Discriminating between ballistic and diffuse components of light propagating through highly scattering media is not only important for imaging purposes but also for investigating the fundamental diffusion properties of the medium itself. Massively developed to this end over the past 20 years, nonlinear temporal gating remains limited to $\sim 10^{-10}$ transmission factors. Here, we report nonlinear time gated measurements of highly scattered femtosecond pulses with transmission factors as low as $\approx 10^{-12}$. Our approach is based on third-order nonlinear cross-correlation of femtosecond pulses, a standard diagnostic used in high-power laser science, applied for the first time to the study of fundamental light scattering properties.

When an ultrashort light pulse propagates through a scattering medium, its intensity undergoes an exponential decrease with ballistic propagation quantified by the scattering coefficient $\mu_s$. Simultaneously, a slower diffused component of light rises, withholding additional information about the medium. In a transmission configuration, temporal gating of the ballistic component may be exploited for shadow imaging [1] or to simply extract duration, temporal gating of the ballistic component may be exploited for shadow imaging [1] or to simply extract $\mu_s$ from the attenuation $e^{-\mu_s L}$ factor [2, 3], where $L$ is the length of the medium. In the highly scattering regime, where propagation is described by a diffusion equation [4], fitting the temporal shape of either the transmitted or reflected light at longer times ($\gg s$) provides a measure of the diffusion coefficient $D = v_e/(3\mu_s')$, where $v_e$ is the energy velocity [5] and $\mu_s'$ the inverse of the transport mean free path [4]. Measuring both $\mu_s$ and $\mu_s'$ is crucial to fully characterize a scattering media as they are related by the relation $\mu'_s = \mu_s(1-g)$, where $g$ is the anisotropy which quantifies the directionality of the scattering process. Although direct measurements of $\mu_s'$ often rely on the use of coherent back-scattering (CBS) techniques [6, 7] or photonic Ohm-law static transmission [8], time gating methods may also be applied to the characterization of biological samples or scattering phantoms whenever the value of $v_e$ is known [9, 10]. The main advantage of temporal gating over CBS is its sensitivity to $D$ over time as opposed to $\mu_s'$ only, hence the additional information it provides about the spatial or spectral behavior of the scatterers inside the medium. In the early 2000s, temporal gating was for instance used to demonstrate the transition from diffuse to localized propagation states when $\mu_s' \sim \lambda^{-1}$ [11], where $\lambda$ designates the wavelength of the scattered light. Although this interpretation has since been subject to debate and most likely attributable to fluorescence [12], temporal gating remains a powerful experimental tool for exploring deviations from classical diffusion behavior and their link to the mesoscopic topology of the scattering medium [13–16].

We often undermine how crucial the choice of temporal detection method is relative to the application or sample properties. Coherent gating either in the temporal [17, 18] or spectral domains [19, 20] has been extensively used to probe the temporal dynamics of multiply scattered light. The measured quantity however is not the averaged diffused intensity by the medium but rather its temporal (Green function) [16] or spectral response (transfer function) [15, 19] for one realization of disorder. Probing the diffusion properties of a given scattering medium therefore requires averaging over multiple realizations of disorder [11, 15, 20]. In addition, the bandwidth of the measured transfer function is limited by that of the illumination source [20], and the maximum measurable time window either by the excursion of the delay stage used for temporal measurements or by the resolution of the spectrometer in the case of spectral measurements. This limitation is extremely problematic because non-classical propagation behavior such as localisation effects [21, 22] are expected for very long delays and low transmission factors. To circumvent this experimental difficulty, one must rely on incoherent temporal detection that is sensitive to the intensity of the scattered light.

Historically, such time-resolved experiments were based on streak camera gating [23–27], but the linear dynamic range of digital sensors makes it inadequate for temporal acquisitions with log-variation in time. Single-photon counting detectors offer excellent sensitivity but feature limited temporal resolution, such that temporal traces have only been reported in the nanosecond range [9, 11]. In a transmission measurement where the spreading of the incident pulse scales with the Thouless time $\tau_t = L^2/D$ [28], the scope of investigation is therefore restricted to highly scattering phantoms.
such as solid powders [11, 29], unressembling biological tissues or diluted phantoms, unless the measurement is performed in (less precise) semi-infinite reflection configuration [9, 20].

