CLAIMS

~~What is claimed is:~~

1. A quantum information processing (QIP) system comprising:

a data qubit; and

an ancilla qubit with an asymmetric error channel, the data qubit coupled to the ancilla qubit,

wherein an error channel of the ancilla qubit is dominated by phase-flip errors and not bit-flip errors.

2. The QIP system according to claim 1, further comprising a measurement device configured to measure a property of the data qubit using the ancilla qubit and using a quantum non-demolition measurement by:

causing the data qubit and the ancilla qubit to interact such that a state of the ancilla qubit is based on the property of the data qubit; and

measuring the state of the ancilla qubit to determine the state of the data qubit.

~~3, The QIP system according to claim 2, wherein the measurement device is configured to measure the property of the data qubit using a quantum non-demolition measurement.~~

~~4. The QIP system according to claim 3, wherein the measurement device is configured to perform the quantum non-demolition measurement by:~~

~~causing the data qubit and the ancilla qubit to interact such that a state of the ancilla qubit is based on the property of the data qubit; and~~

~~measuring the state of the ancilla qubit to determine the state of the data qubit.~~

~~5, The QIP system according to claim 4, wherein the measurement device is configured to suppress errors of a first type in the ancilla qubit by repeatedly performing the quantum non-demolition measurement.~~

~~6~~3. The QIP system according to claim ~~4~~2, wherein the measurement device comprises:

a readout cavity coupled to the ancilla qubit; and

a cavity state detector configured to measure the state of the readout cavity.

~~7. The QIP system according to claim 6, wherein the measurement device is configured to measure the state of the ancilla qubit by:~~

~~causing the ancilla qubit and the readout cavity to interact such that a state of the readout cavity is based on the state of the ancilla qubit;~~

~~measuring the state of the readout cavity to determine the state of the ancilla qubit.~~

~~8. The QIP system according to claim 7, wherein the cavity state detector comprises a phase-sensitive detector.~~

~~9. The QIP system according to claim 8, wherein the cavity state detector comprises a homodyne detector.~~

~~10~~4. The QIP system according to claim 2, further comprising a microwave field source configured to cause the data qubit and the ancilla qubit to interact such that a z-component of a state of the ancilla qubit is based on the property of the data qubit.

~~11~~5. The QIP system according to claim ~~10~~ 4, wherein:

the ancilla qubit is an ancilla superconducting nonlinear asymmetric inductive element (SNAIL) with a resonance frequency; and

the microwave field source is configured to apply a pump microwave field to the ancilla SNAIL at a pump frequency that is twice the resonance frequency of the SNAIL.

~~12~~6. The QIP system according to claim ~~11~~ 5, wherein the microwave field source is configured to:

apply at least one initialization microwave field to the ancilla qubit to initialize the ancilla qubit in a cat state along the x-axis of a Bloch sphere; and

apply at least one drive microwave field to at least one of the data qubit and the ancilla qubit to create an interaction between the data qubit and the ancilla qubit.

~~13~~7. The QIP system according to claim ~~12~~ 6, wherein the microwave field source is configured to apply the at least one initialization microwave field to the ancilla qubit by adiabatically increasing an amplitude of a pump microwave field of the ancilla SNAIL, prepared in a vacuum state, from 0 to a pump amplitude value equal to $K|\alpha|^2$, where K is a strength of a Kerr nonlinearity of the ancilla SNAIL and α is a coherent state amplitude associated with the cat state.

~~14~~8. The QIP system according to claim ~~11~~ 5, wherein:

the data qubit is a transmon;

the property of the data qubit is σ_Z of the transmon; and

the microwave field source is further configured to apply a drive microwave field to the transmon at the resonance frequency of the SNAIL and in phase with the pump microwave field to cause the data qubit and the ancilla qubit to interact such that a z-component of the state of the ancilla qubit is dependent on σ_Z of the data qubit.

~~15~~9. The QIP system according to claim ~~11~~ 5, wherein:

the data qubit comprises a cat state in a linear oscillator;

the property of the data qubit is a photon number parity of the cat state; and

the microwave field source is further configured to apply a drive microwave field to the cat state in the linear oscillator at the resonance frequency of the SNAIL and in phase with the pump microwave field to cause the data qubit and the ancilla qubit to interact such that a z-component of the state of the ancilla qubit is dependent on the photon number parity of the data qubit.

