STABILIZED, RESONANT OPTOACOUSTIC ARRAY DETECTORS FOR MEDICAL IMAGING

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Abstract

Optoacoustic (OA) detectors have typically suffered reduced sensitivity with respect to piezoelectric detectors. Here, we present our results on studies of stabilized, resonant OA detectors with high sensitivity potential.

We show that acceptable sensitivity requires resonant OA detector (ROAD) finesse (F) > 200. As a result, application of the ROAD as an imaging array with a suitable dynamic range of at least 40 dB requires ROAD surfaces with parallelism better than 0.01 nm. Surface precision limits for appropriate materials are near 5 nm, so we have studied active stabilization of the ROAD to circumvent this constraint.

Stabilization can be effected by tuning ROAD surface spacing, wavelength, or index of refraction. Our studies indicate that index of refraction tuning is especially promising in terms of response time (1 ms to <1 ns), tuning range (1 nm to >20 nm), tuning sensitivity (<0.01 nm), and simplicity of design.

Introduction

Optoacoustic (OA) detectors have been much-touted for their potential as high resolution, high bandwidth transducers with the possibility of miniaturization, selectable operating frequency, and simple fabrication.

To date, two primary classes of optoacoustic detection transducers have been developed: single-reflective-surface (SRS) deflection transducers (employed in commercial laser-based ultrasound systems) and dual-reflective-surface (i.e., resonant) element transducers. In both cases, the OA detector sensitivities fall short of ideal, appropriately-sized piezoelectrics. Details on the sensitivity of SRS OA detectors and resonant OA detectors (ROADs) can be found in Hamilton and O'Donnell [1] and in Hamilton et al [2], respectively.

ROADs have been successfully implemented by Beard and Mills as both detectors [3] and as imaging arrays [4]. Existing ROADs [2,3,4] have employed resonators of low (< 30) finesse (F), resulting in a self-imposed sensitivity limit. Here, we study ROADs with F > 200 for higher sensitivity detection.

Detection sensitivity of both piezoelectrics and ROADs is frequency-dependent. A fully OA imaging system would be particularly useful for high frequency applications, so we aspire to a 50 MHz center frequency in developing operating requirements for the ROAD.

Sensitivity equivalence to piezoelectrics

As computed in [1], the ideal (thermal limit) minimum detectable piezoelectric deformation is:

$$\Delta D_{min\,PZ} = \frac{1}{f}\sqrt{\frac{4k_B TB}{ZA}}, \qquad (1)$$

where f is the acoustic center frequency (Hz), k_B is the Boltzmann constant (1.38 x 10^{-23} J/°K), T is temperature (°K), B is transducer bandwidth (Hz), Z is acoustic impedance (Rayls), and A is transducer active area (m^2). From [2], the shot-noise limited minimum detectable displacement of a ROAD is:

$$\Delta D_{min\,OA} = \frac{\lambda}{F}\sqrt{\frac{4eB}{27SI_0}}, \qquad (2)$$

where λ is laser wavelength (m), e is electron charge (1.6 x 10^{-19} coulombs), B is acoustic modulation bandwidth of the optical signal (Hz), S is photo-detector sensitivity (A/W), and I_0 is incident laser intensity (W). Assuming appropriate piezoelectric array element dimensions for imaging, equating (1) and (2) leads to:

$$F = \frac{\lambda_{opt}}{4}\sqrt{\frac{\pi eZc^2}{27Sk_B TI_0}}, \qquad (3)$$

where c is the speed of sound in the propagation medium (m/s). (3) defines the finesse required for ROAD sensitivity equivalence to piezoelectric detection. With typical values of Z near 34 MRayls for piezoceramics, c = 1500 m/s in water, ambient temperature T = 300 K, and a typical value for photodetector sensitivity (S = 0.5 A/W), we consider F as a function of laser wavelength and intensity. Figure 1 is a plot of F vs. λ and I_0 for wavelengths between 600 nm and 1100 nm and laser intensities between 1 and 20 mW. These values correspond to those available on standard laser systems, as well as to those suitable for application in the clinic.

For reduced cost as well as adherence to safety constraints associated with clinical applications, laser intensities below 5 mW are preferred. As can be seen in Figure 1, this puts the finesse requirement over 200. Specifically, with a 1 mW, 1100 nm laser, the finesse of the ROAD must be 225 to achieve the desired sensitivity.