The 1990s witnessed the emergence of nonlinear temporal gating techniques with femtosecond laser pulses [2, 3, 31–33], combining both high temporal resolution and high dynamic detection range. Although techniques such as second harmonic generation (SHG) gating [33] or optical Kerr gating (OKG) [2, 3, 31] are very efficient to probe complex media, the lowest transmission factor reported is \(\sim 10^{-10}\) [2, 34], which is still too high for characterizing fat emulsions in transmission. In this work, we show how third-harmonic generation (THG), a standard technique in high-power laser science with sensitivities of \(\sim 10^{-12}\) or higher, can be used to characterize a highly scattering slab in transmission. Although comparable sensitivities have been reported using state-or-the-art setups based on optical parametric amplification or even SHG in one case [35, 36], could in principle reach similar sensitivities, our approach offers immediate access to this record level of sensitivity using almost the highest dynamic range accessible today, all this using a commercially available device that anybody can buy and operate. We illustrate this by performing the first simultaneous measurement of both the scattering coefficient, \(\mu_s\), and reduced scattering coefficient, \(\mu_s'\), of a fat emulsion in a transmission geometry.

THG cross-correlators were originally developed to diagnose unwanted pedestals, pre-pulses or amplified spontaneous emission (ASE) on the picosecond-to-nanosecond timescale surrounding the peak of ultra-intense femtosecond laser pulses [37–40], and can reach up to \(10^{13}\) dynamic range in the near-IR (NIR) spectral region [39, 41, 42]. In our experiment, we use a commercial all-reflective third-order cross-correlator (Tundra, Ultrafast Innovations GmbH) featuring \(10^{12}\) dynamic detection range. A schematic representation of the cross-correlator setup is shown in Fig 1(c). S-polarized 30fs input pulses, centered at 790 nm, with 400 µJ energy, are sent into the device at 1 kHz repetition rate. Each pulse is separated into a probe and a gate pulse with a 5-95% beamsplitter. The 20 µJ probe pulse of \(\approx 5\) mm in diameter is attenuated using variable calibrated reflectivity mirrors (RA in Figure 1) so as to keep the PMT response linear. The pulse is then sent through the scattering medium, located in between two long-range delay lines, while the gate pulse undergoes type I SHG in a BBO crystal to generate a P-polarized SHG gate pulse centered at \(2\omega\), where \(\omega\) is the central laser frequency. The SHG gate pulse is filtered out from the residual NIR pulse using dichroic mirrors, converted back to S-polarization with a periscope and mixed with the time-delayed S-component of the scattered pulse in a type I THG crystal to generate the cross-correlation signal at \(3\omega\). The cross-correlation trace is obtained by recording the spatio-spectrally filtered \(3\omega\) signal with a solar blind photo-multiplier tube (PMT) as a function of delay between scattered and gate pulses, with a maximum delay of up to ±2 ns and \(\sim 100\) fs temporal resolution at best. Each data point is an average of 100 consecutive shots of up to \(\sim 2\) ns and \(\sim 100\) fs temporal resolution at best. Each data point is an average of 100 consecutive shots recorded in 100 fs time steps, except for the range spanning from -10 ps to +10 ps, where data are recorded in 10 fs time steps. A typical cross-correlation trace of the (unscattered) input laser pulse is shown in Figure 1(a) over a 350 ps time window around the pulse peak. A detection noise floor of \(\sim 10^{-12}\) can indeed be measured by blocking the \(\omega\) probe arm at early times in the trace. The key to noise reduction in THG cross-correlators is the very low level of self-generated signal leaking from either arms of the optical setup into the \(3\omega\) detector [38, 41].

To demonstrate the potential of a \(\sim 10^{-12}\) sensitivity for the detection of diffused light, we characterized the scattering properties of a commercial intralipid-10% emulsion used in previous scattering experiments [43]. Fat emulsions are extensively used as light scattering models or as phantoms for biological applications [43, 44]. The reason is an accessible price, low absorption (\(\mu_a \ll \mu_s\)), scalability of scattering properties with dilution, and the spherical shape of the fat droplets, which makes them easy to model using Mie theory. Despite this, measuring their scattering properties remains a challenge and differ-

