Design and Simulation of Temperature Sensors Based on Thermo-Optical WGM Shifts in Silica and Non-Silica Glass Microcavities

M.P. Marisova *, A.V. Andrianov, and E.A. Anashkina
Institute of Applied Physics of the Russian Academy of Sciences
46 Ul'yanov Street, Nizhny Novgorod, 603950, Russia
*email: marisova.mariya@rambler.ru

Abstract – **Sensing applications of dielectric microcavities with whispering-gallery modes (WGMs) have been actively studied in the recent years. Here we investigated theoretically temperature microsensors based on different glasses, including common silica glass, as well as special germanate, tungsten-tellurite, arsenic sulfide and arsenic selenide glasses. We developed numerical model describing sensing characteristics of the considered microcavities. We found that the calculated temperature sensitivity does not depend on the microsensor size in the examined parameter range. The obtained temperature sensitivities for arsenic sulfide (42.2 pm/K near 1.55 µm) and arsenic selenide (48.1 pm/K near 1.55 µm) glass microcavities are several times larger than for common silica ones; it could facilitate the development of new precise microcavity-based sensors.**

I. Introduction

Microcavities with whispering-gallery modes (WGMs) are extensively investigated for various purposes [1]. One of their main applications is sensing; this area has been actively attracting researchers' attention in the recent years [2].

Here we contribute to a study of microcavity temperature sensors based on various glasses. Although some of the most common glass microcavities are manufactured from fused silica, investigating a broader set of optical glasses could facilitate the development of new microsensors with different parameters and characteristics. The following glasses were considered: common silica (SiO_2), germanate (GeO_2), tungsten-tellurite (TeO_2–WO_3–La_2O_3), arsenic sulfide (As_2S_3), and arsenic selenide (As_2Se_3).

II. Numerical Model

In this section we consider theoretically a spherical glass microcavity. The WGM eigenfrequencies are defined by the characteristic equations (obtained directly from Maxwell equations' solution as provided, for example, in [3]):

$$\frac{[(nkR)^{1/2}J_\nu(nkR)]'}{(nkR)^{1/2}J_\nu(nkR)} = n^p\,\frac{[(kR)^{1/2}H_\nu^{(1)}(kR)]'}{(kR)^{1/2}H_\nu^{(1)}(kR)}. \quad (1)$$

Here p=1 for TM modes, p=−1 for TE modes, n is the glass refractive index, k is the wave number, R is the microcavity radius, $\nu = l + ½$, l is the mode index, J_ν and $H_\nu^{(1)}$ are Bessel function and Hankel function of the first kind of order ν, respectively; the prime denotes the derivative. We previously employed this approach to calculate WGMs of a tungsten-tellurite glass microcavity in [4].

Refractive index dependence on the wavelength $\lambda=2\pi/k$ for the considered glasses is given by the following relation:

$$n(\lambda) = A_0 + \sum_{j=1}^{N} \frac{A_j\lambda^2}{\lambda^2 - B_j}, \quad (2)$$

where material constants N, A_j, B_j are given in [5] for silica and germanate glasses, in [6] for tungsten-tellurite glass, in [7] for arsenic sulfide glass, and in [8] for arsenic selenide glass.

As a microcavity temperature changes, its size varies correspondingly due to the effect of thermal expansion. The glass refractive index n also depends on the temperature because of the thermo-optic effect. For a homogenous microcavity temperature change ΔT, these processes can be described in the following way:

$$\Delta R = R \cdot \alpha\Delta T, \quad (3)$$

$$\Delta n = \varepsilon\Delta T, \quad (4)$$

where ΔR is the microcavity radius change, Δn is the glass refractive index change, α and ε are the glass thermal expansion and thermo-optic coefficients, correspondingly; α and ε for the considered glasses are given in Table I.

Equation (1) was solved numerically taking into account glass dispersion (2) and temperature-induced changes in R and n (given by (3) and (4)). The initial guess for the root-finding algorithm was calculated using an approximate relation which can be found in [3]. Equation (1) has multiple roots, corresponding to WGMs with different radial indices q. For all our calculations below we considered only the fundamental WGM (q=1, one radial variation), corresponding to the smallest k, unless explicitly stated otherwise.

III. Simulation Results

First, we calculated WGM wavelength shift Δλ as a function of temperature change ΔT for same-sized microcavities (R=100 µm) made of different glasses. The results for modes, which at the reference temperature (20 °C) are the closest to λ=1.55 µm and λ=2.0 µm, are shown in Fig. 1(a) and Fig. 1(b), respectively. We found that the difference between TE and TM fundamental modes is negligible; therefore, the plots are shown only for TE modes. As it can be seen from Figs. 1(a,b), the calculated wavelength shifts depend almost linearly on ΔT; the illustrative linear fits are shown as gray dotted lines.

