resonator to  $n_b = 0$ , the fidelity can increase to  $\mathcal{F} = 89.6\%$  at  $\kappa t_2 = 0.41$  and  $\mathcal{F} = 78.3\%$  at  $\kappa t_2 = 0.84$ .

[0073] In addition there is also shown the states 34, 35, 36 of the various components at the times  $\kappa t = 0.0, 0.39, 0.85$ , showing the Wigner functions for the OR & MR and the real part of the reduced density matrix of the SQ (imaginary components are zero). The system is initially prepared in the state  $\rho_i = \rho_i^{SQ,OR} \otimes \rho_i^{MR}$ , with  $\rho_i^{SQ,OR}$  a pure excited (vacuum) state for the qubit (optical) modes,  $|\psi_{q,o}\rangle_i = |e, 0\rangle$ , and  $\rho_i^{MR}$  is a mechanical thermal state with  $\bar{n} = 0.2$  phonons. No cooling has been assumed here and the initial phonon is  $n_b = 0.2$ , while  $\gamma_q = 0.02$  MHz and  $\kappa = 10$  MHz. Other parameters are  $\Delta_c = \Omega = 0.9\omega_m = 33\kappa$  and  $\Lambda = G = 5\kappa$ . Such high power can be practical in designs discussed below. The photonic and phonon spaces are truncated to  $N_a = 4$  and  $N_b = 6$ , respectively.

[0074] In alternative embodiments, many nodes can be connected together using the optical fiber as a quantum bus. Such a quantum network allows one to transfer a quantum state between two

distant nodes. Fig. 2 illustrates the simplest case consisting of two nodes only and assume that these two nodes are identical so that  $\zeta_1 = \zeta_2$ . Currently, a superconducting flux qubit with a decay rate of  $\gamma_q \sim \text{kHz}$  is available using the existing technology [30–32]. This decay rate  $\gamma_q$  is much smaller than that of the optical cavity. The distant transfer of quantum information is shown in Fig. 4. We assume a small decay rate for the flux qubit  $\gamma_q = 0.02 \text{ MHz}$ . When the effective Raman coupling  $\zeta = \Lambda G / (\Delta_c - \omega_m)$ , is much smaller than the decay rate  $\kappa/2$ , we find that constant coupling rates  $\Lambda$  and  $G$ , allow for a transfer of quantum information from node A to node B with a high fidelity. This is an advantage over the complicated time - varying modulation of these rates required in related protocols [4, 23–28]. Since  $\gamma_q \ll \kappa$ , it is possible to transfer quantum information between nodes using weak coupling rates  $\Lambda$  and  $G$ . The occupation swapped to the photon from the flux qubit within the donator node quickly transfers to the photon in the acceptor node and then to the acceptor flux qubit. As shown in Fig. 4, the state  $|e\rangle$  is transferred with the fidelity  $\mathcal{F} = 0.89$  corresponding to 80% occupation from the qubit 1 to the qubit 2 for constant coupling rates  $\Lambda = 4\kappa$ ,  $G = 1.8\kappa$  and  $\Delta_c = 0.1\omega_m$  yielding  $\zeta = 0.25\kappa$ . The fidelity  $\mathcal{F}$  to successfully transfer the quantum state is limited by the decay rate  $\gamma_q$  of the flux qubit, is about  $\mathcal{F} \approx e^{-\gamma_q t_d}$ , where  $t_d$  is the time to complete the maximal transfer. Therefore, a large  $\kappa_{ex}$  but a small  $\gamma_q$  is preferable for a high fidelity transfer. During the transfer the symmetric linear combination of both optical modes is hardly excited while the anti symmetric one is only weakly excited.

[0075] In Fig. 4 there is illustrated the time state evolution of the photonic coupling. The photonic excitation decays 41 from the optical cavity A and is collected by the optical fiber and then is transferred to the flux qubit in the node B via the optical cavity B. However, there is a small probability in practice that the photon escaping from the optical cavity enters into the environment but not couples to the optical fiber, or is lost in transit through the fiber, and is not collected by node B. In this case, the fidelity of the transfer can be lower. Simulations were conducted for both  $\zeta = 1$  and  $\zeta < 1$  for the state of transfer from qubit A to qubit B. For a relative large loss to the environment, e.g.  $\zeta = 0.9$ , transfer of the quantum state is still provided with  $\mathcal{F} \approx 0.81$  corresponding to a probability of 65% from node A to node B.

[0076] The time-dependent population during the evolution of system is shown when  $\gamma_q = 0.02 \text{ MHz}$ ,  $\kappa = 10 \text{ MHz}$ , coupling rates  $\Lambda = 4\kappa$ ,  $G = 1.8\kappa$  and  $\Delta_c = \Omega = 0.1\omega_m$  requiring an inject laser power  $P_{in} < 16 \text{ mW}$ . The temperature  $T = 10 \text{ mK}$ , yielding  $\bar{n}_{th} = 0.2$ . The initial phonon number was assumed to be  $\bar{n} \approx 0.1$ .

[0077] The lines 41, 42, 43, 46 simulated  $\zeta = 1$  for a complete collection of photon by and from the optical fibre. The lines 41, 44, 45, 46 simulated the transfer when photons loss to the environment with some probability,  $\zeta = 0.9$ . For the simulation, the space of the cavity was truncated

- 11 -

and the mechanical modes to  $N_a = 3$  and  $N_b = 3$  for each node, respectively. This is large enough for the single excitation transfer. The line 41 shows the population of the excited state  $|e\rangle_A$  in node A; The lines 43, 45 show the population of the excited state  $|e\rangle_B$ . The dashed lines e.g. 44, 45 depict the behaviour with no loss in optical transfer between nodes ( $\xi = 1$ ) whilst the solid lines 42, 43 account for 10% loss ( $\xi = 1$ ). The lines 42, 44 illustrate the anisymmetric excitation of the cavity modes, and the lines 46 represents the symmetric excitation of the cavity modes.

