Thermo-optical properties of nanophotonic devices with carbon nanotube films

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Abstract. Here, thermo-optical properties of hybrid nanophotonic circuits SWCNTs/SiN were investigated by studying the temperature dependence of the resonance wavelengths. After experimental and theoretical study, we found the thermo-optical coefficient of SWCNTs film is equal to 2.02 10⁻⁶ RIU/°C.

1. Introduction
Integrated optical devices operating in the near-infrared wavelength range have become a popular platform for sensing applications, communication, and optical signal processing, and for studying the interaction of light and matter [1]. One of the main tasks of these schemes is to match the spectral responses of all-optical devices. Despite the advanced fabrication technologies, the inhomogeneity of fabrication leads to a discrepancy between the spectral responses [2]. One of the ways for solving the problem is the use of metallic microheaters [3]. However, metals absorb near-infrared wavelengths, so they must be placed a few microns away from the devices being tuned to avoid degrading the performance of optical devices. Thus, heating is not localized and results in thermal crosstalk between multiple optical devices. Silicon nitride has proven as a platform for thermal tuning. On the one hand, due to its wide bandgap (5 eV) and low optical loss (<0.1 dB/cm), the silicon nitride platform, is mainly used to create high-end on-chip passive photonic devices [4]. On the other hand, due to its weak nonlinearity, active optical elements should be performed based on additional nonlinear materials. A promising candidate for waveguide integration is single-walled carbon nanotubes (SWCNTs) films because of their unique electrical [5], mechanical [5], and optical [6] properties. Integration of silicon nitride waveguides with SWCNT films for thermal tuning can be eliminated from the disadvantages of metal heaters since the film can be placed directly on the waveguide. The development of photonic devices based on SWCNTs requires knowledge of the thermo-optical properties of films. Since the expected value of the thermo-optical coefficient is small, it cannot be measured by direct methods. Therefore, we made the SiN O-ring resonators (ORRs) with SWCNT film cells atop. Since the SiN thermo-optical coefficient is also small enough (dn/dT)Si3N4 =2.51×10⁻⁵ [7], due to the shifts of resonances in the transmission spectrum of OR, such a device provides a possibility to find refractive index and small thermo-optic coefficient of a hybrid waveguide structure (SiN/SWCNTs).
2. Device design and fabrication

For device fabrication, we used commercially available 540 μm thickness silicon wafers with 2.6 μm thermally oxidized and low-pressure chemical vapor deposited (LPCVD) 450 nm layer of Si₃N₄ atop. The ORRs were formed by direct e-beam lithography. E-beam resist ZEP 520A was used as a sensitive layer. Silicon nitride was etched at 225 nm in a CHF₃ plasma atmosphere. The resonator waveguide width of 1.6 μm, the ring length of 400.417 μm, and the 1.4 μm gap between the ring and bus waveguide were chosen, supporting a free spectral range (FSR) of about 3 nm. Focusing grating couplers are used for the input/output of light and have been optimized for wavelength 1565 nm and provide a coupling efficiency of 18%.

To measure the properties of SWCNTs films were deposited on the nanophotonic chips. The films were made by the aerosol (floating catalyst) chemical vapor deposition (ACVD) method [8]. In this method, nanotubes grow on aerosol particles in the hot zone of the reactor and collect on a filter at the outlet, forming thin uniform films that do not require further purification. Further, the nanotube film was transferred to photonic device by dry transfer. Fabrication steps are shown in Figure 1(a). The nanotubes were grown so that the diameter corresponded to the S₁₁ optical transition in the region of 1550 nm. The thickness of the film was measured as 22±4 nm. The AFM image of the SWCNTs film on the waveguide is shown in Figure 1(a). As can be seen from the image, the nanotubes in the film, intertwining with each other, completely cover the waveguide from all sides. In the end, the rectangular cells of SWCNT films using laser lithography and O₂ plasma etching were finalized (Figure 1 (c)). The SWCNTs cell width is 350 nm.

Figure 1. (a) Schematic view of the device fabrication process; (b) AFM image of SWCNTs film atop of SiN waveguide; (c) Optical micrograph of the fabricated device. White arrows show the propagation of light. The transparent light blue area shows the SWCNTs film cell.
3. Experimental results
To study the thermo-optical properties of the SWCNTs film, the transmission spectra of the fabricated devices were measured at different temperatures. The obtained spectra were analyzed and using finite element method, the thermo-optical coefficient of the SWCNTs film was obtained.