~~16~~10. The QIP system according to claim ~~11~~ 5, wherein:

the data qubit comprises a Gottesman-Kitaev-Preskill (GKP) state in a linear oscillator;

the property of the data qubit is a stabilizer of the GKP state; and

the microwave field source is further configured to apply a drive microwave field to the ancilla SNAIL at a drive frequency equal to a difference between the resonance frequency of the SNAIL and a resonance frequency of the linear oscillator to cause the data qubit and the ancilla qubit to interact such that a z-component of the state of the ancilla qubit is dependent on a stabilizer of the GKP state of the data qubit.

17. The QIP system according to claim 16, wherein:

the microwave field source is configured to apply the drive microwave field to the GKP state in phase with the pump microwave signal; and

the stabilizer of the GKP state of the data qubit is a S_q stabilizer.

18. The QIP system according to claim 16, wherein:

the microwave field source is configured to apply the drive microwave field to the GKP state 90° out of phase with the pump microwave signal; and

the stabilizer of the GKP state of the data qubit is a S_p stabilizer.

19. The QIP system according to claim 11, wherein:

the data qubit comprises a cat state in a data SNAIL;

the property of the data qubit is σ_z of the data SNAIL; and

the microwave field source is further configured to apply, over an interaction time duration, a plurality of microwave fields to the data qubit and the ancilla qubit to cause the data qubit and the ancilla qubit to interact such that a z-component of the state of the ancilla qubit is dependent on σ_z of the data qubit, wherein applying the plurality of microwave fields comprises:

applying a first microwave field with a frequency $2\omega_e$ to the ancilla qubit, wherein ω_e is a resonance frequency of the ancilla qubit;

applying a second microwave field with a frequency $2\omega_t$ to the data qubit, wherein ω_t is a resonance frequency of the data qubit;

applying a third microwave field with a frequency $2\omega_t - \omega_e$ to the data qubit;

applying a fourth microwave field with a frequency ω_e to the ancilla qubit; and

applying a fifth microwave field with a frequency ω_e to the data qubit.

20. The QIP system according to claim 19, wherein:

an amplitude of the first microwave field is constant over the interaction time duration;

an amplitude of the second microwave field is time-varying over the interaction time duration;

an amplitude of the third microwave field is time-varying over the interaction time duration;

an amplitude of the fourth microwave field is time-varying over the interaction time duration; and

an amplitude of the fifth microwave field is constant over the interaction time duration.

21. The QIP system according to claim 20, wherein:

a phase of the first microwave field decreases linearly over the interaction time duration;

a phase of the second microwave field is constant at a first phase value during a first portion of the interaction time duration and constant at a second phase value during a second portion of the interaction time duration, wherein the first phase value is less than the second phase value;

a phase of the third microwave field increases linearly over the interaction time duration;

a phase of the fourth microwave field decreases linearly during the first portion of the interaction time duration and decreases linearly during the second portion of the interaction time duration; and

a phase of the fifth microwave field decreases linearly over the interaction time duration.

22. The QIP system according to claim 10, wherein the microwave field source is configured to cause the data qubit and the ancilla qubit to interact such that a CNOT gate is performed between the data qubit and the ancilla qubit.

23. The QIP system according to claim 1, wherein the ancilla qubit comprises a Kerr-nonlinear cavity.

24. The QIP system according to claim 23, wherein a Kerr-nonlinearity of the Kerr-nonlinear cavity is greater than 1 MHz.

25. The QIP system according to claim 24, wherein a strength of a parametric drive of the ancilla qubit is greater than the Kerr-nonlinearity of the Kerr-nonlinear cavity.

26. The QIP system according to claim 23, wherein a Kerr-nonlinearity of the Kerr-nonlinear cavity is greater than a rate of phase-flips in the ancilla qubit.

27. The QIP system according to claim 23, wherein the ancilla qubit comprises a cat state in the Kerr-nonlinear cavity.

28. The QIP system according to claim 27, wherein the ancilla qubit comprises at least one Josephson junction configured to create a Kerr-nonlinearity in the Kerr-nonlinear cavity.

