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Refractometry-based air pressure sensing using glass microspheres as high-Q whispering-gallery mode microresonators

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ABSTRACT

In this work a refractometric air pressure sensing platform based on spherical whispering-gallery mode microresonators is presented and analyzed. The sensitivity of this sensing approach is characterized by measuring the whispering-gallery mode spectral shifts caused by a change of air refractive index produced by dynamic sinusoidal pressure variations that lie between extremes of ± 1.8 kPa. A theoretical frame of work is developed to characterize the refractometric air pressure sensing platform by using the Ciddor equation for the refractive index of air, and a comparison is made against experimental results for the purpose of performance evaluation.

1. Introduction

Optical microresonators have attracted significant interest for various sensing applications [1–4]. In whispering-gallery mode (WGM) microresonators, the light propagates inside the structure as a result of total internal reflection. The evanescent field of the WGM extends up to approximately 100 nm in the surrounding medium and the overlap with host environment surrounding media allows for the measurement of refractive index changes. Since fused silica microresonators can achieve up to 10^9 quality factors (Q's) [4], refractometric changes can be measured with high sensitivity. These characteristics make WGM resonators attractive for a variety of chemical sensing applications. WGM sensors have also been utilized as physical sensors for magnetic and electric fields [5], temperature [3], force [6], and pressure [7].

In pressure sensing, the established sensing mechanism is based on pressure induced deformations of the microcavity which can be implemented in different geometries and materials, such as microbubbles, polymer spheres, polymer microrings, and droplet resonators [8–12]. Thin-walled microbubble resonators exhibit a particularly high sensitivity towards monitoring air pressure changes yet require complex fabrication techniques [13,7].

Glass microspheres can also be used as WGM pressure sensors. They are easy to fabricate (e.g. by melting the tip of an optical fiber [14]) and capable of achieving extremely high sensitivities in refractometry based sensing due to the high Q-factor of WGM's. Glass is less responsive to pressure induced deformations as compared to less dense materials; however, the high Q of glass microspheres can enable an alternative approach for pressure sensing, by detecting small, pressure induced refractive index changes in the surrounding medium. To the best of our knowledge, solid glass microsphere WGM pressure sensors were not presented and evaluated accordingly. These issues are important to be analyzed as they can provide insight for developments in the field of high Q-factor whispering-gallery mode microresonators.

In this work, we present and analyze a refractometry based pressure sensing scheme using spherical glass WGM microcavities. The sensitivity is characterized by measuring the WGM spectral shifts in response to quantitative pressure variations in the surrounding air medium. A theoretical framework is developed to predict the sensor response and a comparison to theoretical predictions with experimental results is carried out to evaluate the refractometry based sensing mechanism.

2. Theoretical description

WGM's can be characterized by three integer quantum numbers: l, q, and p. The number of intensity maxima in the radial direction corresponds to q, the number of intensity maxima in the polar direction corresponds to p, and $(l - p)$ accounts for the number of field oscillations around the cavity for the fundamental mode l. l can be

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estimated by means of the relation $l \approx 2\pi R n_s/\lambda_0$. λ_0 is the wavelength, R is the average radius of the optical path, and n_s is the refractive index of the sphere (fused silica's $n_s = 1.45$). In the case of refractometric sensing, the dependence of the resonance wavelengths $\lambda^{(l,q)}$ on changes in the host refractive index n_h can be calculated by using the Lamb approximation for a spherical microcavity geometry [15].

$$\frac{\partial \lambda^{(l,q,TE)}}{\partial n_h} = \alpha\left[1 - \frac{\zeta(q)}{2^{1/3}}\frac{n_s^2}{n_s^2 - n_h^2}\left(l + \frac{1}{2}\right)^{-2/3}\right], \quad (1)$$

$$\frac{\partial \lambda^{(l,q,TM)}}{\partial n_h} = \frac{\alpha}{n_s^2}\left[2n_s^2 - n_h^2 - \frac{\zeta(q)}{2^{1/3}}\frac{2n_s^6 + n_s^4 n_h^2 - 4n_s^2 n_h^4 + 2n_h^6}{n_s^2(n_s^2 - n_h^2)}\left(l + \frac{1}{2}\right)^{-2/3}\right], \quad (2)$$

with

$$\alpha = \frac{\lambda^2}{2\pi R}\frac{n_h}{(n_s^2 - n_h^2)^{3/2}},$$

where $\zeta \in \{-2.338, -4.088, -5.521\}$ are the first, second, and third zeros of the Airy function. We assume fundamental modes with $q \in \{1, 2, 3\}$. Those modes typically exhibit the highest Q-factors in WGM experiments. We differentiate TE and TM modes, with a major electric field component parallel and perpendicular to the surface, respectively. We set $p = 0$ as the fabricated microspheres exhibit a near-perfect radial symmetry about the equator where the fundamental WGM's circulate.

To predict the WGM resonance wavelength shifts in refractometry based air pressure sensing, we modify Eqs. (1) and (2) by adopting the Ciddor equation which calculates the refractive index of air as a function of pressure, temperature, and humidity [16]. We then use the modified equation to calculate the WGM sensor response. To calculate the WGM wavelength shift, we vary one of the pressure, temperature, and humidity parameters while keeping the other parameters set to their nominal values (i.e. $P_N = 100$ kPa, $T_N = 25$ °C, $RH_N = 50\%$, $\lambda_N = 0.780$ µm). Table 1 shows the predicted values of resonance wavelength shift over refractive index change [pm/RIU] for different sphere sizes ($r_1 = 30$ µm, $r_2 = 120$ µm, $R_1 = 127$ µm, $R_2 = 89$ µm). Next, the pressure is varied from $P = 60$ kPa to 120 kPa, temperature T from −40 °C to 100 °C, and relative humidity RH from 0% to 100%, as to plot the sensor response in Fig. 1. RH is defined according to the Birch and Downs equation ([17]) as $RH = 100 \cdot p_v/p_{sv}(T)$ where p_v is the partial pressure of water vapor and p_{sv} is the saturation vapor pressure at the air temperature T. It is worth mentioning that the sensitivity is mainly determined by the difference between squared refractive indices of the sphere and the medium ($n_s^2 - n_h^2$), and by the radius R of the microsphere sensor.

