Open-Loop Operation of MEMS-Based $1 \times N$ Wavelength-Selective Switch With Long-Term Stability and Repeatability

Jui-che Tsai, Sophia Huang, Dooyoung Hah, Hiroshi Toshiyoshi, *Member, IEEE*, and Ming C. Wu, *Fellow, IEEE*

***Abstract*—We report on a microelectromechanical-systems (MEMS)-based $1 \times N$ wavelength-selective switch (WSS) with excellent open-loop stability and repeatability. The optical power fluctuation of the WSS is $< \pm 0.0035$ dB over a 3.5-h period. The variation of optical power during 30 ON–OFF switching periods is $< \pm 0.0026$ dB. Experiments were also performed on the analog MEMS mirror. The stability and repeatability are $\pm 0.00085°$ and $\pm 0.0013°$, respectively.**

***Index Terms*—Microelectromechanical devices, optical components, optical fiber switches, wavelength-division multiplexing.**

I. Introduction

MICROELECTROMECHANICAL mirrors are key enabling devices for many wavelength-division-multiplexing functions. They offer low optical insertion loss and low crosstalk, independence of polarization and wavelength, as well as optical transparency for bit rate and data format. Examples include two-dimensional [1], [2] and three-dimensional [3] microelectromechanical-systems (MEMS) optical switches, dynamic gain equalizers [4], wavelength add–drop multiplexers [5], and wavelength-selective switches (WSSs) [6]–[8].

The multiport WSS has received increasing interests recently because it combines wavelength demultiplexing, $1 \times N$ switching, and wavelength remultiplexing functions in a very compact module. It is realized by placing a linear array of analog micromirrors in the focal plane of a grating spectrometer. Individual wavelengths can be directed to any arbitrary output port, depending on the tilting angle of the MEMS mirrors. Since the power coupled to the output fiber is directly related to the angle of the micromirror, its stability and repeatability play a critical role in the long-term performance of the WSS. It has been reported that electrostatically actuated MEMS devices could have a high drift rate due to charging of exposed dielectric layers [9]. However, the stability of analog micromirror arrays and their impact on WSS have not been reported. Previously, we have reported a novel analog micromirror array with hidden vertical combdrive actuators [10]. Large continuous scan range, high fill factor, and low operating voltage (6 V) have been achieved. The open-loop stability of the WSS using such mirrors was first reported in [11].

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J. Tsai, S. Huang, D. Hah, and M. C. Wu are with the Department of Electrical Engineering, University of California, Los Angeles, CA 90095 USA (e-mail: jctsai@icsl.ucla.edu).

H. Toshiyoshi is with the Institute of Industrial Science, University of Tokyo, Tokyo 153-8505, Japan.

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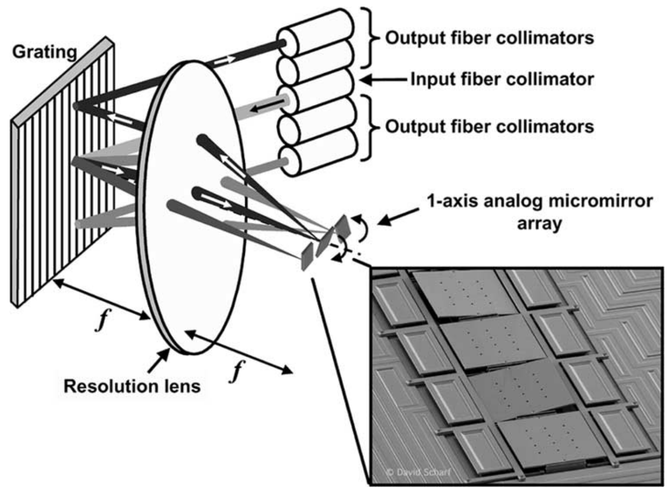

Fig. 1. Schematic of the MEMS-based $1 \times N$ WSS. The inset shows the SEM micrograph of the analog micromirror array with hidden vertical combdrive actuators.

In this letter, we report on the systematic study of the stability and repeatability of both the analog micromirrors and the WSS. By eliminating exposed dielectrics in the high field region and grounding all electrodes near the mirror, excellent stability ($\pm 0.000\,85°$ over 3 h) has been achieved for our mirrors with vertical combdrive actuators. Our results also show that open-loop operation of WSS is feasible with minimum loss variation (± 0.0035 dB over 3.5 h).