![Figure 1](image-url)
ent methods can yield significantly different results [4]. In particular, temporal gating characterization requires fulfilling the diffusion approximation, i.e. (i) \( L\mu_s' \gg 1 \), (ii) \( \mu_0 \ll \mu_s \) and (iii) \( t \gg (\nu_c \mu_s')^{-1} \). Considering a short pulse incident on a fat emulsion slab modeled by a Dirac function in time, the average intensity \( I_d[W/cm^2] \) of the diffused component writes [4]:

\[
I_d(t) = E_{in} \left( \frac{H(t)D}{d} \right)^2 \sum_{m=1}^{\infty} \frac{m\pi}{d} \sin \left( \frac{m\pi L}{d} \right) e^{-\frac{m^2 \pi^2 dx^2}{L^2}} e^{-\mu_s ct},
\]

where \( H(t) \) is the Heaviside function, \( t \) the time following the pulse arrival time on the slab, \( L \) the slab width, \( d = L + z_0 \), with \( z_0 \) as an adjustable parameter on the order of \( z_0 \approx (\mu_s')^{-1} \), necessary to account for boundary conditions at the slab interface [4], and \( E_{in}[J/cm^2] \) the incident pulse fluence. We now define the transmission, \( T_d \), as the ratio between detected and incident pulse fluence, over the gate time \( \tau \), the solid angle \( \delta\Omega \) and a single polarisation state, such that \( T_d = \tau \delta \Omega I_d(t)/(4\pi E_{in}) \). Recalling that for non-resonant scattering media, \( v_c = c/n \), where \( c \) is the velocity of light in vacuum, and \( n \) the effective index of the medium, the maximum transmission evaluated from Eq 1 occurs at \( t \sim 0.09L^2/D \), and yields the scaling law:

\[
T_{d,\text{max}} \sim \frac{0.1\pi c \tau \delta\Omega}{n(1-g)^2 \mu_s'^2 L^3} \sim \frac{1.4 \times 10^{-9}}{(1-g)^2 OD^2 L(cm)},
\]

where the numerical evaluation on the right hand side is done for \( \tau = 25 \text{ fs} \), \( n = 1.33 \) and \( \delta\Omega = 2\pi 10^{-6} \text{ sr} \), taken as a reference value from the SHG gating measurement reported in [4]. This simple scaling shows how crucial the detection sensitivity should be in order to explore large optical depths. In Fig 2 we plot the maximum transmission of the diffused component obtained using Eq 1 as we increase the propagation length \( L \), for a given value \( \mu_s = 20 \text{ cm}^{-1} \) and \( \mu_0 = 0 \text{ cm}^{-1} \) and \( g = 0.5 \). The ballistic transmission in the same condition is plotted in red for comparison. In particular, by imposing \( L\mu_s' \geq 10 \) to satisfy the diffusion approximation, we have \( T_{d,\text{max}} \lesssim 10^{-11}/L(cm) \), which is lower than the lowest transmission factor measured in [2], unless phantoms thinner than \( \sim 1 \text{ mm} \) are used. In particular, the simultaneous measurement of both \( \mu_s \) and \( \mu_s' \) in fat emulsions has never been done using non-linear gated detection, but rather restricted to phantoms with high \( \mu_s' \) and low \( L \) such as TiO$_2$ powders.

In our experiment, we measured the temporal transmission through a \( L = 10 \text{ mm} \) long PMMA cuvette designed for absorption spectrometers (@plastibran) filled with intralipid-10% solution diluted in water at varying concentration \( [c] \). The reference trace shown in Fig 2(a) corresponds to a cuvette filled with only pure demineralized water and used for normalisation. The ballistic peak is measured at a delay of \( +15 \pm 0.2 \text{ ps} \), corresponding to the propagation delay induced by the water-filled cuvette relative to air (see Figure 1(a)). Note that we expect a change in effective index limited to \( \delta n \sim 4.10^{-4} \) for the highest concentration of intralipid, which means a ballistic delay shift hardly resolvable with our detector. On the left panel of Fig 3(b), a zoom on the ballistic component is plotted for \( [c] = 3.3, 6.7, 8.3, 10, 11.7 \) and \( 20\% \), and the peak value is reported on the right panel plot using the same color scale. A good fit of the ballistic attenuation is extracted from the \( [c] = 13.3\% \) trace and represented by the black dotted line. we retrieve \( \mu_s = (189 \pm 10)[c] \text{ cm}^{-1} \), where \( 0 \leq [c] \leq 1 \) is the dimensionless diluted concentration of intralipid. This value is lower than \( \mu_{s,th} = 281[c] \text{ cm}^{-1} \) reported in [40] at 790 nm, but higher than \( \mu_{s,th} = 100[c] \text{ cm}^{-1} \) reported in [44]. Although the use of different brands or preparation methods could explain the discrepancy with values found in literature [43], we believe our method to be more precise because it is based on temporal gating.

