Dielectrically actuated attenuator at 1.55 μm

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Abstract

We prepared a variable optical attenuator (VOA) at λ ~ 1.55 μm using dielectrically actuated liquids. This VOA works in the principle of absorption. Electro-optical characteristics of this VOA were measured in both transmissive and reflective modes. Compared to transmissive mode, reflective mode could offer much larger attenuation without changing other performances. By applying a voltage of 27 Vrms, this VOA could obtain ~19 dB in transmissive mode, and 38 dB in reflective mode. It had insertion loss (IL) of ~0.76 dB with negligible polarization dependent loss (PDL) at various voltages. Due to its competitive features such as voltage actuation, optical isotropy, and large attenuation with zero PDL, this VOA in reflective mode has potential applications in fiber-optic switches, sensing, and other infrared attenuators.

1. Introduction

A variable optical attenuator (VOA) is an essential component in fiber-optic switches, infrared (IR) light shutters, sensing, and other power control systems. In a fiber-optic switch, the level of input optical power should be controlled so that the output power will not damage or saturate the receiver. To reduce output power, various VOAs based on MEMS [1–4], liquid crystal (LC) or polymer dispersed liquid crystal (PDLC) [5–11], electrowetting [12–14], dielectrophoretic effect [15], optofluidic [16–20], and other types [21] have been developed. Most of these VOAs work by reflection, deflection, refraction or interference. MEMS VOAs usually work by reflection. When an input light is reflected, unwanted back reflection might occur in their optical system. Because the driving system is mechanical, they face an issue of friction. LC- and PDLC-based VOAs control light by phase modulation and scattering, respectively. They have advantages of compact structure and simple actuation. However, their insertion loss (IL) and polarization dependence loss (PDL) are fairly large. Electrowetting and dielectrophoretic based VOAs can control light by reflection and/or refraction. Their IL and PDL also need to be reduced. Optofluidic VOAs can obtain good optical performances. However, their device systems are complex and bulky, their driving method is also mechanical.

In contrast to VOAs working by pure reflection, deflection, scattering, and interference, optical switch in principle of absorption is much popular in the design of VOA, since it is simple. In addition, it can reduce optical power effectively. Based on dielectrophoretic (or dielectric) effect, a glycerol droplet can be used to switch a near infrared (IR) light at wavelength of ~1.55 μm. To attenuate IR light, two methods have been proposed. One method is by moving a glycerol droplet in a cell using a voltage. The glycerol attaches onto a substrate [22]. If the droplet travels a short distance with a low voltage, then it can keep a spherical shape during motion. If it travels a large distance, it can get rid of its original position, leading to out of work for the device. The other method is by placing a glycerol droplet in a wedge cell [23]. By applying a voltage, the droplet is dragged to move towards the region with narrower gap. This device has good mechanical stability because the droplet touches both substrates. However, the required driving voltage is high while the returning speed of the droplet is very slow. Because the two devices work in transmissive mode, a rather limited attenuation can be offered.

In this report, we prepared a VOA using a glycerol droplet. The glycerol droplet is sealed in a glass cell. One substrate with an anchor spot can pin down the droplet. The surrounding of the droplet is filled with silicon oil.
Optical switch is obtained by stretching the surface of the droplet. Optical performances of the VOA are measured in both transmissive and reflective modes. The reflective mode can offer attenuation twice as much as the transmissive mode, with unchanged IL and PDL. Using the anchor spot, the droplet can be safely attached onto the substrate with good mechanical stability.

2. Device structure and basic theory

The structure of the proposed VOA is shown in figure 1. An electrode on a glass substrate has an interdigitated pattern. An anchoring spot formed on the substrate partially covers the border of the electrode. The substrate surface is coated with a dielectric layer. A liquid droplet attaches onto the anchor spot without touching the electrode. A dielectric liquid (not given) is used to fill the surrounding of the liquid droplet to reduce its gravitational effect and lubricate the surface of the substrate.

