A highly flexible pulsed photoacoustic setup based on a tunable laser source and external modulation

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Abstract. In this paper performance enhancement in PA measurements through optical pulse shaping is explored and demonstrated. A recently introduced setup, which is based on a CW tunable laser source operating in the optical communications band (1510-1620nm) and an electro-optic modulator, offers exceptional flexibility in controlling the temporal and spectral characteristics of the excitation waveform. Despite its being remarkably simple to construct and to operate, the unique optical configuration of this setup opens the possibility for a range of attractive applications which cannot be implemented by the commonly used pulsed lasers: responsivity and sensitivity optimization through pulse-shaping, enhancement of spatial resolution through pulse compression and simple implementation of high-resolution quantitative spectroscopy.

1. Introduction

Photoacoustic (PA) imaging is a field of growing interest, especially for biomedical applications, where it combines the advantages of the high contrast achieved by optical absorption and the high spatial resolution obtained via ultrasound detection [1]. Photoacoustic spectroscopy (PAS) for biomedical uses has also attracted much attention mainly due to its compatibility to in-vivo applications. The optical sources in most PA setups are either Q-switched or mode-locked pulsed lasers with pulse-widths in the nanoseconds range. While providing robust and high-power excitation, such sources allow very limited control over the pulse temporal shape, and in many cases also have limited spectral tunability. One method to control the temporal characteristics of the optical excitation is via direct modulation of laser diodes, however achieving short rise times using this approach is often difficult due to dynamical effects such as ringing and pulse distortion [2].

Recently we have introduced a PA setup that allows simple and accurate control of the excitation pulse via external modulation of a CW optical source [3, 4]. The current implementation of the setup comprises a CW tunable laser operating in the optical communication band and an electro-optic external modulator (EOM) driven by an arbitrary waveform generator (AWG). This modulation method allows synthesis of ultra broadband waveforms with arbitrary shapes. The current spectral range of the setup, around 1550nm, has indeed a disadvantage of relatively high absorption and short penetration depth in water, which might limit its usage for biomedical imaging applications. However, this setup was constructed as a test platform for exploring and demonstrating the benefits of pulse-shaping in PA applications. Similar waveform synthesis implementations at other interesting wavelength ranges are currently under development.
In this paper we briefly describe several applications of the proposed setup which demonstrate the unique advantages that it can offer in PA measurements. Previously we showed how matched pulses can be used for optimization of the responsivity or sensitivity of a PA measurement setup [3]. In this paper we will describe two additional applications: the use of pulse compression for optimization of the tradeoff between SNR and spatial resolution for a given peak power and quantitative PA spectroscopy which take advantage of the knowledge of the pulse temporal shape. The various examples for pulse shaping applications show that by using external modulation pulses can be tailored to meet specific requirements in the lowest possible total or peak optical energy, which may be crucial for in-vivo biomedical applications.

2. Theory

For waveforms which satisfy the thermal confinement condition the response of a typical PA system can be expressed as the following convolution [5]:

\[ p(t) = h(t) \ast f(t) \ast d(t) \]  \hspace{1cm} (1)

Where \( f(t) \) is the instantaneous power of the excitation optical pulse, \( d(t) \) is the impulse response of the acoustical receiver (typically a piezoelectric transducer followed by an RF amplifier) and \( h(t) \) is the response of the medium to an optical impulse, given by:

\[ h(t) = \frac{\beta}{4\pi C_p} \frac{d}{dt} \left( \frac{1}{t} \int_{y=t} A(\mathbf{r})dS \right) \]  \hspace{1cm} (2)

with \( \beta \) being the isobaric volume expansion coefficient, \( C_p \) the specific heat, \( c \) the speed of sound and \( A(\mathbf{r}) \) being the spatial absorption distribution.

If \( f(t) \) and \( d(t) \) are known, it is possible to extract \( h(t) \) from the measured PA response. In a homogeneous medium, once \( h(t) \) is known, the absorption coefficient can be found through numerically fitting the right-hand side of equation (2) to the measured waveform. In inhomogeneous media \( A(\mathbf{r}) \) can be similarly calculated from multiple projections. Since this approach is based on the shape of the response rather than its amplitude, it is immune to fluctuations in the laser intensity.

In previous work we presented the use of pulse shaping for SNR optimization at a given total optical energy [3]. In cases where the peak optical power is limited rather than the total optical energy, the optimal tradeoff between SNR and spatial resolution can be achieved by using pulse compression. In this technique, which is well known in radar theory and also in ultrasonography and a few recent works in photoacoustics [6-8], the transmitted pulse has linear frequency modulation (LFM) of the form:

\[ f(t) = \begin{cases} 
A \cos \left[ 2\pi t \left( f_0 - \frac{\Delta f}{2} - \frac{\Delta f}{2T_p}t \right) \right] & 0 \leq t \leq T_p \\
0 & \text{else}
\end{cases} \]  \hspace{1cm} (3)