[0078] Fig. 5 illustrates schematically one form of setup for the microwave-optical interface node 50 for the hybrid flux-qubit cavity opto- magneto-mechanical system. Light is injected 51 into a Fabry-Perot micro-cavity 52 that comprises a rigid curved input mirror 53 and a smaller back mirror (cavity length  $L$ ) 54, where the back mirror sits on a substrate containing a superconducting flux qubit 56. The back mirror 54 mediates qubit-optical coupling via a bulk-acoustic-wave mechanical resonance in the hundreds of MHz regime. This mechanical mode, where the thickness  $t(|B|)$  of the back mirror oscillates, modulates the resonance frequency of the optical cavity and can be resonantly driven by a magnetic field using a surrounding magnetostrictive material 57 such as Terfenol-D. This form of magnetic coupling is considerably stronger than that achievable using a piezoelectric coupling. With this engineered quantum system, the quantum state of the superconducting flux qubit can then be made to interact with the optical field. This configuration is not restricted for operation at a particular optical wavelength and can be operated at the telecommunications wavelength of 1,550nm. To achieve strong opto-mechanical coupling it is desirable however to use low wavelength light such as 532nm. In this case, group II-VI crystalline mirror materials, such as magnesium selenide, simultaneously provide high mechanical quality and high optical reflectivity at this lower wavelength [33].

[0079] The resulting interface node provides a design for an individual node based on a Fabry-Perot (FP) optical microcavity which is magnetically coupled to a nearby flux-qubit. The design has a large mechanical resonance frequency  $\omega_m$  to reduce  $\bar{n}_m^{\text{th}} \sim 0.2$ , and with pre-cooling to have  $\bar{n}_m = 0.1$  initially. There is a reduced transfer fidelity when  $\bar{n}_m^{\text{th}} > 1$ . Further, high transfer fidelity requires  $G/\kappa \gg 1$  i.e. strong optomechanical coupling [29]. The arrangement also provides a relatively strong magnetic coupling between the mechanics and flux qubit.

[0080] One end mirror 53 can be constructed of a semiconductor multilayer Bragg circular mirror for light at  $\lambda = 1064\text{nm}$  ( $\omega_\lambda = 2\pi c/\lambda$ ), made from AlGaAs [34] ( $\rho = 4200\text{kg/m}^3$ , of thickness  $t = 7\mu\text{m}$  and radius  $r = 5\mu\text{m}$  [35]). With a Finesse  $F \sim 2 \times 10^5$  and cavity length  $L = 10\mu\text{m}$ , the effective mass of the BAW mode  $m_{\text{eff}} \approx \pi r^2 t \rho / 3$ , the fundamental BAW mode frequency ( $\nu_m = \nu_L / 2t$  where  $\nu_L$  is the longitudinal velocity of sound in the semiconductor,  $\nu_L \sim 5130\text{m/s}$ , zero-point motional

- 12 -

extent ( $\Delta x_{zp}^2 = \hbar/(2m_{eff}\omega_m)$ ), thermal phonon number at  $T = 10\text{mK}$ , and bare optomechanical coupling rate ( $g_0 = \omega_\lambda \Delta x_{zp}/L$ ) are:  $m_{eff} \sim 770\text{pg}$ ,  $\omega_b/2\pi \sim 366\text{MHz}$ ,  $\bar{n}_m^{th} \sim 0.2$ ,  $g_0 \sim 8.3\text{kHz}$ .

[0081] To achieve large enough coupling rates  $G/\kappa \approx 1.8$  with a cavity detuning  $\Delta_c/\kappa = 0.1\omega_m$ , it is necessary to drive the FP cavity with an optical power  $P_{FP} = (G/g_0)^2 (\Delta_c^2 + \kappa^2) \hbar \omega_\lambda / (2\kappa) \sim 16\text{mW}$ , which is an acceptable power level for such an optical cavity. With these parameters  $|\alpha_s| \approx 14$ , 000.

[0082] The magneto-mechanical actuation can be achieved by using a collar of magnetostrictive material (e.g. Terfenol-D) 57, surrounding the moving mirror. When this collar sits in the local magnetic field of the flux qubit ( $|B_{local}| \sim 6.7\text{nT}$ ), the collar exerts stress on the mirror, coupling to the BAW mode. Large effective magneto-mechanical coupling strength  $\Gamma \approx 1.2\text{GHz}$  can be provided. However, a more modest coupling strength which is 2-orders of magnitude smaller  $\Lambda \approx 4\kappa = 40\text{MHz}$  is all that is required. This small coupling strength can greatly relax the requirement in the design of the structure.

[0083] To avoid light interfering with the operation of the flux qubit one may arrange an aperture for the light to pass through contained within the flux qubit loop. Typically, the transition frequency of a flux qubit is much higher than that of a mechanical resonator. This large frequency difference prevents the quantum information exchange between them. To create an effective coupling, a coherent magnetic field  $\Phi_{dj}(t)$  is applied to strongly drive the flux qubit. As a result, the flux qubit oscillates at a Rabi frequency which matches the mechanical resonance frequency and this enhances their mutual coupling by several orders of magnitude [22]. A microwave pulse of  $P = -112\text{ dBm}$  propagating in an open transmission line is large enough to drive a flux qubit oscillating at about  $\Omega = 57\text{ MHz}$  for  $I_p = 195\text{ nA}$  [37]. Thus a pulse of  $P = -132\text{ dBm}$  (also used in [37]) can provide a Rabi frequency  $570\text{ MHz}$ . Therefore, flux qubit Rabi frequencies of hundreds MHz are possible using existing technology. On the other hand, the available enhancement of the zero-point optomechanical coupling is limited by the usable photon number  $|\alpha_s|^2$  in the cavity.

[0084] Some embodiments described above specify magnetostrictive coupling between the SQ and MR. However, in other embodiments of the invention inductive coupling can be used between the SQ and MR. A number of configurations are possible to achieve an inductive coupling between the SQ and MR. For example, in one embodiment the inductive coupling between the SQ and MR is achieved by attaching a permanent magnet to the MR that is in close proximity to an electrical inductor that forms part of the electrical circuit with the SQ. In another embodiment the inductive coupling

- 13 -

between the SQ and MR is achieved by using two inductors, one placed on the MR and the other forming part of the microwave circuit.

[0085] In other embodiments, it will be appreciated that configurations other than those specified above are used to achieve the inductive coupling between the SQ and MR. For example, in one embodiment, more than one permanent magnet is used to achieve the inductive coupling between the SQ and MR. Furthermore, in another embodiment, more than two inductors are used to achieve the inductive coupling between the SQ and MR.

