Continuous Operation of a Hybrid Solid-Liquid State Reconfigurable Photonic System without Resupply of Liquids

CNF Project Number: 1764-09
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Abstract:
In this work, we demonstrate solutions to the two major technical roadblocks that prevent the widespread adoption of liquid state photonics. By developing an on-chip gravity based liquid core/cladding separation system and unique solid-to-liquid-to-solid state coupling techniques, we have demonstrated here the ability to address two major roadblocks in cooperating solid and liquid state optical components. Quantitatively, we demonstrate the ability to reduce liquid consumption over 1,000-fold compared to the state of the art, while enabling reconfiguration on the order of 100 times greater than what is achievable with other optomechanical approaches.

Summary of Research:

Introduction. Optofluidics offers a number of potentially transformative advantages for photonic systems [1]. At present, however, there are a number of technological roadblocks that prevent the practical integration of liquid-state elements into traditional high-speed solid-state photonic systems. Two of the most important of these are the need for continuous resupply of liquids and the difficulty in shuttling light between the liquid- and solid-states. In the paper [2] we present an integrated system that solves both these problems.

Discussion. Figure 1a-1c, shows the fabrication method used to integrate the liquid and solid waveguides onto a single substrate. Briefly, standard photolithography techniques were used to fabricate a single layer SU-8 structure that contains: the microfluidic channels to form the liquid-core waveguide, the input and output solid-core waveguides, and the separation reservoir. The patterned SU-8 layer was covered by a single PDMS sheet to seal the microfluidic channels and provide more capacity for the separation reservoir (Figure 1c). Working principle of the recirculation system and a microscopic view of the actual device are shown in Figure 1d and 1e. The recirculation was enabled by the use of immiscible liquids, DI water (RI = 1.336) as the core solution and Fluorinert electronic oil (FC-40, RI = 1.22) as the cladding. After forming the liquid waveguide, the core and cladding liquids were collected and separated in the reservoir by taking advantage of the differences in their densities and pumped back into microfluidic channels by external micropumps.
Figure 2a shows an overview of the hybrid photonic system during operation with Figures 2b and 2c illustrating the two end-fire switching states for the liquid core waveguide. Figure 2d shows the profile of the normalized optical intensities for the coupled (red) and non-coupled waveguides (blue) projected onto the reflectors. To test the effects of liquid waveguide curvature on the coupling performance, the coupled output solid waveguides were offset between 5 µm (Figure 2e) and 95 µm (Figure 2f) from the center axis (equivalent to a curvature change from $10^2$ to $10^3$ m⁻¹), while the output solid waveguides were fixed a 35 µm from the center axis. Figure 2g shows cross-talk values as a function of the offset of the output waveguide. Figure 2h-2i show adaptation of the width of the liquid core by changing the upstream flow conditions. As we decreased the applied pressure of the core flow from 70 to 17 kPa, the width of the liquid waveguide decreased from 50 to 20 µm (shown in Figure 2j) improving the cross-talk value from 5 dB to 12 dB.

We demonstrate evanescent coupling between liquid- and solid-core optical waveguides for the first time. By controlling the pressure of the cladding flow on the left side channel in Figure 3a, we could alter the width of the cladding flow between the liquid and the solid waveguide to change the cross-talk value. Figures 3d and 3e show the projected light on the reflector placed at the end of the output solid waveguide and cross-talk values as a function of the pressure of the cladding flow. The coupling ratio increased as the pressure of the flow decreased to narrow the gap between the liquid and the solid waveguide. At pressures lower than 7 kPa, stable physical contact between the liquid waveguide and the solid waveguide was obtained as shown in Figures 3b and 3c.

Fluidic recirculation is fundamentally important to the development of a practical hybrid system as it allows one to operate the device continuously without having to refill or remove liquids from the chip. To demonstrate the long-term operation of our device we performed the end-fire optical switching for 20 continuous hours, without requiring the resupply of liquids. As above, we measured the system performance using cross-talk values at different switching speeds (1 s, 3 s, and 5 s). The results are shown in Fig. 4.

Figure 4a shows images of the end fire coupling at the start and at the end of the 20 hour operational period at 1s switching speed and Figure 4b shows the cross talk values measured periodically during the operation. The liquid consumption compares with the 40 mL/20 hours of liquid consumed by the previous device for the same time period, representing 200-fold improvement.

Conclusions:
For the first time we demonstrate direct evanescent and end-fire coupling between liquid- and solid-state waveguides and an on-chip fluid core/cladding separation and recirculation system that reduces the consumption of liquids more than 200 fold over the state of the art. The device is operated continuously for over 20 hrs without performance degradation or requiring the replenishment of liquids. We believe that our system represents an important step towards the development of practical optofluidically enabled photonic systems.

References: