Fast interrogation wavelength tuning for all-optical photoacoustic imaging

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1. Introduction

Relying on the emission of ultrasound waves upon the absorption of transient illumination, photoacoustic imaging has been developed to image objects embedded deep inside scattering biological tissue [1]. Since these pressure waves are only weakly scattered when propagating through soft tissue, the acoustic field can be detected at the tissue surface and the optically-absorbing structures can then be reconstructed with acoustic resolution [2]. As compared to conventional piezoelectric sensors, Fabry-Pérot based optical sensors provide larger bandwidth and better sensitivity at high ultrasound frequencies. Moreover, their transparency allows to illuminate the sample and measure the emitted acoustic field from the same aperture [3–7].

The performances of this detection technique are affected by fabrication constraints of the FP sensor, in particular the thickness homogeneity of the sensing polymer layer. For a total thickness of a few tens of micrometers, fluctuations of this thickness around a few tens of nanometers (corresponding to a typical surface quality of $\lambda/10$ for mid-range optical components) would result in a spectral shift of the reflection spectrum up to a few nanometers. The interrogation wavelength must then be adjusted pixel-to-pixel to compensate for these thickness fluctuations and maintain the highest sensitivity range. This significantly limits the final frame rate, as typical continuous-wave interrogation sources have a limited tuning speed of the order of 1-10 nm/s, or conversely sets stringent constraints on the fabrication tolerance of the polymer spacer, increasing the complexity of coating steps and associated costs.

The combination of both affordable FP sensors and high imaging rates therefore requires a fast tuning of the interrogation source wavelength. Here we propose to use a broadband source and select the optimal interrogation wavelength at any pixel of the FP sensor with a narrow, fast-tunable filter. We implement this approach using a broadband amplified spontaneous emission (ASE) source and an acousto-optic tunable filter (AOTF). We experimentally demonstrate its performances and show that fine tuning of the interrogation wavelength is crucial to detect the high frequency content of the photoacoustic signal.

2. Methods and results

The tri-dimensional image of the optical absorption distribution is formed by reconstructing the initial pressure rise, following the nanosecond pulsed illumination of the medium. This requires measuring the time-varying ultrasonic field over a large area at the surface of the medium. As depicted in Fig.1, the imaging system can be split in three main parts: an interrogation source, a raster-scanning microscope, and a detection system. The interrogation source uses a broadband amplified spontaneous emission (ASE) source with a 10 nm bandwidth, centered around 1027 nm. The beam is spectrally filtered by an acousto-optic tunable filter (AOTF), allowing to switch between different wavelengths in just 15 $\mu$s, independently of the extent of the wavelength shift. The spectral linewidth of the filtered diffracted beam is about 0.5 nm. The Fabry-Perot sensor is interrogated with a custom-made laser-scanning microscope. The light reflected by the FP cavity is focused into a single-mode fiber splitter.
which send the signal both to an optical spectrum analyzer (OSA) and to an avalanche photodiode. The signal is digitized at 500 MS/s with a fast oscilloscope card.

![Diagram](image)

**Figure 1:** (Left) Experimental setup – Interrogation source: ASE: amplified spontaneous emission source; AOTF: acousto-optic tunable filter; WF: waveform generator; HWP: half waveplate; FM: flip mirror; BS: beam splitter (50:50); BB: beam block. Detection: SMF-BS: single mode fiber splitter (10:90); OSA: optical spectrum analyzer; APD: avalanche photodiode; DAQ: data acquisition system. (Right) Maximum intensity projection of the reconstructed volume after filtering the PA signals on three different frequency bands, with optimal wavelength tuning (top row) and with mean wavelength of the calibration map (bottom row). All pairs of images are normalized to the maximum value of the top one (reconstructed volume with wavelength tuning). The color bars on the left are valid for all images within the same column. Scale bar: 200 µm.

The FP sensors are based on a 1 mm thick glass substrate. The cavity is formed by dielectric Bragg mirrors (ZnS/YF3), made by electron-beam deposition. Two polymers are used for the sensing layer: Parylene C (deposited by chemical vapor deposition), or SU-8 (deposited by spin-coating, results in [8]).

We image black wires (20 µm diameter) embedded in agarose gel. A nanosecond pulsed laser (wavelength: 515 nm, repetition rate: 2 kHz, pulse duration: 1.2 ns) illuminates the sample with a fluence of 10µJ/mm² per pulse. The FP cavity is first calibrated by illuminating it with the full ASE source spectrum (flip mirror in, see Fig.1 left). The focused interrogation beam is then scanned over a 2 mm field-of-view (FOV) with a 20 µm step. For each position, the reflection spectrum of the FP cavity is measured with the OSA, and the optimal wavelength is computed and stored. This calibration procedure yields a map of optimal wavelengths that should be used at each pixel to get the highest sensitivity. PA signals are then acquired by scanning the FP sensor with the 1st diffraction order beam of the AOTF (flip mirror out). A waveform generator drives the AOTF so that the optimal interrogation wavelength is used at each pixel, with a wavelength tuning time of only 15 µs. The acquisition of each photoacoustic signal is triggered by the emission of a nanosecond pulse, and multiple signals are averaged at each pixel to provide sufficient signal-to-noise ratio. The signals are then digitally filtered on a given bandwidth, and the photoacoustic images are reconstructed using a custom delay-and-sum beamforming algorithm [2]. Finally, the modulus of the Hilbert transform of this reconstructed volume is computed and maximum intensity projection are used for display.

Results are shown in Fig.1 right. Black wires are imaged either using the full calibration of the FP sensor (Fig.1 right, top row), or using the mean wavelength of this calibration (Fig.1 right, bottom row). We investigate the effect of the fine interrogation wavelength tuning on the high frequency content of the detected ultrasound signals. Images are reconstructed after digitally band-pass filtering the PA signals either between 10 MHz and 120 MHz, 30 MHz and 120 MHz, or 50 MHz and 120 MHz. We observe that...
precise tuning of the interrogation wavelength is critical to provide the highest sensitivity for large ultrasonic frequencies, and thus the best possible resolution.

3. Significance and conclusion

We presented a new method for optical interrogation of FP sensors for ultrasound field measurement. Instead of relying on a slowly tunable narrowband laser source, we use a broadband ASE source and take advantage of the short microsecond response time of an acousto-optic tunable filter. This allows us to quickly select the most adequate interrogation wavelength at each pixel of the FP sensor. The primary advantage of this approach is the ability for the interrogation beam to hop from one wavelength to another in a short amount of time, independently of their values. This provides a significant asset compared to tunable laser sources which need to scan the wavelength through the entire range separating two values. We also stress that the proposed interrogation source provides a few mW of optical power on the FP sensor, which is comparable to what is achieved with conventional telecom tunable laser sources [9].

The wavelength shifting time of the AOTF is comparable to the minimum time per pixel set by the galvanometric scanners due to inertia. The maximum line rate is indeed about 1 kHz, yielding a pixel dwell time of 10 µs for 100 pixels per line, or equivalently a pixel rate of 100kHz. The ultimate limitation is then set by the 2 kHz repetition rate of the nanosecond excitation laser, still much lower than the 67 kHz that could be achieved with our technique. However, the noise level in our setup does not allow us yet to fully benefit from this repetition rate, as we need to average several PA signals per pixel. Nonetheless, we showed that this technique could be used to perform photoacoustic imaging with FP sensor even when the thickness of the polymer spacer was highly inhomogeneous. Fast optical compensating of the low quality of the polymer deposition could allow the use of polymers that cannot be deposited by CVD, potentially with more adequate acoustic properties. This also opens the way towards cheaper and disposable FP cavities, which is still a strong requirement for implantable sensors [10].

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