[0086] The inductive coupling between the SQ and MR allows the state of the electrical circuit to modify the mechanical motion, which in turn modifies the optical field, thus enabling microwave-to-optical state transfer.

[0087] In conclusion, optical coupling of distant superconducting circuits opens up a new paradigm which may allow for quantum repeaters, distributed quantum computation, quantum sensing and quantum networking over large spatial scales. The preferred embodiments provide for the facilitation of quantum repeaters making use of magneto-mechanical coupling between a flux qubit and micro-optical cavity.

### **Interpretation**

[0088] Reference throughout this specification to “one embodiment”, “some embodiments” 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”, “in some embodiments” or “in an embodiment” in various places throughout this specification are not necessarily all referring to the same embodiment, but may. Furthermore, the particular features, structures or characteristics may be combined in any suitable manner, as would be apparent to one of ordinary skill in the art from this disclosure, in one or more embodiments.

[0089] As used herein, unless otherwise specified the use of the ordinal adjectives “first”, “second”, “third”, etc., to describe a common object, merely indicate that different instances of like objects are being referred to, and are not intended to imply that the objects so described must be in a given sequence, either temporally, spatially, in ranking, or in any other manner.

[0090] In the claims below and the description herein, any one of the terms comprising, comprised of or which comprises is an open term that means including at least the elements/features that follow, but not excluding others. Thus, the term comprising, when used in the claims, should not be

- 14 -

interpreted as being limitative to the means or elements or steps listed thereafter. For example, the scope of the expression a device comprising A and B should not be limited to devices consisting only of elements A and B. Any one of the terms including or which includes or that includes as used herein is also an open term that also means including at least the elements/features that follow the term, but not excluding others. Thus, including is synonymous with and means comprising.

[0091] As used herein, the term “exemplary” is used in the sense of providing examples, as opposed to indicating quality. That is, an “exemplary embodiment” is an embodiment provided as an example, as opposed to necessarily being an embodiment of exemplary quality.

[0092] It should be appreciated that in the above description of exemplary embodiments of the invention, various features of the invention are sometimes grouped together in a single embodiment, FIG., or description thereof for the purpose of streamlining the disclosure and aiding in the understanding of one or more of the various inventive aspects. This method of disclosure, however, is not to be interpreted as reflecting an intention that the claimed invention requires more features than are expressly recited in each claim. Rather, as the following claims reflect, inventive aspects lie in less than all features of a single foregoing disclosed embodiment. Thus, the claims following the Detailed Description are hereby expressly incorporated into this Detailed Description, with each claim standing on its own as a separate embodiment of this invention.

[0093] Furthermore, while some embodiments described herein include some but not other features included in other embodiments, combinations of features of different embodiments are meant to be within the scope of the invention, and form different embodiments, as would be understood by those skilled in the art. For example, in the following claims, any of the claimed embodiments can be used in any combination.

[0094] Furthermore, some of the embodiments are described herein as a method or combination of elements of a method that can be implemented by a processor of a computer system or by other means of carrying out the function. Thus, a processor with the necessary instructions for carrying out such a method or element of a method forms a means for carrying out the method or element of a method. Furthermore, an element described herein of an apparatus embodiment is an example of a means for carrying out the function performed by the element for the purpose of carrying out the invention.

[0095] In the description provided herein, numerous specific details are set forth. However, it is understood that embodiments of the invention may be practiced without these specific details. In other instances, well-known methods, structures and techniques have not been shown in detail in order not to obscure an understanding of this description.

- 15 -

[0096] Similarly, it is to be noticed that the term coupled, when used in the claims, should not be interpreted as being limited to direct connections only. The terms "coupled" and "connected," along with their derivatives, may be used. It should be understood that these terms are not intended as synonyms for each other. Thus, the scope of the expression a device A coupled to a device B should not be limited to devices or systems wherein an output of device A is directly connected to an input of device B. It means that there exists a path between an output of A and an input of B which may be a path including other devices or means. "Coupled" may mean that two or more elements are either in direct physical or electrical contact, or that two or more elements are not in direct contact with each other but yet still co-operate or interact with each other.

[0097] Thus, while there has been described what are believed to be the preferred embodiments of the invention, those skilled in the art will recognize that other and further modifications may be made thereto without departing from the spirit of the invention, and it is intended to claim all such changes and modifications as falling within the scope of the invention. For example, any formulas given above are merely representative of procedures that may be used. Functionality may be added or deleted from the block diagrams and operations may be interchanged among functional blocks. Steps may be added or deleted to methods described within the scope of the present invention.

**CLAIMS**

1. A quantum state transfer device, the device including:
  - a first magnetic state sensor adapted to sense the quantum state of a magnetic flux qubit;
  - a magnetic state to optical state transfer system, interconnected to the first magnetic state sensor and adapted to transfer the quantum state of the magnetic flux qubit to a corresponding optical quantum state in an output optical signal.
2. A quantum state transfer device as claimed in claim 1 wherein the magnetic state to optical state transfer system includes a magnetically controlled optical modulator which modulates an optical signal in accordance with a corresponding magnetic signal so as to produce said output optical signal.
3. A quantum state transfer device as claimed in claim 2 wherein said magnetically controlled optical modulator includes an optical cavity in which said output optical signal is modulated.
4. A quantum state transfer device as claimed in claim 3 wherein said optical cavity includes a Fabry Perot cavity having dimensions modulated by a magnetically sensitive material.
5. A quantum state transfer device as claimed in any previous claim wherein said first magnetic state sensor comprises a magnetostrictive material.
6. A quantum state transfer device as claimed in claim 3 wherein the optical cavity dimensions are modulated by a magnetostrictive material.
7. A quantum state transfer device as claimed in claim 1 wherein said magnetic flux qubit comprises a superconducting qubit.
8. A quantum state transfer device as claimed in claim 1 wherein the magnetic state to optical state transfer system includes an inductive coupling system.
9. A quantum state transfer device as claimed in claim 8 wherein the inductive coupling system includes at least one permanent magnet.
10. A quantum state transfer device as claimed in claim 8 wherein the inductive coupling system includes two or more inductors.