In the voltage-off state, the droplet presents the smallest surface area due to minimal surface energy, as shown in figure 1(a). When a voltage is applied to the electrode, a fringing field is generated across adjacent electrode stripes. The region close to the substrate has the largest gradient of the electric field (V/ε). According to Kelvin’s theory [24], the droplet will experience a dielectric force. The dielectric force is expressed by

\[ F = -\frac{1}{2} \varepsilon_0 (\varepsilon_1 - \varepsilon_2) \nabla E^2 \]

(1)

where \( \varepsilon_0 \) represents the permittivity of free space, \( \varepsilon_1 \) and \( \varepsilon_2 \) represent relative dielectric constants of the droplet and surrounding liquid, respectively. If \( \varepsilon_1 > \varepsilon_2 \), then the generated dielectric force can drag the droplet to shift toward the region with higher electric field. Because the adhesive force generated from the anchor spot is in the direction against the dielectric force, the droplet is stretched along the electrode stripes, as shown in figure 1(b). When the voltage is removed, the dielectric force will vanish, and the droplet can return to its initial position.

According to Beer-Lamber law, when a beam of light with an intensity of \( I_0 \) penetrates a material, it is absorbed exponentially. Theoretically, the transmitted light intensity can be written as [25]

\[ I = I_0 \exp(-\beta t) \]

(2)

where \( t \) is the thickness of the material and \( \beta \) is the light absorbing coefficient. To change light intensity (\( I \)), the thickness (\( t \)) should be changed. The glycerol droplet shown in figure 1 simply obeys this rule because its -CH2-bending vibration absorption peak is at \( \sim 1.55 \mu m \). To change the thickness \( t \) of a glycerol, two methods can be considered as shown in figure 2.

One method is by filling glycerol in a uniform glass cell, as shown in figure 2(a). The light intensity of an incident ray is \( I_0 \). When the cell gap is increased from \( t_1 \) (left) to \( t_2 \) (right), the output light intensity of the ray is reduced from \( I_1 \) to \( I_2 \). It is hard and awkward to change the cell gap using this method. The second method is by filling a glycerol droplet in the glass cell as shown in figure 2(b). The shape of the droplet can be deformed by a voltage. At \( V = 0 \), the incident ray can penetrate the edge of the glycerol droplet with a thickness \( t_1 \) (left). By applying a voltage, its thickness is increased to \( t_4 \) (right). As a result, the light intensity can be attenuated from \( I_1 \) to \( I_4 \). Compared to the first method, the second method can be easily obtained. If the incident light is a beam rather than a ray, then the thickness of the droplet is inhomogeneous. From figures 2(a) and 2(b), we suppose \( I_1 \) and \( I_4 \) are transmitted light intensities of the beam passing through the droplet. If \( I_1 = I_0 \), then \( t_1 \) is considered as the equivalent thickness of \( t_3 (= t_1) \). Similarly, if \( I_4 = I_0 \), then \( t_4 \) is considered as the equivalent thickness of \( t_2 (= t_4) \). When the beam of light is controlled by the glycerol droplet, we can find an equivalent thickness to replace the non-uniform thickness. By doing so, light absorption of the droplet still can be described using (2). If the contrast ratio (CR) is simply the inverse of \( I_0/I_1 \), then we have \( CR = \exp(\beta t) \). For a small droplet, it can offer rather limited CR. Increasing \( t \) can enhance CR exponentially. It is possible to increase \( t \) by enlarging the size of the
droplet. However, the device will face the issues of bulky structure and mechanical instability. To overcome this obstacle, the droplet may work in reflective mode or twice transmission. From (2), if the droplet works in reflective mode, then the incident light can traverse it twice. As a result, CR can be written as [26]:

$$CR = \exp^{2/\eta_l}$$

As a comparison, its CR is squared to that of its transmissive counterpart. Since the device structure is not changed, its other performances such as driving voltage and response time are unchanged. To obtain a reflective mode, a mirror is placed right behind the glass cell.

