Making temperature-insensitive optofluidic photonic-crystal devices

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Infiltrating the air holes of a lattice with liquid enables construction of thermally stable resonant devices.

Resonant optical cavities are major building blocks in many applications, from microlasers and high-sensitivity biomedical sensor systems to optical filters, switches, and integrated circuits. Device performance depends strongly on their stability against changes in ambient conditions. For example, refractive-index sensors based on optical-resonance techniques suffer from temperature drift that introduces noise and degrades sensitivity.¹ As a second example, the thermal stability of integrated photonic devices is crucial for making commercially viable integrated optoelectronic circuits.

Recently, several techniques have been proposed to create temperature-insensitive nanophotonic devices. One group micromachined a Fabry-Pérot cavity into a single-mode optical fiber.² A second team employed a microstructured fiber containing a Bragg grating and infiltrated its holes using a refractive-index material with a negative thermo-optic coefficient.³ Other approaches include silicon-on-insulator waveguides coated with negative-coefficient polymer cladding⁴ and silicon waveguides in a balanced Mach-Zehnder configuration.⁵ We suggest a novel approach that is adaptable to a wide range of applications.⁶ It is based on the tendency of fluid refractive indices to decrease with temperature, while those of a range of dielectrics vary in the opposite way. Thus, with an appropriate design, these opposing tendencies cancel each other out, creating a thermally balanced optical configuration.

The key concept of our scheme relies on infiltrating the lattice with a liquid that has a negative thermo-optic coefficient, which balances the positive thermal drift of the host photonic-crystal (PhC) material. Figure 1 shows the temperature dependence of the refractive indices for silicon and a commercially

Figure 1. Refractive index versus temperature for silicon and a liquid at a wavelength of $\approx 1410\text{nm}$.

available Cargille immersion oil, type B (with thermo-optic coefficients $\partial n_{\text{Si}}/\partial T = +2 \times 10^{-4}/\text{K}$ for the former and $\partial n_{\text{L}}/\partial T = -3 \times 10^{-4}/\text{K}$ for the latter). For PhC waveguides with air holes penetrated by liquid, the effective refractive index experienced by guided modes depends on the combination of the two (host material and liquid), weighted by the filling fraction f . This represents the relative electric-field overlap with the corresponding material. PhC host materials (silicon and III-V-type semiconductors) have positive coefficients,⁷ as opposed to most liquids⁸ and polymers.⁹ Therefore, a large range of pairings has an effective combined index that renders devices temperature-insensitive if the guided mode has an appropriate fraction of electric-field overlap in each material.

To form a microfluidic double-heterostructure cavity (see Figure 2),^{10–12} we infiltrated Cargille immersion oil (see Figure 3) into-silicon PhC membranes. Figure 4 shows transmission

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Figure 2. Schematic of the optofluidic double-heterostructure cavity. (top) Photonic-crystal slab containing a line defect. Fluid penetrating the air holes leads to a mode-gap effect. (bottom) Band diagram along the waveguide direction. The transmission region (gray) allows photon propagation in the waveguide, which is suppressed by the mode-gap section (red). Photons with frequencies within the mode gap can only propagate in the infiltrated waveguide region. a : Lattice period of the crystal. L : infiltrated cavity length. ω : Frequency. c : Speed of light. λ : Wavelength. $\Gamma-K(x)$: Direction of symmetry in the crystal lattice.

Figure 3. Infiltration process. We immerse a microtip into a liquid and draw it across a photonic crystal to create a microfluidic cavity.

spectra as a function of temperature while probing an infiltrated optofluidic cavity. The microfluidic cavity sustained Fabry-Pérot resonances with moderate quality factors of order 15,000–20,000.

We found that the resonance wavelengths of the Fabry-Pérot cavity shift with temperature (see Figure 4). In the temperature range investigated, resonances (2) to (5) show a blue shift between -0.03 (2) and -0.06nm/K (5), while (1) remains exceptionally stable at $\lambda = 1405\text{nm}$, with an extremely low gradient of -0.003nm/K . This represents a 20-fold reduction in temperature sensitivity compared to (5) and a 27-fold decrease compared

Figure 4. Transmission spectra at various temperatures measured on an optofluidic cavity of length $6.8\mu\text{m}$. (1)–(5) indicate the resonance wavelengths. a.u.: Arbitrary units.

to a standard silicon-PhC waveguide.¹³ The data in Figure 4 demonstrates an important generic property: if a system of elements with opposing temperature dependencies creates a range of resonances, then there will often be one where field sharing leads to temperature insensitivity.

In summary, we have demonstrated a scheme to make nanophotonic devices independent of their environment's temperature. This promotes development of robust, high-sensitivity sensor systems that respond to liquid refractive-index changes, while reducing the complexity caused by thermal fluctuations. Temperature insensitivity may also pave the way for high-precision nanophotonic components such as microlasers, filters, and switches. Future work will incorporate thermally stable cavities into fully integrated, reconfigurable optical circuits. We plan

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to combine numerous optofluidic components on the same platform through selective air-hole infiltration, enabling highly complex optical capabilities.

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