Electromagnetic Analysis of Polarization and Frequency Selective Tunable Optical MEMS

Ugur Akcakoca, René Marklein, and Bernd Witzigmann
Computational Electronics and Photonics Group
University of Kassel
Wilhelmshöher Allee 71, D-34121 Kassel, Germany
Email: bernd.witzigmann@uni-kassel.de

Hartmut Hillmer
Institute of Nanostructure Technologies and Analytics
University of Kassel
Heinrich-Plett-Str. 40, D-34132 Kassel, Germany
Email: hillmer@ina.uni-kassel.de

Abstract—**In this work, we present the computation of different integrated optical micro-electro-mechanical systems by applying the finite element method to the electromagnetic vectorial Helmholtz equation. The finite element solver combines state-of-the-art features with sophisticated symmetry handling and the perfectly matched layer approach to simulate open boundaries. The focus of investigation is on a photonic crystal slab for the purpose of a polarization selective filter in an integrated optical sensor system. The transmission characteristics of the filter is modeled with a finite element solver and the results are compared to analytic computations, published results, and the transfer matrix method for selected designs. A final design is found for maximum polarization selectivity at a given operation wavelength.**

I. INTRODUCTION

Micro-electro-mechanical systems (MEMSs) based on InP Fabry-Pérot (FP) filters are compact and tunable narrow-band integrated optical devices. They are currently available in the wavelength range from 1 μm to the far infrared and can improve the efficiency of optical detection systems in the field of integrated sensors for spectroscopic or communications applications. Such a filter consists of a top and bottom distributed Bragg reflector (DBR) which terminate a FP cavity and act as an integrated optical system. By micro-mechanically tuning the distance of the inner DBR layers, the resonance can be tuned with high accuracy. One or more layers of the filter are laterally structured with a photonic crystal (PC) [1] pattern. Figure 1 shows a realization of such a MEMS filter structure.

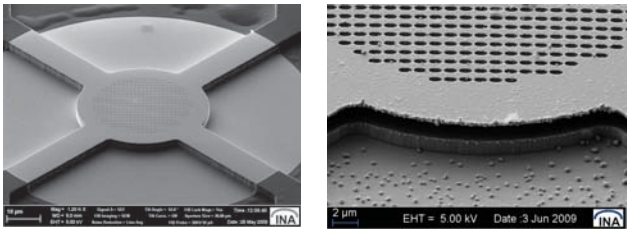

Fig. 1. Micrographs of a MEMS filter structure [2]

This kind of PC structure supports guided modes as well as guided resonances [3]–[5]. Using elliptical holes in the pattern, a polarization anisotropy is introduced, which adds to the functionality of the entire filter. In the present paper this optical functionality is incorporated into the system.

In the following, we investigate the design of the polarization sensitive element by means of rigorous electromagnetic modeling.

II. FINITE ELEMENT SOLVER: LUMI3

The 3-D finite element (FE) solver is called Lumi3 [6], it combines state-of-the-art features with sophisticated symmetry handling and the perfectly matched layer (PML) approach to simulate open boundaries. The inhomogeneous Helmholtz equation is solved numerically by applying the FE method [7]. Different designs starting from a single dielectric slab (DIS) to a combined filter structure consisting of a membrane with PC structure and FP resonator are modeled with the FE solver.

III. SIMULATION RESULTS

In the following selected FE modeling results of different MEMS structures are presented.

A. Photonic Crystal Slab (PCS) with Circular and Elliptical Holes

In the first example we start with a DIS with a refractive index of $n = \sqrt{12}$ and a thickness of $d = 0.5a$, with a square unit cell PC and a periodicity of $a = 1$ μm. For a comparison of our results we selected the same parameters as in [3]. The circular holes in the PC have a radius of $A = B = 0.1a$ (see Fig. 2).

The black line (see Fig. 3) shows five distinct resonances, which can be identified as guided resonances [3]. This result has been validated against Fig. 12b of [3], with excellent agreement. The dimensions of the elliptical holes are $A = 2B = 0.2a$. Fig. 3 shows the transmittivity spectrum of the circular structure (black), and the respective characteristics for the electric field vector in x polarization (blue) and y polarization (red). Both the FP peaks and the guided resonances are blue-shifted for the structure with elliptical holes compared to the circular ones. This can be understood qualitatively by the reduced effective index of the PCS.