29. The QIP system according to claim 28, wherein the ancilla qubit comprises a transmon in the Kerr-nonlinear cavity.

30. The QIP system according to claim 28, wherein the ancilla qubit comprises a superconducting nonlinear asymmetric inductor element (SNAIL) in the Kerr-nonlinear cavity.

31. The QIP system according to claim 1, wherein an error syndrome is determined based on a conditional rotation of the cat state.

32. The QIP system according to claim 31, wherein the conditional rotation is implemented using only local interactions.

33. The QIP system according to claim 1, wherein an error channel of the ancilla qubit is dominated by phase-flip errors, not bit-flip errors.

34. The QIP system according to claim 33, wherein the phase-flip errors result from photon loss.

35. The QIP system according to claim 34, wherein, when a phase-flip error occurs in the ancilla qubit, a state of the data qubit is unaffected.

36. The QIP system according to claim 33, wherein the bit-flip errors are exponentially suppressed as a function of a power of a pump used to create a cat state in the ancilla qubit.

37. The QIP system according to claim 1, wherein a quantum data gate is implemented between the data qubit and the ancilla qubit.

38. The QIP system according to claim 37, wherein the quantum data gate is a CNOT gate, the data qubit is a target qubit of the CNOT gate, and the ancilla qubit is a control qubit of the CNOT gate.

39. The QIP system according to claim 38, wherein the control qubit comprises a first cat state and the target qubit comprises a second cat state.

40. The QIP system according to aspect 40, wherein the CNOT gate is implemented by rotating the first cat state in phase space.

41. The QIP system according to claim 40, further comprising a microwave field source configured to apply, over a gate time duration, a plurality of microwave fields to the data qubit and the ancilla qubit to implement the CNOT gate.

42. The QIP system according to claim 41, wherein the microwave field source is configured to:

apply a first microwave field with a frequency $2\omega_c$ to the control qubit, wherein ω_c is a resonance frequency of the control qubit;

apply a second microwave field with a frequency $2\omega_t$ to the target qubit, wherein ω_t is a resonance frequency of the target qubit;

apply a third microwave field with a frequency $2\omega_t - \omega_c$ to the target qubit;

apply a fourth microwave field with a frequency ω_c to the control qubit; and

apply a fifth microwave field with a frequency ω_c to the target qubit.

43. The QIP system according to claim 42, wherein:

an amplitude of the first microwave field is constant over the gate time duration;

an amplitude of the second microwave field is time-varying over the gate time duration;

an amplitude of the third microwave field is time-varying over the gate time duration;

an amplitude of the fourth microwave field is time-varying over the gate time duration; and

an amplitude of the fifth microwave field is constant over the gate time duration.

44. The QIP system according to claim 43, wherein:

a phase of the first microwave field decreases linearly over the gate time duration;

a phase of the second microwave field is constant at a first phase value during a first portion of the gate time duration and constant at a second phase value during a second portion of the gate time duration, wherein the first phase value is less than the second phase value;

a phase of the third microwave field increases linearly over the gate time duration;

a phase of the fourth microwave field decreases linearly during the first portion of the gate time duration and decreases linearly during the second portion of the gate time duration; and

a phase of the fifth microwave field decreases linearly over the gate time duration.

4511. The QIP system according to claim 1, further comprising a microwave field source configured to apply a stabilizing microwave field to the ancilla qubit to create the asymmetric error channel.

46. The QIP system according to claim 45, wherein the stabilizing microwave field stabilizes a state of the ancilla qubit against rotation around at least one axis of an ancilla Bloch sphere.

47. The QIP system according to claim 46, further comprising a readout cavity coupled to the ancilla qubit.

48. The QIP system according to claim 47, further comprising a cavity state detector configured to determine a state of the readout cavity is configured to measure the state of the ancilla

49. The QIP system according to claim 47, wherein the readout cavity is configured to be conditionally displaced based on a state of the ancilla qubit.