- 17 -

11. A quantum state transfer device including:

an optical cavity modulating an optical input signal, including a first mirror surface for reflection of the optical input signal and a second semi mirrored partially transparent surface for forming an optical input output signal interface; and

a magnetically inductive material mechanically coupled to said first mirror surface, and further magnetically coupled to a quantum flux qubit for sensing the quantum state of the quantum flux qubit;

wherein the magnetic state of the quantum flux qubit is inductively transferred to an optical quantum state of the optical input signal and output by the optical cavity device.

12. A quantum state transfer device including:

an optical cavity modulating an optical input signal, including a first mirror surface for reflection of the optical input signal and a second semi mirrored partially transparent surface for forming an optical input output signal interface; and

a magnetostrictive material mechanically coupled to said first mirror surface, and further magnetically coupled to a quantum flux qubit for sensing the quantum state of the quantum flux qubit;

wherein the magnetic state of the quantum flux qubit is transferred to an optical quantum state of the optical input signal and output by the optical cavity device.

13. A method of transfer of a magnetic flux qubit quantum state to a corresponding optical quantum state, the method including the steps of:

(a) sensing the quantum state of the magnetic flux qubit utilising magnetostrictive material;

(b) utilising the magnetostrictive material to modulate an optical signal so as to impart the corresponding optical quantum state to the optical signal.

14. A method as claimed in claim 13 wherein the magnetostrictive material is utilised to modulate the surface position of one surface of an optical cavity containing said optical signal to thereby impart the corresponding optical quantum state to the optical signal.