The value \( \mu_s' \) is obtained by fitting the temporal profile at long times with Eq 1 using the same trace used to measure \( \mu_s \). The effective index \( n \) is extrapolated from the relative percentage of water and soybean at a given concentration \( [c] \) [44], \( \tau = 25 \text{ fs} \), and by manually adjusting the angle of collection to \( \delta\Omega = 5.1\pi 10^{-6} \text{ sr} \), corresponding to a half collection angle of \( \sim 0.13^\circ \). We obtained the fit plotted in red in Fig 3(c), where we retrieve \( \mu_s' = (79 \pm 7)[c] \text{ cm}^{-1} \). Note that at this concentration, the diffusion approximation is verified since \( \mu_s'L \gtrsim 10 \). By fixing that value of \( \mu_s' \), we superimposed theoretical prediction with experimental data obtained for \( [c] = 6.7, 8.3 \) and \( 20\% \) in Fig 3(a,b) and d), respectively. The slight departure from the theoretical fit observed in Fig 3(a) and Fig 3(b) correspond to an error of up to 13% in the evaluation of \( \mu_s' \). This slope deviation may be attributed to error bars in the concentration calibration of our samples, or to a
FIG. 3. (a) THG cross-correlation measurement through the cell filled with pure demineralized water and used for reference (b) Same measurement with increasing intralipid-10% concentration [c] (color coded) zoomed in over a 20 ps time window around the ballistic component centered at \( \sim 15 \) ps (left) and linear fit of the peak value using \( \mu_s = (189 \pm 10) [c] \text{ cm}^{-1} \) (right).

FIG. 4. THG cross-correlation traces obtained for [c] = 6.7% (a), [c] = 8.3% (b), [c] = 13.3% (c) and [c] = 20% (d). All red line fits are extracted from (c) providing \( \mu_s = (79 \pm 7) [c] \text{ cm}^{-1} \) and \( \mu_s' = (79 \pm 7) [c] \text{ cm}^{-1} \), from which we deduce \( g = 0.58 \pm 0.08 \text{ at 790 nm wavelength.} \) Although intralipid is extensively used in scattering experiments and in the design of biological phantoms, the simultaneous measurement of both \( \mu_s \) and \( \mu_s' \) had never been performed using nonlinear temporal gating. The reason for this is two-fold: (i) nonlinear temporal gating is highly restricted in angular collection angle such that expected transmissions can easily be \( \leq 10^{-10} \) for diffused light, and (ii) all detection systems used so far were limited in dynamic range to \( \sim 10^{10} \), making the characterization of the diffused light almost impossible.

In conclusion, we used THG cross-correlation to perform the first simultaneous measurement of both \( \mu_s \) and \( \mu_s' \) by measuring the ballistic transmission and long time semi-log variation of a short femtosecond NIR pulse transmitted through a scattering solution of [c]-diluted solution of intralipid-10% in water. We measured \( \mu_s = (189 \pm 10) [c] \text{ cm}^{-1} \) and \( \mu_s' = (79 \pm 7) [c] \text{ cm}^{-1} \), from which we deduce \( g = 0.58 \pm 0.08 \text{ at 790nm wavelength.} \) Although intralipid is extensively used in scattering experiments and in the design of biological phantoms, the simulateneous measurement of both \( \mu_s \) and \( \mu_s' \) had never been performed using nonlinear temporal gating. The reason for this is two fold: (i) nonlinear temporal gating is highly restricted in angular collection angle such that expected transmissions can easily be \( \leq 10^{-10} \) for diffused light, and (ii) all detection systems used so far were limited in dynamic range to \( \sim 10^{10} \), making the characterization of the diffused light almost impossible.

We have demonstrated how to overcome these challenges by implementing third-order nonlinear femtosecond temporal gating with a limit of detection of the order of \( \sim 10^{-12} \), which is two orders of magnitude beyond the current state-of-the-art in terms of time-gated light scattering measurements. The sensitivity of most recent commercially available THG cross-correlators can reach up to \( \sim 10^{-14} \) (https://www.ultrafast-innovations.com/devices/TUNDRA.html ). This record level of sensitivity could greatly facilitate the characterization of fat emulsion phantoms and open the door to the exploration of diffusion dynamics that may deviate from classical prediction.

