



Universiteit  
Leiden  
The Netherlands

## Optical cavities and quantum emitters

Koks, C.

### Citation

Koks, C. (2024, January 25). *Optical cavities and quantum emitters. Casimir PhD Series*. Retrieved from <https://hdl.handle.net/1887/3715075>

Version: Publisher's Version

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

License: <https://hdl.handle.net/1887/3715075>

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

## **OPTICAL CAVITIES AND QUANTUM EMITTERS**



# **OPTICAL CAVITIES AND QUANTUM EMITTERS**

## **Proefschrift**

ter verkrijging van  
de graad van doctor aan de Universiteit Leiden,  
op gezag van rector magnificus prof. dr. ir. H. Bijl,  
volgens besluit van het college voor promoties  
te verdedigen op donderdag 25 januari 2024  
klokke 10.00 uur

door

**Corné Koks**

geboren te Oosterhout  
in 1996

Promotores: Prof. dr. M. P. van Exter  
Prof. dr. M. A. G. J. Orrit

Promotiecommissie: Dr. S. R. K. Rodríguez AMOLF  
Dr. M. Wubs Technical University of Denmark  
Prof. dr E. R. Eliel  
Prof. dr. D. J. Kraft  
Prof. dr. ir. S. J. van der Molen

Copyright © 2023 by C. Koks

Casimir PhD Series, Delft-Leiden 2023-41

ISBN 978-90-8593-586-5

An electronic version of this dissertation is available at  
[https://scholarlypublications.universiteitleiden.nl/.](https://scholarlypublications.universiteitleiden.nl/)

*Tomorrow, we will do beautiful things.*

-A. Gaudí



# CONTENTS

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Quantum communication and quantum measurements . . . . .	1
1.2	Quantum emitters in an optical resonator . . . . .	1
1.3	Open microcavities . . . . .	3
1.4	Single-photon emitters . . . . .	3
1.5	Outline of this thesis . . . . .	4
<b>2</b>	<b>Microcavity resonance condition, quality factor, and mode volume are determined by different penetration depths</b>	<b>7</b>
2.1	Introduction . . . . .	7
2.2	Optical penetration in DBRs . . . . .	8
2.3	Methods . . . . .	12
2.4	Results . . . . .	13
2.5	Discussion . . . . .	17
2.A	Coupled-mode theory and shift of (anti-)nodes . . . . .	18
2.B	Effect of incident medium on frequency penetration depth $L_\tau$ . . . . .	19
2.C	Ratio $L_\tau$ and $L_D$ . . . . .	20
<b>3</b>	<b>Observation of mode-mixing in the spatial eigenmodes of an optical microcavity</b>	<b>23</b>
3.1	Introduction . . . . .	23
3.2	Results . . . . .	24
3.3	Conclusion . . . . .	29
3.A	Roundtrip operator $M$ . . . . .	29
3.B	Dynamic operator $K$ and coupled modes . . . . .	32
3.C	Complex fitting mode mixing ratio . . . . .	33
3.D	AFM data yield mirror profile and coupling parameter . . . . .	34
3.E	Repeated measurements on other microcavities . . . . .	37
<b>4</b>	<b>Fine structure in Fabry-Perot microcavity spectra</b>	<b>41</b>
4.1	Introduction . . . . .	41
4.2	Paraxial scalar modes . . . . .	43
4.3	Roundtrip operator and perturbation theory . . . . .	44
4.4	Nonparaxial scalar corrections . . . . .	50
4.5	Vector correction & L-S coupling . . . . .	54
4.6	Bragg (vector) correction $\mathcal{H}_{\text{Bragg}}$ . . . . .	57
4.7	Mirror-astigmatic corrections. . . . .	59
4.8	Discussion & residual $\mathcal{H}_{\text{rest}}$ . . . . .	62
4.9	Summary & outlook. . . . .	63
4.A	Comparison with Zeppenfeld-Pinkse . . . . .	65
4.B	Bragg correction in detail . . . . .	66

4.C Operator algebra . . . . .	67
4.D Hyperfine splittings . . . . .	71
<b>5 Observation of microcavity fine structure</b>	<b>73</b>
5.1 Introduction . . . . .	73
5.2 Labeling of cavity eigenmodes . . . . .	75
5.3 Comparison with theoretical predictions . . . . .	77
5.4 Astigmatic correction . . . . .	78
5.5 Conclusion . . . . .	78
5.A Coupling matrix for astigmatic and aspheric corrections . . . . .	80
5.B Hyperfine splitting . . . . .	81
<b>6 Probing microcavity resonance spectra with intracavity emitters</b>	<b>85</b>
6.1 Introduction . . . . .	85
6.2 Setup . . . . .	86
6.3 Joined length-wavelength scan . . . . .	87
6.4 Penetration depths . . . . .	88
6.5 Transverse mode group structure . . . . .	90
6.6 Mode coupling . . . . .	91
6.7 Conclusions. . . . .	92
6.8 Acknowledgments . . . . .	93
6.A Third-order frequency dispersion of DBRs . . . . .	93
<b>7 Exploring polarization orientation and power-dependent dynamics of single-photon emitters in hexagonal Boron Nitride</b>	<b>97</b>
7.1 Introduction . . . . .	97
7.2 Experimental setup . . . . .	98
7.3 Confocal scan of the emitters . . . . .	100
7.4 Dipole orientation . . . . .	100
7.5 Blinking at two time scales . . . . .	102
7.6 Four-level system . . . . .	104
7.7 Conclusion . . . . .	105
7.8 Acknowledgments . . . . .	107
7.A Rate equations . . . . .	107
7.B Transition rates of emitter A . . . . .	109
7.C Measurements on emitter C . . . . .	111
<b>References</b>	<b>113</b>
<b>Summary</b>	<b>123</b>
<b>Samenvatting</b>	<b>127</b>
<b>Acknowledgements</b>	<b>131</b>
<b>Curriculum Vitæ</b>	<b>133</b>
<b>List of Publications</b>	<b>135</b>