Fig. 1

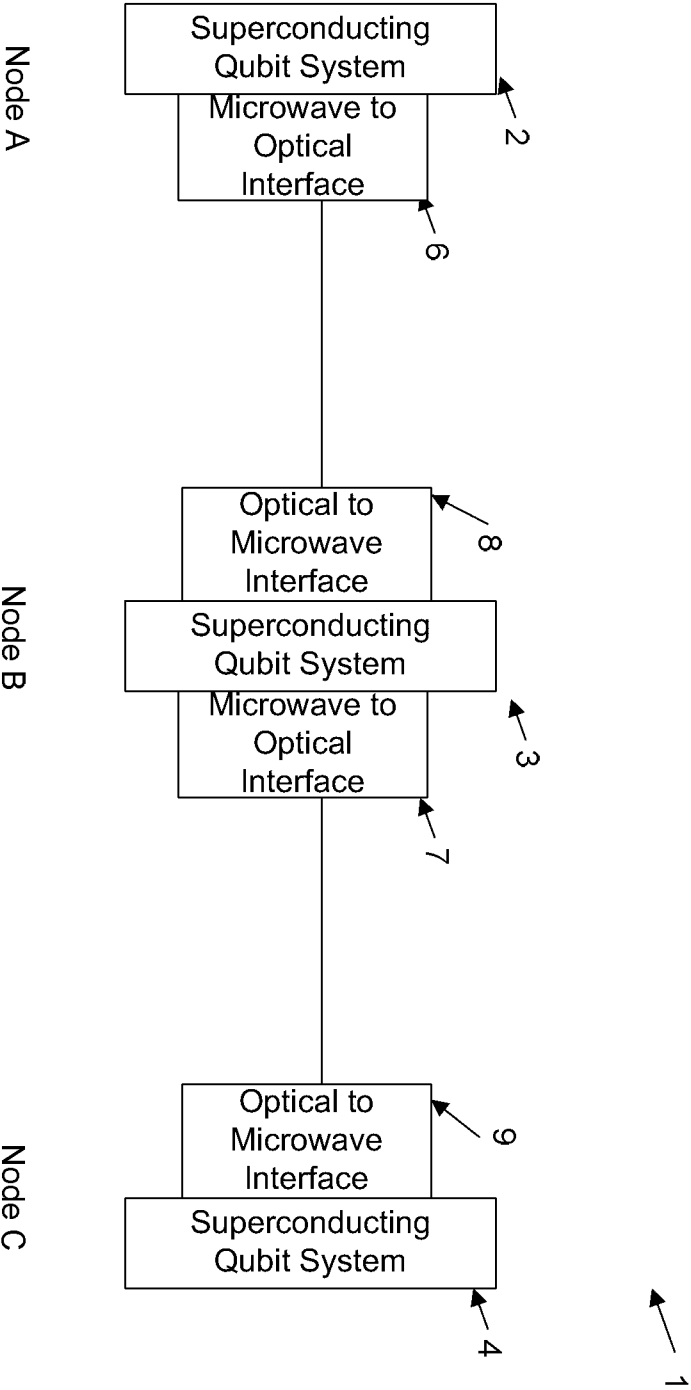


Fig. 1

20

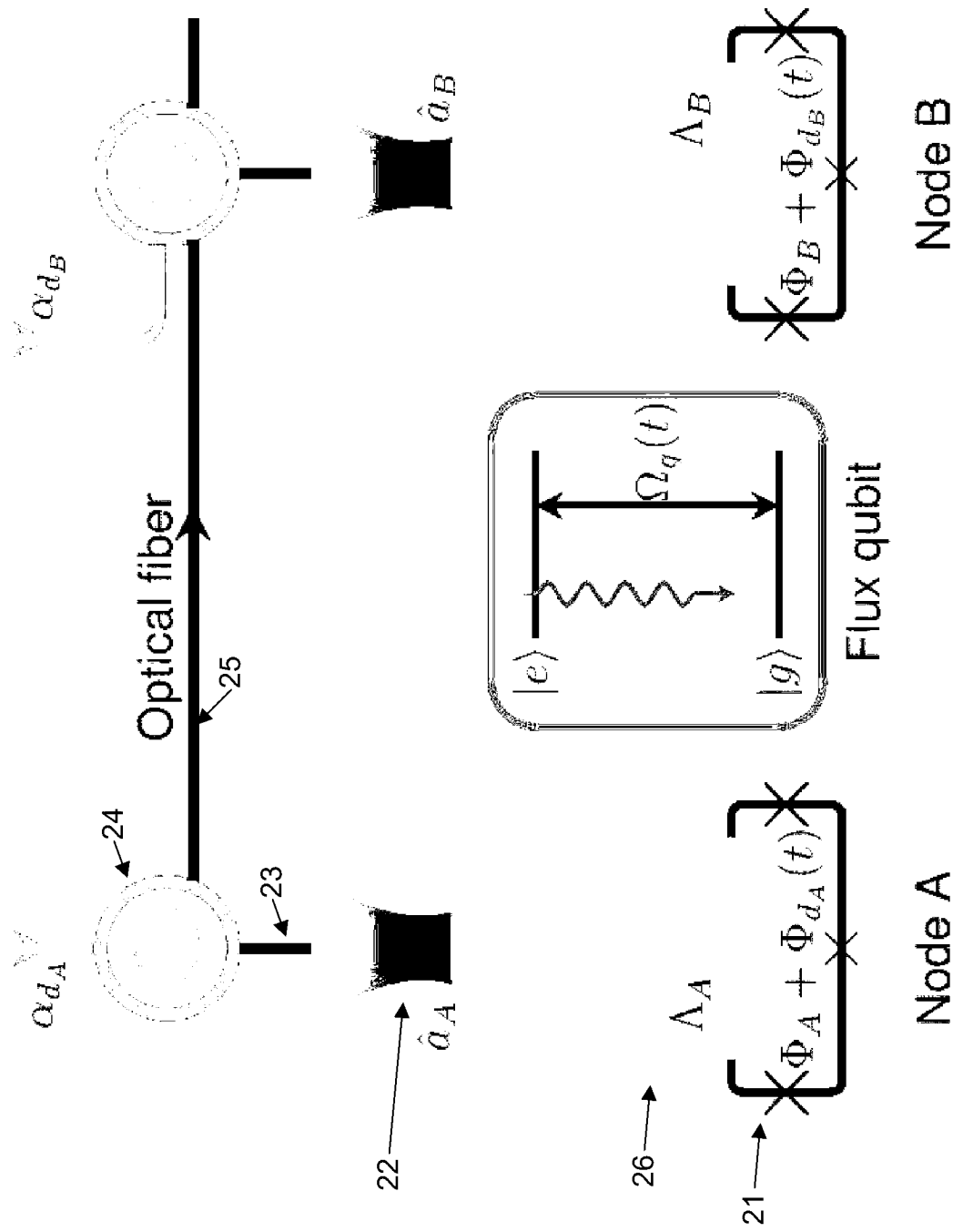


Fig. 2

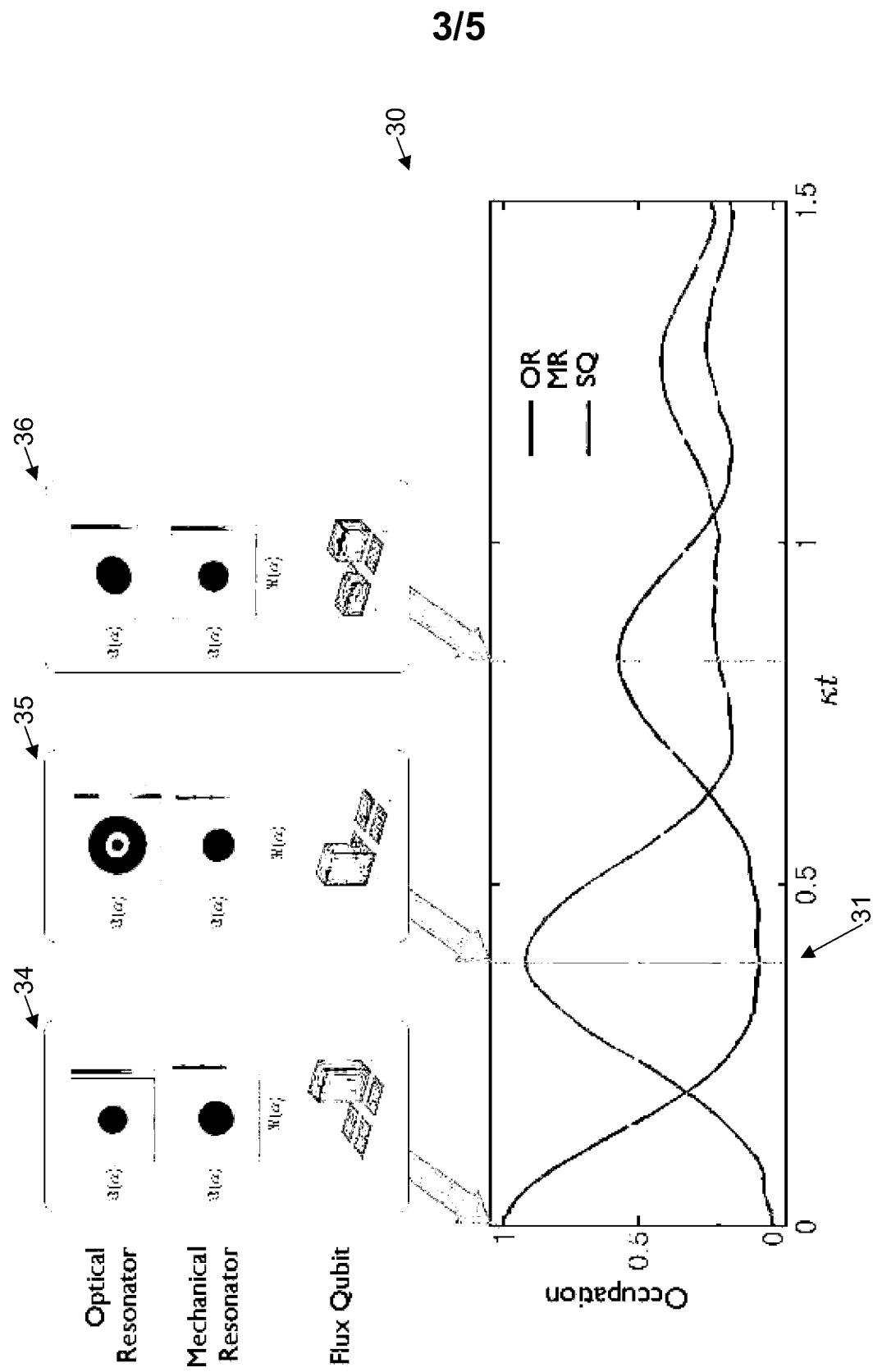


FIG. 3

40

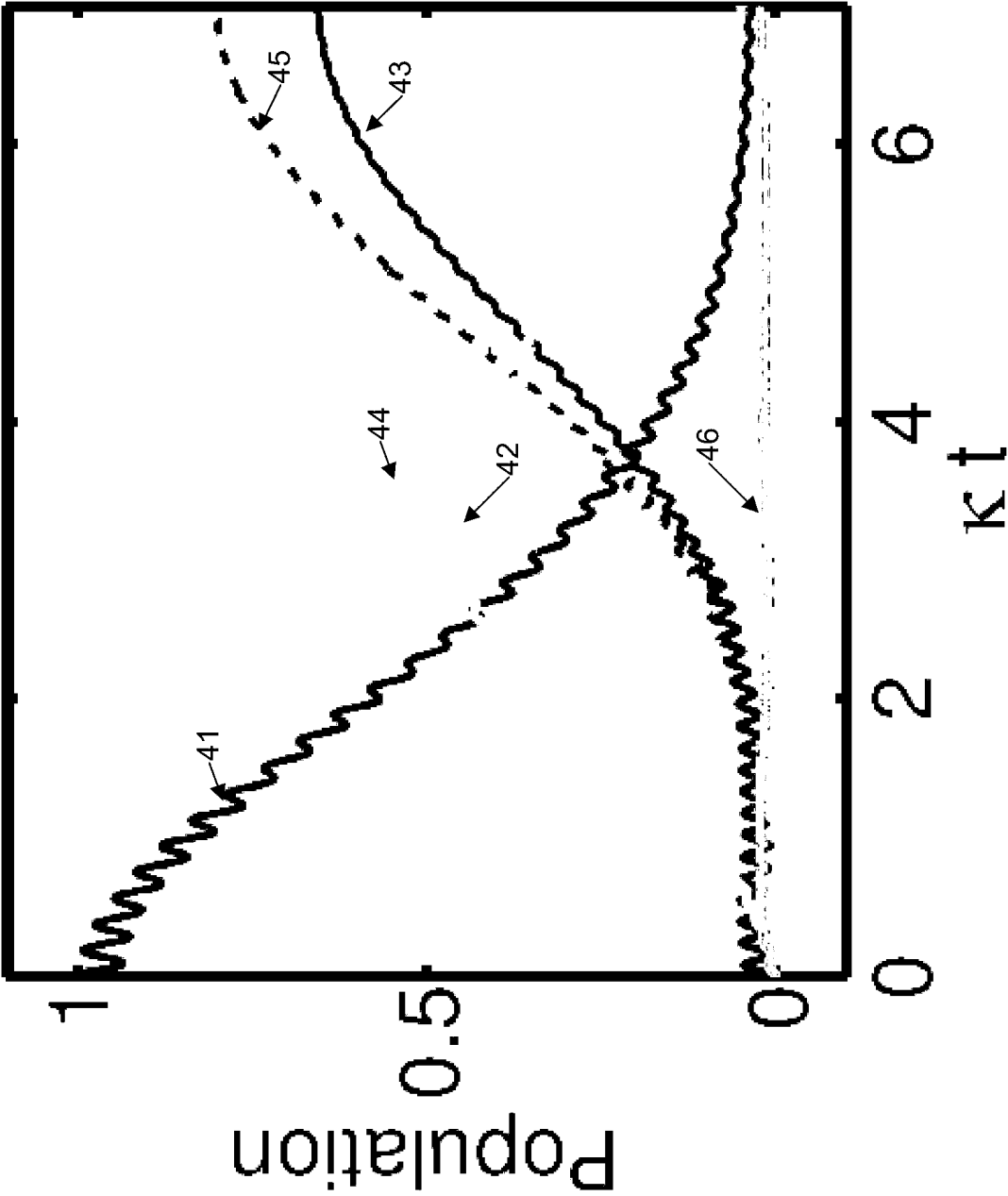


FIG. 4

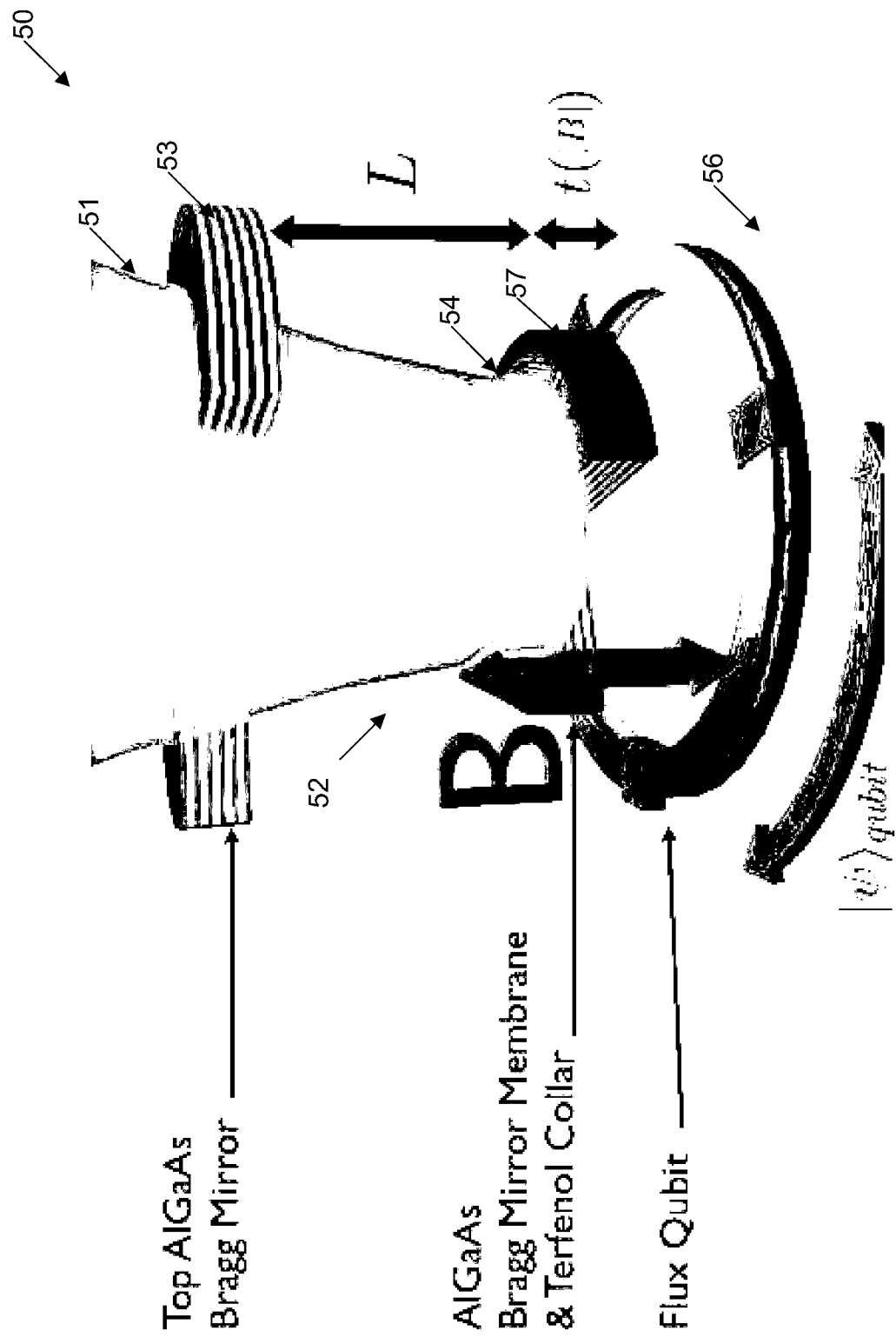


FIG. 5

## INTERNATIONAL SEARCH REPORT

International application No.  
**PCT/AU2015/000107**

## A. CLASSIFICATION OF SUBJECT MATTER

**H04B 10/70 (2013.01) B82Y 20/00 (2011.01) B82Y 25/00 (2011.01) G02B 1/10 (2015.01)**

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPODOC, DWPI, WPIAP, INSPEC, ESPACENET, GOOGLE: (OR (MAGNET+ 2D RESISTIV+), (QUANTUM 2D (OR INDUC+, TRANSFER+, CHANG+, TRANSDUC+)), (OPTO\_MAGNET+), (QUANTUM 2W TELEPORT+), (MAGNETO\_MECHANICAL 2D ACTUAT+), TERFENOL\_D, METGLA?, (MECHANIC+ 2D TRANSFER+), MAGNETOMETER?, MAGNETOSTRICT+, (QUBIT 2W DEVICE?), OPTO\_MECHANICAL+); (OR (MAGNET+ 2W QUBIT?), (FLUX 2W QUBIT?), (SUPER\_CONDUCT+ 2W QUBIT?)); SQUID?, (OR FABRY\_PEROT, (OPTIC+ 2W +CAVIT+), MIRROR, MICROTOROID?)); (6UG MICROWAVE?, OPTICAL, INTERFACE), (OR MODULAT+, CHANG+, TRANSFER+, ALTER+, MODIF+, TRANSFORM+, ADJUST+, AMEND+, VARY+, CONVERT+, AMEND+, TRANSMUT+, SWITCH+) and similar terms. UNIV QUEENSLAND as the applicant and XIA or TWAMLEY or VANNER as the inventor/author searches.

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|-----------|------------------------------------------------------------------------------------|-----------------------|
|           | Documents are listed in the continuation of Box C                                  |                       |



Further documents are listed in the continuation of Box C



See patent family annex

|          |                                                                                                                                                                     |     |                                                                                                                                                                                                                                              |
|----------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| *<br>"A" | Special categories of cited documents:<br>document defining the general state of the art which is not considered to be of particular relevance                      | "T" | later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention                                              |
| "E"      | earlier application or patent but published on or after the international filing date                                                                               | "X" | document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone                                                                     |