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[1] M. R. Hee, J. A. Izatt, J. M. Jacobson, J. G. Fujimoto, and E. A. Swanson, Femtosecond transillumination opti-
cal coherence tomography, Optics letters 18, 950 (1993).
[2] J. Tong, Y. Yang, J. Si, W. Tan, F. Chen, W. Yi, and
X. Hou, Measurements of the scattering coefficients of intralipid solutions by a femtosecond optical kerr gate, Optical Engineering 50, 043607 (2011).
[3] L. Wang, X. Liang, P. Galland, P. Ho, and R. Alfano, True scattering coefficients of turbid matter measured by early-time gating, Optics letters 20, 913 (1995).
[4] R. Carminati and J. C. Schotland, Principles of Scattering and Transport of Light (Cambridge University Press, 2021).
[5] A. Lagendijk and B. A. Van Tiggelen, Resonant multiple scattering of light, Physics Reports 270, 143 (1996).
[6] P. Wolf, G. Maret, E. Akkermans, and R. Maynard, Optical coherent backscattering by random media: an experimental study, Journal de Physique 49, 63 (1988).
[7] U. Tricoli and R. Carminati, Modeling of full-field optical coherence tomography in scattering media, JOSA A 36, C122 (2019).
[8] R. Sapienza, P. D. García, J. Bertolotti, M. Martín, A. Blanco, L. Vina, C. López, and D. Wiersma, Observation of resonant behavior in the energy velocity of diffused light, Physical review letters 99, 233902 (2007).
[9] S. J. Madsen, B. C. Wilson, M. S. Patterson, Y. D. Park, S. L. Jacques, and Y. Hefez, Experimental tests of a simple diffusion model for the estimation of scattering and absorption coefficients of turbid media from time-resolved diffuse reflectance measurements, Applied optics 31, 3509 (1992).
[10] I. Burgiaia, A. Tosi, A. B. Shehata, A. Della Frera, A. Farina, A. Bassi, P. Taroni, A. Dalla Mora, F. Zappa, R. Cubeddu, et al., Time-resolved diffuse optical spectroscopy up to 1700 nm by means of a time-gated ingaas/inp single-photon avalanche diode, Applied spectroscopy 66, 944 (2012).
[11] M. Störzer, P. Gross, C. M. Aegerter, and G. Maret, Observation of the critical regime near anderson localization of light, Physical review letters 96, 063904 (2006).
[12] T. Sperling, L. Schertel, M. Ackermann, G. J. Aubry, C. M. Aegerter, and G. Maret, Can 3d light localization be reached in ‘white paint’?, New Journal of Physics 18, 013039 (2016).
[13] M. P. van Albada, B. A. van Tiggelen, A. Lagendijk, and A. Tip, Speed of propagation of classical waves in strongly scattering media, Physical review letters 66, 3132 (1991).
[14] K. Busch and C. Soukoulis, Transport properties of random media: A new effective medium theory, Physical review letters 75, 3442 (1995).
[15] P. M. Johnson, A. Imhof, B. P. Bret, J. G. Rivas, and A. Lagendijk, Time-resolved pulse propagation in a strongly scattering material, Physical Review E 68, 016604 (2003).
[16] D. S. Wiersma, A. Muzzi, M. Colocci, and R. Righini, Time-resolved experiments on light diffusion in anisotropic random media, Physical Review E 62, 6681 (2000).
[17] L. A. Cobus, G. Maret, and A. Aubry, Transient critical regime for light near the three-dimensional anderson transition, arXiv preprint arXiv:2109.11188 (2021).
[18] A. Badon, G. Lerosey, A. C. Boccara, M. Fink, and A. Aubry, Retrieving time-dependent green’s functions in optics with low-coherence interferometry, Physical Review Letters 114, 023901 (2015).
[19] R. H. Kop and R. Sprik, Phase-sensitive interferometry with ultrashort optical pulses, Review of Scientific instruments 66, 5459 (1995).
