A NANO-OPTOFLUIDIC WAVEGUIDE COUPLER WITH SUPER-RESOLUTION VIA CONCURRENT DEAN FLOWS

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ABSTRACT
This paper presents a nano-optofluidic waveguide coupler realized by a pair of concurrent dean flows. Distinctively different from solid waveguide coupler, this nano-optofluidic waveguides consists of a laminar liquid flow, which exhibits spatially varying bidirectional refractive index profile that support novel evanescent coupling phenomenon. The nano-gap and the refractive index contrast of the nano-optofluidic waveguides can be measured with super-resolution in nm by analyzing its resulted evanescent coupling pattern. The nano-optofluidic waveguides can be used for biomolecular manipulation and detection in near future.

KEYWORDS
Optofluidics, Transformation optics, Dean flows, waveguide coupling, micro/nanofluidics.

INTRODUCTION
Optofluidics is one of the main research areas in Lab-on-a-Chip research, combining microfluidics and photonics in synergy to innovate optical based integrated systems with photonic functionalities. Basic geometrical optical components have been widely demonstrated in optofluidic systems such as liquid microlenses [1, 2], droplet gratings [3, 4], liquid prism [5], droplet-based color filter [6] etc. In addition, integrated optical detection systems have been developed for biomedical applications, such as single cell biophysical measurements [7, 8]. Recently, optofluidic transformation optics is employed to design an optical waveguide with distinctive photonic phenomena, including lightwave bending and manipulation [9]. This work has opened new door for optofluidic research in the field of transformation optics.

To overcome the limitation in solid waveguide coupling, in this paper, an optofluidic waveguide coupler is demonstrated. The two optofluidic waveguides are realized by concurrent Dean Flows in a single microchannel, with a tunable nano-gap between the waveguides. The refractive index profile along the microchannel is controlled by tuning the flow rates of the liquid flows. Distinctive evanescent coupling patterns can be designed through transformation optics and realized based on the optofluidic technology.

DESIGN AND THEORETICAL ANALYSIS

![Figure 1: (a) Schematic of the nano-optofluidic waveguide coupling. (b) Bidirectional refractive index gradient profile in the microchannel. (c) Cross-sectional refractive index profiles of (b) at z = 0, L/2 and L.](image)

Figure 1(a) shows the schematic design of the nano-optofluidic waveguide coupler. It consists of four inlets, whereby each optofluidic waveguide is realized by using two flow streams via Dean’s flow in a curved microchannel. When Dean’s flow is acted on the two flow streams, the transverse flow transport the inner flow stream towards the outer wall, and consequently the outer...
Therefore, the power variation along and 2 can be determined as

\[ P_1(z) = P_2(0) \cos^2 \kappa z \]  

and

\[ P_2(z) = P_2(0) \sin^2 \kappa z \]  

The coupling length can be determined as

\[ L = \frac{\pi}{2\kappa} \]  

For optofluidic waveguide coupler, the coupling is more complicated than the one in solid waveguide coupler. Since the refractive index profile is varying along \( z \) and \( y \), the coupling coefficient is no longer a constant value. The power variation along \( z \) for waveguide 1 and 2 can be expressed as

\[ P_1(z) = P_2(0) \left[ \cos^2 \gamma(y,z) z + \left( \frac{\Delta\beta(y,z)}{2\gamma(y,z)} \right)^2 \sin^2 \gamma(y,z) z \right] \]  

and

\[ P_2(z) = P_2(0) \left( \frac{\kappa}{\gamma(y,z)} \right)^2 \sin^2 \gamma(y,z) z \]  

where \( \Delta\beta \) is the difference in propagation constant, and

\[ \gamma(y,z)^2 = \left( \frac{\Delta\beta(y,z)}{2} \right)^2 + \kappa(y,z)^2 \]  

The coupling length can be expressed as

\[ L = \frac{\pi}{2\gamma(y,z)} \]  

Figure 2 shows the coupling patterns under different conditions. When the gap between the two optofluidic waveguides is decreased from 1-\( \mu \)m to 200 nm, the coupling length is reduced from 9.5 mm to 5.5 mm as shown in Fig. 2(a) and (b). For symmetrical optofluidic waveguides, the coupling pattern is identical between the two optofluidic waveguides. On the contrary, for asymmetrical optofluidic waveguide, i.e. the core liquids of the two optofluidic waveguides have different contrast (0.001 & 0.002), the coupling pattern is significantly different as shown in Fig. 2(c). When light is injected to the one with lower refractive index, most of the light is still being confined in the waveguide, but periodic micro-sized evanescence leak wave can be observed in the other optofluidic waveguide. For optofluidic waveguide, a triangular cross-sectional fluidic profile is achieved. The coupling pattern of such profile is shown in Fig. 2(d), which is significantly different from the circular one. The coupling pattern is relatively irregular.
The optofluidic chip is fabricated by using the standard soft-lithography techniques. First, a 100-µm SU8 photoresist (SU8-100, MicroChem) is spin-coated onto a silicon wafer by using the CEE-200 spin coated (Brewer Science). The coated wafer is prebaked for 10 min at 65°C and 30 min at 95°C before being exposed to 19-s of UV light (Mask aligner 506, OAI). Then, a postbaking step is applied with 1 min at 65°C and 10 min at 95°C, following by a development step. With the developed master, a mixture of prepolymer and curing agent of polydimethylsiloxane (PDMS) is poured over it, degassed and baked for 2 hours. The solidified PDMS chip is peeled off from the master and bonded with a PDMS slab by air plasma (corona treated BD-25, Electro-Technic Products). A single mode 488-nm optical fiber is integrated and aligned by the aid of the fiber groove patterned by the soft lithography process. Syringe pumps (NE-1000, New Era Pump Systems Inc) are used for liquid injection, a confocal microscope (LSM710 META, Zeiss) and a fluorescent microscope (Eclipse Ti-U, Zeiss).
Nikon) are used for imaging the liquid cross-sectional profile and the evanescence coupling pattern, respectively.

RESULTS AND DISCUSSIONS
Figure 3(a) shows the formation of the two optofluidic waveguides. When the core flow streams and the cladding flow streams have a same flow rate of 70 μL/min (1 : 1), a measured 200-μm gap is achieved (Fig. 3(b)). The cross-sectional image shows that the waveguide has a triangular shape. At 1 : 2, the gap is increased to 800 nm (Fig. 3(c)). The cross-sectional area of the waveguide is reduced. Subsequently, at 1 : 3, the gap is further increased to approximately 1.4 μm as shown in Fig. 3(d). This shows that the nano-gap between the two optofluidic waveguides can be easily tuned by varying the flow rate ratio between the inner and outer liquid flow streams.

Figure 4(a-c) shows the coupling patterns of the three flow conditions as illustrated in Fig. 4(b-d). The coupling length is increased when the gap between the optofluidic waveguides is increased, as predicted in the simulation results. Fig. 4(d) shows the comparison between the simulation and experimental results (1 : 2). Both results agree well with each other.

CONCLUSIONS
In conclusions, a nano-optofluidic waveguide coupler is demonstrated. The two 3D optofluidic waveguide is realized by concurrent Dean’s flow in the microchannel. As compared to solid waveguide coupler, this nano-optofluidic waveguides exhibit distinctive evanescent coupling phenomenon due to its spatially varying bidirectional refractive index profile in the microchannel. The nano-gap and the refractive index contrast of the nano-optofluidic waveguides can be measured with super-resolution in nm by analyzing its evanescent coupling pattern. The nano-optofluidic waveguides can be used for biomolecular manipulation and detection in near future.

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