3.1. Experimental setup
The measurements were performed using a setup, that included a tunable laser source (New Focus TLB-6600), an optical Erbium-Doped Fiber Amplifier (EDFA), polarization controller, an array of optical fibers aligned with on-chip focusing grating couplers by motorized x, y, z, θ – stage (Figure 2 (a)) and temperature stabilized using proportional integral derivative (PID) controller. This setup makes it possible to measure the transmission spectra of devices at different temperatures. The optical signal transmitted through the waveguide was recorded with a fast photodetector. One of the transmission spectra of our devices is shown in Figure 2 (b).

Figure 2. (a) Experimental setup for measurements of the thermo-optical characteristics of fabricated hybrid waveguide devices with SWCNTs. Electric cables are shown by black lines, orange and blue are optical fibers; (b) Measured transmission spectrum of one of the fabricated O-ring resonator with SWCNTs film (top), the same spectrum normalized to the transmission of FGC (bottom); (c) The cross-section of a waveguide structure with SWCNTs atop. Color change shows field distribution for TE-like mode of waveguide. On the inset is an enlarged image showing the coverage of the film of the waveguide and its thickness; (d) Transmission spectra of one of O-ring resonator with SWCNTs for different temperatures. Along the Y-axis an offset of 0.25 is used.
3.2. Calculation method and results

Heating the sample led to a shift of resonance peaks in the transmission spectrum of the ORRs (Figure 2 (d)). Compared to ORR without nanotubes, the shift of the resonance wavelength occurs faster, which indicates that such a scheme is sufficiently sensitive to measuring the thermo-optical coefficient of the SWCNTs film. From the analysis of the transmission spectra, the shifts of the resonance peak wavelength with a temperature change were obtained. The wavelength shift without SWCNTs is equal to \(1.922 \times 10^{-2}\) nm K\(^{-1}\), as well as the wavelength shift with SWCNTs is equal to \(1.941 \times 10^{-2}\) nm K\(^{-1}\) (Figure 3 (a)). Then using the formula: \(\Delta n_{\text{eff}} = \Delta \lambda (T) / 2 \pi R_m\), connected the order of interference \(m\), waveguide parameters, and resonance peak wavelength the effective refractive index change from a temperature of the ORRs was extracted. The average value of \(dn_{\text{eff}}/dT\) extracted from the linear fit was found as value refractive index units per Celsius degree \(1.6616 \times 10^{-5}\) RIU/°C.

The calculation of the thermo-optical coefficient was carried out by the finite element method implemented in the COMSOL Multiphysics® software. For this, the cross-section of a waveguide with nanotubes atop was constructed. In the model, the film covers the waveguide from all sides as a solid object. Then, using the literature data for \(\langle dn/dT\rangle_{\text{SiN}} = 2.51 \times 10^{-5}\), \(\langle dn/dT\rangle_{\text{SiO2}} = 0.96 \times 10^{-6}\) [7] and the cross-section simulation of the effective refractive index value, the value \(\langle dn/dT\rangle_{\text{SWCNTs}}\) was selected in such a way that the theoretical value of the change in \(n_{\text{eff}}\) from temperature was consistent with the experimental one. The thermo-optical coefficient of the SWCNTs film is linear within the temperature range from 25 °C to 70 °C and equal to \(2.02 \times 10^{-6} \pm 0.25 \times 10^{-6}\) RIU/°C (Figure 3 (b)).

![Figure 3](image)

**Figure 3.** (a) Change in the resonance wavelength of a ring resonator with a change in temperature for a device with nanotubes (circles) and without (triangles). The lines are linear fit for each case, respectively; (b) The refractive index of SWCNTs film from temperature.

4. Conclusion

Here we demonstrated easy way for hybrid SiN/SWCNT on-chip integration Using experimental and theoretical studies, we found the thermo-optical coefficient of SWCNTs film as a function of temperature between 25 °C to 70 °C. The thermo-optical coefficient of the SWCNTs film is linear within this temperature range and equal to \(2.02 \times 10^{-6}\) RIU/°C. The presented results provide new practical guidelines in designing photonic circuits for studying temperature optical phenomena. The proposed method can also be used to study other materials with a weak dependence of the refractive index on temperature.

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