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Thermal and Loss Characterization of Mechanically Released Whispering Gallery Mode Waveguide Resonators

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Abstract: We present an empirical methodology for thermally characterizing and determining absorption and scattering losses in released ring whisper gallery mode optical resonators. We used the methodology to deduce absorption and scattering contributions in Q = 400,000 silicon nitride resonators coupled to on-chip waveguides.

OCIS codes: (130.3120) Integrated optics devices; (140.6810) Thermal effects; (230.5750) Resonators.

On-chip whispering gallery mode (WGM) optical resonators are of interest due to recent demonstrations of high-Q (Q>10^6) devices for applications ranging from frequency synthesis to quantum state preparation [1,2]. The released ring WGM resonators evanescently coupled to free space waveguides utilized in this paper present unique challenges for thermal and loss characterization, which have been unaddressed to date.

In this work, we develop an empirical technique for quantitatively determining the scattering and absorption loss mechanisms in optical ring and disk resonators. We rely on thermally induced resonant wavelength shifts due to the thermo-optic effect and thus also determine the specific heat capacity (C_p), thermal time constant (τ_{th}), and thermal conductivity (κ_{th}) of released WGM resonators. The device used, shown in Fig. 1(a), is composed of a silicon nitride core with an air cladding fabricated on a silicon wafer. The on-chip coupling waveguide is designed for single-mode TE operation at 1550 nm. The power loss in such devices arises primarily from absorption and scattering, so the dropped power into the device, P_d, measured by an output photodetector may be understood as a sum of these two components:

$$P_d = P_{abs} + P_{scat} = \alpha P_d + (1-\alpha)P_d \quad (1)$$

where P_{abs} is the power lost to absorption, P_{scat} is the power lost to scattering, and α is the percentage of the total power that is lost to absorption. A 1550nm DFB pump laser tuned on resonance was used to heat the device, while a tunable IR probe laser concurrently monitored a different resonance, as shown in Fig 1(b). Absorbed power from the pump laser caused the temperature to increase and, consequently, increased the resonant wavelength of every cavity mode due to the thermo-optic effect, as depicted in Fig 1(c).

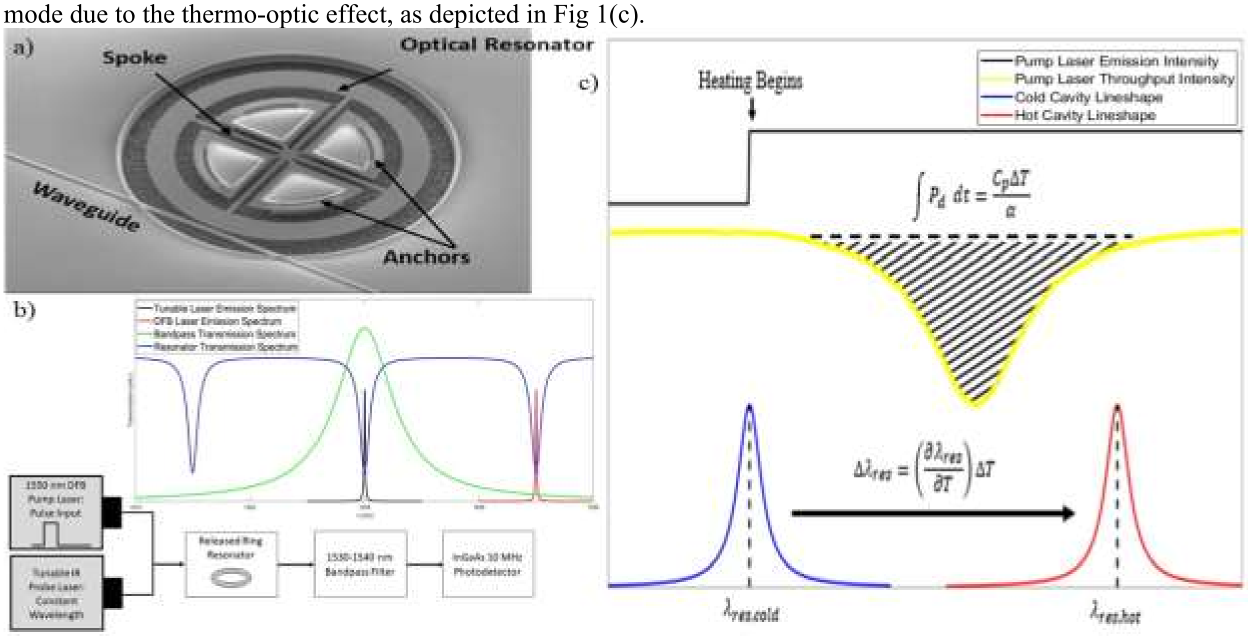

Fig. 1. (a) SEM Image of SiN resonator (b) Schematic of experimental setup and spectral response of the utilized devices (not to scale) (c) Illustration of core thermal phenomena: i. Heating causes resonant wavelength to increase proportional to the temperature increase ii. The dropped power may be measured from the throughput power.