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TABLE I
GLASS PROPERTIES USED IN SIMULATION

	Silica	Germanate	Tungsten-tellurite	Arsenic sulfide	Arsenic selenide
Thermal expansion coefficient (α , 10^{-6} K^{-1})	0.55 [9]	7.5 [10]	13 [6]	25 [12]	21 [12]
Thermo-optic coefficient (ε, 10^{-6} K^{-1})	11.9 [9]	16 [11]	−8 [6]	9 [7]	35 [13]

An important characteristic of a microsensor is temperature sensitivity $\Delta\lambda/\Delta T$. The calculated values of thermal sensitivity as a function of microcavity radius are shown in Fig.1(c) and Fig.1(d) for modes near λ=1.55 μm and λ=2.0 μm, respectively. It was found that the sensitivity almost does not depend on R (relative variations are less than 1%); it is an important quality for sensor design.

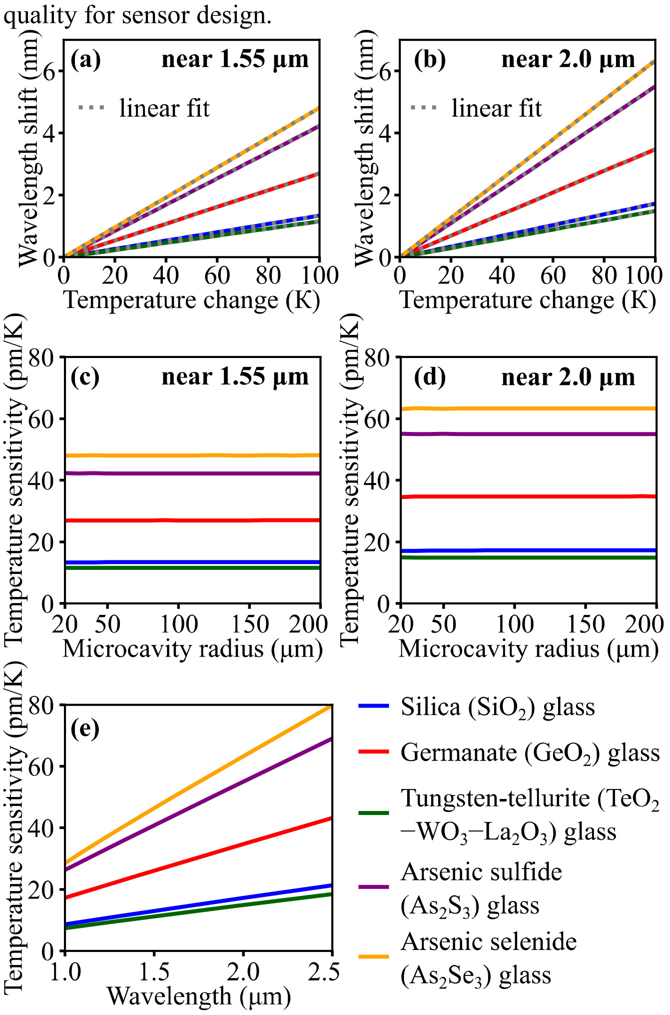

Fig. 1. (a, b) Calculated WGM wavelength shifts as a function of temperature change for modes near λ=1.55 μm (a) and λ=2.0 μm (b). Gray dotted lines denote linear fit; data is shown for microcavities with the radius R=100 μm. (c, d) Numerically simulated WGM wavelength temperature sensitivity $\Delta\lambda/\Delta T$ for spherical microcavities made of different glasses as a function of R for modes near λ=1.55 μm (c) and λ=2.0 μm (d). (e) Calculated temperature sensitivity of microsensors made of different glasses as a function of wavelength. All figures share the same color legend for glass types.

Temperature sensitivity as a function of wavelength (λ=1.0…2.5 μm) is plotted in Fig. 1(e) for microcavities made of different glasses. Note that it is an almost linear function in the considered parameter range. Temperature sensitivity of a tungsten-tellurite microsensor is the lowest (11.6 pm/K near λ=1.55 μm) among the investigated in the present work due to the negative thermo-optic coefficient of the glass. The highest temperature sensitivity values are achieved for arsenic sulfide (As_2S_3) and arsenic selenide (As_2Se_3) microcavities: 42.2 pm/K and 48.1 pm/K near λ=1.55 μm, respectively; it is several times larger than for common silica glass microcavities (13.4 pm/K). The use of arsenic-based glasses is especially promising for longer wavelengths not only because of the increased thermal sensitivity, but also due to their ultra-wide transparency window.

We also checked that for non-fundamental WGMs ($1<q\leq10$) the values of thermal sensitivity are the same. This fact is crucial to the development of temperature sensors based on microcavities as control over mode excitation is not required to provide consistent sensing results.

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