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# Controlling thermo-optic response in microresonators using bi-material cantilevers

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We demonstrate a novel platform to control the thermo-optic sensitivity in nanophotonic devices by evanescent coupling of light with bimaterial cantilevers. The cantilever can be designed to provide a negative thermal feedback to passively compensate for the positive thermo-optic effect in the waveguide core. We demonstrate athermal operation over 14 degrees in cantilever coupled Silicon ring resonators, limited only by fabrication tolerances. We also show how the same platform can provide positive thermal feedback and overcome the material thermo-optic limit for increasing sensitivity of resonant detectors and thermal imagers. © 2014 Optical Society of America

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Thermal sensitivity of optical microresonators is one of the major bottlenecks for technology implementation of silicon photonics. The sensitivity of any photonic structure to ambient temperature fluctuations is caused by the change in material refractive index with temperature, which is called thermo-optic (TO) effect [1]. Thermo-optic coefficient of Si ( $1.86 \times 10^{-4} \text{ K}^{-1}$ ) is almost an order of magnitude higher than that of most other commonly used photonic materials ( $\text{SiO}_2$ ,  $\text{Si}_3\text{N}_4$  etc.). This leads to a resonance sensitivity of  $\sim 0.1 \text{ nm/K}$  for an optical mode tightly confined in Si, irrespective of device design or dimension. This sensitivity is frequently exploited to tune the resonance wavelength [2] or make sensitive detectors and thermal imagers [3]. However this temperature sensitivity also makes Si photonic devices extremely unstable in integrated platforms [4]. For example the resonance wavelength of a Si ring resonator, with a moderate quality factor of 10000, will shift by one linewidth with only  $1^\circ\text{C}$  change in temperature.

Most of the approaches proposed to overcome the problem of temperature sensitivity in Si photonics are power hungry, CMOS-incompatible or lead to delocalized optical modes. Temperature stabilization schemes using negative thermo-optic coefficient based polymers are not compatible with front-end CMOS processing and lead to delocalized optical modes [5, 6, 7]. Active stabilization involving sensors and heaters can be extremely power hungry, especially since heaters need to be placed far from the optical mode to avoid metal induced losses [8, 9, 10, 11, 12]. Recently there have been novel demonstrations of thermal stabilization of a resonator by coupling it to a larger interferometer which counteracts the thermally induced phase change in the resonator [13, 14, 15, 16]. This scheme is CMOS-compatible and passive, but needs extra footprint for the interferometer. Finally recent

works have used  $\text{TiO}_2$  as cladding, which has an inherent negative TO effect to counter the positive TO effect of Si [17, 18, 19, 20]. The drawback of this scheme is that the optical mode needs to be delocalized and any further tuning or modulation becomes extremely power hungry.

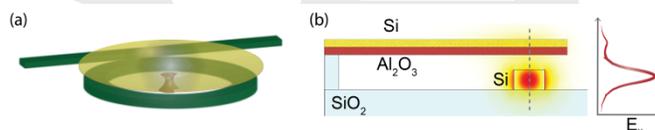


Fig. 1. (a) Schematic of the proposed platform: a bimaterial cantilever is evanescently coupled to the resonator waveguide. (b) Cross-section view and TE polarized optical mode of the coupled cantilever-waveguide system. E-field along the dashed line is also shown.

While some schemes have been proposed and implemented to reduce the TO effect in photonic devices, very limited work has been done to fully control the TO effect or even increase the temperature sensitivity for certain applications. The primary reason is that upper limit in thermal sensitivity of photonic devices is a fundamental material constant (TO coefficient), which is set by sensitivity of the material bandgap to temperature due to electron-phonon coupling, lattice expansion coefficients [21] etc. In practice, measured thermal sensitivities are slightly lower than this upper limit because only part of the optical mode is confined in the waveguide core. Hence applications which need high thermal sensitivities, like thermal tuning and thermal detectors [3, 22, 23], are also constrained in their sensitivity/ efficiency by this upper limit.

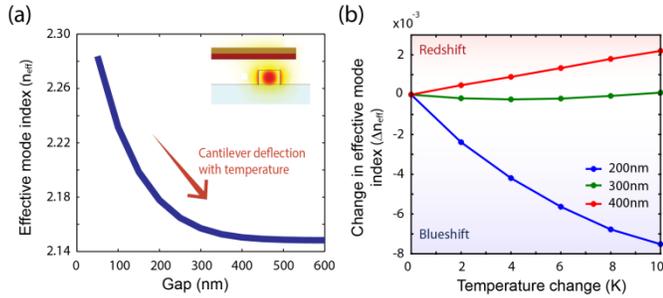


Fig. 2. (a) Effective index of the coupled optical mode as a function of coupling gap. (b) Change in effective index of the optical mode as a function of temperature for different coupling gaps of the cantilever. When the cantilever is far from the resonator waveguide, change in effective index is positive and close to TO limit ( $\sim 2 \times 10^{-4} \text{ K}^{-1}$ ). As the coupling gap is reduced, the cantilever interacts strongly with the optical mode and causes giant negative change. One can see that there is an optimum coupling gap where change in  $n_{\text{eff}}$  with temperature is minimal.