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Accordingly, λ_{res} may be used to measure changes in the device's temperature in response to absorbed power. This response is determined by the device's specific heat capacity, as described below:

$$\int P_{abs}\,dt = \int \alpha P_d\,dt = C_p \Delta T = C_p \left(\frac{\partial \lambda_{res}}{\partial T}\right)^{-1} \Delta \lambda_{res} \tag{2}$$

where T is the resonator temperature and $\partial\lambda_{res}/\,\partial T$ is the thermo-optic coefficient, measured to be 10 pm/°C.

A primary challenge of thermal characterization in these devices is to determine the value of C_p with an unknown value of α. By depositing an extremely thin film of carbon on the top surface of the resonator, absorption becomes the dominant source of loss and α approaches unity ($P_d \approx P_{abs}$). This process is assumed to have negligible effects on the C_p of the device, as heat capacity is primarily affected by the bulk of the material. Consequently, C_p may be determined by probing the resonance shift in the carbonized sample in response to a known P_{abs}. The carbon layer may then be stripped through plasma oxidation cleaning, and the calculated value of C_p may be used to estimate α by probing the resonance shift in the clean sample in response to a known P_d. Figure 2(a) shows a typical response to such a pulse. Typical values of the specific heat of silicon nitride range from 850 to 950 J kg^{-1} K^{-1} [3], so the value total heat capacity of this device is approximately 2.2 nJ K^{-1}. Consequently, preliminary findings reveal an estimation of 0.60 for α.

The thermal time constant, τ_{th}, may be deduced by heating the device with a sufficiently long pulse to increase λ_{res} by several linewidths and measuring the time required for the resonance to pass through several known probe wavelengths as it cools, as shown in Figure 2(b). The exponential decay of device temperature was observed, and a numerical fit was used to calculate a value of 41 µs for τ_{th}.

The thermal conductivity κ_{th} can be calculated simply from the measured values of Cp and τ_{th}:

$$\kappa_{th} = \frac{mC_p}{\tau_{th}} \tag{3}$$

where m is the mass of the ring. Armed with these three parameters, which have typically been determined from simulations, a complete thermal analysis may be performed to predict the response to arbitrary thermal stimuli [4].

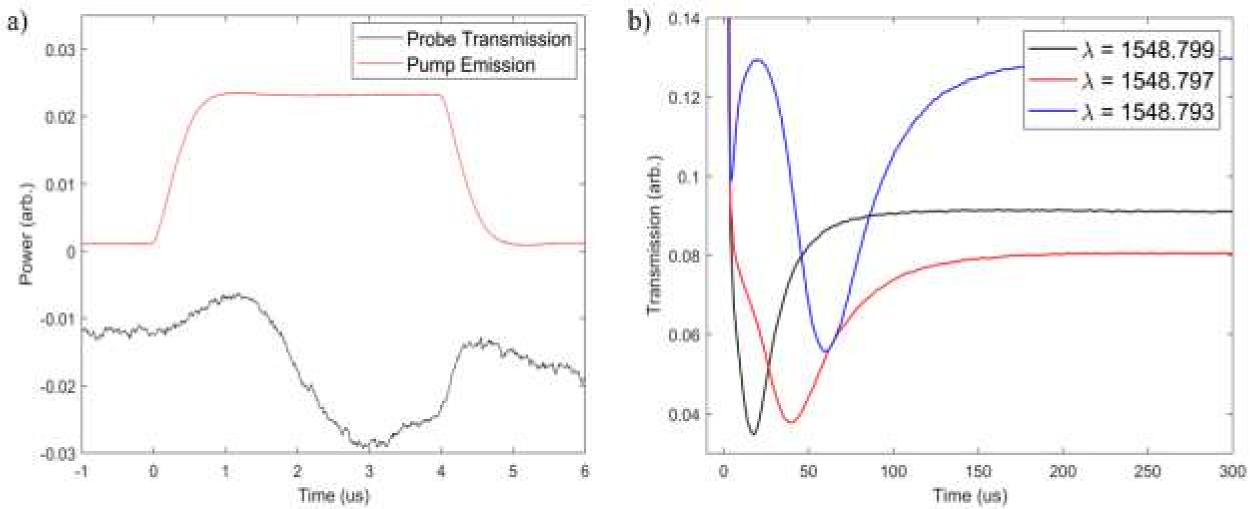

Fig. 2. (a) Pump-Probe measurements of cleaned sample showing the probed resonance's transmission at 1531.25 nm in response to heating (b) Resonance Detection in Response to Device Cooling at Different Probe Wavelengths.

Finally, using the measured Q factor of 400,000 for the clean device obtained by a low power wavelength scan of the device, the device's loss per unit length and effective index were determined to be 0.00895/mm and 1.753, respectively. The measured value of α now permits a determination of the absolute values of P_{abs} and P_{scat} and thus facilitates loss reductions by revealing the loss origins in the device.

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