Integrated Wavelength-Selective Optical MEMS Switching Using Ring Resonator Filters

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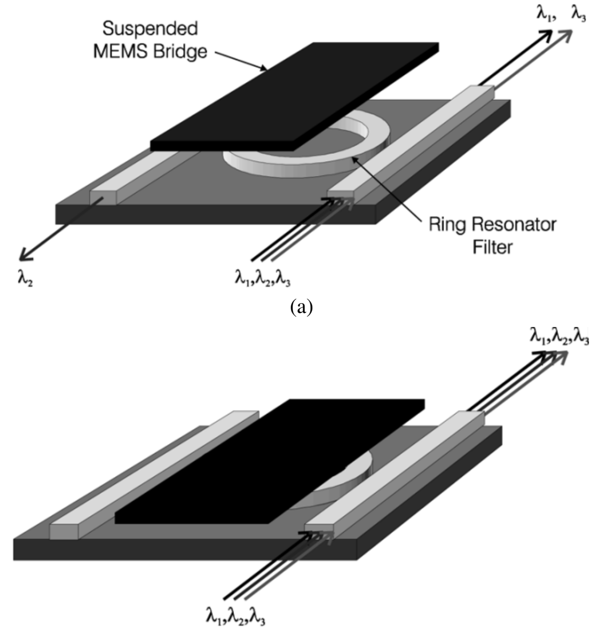
***Abstract*—An integrated optical microelectromechanical system (MEMS) switch that provides wavelength selectivity is described. The switching mechanism is based on moving a MEMS actuated optically absorbing membrane into the evanescent field of a high-index-contrast optical ring resonator. By controlling the loss, and thus, the cavity quality factor, the resonant wavelength is switched between the drop and through ports.**

***Index Terms*—Integrated optics, microelectromechanical devices, optical filters, optical switches.**

I. INTRODUCTION

THE DRIVE toward low-cost wavelength-division-multiplexed (WDM) optical networks necessitates the integration of various optical components into integrated optical circuits [1], [2]. One basic component of a WDM integrated optical circuit is a wavelength-selective optical switch. Conventional integrated optical switches utilize electrooptic and electroabsorption effects; however, these are only possible in a limited number of materials, and therefore, are of limited use. Recent theoretical studies have suggested that optical switching can be enabled in any material system by moving an external body, using microelectromechanical systems (MEMS), into the evanescent field of an optical ring resonator, affecting the loss and, therefore, the quality factor (Q) of the optical cavity [3]–[5].

In this letter, we describe the design, fabrication, and testing of an integrated optical MEMS switch that operates by manipulating the optical propagation constants of an integrated high-index-contrast ring resonator filter by moving a structure suspended over the ring resonator. By using a ring resonator as a functional element of the switch, intrinsic wavelength-selective switching is provided. The ring resonator is switched OFF and ON by moving an optically lossy MEMS structure into and out of the evanescent field of the ring resonator [4], [5]. The optical loss introduced by the membrane is a combination of absorption and scattering loss.



(a)

(b)

Fig. 1. Illustration of the switch structure with the optically lossy suspended MEMS structure in its two positions. (a) Shows the MEMS structure up and the ring resonator dropping the resonant wavelength. (b) Shows the MEMS structure down and all wavelengths passing by the ring resonator unaffected.

Intrinsic wavelength switching is a unique characteristic of this switch. Typically, wavelength-selective switching is achieved by demultiplexing the WDM signal, switching the individual wavelength, and then remultiplexing the output signal. This switch reproduces that entire process with a single element.

This switch is ideally suited for creating reconfigurable integrated optical circuits for a variety of optical networking purposes. Although a number of other integrated optical switches have been demonstrated, the switch demonstrated in this letter is unique due to its wavelength-selective switching capability, complementary metal–oxide–semiconductor (CMOS) compatibility, small footprint, and low power consumption. These characteristics are all important to achieve large-scale integration of optical switches into low-cost high-performance WDM optical networks [1], [2].

The switch uses a parallel plate MEMS actuator structure to move the lossy membrane (aluminum) into and out of the ring resonator's evanescent field, as in Fig. 1. When the lossy material is up and away from the evanescent field, the ring couples the resonant wavelength from the through port to the drop port. When the lossy material is in the evanescent field, the optical absorption spoils the resonance and all wavelengths pass by the ring unaffected in the through port.

