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Numerical analysis of a microelectromechanical system-based color filtering device with surface plasmon resonance modulation☆

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A B S T R A C T

In this study, a microelectromechanical system (MEMS)-based color filtering device comprising a silicon-on-insulator MEMS, an elastomer, and an array of metallic nanostructures with adjustable surface plasmon resonance (SPR) modulation was proposed. The MEMS stretched the elastomer suspended above it, which modified the arrangement of the metallic nanostructures on the elastomer. Consequently, the SPR could be tuned under various MEMS operating conditions using a single fundamental design. An optimized hybrid MEMS-elastomer configuration was obtained with a maximum strain of 35.91% through evaluations done with three parameters in the MEMS and three parameters in the elastomer. The SPR modulation was demonstrated using an example involving color filtering and switching among the three primary colors in the visible range. In addition to design optimization, the asymmetrical strain distribution in the elastomer and its influence on SPR modulation were studied through comprehensive simulations and analyses.

1. Introduction

Color filtering is an important operation in many applications. Display devices such as liquid crystal displays, light emitting diodes (LEDs), and quantum dot panels have already introduced filters to enhance the color appearance and its saturation. These devices realize color filtering by using specific dyes or nanostructure arrangements, which exhibit drawback on operation flexibility or application variation in terms of color switching. One subpixel of these devices constantly displays a specific color unless unexpected characteristic such as material degradation appeared. However, many potential applications other than displays may exist that require adjustable color filtering in limited space. For example, wireless endoscopy may present enhanced sensitivity and responsivity in various medical diagnoses when the images were taken with selected wavelengths. Because currently light source in the capsule endoscopy is composed of few LEDs that only produce white spectra, a wavelength-variable light source would be expected to support the aforementioned operation variety. To realize it in an existing endoscope, a microelectromechanical system (MEMS) that modulates optical filtering effects located above the white LED would suffice the requirement.

Among MEMS-based color filtering devices, the interferometric modulation (iMOD) [1], grating light valve (GLV) [2], digital microshutter (DMS) [3], and Fabry-Pérot interferometer (FPI) [4] have been reported for display applications. Generally speaking, iMOD and GLV show large apertures, but they do not provide transmissive operations; DMS operates under transmissive mode, but its aperture is substantially limited by the suspended MEMS structure. Even though compact FPI operates under transmissive mode with a large aperture, its two multilayer distributed Bragg reflectors require additional fabrication processes using various materials. On the other hand, iMOD, GLV, and DMS contain simple structures with limited and low-cost materials (generally silicon and silicon dioxide only). Furthermore, although FPI could support the application in endoscopes, it could be cost-inefficient. Thus, as a stand-alone MEMS-based device with a simple structure that can provide a suitable transmissive aperture and be fabricated using inexpensive materials has not been proposed, we were motivated to design and numerically evaluate a MEMS-based color filtering device that modulates visible light through surface plasmon resonance (SPR) in this study. The proposed device is based on a silicon-on-insulator (SOI) structure with integrated SPR nanostructures on an elastomer that is suspended above the MEMS. When the MEMS is driven by various applied voltages, the elastomer is strained and the arrangement of the SPR nanostructures is modified. Consequently, transmissive white light is filtered into various spectra, and color switching occurs.

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2. System design and analysis

2.1. Structure

To attain the aforementioned characteristics, a hybrid MEMS-elastomer configuration was designed. As indicated in Fig. 1, the elastomer with SPR nanostructures was suspended from one end of the four supporting beams of the MEMS, and the supporting beams were suspended from bulk silicon (Si). The supporting beams were held by springs located on both sides, and the other ends of the supporting beams comprised one movable and one fixed comb with many fingers. Because the springs were fixed by anchors, the supporting beams were held at neutral positions when electrostatic forces were not introduced. The spring width, beam length, beam width, finger length, finger width, and finger space of the MEMS throughout this work was 3, 870, 100, 50, 3, and 3 μm unless modified.