II. WSS

Fig. 1 shows the schematic of the $1 \times N$ WSS. Each wavelength of the input optical signal is imaged to a distinctive micromirror at the focal plane of a grating spectrometer. Switching of individual wavelength is achieved by rotating the corresponding micromirrors. The analog micromirror array (inset of Fig. 1) used in this experiment is similar to those reported in [10]. It is made by a five-layer polysilicon surface-micromachining process (SUMMiT-V) at Sandia National Laboratory. The device exhibits low operating voltage (6 V), large scan angle (23.6° optical), high fill factor (91%), high resonant frequency (3.4 kHz), and good uniformity ($< \pm 3.2\%$) [10].

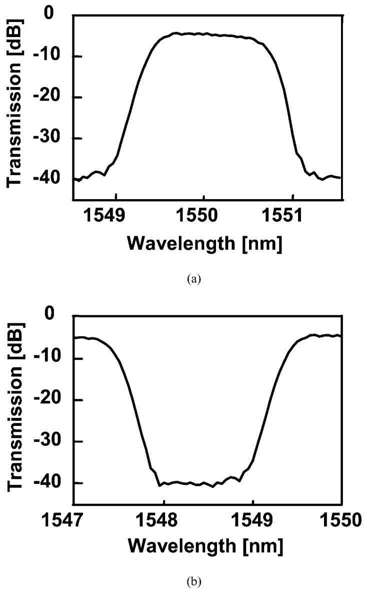

Fig. 2. Measured optical spectra of (a) a bandpass signal at 1550 nm and (b) a band-rejected signal at 1548.5 nm.

The 1×4 WSS is built on an optical bench using a resolution lens with a focal length of 7.5 cm. The minimum fiber-to-fiber optical insertion loss is 5 dB. Fig. 2 shows the spectra of a passed band and a rejected band. The spectra exhibit a broad flat-top response. The channel spacing is 200 GHz, obtained using a 600-grooves/mm grating. An extinction ratio of 35 dB and a switching time of less than 380 μs have been achieved.

III. Stability Characterization

Electrostatically actuated MEMS devices often exhibit drift under constant dc biases. Dielectric charging is the major cause of the drift [9]. When a dc voltage is applied across electrodes, charge carriers are trapped in the insulating dielectric, resulting in a change of the electric field distribution and, therefore, the force exerted on the mirror. Several approaches have been proposed to minimize this undesirable effect, including ac bias [5] and removal of the exposed dielectric [12]. Though ac biasing reduces the drift by neutralizing the charged carriers, the long-term effect is yet to be determined.

Our mirror is inherently more stable than the commonly used parallel-plate-actuated micromirrors. There is no exposed dielectric in the high field region between the comb fingers, as shown by the cross-sectional drawing of the mirror in Fig. 3. The only uncovered dielectric near the anchors of the fixed comb fingers is far away from the mirror. Extensive grounding and shielding are also employed to control the electric field around the mirror. All of the mirrors are connected to an extended ground plane underneath the mirrors through torsion beams. The only ungrounded structures around the mirrors are the biasing combs.

We have measured the stability of the mirror angles under dc voltage bias condition. The mirror angles are measured using a position-sensing diode (PSD). Fig. 4(a) shows the variation of the mirror angles over a 3-h period. One electrode is biased at 4.5 V while the counter electrode is grounded. No systematic drift is observed in the mirror angle. The angular variation over the 3-h period is measured to be $< \pm 0.000\,85^\circ$. It is important to point out that any floating electrodes around the mirror can also cause angular drift. For example, if the counter fixed comb is left floating, the mirror drift increases dramatically (the WSS output power changes by as much as 30% in just 5 min).

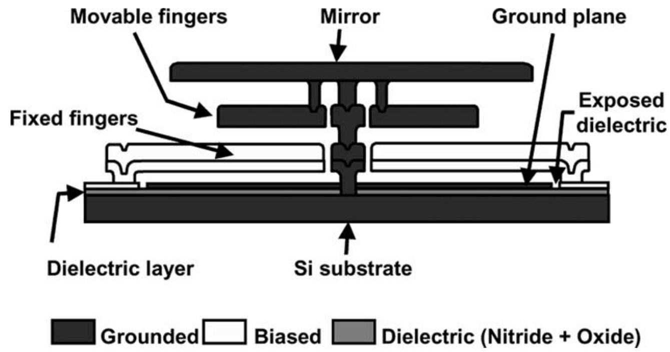

Fig. 3. Cross section of the analog micromirror. The mirror is shielded by an underlying ground plane.