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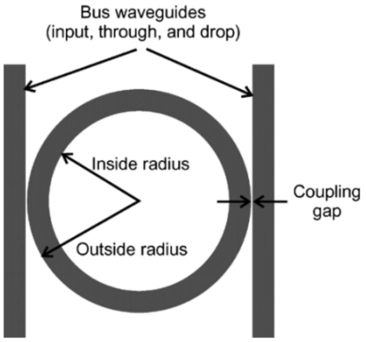

Fig. 2. Schematic showing the layout of the optical waveguides comprising the ring resonator filter and bus waveguides.

II. MEMS Ring Resonator Switch Design

The wavelength selectivity of the switch is created by high-index-contrast optical ring resonator filters. The high-index-contrast between the core and cladding materials allows the rings to have a small radius ($\sim 10\ \mu$m), and therefore, a large free spectral range (FSR), with low bending loss [5], [6]. A single-ring filter was selected for this initial device to minimize complexity, however, the switching technique could be easily applied to multiring filters that have much better optical filter performance [7], [8].

The high-index core material used for the waveguides is silicon-rich silicon nitride with a refractive index of 2.2. The waveguide core cross section is 1050 nm wide for the bus waveguides and 1010 nm wide for the ring-resonator waveguides, both were 330 nm thick. The cladding is 3-μm-thick silicon oxide $(n = 1.45)$ on the bottom and air $(n = 1.0)$ on the top and sides.

Fig. 2 shows a schematic of the ring resonator filter. The inside and outside radii are 13.47 and 14.48 μm, respectively. The coupling gap between the ring and the bus waveguides is 185 nm. The FSR of this ring resonator is 12.5 nm for wavelengths around 1550 nm (C-band). The ring resonator filters were fabricated as reported in [6].

The ring resonator in this switch was designed to be polarization-dependent, thus making the overall device polarization-dependent. This approach was taken with the eventual goal of using a polarization diversity scheme to make the overall behavior of the integrated optical chip polarization-independent [5]. However, the MEMS switching mechanism is not polarization-dependent, that is, it would switch polarization-independent ring resonators equally well.

The nonlinear nature of electrostatic parallel plate actuators creates an equilibrium bifurcation that results in a pull-in effect that provides a binary switching mechanism [9]. Because of this behavior, parallel plate actuators are commonly used in a variety of radio-frequency and optical MEMS switches.

In designing this switch, the key parameters include the stiffness of the structure k, the overlap area of the parallel plate electrodes A, and the initial gap between the plates d_0. These parameters relate to the pull-in voltage $V_{\rm pi}$ (the voltage at which the movable plate snaps down) according to

$$V_{\rm pi} = \sqrt{\frac{8kd_0^3}{27\varepsilon A}} \tag{1}$$

where ε is the permittivity of air [9].

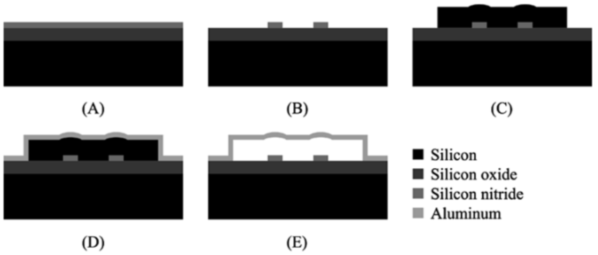

Fig. 3. Fabrication process flow for the integrated wavelength selective optical switch. (a) The 3-μm silicon oxide layer is first grown by thermal oxidation, then the 0.33-μm silicon nitride layer is deposited by low-pressure chemical vapor deposition (LPCVD). (b) The silicon nitride is patterned by e-beam lithography and reactive ion etching (RIE). (c) The 1.0-μm polysilicon sacrificial layer is deposited by LPCVD and patterned with contact photolithography and RIE. (d) The 0.35-μm aluminum layer is deposited by sputtering and patterned by contact photolithography and wet etching. (e) The completed device is released by gas phase xenon difluoride etching.

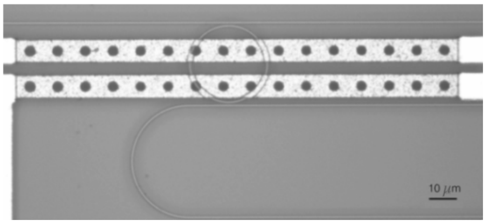

Fig. 4. Optical micrograph of an integrated wavelength-selective optical switch after completion of the fabrication process.

The initial gap between the substrate (the bottom plate) and the bridge structure is comprised of the thicknesses of the oxide cladding layer, the silicon nitride waveguides, and the air gap between the bridge and the top surface of the ring resonator. At a separation of 1 μm, the bridge's effect on the evanescent field is negligible. Accounting for the relative permittivity of the oxide, the required effective initial gap d_0 is 2.2 μm.