| "L"      | document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) | "Y" | document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art |
| "O"      | document referring to an oral disclosure, use, exhibition or other means                                                                                            | "&" | document member of the same patent family                                                                                                                                                                                                    |
| "P"      | document published prior to the international filing date but later than the priority date claimed                                                                  |     |                                                                                                                                                                                                                                              |

Date of the actual completion of the international search  
18 May 2015

Date of mailing of the international search report  
18 May 2015

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Telephone No. 0262832287

| INTERNATIONAL SEARCH REPORT                           |                                                                                                                                                                                                                                                                                                                           | International application No. |
|-------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------|
| C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT |                                                                                                                                                                                                                                                                                                                           | PCT/AU2015/000107             |
| Category*                                             | Citation of document, with indication, where appropriate, of the relevant passages                                                                                                                                                                                                                                        | Relevant to claim No.         |
| X                                                     | S. FORSTNER et. al.: "Sensitivity and Performance of Cavity Optomechanical Field Sensors", Photonic Sensors, Vol. 2, No. 3, (2012), pg 259-270<br>Refer to the whole document and in particular to Fig. 1, Pg 260, 267                                                                                                    | 1-6, 13-14                    |
| X                                                     | ZE-LIANG XIANG et. al.: "Hybrid quantum circuits: Superconducting circuits interacting with other quantum systems", Reviews of Modern Physics Vol. 85, (2013), pg 623-653<br>Refer to the whole document and in particular to section titled: 1. Optical Cavities; "2. Superconducting resonators"; Figs. 1, 3a, 4(b), 13 | 1-4, 7-8, 10                  |
| X                                                     | S. FORSTNER et. al.: "Cavity Optomechanical Magnetometer", Physical Review Letters, Vol. 108, March 2012<br>Refer to the whole document and in particular to abstract, Fig. 1b and associated description                                                                                                                 | 1-6, 13-14                    |
| X                                                     | WO 2012/142654 A1 (THE UNIVERSITY OF QUEENSLAND) 26 October 2012<br>Refer to the whole document and in particular to abstract, claims 2, 4, 6, 12, pg 6 line 20, pg 7 13-15 and line 22, pg 8 lines 3-30, pg 9 lines 8-13, Fig. 1                                                                                         | 1-6, 8-14                     |
| X                                                     | US 4937833 A (KABACOFF) 26 June 1990<br>Refer to the whole document and in particular to col. 2 lines 4-17, col. 4 to col. 5 lines 5, claims, Fig. 2                                                                                                                                                                      | 1-3, 5-6, 12-14               |
| A                                                     | WO WO 2005/093649 A1 (D-WAVE SYSTEMS, INC.) 06 October 2005<br>Refer to the whole document and in particular to pg 2-3, 81-88                                                                                                                                                                                             | 1-14                          |
| A                                                     | STEPHAN RITTER et. al.: "An elementary quantum network of single atoms in optical cavities", Nature, Vol. 848, 12 April 2012, pg 195-201<br>Refer to the whole document                                                                                                                                                   | 1-14                          |

