An in-plane, variable optical attenuator using a fluid-based tunable reflective interface

Michael Ian Lapsley, Sz-Chin Steven Lin, Xiaole Mao, and Tony Jun Huang[a)]
Department of Engineering Science and Mechanics, The Pennsylvania State University, University Park, Pennsylvania 16802, USA

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We introduce an optofluidic based variable optical attenuator with high stability, high reliability, simple and inexpensive fabrication, and an attenuation performance comparable to commercial devices. A standard soft lithography process produces a single-layered polydimethylsiloxane (PDMS) microfluidic device integrated with optical fibers. By altering the refractive index of the fluid within the microchannel, we can control the reflectivity of the fluid/PDMS interface and thus achieve variable attenuation. Theoretical calculations are conducted based on Snell's law of refraction and the Fresnel equations of reflection, and the calculated attenuation response matches well with experimental data. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3213348]

Variable optical attenuators are essential to applications such as wavelength-division multiplexing systems.[1] Currently, many variable optical attenuators are implemented through two means: microelectromechanical systems (MEMS) or planer lightwave circuits (PLC). MEMS-based attenuators use microfabrication processes to create moving mirrors or shutters to achieve attenuation.[2,3] PLC-based devices manipulate light properties through mechanisms such as wave interference, thermo-optical effect, and liquid crystals.[4–7] Although both MEMS and PLC approaches have led to devices with good performance, they suffer from complicated multistep-lithography fabrication processes.

Recently, the emerging field of optofluidics provides exciting opportunities for a new class of optical devices with attractive features such as large tunability, low power, and nonmechanical operation.[8–10] Thus far, optofluidic devices such as optical modulators,[11–14] optical gratings,[15] waveguides,[16] lenses,[17–19] and sensors[20] have been demonstrated. In this work, we introduce an optofluidic approach for variable optical attenuation. We take advantage of fluid mixing to manipulate the optical properties of our device to control optical reflectivity. In contrast to the existing counterparts that require complicated multistep fabrication processes, our device is much simpler and can be fabricated via single-step soft lithography.

Figure 1 shows the operating mechanism of our device. It is composed of four main sections: the fluid inputs, microfluidic mixer, tunable interface, and fluid output. Two optical fibers are aligned at the same side of a microfluidic channel created in polydimethylsiloxane (PDMS). A refractive index mismatch between the PDMS and the fluid will cause part of the incident optical beam to be reflected at the interface. The refractive index of the fluid, and thus the intensity of the reflected light (R), can be tuned by controlling the concentration of solutes, such as calcium chloride ($CaCl_2$), by means of a micromixer. As a result, variable optical attenuation is achieved.

The PDMS-based device was created using standard soft lithography.[21] The microchannel was 200 μm wide, the optical fiber slots were 155 μm wide, and all features were 155 μm tall. Fluid was injected at the fluid inputs using 5 ml syringes pumped by two separate syringe pumps. One syringe was filled with de-ionized (DI) water, having a refractive index approximately $n_1=1.333$ and the other syringe was filled with a 3.5M solution of $CaCl_2$, having an approximate refractive index of $n_2=1.41$.[16] The value of n_2 was intentionally set to match the refractive index of PDMS, $n_4=1.41$. The passive microfluidic mixer was used to create a homogeneous mixture between the two input fluids. The two input flow rates can be adjusted to alter the volume ratio of the fluid mixture and therefore, tune its refractive index (n_3).

When the incident beam (I), ejected from the input optical fiber, contacts the first fluid/PDMS interface, it is split into a reflected beam (R) and a transmitted beam (T). The angle of the reflected beam is the same as the angle of the incident beam (θ), allowing R to be captured by the output optical fiber; however, the transmitted beam is difficult to capture because after it is refracted twice (at each wall of the microchannel) it experiences some displacement (d) from the trajectory of the incident beam that varies with n_3.

The optical images shown in Fig. 2 depict the device at three separate stages of its operation. The input and output fibers had a numerical aperture of 0.22. A set of collimating lenses, with circular radii of 160 μm, were positioned at the termination of each fiber to couple the divergent light into and out of the optical fibers. When $Q_2=0$, there was only

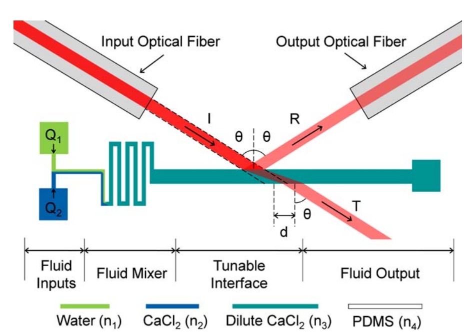

FIG. 1. (Color online) A schematic of the optical attenuator device. Altering the flow rates Q_1 and Q_2 changes the reflected power (R) of the incident beam (I).