In this paper, we present a platform that achieves full control over the thermo-optic response of a resonator, independent of the material TO coefficients, based on evanescent coupling between a bimaterial cantilever and an optical resonator. Cantilevers have previously been coupled to microresonators for achieving ultralow power wavelength tuning [24] or for decoupling optical and mechanical resonators in optomechanics [25, 26, 27, 28], but not in the context of manipulating thermal properties. Bimaterial cantilevers have been used for ultra-sensitive temperature measurements, such as near-field radiative heat transfer [29, 30]. In the proposed platform, the bimaterial cantilever deflects with change in temperature due to thermal stress, which provides a feedback to the resonator. The gap between the cantilever and the resonator can be adjusted to control the strength of this feedback. Figure 1(a) shows a schematic of a ring resonator with a bimaterial cantilever on top. For simplicity we chose a circular cantilever, though other designs can be similarly implemented. Fig. 1(b) shows a cross section of the waveguide, which has a Si core and the cantilever is made of Si on top and  $\text{Al}_2\text{O}_3$  at bottom. This particular cantilever is designed to provide a negative thermal feedback and lower the overall temperature sensitivity of the resonator. Note that one could use the same principle for increasing the temperature sensitivity by reversing the order of material layers in the cantilever. E-field distribution of the optical mode (Fig. 1(b) inset) shows that most of the field is still in the waveguide core, with only a small fraction delocalized in the cantilever.

Based on this concept, we show an athermal resonator where the thermo-mechanical response of the cantilever and the optomechanical coupling are designed to exactly cancel out the thermo-optic drift of the ring. The bimaterial cantilever is designed to bend upwards as temperature increases, thereby decreasing the effective index of the coupled mode and counteracting the thermo-optic effect. This is achieved by ensuring that the bottom layer of the cantilever has a higher thermal expansion

coefficient ( $\alpha$ ) than the top layer. In our specific design we chose  $\text{Al}_2\text{O}_3$  ( $\alpha=8 \times 10^{-6} \text{ K}^{-1}$ ) and Silicon ( $\alpha=3 \times 10^{-6} \text{ K}^{-1}$ ), each 100 nm thick. Figure 2(a) shows the strength of the optomechanical coupling. When the cantilever is far from the waveguide, the optical mode would be minimally perturbed by change in cantilever position. Effective index ( $n_{\text{eff}}$ ) of the coupled mode increases strongly as gap is reduced. The strength of this coupling can be engineered by refractive indices of the layers, material thicknesses and the initial gap. Figure 2(b) shows the change in effective mode index of the TE mode ( $n_{\text{eff}} \sim 2.27$ ) as a function of temperature for several different gaps. It is evident that when gap is large enough ( $>400 \text{ nm}$ )  $n_{\text{eff}}$  increases with temperature at a rate of  $\sim 2 \times 10^{-4} \text{ K}^{-1}$ , dominated by TO effect in waveguide core. At very small gaps ( $<250 \text{ nm}$ ),  $n_{\text{eff}}$  strongly decreases with temperature. At some intermediate gaps (250 - 350nm), where coupling is just right for thermal deflection of cantilever to cancel out refractive index changes in the waveguide, change in  $n_{\text{eff}}$  is minimal with change in temperature.

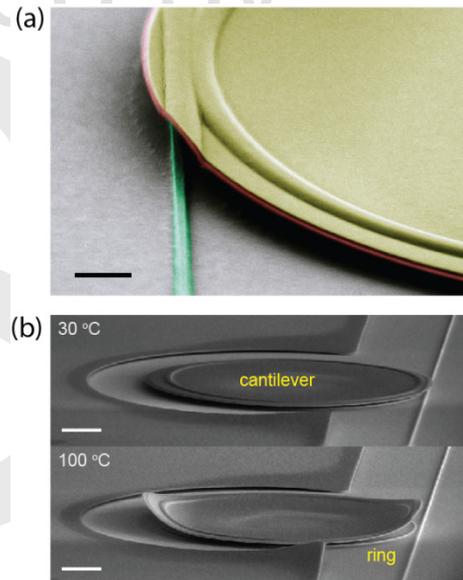


Fig. 3. (a) False colored SEM image showing the coupling waveguide and the bimaterial cantilever. Scale bar is  $2 \mu\text{m}$ . (b) Cantilever position at room temperature (above) and  $100^\circ\text{C}$  (below). Scale bar is  $20 \mu\text{m}$ .