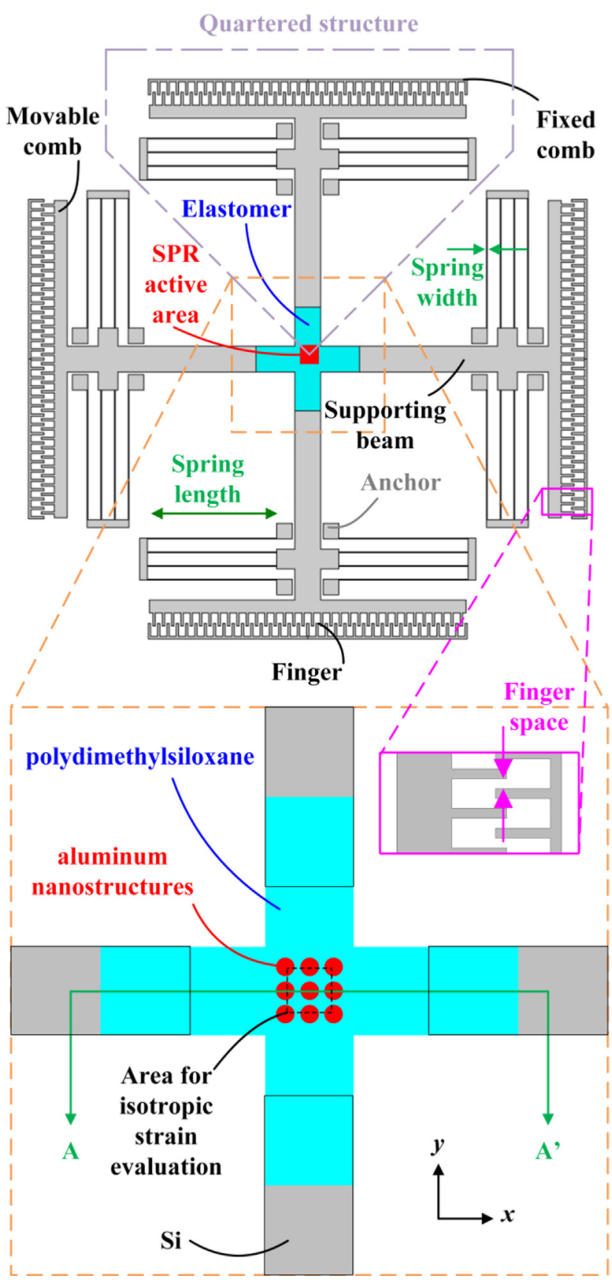

Fig. 1. Schematic plot of the MEMS, elastomer, and SPR nanostructures. All structures were arranged symmetrically in the x and y directions. The MEMS, elastomer, and SPR nanostructures were designed with Si, polydimethylsiloxane, and aluminum, respectively (plots are not to scale).

When sufficient charges accumulated on the fingers of the paired combs, the electrostatic force increased and the supporting beams were pulled outward. The four supporting beams moved identically and simultaneously when their corresponding combs were electrically connected, and they returned to their original neutral positions when the electrostatic force was removed. Because the four supporting beams were symmetrically and simultaneously operated, an isotropic expansion of the elastomer occurred in the *xy* plane when the size of the active area was optimized. In this study, the elastomer and SPR nanostructures were made of polydimethylsiloxane (PDMS) and aluminum (Al), respectively; and the MEMS was based on an SOI structure. The hybrid MEMS-elastomer configuration and SPR nanostructures were expected to be supported by previously demonstrated soft-lithography lift-off and grafting [5,6] (SLLOG) and strain lithography [7], respectively. This study proposed and tested a technique for SPR modulation in a hybrid MEMS-elastomer configuration, and numerically demonstrated the color filtering properties.

2.2. Operation

The arrangement of the metallic patterns on elastomers is isotropically modified irrespective of their position, shape, size, and density when the elastomer is isotropically expanded [7]. As a result, SPR nanostructures located in the active area of the hybrid MEMS-elastomer configuration could be modified to render SPR modulation possible (Fig. 2). This study tested the proposed technique to achieve transmissive color filtering in the visible range. Therefore, the SPR modulation was evaluated for distinguishable spectral changes (e.g., among the three primary colors) under corresponding operating conditions. Moreover, the SPR nanostructures that supported the three primary colors required a noticeable dimensional difference. As a result, generating large strains by proper MEMS and elastomer designs without physically enlarging the device was the objective of the following evaluations.

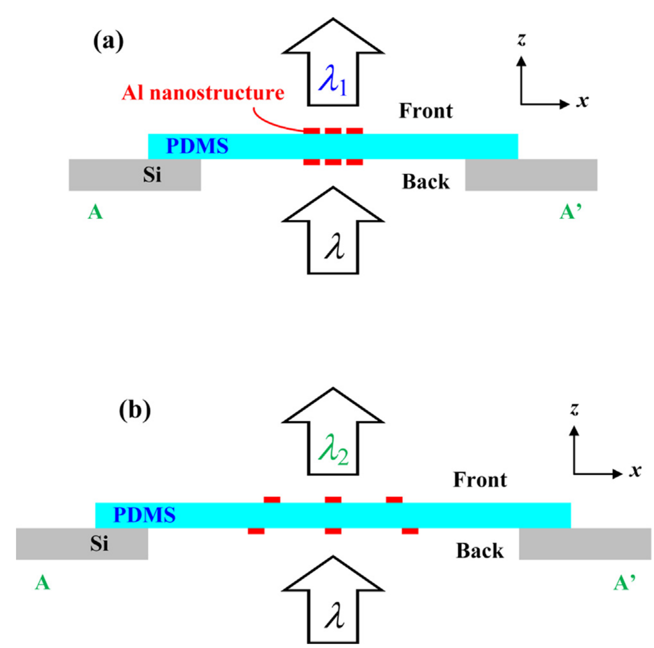

Fig. 2. Schematic plot of SPR (a) without and (b) with strain generated in the MEMS. An incident light beam (λ) was modulated through SPR into different colors (λ_1 and λ_2) under different MEMS operating conditions. The SPR nanostructures at the front and back were not strained identically (plots are not to scale).