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Thermal Microphotonic Focal Plane Array (TM-FPA) for Uncooled High Sensitivity Thermal Imaging

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Abstract: We report on a new microphotonic technique for high-sensitivity, uncooled, thermal imaging. The technique, based on the massive thermo-optic effect in thermally isolated micro-resonators offers potential for significantly higher sensitivity than bolometric techniques.

OCIS codes: (130.3120) Integrated optics devices; (230.5750) Resonators; (230.7370) Waveguides.

1. Introduction

In recent years high-Q microphotonic resonators have demonstrated substantial improvements over traditional techniques for chemical and biological sensing [1-3]. Yet, little attention has been paid to the area of thermal imaging, where despite many years of development, traditional bolometric techniques have yet to reach theoretical limits of sensitivity. Moreover, in many applications (e.g. large *f*/#'s and terahertz bands), cryogenic cooling is required to achieve an acceptable level of sensitivity, greatly increasing imager power consumption and weight.

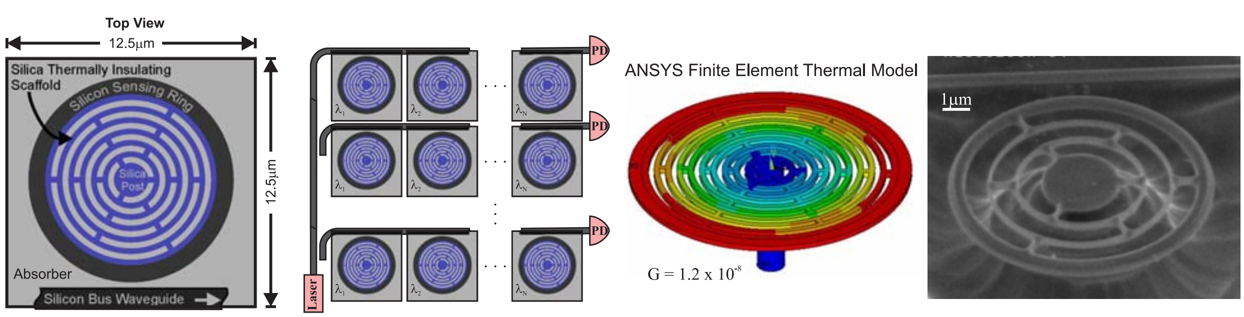
Here, we consider the use of microresonators for uncooled thermal imaging. We show, through rigorous analysis, that thermal imagers based on high-Q microphotonic-resonators can achieve scale factors that far exceed bolometric techniques. In addition, interrogation of microphotonic resonators does not require intimate thermal contact leading to a lower phonon noise limit. As a result, microphotonic thermal imagers have the potential to reach noise limits two-orders of magnitude lower than bolometers. Detailed sensor designs, modeling results, imager layouts, along with fabrication and experimental results will be presented.

2. Discussion and Results

Diagrams of the sensor and thermal microphotonic focal plane array (TM-FPA) are depicted in Fig. 1a and 1b. A microring resonator is chosen as the sensing element for its high-Q, ease of fabrication, integration, and interrogation. Incident radiation is absorbed in an absorbing element, which serves to raise the temperature of the microring-resonator and shift its resonant frequency via the thermo-optic effect. The microring is further suspended with a silica scaffold to minimize the thermal conductance G to the substrate. A rigorous finite element thermal model of the sensor, depicted in Fig. 1c, indicates a thermal conductance of $G = 1.2\times10^{-8}$W/K, an order of magnitude lower than is achieved in bolometers [3]. Since the scale factor SF of the TM-FPA technique is given by

$$SF = \frac{1}{G}\frac{Q}{\omega_0}\frac{d\omega_0}{dn}\frac{dn}{dT} \qquad \text{(Fractional Signal Change/Received Power)}$$

where $Q = \omega_0/\Delta\omega$ is the resonator quality factor, and dn/dT is the thermo-optic coefficient, minimizing the thermal conductance maximizes the scale factor. Moreover, minimizing the thermal conductance also minimizes the



(a) (b) (c) (d)

Fig. 1: (a) A diagram (top view) of a sensor element. The sensor consists of a microring-resonator evanescently coupled to a bus waveguide and thermally coupled to an absorbing element. In the example, the silicon sensing ring is thermally insulated from the substrate via a silica scaffold which serves to maximize the frequency shift and minimize phonon noise. (b) An array of sensors forming a TM-FPA can be achieved using a wavelength-division-multiplexing (WDM) approach. (c) An ANSYS finite-element thermal model was implemented to determine the thermal conductance (G) to the substrate. (d) An SEM of a fabricated silicon nitride sensor element. Silicon sensors are in fabrication and antenna / absorber designs are being developed.

