



Universiteit
Leiden
The Netherlands

Cavity quantum electrodynamics with quantum dots in microcavities

Gudat, J.

Citation

Gudat, J. (2012, June 19). *Cavity quantum electrodynamics with quantum dots in microcavities*. *Casimir PhD Series*. Retrieved from <https://hdl.handle.net/1887/19553>

Version: Not Applicable (or Unknown)

License: [Licence agreement concerning inclusion of doctoral thesis in the Institutional Repository of the University of Leiden](#)

Downloaded from: <https://hdl.handle.net/1887/19553>

Note: To cite this publication please use the final published version (if applicable).

Cover Page



Universiteit Leiden



The handle <http://hdl.handle.net/1887/19553> holds various files of this Leiden University dissertation.

Author: Gudat, Jan

Title: Cavity quantum electrodynamics with quantum dots in microcavities

Issue Date: 2012-06-19

Cavity Quantum Electrodynamics
with
Quantum Dots in Microcavities

Jan Gudat

Cover: The picture on the cover shows an optical cavity with a dipole inside. The curves in the background illustrate a cavity reflectivity measurement. The photon entering the cavity (from the left) interacts with the dipole. When the dipole is coupled to the cavity and the photon is interacting on resonance with a dipole electron spin, the photon gets reflected. This can be measured by a peak in the dip of the reflection (blue) curve. In the uncoupled case with the dipole being out of resonance, the photon gets transmitted and a dip in the reflection (red) curve can be observed. This simplified idea can be realized with a quantum dot in a microcavity, which could serve as the building block (a qubit) for a quantum computer.

**Cavity Quantum Electrodynamics
with
Quantum Dots in Microcavities**

PROEFSCHRIFT

ter verkrijging van
de graad van Doctor aan de Universiteit Leiden,
op gezag van Rector Magnificus prof. mr. P.F. van der Heijden,
volgens besluit van het College voor Promoties
te verdedigen op dinsdag 19 juni 2012
klokke 10:00 uur

door

Jan Gudat

Promotiecommissie:

Promoter:	Prof. dr. D. Bouwmeester	Universiteit Leiden / University of California, Santa Barbara
Leden:	Dr. M.P. van Exter	Universiteit Leiden
	Dr. M.J.A. de Dood	Universiteit Leiden
	Prof. dr. E.R. Eliel	Universiteit Leiden
	Prof. dr. A. Fiore	Technische Universiteit Eindhoven
	Dr. H. Krenner	Universtät Augsburg
	Prof. dr. ir. C.H. van der Wal	Rijksuniversiteit Groningen

The work presented in this thesis has been made possible by financial support from the Marie-Curie Program No. EXT-CT-2006-042580.

Casimir PhD series, Delft-Leiden, 2012-15

ISBN: 978-90-8593-126-3

Contents

1	Introduction	1
1.1	Controlling electron spin interactions via photons	4
1.1.1	Vision	5
1.1.2	Required developments	9
1.2	Challenges	9
1.2.1	Deterministic spin positioning at the center of optical micro resonators	11
1.2.2	Controlled emitter-cavity interaction in the weak-coupling regime	11
1.2.3	Controlled emitter-cavity interaction in a polarization degenerate way	13
1.2.4	Single electron spin preparation in QDs	15
1.2.5	Entangle a single spin with a photon via the trion state	16
1.2.6	Enhance single spin coherence time	17
1.2.7	Couple multiple microcavity-QD systems	18
1.2.8	Entangle two electron qubits via the hybrid scheme . . .	18
1.3	Quantum dots	19
1.3.1	Types of QDs	19
1.3.2	Fabrication of self-assembled QDs	19
1.3.3	Optical and electrical properties	21
1.3.4	QD tuning via the Stark effect	26
1.4	Microcavities	29
1.5	Cavity quantum electrodynamics	30
1.5.1	Cavity coupling parameters	30
1.5.2	The Jaynes-Cummings model	31
1.5.3	Dynamics of the Jaynes-Cummings model	34
1.5.4	The strong coupling regime	38
1.5.5	The weak coupling regime	38
1.5.6	Spontaneous emission and Purcell effect in microcavities	40
1.5.7	Cavity reflectivity with a single QD	42

2	Experimental Setup	45
2.1	Optical setup	45
2.2	Laser and detector options	46
2.3	Cryostat	48
3	Optical Modes in Oxide-Apertured Micropillars	51
3.1	Introduction	52
3.2	Oxide-apertured micropillars design and fabrication	53
3.3	Theoretical model of the optical modes	60
3.3.1	Theoretical spectrum of the modes	64
3.3.2	Anisotropic materials	65
3.3.3	Relative mode splitting and Purcell factor	66
3.4	Measurements	67
3.5	Results	68
3.6	Improving the theoretical model	77
3.7	Conclusion and discussion	84
4	Microcavity Tuning	87
4.1	Introduction	88
4.2	Oxide-apertured micropillar design and properties	89
4.3	Tuning micropillar cavity birefringence by laser induced surface defects	91
4.3.1	Experimental procedure	92
4.3.2	Data analysis	93
4.3.3	Summary and outlook	98
4.4	Permanent tuning of quantum dot transitions to degenerate microcavity resonances	99
4.4.1	Experimental procedure	99
4.4.2	Summary	106
4.5	Theoretical model	107
4.5.1	Effect on cavity modes	108
4.5.2	Effect on QD optical transitions	110
4.6	Conclusion and discussion	115
5	Active Positioning of Single QDs in Microcavities	117
5.1	Optical positioning of single QDs	118
5.1.1	Physical limits of the scanning method	119
5.1.2	QD positioning in planar cavities	120
5.2	Strong coupling through optical positioning of a QD in a photonic crystal cavity	121
5.2.1	Sample design	121

5.2.2	Scanning technique	121
5.2.3	Photonic crystal fabrication	123
5.2.4	Demonstration of strong coupling	125
5.3	Waveguide-coupled photonic crystal-QD cavities	127
5.3.1	Sample design and fabrication	127
5.3.2	Measurements and results	130
5.4	Conclusion and discussion	134
6	Spin Quantum Jumps	135
6.1	Open quantum systems	136
6.1.1	Density operator	137
6.1.2	Liouville operator	138
6.1.3	Master equation	139
6.2	Separation of time scales	140
6.3	Spin quantum jumps in a singly charged quantum dot	143
6.3.1	The four-level system	145
6.3.2	Separation of time scales	148
6.3.3	Jump rate due to coherent spin coupling	151
6.3.4	Experimental possibilities	157
6.4	Conclusion	158
6.5	Further extension of the model	159
7	Schemes in the Weak-Coupling Cavity QED Regime	161
7.1	Introduction	161
7.2	Optical selection rules	162
7.3	CNOT gate	164
7.4	Bell-state analyzer	166
7.5	Experimental feasibility	168
7.6	Conclusion	169
8	Reflection Spectroscopy of a Quantum Dot in a Microcavity	171
8.1	Introduction	171
8.2	Experimental procedure	172
8.3	Experimental results	173
8.4	Conclusion and discussion	178
	Appendices	181
A	Experimental setup	183

B Fabrication of micropillars	189
B.1 Process structure for different sample types	189
B.2 Step details	190
C Glossary of Terms	195
Bibliography	197
Summary	215
Nederlandse samenvatting	219
Curriculum Vitae	223
List of Publications	225
Acknowledgements	227