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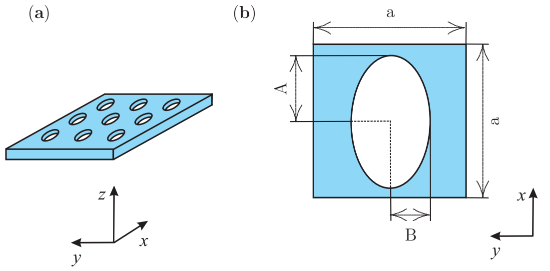

Fig. 2. Geometry of the periodic PC (a) and a single elliptical hole (b)

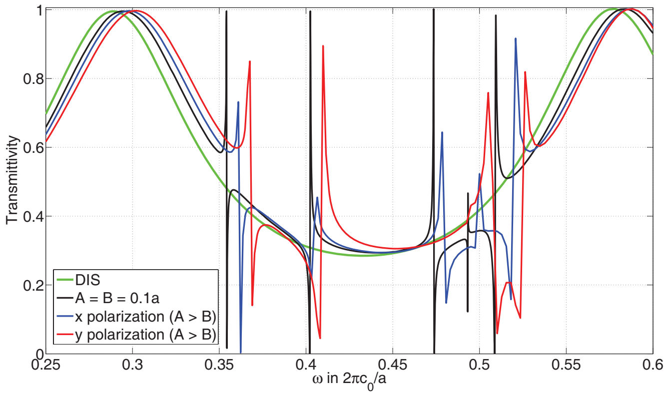

Fig. 3. Transmittivity spectrum of a PCS with circular holes (black curve), DIS (green curve) and elliptical holes embedded in free space; blue curve: electric field polarization parallel to x axis (major axis of ellipse); red curve: electric field polarization parallel to y axis (minor axis of ellipse); slab parameter: refractive index $n = \sqrt{12}$, thickness $d = 0.5a$

B. PCS of Indium Phosphide (InP) with Elliptical Holes: Optimization for Polarization Sensitivity

The PCS thickness has a strong influence on the spectral position and density of the guided resonances. Decrease of the slab thickness reduces the density of guided resonances. For good polarization selectivity designs, the density should be high in order to create broad frequency bands of high and low transmittivity. The hole size on the other hand is mainly responsible for the width of the guided resonance, and also the exact position. These are spectrally broadened in large hole sizes compared to smaller hole sizes. The goal for this example is now to find a polarization selectivity at the normalized frequency of 0.77, which corresponds to the target wavelength of $\lambda = 1550$ nm for the integrated filter. In the following, the thickness of the PCS is reduced to $d = 0.306a$, the elliptical hole size dimensions $A = 0.463a$ and $B = 0.265a$ where $a = 1.2$ μm. For the refractive index, we choose $n = 3.194$, which represents the material InP. The result of the transmittivity spectrum is shown in Fig. 4.

A good polarization selectivity is obtained around the wavelength $\lambda = 1550$ nm ($\omega_{\text{norm}} = 0.77$). As well we archive a very good polarization sensitivity in the normalized frequency interval 0.8 to 0.85. At $\omega \approx 0.82 \times 2\pi c_0/a$ an incident x polarized plane wave is attenuated to relative amplitude of below 10 % and an incident y polarized plane wave is almost completely transmitted through the PC structure. Future work will focus on the integration of PCS into the full structure consisting of the DBR and the FP cavity, and studying the tuning capabilities of the integrated MEMS filter.

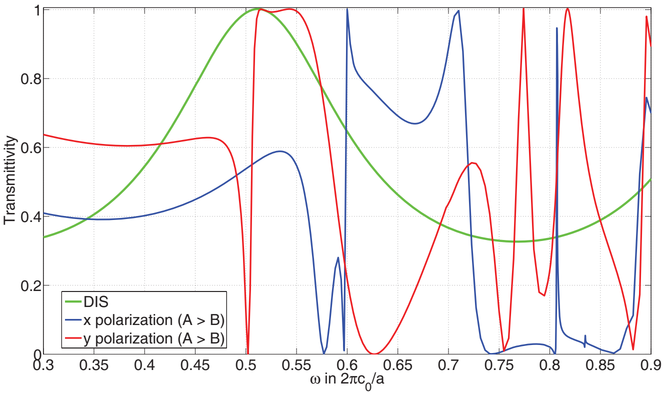

Fig. 4. Transmittivity spectrum of a PCS of InP with elliptical holes and solid slab (green curve) embedded in free space; blue curve: electric field polarization parallel to x axis (major axis of ellipse); red curve: electric field polarization parallel to y axis (minor axis of ellipse); InP membrane parameter: refractive index $n = \sqrt{10.2}$, thickness of $d = 0.306a$.

IV. CONCLUSION

In this paper we discuss the modeling of the polarization and frequency selective filter properties of an optical MEMS. The focus is on the polarization selective PCS. Rigorous electromagnetic analysis by the 3-D finite element tool Lumi3 is used, and design parameters such as slab thickness, hole shape and size are investigated. As result, a design is shown that fulfills the requirements in terms of fabrication technology and optical specifications.

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