Semi-Analytical Models for the Dynamic Characterization of Integrated Photonic Ultrasound Transducers

[1]Delft University of Technology, [2]TNO

Sabiju Valiya Valappil[1], Peter Harmsma[2], Martin Verweij[1], Maurits van der Heiden[2], Paul van Neer[2]

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Introduction

Integrated photonic ultrasound transducers (IPUTs) are ultrasound transducers (UTs) consisting of an optical circuit and a mechanical resonator, where the acoustic pulse is measured optically minimizing the device-level noise generation.

GOAL: We develop semi-analytical models to characterize the IPUTs' receive transfer function (RTF) and thermal noise-induced noise equivalent pressure (NEP), which are validated by comparing them with the literature.

Method

IPUT (**Fig. 1**) is separated into optical and mechanical components. A time-domain finite element model is developed to characterize the IPUT's mechanical behavior shown in **Fig. 2**. The incoming ultrasound pulse excites the membrane in its fundamental resonant mode, which influences the geometry and stress distribution of the optical waveguide (see **Fig. 3**). The axial and radial dynamic responses of the waveguide are determined, which are used to obtain the RTF. NEP is calculated by assuming the IPUT's behavior to be similar to a weakly-damped harmonic oscillator and using the equipartition theorem.

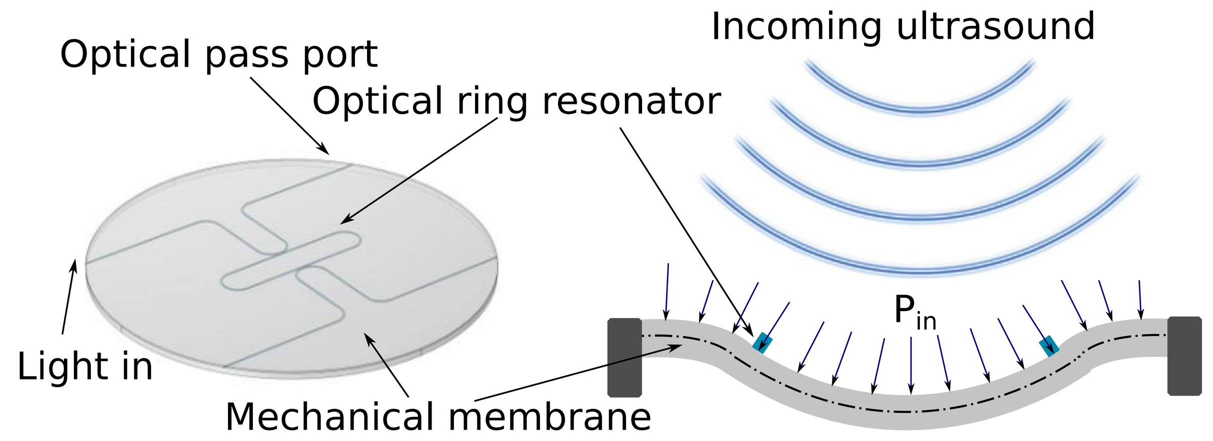

Fig.1 Schematic of a racetrack ring resonator-mechanical membrane IPUT[1] excited by an incoming ultrasound where the different ports (light in and pass) are also marked.