[20] I. Vellekoop, P. Lodahl, and A. Lagendijk, Determination of the diffusion constant using phase-sensitive measurements, Physical Review E 71, 056604 (2005).
[21] S. John, Strong localization of photons in certain disordered dielectric superlattices, Physical review letters 58, 2486 (1987).
[22] M. Segev, Y. Silberberg, and D. N. Christodoulides, Anderson localization of light, Nature Photonics 7, 197 (2013).
[23] T. Schwartz, G. Bartal, S. Fishman, and M. Segev, Transport and anderson localization in disordered two-dimensional photonic lattices, Nature 446, 52 (2007).
[24] K. Yoo and R. Alfano, Time-resolved coherent and incoherent components of forward light scattering in random media, Optics letters 15, 320 (1990).
[25] P. P. Ho, P. Baldeck, K. Wong, K. Yoo, D. Lee, and R. Alfano, Time dynamics of photon migration in opisomopque random media, Applied optics 28, 2304 (1989).
[26] J. C. Hebden, R. A. Kruger, and K. Wong, Time resolved imaging through a highly scattering medium, Applied optics 30, 788 (1991).
[27] N. Bruce, F. Schmidt, J. Dainty, N. Barry, S. Hyde, and P. French, Investigation of the temporal spread of an ultrashort light pulse on transmission through a highly scattering medium, Applied optics 34, 5823 (1995).
[28] D. J. Thouless, Electrons in disordered systems and the theory of localization, Physics Reports 13, 93 (1974).
[29] G. Watson Jr, P. Fleury, and S. McCall, Searching for photon localization in the time domain, Physical review letters 58, 945 (1987).
[30] M. S. Patterson, B. Chance, and B. C. Wilson, Time resolved reflectance and transmittance for the noninvasive measurement of tissue optical properties, Applied optics 28, 2331 (1989).
[31] L. Wang, P. Ho, C. Liu, G. Zhang, and R. Alfano, Ballistic 2-d imaging through scattering walls using an ultrafast optical kerr gate, Science 253, 769 (1991).
[32] S. Mujumdar and H. Ramachandran, Imaging through turbid media using polarization modulation: dependence on scattering anisotropy, Optics communications 241, 1 (2004).
[33] C. Hauger, E. Baigar, T. Wilhelm, and W. Zinth, Time-resolved backscattering of femtosecond pulses from scattering media—an experimental and numerical investigation, Optics communications 131, 351 (1996).
[34] C. Calba, L. Mées, C. Rozé, and T. Girasole, Ultrashort pulse propagation through a strongly scattering medium: simulation and experiments, JOSA A 25, 1541 (2008).
[35] E. J. Divall and I. N. Ross, High dynamic range contrast measurements by use of an optical parametric amplifier correlator, Optics letters 29, 2273 (2004).
[36] O. Konopolev, Y. Fisher, and D. Meyerhofer, Ultrahigh dynamic range measurement of high-contrast pulses using a second-order autocorrelator, LLE review, 159–170 (1998).
[37] K.-H. Hong, B. Hou, J. Nees, E. Power, and G. Mourou, Generation and measurement of > 108 intensity contrast with ultrashort optical pulses, Applied Physics B 81, 447 (2005).
[38] S. Luan, M. Hutchinson, R. Smith, and F. Zhou, High dynamic range third-order correlation measurement of picosecond laser pulse shapes, Measurement Science and Technology 4, 1426 (1993).
[39] J. Itatani, J. Faure, M. Nantel, G. Mourou, and S. Watanabe, Suppression of the amplified spontaneous emission in chirped-pulse-amplification lasers by clean high-energy seed-pulse injection, Optics Communications 148, 70 (1998).