The dimensions of the bridge are 160-μm length, 20-μm width, and 350-nm thickness. The bridge was designed to provide a relatively fast response and adequate stiction[1] resistance at a moderate voltage (15 V).

One appealing characteristic of parallel plate actuators is their low power consumption. Since no current flows in either switch state, no power is required to maintain the switch in either state. During switching, the switch requires only a small amount of power. For example, this switch requires only about 1 μW of power to operate at 100 kHz.

III. Fabrication

The wavelength-selective switch is completely fabricated using CMOS compatible microfabrication techniques at the wafer level. This makes the switch not only inexpensive but also allows the switch to be integrated into larger optical systems that reside completely on a single chip. Furthermore, the MEMS switching technique is material system independent, that is, it can be easily ported to virtually any of the materials systems currently being used for integrated photonics. Fig. 3 illustrates the fabrication process used to create the switch. Fig. 4 shows a typical device.

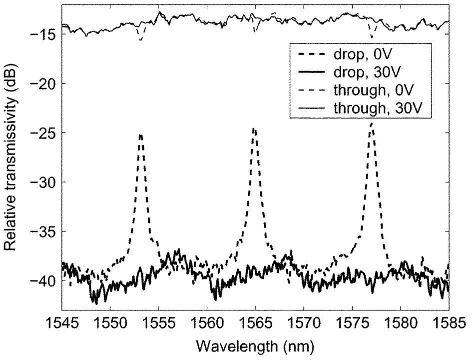

Fig. 5. Spectral results of the integrated wavelength-selective optical switch.

The fabricated aluminum bridge structure possessed a residual stress gradient through the thickness of the film. This stress gradient caused the bridge to deform upon release, decreasing the initial gap from the required 1.0–0.34 μm. This deformation increased the insertion loss due to the unintentional proximity of the bridge in its "up" position to the resonator, but did not otherwise affect the switch's optical performance.

IV. EXPERIMENTAL RESULTS

The performance of the switch was characterized both mechanically and optically. The mechanical testing consisted of measuring the displacement of the bridge with applied voltage using a white light Zygo profilometer. Using this technique, a 24-V pull-in voltage was observed. The difference between this value and the 15-V design voltage is attributed to the bridge deformation resulting from residual stress and charge trapping in the oxide layer [10]. The 24-V pull-in voltage was also seen during the optical testing.

Spectral testing was performed with a computer-controlled lock-in amplifier and tunable laser. Spectral measurements of the drop and through response of the ring resonator can be seen in Fig. 5 for both the "OFF" and "ON" states. With no applied voltage, a drop-port insertion loss of 11 dB is observed, while an extinction of 1.6 dB is observed in the through-port. With 30 V applied, the drop signal is reduced by 15 dB while the through-port extinction becomes negligible.

The high insertion loss is due to the unintentional bridge deformation noted earlier. A different bridge material, such as titanium nitride [10], [11], can alleviate that problem, resulting in insertion loss comparable to static ring resonators [6]–[8].

Temporal switching measurements were performed with a fixed wavelength tuned to the optical resonance of the device. The through-port optical power was measured while applying a 0- to 30-V square wave to the MEMS device. Fig. 6 shows 2-kHz switching results. Switching times of 16 μs (up—voltage OFF) and 60 μs (down—voltage ON) were observed with switching rates demonstrated up to 8 kHz. The temporal switching tests were limited by the test equipment bandwidth. Faster test equipment should lead to switching speeds of about 10 μs for both directions. In these tests, the switch was cycled more than 5 000 000 times without failure.

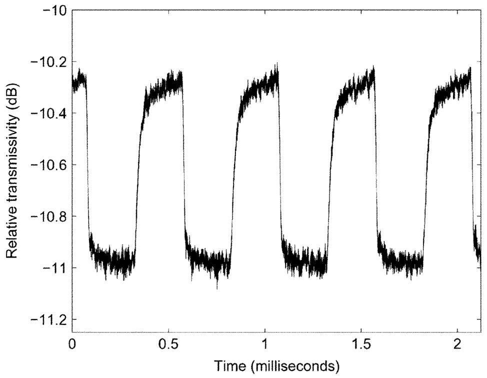

Fig. 6. Through-port temporal switching results.

V. CONCLUSION

A fully integrated wavelength-selective optical switch using a ring resonator filter coupled with a MEMS parallel plate actuator has been demonstrated. This approach to optical switching is compelling because its CMOS compatibility, small footprint, wavelength selectivity, and low power consumption allows it to be readily used in integrated optical circuits for WDM applications.

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