Limits of high-Q optical resonator sensors for photoacoustic imaging

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Abstract: Deep-tissue applications (>1cm) for photoacoustic imaging require high-sensitivity ultrasound transducers. High-Q resonator sensors are being developed to overcome current limits. Here we analyse the potential, limits and challenges on their design, fabrication, and interrogation.

1. Introduction

Photoacoustic (PA) imaging requires ultrasound transducers with high sensitivity, broadband frequency response, wide directivity, and small element size. One approach that overcomes the element size and bandwidth limitations of conventional piezoelectric technology is a planar Fabry-Perot (FP) sensor [1]. Scanning a tightly focused laser beam across the surface of the sensor and measuring the acoustically-induced perturbations at each point allows the reconstruction of high-resolution 3D PA images. However, the interrogation beam diverges inside planar FP interferometers and walks off, reducing the cavity Q-factor. This phenomenon decreases the sensitivity and limits the imaging depth to <1cm.

To overcome this problem, plano-concave optical microresonator (PCMR) sensors have been developed. Their geometry corrects the divergence of the interrogation beam by refocusing the light after each round trip undergone inside the resonator (Fig. 1) enabling high Q factors to be achieved. Experimental studies demonstrated an improvement in the sensitivity and penetration depth in tissue-realistic phantoms using this configuration [2-3]. Further theoretical studies predicted a potential order-of-magnitude improvement of the PCMR sensors cavity Q-factor by optimising their design [4].

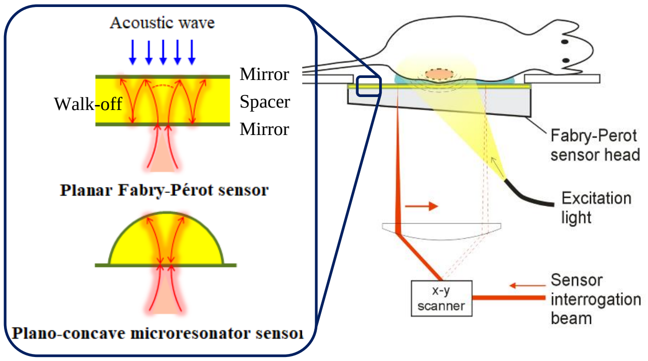

Fig. 1. Illustration of PA system and focussed-beam propagation inside a planar FP sensor and a PCMR sensor.

In the current study, we investigate the true potential of high-Q PCMR devices for ultrasound sensing when accounting for the practical limits and challenges in their fabrication and interrogation. We fabricated PCMR sensors with optimised design and compared their performance to the theoretical predictions. Then, we explored the impact of several parameters such as optical absorption, elasticity, and phase noise on the Noise Equivalent Pressure (NEP), which is the minimum detectable pressure by the PA system. By minimising the limiting factors identified in this study, we estimate NEPs more than an order of magnitude lower than that of planar FP sensors are ultimately feasible.

2. Limiting factors

We have identified two main parameters that determine the performance of high-Q ultrasound sensors:

2.1. Laser phase noise

We fabricated a series of PCMR sensors using a low-absorption material such as fused silica, and a variable mirror reflectivity that rendered values of the resonator Q-factor between 10^3 and 10^6 (up to 1000x higher than previously achieved with planar FP sensors). The measured optical sensitivity, which represents the sensitivity of the sensor to a change in optical thickness and is defined by the Q-factor, was in good agreement with theoretical predictions obtained by the ABCD model simulations [4]. However, although higher Q factor, and thus higher optical sensitivity, than the planar FP sensors was achieved with the PCMR design, it was observed that the noise was also higher. This was found to be due to the phase noise of the interrogation laser (due to its finite linewidth) which is converted to intensity noise by the cavity transfer function. Since this noise component is proportional to optical sensitivity, it is significantly higher for the PCMRs than the FP planar sensors due to the higher Q-factors of the former. The phase noise became dominant (over shot noise and RIN) when $Q>5 \cdot 10^4$, for a laser linewidth of 20 kHz. As a result, the NEP was limited to tens of Pascals, a factor of 2 lower than planar FP sensors.

Using a 10 kHz linewidth laser reduced the NEP by 25%. We estimate that a 1 kHz linewidth laser would remove the effects of phase noise for a 10^6 Q-factor resonator, in which case the NEP would be 5x lower.

2.2. Optical absorption

We fabricated a second series of PCMR sensors using polymer spacers, which are more elastic than fused silica and hence the change in the cavity optical thickness produced by the incident acoustic wave is higher. This change is characterised by the acoustic sensitivity and is defined by the Young's modulus of the material, which in the case of polymers can be 20x lower than fused silica. However, optical absorption in a polymer spacer can be 10x higher. Based on our theoretical estimations, optical absorption limits the travel path of light inside a polymer cavity to few tens of centimetres, while inside a fused silica resonator can extend up to 2 metres. This limits the Q-factor of polymer sensors to $5 \cdot 10^4$.

However, despite the relatively low Q-factors achieved with polymer PCMRs, the NEP was still a factor of 2 lower than the fused silica PCMRs (4x lower than planar FP sensors), a consequence of the lower Young's modulus of the polymer. Although the lower Q-factor meant that the laser phase noise contribution was lower, a narrower laser linewidth would also benefit these sensors. If a 5 kHz linewidth laser was used, we estimate that an NEP of near 1 Pa could be achieved.

3. Conclusion

This study has explored the trade-offs associated with optimising the sensitivity of PCMR sensors. It has shown that fused silica PCMR sensors can provide much higher Q-factors and thus optical sensitivities than polymers. In principle, this can compensate for their relatively high Young's modulus enabling high overall sensitivity to be achieved. However, in practice, the high Q-factor results in the phase noise due to the linewidth of commercially available tunable lasers limiting NEP. If in future however, tunable lasers with kHz linewidths become available, or phase noise compensation techniques can be employed, then fused silica ultrasound sensors have the potential of approaching NEPs 10x lower than the well-established planar FP sensors. On the other hand, more compliant materials such as polymers benefit from lower Young's moduli but they suffer from higher absorption coefficient. This in turn sets an upper limit on the cavity Q-factor which limits the NEP. Based on current tunable laser technology and the materials that we have investigated, it is concluded that the use of polymers as the cavity material still remains optimal, despite the optical losses they incur; our current generation of polymer PCMRs provide NEPs 4x lower than planar FP sensors. We estimate that further minimisation of the limiting factors can render NEP values comparable to those of mm-scale piezoelectric receivers used in breast imaging systems but with much smaller element sizes (<150μm) and broader bandwidths provided by the PCMRs and would pave the way to multi-cm imaging depths in tissue.

4. References

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