Finesse determines the required reflectivity [2] which, in turn, determines the computed ROAD linear detection range. For F = 225, R = 98.6%, and the linear detection range of a 98.6% ROAD is < 1 nm.

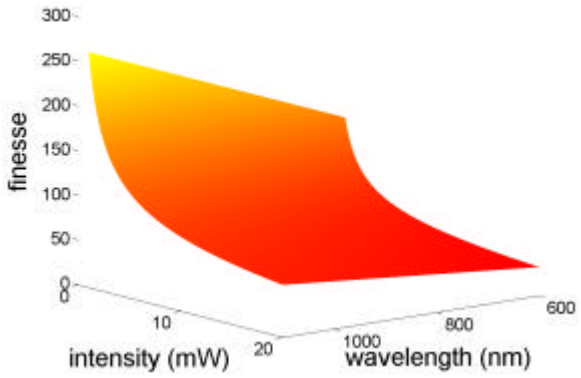

Figure 1: ROAD finesse to match piezoelectric sensitivity for a range of laser wavelengths and intensities.

Fused silica is a standard substrate for optical grade etalons. Surface quality is typically quoted as λ/10 at 632 nm, with a wedge angle < 1 arcsecond: far from the required thickness uniformity of < 1 nm.

With low bulk modulus and the potential for economic fabrication, polymers present an attractive alternate for the ROAD substrate. Polymer films can be formed by spin-coating the liquid polymer precursor onto a substrate, then curing. The surface quality achieved with this technique is highly variable, with strong dependence on the substrate (size, shape, flatness), the selected polymer and dilution agent (as well as the dilution ratio), and the parameters of the spin coating process (coater model, spin settings). At optimized settings, a surface of 50-100 nm rms roughness can be expected.

Highly uniform surfaces may be fabricated by 'growing' an appropriate substrate material molecular layer by molecular layer. Techniques include Langmuir-Blodgett and electrostatic self-assembly (ESA). The resulting substrates can be flat to within a molecular length, and thickness precision < 5 nm is possible.

Approach: Active ROAD Stabilization

To achieve desired surface flatness of 0.01 nm, we turn to active stabilization of the ROAD substrate. By monitoring the steady-state optical output of the ROAD, we can stabilize the operating point by tuning the ROAD to maintain constant output over timescales corresponding to a zero integral over the ultrasound signal. In this case, the ultrasound signal encodes the optical intensity output, while other noise sources (including surface variations encountered in scanning to form a synthetic array) are eliminated.

The operating point of the ROAD is ultimately determined by the phase difference (i.e., accrued phase, $\Delta\phi$) between successively reflected beams [2]:

$$\Delta\phi = \frac{4\pi n D \cos\theta_i}{\lambda}, \qquad (4)$$

where D is the mirror separation, λ the laser wavelength, n the index of refraction, and θ_i the laser angle of incidence. Normal incidence ($\theta_i = 0$) provides superior ROAD performance, so we limit consideration of tuning methods to mechanical (ΔD), wavelength (Δλ), and refractive index (Δn).

Potential sources of noise in the accrued phase include vibrations, ambient temperature fluctuations, and thickness nonuniformity between array elements (for synthetic array operation, the laser scans the transducing surface). The corresponding timescales are slow (> 1 ms), so, at a minimum, the stabilization response time should not exceed 1 ms. Ideally, however, we would like to image at > 50 frames per second, so prefer response times < 1 μs.

Table 1 : active stabilization requirements

response time	< 1 ms (< 1μs)
control sensitivity	< 0.01 nm
tuning range	> 1 nm

Mechanical tuning can be effected by controlling the mirror separation. With piezoelectric actuators having minimum incremental motion on the order of 1 nm, this method lacks the required sensitivity. Thermal expansion can be a sufficiently sensitive tuning method (0.01 nm control corresponds to temperature increments of about 0.01 °C for both polymers and fused silica,) but prohibitively high temperature differentials would be required to achieve the desired range (> 1 nm). A combination of thermal expansion and mechanical tuning could provide fine and coarse tuning, but would introduce an undesirable level of complexity.

Generally, laser wavelength output can be controlled by varying the laser crystal temperature. This method is slow and lacks range. Tunable VCSELs have been developed where the output wavelength depends on applied voltage – here, the response time is fast, but the wavelength output is discontinuous (i.e., there are 'jumps' between output wavelengths). An alternative is to use a broadband laser together with an acousto-optic modulator (AOM), with the primary limitations being tuning range and expense.

