A Tunable MOEMS Open Microring Resonator for the Detection of Water Concentration in Ethanol Solutions

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***Abstract*—In this work, we present a micro-opto-electro-mechanical system (MOEMS) designed as a tunable microring resonator with a novel open-ring configuration. The device incorporates a low-voltage rotary electrostatic actuator to mechanically tune the overlapping region of the open ring, thereby adjusting the resonant frequency and eliminating the need for costly tunable laser sources. The behaviour and performance of the structure are assessed by employing it as an ethanol purity sensor through electromechanical and optical simulations. Results demonstrate the overall feasibility of the device, highlighting its mechanical stability and its ability to detect ethanol concentration changes via shifts in the resonant frequency.**

***Index Terms*—optical ring resonators, Micro-electro-mechanical systems, ethanol purity, microsensors**

INTRODUCTION

Ethanol has a central role in a wide range of industrial applications, including chemical synthesis, pharmaceuticals, food preservation, and sustainable fuel production [1], [2]. However, despite the improvement of the process, water is frequently present in the final stages of production and must be subject to regular monitoring to ensure the maintenance of the required ethanol/water ratio [3]. The necessity of ensuring the purity of ethanol has led to the development of cost-effective, efficient, simple, and reliable methods to quantify the water content in ethanol [4]–[7]. The most common approach to measure the resonance shift is to use a tunable laser source or a broad-band optical source as input, and a spectrometer as output [8]. Despite their efficacy, the use of these methods gives rise to a number of issues, including increased complexity, cost, and portability.

In this work, a novel micro opto-electromechanical system (MOEMS) structure is studied for the determination of the water content of ethanol solutions. The microring's resonant frequency can be shifted to change the input wavelength through a small voltage, enabling single-laser scanning and avoiding expensive input sources.

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I. WORKING PRINCIPLE

The proposed device, schematically illustrated in Fig. 1, consists of a mechanically tunable ring resonator deliberately designed with an open-loop configuration. This includes a dedicated coupling region between its two ends, where a tailored overlap section facilitates controlled optical coupling. The ring is mechanically linked to a rotary comb-drive actuator which, upon voltage application, generates a controlled in-plane rotational displacement. This mechanical actuation modifies the optical path length, thereby shifting the resonant frequency. When the microring is exposed to a fluid mixture, the refractive index of the surrounding medium changes depending on the composition, resulting in a shift in the resonance condition. Instead of sweeping the input wavelength, the device operates with a fixed-wavelength laser: the applied voltage is varied to shift the microring's resonance until it aligns with the laser. When resonance occurs, a transmission peak is observed, and the corresponding voltage provides a direct indication of the ethanol-water concentration.

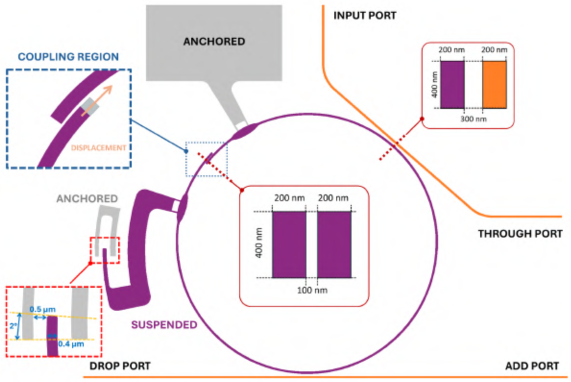

Fig. 1. Schematic representation of the MOEMS-based microring resonator sensor.

II. Results

The device was analyzed using Ansys Lumerical FDTD simulations with a 1550–1555 nm light source to observe resonance shifts. Mechanical and electrostatic analyses were performed in COMSOL Multiphysics to evaluate the device's deformation under voltages ranging from 0 to 0.5 V. The refractive index increases with the water content, ranging from 1.361876 at 1.09 mol% to 1.362936 at 9.05 mol% [9]. Fig. 2a presents the transmission spectra of the microring resonator for different ethanol-water mixtures used as cladding. As the water concentration increases, a red-shift of the resonance wavelength is observed. The shift is approximately 4 pm for the lowest concentrations, up to approximately 170 pm for the highest concentrations with a quadratic trend, as shown in Fig. 2b. A voltage ranging from 0 to 0.5 V, in steps of 0.1 V, was applied to the MEMS actuator to induce a controlled mechanical deformation of the resonator. Fig. 2c illustrates the simulated transmission spectra of the microring resonator at different applied voltages, showing a clear and progressive blue-shift of the resonance peak; as shown in Fig. 2d, the resonance shifts from 8.2 pm at 0.1 V up to 204 pm at 0.5 V. The data presents a quadratic dependence in agreement with the expected behaviour of an electrostatically actuated MEMS structure, where displacement scales with the square of the applied voltage.

III. Conclusions

In this work, we have presented and analyzed a MOEMS-based microring resonator designed for sensing the concentration of water in ethanol-water solutions. The key operating principle relies on the shift of the resonance wavelength caused by changes in the cladding refractive index and by mechanical deformation of the resonator induced through electrostatic actuation. We demonstrated that by applying a variable voltage, it is possible to effectively control the resonance condition, enabling a voltage-based interrogation scheme at a single fixed laser wavelength. This approach eliminates the need for an expensive tunable laser source, as only a simple fixed-wavelength laser is required.

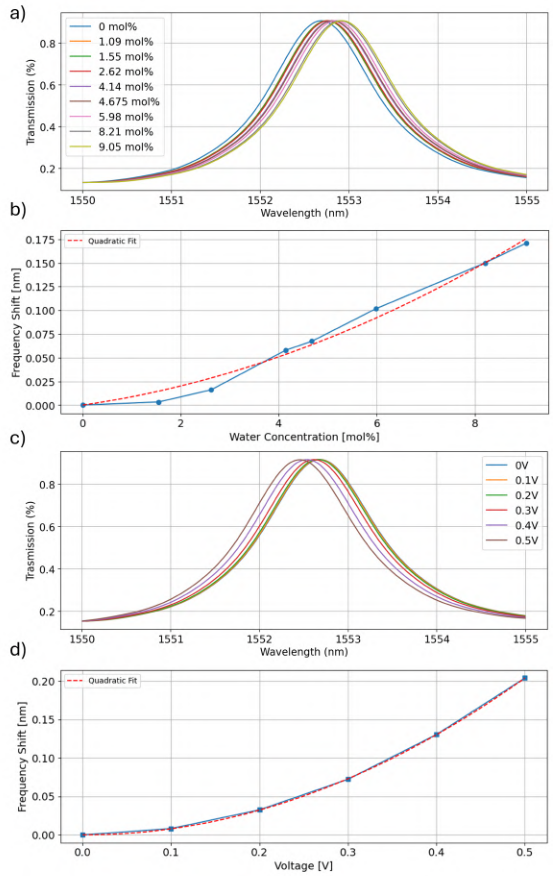

Fig. 2. (a) Simulated transmission spectra of the microring resonator for increasing water concentrations in ethanol. (b) Quadratic fit of resonance frequency shift as a water concentration. (c) Transmission spectra at different applied voltages. (d) Quadratic fit of resonance frequency shift as a function of applied voltage.

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