[a)]Author to whom correspondence should be addressed. Electronic mail: junhuang@psu.edu.

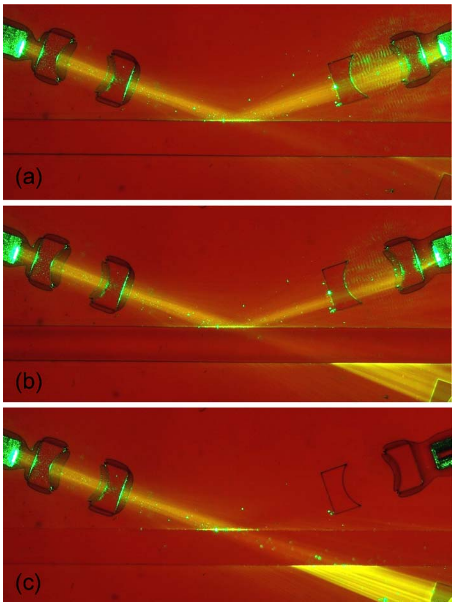

FIG. 2. (Color online) Experimental images of the optical attenuator. (a) The device at its lowest attenuation value. (b) An intermediate stage where part of the light is transmitted and part of the light is reflected. (c) The device at its maximum attenuation.

pure DI water in the channel ($n_3=1.333$) and almost the entire incident beam was reflected and recorded by the output fiber [Fig. 2(a)]. When the refractive index of the mixed solution was $n_3=1.353$, the reflected beam intensity and the transmitted beam intensity were approximately equal [Fig. 2(b)]. When $Q_1=0$, the channel was filled with undiluted $CaCl_2$ ($n_3=1.41$) and as a result, maximum attenuation of the reflected light was achieved [Fig. 2(c)].

We further characterized the attenuation response of the device (Fig. 3). Light from an unpolarized laser diode with a 532 nm wavelength was coupled into the incident fiber using a tunable fiber port. The output fiber was mounted to project upon a high-speed silicon detector. Analyzing the full range of the device required the refractive index of the $CaCl_2$ solution (n_2) to be above 1.41. In our experiments, n_2 was adjusted to 1.414, which sets the refractive index of the mixed solution to a range of $1.333<n_3<1.414$ and ensured that the full range of the device was characterized. The total flow rate of the mixed solution remained constant at 40 μl/min and only the concentration of $CaCl_2$ changed as Q_1 and Q_2 were adjusted. Figure 3 shows the normalized reflection of the optical signal in decibels as a function of the $CaCl_2$ flow rate (Q_2) and the corresponding refractive index of the mixed solution. Initially, when Q_2 is zero, the channel is filled with pure DI water and the attenuation is close to zero. As Q_2 increases, the refractive index of the mixed solution increases, causing the interface to become less reflective, and thus, controllable attenuation is achieved. The maximum attenuation was measured around 35 dB and took place at $Q_2=38$ μl/min which corresponds to a refractive index of $n_3=1.41$. The performance of the device could be improved by using asymmetric lens rather than circular lens to achieve better coupling with the optical fibers and further reducing the roughness of the PDMS sidewalls by utilizing a high aspect ratio SU-8 mold.[22]

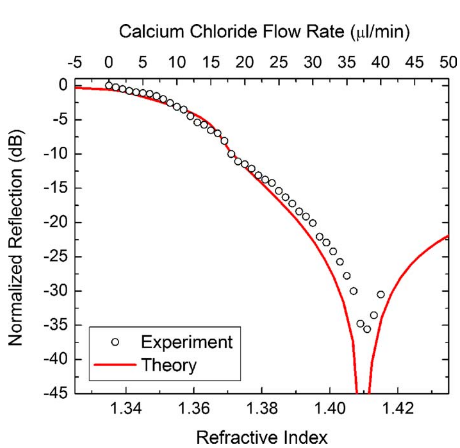

FIG. 3. (Color online) The attenuation response of the device. Increasing the refractive index of the solution at the tunable interface causes an increase in signal attenuation. The maximum attenuation is about 35 dB.