3. Experiment

A device cell was prepared according to the structure shown in figure 1 (a). An indium-tin-oxide (ITO) glass substrate was chosen. The ITO electrode was etched with a comb-like pattern. The width and gap of adjacent ITO stripes were both 10 μm. A small amount of NOA65 (Norland Optical Adhesive) was dripped on the substrate to form a ∼0.4 mm-diameter droplet. It partially covered the border of ITO stripes. The NOA65 droplet was then solidified by UV light. The cured NOA65 droplet was treated as an anchor spot. A thin Teflon layer (400S1-100-1, from DuPont, USA) was coated on the substrate except the anchor spot. The Teflon layer has low surface tension ($\gamma_T \sim 18$ mN m$^{-1}$) at room temperature. A small amount of glycerol ($\varepsilon_g \sim 47$, $\rho_g \sim 1.25$ g cm$^{-3}$, Sigma-Aldrich) was dripped on the anchor spot to form a droplet. For easy observation, the glycerol was doped with ∼0.1 wt % Rose Bengal (Sigma-Aldrich). Rose Bengal can highly absorb mid-IR wavelength ranging from 6.85 to 6.94 μm. Silicone oil ($\varepsilon_o \sim 2.9$, $\rho_o \sim 1.01$ g cm$^{-3}$) was used to fill the surrounding of the droplet. These two liquids were immiscible. A bare glass plate was used to cover the two liquids to form a cell. The cell gap was controlled to be ∼4.3 mm using glass spacers. The periphery of the cell was sealed using epoxy glue. The diameter of the glycerol droplet touching the substrate was measured to be ∼3.95 mm.

4. Results and discussion

Since the dielectric constant of glycerol ($\varepsilon_g \sim 47$) is much larger than that of silicone oil ($\varepsilon_o \sim 2.9$), the glycerol droplet can be stretched when it is driven by a voltage. Figure 3 shows droplet actuated with two different voltages. At $V = 0$, a round droplet is observed (left). The red color is due to the doped dye. From side-view observation, the contact angle of the droplet on the substrate is ∼130°. When an AC voltage (300 Hz) is gradually increased to ∼6.5 Vrms, the droplet begins to stretch toward left. At $V = 40$ Vrms, the droplet is stretched with a slug-like shape (right). Form the side-view observation, the contact angle changes to ∼90°. As the voltage is increased continuously, the droplet still can be lengthened. When the voltage is removed, the droplet can return to its original shape.

The absorption spectra of glycerol and silicone oil are measured. Results are shown in figure 4. The thickness of each liquid is ∼3 mm. A glycerol molecular can strongly absorb 1.55 μm wavelength while the silicone oil is highly transparent to this wavelength. Therefore, glycerol and silicone oil are suitable partners for an optical switch.
As shown in figures 3 and 4, the stretched glycerol droplet can be used for optical attenuation at $\lambda \sim 1.55 \, \mu m$. To characterize the attenuation, an experimental setup is built, as shown in figure 5. A probing beam (LAS DFB-1550-6, $\lambda = 1.55 \, \mu m$, Laser Max, USA) is normally incident on the device cell at the position close to the edge of the droplet. The position is marked using a dashed circle in figure 1 to make sure that there is no light absorption by the droplet at $V = 0$. The diameter of the beam is controlled to be $\sim 0.7 \, mm$. Figure 5(a) for transmissive mode and figure 5(b) is for reflective mode. Compared to the transmissive mode, a mirror is placed right behind the glass cell in the reflective mode. Transmitted or reflected light intensity is detected using a photodiode (DET10C, Thorlabs, USA). For the reflective mode, the incident ray and the reflected ray lie in the same plane with an intersection angle of $\sim 5^\circ$. The stretching direction of the droplet is perpendicular to this plane.