fundamental thermal phonon noise ($NEP_{phonon} = \gamma\sqrt{4k_B G}T \approx 2\cdot10^{-13}$W/√Hz @300K, γ≈1) [4]. Resonator quality factors of ~ 10^6 have been achieved in silicon [1,2] and silicon-nitride microrings [3]. Inserting $Q = 10^6$, $dn/dT = 2\times10^{-4}$/K (silicon), and $G = 1.2\times10^{-8}$W/K, we arrive at a scale factor of $SF \sim 5\times10^9$/W. For comparison, vanadium oxide bolometers have a temperature coefficient of resistance of $R_T = 0.02$/K, and scale factor SF = $R_T/G \sim 2\times10^5$/W (here, $G = 10^{-7}$W/K). The scale factor of the TM-FPA approach is ~25,000 times larger than in a typical resistive bolometer. Importantly, the massive scale factor affords the TM-FPA approach the potential to reach its phonon noise limit directly, a limit two orders of magnitude lower than that achieved by the best uncooled bolometers [5-7].

Both silicon and silicon nitride designs are being pursued. Silicon nitride has the advantage of being transparent in the telecom bands, yet highly absorbing in the long-wave infrared (8-12μm). The device shown in the SEM image Fig. 1d was fabricated on Sandia's CMOS fabrication line by defining the resonator/waveguide geometry in an ASML scanner, using Deep UV photo resist with a bottom antireflection coating (BARC). The pattern was etched in the 250 nm silicon nitride film using RIE and then annealed at high temperature. Using a second lithography step an opening was defined around the outside of the ring patterns so that the enchant would undercut the disks from the outside of the ring-scaffold devices as well as a small section of the bus wave guide leaving a silica support post in the ring center. Structurally, these devices have held up well under fabrication despite sub-100nm features.

As a proof-of-principle, experimental results on a large (500μm) non-suspended silicon nitride ring ($Q \sim 10^6$) are depicted in Fig 2. Here, a beam from a mechanically modulated helium-neon laser was used to change the temperature of the microring-resonator. Since silicon-nitride does not absorb at 633nm, the laser power was absorbed by the chip substrate which in-turn heated the microring. The microring was interrogated with a DFB laser tuned to one side of the resonance ($\lambda_0 \sim 1.55$μm), a change in output current was sensed as the helium-neon laser was modulated on and off. The signal level as a function of frequency is depicted in Fig. 2a with the RMS noise level obtained from a lock-in amplifier; the slow frequency response is due to the large thermal mass of the chip. The signal itself is depicted in Fig. 2b. The noise level corresponds to ~1mK temperature change. In a thermally isolated ring, the noise in this proof-of-principle experiment would match that of high quality uncooled bolometers (i.e. $NEP = \Delta T_{RMS} G \approx 10^{-11} W\sqrt{Hz}$, if G = 10^{-8}W/K).

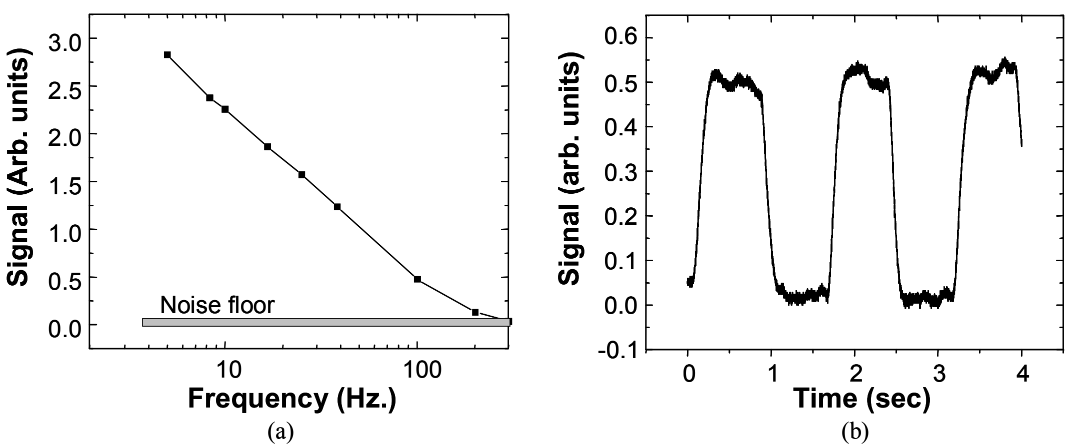


Fig. 2: A 500μm diameter silicon-nitride ring-resonator's temperature was modulated by an external helium-neon laser. The ring resonator frequency was interrogated by a DFB laser and the signal level vs. modulation frequency is depicted in (a) while the signal is depicted in (b). The noise floor (SNR ~ 70) corresponds to a ~1mK temperature change.

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