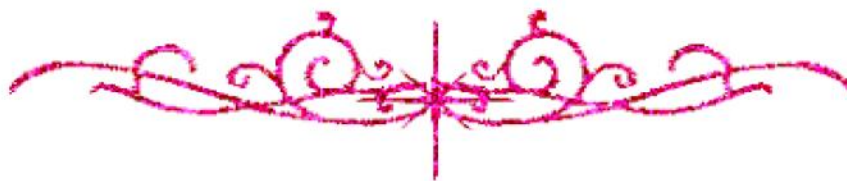


بسم الله الرحمن الرحيم





شبكة المعلومات الجامعية التوثيق الالكتروني والميكرو فيلم



جامعة عين شمس

التوثيق الإلكتروني والميكروفيلم

قسم

نقسم بالله العظيم أن المادة التي تم توثيقها وتسجيلها
علي هذه الأقراص المدمجة قد أعدت دون أية تغيرات



يجب أن

تحفظ هذه الأقراص المدمجة بعيدا عن الغبار





بعض الوثائق الأصلية تالفة





بالرسالة صفحات
لم ترد بالأصل





AIN SHAMS UNIVERSITY

FACULTY OF ENGINEERING

Engineering Physics and Mathematics Department

Micro-Cavity Optical Sensors

A Thesis submitted in partial fulfilment of the requirements of the degree
of

Doctor of Philosophy in Engineering Physics

by

Mohamed Nabil Ali Mohamed

Master of Science in Engineering Physics

Faculty of Engineering, Ain Shams University

Supervised By

Prof. Daaa Abdel Maguid Khalil

Prof. Khaled Abdel Wahhab Kirah

Dr. Yasser Mohamed Sabry

Cairo - 2020



AIN SHAMS UNIVERSITY
FACULTY OF ENGINEERING
Engineering Physics and Mathematics Department

Micro-Cavity Optical Sensors

by
Mohamed Nabil Ali Mohamed
Master of Science in Engineering Physics
Faculty of Engineering, Ain Shams University, 2013

Examiners' Committee

Name and Affiliation	Signature
Prof. Dr. Kamel Mohamed Mahmoud Hassan Electronics and Communications , Future University
Prof. Dr. Adel Helmy Philips Physics and Mathematics , Ain Shams University
Prof. Dr. Diao Abdel Maguid Khalil Electronics and Communications , Ain Shams University
Prof. Dr. Khaled Abdel Wahhab kirah Physics and Mathematics , Ain Shams University

Date: 18 May 2020

Statement

This thesis is submitted as a partial fulfilment of Doctor of Philosophy in Engineering Physics, Faculty of Engineering, Ain-Shams University.

The author carried out the work included in this thesis, and no part of it has been submitted for a degree or a qualification at any other scientific entity.

Mohamed Nabil Ali Mohamed

Signature

.....

Date: 18 May 2020

Researcher Data

Name : Mohamed Nabil Ali Mohamed

Date of birth : 12/9/1984

Place of birth : Cairo

Last academic degree : Master of Science

Field of specialization : Engineering Physics

University issued the degree : Ain Shams University

Date of issued degree : 2013

Current job : Teaching Assistant

Thesis Summary

Optical micro-cavities-based sensors are the subject of intensive researches and are expected to revolutionize the sensor market especially in biological and chemical applications. In this context, a proposed form of coupled cavities is presented to enhance the performance of cavity-based sensors in terms of the range of detection and accuracy. Other applications can also use the same concept to enhance the performance like in dye lasers. The basic drawback of these micro-cavities is that they are less tolerable to technological artifacts. A good control of fabrication processes is required for proper operation. The fabrication tolerance is analyzed and experimentally characterized. The proposed coupled cavity was modelled, designed, fabricated on Si wafer based on MEMS compatible technology. Characterization of these cavities reveal a widened free spectral range and high quality factor compared to conventional single cavities. In order to further understand the behaviour of micro-cavities, a model based on Fourier optics was built to take into account some effects that were not included in previous models like the small size of the mirrors, verticality, roughness, and mirror shaping. The results of this model explain some of the mismatch between the expected and measured performance. Slotted micro-mirrors are expected to solve some problems found in conventional Bragg mirrors and metallic ones. Therefore, a new model for the slotted micro-mirror was presented to include the effect of mirror small thickness and the expected multiple reflections inside it. The model results are compared to FDTD simulations and good matching was observed.

Key words: Optical sensors, Optical cavities, Coupled cavities, Fabry-Perot cavities, Slotted mirrors

Acknowledgment

I would like to express my deepest gratitude to my supervisors Prof. Dr. Diaa Abdel Maguid Khalil, Prof. Dr. Khaled Abdel Wahhab Kirah and Dr. Yasser Mohamed Sabry for their continuous support and valuable guidance. Without their help to the point suggestion and continuous follow-up, this work would have never been completed and presented in its current form. I will always be indebted for their encouragement and support.

Thanks to ESIEE France, Prof. Dr. Tarik Borouina for the support in samples fabrication.

Last but not least, I would like to thank my family for their kind understanding and encouragement during the time I devoted to this thesis. Without the comfortable atmosphere they provided this work would have never seen the light.