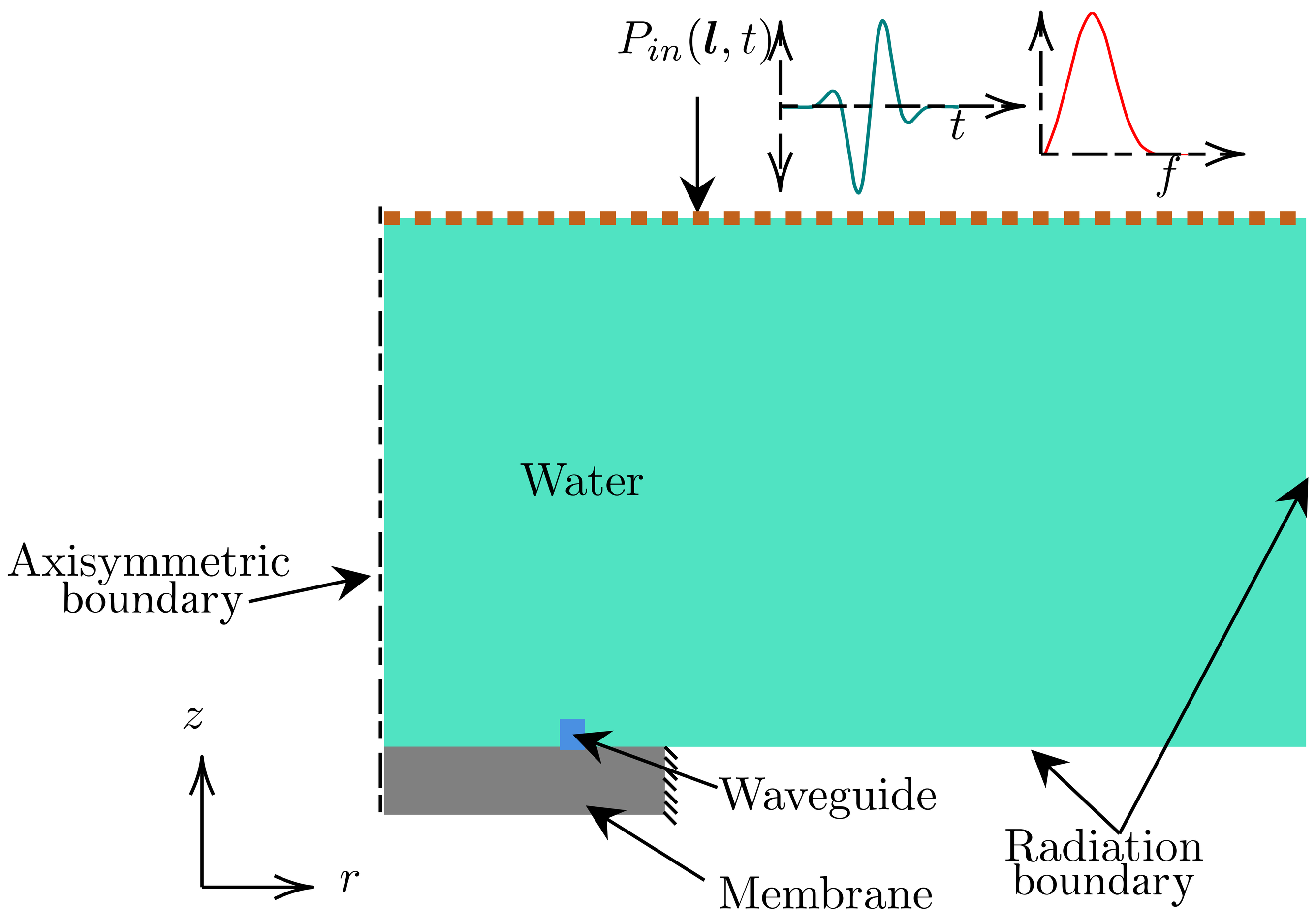

Fig.2 Axisymmetric model of the plane wave (acoustic) propagation through IPUT where the waveguide and the membrane are marked. P_{in} input pressure pulse (prescribed).

