

# Two-state Optical Filter Based on Micromechanical Diffractive Elements

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**Abstract**—We have designed a robust two-state filter for infrared gas measurement, where the filter transmittance alternates between a single bandpass function, and a double-band offset reference. The device consists of fixed and movable diffractive sub-elements, micromachined in the device layer of a bonded silicon on insulator (BSOI) wafer. Switching between the two states of the filter is obtained by actuation of the movable sub-elements between idle and pull-in positions, which affects the interference of reflected light. The characteristics of the filter are defined by a diffractive microrelief pattern etched on top of the sub-elements and by the position of the movable sub-elements at pull-in, the latter mechanically defined by the buried oxide layer. Thus, no accurate electrical control is needed to operate the filter. The first test components operate at  $2\mu\text{m}$  wavelength using a displacement of  $500\text{ nm}$  and an actuation voltage of  $5\text{ V}$ . No sticking or change in filter characteristics have been observed after repeated pull-in operations. The simplicity of fabrication and operation is likely to make the two-state filter an attractive component for sensors such as non-dispersive infrared gas detectors.

## I. INTRODUCTION

Non-dispersive infrared (NDIR) measurements of gas concentration is a widely used technique. The principle is to measure the attenuation of light that has passed through a volume containing the gas sample. The light is band-pass filtered to match the absorption band of the desired gas. For reliable and drift-compensated operation the instrument must have a built-in reference measurement, either in the form of a reference absorption path, or a reference wavelength, or a combination of the two. The advantage of the NDIR method compared to low-cost electrochemical methods is first of all its robustness towards issues such as saturation or contamination from other gases.

It is the purpose of our work to provide a two-state optical MEMS band-pass filter for infrared gas measurements. One of the filter states defines the absorption band, and the other defines the reference wavelength band(s). Traditionally such a filter is realized with a rotating filter wheel having two or more interference filters. Compared to the filter wheel, MEMS technology has potentially the following advantages: Precise switching, smaller size, no motors, higher modulation frequency, and lower cost.

Fabry-Perot interferometers have previously been developed as MEMS devices for the above purpose [1]. Here we present a filtering device which is based on a different optical principle and requires fewer processing steps than a Fabry-Perot interferometer: The two-state controllable diffractive optical

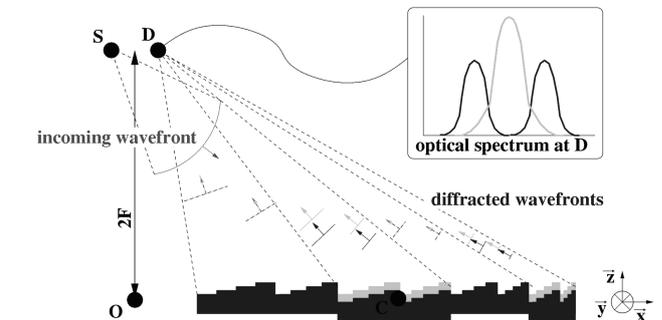


Fig. 1. Principle of the two-state controllable diffractive optical element. When a spherical wavefront propagates from the source S, it is reflected by Fresnel zone-shaped diffractive sub-elements. Here, four sub-elements are shown, each consisting of two periods (four Fresnel zones) and four height levels. The reflected wavefronts recombine in phase at the detector D only for a chosen wavelength  $\lambda_c$  (light gray). If we pull down every second sub-element a distance  $\lambda_c/4$ , the wavefronts will recombine destructively for  $\lambda_c$ , but constructively for the two side-bands (dark gray).

element (CDOE). The two-state CDOE has much in common with grating light valves (GLV) [2], and is a special case of a group of optical MEMS devices using phase-controlled arrays of reflectors [3].

## II. DESIGN

The two-state CDOE can be viewed as grating light valves operated in a high ( $m > 1$ ) diffraction order. Reducing the light intensity at one wavelength will increase the intensity at the neighboring wavelengths (side-bands). The principle is shown in Figure 1 with four sub-elements, and diffraction order  $m = 2$ . The distance between the side-bands decreases with increasing diffraction order. An external focusing lens is not needed, since focusing is achieved using a Fresnel zone-shaped microrelief pattern. For mechanical simplicity, the fabricated test component shown in Figure 2 has an array of *rectangular* diffractive sub-elements of equal size and distance. In this case the sub-element edges do not coincide with Fresnel zone borders, something that broadens and reduces the intensity of the side-bands.

The operation of the device requires only a single voltage signal applied between the device and the substrate. The optimum modulation frequency is dependent on the selected application and detector type. Since the mechanical movement is defined to sufficient accuracy by the fabrication

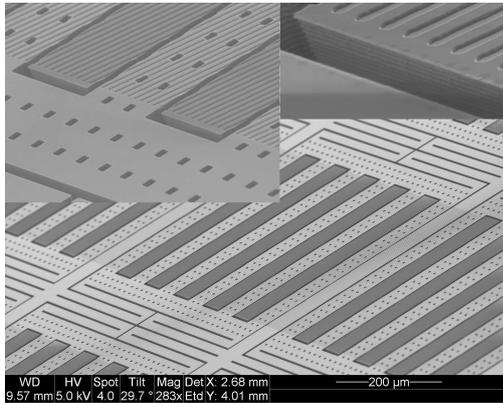


Fig. 2. This scanning electron micrograph (SEM) shows the fabricated two-state filter. The inserts above are close-ups of the diffractive sub-element. Every second sub-element (with etch-holes) is freely suspended, and the remaining sub-elements are attached to the substrate. The suspended sub-elements are mechanically connected to a frame, which is again connected to the substrate through narrow beams that function as springs. A single filter device consists of an arbitrary number of frames. The component used for testing has 5 by 5 frames, where each frame is approximately one by one millimeter. The diffractive pattern is a quarter wavelength deep and covers the optically active area.

