Advanced material characterization by imaging of transient light transport regimes

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Project goal:

The aim of this PhD project is to study transient light transport regimes in complex photonic media and define unique propagation fingerprints to identify the position and orientation of different materials. The study will focus on the spatial and angular evolution of reflectance profiles down to a sub-ps scale. The analysis will consider both incoherent and coherent effects and explore novel descriptors such as the scaling of fractional moments of displacement (which have never been applied to light propagation studies) to identify the onset of strongly and weakly self-similar transport regimes [1].

By introducing a generalized and multi-domain approach to the description of ubiquitous anomalous light transport phenomena, the expected results of this project are relevant not only from a fundamental standpoint, but also for application fields such as ranging and 3d scene reconstruction, autonomous driving, non-line-of-sight imaging, biomedical diagnostics and food quality analysis, to name a few.

State of the art:

The rich transport dynamics that arises in complex environments, materials and geometries represents an exciting opportunity to infer information regarding their (chemical, physical, structural) properties and the nature of the interactions driving the transport process. In particular, using light as a probe is incredibly useful to study transport phenomena due to its non-destructive and non-invasive nature. In many cases, however, the fine features and short transients that characterize light propagation inside a material occur on a time scale that is too fast for traditional detection techniques. As opposed to long-time and asymptotic light transport regimes, which can be usually described by a universal diffusion behavior [2], these early features are likely to deviate from this simple theoretical modeling, thus revealing additional information about the properties of the sample under study, which would be difficult to retrieve otherwise. However, relevant studies up to now are typically limited to the sole temporal domain or not yet verified experimentally [3,4].

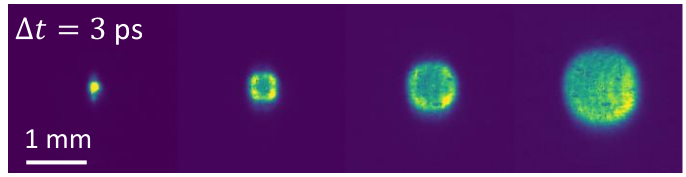

Fig.1 - Example of the evolution of the transverse spatial distribution in a diffusive process.

The earliest time-domain features that can be observed are in general those occurring in reflection, immediately after the interaction with the external surface of a sample. In this regime, specularly reflected and low-order scattered light are inevitably mixed, which is why most time-domain light transport experiments are typically performed in transmission. In most cases, however, the reflection geometry is more relevant for applications, which include for instance time-of-flight imaging applications for ranging [5,6], object tracking, material determination and free-space optical communication links.

Measuring early transport regimes is also relevant from a more fundamental point of view, as it can reveal transient speckle statistics [7], the breakdown of similarity invariance principles [3] or even more exotic anomalous transport regimes [4]. Traditionally, different transport regimes have been identified based on the evolution of the second spatial moment. In this project, we plan to extend this classification to the richer classification scheme of weakly and strongly self-similar transport regimes, which require the analysis of multiple and possibly fractional moments of displacement beyond the simple variance. Another interesting opportunity for the fundamental study of effective medium properties of disordered media arises from measuring of both transmitted and reflected time-of-flight distributions under Lambertian illumination, which must obey the recently discovered pathlength invariance principle thus revealing the effective permittivity of the medium [8].

Setup implementation and upgrades:

For this research, an optical time-gating apparatus will be used, leveraging non-linear upconversion of femtosecond pulsed laser sources which are required to increase the temporal (and hence, spatial) resolution of the reconstruction technique. Up to date, this setup has only been used in a simple transmission configuration, with no control on the input and output polarization channels, and disregarding the angular domain.

During the PhD project, the current capabilities of the setup will be expanded to allow us to work for the first time in both a transmission and reflection configuration, as well as to measure the time-dependent evolution of outgoing radiance in the angular domain. This will be achieved by mounting the sample on a rotating mount in order to keep the laser source and detectors at fixed positions. As a further addition, the polarization of incoming and outgoing light will be controlled, allowing selective filtering of the upconverted components and the specularly reflected signal (which has a specific polarization signature and carries almost no information about the sample's properties). This will allow studying the transient response of scattered light incoming and/or received also at near-grazing angles from the sample, where subtle light propagation differences due to different optical parameters are typically magnified.

Organization of work:

The first year of the project will be devoted to designing and implementing the modifications required to use the time-resolved optical gating apparatus in a reflection configuration. Reference scattering samples with known scattering and absorption properties will be fabricated in a target range of thicknesses. Both steady state and time-domain measurements will be performed on the samples to validate their optical properties. In parallel, theoretical and numerical codes will be prepared to model the outgoing radiance from a scattering sample, based on the simple diffusion approximation and on Monte Carlo simulations.

During the second year, transient measurements in the spatial and angular domain will be extended to a broader range of common materials such as plastic, wood or ceramic. This will allow us to generate a database of multi-domain data for different materials and to identify the transient "fingerprint" of each sample before the onset of the asymptotic diffusion regime. The database will also be analyzed to evaluate possible cross-talk effects between optical parameters that may exist – for instance – in the temporal domain, and yet vanish when also including the spatial domain or angular domain (typical examples being the scattering-absorption cross-talk, or the similarity degeneracy in the diffusion approximation).

Upgrades to the experimental setup will be considered to include either back-focal plane imaging, multiple wavelengths, or different detectors. On the modeling side, advanced numerical simulations will be performed considering additional factors such as meshed geometries, anisotropic transport, or surface roughness.

On a more fundamental side, customized samples will be fabricated with extremely high scattering strength by e.g., packing metal oxides nanoparticles with optimal size and volume fraction. Studies on the transient transport properties for this class of materials are sporadic and deviations are expected to arise at early times for tightly focused excitation and/or quenched disorder configurations, including in their time-dependent speckle statistics. Similarly, by exploiting the recently discovered invariance property of scattered light, another possible experiment that can be envisioned is a measurement of the effective energy velocity inside these complex, nanostructured media based on the expectation values of the transmitted and reflected time-of-flight distributions. Indeed, determining the effective permittivity of such complex, dense materials is an open question for which there are no available experimental or theoretical models at the moment, despite its relevance for several applications.

These additional experiments will be performed throughout the first months of the third year, together with the development of heuristic models to parametrize the transient fingerprints of different materials.

References:

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