Figure 6 shows voltage-dependent light transmission (curve-a) and double-transmission (reflection, curve-b) of the device. At $V = 0$, the droplet does not cut the beam. Therefore, the transmission is maximum. When the applied voltage exceeds $V \sim 6.5 \, V_{rms}$, the droplet begins to attenuate the beam. As a result, the transmission starts to decrease. By increasing the voltage, the droplet progressively cuts the beam. When the voltage is higher than $V \sim 27 \, V_{rms}$, the transmission approximates to saturation. The insert chart is the enlarged part in the lowest transmission region. This result implies that the beam is completely covered by the droplet. In the transmissive curve, the highest transmission is $T_{max} \sim 0.84$ at $V = 0$ while the lowest transmission is $T_{min} \sim 0.0105$ at $V = 27 \, V_{rms}$. As a result, contrast ratio (CR) is $I_{max}/I_{min} \sim 80$. In the reflective curve, the droplet cuts the beam extremely and the reflectance is measured to be zero at $V \sim 27 \, V_{rms}$. This result implies that the lowest light intensity is beyond the highest sensitivity of the CCD detector. However, CR can be estimated using (5). Since CR in transmissive mode is $\sim 80$, the CR in reflective mode should be $\sim 6400$. From
Figure 6, the transmission loss is \(\sim 0.16\). This loss is mainly due to reflection and absorption of ITO glass substrates, the Teflon layer, and silicone oil. The reflection of ITO electrode is measured to be \(\sim 10\%\). Since the used ITO electrode is patterned with stripes, the transmission loss by ITO stripes is below \(\sim 5\%\). The transmission loss can be reduced by using an AR coating, and choosing a desired dielectric liquid to replace silicone oil.

Using (4), the absorbing coefficient \(\beta\) of the glycerol can be estimated. To measure \(\beta\), a glass cell with a uniform gap (\(\sim 2.1\) mm) is prepared. We first fill the glass cell using a glycerol. We then use the laser beam to normally incident on the glycerol layer. The output light intensity is measured to be \(\sim 0.213\) arbitrary. After that, we remove the glycerol and fill fluidic NOA65 in the cell. NOA65 is highly transparent to \(\lambda \sim 1.55\) \(\mu\)m. The output light intensity passing through the NOA65 layer is measured to be \(\sim 4.39\) arbitrary. Using (4), \(\beta\) is calculated to be \(\sim 1.44\) /mm.

To avoid large error, the equivalent thickness (\(t\)) is calculated when \(V \geq 20\) \(V_{\text{rms}}\), because the deformed droplet can efficiently cover the beam. Using the transmissive curve-a (figure 6), \(\beta\) and (4), \(t\) can be simply calculated. Results are given in table 1. When the voltage is increased, \(t\) tends to increase slightly. Compared to the apex height of the droplet (\(\sim 3.45\) mm), the estimated \(t\) is reasonable.

If the device is used for a fiber optical switch, results shown in figure 6 can convert to attenuation using dB = 10 \times \log(T_0/T). The calculated results are given in figure 7. In the transmissive mode, the largest attenuation is \(\sim 19.0\) dB at \(V \sim 27\) \(V_{\text{rms}}\). IL and PDL are measured to be \(\sim 0.75\) dB and \(\sim 0\), respectively. The zero PDL is mainly due to isotropic glycerol and light control by absorption. In the reflective mode, IL is measured to be \(\sim 0.76\) dB and PDL is \(\sim 0\) as well. At \(V = 20\) \(V_{\text{rms}}\), the attenuation is \(\sim 19.0\) dB. Theoretical calculation shows that the attenuation can reach 38.0 dB at \(V = 27\) \(V_{\text{rms}}\) (shown by dash triangles).

As a VOA, response time of the stretched droplet is measured as well. A squared pulse voltage with 30 \(V_{\text{rms}}\) (300 Hz) is used to repetitively impact the droplet for three cycles. The duration of the pulse voltage is 2.5 s. Time-dependent light intensity change is monitored by an oscilloscope. Results are shown in figure 8. It takes \(\sim 1.2\) s for the droplet to completely cover the laser beam, and \(\sim 1\) s for the droplet to restore its original shape. Numerous cycles show that electro-optical characteristics of the droplet repeat well.