Form PCT/ISA/210 (fifth sheet) (July 2009)

**Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)**

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:  
because they relate to subject matter not required to be searched by this Authority, namely:  
the subject matter listed in Rule 39 on which, under Article 17(2)(a)(i), an international search is not required to be carried out, including
2. ☐ Claims Nos.:  
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☐ Claims Nos.:  
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a)

**Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)**

This International Searching Authority found multiple inventions in this international application, as follows:

**See Supplemental Box for Details**

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☒ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

**Remark on Protest**

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

**Supplemental Box****Continuation of: Box III**

This International Application does not comply with the requirements of unity of invention because it does not relate to one invention or to a group of inventions so linked as to form a single general inventive concept.

This Authority has found that there are different inventions based on the following features that separate the claims into distinct groups:

- Claim 1-4 and 7 are directed to a quantum state transfer device including a first magnetic state sensor adapted to sense the quantum state of a magnetic flux qubit a magnetic state to optical state transfer system, interconnected to the first magnetic state sensor and adapted to transfer the quantum state of the magnetic flux qubit to a corresponding optical quantum state in an output optical signal. The feature of a magnetic state to optical transfer system, interconnected to the first magnetic state sensor and adapted to transfer the quantum state of the magnetic flux qubit to a corresponding optical quantum state in an output optical signal is specific to this group of claims.
- Claim 11 is directed to a quantum state transfer device including: an optical cavity modulating an optical input signal, including a first mirror surface for reflection of the optical input signal and a second semi mirrored partially transparent surface for forming an optical input output signal interface; and a magnetically inductive material mechanically coupled to said first mirror surface, and further magnetically coupled to a quantum flux qubit for sensing the quantum state of the quantum flux qubit; wherein the magnetic state of the quantum flux qubit is inductively transferred to an optical quantum state of the optical input signal and output by the optical cavity device. (Note that dependent claims 8-10, appended to claim 1, are directed to inductive coupling systems which is the special technical feature of claim 11). The feature of a magnetically inductive material mechanically coupled to said first mirror surface, and further magnetically coupled to a quantum flux qubit for sensing the quantum state of the quantum flux qubit; wherein the magnetic state of the quantum flux qubit is inductively transferred to an optical quantum state of the optical input signal and output by the optical cavity device is specific to this group of claims.
- Claims 12-14 are directed to a quantum state transfer device and a method of transfer of a magnetic flux qubit quantum state to a corresponding optical quantum state, where sensing the quantum state of the magnetic flux qubit is by utilising magnetostrictive material and further using it to modulate an optical signal so as to impart the corresponding optical quantum state to the optical signal. (Note that dependent claims 5-6, appended to claim 1, are directed to magnetostrictive material which is the special technical feature of claims 12-14). The feature of utilising magnetostrictive material and further using it to modulate an optical signal so as to impart the corresponding optical quantum state to the optical signal is specific to this group of claims.

PCT Rule 13.2, first sentence, states that unity of invention is only fulfilled when there is a technical relationship among the claimed inventions involving one or more of the same or corresponding special technical features. PCT Rule 13.2, second sentence, defines a special technical feature as a feature which makes a contribution over the prior art.

When there is no special technical feature common to all the claimed inventions there is no unity of invention.

In the above groups of claims, the identified features may have the potential to make a contribution over the prior art but are not common to all the claimed inventions and therefore cannot provide the required technical relationship. The only feature common to all of the claimed inventions and which provides a technical relationship among them is a quantum state transfer device or method

However this feature does not make a contribution over the prior art because it is disclosed in:  
Anyone of D1-D5 or D7

D1: S. FORSTNER et. al.: "Sensitivity and Performance of Cavity Optomechanical Field Sensors", Photonic Sensors, Vol. 2, No. 3, (2012), pg 259-270

D2: ZE-LIANG XIANG et. al.: "Hybrid quantum circuits: Superconducting circuits interacting with other quantum systems", Reviews of Modern Physics Vol. 85, (2013), pg 623-653 - refer to Fig. 14

**Supplemental Box**

D3: S. FORSTNER et. al.: "Cavity Optomechanical Magnetometer", Physical Review Letters, Vol. 108, March 2012

D4: WO 2012/142654 A1 (THE UNIVERSITY OF QUEENSLAND) 26 October 2012

D5: US 4937833 A (KABACOFF) 26 June 1990

D7: STEPHAN RITTER et. al.: "An elementary quantum network of single atoms in optical cavities", Nature, Vol. 848, 12 April 2012, pg 195-201 - refer to Fig. 1

Therefore in the light of this document this common feature cannot be a special technical feature. Therefore there is no special technical feature common to all the claimed inventions and the requirements for unity of invention are consequently not satisfied *a posteriori*.

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|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------|-----------------------------------------------------------|-------------------------|
| <b>INTERNATIONAL SEARCH REPORT</b><br>Information on patent family members                                                                                                                                                                                            |                         | International application No.<br><b>PCT/AU2015/000107</b> |                         |
| This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information. |                         |                                                           |                         |
| <b>Patent Document/s Cited in Search Report</b>                                                                                                                                                                                                                       |                         | <b>Patent Family Member/s</b>                             |                         |
| <b>Publication Number</b>                                                                                                                                                                                                                                             | <b>Publication Date</b> | <b>Publication Number</b>                                 | <b>Publication Date</b> |
| WO 2012/142654 A1                                                                                                                                                                                                                                                     | 26 October 2012         |                                                           |                         |
| US 4937833 A                                                                                                                                                                                                                                                          | 26 June 1990            |                                                           |                         |
| WO WO 2005/093649 A1                                                                                                                                                                                                                                                  | 06 October 2005         | None                                                      |                         |
| <b>End of Annex</b>                                                                                                                                                                                                                                                   |                         |                                                           |                         |
| <div> <p>Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.</p> <p>Form PCT/ISA/210 (Family Annex)(July 2009)</p> </div>                                                                       |                         |                                                           |                         |