To achieve a fundamental understanding of the attenuation response, theoretical analysis was conducted and compared to the experimental results. The reflectivity of the interface can be approximated analytically by combining Snell's law with the Fresnel equations of reflection. The combination of these equations leads to the reflection coefficients (r_{TE} and r_{TM}) for both TE and TM polarized light [Eqs. (1) and (2)], and the power reflectance of unpolarized light, which contains equal amounts of TE and TM polarized light, is given in Eq. (3):[23]

$$r_{TE}=\frac{n_4\cos\theta-n_3\sqrt{1-\left(\frac{n_4}{n_3}\sin\theta\right)^2}}{n_4\cos\theta+n_3\sqrt{1-\left(\frac{n_4}{n_3}\sin\theta\right)^2}}, \tag{1}$$

$$r_{TM}=\frac{n_4\sqrt{1-\left(\frac{n_4}{n_3}\sin\theta\right)^2}-n_3\cos\theta}{n_4\sqrt{1-\left(\frac{n_4}{n_3}\sin\theta\right)^2}+n_4\cos\theta}, \tag{2}$$

$$\bar{R}=\frac{|r_{TE}|^2+|r_{TM}|^2}{2}. \tag{3}$$

Thus, the reflection ($\bar{R}$) is a function of the refractive index of PDMS (n_4), the refractive index of the fluid (n_3), and the incident angle (θ) of the input light. In our experiments n_4 and θ remained constant. Therefore, n_3 was the only variable in this device for adjusting the reflection of the tunable interface. A logarithmic plot of Eq. (3) was included in Fig. 3 to verify the response of the device. Inspection of Fig. 2 indicated that the reflected beam was not ideally collimated and the angle of reflection (θ) varied from 72° to 76°. The best theoretical fit of our data was made when averaging the reflective effect of many beams traveling at angles between 72° to 76°, which were weighted by a Gaussian distribution obtained from the input beam. The excellent match between the experimental data and the theoretical results shown in Fig. 3 reinforces the stable and predictable response of this device.

Next we investigated the dynamic response of the device (Fig. 4). When the attenuator was in the "on" state, Q_1 and Q_2 were set to 40 and 0 μl/min, respectively, and maximum reflectivity was achieved as depicted in Fig. 2(a). In the "off" state, the pumps were switched so that $Q_1=0$ μl/min and

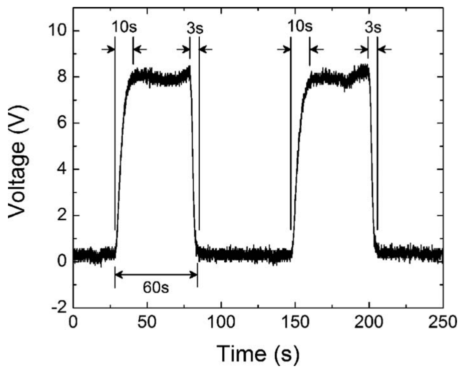

FIG. 4. The dynamic response of the optical attenuator.

$Q_2=40$ μl/min and this was the state of minimum reflection as depicted in Fig. 2(c). There is a slight discrepancy between the rising and falling times of the device, as seen in Fig. 4, which is caused by the buildup of backpressure in our pumping system. Replacing the high-viscosity $CaCl_2$ solution with low-viscosity water (during the rising time) builds up a significant level of backpressure; however, replacing water with $CaCl_2$ (during the falling time) builds up little backpressure.[24] Therefore, the falling time is less effected by the viscosity difference. This effect would be eliminated by using a less compliant pumping system.

In conclusion, we fabricated and tested an optofluidic-based variable optical attenuator that operates by applying fluid mixing to alter the refractive index of a tunable interface. This device uses simple fabrication techniques incorporating optical fiber coupling and optical alignment in a basic soft-lithography process which could easily lead to mass production of the device. A maximum attenuation of 35 dB was achieved, which is comparable to the existing optical attenuators while the design and fabrication of our device is much simpler. The experimental data of the attenuation response matched well with the theoretical predictions. This device could be used directly as an optical attenuator for communications applications, as a microrefractometer to measure the refractive index of fluids, or as a biochemical sensor to detect refractive index changes during biochemical reactions.

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