where \( T_p \) is the pulse duration, \( f_0 \) is the center frequency and \( \Delta f \) is the spectral width of the pulse. The latter two parameters should match those of the acoustical receiver frequency response for optimal efficiency. The total energy conveyed by the pulse and in turn the SNR, can be increased by increasing \( T_p \). By applying matched filtering to the measured PA response it is ensured that the temporal resolution will return to the inherent limit dictated by the acoustical receiver, namely \( \sim \Delta f^{-1} \ll T_p \).
3. Experimental setup and results
The optical part of the experimental setup (figure 1) comprised a fiber-coupled Tunable Laser Source (TLS) in the range of 1510-1620nm, a polarization controller, a Lithium-Niobate Electro-Optic Modulator (EOM) driven by an Arbitrary Waveform Generator (AWG) and an Optical Erbium Doped Fiber Amplifier (EDFA) followed by an optical filter. The use of the modulator and the AWG enabled synthesis of pulses of arbitrary temporal shapes, with bandwidths of up to 100MHz. The output of the optical filter was collimated and the beam was directed into a cell containing the tested sample.

The acoustical detection was performed either by a ceramic piezoelectric transducer (PZT) disk with resonance frequency of 200KHz and fractional bandwidth of 70% that was glued to the cuvette wall for the spectroscopy experiments, or with a 1MHz immersion ultrasound transducer (I3-0108, Harisonic) for the imaging experiments. The output of the acoustical receiver was amplified by a RF preamplifier and sampled and averaged by a digital oscilloscope.

To demonstrate the application of quantitative spectroscopy in liquids, we measured the PA responses of ethanol and its mixtures with water and deuterium oxide (D\textsubscript{2}O) in different concentrations and in several wavelengths in the range 1535-1565nm. This yielded a wide range of absorption coefficients that extended from 300 to 1000 [m\textsuperscript{-1}]. The normalized responses were the inputs to a numerical simulation that calculated the theoretical responses based on equations (1) and (2), given the detector response, obtained from its specifications, and the system parameters: beam diameter, detector location and the speed of sound. For simplicity, the pulse shape that was used was a long square pulse (about 100\,\mu s). To obtain the absorption coefficient, the normalized measured PAS responses were iteratively fitted against the simulated responses. In order to avoid the influence of both reflections from the cuvette walls and the PZT oscillations due to non-perfect damping, only the leading edge of the response was fitted against the simulated signal. Examples of PAS responses and the corresponding simulated versions, obtained at the wavelength of 1550nm, are shown in figure 2(a). The estimated absorption spectra in the range of 1535-1565nm, as well as reference spectra from transmission spectroscopy, are shown in figure 2(b). The good agreement between the signal shapes and between the absorption spectra from PAS and from transmission spectroscopy is evident.

![Figure 1. The experimental setup](image-url)
To demonstrate pulse compression, the PA response of a 0.3mm steel wire immersed in D$_2$O was measured by an immersion transducer. The excitation waveforms were LFM pulses with durations ($T_p$) of 8, 64 and 128 μsec, and $f_0$=1MHz and $\Delta f$=1MHz to match the frequency response of the immersion transducer. The PA responses were filtered by match filters of the input pulses, and the results were compared to a matched-filtered response obtained from a Gaussian pulse with the same spectral width $\Delta f$, modulated by $f_0$=1MHz, but without chirp. All excitation pulses had the same peak amplitude and the matched filters were normalized so that the signals energy was preserved.

Examples of linearly chirped and non-chirped excitation pulses are shown in the inset of figure 3. The matched-filtered responses of the steel wire to the different pulses are shown in the figure main plot. The pulse-duration dependent LFM gain is clearly seen. The gain, however, is lower than the theoretical prediction due to imperfect synthesis of the optical pulse. Methods for improving the fidelity of the waveform synthesis through pulse pre-distortions are currently under study.

Figure 2. (a): Measured (solid) and simulated (dotted) PA signals: Ethanol (blue, rightmost), Ethanol-Water: 75% (green, middle) and 50% (red, leftmost)
(b): Measured absorption spectra – PAS (squares) transmission spectroscopy (solid lines): Ethanol-water: 75% (green, 1st from top) and 50% (pink, 2nd from top), Ethanol (blue, 3rd from top), Ethanol-D2O 50% (black, 4th from top)

Figure 3. Matched-filtered response of wire in D$_2$O for different excitations: Modulated Gaussian pulse (black) and LFM pulses of durations 8, 64 and 128 μsec (green, pink and blue respectively). Inset – two corresponding excitation pulses.
4. Conclusions
In this paper performance enhancement in PA measurements through optical pulse shaping was explored and demonstrated. To enable synthesis of the excitation waveforms a recently introduced PA setup based on a CW laser source and external modulation was used. The setup offers exceptional flexibility and accuracy in controlling the temporal and spectral shape of the excitation waveform. The demonstrations included optimization of the SNR-resolution tradeoff for PA imaging using pulse compression and quantitative estimation of the absorption coefficient in PA spectroscopy. The specific setup which was used for the demonstration was based on optical communications components and thus operated in the 1550nm wavelength range. Implementation of this promising approach in additional spectral ranges is currently under study.

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