AN OPTOFLUIDIC BEAM SPLITTER
WITH LARGE TUNING ANGLE
VIA CONTROL OF FLOW RATE
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ABSTRACT
This paper reports a phenomenon of light in which light is split by three flow streams with a large tunable angle up to 30\(^\circ\). The core flow stream with lower refractive index is sandwiched by the cladding flow streams with higher refractive index. The miscible fluids creates a refractive index gradient in the microchannel that split an incident beam into two propagating paths. The angle is controlled by the composition of the fluids and the flow rates. The optofluidic splitter has high potential applications in biomedical and chemical solution measurement and detection.

KEYWORDS: Optofluidic, Beam splitter, Diffusion

INTRODUCTION
Optofluidics combine fluid and light to produce a new class of tunable devices, such as adaptive optical lenses\(^1\), optofluidic microscopes\(^2\) and liquid waveguides\(^3\). Optical splitter is another important device in integrated optics. Recently, an optical splitter comprises six streams to form two parallel liquid waveguides is designed\(^4\). The incident light can be split with a split angle \(\theta < 0.5\degree\) (\(\lambda = 780\) nm) by the diffusion between the two parallel liquid waveguides. The main limitation of the device is its limited split angle. In this paper, we report an optofluidic splitter with a larger tunable split angle from 0\(^\degree\) to 30\(^\degree\) formed by the laminar flow of three streams of liquids in the microchannel. In the microchannel, two streams of liquid with higher refractive index sandwich a stream of liquid with lower refractive index. The ability of the streams of miscible fluids to create gradients in optical properties by diffusion will divide the incident beam into two propagating paths. The angle is controlled by the composition of the fluids and the flow rates. The optofluidic splitter in the microchannel is investigated both theoretical analysis and experimental study.

Figure 1: Schematic illustration of the tunable liquid splitters.
DESIGN AND FABRICATION

The design of the tunable beam splitter is schematically illustrated in Fig. 1. Unlike liquid waveguide, the central stream with lower refractive index (core) is sandwiched by two streams of liquid with higher refractive index (cladding). Fig. 2(a) shows the simulation results of the diffusion process in the microchannel based on the convective-diffusive transport equation. Methanol and ethylene glycol were used as the fluids for the core ($n = 1.329$) and the cladding ($n = 1.431$). Diffusion coefficients for the methanol/ethylene glycol system were assumed to be similar to those found in water/ethylene glycol system. Fig. 2(b) shows that the input light at 488 nm wavelength is divided into two propagating paths and the split angles $\theta = \theta_1 + \theta_2$ is controlled by the flow rates and the refractive index gradient.

The optofluidic splitter was fabricated by polydimethylsiloxane (PDMS) using standard soft-lithography process. The solutions do not swell PDMS and therefore do not affect the dimensions of the microchannels. In addition, organic dye, i.e. Rhodamine 6G, is added to both fluids to visualize the light propagation in the microchannel.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 3 shows the light propagation in the microchannel when the three laminar flow streams are formed. The light beam is clearly seen to be split into 2 paths and propagates in the cladding flow streams. Fig. 4 shows the split angle $\theta$ is tuned by varying the flow rates when the cladding flow streams are injected with $n_1 = n_2 = 1.431$. The split angle is increased from 0° to 15° when the core and cladding flow rates are tuned from 50 µl/min to 1 µl/min and 0.5 µl/min as shown in Fig. 4(a-c). By maintaining the core flow rate at 0.5 µl/min, the split angle can be further increased from 20° to 30° by increasing the cladding flow rate from 1 µl/min to 1.5 µl/min and 2 µl/min. As a result, $\theta$ can be tuned.
tuned from 0° to 30°.

Figures 5(a)-(f) shows the tuning of the split angle θ with the cladding flow streams injected with different refractive indices of CaCl₂ solution (n₁ = 1.42 and n₂ = 1.46). The same flow rates in the cladding flow streams with different refractive indices cause a asymmetry splitter, i.e. 9.5° in cladding stream with n₁ as compared to 9° in cladding stream with n₂ as shown in Fig. 5(b).

CONCLUSIONS

In conclusion, an optofluidic beam splitter with tunable split angle controlled by the flow rates in a microchannel is designed, fabricated and demonstrated. The split angle can be tuned up to 30°. It can be designed for optical spectrometers and sensors, and has high potential applications in biological, chemical and medical solution measurements and detection.

REFERENCES