Non-imaging statistical method for characterizing scattering media

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In a new stochastic sensing approach statistical properties of illumination are controlled to provide an efficient optical probe, even in poor experimental conditions.

In many remote sensing and biomedical applications it is important to recover the statistical properties of scattering potentials that generate measured signals. It is notoriously difficult, however, to characterize unknown scattering media. In addition, ubiquitous fluctuations of measured signals are not always artifacts. To meaningfully assess the statistical properties of disordered systems, stochastic analyses are therefore required. Moreover, in most sensing techniques it is often necessary to enhance the information-carrying signal with respect to all the unwanted sources of noise.

It has previously been demonstrated that when the desired information is embedded within the statistics of a measured signal (i.e., within the noise of a weak signal), the so-called stochastic resonance can be used to amplify and augment the fluctuations. The stochastic resonance phenomenon arises in nonlinear systems and behaves in relation to the noise level of the system. However, the nonlinearity of the system’s response, as well as the non-energy-conserving measurement process, severely limits the range of possible applications of the stochastic resonance.

In our work, we have demonstrated an alternative sensing approach known as ‘stochastic optical sensing.’ For this linear and energy-conservative methodology we exploit the fluctuations of the integrated scattered intensity originating from a scattering potential exposed to stochastic illumination. As a result of the random interactions between the illumination pattern and the scattering potential, a new type of resonance occurs. In this scenario, the measured fluctuations carry information about the random interactions. These fluctuations include two statistically independent zero-mean stochastic processes, i.e., one that generates noisy fluctuations and one that encodes the interaction.

For the noisy process, we can maintain stationary statistics as long as the average illumination power is conserved and the perturbation sources are statistically stationary. For the interaction-encoding process, however, we can modulate the non-stationary statistics by manipulating the statistics of the illumination intensity. We have also shown that our stochastic modulation approach is a reliable tool for measuring the statistical parameters of a scattering potential (i.e., which does not require imaging of the potential).

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Correlation length is a parameter that can be used to characterize the random scattering potential. This specific length can usually be observed repeatedly in the potential and may define its physical state. For example, the size of a cell in a culture can encode its biological status. We have shown that our stochastic optical sensing approach can be used to non-invasively measure characteristic length(s) of the scattering potential. Indeed, we can achieve this without actually imaging the target. To do this, we use a set of unknown random patterns (with known characteristic lengths and constant average power) to illuminate the targeted potential. At the same time, we collect the backscattered light with an integrating detector. For a given correlation length in the illumination patterns, we calculate the mean variation of the measured signal (also known as the Fano factor). When the correlation length of the illumination and the characteristic length of the targeted potential match, the Fano factor of measured signal is at a maximum. In other words, in this regime (see Figure 1), small changes in the illumination cause large fluctuations in the measured intensity. This drastic change in the statistical properties of the measured signal can therefore be used to directly identify the characteristic lengths of the scattering potential.

We have experimentally demonstrated our sensing concept in a number of circumstances. For example—see Figure 2(a) and (b)—the characteristic length is clearly recovered in the corresponding Fano spectrum. We can also recover the characteristic lengths for targets that are significantly affected by noise, as shown in Figure 2(c) and (e), where the highly perturbed conditions correspond to a signal-noise-ratio of 2.5 and 1.8dB, respectively. With these examples we therefore clearly show that the Fano spectra associated with the integrated signal can be used efficiently to recover target information. This is the case in both noise-free conditions and in highly perturbed circumstances (i.e., that are typical in challenging sensing situations).

Our stochastic optical sensing method is robust because it relies on the exploitation of statistical parameters. In addition, changes in the fluctuating signal are independent of the perturbation sources. Small signal modifications caused by weakly scattering objects can consequently still be identified in the Fano factor spectra. These characteristics of our approach are appealing for biological sensing applications. For example, we can use the weak signal alteration to measure the characteristic length (about 10 µm) of an H2c9 cell in an aqueous medium (see Figure 3). We recovered the characteristic length of this low-reflectivity and low-contrast target with the use of 250ms illumination (i.e., an average irradiation that is about seven orders of magnitude lower than the intensity of sunlight).

In summary, we have developed a new sensing technique—stochastic optical sensing—which operates on statistical optics principles to recover information about random...
scattering potentials. Our method relies on controlled spatial and temporal modulations of an interrogating field, in combination with an efficient integration of the outgoing field. In this way, we can achieve a stochastic-like resonance of the fluctuations of scattered light. The variance of these fluctuations is a measure of the statistical similarity between the illuminating probe and the target. This measure can be used for efficient target characterization at low light levels and in extremely perturbed conditions. We are currently pursuing applications of our approach, e.g., for monitoring live biological processes and for active remote sensing.

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References