Tuning the refractive index can be approached in two particularly promising ways: via the thermo-optic and electro-optic effects. In both cases:

$$\delta\Delta\phi \propto D\delta n, \qquad (5)$$

and we face a design trade-off: smaller D is preferred for increased bandwidth and reduced optical loss, while large D enables increased refractive index tuning capability. Ultimately, ultraflat polymers that

are grown layer by layer will be < 10 um, so this is an effective upper limit.

The thermo-optic effect is quantified by:

$$\delta n = C_{TO} \Delta T , \quad (6)$$

where C_{TO} is the thermo-optic coefficient of the material. Fused silica has a C_{TO} = 12.8 x 10^{-6}; for polymers, the C_{TO} ranges from -100 x 10^{-6} to -400 x 10^{-6}. For a 4 mm fused silica etalon used with a HeNe laser (λ = 632.8 nm), the temperature change required for full thermo-optic tuning is 2.13 °C, with a desired tuning sensitivity of 1.4 x 10^{-4} °C. (Such precise temperature control is beyond current capabilities.) A 2.25 μm polymer etalon used with an Nd:YAG laser (λ = 1064 nm) requires over 300 °C for full thermo-optic tuning (about 2.6 °C for linear tuning) and a temperature control sensitivity of 2.6 x 10^{-2} °C. We see that range and sensitivity are not readily satisfied simultaneously: fine control is challenging for thicker fused silica etalons, while it is unlikely to achieve full range thermo-optic control for thin polymers.

The electro-optic (EO) effect in a material is generally broken down into two components: the Pockels and Kerr effects [5]. The Pockels effect produces a change in refractive index which is linear in the applied electric field:

$$\delta n_{EOP} = r \frac{n^3}{2} E = r \frac{n^3}{2} \frac{V}{d}, \quad (6)$$

where r is the Pockels electro-optic coefficient, E is the applied electric field, and V the corresponding voltage for a distance, d, between electrodes. To establish the required range and sensitivity of applied voltage for effective ROAD stabilization at normal incidence, we equate (6) to the refractive index change as it is related to change in accrued phase ($\delta\Delta\phi$) according to (4):

$$V_P = \frac{\lambda d}{r n^3 D} \delta\Delta\phi . \quad (7)$$

Only non-centrosymmetric materials exhibit the Pockels effect [5]. All materials, however, exhibit the Kerr effect - a change in refractive index that is proportional to the square of the electric field:

$$\delta n_{EOK} = s \frac{n^3}{2} E^2 = s \frac{n^3}{2} \frac{V^2}{d^2}, \quad (8)$$

where s is the Kerr electro-optic coefficient. Again establishing the required range and sensitivity of applied voltage, we equate (8) to δn as it is related to $\delta\Delta\phi$:

$$V_K = d \sqrt{\frac{\lambda}{2\pi s n^3 D} \delta\Delta\phi} . \quad (9)$$

Typically, r is on the order of 10^{-10} to 10^{-12}, and typical values of s of 10^{-14} for crystals, 10^{-22} for liquids, and on the order of 10^{-18} for polymers. The response time for the EO effect depends on the amplitude of the voltage but even in optical switching applications, where a full π rads modulation is needed, EO modulation bandwidths exceed 1 GHz. This rapid response is one of the main attractions of using the electro-optic effect for stabilizing ROADs.

To evaluate the potential of EO stabilization, we have modeled EO tuning of a 2 μm thick polymer with a nominal refractive index of 1.5. Using (4), quantification of the linear region for an F = 225 etalon can be expressed as a change in accrued phase ($\delta\Delta\phi$), and corresponds to $\delta\Delta\phi$ slightly less than 0.015 rads. For a 2 μm film that satisfies the requirement of thickness variations < linear region (at F = 225), EO tuning over the full linear range, as well as fine tuning to provide the desired dynamic range, is easily achieved (Figure 2) with reasonable applied voltages. (We have assumed a Pockels coefficient, r, of 10^{-10} and a Kerr coefficient, s, of 10^{-18}. These values correspond to available ESA films that satisfy the thickness uniformity requirement.)

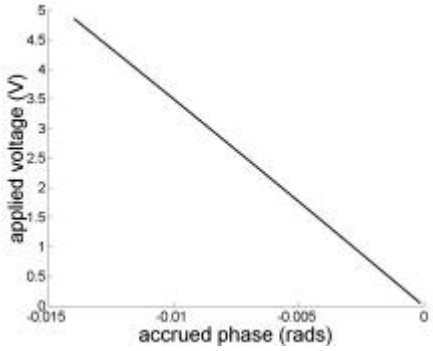

Fig 2: Linear range tuning via the electro-optic effect (Pockels + Kerr).