[40] K. Osvay, M. Csatári, I. Ross, A. Persson, and C.-G. Wahlström, On the temporal contrast of high intensity femtosecond laser pulses, Laser and Particle Beams 23, 327 (2005).

[41] V. Schanz, C. Brabetz, D. Posor, D. Reemts, M. Roth, and V. Bagnoud, High dynamic range, large temporal domain laser pulse measurement, Applied Physics B 125, 1 (2019).

[42] J. Ma, P. Yuan, X. Ouyang, J. Wang, G. Xie, and L. Qian, Resolving ultrahigh-contrast ultrashort pulses with single-shot cross-correlator at the photon noise limit, arXiv preprint arXiv:2102.12696 (2021).

[43] M. Bocoum, J. L. Gennisson, C. Venet, M. Chi, P. M. Petersen, A. A. Grabar, and F. Ramaz, Two-color-interpolation of the absorption response for quantitative acousto-optic imaging, Optics Letters 43, 399 (2018).

[44] R. Michels, F. Foschum, and A. Kienle, Optical properties of fat emulsions, Optics express 16, 5907 (2008).

[45] A. Pifferi, A. Torricelli, A. Bassi, P. Taroni, R. Cubeddu, H. Wabnitz, D. Grosenick, M. Möller, R. Macdonald, J. Swartling, et al., Performance assessment of photon migration instruments: the medshot protocol, Applied optics 44, 2104 (2005).

[46] H. J. Van Staveren, C. J. Moes, J. van Marie, S. A. Prahl, and M. J. Van Gemert, Light scattering in Intralipid-10% in the wavelength range of 400–1100 nm, Applied optics 30, 4507 (1991).

[47] V. Ntziachristos, Going deeper than microscopy: the optical imaging frontier in biology, Nature methods 7, 603 (2010).

[48] M. Floess, T. Steinle, I. Gerhardt, and H. Giessen, Femtosecond tunable light source with variable repetition rate between 640 kHz and 41 MHz with a 130 dB temporal pulse contrast ratio, Optics Express 30, 1 (2022).

[49] S. Mujumdar, G. Dice, and A. Elezzabi, Few-cycle pulse propagation in multiple scattering media, Optics communications 247, 19 (2005).

[50] N. Curry, P. Bondareff, M. Leclercq, N. F. Van Hulst, R. Sapienza, S. Gigan, and S. Grésillon, Direct determination of diffusion properties of random media from speckle contrast, Optics letters 36, 3332 (2011).

[51] P. Martelli and G. Zaccanti, Calibration of scattering and absorption properties of a liquid diffusive medium at NIR wavelengths CW method, Optics express 15, 486 (2007).

[52] H. Jiang, J. Pierce, J. Kao, and E. Sevick-Muraca, Measurement of particle-size distribution and volume fraction in concentrated suspensions with photon migration techniques, Applied optics 36, 3310 (1997).

[53] C. J. Moes, M. J. Van Gemert, W. M. Star, J. P. Marijnissen, and S. A. Prahl, Measurements and calculations of the energy fluence rate in a scattering and absorbing phantom at 633 nm, Applied optics 28, 2292 (1989).

[54] A. Dimofte, J. C. Finlay, and T. C. Zhu, A method for determination of the absorption and scattering properties interstitially in turbid media, Physics in Medicine & Biology 50, 2291 (2005).

[55] S. T. Flock, S. L. Jacques, B. C. Wilson, W. M. Star, and M. J. van Gemert, Optical properties of Intralipid: a phantom medium for light propagation studies, Lasers in surgery and medicine 12, 510 (1992).

[56] R. Pierrat, J.-J. Greffet, and R. Carminati, Photon diffusion coefficient in scattering and absorbing media, JOSA A 23, 1106 (2006).

[57] K. Yoo, Q. Xing, and R. Alfano, Imaging objects hidden in highly scattering media using femtosecond second-harmonic-generation cross-correlation time gating, Optics letters 16, 1019 (1991).

[58] B. Beauvoit, H. Liu, K. Kang, P. Kaplan, M. Miwa, and B. Chance, Characterization of absorption and scattering properties for various yeast strains by time-resolved spectroscopy, Cell biophysics 23, 91 (1993).

[59] J. Chang, H. L. Graber, R. L. Barbou, and R. Aronson, Recovery of optical cross-section perturbations in dense-scattering media by transport-theory-based imaging operators and steady-state simulated data, Applied Optics 35, 3963 (1996).

[60] D. A. Bous, D. H. Brooks, E. L. Miller, C. A. DiMarzio, M. Kilmer, R. J. Gaudette, and Q. Zhang, Imaging the body with diffuse optical tomography, IEEE signal processing magazine 18, 57 (2001).

[61] S. Karbasi, C. R. Mirr, P. G. Yarandi, R. J. Frazier, K. W. Koch, and A. Mafi, Observation of transverse andersson localization in an optical fiber, Optics letters 37, 2304 (2012).

[62] I. Freund, M. Rosenbluh, and S. Feng, Memory effects in propagation of optical waves through disordered media, Physical review letters 61, 2328 (1988).