Compared to its transmissive counterpart, the reflective mode can obtain much larger attenuation. It is suitable for a single-mode fiber VOA. Its measured IL is low and its PDL is negligible. The IL loss is mainly due to

| Voltage \((V_{\text{rms}})\) | \(t\) (mm) |
|-----------------|----------|
| 21              | 2.45     |
| 22              | 2.53     |
| 23              | 2.79     |
| 24              | 2.89     |
| 25              | 3.03     |
| 26              | 3.09     |
| 27              | 3.16     |
| 28              | 3.16     |
the reflection and absorption of ITO glass substrates and Teflon layer. By applying anti-reflection coating to the substrate surface, IL loss can be reduced. To compact the device, a dielectric mirror layer can be coated on the inner surface of one substrate. Since the travel distance of the droplet is in ∼1 mm scale, the required actuating voltage is not high, and the response time is not slow. When the droplet is used to attenuate a large-diameter laser beam, the droplet should be stretched largely. This can cause issues such as slow response time, high driving voltage, and distinct hysteresis. Therefore, a small droplet is suitable for attenuating a thin beam. To switch a beam with large-area, a droplet array should be adopted.

Although the size of the droplet is relatively large, and their densities do not match (∇ρ ∼ 0.24 g cm⁻³), the device can work well in horizontal position. This is because the adhesion between the glycerol droplet and the convex anchor spot is stronger. When the cell is tiled 45° along the horizontal position, the gravitational effect on deforming the shape of the droplet is relatively small. Since the glycerol droplet is used for optical attenuation rather than for imaging, slight shape distortion by gravitational effect is not a concern. When the device cell is placed vertically, the droplet may not be firmly held by the anchor spot. To solve this issue, it is feasible to choose density-matched liquid to replace silicone oil or decrease the size of the droplet. Using the glycerol droplet, the attenuation can cover the entire C-band (1530 to 1565 nm). This region is relatively narrow. However, the absorption band can be extended by doping the droplet with an IR dye. For example, the droplet doped with Rose Bengal can also attenuate near-IR wavelengths ranging from 6.85 to 6.94 μm. By doping a suitable IR dye, the attenuation can be extended to mid-IR wavelengths.

In contrast to previous optical switches, our VOA in reflective mode (twice transmission) has several merits: larger attenuation range with a low driving voltage, low IL, and negligible PDL. In transmissive mode, transmitted light keeps the same direction of propagation. In reflective mode, the transmitted light is reflected back after twice transmission. Because of this feature, the reflective-mode is particularly suitable for fiber-optical switch. In fiber-optic switches, the diameter of the beam is ∼0.4 mm or smaller. When the droplet is used to attenuate such a thin beam, a little stretching of the droplet will be sufficient to cut the beam completely.
Therefore, the required voltage can be reduced further. Although the cell works by absorption, the liquid can still present good thermal stability because the surrounding medium can dissipate the generated heat.

5. Conclusion

We have reported a VOA using a glycerol droplet and silicone oil. Optical attenuation is obtained based on the principle of absorption. By stretching the glycerol droplet in one direction, a thin laser beam ($\lambda \sim 1.55 \, \mu m$) can be attenuated. Voltage-dependent transmission of this device is measured in both transmissive and reflective modes. The device in reflective mode can offer much larger attenuation than its transmissive counterpart while other performances are unchanged. In the reflective mode, the attenuation can reach $\sim 38 \, dB$ at $V = 27 \, V_{rms}$. IL is $\sim 0.75 \, dB$ and PDL is negligible at various voltages. Total response time is measured to be $\sim 2.2 \, s$. Due to the anchor spot, the device has good mechanical stability during actuation. By doping a suitable IR dye to glycerol droplet, the attenuation range can be extended. Such VOA in reflective mode has potential applications in IR light shutter, fiber-optic switch, sensing, and other lab-on-a-chip systems.

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