Thermophotonic radar imaging: An emissivity-normalized modality with advantages over phase lock-in thermography

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One major problem of frequency-domain photothermal radiometry, or alternatively in two-dimensional lock-in thermography, is the compromise one has to make between dynamic range (probing depth) and depth resolution. The thermal-wave radar incorporates chirped excitation through matched filtering to maintain good resolution and depth range inside a sample. This letter experimentally demonstrates the advantages of chirped modulation and introduces a thermophotonic modality of thermal-wave radar based on an emissivity-normalized, higher-dynamic-range contrast parameter known as cross-correlation phase. Finally, comparisons made on a biological (dental) sample show potential applications of the method. © *2011 American Institute of Physics*. [doi:10.1063/1.3582243]

One of the problems encountered in lock-in thermography (LIT) is the compromise one needs to make between maximum detection depth and depth resolution. While lowfrequency thermal waves can "see" deep into the sample (~mm), they lack the desired depth resolution. Highfrequency thermal waves, on the other hand, display exactly the opposite behavior due to the reduced thermal diffusion length and thermal wavelength. In the radar sciences, matched filtering has been used since the early 1940s to detect preknown signals within highly noised channels and to augment range resolution. The first application of correlation and spectral analysis to a photothermal-wave system using frequency chirps was introduced by Mandelis et al. in a series of papers in 1986.¹⁻³ More recently, Mulaveesala and Tuli⁴ and Tabatabaei and Mandelis (thermal-wave radar, TWR) (Ref. 5) applied this methodology to thermal-wave nondestructive imaging. It is the intention of this letter to experimentally show that the TWR technique can break through the maximum detection depth/depth resolution limitations of LIT, to introduce an optically resolved thermophotonic imaging modality and the cross-correlation phase as an emissivity-normalized contrast parameter exhibiting enhanced dynamic range and higher sensitivity. The crosscorrelation (CC) technique is a special case of matched filtering that, for a photothermal signal can be defined as

$$CC(\tau) = \varepsilon \times \mathfrak{I}^{-1} \{ REF(\omega)^* S(\omega) \}, \tag{1}$$

where REF(ω) and S(ω) are the Fourier transforms of the reference/modulation signal, ref(t), and the highly noised photothermal signal, s(t). ε is the emissivity and \mathcal{I}^{-1} and * denote the inverse Fourier transform and complex conjugate operators, respectively. The independent variable τ determines the delay between the applied optical excitation and the radiometric response from the sample. In matched filtering, the role of pulse compression methods, such as linear

frequency modulation or chirped modulation, is to reduce the width of the CC main lobe (peak) and, therefore, increase the amplitude of the peak as the area under the curve must be conserved. Our previous publication⁵ showed theoretically and experimentally that this increase in signal-to-noise ratio (SNR) also holds in the photothermal field. While the amplitude of the CC peak strongly depends on the amplitude of the received signal, its location on the delay time axis ($\tau = \tau_p$) is linked to the depth of the signal source. One can further develop this concept by calculating the CC phase [schematically shown as a sawtooth structure⁵ in Fig. 1(a)] and find

$$\theta_{\rm CC}(\tau) = \frac{\boldsymbol{\pounds} \times \mathfrak{I}^{-1}\{\operatorname{REF}(\omega)^* S(\omega)\}}{\boldsymbol{\pounds} \times \mathfrak{I}^{-1}\{[-i\,\operatorname{sgn}(\omega)\operatorname{REF}(\omega)]^* S(\omega)\}},\tag{2}$$

where $sgn(\omega)$ and *i* are the signum function and the imaginary unit, respectively. The expression inside the square bracket in the denominator is the Fourier transform of the quadrature reference signal, obtained through the Hilbert and then Fourier transforms as shown in Fig. 1(a). The significance of CC phase is that according to Eq. (2) the emissivity is cancelled out and as a result the CC phase is an emissivitynormalized quantity.

The experimental setup consists of a continuous-wave fiber-coupled 808 nm NIR laser (JENOPTIK, Germany), a midinfrared camera (Cedip Titanium 520M, France, spectral range of 3.6–5.1 μ m and frame rate of 370 Hz), a signal generation/acquisition device (National Instruments NI-6229 BNC), and a four-axis sample positioning system.⁶ The laser power is modulated sinusoidally either at a fixed frequency (conventional LIT) or in a chirped mode (TWR imaging) to generate photothermal waves inside the sample. The data acquisition/signal processing program (designed in LabView environment) captures and averages the camera frames and their corresponding reference/modulation signal values. In the case of LIT, a standard two-dimensional quadrature demodulation is used to determine the amplitude and phase values of the thermal waves generated inside the sample." For the case of TWR imaging, based on Eqs. (1) and (2), the temporal infrared signal corresponding to each pixel, s(t), is

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FIG. 1. (Color online) (a) Thermophotonic radar signal processing block diagram. The CC and phase signals are schematic signals from two absorbers at different depths; (b) sample 1: Cross-section of the plastic step wedge inside the scattering medium; (c) sample 2, strip pattern left to right: green, transparent, black; and (d) sample 3, a tooth on LEGO® block; the solid and dashed squares indicate the locations of the treatment windows and the imaged area, respectively.

cross-correlated once with the modulation/reference signal, ref(t), and once with its quadrature. Subsequently, the CC and phase signals are calculated, Fig. 1(a). Depending on the contrast parameter chosen (the peak amplitude or its corresponding delay time, τ_p), two kinds of images can be produced from the CC signal: amplitude image or peak delay time τ_p image, respectively. Moreover, based on Eq. (2), it is also possible to produce emissivity-normalized CC phase images using the phase signal value at $\tau=0$ as the contrast parameter allocated to each pixel.