Si ring resonators with properly designed circular bimaterial cantilevers were fabricated on a silicon-on-insulator (SOI) wafer with 240nm Si device layer and  $3 \mu\text{m}$  buried oxide layer (BOX). Waveguides were defined using electron beam lithography and etched in a  $\text{C}_4\text{F}_8/\text{SF}_6/\text{Ar}/\text{O}_2$  chemistry. A 10nm Si slab was left behind to isolate the buried oxide layer from subsequent release step. The device was cladded with 50nm  $\text{Al}_2\text{O}_3$  deposited using Atomic Layer Deposition. This  $\text{Al}_2\text{O}_3$  layer encapsulates the Si and further protects the BOX layer from the release step. 300nm  $\text{SiO}_2$  was deposited using plasma enhanced chemical vapor deposition (PECVD) which defines the gap between the cantilever and the waveguide and will act as sacrificial layer during cantilever release step. Circular cantilevers made of

100nm thick  $\text{Al}_2\text{O}_3$  and Si were deposited on top using electron beam evaporation and lift-off. Finally the cantilevers were released in HF-vapor based dry isotropic etch to obtain free standing bimaterial cantilevers on top of un-released Si ring resonators. Figure 3(a) shows scanning electron microscope (SEM) image of the coupling region of ring resonator with the cantilever on top. The deflection of cantilever was measured using a temperature stage inside a SEM chamber. Figure 3(b) shows that the cantilever indeed deflects upwards with increases in temperature due to larger thermal expansion of the bottom layer. The deflection is exaggerated since the cantilever is heated to over 100 degrees.

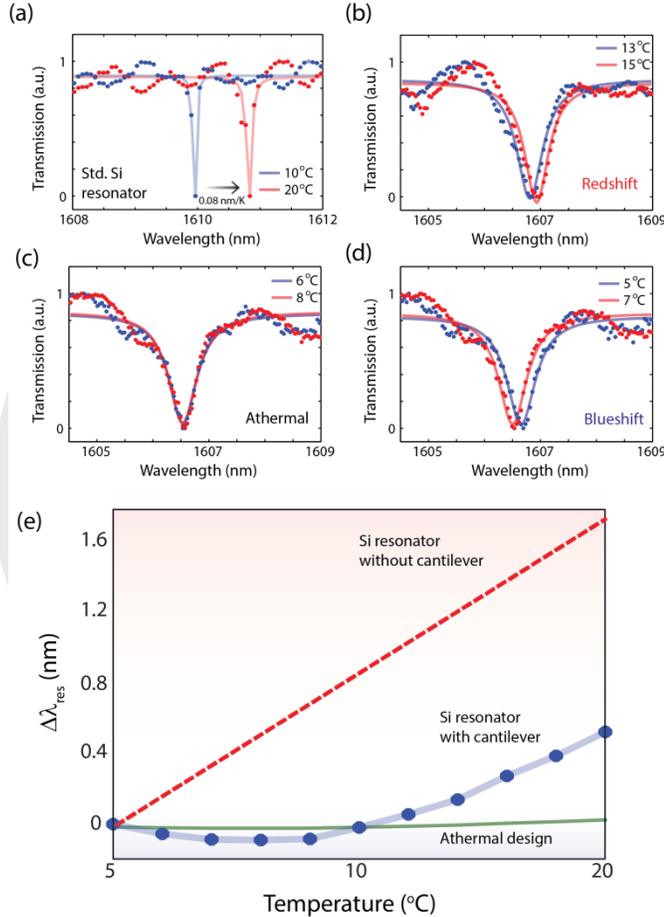


Fig. 4. (a) 0.08 nm/K redshift from standard Si resonator (b-d) Redshift, near-zero shift and Blueshift of resonances observed in a resonator coupled to a bimaterial cantilever. (e) Resonance sensitivity to temperature for Si resonator, with and without a compensating cantilever.

We demonstrate the ability to control the thermal sensitivity of the resonator, and capability of athermal operation over 14 degrees, limited only by our fabrication tolerance. Transmission spectrum of a  $40\mu\text{m}$  radius Si ring resonator was measured at different temperatures. For comparison, Fig. 4(a) shows the transmission spectrum of a Si resonator without any cantilever at two different temperatures. It shows a constant redshift of  $\sim 0.08$  nm/K, set by the TO coefficient of Si. Figures 4 (b-d)