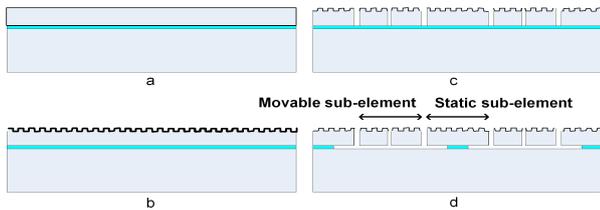


Fig. 3. Fabrication of the device. The diffractive filter is fabricated from a bonded silicon-on-insulator (BSOI) wafer using only two mask layers.

process, neither closed-loop operation nor individual calibration should be necessary.

### III. FABRICATION

The fabrication process starts with the structuring of the diffractive microrelief pattern (Figure 3b). The depth of the microrelief is 500 nm, which was achieved by using a highly uniform, well tuned shallow reactive ion etching process based on a plasma that consisted of a mix of  $\text{SF}_6$  and  $\text{C}_4\text{F}_8$ . The wafer is then coated with a 100 nm layer of aluminum by sputter deposition, followed by patterning and etching of the aluminum using wet etching. The 15  $\mu\text{m}$  thick device silicon is then etched down to the buried oxide (BOX) of the SOI wafer using traditional deep reactive ion etching (Figure 3c). The final step is the release of the movable frame by partial removal of the buried oxide using vapor phase HF etching (Figure 3d). The movable parts of the filter structure contain release holes that ensure complete removal of the oxide underneath, while the absence of release holes on the static part of the filter ensure that some oxide remains, supporting the structure.

### IV. MEASUREMENTS

Figure 4 shows the static deflection of the diffractive elements, measured in an optical profilometer for a range of

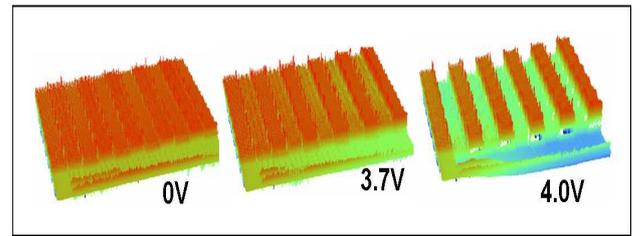


Fig. 4. Interferometric measurements of the mechanical deflection at three different voltages. The initial height difference between static and movable elements is less than 50 nm. The pull-in voltage is 4 V, creating a height difference of approximately 450 nm. At higher voltages there is little change, except that the frame becomes increasingly flat towards the edges. The measured area is 600 by 500  $\mu\text{m}$  and corresponds to approximately a quarter of a complete frame.

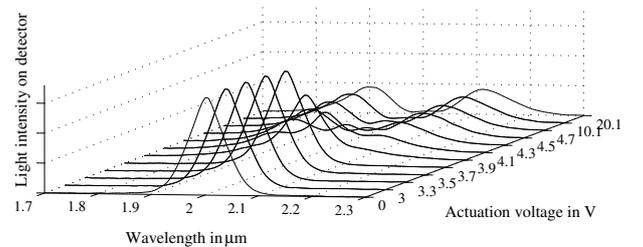


Fig. 5. Fourier-Transform Infra-Red (FTIR) measurements show the detected light intensity as a function of wavelength, for a range of actuation voltages. The two side-bands are located at  $\lambda \approx \lambda_c(1 \pm 1/2m)$ , where  $\lambda_c$  is the center wavelength and  $m$  is the order, or average number of grating periods on each sub-element. The total intensity of the reference double-band is 66% of the central band, and the band-widths are larger. Stronger and narrower reference bands can be achieved with optimal sub-element sizes and shapes.

actuation voltages. The movable frame snaps down onto the substrate at 4 Volts, creating a height modulation corresponding to the thickness of the removed oxide layer. We characterized the filtering properties by mounting the component on an optical bench with illumination and detection through fibers, using a geometry as in Figure 1 with a focal length of 41 mm. The system f-number was approximately  $f/8$ . The light source was a tungsten halogen lamp, and we connected the detection fiber to a Fourier Transform Infra-Red (FTIR) spectrometer. The resulting spectra are shown in Figure 5.

### V. CONCLUSION

We have designed, fabricated, and characterized a controllable micromechanical diffractive element and verified that it works as a two-state optical filter for near-infrared wavelengths. The main benefits of the filter device are the simplicity of fabrication and operation, and that few external lenses or mirrors are needed in a complete sensor system.

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