Experiment: Index of refraction tuning

Using a 4 mm thick, 97.6% reflective fused silica etalon (CVI Laser Corp., ET-25.4-4.00-UV-632.8-97.6) with a 1.5 mW HeNe laser (Spectra Physics, model 117A), and a thermal control system (based on a Peltier junction heater/cooler, Melcor # RH 1.4-14-06-L-EC), we demonstrated index of refraction tuning of the etalon operating point.

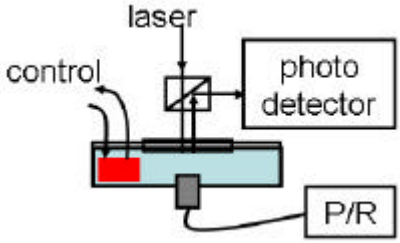

Fig 3: Index of refraction ROAD tuning experiment sketch. The control mechanism was thermal.

A 5 MHz center frequency transducer (Aerotech #018275H) driven by a pulser/receiver (GE / Panametrics model 5072PR) provided the acoustic source. The source transducer face was aligned for normal incidence to the fused silica ROAD. At 18.95 °C, a ROAD tilt of approximately 0.8° provided maximum linear detection sensitivity. The detected signal is shown in Figure 4. With the temperature increased to 19.8 °C, a reduced tilt (about 0.3°) corresponded to optimal linear detection sensitivity. The detected signal from the thermally-tuned fused silica is displayed in Figure 5. (Pulse echos for each experiment had maximum amplitudes differing by < 9%.)

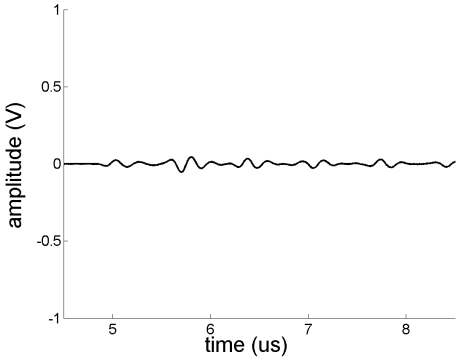

Fig 4: ROAD signal, 18.95 C

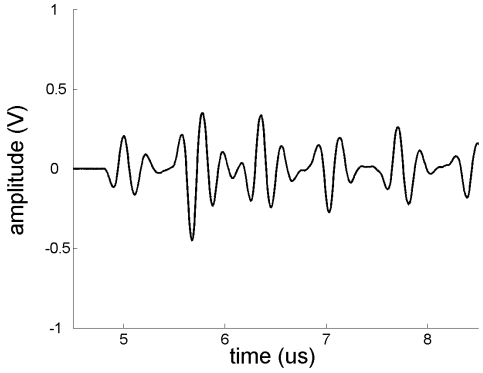

Fig 5: Thermo-optic tuning: ROAD signal, 19.80 C.

Discussion

Comparing Figures 4 and 5, the improved sensitivity of the index of refraction tuned ROAD is evident. With a peak optical amplitude ratio of 8.4, we observe the impressive effect of minimizing laser angle of incidence. Tuning within the linear region does not lead to improved sensitivity – however, decreased incidence angle (and, thus, better localization of the multiply reflected beams) reduces contributions from potentially different ROAD thicknesses attributable to etalon surface nonuniformity.

Thermo-optic tuning, though possible, suffers from relatively slow response times. Therefore, we are most interested in electro-optic ROAD stabilization.

Attempts at EO tuning with ESA materials (provided by NanoSonic, Inc., Blacksburg, VA, USA) have been thwarted by adhesion problems between the required layers: EO polymer sandwiched between metallic, partially reflecting mirrors (doubling as electrodes). Resolution of this issue is expected in the near future.

Conclusions

Resonant optoacoustic detectors have typically been operated at low finesse due to insufficient thickness uniformity and stability. We have proposed and studied active stabilization of ROADs using a variety of methods: mechanical, wavelength, and refractive index control. We have demonstrated thermo-optic tuning of a fused silica ROAD with an associated detection sensitivity improvement of nearly an order of magnitude. Attempts at electro-optic tuning were unsuccessful due to unresolved issues with the electrostatic self-assembly of multi-material films.

Acknowledgement

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References

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