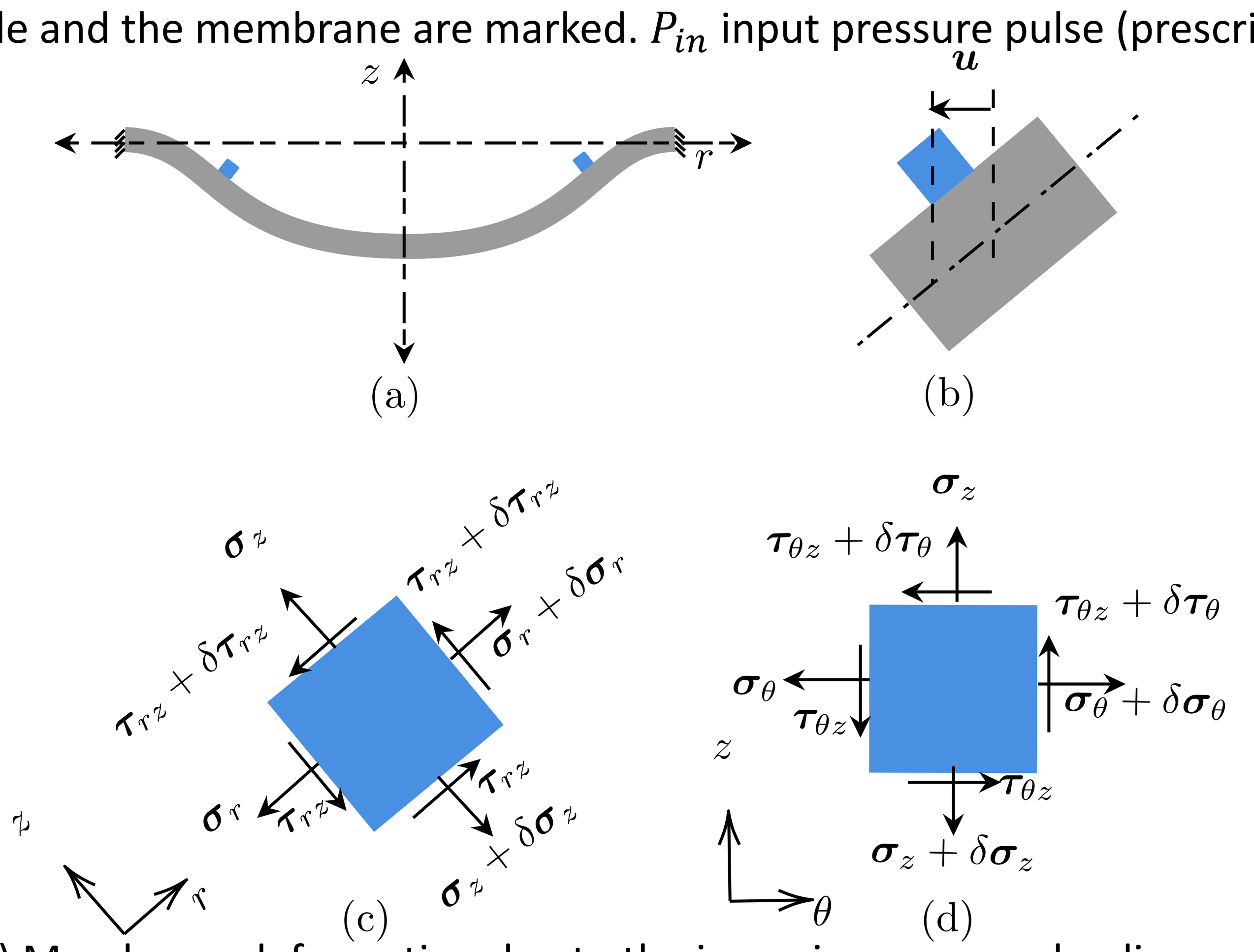

Fig.3 (a) Membrane deformation due to the incoming pressure leading to the (b) displacement and (c) and (d) stress of the waveguide. $\boldsymbol{u}$ - radial displacement, $\sigma_{i,j}$ - normal stress, $\tau_{i,j}$ - shear stress of the waveguide.

RTF is calculated by using the **radial displacement** and **stress**-induced changes in the effective refractive index extracted along the waveguides:

$$\left(\frac{d\lambda}{dP}\right) = \frac{\lambda}{n_g L}\left(n_{eff}\frac{dL}{dP} + L\frac{dn_{eff}}{dP}\right)$$

λ = wavelength, P = pressure, n_g = group index, L = waveguide's length= $2\pi r$, r = waveguide's radius, elongation dL = $2\pi u$, n_{eff} = effective refractive index.

NEP is derived by extracting the dynamic response of the IPUT with the thermal displacement (Brownian motion of the particles) as the only source term.

Results

From the time-domain acoustic analysis of the IPUT, its axial displacement is extracted as a function of time (**Fig. 4(a)**, transformed to the frequency domain (**Fig. 4(b)**). The central frequency and Q factor are then obtained, which are used along with the properties of the IPUT to obtain its NEP due to the thermal noise:

$$NEP = \sqrt{\frac{4k_B T \omega_0 m_{eff}}{Q A_s^2}}$$

k_B = Boltzman's constant, T = temperature, ω_0 = resonance frequency in rad/s, m_{eff} = effective mass, Q = Quality factor, A_s = surface area.