shows the spectra of a fabricated Si resonator coupled to a bimaterial cantilever on top, designed to provide a negative thermal feedback. At temperatures of  $13^{\circ}\text{C}$  and above (Fig. 4(b)), the gap between the cantilever and the waveguide is large enough such that TO effect dominates and resonance redshifts with increase in temperature. As temperature is reduced, the cantilever moves closer to the waveguide and the TO effect is compensated by refractive index change caused due to the mechanical deflection of the cantilever. This is the athermal operating regime (Fig. 4(c)). Further reduction in temperature brings the cantilever even closer to the waveguide where optomechanical shift dominates causing blueshift of resonance wavelength (Fig. 4(d)). Figure 4(e) shows the resonance position over a wide temperature range. The resonance of a conventional resonator without any cantilever is shown in red. Temperature sensitivity in our cantilever coupled devices is significantly lower and changes sign as previously mentioned. Athermal operating range is around 14 degrees (defined by the range where change in resonance wavelength in less than half of the linewidth). Green line in Fig. 4(e) shows athermal behavior for ideal coupling gap of 300nm. In our devices, the cantilever bent up slightly during release due to residual stress, thus affecting the designed coupling gap. Accurate control of the coupling gap can extend athermal operation over a much wider temperature range.

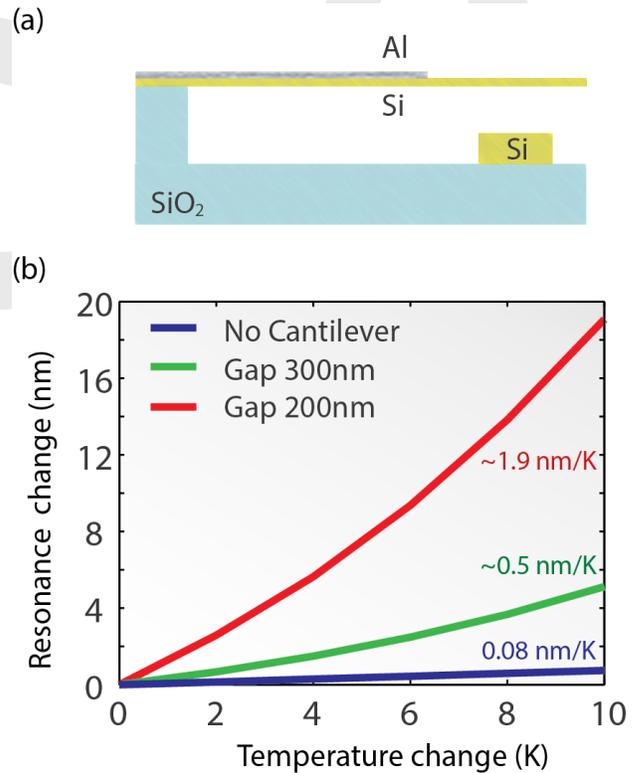


Fig. 5. (a) Cantilever design for enhanced thermo-optic response. (b) Temperature sensitivity of cavity resonance wavelength for different coupling gaps. At a gap of 200nm, over two orders of magnitude enhancement in temperature sensitivity is expected.

The above platform could, in principle, be used to also enhance the thermo-optic response of photonic structures and break the material TO limit of Si based thermal/ mid-IR all-optical detectors by over two orders of magnitude. Schematic of such a device is shown in Fig. 5(a), where a Si microresonator is evanescently coupled to a bimaterial cantilever made of Si and Al. Unlike the athermal design, this cantilever is designed to bend down with increase in temperature (Al has much higher thermal expansion coefficients ( $\alpha_{Al}=23 \times 10^{-6} \text{ K}^{-1}$ ) than Si ( $\alpha_{Si}=3 \times 10^{-6} \text{ K}^{-1}$ )). As temperature increases, cantilever comes closer to the waveguide increasing the effective index of the coupled optical mode, same as TO effect. This positive feedback greatly enhances the overall temperature sensitivity. Figure 5(b) shows the temperature sensitivity of the resonance wavelength for different coupling gaps. For a modest coupling gap of 200nm, the temperature sensitivity is  $\sim 1.9 \text{ nm/K}$ , which is an enhancement of over two orders of magnitude compared to the thermo-optic limit of Si ( $\sim 0.1 \text{ nm/K}$ ).

In summary, we have presented a novel platform to accurately control the TO sensitivity of optical resonators. We demonstrated that this technique allows us to achieve athermal operation of any Si / SiN based microring resonator independent of cavity size or quality factor. The device is compact, CMOS-compatible (all materials including those used in the cantilever are compatible with thermal budget of front-end CMOS) and has relatively large modal confinement in Si, in contrast to some of the previous works on attempting thermal stabilization using mode delocalization [5, 18, 19]. High confinement in Si is necessary for dense integration and low power tuning (thermo-optic or electro-optic). Mechanical design of the cantilever [31] (to linearize its deflection with temperature) and coupling gap can be optimized to yield a very large athermal operating range. The same platform can be modified to significantly enhance TO sensitivity of photonic devices. This is especially important for thermal/ mid-IR detectors, where the sensitivity is limited by optical quality factor, TO sensitivity, material absorption and thermal isolation. The overall photonic structure can in principle have TO sensitivities two orders of magnitude higher than material TO limit.

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