



# Contents

<b>Introduction</b>	<b>1</b>
<b>1 Basics - Superconductivity and Josephson effect</b>	<b>5</b>
1.1 Short introduction to superconductivity . . . . .	5
1.2 Flux quantization . . . . .	7
1.3 The Josephson effect . . . . .	9
1.4 Quantum mechanics of a Josephson junction . . . . .	11
<b>2 Theoretical analysis of flux qubits and cavities</b>	<b>13</b>
2.1 The quantum two-level system . . . . .	13
2.2 The superconducting flux qubit . . . . .	14
2.3 The flux qubit as quantum two-level system . . . . .	18
2.4 Coupling to the environment - Relaxation and Decoherence . . . . .	20
2.5 The superconducting CPW resonator . . . . .	22
2.6 Hamiltonian of a CPW resonator . . . . .	24
2.7 Coupling the resonator to its environment . . . . .	29
2.8 Relaxation of the resonator . . . . .	32
2.9 Input field and transmission coefficient . . . . .	33
<b>3 Experimental requirements and setup</b>	<b>37</b>
3.1 Experimental setup . . . . .	37
3.2 Measurement setup . . . . .	38
3.3 Sample fabrication and preparation . . . . .	40
<b>4 Coupling a flux qubit to a resonator</b>	<b>43</b>
4.1 Magnetic coupling . . . . .	43



4.2	Continuous monitoring of a flux qubit with a CPW resonator . . . . .	46
4.3	Two-tone spectroscopy . . . . .	49
4.4	Transmission of the qubit-resonator system . . . . .	53
<b>5</b>	<b>Dressed qubit-resonator system and lasing</b>	<b>61</b>
5.1	Strong AC-Zeeman shift and three-tone spectroscopy . . . . .	61
5.2	The dressed qubit . . . . .	65
5.3	Coupling between the dressed qubit and the resonator . . . . .	69
5.4	Dressed-state lasing of a single artificial two-level system . . . . .	75
5.5	Emission from the dressed qubit and lasing . . . . .	81
5.6	Strong driving - Beyond the two-level approximation . . . . .	85
	<b>Summary</b>	<b>97</b>
	<b>Acknowledgment</b>	<b>99</b>
	<b>Appendix</b>	<b>101</b>
A	Notes to the qubit and the resonator . . . . .	101
A.1	Kinetic part of the flux qubit Hamiltonian . . . . .	101
A.2	Diagonalizing the Hamiltonian . . . . .	102
A.3	Classical results of the resonator . . . . .	104
B	Time evolution of the density matrix by damping . . . . .	106
B.1	Qubit dissipation . . . . .	106
B.2	Resonator photon decay . . . . .	107
C	Basic transformations . . . . .	110
C.1	Rotating frames . . . . .	110
C.2	Dispersive regime . . . . .	111
C.3	Dressed-state basis . . . . .	112
C.4	Eigenbasis of the multiphoton driven qubit . . . . .	118
C.5	Two-photon interaction with the fundamental mode . . . . .	119
	<b>List of Symbols</b>	<b>121</b>
	<b>References</b>	<b>129</b>
	<b>Publications in Peer-reviewed Journals</b>	<b>141</b>



<b>Conference Contributions</b>	<b>143</b>
<b>Zusammenfassung</b>	<b>145</b>