Mohamed Nabil

Nov., 2019

Table of Contents

Cover page	1
Examiners Committee	2
Statement.....	3
Researcher Data	4
Thesis Summary	5
Acknowledgment	6
Table of Contents	7
List of Figures	10
List of Tables	14
List of Abbreviations.....	15
List of Symbols	17
Chapter 1: Introduction	19
Chapter 2: Background and Introduction to Coupled Cavities.....	24
2.1. Cavity-based optical sensors.....	24
2.1.1. In-Plane Fabry–Perot-Based Accelerometer	24
2.1.2. Gas sensing using deformable Fabry–Perot interferometers	25
2.1.3. Fabry–Perot cavity for volume refractive index measurement	25
2.1.4. Volume refractometry of liquids using stable Fabry–Perot resonator	26
2.2. Review on Some Optical Theories.....	27
2.2.1. Multilayer theory	27
2.2.2. Gaussian beam and linear systems	30
2.3. Introduction to Coupled Cavities	34
2.4. Appendix.....	38
Chapter 3: Analysis and Modeling of Technological Tolerances.....	41
3.1. Introduction.....	41
3.2. Modelling and Design.....	42
3.3. Device Fabrication.....	46
3.4. Experimental Results and Analysis.....	47
Chapter 4: In-Plane Coupled-Cavity Design, Fabrication and Characterization	50
4.1. Introduction.....	50
4.2. Design approach	51
4.3. Device modelling	55

4.3.1. Gaussian beam excitation and curved mirrors	55
4.3.2. Fabrication tolerances	57
4.4. Device fabrication	59
4.5. Measurements and discussions	60
Chapter 5: Fourier Optics Modeling of Micro-Cavities	66
5.1. Model Description	66
5.1.1. Free space propagation	66
5.1.2. Reflection, transmission and mirror shape	67
5.1.3. Surface roughness	68
5.1.4. Verticality	69
5.2. Convergence methods and convergence criteria	70
5.2.1. Standard convergence	70
5.2.2. Accelerated convergence	72
5.3. Modelling Fiber Rod Lens	73
5.4. Finding the cavity resonance	74
5.5. Expanding the model to coupled cavities	75
5.6. Results and Discussion	77
5.6.1. Accelerated versus standard convergence	77
5.6.2. Model testing	78
5.6.3. Mirror shape effects	82
5.6.4. Mirror size effect	84
5.6.5. Verticality and surface roughness effects	89
5.6.6. Fiber Rod lens effect	91
5.6.7. Coupled cavity results	92
Chapter 6: Analysis of Metallic Slotted Micro-Mirrors	94
6.1. Introduction	94
6.2. Reflection and transmission from a single interface	95
6.3. The second interface and multiple reflections	103
6.4. FDTD Simulation	105
6.5. Results and discussion	106
References	113
Conclusion and Future Work	117
شكر	119
الملخص	120

تعريف بمقدم الرسالة.....	121
رسالة دكتورة.....	122
الموافقة على المنح.....	123
صفحة العنوان.....	124

List of Figures

Fig. 2-1: In-Plane Fabry–Perot cavity based accelerometer [32].	24
Fig. 2-2: Gas sensing using deformable Fabry–Perot interferometers [33].	25
Fig. 2-3: Fabry–Perot cavity for volume refractive index measurement in microfluidic systems[34].	26
Fig. 2-4: Volume refractometry of liquids using stable Fabry–Perot resonator[35].	27
Fig. 2-5: A simple thin film arrangement [36].	28
Fig. 2-6: Treatment of linear optical system by superposition	33
Fig. 2-7: Schematic of a coupled cavity composed of three parallel mirrors.	34
Fig. 2-8: Mode splitting in a coupled cavity and its dependence on the second mirror reflectivity	37
Fig. 2-9: The transmittance at resonance versus the middle mirror reflectivity of a coupled cavity.	37
Fig. 2-10: Transmittance of single and coupled cavities showing the larger FSR of the coupled cavity.	38
Fig. 2-11: Transmittance of a coupled cavity at different refractive indices of the filling medium showing the linear relation of the resonance with the refractive index.	38
Fig. 2-12: Schematic of symmetric lossless multilayer structure.	39
Fig. 3-1: Typical MEMS tuneable filter using Bragg mirrors.	42
Fig. 3-2: Designed micromirrors with single and double layers. The fiber is to be inserted from the lower grooves to measure the reflectance. The 45° plane mirror reflects the transmitted light to outside the MEMS die.	43
Fig. 3-3: Illustration of the internal and external over-etching.	44
Fig. 3-4: The simulated reflectance of the double layer mirror without including the side-effects of technology.	45
Fig. 3-5: The effect of over-etching on the centre-wavelength of the different bands of the mirror with double Si layers.	45
Fig. 3-6: The effect of over-etching on the 3-dB bandwidth of the different bands of the double Si layer mirror.	45
Fig. 3-7: The effect of over-etching on the maximum reflectivity of the different bands of the double Si layer mirror.	45
Fig. 3-8: The effect of surface roughness RMS of double Si layer mirror on: (a) centre-wavelength, (b) maximum reflectivity.	46
Fig. 3-9: Fabrication steps of the micro-mirror structures	47
Fig. 3-10: Experimental setup.	48
Fig. 3-11: Measured and theoretical reflectance with and without including the side-effects of technology for the single layer mirror.	49
Fig. 3-12: Measured and theoretical reflectance with and without including the side-effects of technology for the double layer mirror.	49