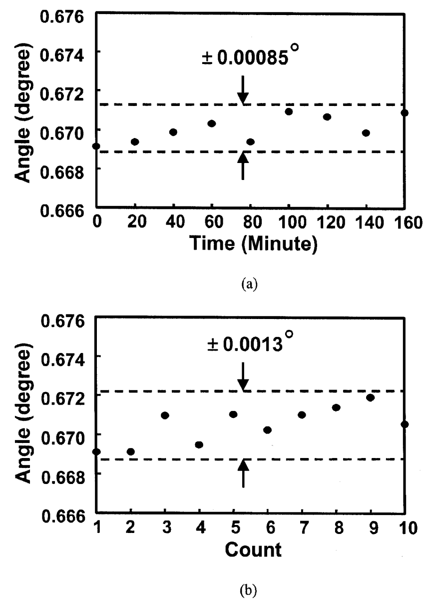

Fig. 4. (a) Long-term drift of the MEMS mirror under dc bias over 3 h. (b) Repeatability of the MEMS mirror during ten ON–OFF switching periods.

We have also measured the repeatability of the mirror angles. The mirror is switched ON (4.5-V bias) for 1 min, during which the mirror angle is monitored by a PSD, and then switched OFF (0 V) for 20 min. The counter electrode is grounded. The process is repeated ten times for a total measurement time of 3 h. Variation of the mirror angles is found to be within $\pm 0.0013^\circ$ [Fig. 4(b)]. Each data point is averaged over a 1-min period. The angular variation caused by the drift of the mechanical parts in the setup is measured to be $\pm 0.000\,55^\circ$.

The stability and repeatability of the WSS in open-loop condition are measured by monitoring the optical power of the output port. Fig. 5(a) shows the fluctuation of the output power when a constant voltage of 6.2 V is applied to one electrode (the counter electrode is grounded). The power fluctuation is measured to be less than ± 0.0035 dB ($\pm 0.08\%$) over a 3.5-h period. The repeatability of the WSS is shown in Fig. 5(b). The power variation is less than ± 0.0026 dB ($\pm 0.06\%$), during

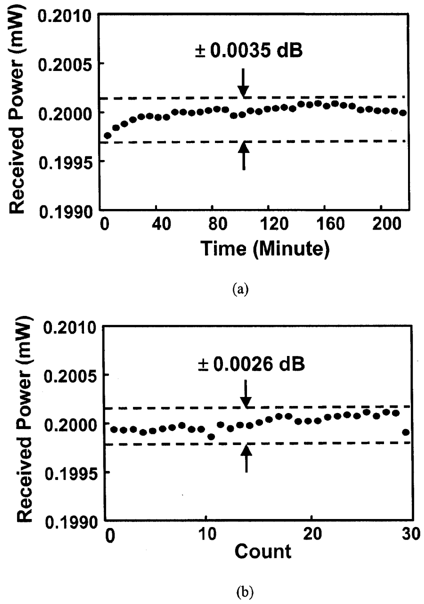

Fig. 5. (a) Long-term drift of the WSS under constant dc bias over 3.5 h. (b) Repeatability of the WSS during 30 ON–OFF switching periods.

30 ON–OFF switching periods over 3 h. Each data point is again averaged over 1 min to eliminate short-term noises. The laser power fluctuation is $< \pm 0.0007$ dB over a 3-h period. The excellent stability and repeatability suggest that the WSS with vertical comb-actuated micromirrors can operate in open loop environment. There are several advantages for open-loop operations. The system complexity is greatly simplified. The power consumption is also drastically reduced by eliminating the control circuits for each individual mirrors.

We have calculated the optical insertion loss of the WSS as a function of the mirror angle using Gaussian beam formulation. For a perfectly aligned WSS, the output power is not sensitive to the random drift of mirror angles (the first derivative is zero). It takes an angular drift of $\pm 0.06^\circ$ to produce a power variation of ± 0.003 dB. This is about an order of magnitude larger than our measured mirror drift. There are two possible explanations for the discrepancy: First, the WSS is not perfectly aligned, at which point the loss is more sensitive to mirror angle variation. Second, the stability of other optical fixtures in our table-top WSS is also contributing to the power variation. This implies there is room for further improvement in the open-loop stability of the WSS.

IV. CONCLUSION

We have experimentally characterized the open-loop performance of our WSS using a low-voltage analog micromirror array with hidden vertical combdrive actuators. Excellent stability and repeatability are observed for both the mirrors and the WSS over a period of 3 h. The stability and the repeatability of the mirror are $\pm 0.000\,85^\circ$ and $\pm 0.0013^\circ$, respectively, while those of the WSS are better than ± 0.0035 and ± 0.0026 , respectively. Our results demonstrate the feasibility of open-loop operation in MEMS-based WSS.

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