~~50. The QIP system according to claim 49, wherein the microwave field source is configured to conditionally displace the readout cavity by:~~

~~applying at least one rotation microwave field to rotate a state of the ancilla qubit around an axis of a Bloch sphere by;~~

~~turning off, for an amount of time, the stabilizing microwave field to allow the state of the ancilla qubit to evolve based on a Kerr nonlinearity of the ancilla qubit;~~

~~re-applying the stabilizing microwave field to re-stabilize the state of the ancilla qubit; and~~

~~applying an exchange microwave field to the ancilla qubit to turn on an exchange coupling between the ancilla qubit and the readout cavity.~~

~~51~~12. A method of performing quantum information processing (QIP) in a system comprising a data qubit coupled to an ancilla qubit, the method comprising:

driving the ancilla qubit with a stabilizing microwave field to create an asymmetric error channel.

~~52~~13. The method according to claim ~~51~~ 12, further comprising measuring a property of the data qubit using the ancilla qubitby performing a quantum non-demolition measurement, wherein performing the quantum non-demolition measurement comprises:

causing the data qubit and the ancilla qubit to interact such that a state of the ancilla qubit is based on the property of the data qubit; and

measuring the state of the ancilla qubit to determine the state of the data qubit.

~~53. The method according to claim 52, wherein measuring the property of the data qubit comprises performing a quantum non-demolition measurement.~~

~~54. The method according to claim 53, wherein performing the quantum non-demolition measurement comprises:~~

~~causing the data qubit and the ancilla qubit to interact such that a state of the ancilla qubit is based on the property of the data qubit; and~~

~~measuring the state of the ancilla qubit to determine the state of the data qubit.~~

~~55. The method according to claim 54, further comprising suppressing errors of a first type in the ancilla qubit by repeatedly performing the quantum non-demolition measurement.~~

~~56. The method according to claim 54, wherein performing the quantum non-demolition measurement is accomplished using a measurement device comprising:~~

~~a readout cavity coupled to the ancilla qubit; and~~

~~a cavity state detector configured to measure the state of the readout cavity.~~

~~57. The method according to claim 56, wherein performing the quantum non-demolition measurement comprises:~~

~~causing the ancilla qubit and the readout cavity to interact such that a state of the readout cavity is based on the state of the ancilla qubit;~~

~~measuring the state of the readout cavity to determine the state of the ancilla qubit.~~

~~58. The method according to claim 57, wherein the cavity state detector comprises a phase-sensitive detector.~~

~~59. The method according to claim 58, wherein the cavity state detector comprises a homodyne detector.~~

~~60~~14. The method according to claim ~~52~~ 13, further comprising causing the data qubit and the ancilla qubit to interact such that a z-component of a state of the ancilla qubit is based on the property of the data qubit.

~~61. The method according to claim 60, wherein:~~

~~the ancilla qubit is an ancilla superconducting nonlinear asymmetric inductive element (SNAIL) with a resonance frequency; and~~

~~causing the data qubit and the ancilla qubit to interact comprises applying a pump microwave field to the ancilla SNAIL at a pump frequency that is twice the resonance frequency of the SNAIL.~~

~~62~~15. The method according to claim ~~61~~14, further comprising:

applying at least one initialization microwave field to the ancilla qubit to initialize the ancilla qubit in a cat state along the x-axis of a Bloch sphere; and

applying at least one drive microwave field to at least one of the data qubit and the ancilla qubit to create an interaction between the data qubit and the ancilla qubit.

~~63. The method according to claim 62, wherein applying the at least one initialization microwave field to the ancilla qubit comprises adiabatically increasing an amplitude of a pump microwave field of the ancilla SNAIL, prepared in a vacuum state, from 0 to a pump amplitude value equal to $K|\alpha|^2$, where K is a strength of a Kerr nonlinearity of the ancilla SNAIL and α is a coherent state amplitude associated with the cat state.~~

~~64. The method according to claim 61, wherein:~~

~~the data qubit is a transmon;~~

~~the property of the data qubit is σ_z of the transmon; and~~

~~the method further comprises applying a drive microwave field to the transmon at the resonance frequency of the SNAIL and in phase with the pump microwave field to cause the data qubit and the ancilla qubit to interact such that a z-component of the state of the ancilla qubit is dependent on σ_z of the data qubit.~~

~~65. The method according to claim 61, wherein:~~

~~the data qubit comprises a cat state in a linear oscillator;~~

~~the property of the data qubit is a photon number parity of the cat state; and~~