Using displacements (**Fig. 4(c)**) and stresses (**Fig. 4(d)**) the RTF is calculated. NEP and RTF of various IPUTs targeted to operate at different frequencies are plotted in **Fig. 5**

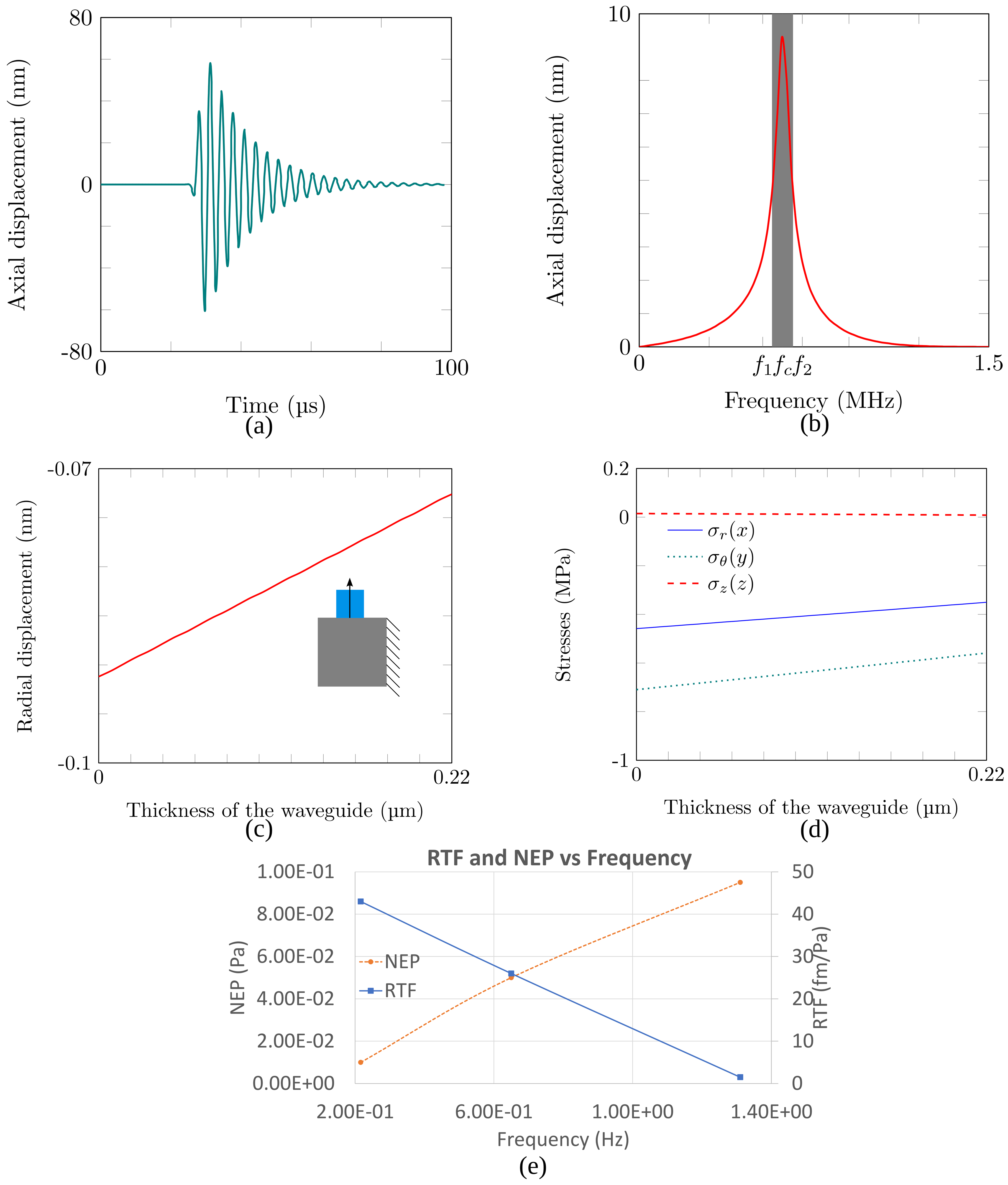

Fig.4 (a) time and (b) frequency response of the axial displacement of the membrane. (c) radial displacement and (d) state of stress of the waveguide extracted along its thickness, (e) RTF and NEP of different IPUTs (targeted at different frequencies).

RTF reported in Westerveld 2014[1] is 67 fm/Pa; the model predicts 33 fm/Pa. The deviation from the literature is due to the influence of the internal stress developed in the membrane during fabrication. The reported NEP is 0.5 Pa; the thermal noise from the model is 0.05 Pa. This variation is because the IPUT is limited by the read-out noise rather than its thermal noise.

Conclusion

IPUT's dynamic response is captured using a semi-analytical model where the influence of the incoming ultrasound pulse on the waveguide's response is characterized. Combining this behavior with optical responses closely predicted the RTF selected from the literature.

References

[1] Westerveld, W.J., 2014. Silicon photonic micro-ring resonators to sense strain and ultrasound, *http://repository.tudelft.nl*.

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