In order to experimentally investigate the capabilities of the TWR imaging method, three samples were designed and prepared. The first sample, Fig. 1(b), was a black plastic step wedge (step height=200 μ m) placed inside a scattering medium [polyvinyl chloride-plastisol with added titanium dioxide (TiO_2) powder for scattering⁸] such that the first step was located approximately 1 mm below the phantom surface. The second sample, Fig. 1(c), was made using 120 μ m thick Fisher Scientific borosilicate microscope cover slips. The glass was covered with commercial green (left) and black (right) paints with no paint applied to the center part to form a three-strip pattern. Six additional microscope cover slips were put on the painted slip to simulate two absorbers 720 μ m below the surface with different absorption coefficients (no glue was used, the edges were clamped to improve intimate physical contact between the slips). To show an application of thermophotonic radar imaging to biological materials, the third sample was chosen to be an extracted human tooth that was locally demineralized using an acidic gel within two square-shaped treatment windows, as shown in Fig. 1(d). The detailed demineralization procedure is described elsewhere.^{6,9} The left and right windows were demineralized for 10 and 20 days, respectively. Our previous studies showed that demineralization in the gel approximates natural caries and produces a subsurface lesion in enamel with a sound surface layer.^{6,9}

Figure 2 shows the results obtained from a comparison study on the depth resolution capabilities of conventional LIT and TWR imaging involving sample 1, Fig. 1(b). Figures 2(a) and 2(d) show the LIT phase image obtained at 0.01 Hz and its mean horizontal phase profile, respectively. It can be seen that due to the very large thermal diffusion length at such low modulation frequency it is impossible to resolve the 200 μ m high steps from each other and as a result the phase image appears as a gradient of colors between the two color bar extremes. Figure 2(b) shows the LIT phase image obtained at 1 Hz. The bar plot of Fig. 2(e) depicts the mean phase values on each step along with their standard deviations. The error bars indicate that statistically only the first two steps can be resolved. Figures 2(a) and 2(b)clearly show the maximum LIT detection depth/depth resolution trade-off. Figure 2(c) is the CC amplitude image obtained from 0.01-1 Hz chirps with 6 s duration using the exact same experimental conditions as Figs. 2(a) and 2(b).







FIG. 3. (Color online) Thermophotonic radar imaging of sample 2 using (a) CC peak amplitude; (b) CC peak delay time; (c) CC phase and their mean horizontal profiles in parts (d), (e), and (f), respectively. Chirp parameters: $0.01r_1/H_2$ in 6.8d-permissions. Download to IP: 128.100.49.199 On: Thu, 24 Mar



FIG. 4. Thermophotonic radar and phase LI imaging of sample 3. (a) CC amplitude image; (b) CC peak delay time image; and (c) CC phase image (chirp parameters: 0.01–1 Hz in 6 s). LIT phase images at (d) 0.01 Hz and (e) 1 Hz; (f) TMR mineral profiles at points 1–3 indicated in part (c), the inset depicts the amount of mineral loss.

Figure 2(f) depicts the mean CC values on each step. It can be seen that thermophotonic radar imaging not only resolves the steps but also detects them all. These advantages are due to the fact that the matched filtering process puts most signal energy under its main narrow (increasing depth resolution) lobe while significantly improving the SNR (maximizing detection depth).

Figure 3 shows the results involving sample 2, Fig. 1(c), to compare the three contrast parameters that can be used in thermophotonic radar imaging. Figures 3(a)-3(c) are the images obtained using cross correlation peak amplitude, peak delay time, and phase, respectively, and Figs. 3(d)-3(f) show their horizontal mean profiles, respectively. It can be seen that the amplitude channel is representative of the amount of energy absorption by the two equally deep absorbers (green and black paints), yielding significantly different CC amplitude values. Consequently, the amplitude channel is not a true measure of the depth of the absorber. However, the CC peak delay time and phase values are linked to the true depth of the absorbers as they maintain the same value over the two absorbers regardless of their absorption coefficients, similar to the LIT phase channel. Nevertheless, in terms of SNR the CC amplitude channel is significantly stronger than the peak delay time and phase channels and therefore the amplitude images should always be used to complement the information obtained from the phase and peak delay time images.

Figures 4(a)-4(c) show the CC amplitude, peak delay time, and phase images obtained from sample 3. In general, tooth demineralization results in higher porosity and leads to more light scattering and shallower absorption, thereby increasing the amplitude of thermal waves and shifting the thermal-wave centroid (i.e., phase shift) closer to the surface than at healthy spots. As a result, the artificially created caries is clearly detectable in all CC images, Figs. 4(a)-4(c). However, due to the emissivity-normalized nature of peak delay time and phase channels more details can be resolved in Figs. 4(b) and 4(c) compared to Fig. 4(a). The higher contrast of the right treatment window clearly indicates greater mineral loss due to the additional treatment days. On the other hand, phase LIT suffers from low depth resolution at 0.01 Hz, Fig. 4(d), and cannot see deep enough at 1 Hz, Fig. 4(e), to show the additional mineral loss in the right treatment window. Figure 4(f) depicts the transverse microradiography⁶ (TMR) mineral profiles along points 1–3 marked in Fig. 4(c), provided as proof of relative mineral loss within the treatment windows.

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