~~the method further comprises applying a drive microwave field to the cat state in the linear oscillator at the resonance frequency of the SNAIL and in phase with the pump microwave field to cause the data qubit and the ancilla qubit to interact such that a z-component of the state of the ancilla qubit is dependent on the photon number parity of the data qubit.~~

~~66. The method according to claim 61, wherein:~~

~~the data qubit comprises a Gottesman-Kitaev-Preskill (GKP) state in a linear oscillator;~~

~~the property of the data qubit is a stabilizer of the GKP state; and~~

the method further comprises applying a drive microwave field to the ancilla SNAIL at a drive frequency equal to a difference between the resonance frequency of the SNAIL and a resonance frequency of the linear oscillator to cause the data qubit and the ancilla qubit to interact such that a z-component of the state of the ancilla qubit is dependent on a stabilizer of the GKP state of the data qubit.

67. The method according to claim 66, wherein:

applying the drive microwave field to the GKP state is done in phase with the pump microwave signal; and

the stabilizer of the GKP state of the data qubit is a S_q stabilizer.

68. The method according to claim 66, wherein:

applying the drive microwave field to the GKP state is done 90° out of phase with the pump microwave signal; and

the stabilizer of the GKP state of the data qubit is a S_p stabilizer.

69. The method according to claim 61, wherein:

the data qubit comprises a cat state in a data SNAIL;

the property of the data qubit is σ_z of the data SNAIL; and

the method further comprises applying, over an interaction time duration, a plurality of microwave fields to the data qubit and the ancilla qubit to cause the data qubit and the ancilla qubit to interact such that a z-component of the state of the ancilla qubit is dependent on σ_z of the data qubit, wherein applying the plurality of microwave fields comprises:

applying a first microwave field with a frequency $2\omega_c$ to the ancilla qubit, wherein ω_c is a resonance frequency of the control qubit;

applying a second microwave field with a frequency $2\omega_t$ to the data qubit, wherein ω_t is a resonance frequency of the data qubit;

applying a third microwave field with a frequency $2\omega_t - \omega_c$ to the data qubit;

applying a fourth microwave field with a frequency ω_c to the ancilla qubit; and

applying a fifth microwave field with a frequency ω_c to the data qubit.

70. The method according to claim 69, wherein:

an amplitude of the first microwave field is constant over the interaction time duration;

an amplitude of the second microwave field is time-varying over the interaction time duration;

an amplitude of the third microwave field is time-varying over the interaction time duration;

an amplitude of the fourth microwave field is time-varying over the interaction time duration; and

an amplitude of the fifth microwave field is constant over the interaction time duration.

71. The method according to claim 70, wherein:

a phase of the first microwave field decreases linearly over the interaction time duration;

a phase of the second microwave field is constant at a first phase value during a first portion of the interaction time duration and constant at a second phase value during a second portion of the interaction time duration, wherein the first phase value is less than the second phase value;

a phase of the third microwave field increases linearly over the interaction time duration;

a phase of the fourth microwave field decreases linearly during the first portion of the interaction time duration and decreases linearly during the second portion of the interaction time duration; and

a phase of the fifth microwave field decreases linearly over the interaction time duration.

72. The method according to claim 60, wherein causing the data qubit and the ancilla qubit to interact results in a CNOT gate being performed between the data qubit and the ancilla qubit.

73. The method according to claim 51, wherein the ancilla qubit comprises a Kerr-nonlinear cavity.

74. The method according to claim 73, wherein a Kerr-nonlinearity of the Kerr-nonlinear cavity is greater than 1 MHz.

75. The method according to claim 74, wherein a strength of a parametric drive of the ancilla qubit is greater than the Kerr-nonlinearity of the Kerr-nonlinear cavity.

76. The method according to claim 73, wherein a Kerr-nonlinearity of the Kerr-nonlinear cavity is greater than a rate of phase-flips in the ancilla qubit.

77. The method according to claim 73, wherein the ancilla qubit comprises a cat state in the Kerr-nonlinear cavity.

78. The method according to claim 77, further comprising creating a Kerr-nonlinearity in the Kerr-nonlinear cavity using at least one Josephson junction of the ancilla qubit.

79. The method according to claim 78, wherein the ancilla qubit comprises a transmon in the Kerr-nonlinear cavity.

80. The method according to claim 78, wherein the ancilla qubit comprises a superconducting nonlinear asymmetric inductor element (SNAIL) in the Kerr-nonlinear cavity.