Table 1
Refractometric sensitivities in pm/RIU obtained from Eqs. (1) and (2) for $\lambda = 0.780$ µm and the normal condition where $P = 100$ kPa, $T = 25$ °C, and $RH = 50\%$.

$r_1 = 30$ µm, $l \approx 350$	TE	q=1	2989.5
		q=3	3259.9
	TM	q=1	4608.3
		q=3	5091.1
$r_2 = 120$ µm, $l \approx 1402$	TE	q=1	717.4
		q=3	744.3
	TM	q=1	1098.6
		q=3	1146.6
$R_1 = 127$ µm, $l \approx 2967$	TE	q=1	677.2
		q=3	701.6
	TM	q=1	1036.8
		q=3	1080.5
$R_2 = 89$ µm, $l \approx 1039$	TE	q=1	973.2
		q=3	1017.4
	TM	q=1	1491.8
		q=3	1570.6

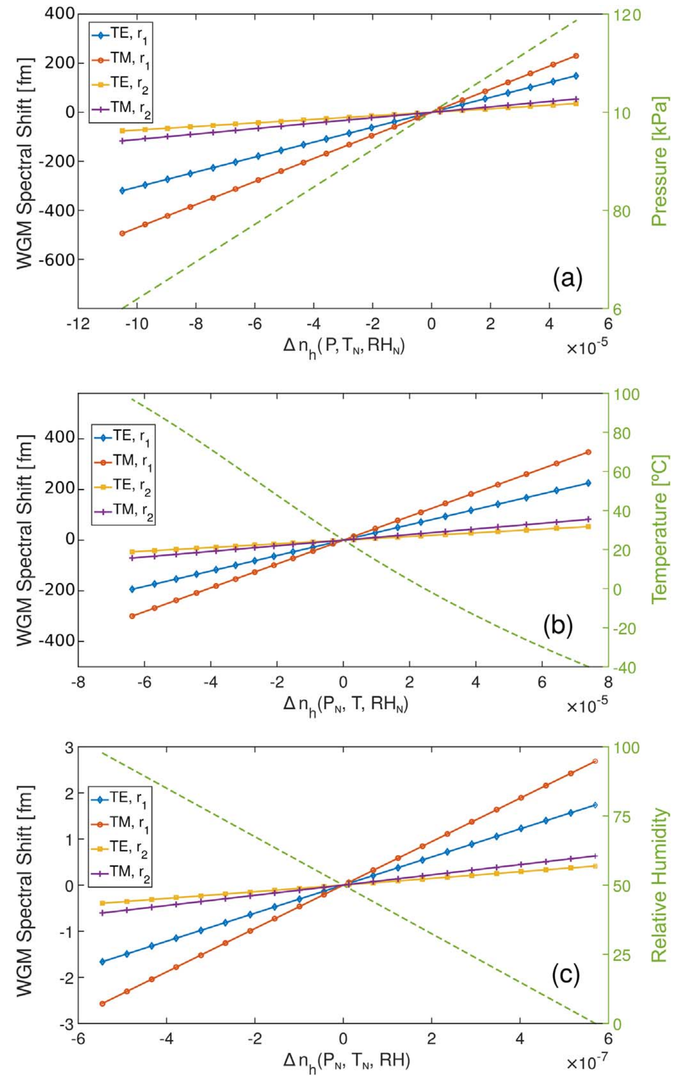

Fig. 1. WGM spectral shifts as a function of the refractive index variations for TE and TM modes and the sphere radii $r_1 = 30$ µm and $r_2 = 120$ µm assuming the conditions: a) P is between 60 kPa and 120 kPa, $T_N = 25$ °C, and $RH_N = 50\%$; b) $P_N = 100$ kPa, T is between −40 °C and 100 °C, and $RH_N = 50\%$; c) $P_N = 100$ kPa, $T_N = 25$ °C, and RH is between 0% and 100%. The dashed line corresponds to: a) Pressure vs. Δn_h, b) Temperature vs. Δn_h, and c) Relative humidity vs. Δn_h.

The displayed values were obtained assuming variations from the normal condition when one variable of the environment is changed at once. The host refractive index variation in pressure is defined as $\Delta n_h(P, T_N, RH_N) \equiv n_h(P, T_N, RH_N) - n_h(P_N, T_N, RH_N)$, with the same rule being applied to T and RH for $n_h(P_N, T, RH_N)$ and $n_h(P_N, T_N, RH)$, respectively. It is worth noting that the WGM spectral shifts due to the pressure variations compete with those for the temperature variations, although this is not the case for the whole relative humidity range which is two orders of magnitude lower. Given that the third-order nonlinear susceptibility of fused silica is negligible with respect to its thermal refraction ($n_r^{-1} dn_r/dT \approx 1.19 \times 10^{-5}$ C^{-1}) and expansion ($R^{-1} dR/dT \approx 5.5 \times 10^{-5}$) coefficients, the thermal drift plays an important role in determining the effective refractive index [18]. Moreover, since both coefficients are positive, a strategy should be implemented for compensation. Through the analysis of this refractometry based air pressure sensing platform, the thermal drift can be characterized by means of monitoring the subtle deviations in the WGM spectral shifts as a consequence of the thermal inertia of the air channel. These