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Supplementary information

A submicrometre silicon-on-insulator resonator for ultrasound detection

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Supplementary information for

Sub-micron silicon-on-insulator resonator for ultrasound detection

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SENSITIVITY

The sensitivity (S) of an optical resonator can be defined as the reflected optical power (P_R) modulation per unit of incident acoustic pressure (p) [S1]:

$$S = \frac{dP_R}{dp} = \frac{dP_R}{d\phi} \cdot \frac{d\phi}{dp} \tag{S1}$$

where $\phi = 4\pi n_{eff} l/\lambda$ is the optical phase, n_{eff} is the effective refractive index of the waveguide, l is the resonator length, and λ is the wavelength. The $dP_R/d\phi$ term is the slope of the resonance of the reflected optical power. This term amplifies the detected signal and can be ignored when comparing resonators with identical Q-factors. The term $d\phi/dp$, on the other hand, also called the acoustic phase sensitivity (S_ϕ), accounts for the properties of the materials from which the detector is constructed as well as for the geometrical arrangement of the resonator and the spatial orientation of the detector relative to the acoustic source. The phase sensitivity can be written as follows:

$$S_\phi = \frac{2\pi n_{eff} l}{\lambda} \cdot \left(\frac{1}{n_{eff}} \frac{dn_{eff}}{dp} + \frac{d\varepsilon_z}{dp} \right) = \frac{2\pi n_{eff} l}{\lambda} \cdot S_\lambda \tag{S2}$$

'here S_λ is the normalised sensitivity and ε_z is the strain along the optical axis. The change in phase can be attributed to two mechanisms: change in n_{eff} of the waveguide due to density changes through the elasto-optic effect, and change in l due to strain experienced by the waveguide.

In order to determine the efficiency of the transduction mechanisms of SOI based resonators, we examine the normalized sensitivities of a detector composed of a Si waveguide embedded in Silica when ultrasound is detected through the waveguide cross-section (**'forward detection'**) and when ultrasound is detected perpendicular to the optical axis of the waveguide (**'side detection'**). In the forward detection scheme, the acoustic wave is propagating along the optical axis, so the applied stress is $\sigma_z = P$, and the elastic deformation perpendicular to the optical axis is $\varepsilon_x = \varepsilon_y = 0$. Using the generalised Hooke's law and accounting for the elasto-optic effect in an isotropic cubic material, we obtain the following relationships:

$$\varepsilon_z = -\frac{(1+\nu)(1-2\nu)}{(1-\nu)E} P \tag{S3}$$

$$\Delta n_x = \Delta n_y = \frac{(\nu C_1 + C_2)}{1-\nu} P \tag{S4}$$

where Δn_x and Δn_y are the perturbations of the refractive index perpendicular to the optical axis; C_1 and C_2 are the elasto-optic constants; E is Young's modulus, and ν is the Poisson ratio. The values of these parameters for silicon and silica were taken from the literature [S2]. The contribution of the strain component to the normalised sensitivity was evaluated directly from **Eq. S3,** and the contribution due to change in n_{eff} was simulated using **Eq. S4** and a vectorial mode solver [S3]. For a detector with the same cross-section as the SWED in this study we found the normalised sensitivity to be $S_{\lambda,forward} = -5.5 \times 10^{-6}$ MPa^{-1}. The negative sign implies that the elastic waveguide deformation has a larger impact than the elasto-optic effect.

In the side detection scheme, the acoustic wave impedes on the waveguide perpendicularly; hence, $\sigma_y = P$ and $\varepsilon_x = \varepsilon_z = 0$. The normalised sensitivity for the side detection geometry of a waveguide with the same geometrical dimensions and material composition as the SWED was previously found to be $S_{\lambda,side} = 4.7 \times 10^{-6}$ MPa^{-1} [S2]. In that case, the positive sign indicates the dominance of the elasto-optic effect.

Comparing the absolute value of the normalised sensitivity of the two detection geometries shows that the forward detection geometry enabled by the SWED is ~20% more efficient than any other SOI-based resonator with similar Q-factor and identical waveguide cross-section dimensions.

The above analysis is a rough estimation of the efficiency of the transduction mechanism. It neglects sensitivity dependency on the acoustic wavelength and other factors like acoustic impedance mismatch.

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