81. The method according to claim 77, further comprising determining an error syndrome based on a conditional rotation of the cat state.

82. The method according to claim 81, further comprising performing only local interactions to implement the conditional rotation.

83. The method according to claim 51, wherein an error channel of the ancilla qubit is dominated by phase-flip errors, not bit-flip errors.

84. The method according to claim 83, wherein the phase-flip errors are a result of photon loss.

~~85. The method according to claim 84, wherein, when a phase-flip error occurs in the ancilla qubit, a state of the data qubit is unaffected.~~

~~86. The method according to claim 83, further comprising applying a pump microwave field to ancilla qubit to create a cat state such that the bit-flip errors are exponentially suppressed as a function of a power of the pump microwave field.~~

~~87~~16. The method according to claim ~~51~~ 12, further comprising implementing a quantum data gate between the data qubit and the ancilla qubit.

~~88~~17. The method according to claim ~~87~~ 16, wherein the quantum data gate is a CNOT gate, the data qubit is a target qubit of the CNOT gate, and the ancilla qubit is a control qubit of the CNOT gate, and wherein the control qubit comprises a first cat state and the target qubit comprises a second cat state.

~~89. The method according to claim 88, wherein the control qubit comprises a first cat state and the target qubit comprises a second cat state.~~

~~90~~18. The method of claim 17~~according to aspect 89~~, further comprising rotating the first cat state in phase space to implement the CNOT gate.

~~91. The method of claim 88, further comprising applying, over a gate time duration, a plurality of microwave fields to the data qubit and the ancilla qubit to implement the CNOT gate.~~

~~92~~19. The method according to claim ~~91~~ 18, further comprising:

applying a first microwave field with a frequency $2\omega_c$ to the control qubit, wherein ω_c is a resonance frequency of the control qubit;

applying a second microwave field with a frequency $2\omega_t$ to the target qubit, wherein ω_t is a resonance frequency of the target qubit;

applying a third microwave field with a frequency $2\omega_t - \omega_c$ to the target qubit;

applying a fourth microwave field with a frequency ω_c to the control qubit; and

applying a fifth microwave field with a frequency ω_c to the target qubit.

~~93~~20. The method according to claim ~~92~~ 19, wherein:

an amplitude of the first microwave field is constant over the gate time duration;

an amplitude of the second microwave field is time-varying over the gate time duration;

an amplitude of the third microwave field is time-varying over the gate time duration;

an amplitude of the fourth microwave field is time-varying over the gate time duration; and

an amplitude of the fifth microwave field is constant over the gate time duration.

~~94. The method according to claim 93, wherein:~~

~~a phase of the first microwave field decreases linearly over the gate time duration;~~

~~a phase of the second microwave field is constant at a first phase value during a first portion of the gate time duration and constant at a second phase value during a second portion of the gate time duration, wherein the first phase value is less than the second phase value;~~

~~a phase of the third microwave field increases linearly over the gate time duration;~~

~~a phase of the fourth microwave field decreases linearly during the first portion of the gate time duration and decreases linearly during the second portion of the gate time duration; and~~

~~a phase of the fifth microwave field decreases linearly over the gate time duration.~~

~~95. The method according to claim 51, wherein the stabilizing microwave field stabilizes a state of the ancilla qubit against rotation around at least one axis of an ancilla Bloch sphere.~~

~~96. The method according to claim 95, further comprising coupling a readout cavity to the ancilla qubit.~~

~~97. The method according to 95, further comprising conditionally displacing the readout cavity based on a state of the ancilla qubit.~~

~~98. The method according to claim 97 wherein conditionally displacing the readout cavity comprises:~~

~~applying at least one rotation microwave field to rotate a state of the ancilla qubit around an axis of a Bloch sphere by;~~

~~turning off, for an amount of time, the stabilizing microwave field to allow the state of the ancilla qubit to evolve based on a Kerr nonlinearity of the ancilla qubit;~~

~~re-applying the stabilizing microwave field to re-stabilize the state of the ancilla qubit; and~~

~~applying an exchange microwave field to the ancilla qubit to turn on an exchange coupling between the ancilla qubit and the readout cavity.~~