[63] F. Böhle, M. Thévenet, M. Bocoum, A. Vernier, S. Haessler, and R. Lopez-Martens, Generation of xuv spectral continua from relativistic plasma mirrors driven in the near-single-cycle limit, Journal of Physics: Photonics 2, 034010 (2020).

[64] L. Chopineau, A. Denoeud, A. Leblanc, E. Porat, P. Martin, H. Vincenti, and F. Quéré, Spatio-temporal characterization of attosecond pulses from plasma mirrors, Nature physics 17, 968 (2021).

[65] M. Paciaroni and M. Linne, Single-shot, two-dimensional ballistic imaging through scattering media, Applied optics 43, 5100 (2004).

[66] A. F. Koenderink, M. Megens, G. Van Soest, W. L. Vos, and A. Lagendijk, Enhanced backscattering from photonic crystals, Physics Letters A 268, 104 (2000).

[67] Y. L. Kim, Y. Liu, R. K. Wali, H. K. Roy, and V. Backman, Low-coherent backscattering spectroscopy for tissue characterization, Applied optics 44, 366 (2005).

[68] S. G. Resnik, W. Steenbergen, and A. C. Boccara, State-of-the art of acousto-optic sensing and imaging of turbid media, Journal of biomedical optics 17, 040901 (2012).

[69] W. Leutz and G. Maret, Ultrasonic modulation of multiply scattered light, Physica B: Condensed Matter 204, 14 (1995).

[70] X. Wang, Y. Pang, G. Ku, X. Xie, G. Stoica, and L. V. Wang, Noninvasive laser-induced photoacoustic tomography for structural and functional in vivo imaging of the brain, Nature biotechnology 21, 803 (2003).

[71] M. Xu and L. V. Wang, Photoacoustic imaging in biomedical science 77, 041101 (2006).

[72] A. Badon, D. Li, G. Lerosey, A. C. Boccara, M. Fink, and A. Aubry, Smart optical coherence tomography for ultra-deep imaging through highly scattering media, Science advances 2, e1600370 (2016).

[73] S. M. Popoff, G. Lerosey, R. Carminati, M. Fink, A. C.
Bocca, and S. Gigan, Measuring the transmission matrix in optics: an approach to the study and control of light propagation in disordered media, Physical review letters 104, 100601 (2010).

[74] L. S. Froufe-Pérez, M. Engel, J. J. Sáenz, and F. Scheffold, Band gap formation and anderson localization in disordered photonic materials with structural correlations, Proceedings of the National Academy of Sciences 114, 9570 (2017).

[75] L. F. Rojas-Ochoa, J. Mendez-Alcaraz, J. Sáenz, P. Schurtenberger, and F. Scheffold, Photonic properties of strongly correlated colloidal liquids, Physical review letters 93, 073903 (2004).

[76] D. S. Wiersma, M. P. van Albada, B. A. van Tiggelen, and A. Lagendijk, Experimental evidence for recurrent multiple scattering events of light in disordered media, Physical Review Letters 74, 4193 (1995).

[77] K. Vynck, R. Pierrat, R. Carminati, L. S. Froufe-Pérez, F. Scheffold, R. Sapienza, S. Vignolini, and J. J. Sáenz, Light in correlated disordered media, arXiv preprint arXiv:2106.13892 (2021).

[78] I. M. Vellekoop and A. Mosk, Focusing coherent light through opaque strongly scattering media, Optics letters 32, 2309 (2007).

[79] J. W. Yoon, C. Jeon, J. Shin, S. K. Lee, H. W. Lee, I. W. Choi, H. T. Kim, J. H. Sung, and C. H. Nam, Achieving the laser intensity of $5.5 \times 10^{22}$ w/cm$^2$ with a wavefront-corrected multi-pw laser, Optics express 27, 20412 (2019).

[80] M. Aoyama, A. Sagisaka, S. Matsuoka, Y. Akahane, F. Nakano, and K. Yamakawa, Contrast and phase characterization of a high-peak-power 20-fs laser pulse, Applied Physics B 70, S149 (2000).

[81] N. Stuart, T. Robinson, D. Hillier, N. Hopps, B. Parry, I. Musgrave, G. Nersisyan, A. Sharba, M. Zepf, and R. A. Smith, Comparative study on the temporal contrast of femtosecond mode-locked laser oscillators, Optics Letters 41, 3221 (2016).