Ballistic attenuation of low-coherence optical fields

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Using a novel experimental geometry, we measured the ballistic attenuation of low-coherence optical fields propagating in multiple-scattering media. The high dynamic range and the angular filtering capability permit detecting the ballistic component through random media thicker than 20 mean free paths. Owing to the accuracy of the technique, we observe deviations from the standard Lambert–Beer law that are induced by the broad incident optical spectrum. We discuss the significance of these observations, their dependence on the type of scattering, and several potential applications. © 2000 Optical Society of America

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The limited temporal coherence of light provides a gate for filtering out the multiple-scattering light component in imaging through turbid media.[1,2] We have shown that interferometry with low-coherence light can also be used to develop an optical path-length spectroscopy in multiple-scattering media.[3] Taking advantage of the high temporal resolution and large dynamic range, subtle effects such as the scatterer size on the diffusion process in bounded media can be investigated.[4] Another issue of outmost importance for applications such as imaging through biological tissue, phototherapy, and random media characterization is the transition process from ballistic to diffusion propagation.[5,6] The subject has been studied not only in the optical domain but also with microwave fields[7] and, more recently, ultrasound waves.[8] A limit for the propagation distance after which the scattering process can be considered diffusive is not unanimously accepted, since the ballistic and the diffusive component always coexist during the scattering process.

The customary description of the attenuation suffered by a monochromatic light beam propagating in a scattering, nonabsorbing medium is given by the Lambert–Beer law: $P = P_0 \exp(-L/l_s)$, where P_0 is the initial power, P is the remaining power after traveling a distance L, whereas l_s is the scattering mean free path that characterizes the medium. When absorption is present, the same exponential decay applies, but the decay rate $1/l_s$ is replaced by $1/l_s + 1/l_a$, where l_a is the absorption length. Deviations from the Lambert–Beer law due to multiple scattering have been quantified,[9] and corrections have been proposed.[10] Various techniques for filtering out the scattered light have been explored, including heterodyne detection,[11,12] confocal spatial filtering,[11] temporal gating,[13–15] and polarization filtering.[16] Modifications of the classical Lambert–Beer dependence of light attenuation have also been observed in the case of highly correlated scattering systems.[17]

In this paper, we propose a novel method for measuring the ballistic component of light that travels through multiple-scattering media. The accuracy of this technique allows, for the first time, to our knowledge, an investigation of the fine details of the attenuation process, such as the influence of the broad optical spectrum on the ballistic light attenuation and its relation with the scatterer size. The experimental setup depicted in Fig. 1 can be described as a Sagnac–Michelson interferometer with a broadband source that emits light with a central wavelength of 1.33 μm and a FWHM bandwidth of 60 nm. The light emitted by the LED is coupled into a single-mode optical fiber that enters the 2 × 2 fiber coupler, FC 1, and, on the probe arm, the beam is divided once more by the 1 × 2 fiber coupler, FC 2. The power delivered in the coupler, FC 2, is ~60 μW. The two fiber ends are connected to the collimators, C1 and C2, which are aligned so that they send the parallel beams in counterpropagating directions, as in a Sagnac interferometer.

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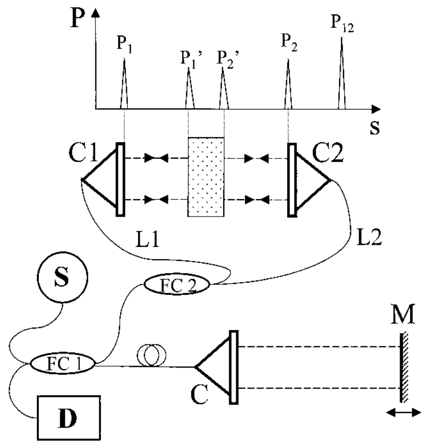

Fig. 1. Experimental setup: S, source; D, detector. The interference peaks correspond to different interfaces, as indicated.

The main components of the electric field reaching the detector are

$$\begin{aligned} E_D(t) = {} & E_0(t)\exp(iks) + E_{11}(t)\exp(ikL_{11}) \\ & + E_{12}(t)\exp(ikL_{12}) + E_{21}(t)\exp(ikL_{21}) \\ & + E_{22}(t)\exp(ikL_{22}). \end{aligned} \tag{1}$$

E_{11} and E_{22} correspond to the paths that involve reflections on C1 and C2, respectively, whereas E_{12} represents the field emitted through C1 and coupled by C2, and E_{21} is the time-reversed counterpart of E_{12}. In Eq. (1), k is the wave vector, L_{ij}, $i, j = 1, 2$ are the optical path lengths associated with the fields E_{ij}, and s is the optical path length traveled on the reference arm. When Eq. (1) is used, the expression for the irradiance at the detector, as a function of the optical path length set by the reference mirror, takes the form

$$I_D(s) = I_0 + \sum_{i,j}^{1,2} I_{i,j} |g[k(s - L_{ij})]| \cos[k(s - L_{ij})]. \tag{2}$$

In Eq. (2), I_0 is the constant term, $I_{i,j}$ is the amplitude of the interference signal given by the summation of the field E_{ij} with the reference field, and g is the complex degree of coherence associated with the source. Equation (2) gives the position of the interference peaks as the mirror, M, sweeps the reference arm. The positions of the interference peaks are denoted in Fig. 1 by P_1, P_2, and P_{12}. Since $L_{12} = L_{21}$, the peaks associated with I_{12} and I_{21} are spatially overlapped. In our arrangement, the fiber lengths differ by approximately 2.5 cm, and therefore P_1 and P_2 appear at different positions. When an object with reflecting boundaries is inserted between C1 and C2, two additional dielectric interfaces are present and two peaks will appear accordingly, as denoted in Fig. 1 by P_1' and P_2'. Thus both the position of the object and its thickness can be measured with an accuracy limited by the coherence length. If the object is transparent, the shift in the position of P_{12} will give the optical path length of the object.

In this paper, we investigate the potential of this geometry for ballistic light measuring in the presence of strong multiple scattering. This geometry is, to our knowledge, being used for the first time in such experiments, and, as we show in the following, it presents a series of advantages over the methodologies described previously.[11–15] When a scattering medium is placed between C1 and C2, the magnitude of the peak P_{12} describes quantitatively the beam attenuation due to the scattering process. Using the heterodyne detection, as described in Ref. 3, we are able to evaluate this attenuation over a dynamic range of more than 80 dB, and the short coherence length of the light offers the temporal selectivity necessary to isolate the early-arriving ballistic waves. As is well known, angular filtering is one of the main concerns in measurements of ballistic light.[11,18,19] In the current geometry, the field of view (FOV) of our system can be continuously narrowed by moving the collimators, C1 and C2, farther apart. Throughout our experiments, the distance between C1 and C2 was set at 12 cm, the focal distance of the collimators was 6.2 mm, and the diameter of the fiber core was 9 μm. For these parameters, the FOV was measured to be 0.85 mrad. Note that the present angular filtering obtained is superior to that achieved in an open-beam confocal geometry,[11] and moreover it can be further improved by increasing the distance C1–C2. Another characteristic is that this configuration allows testing of the medium with a collimated beam over a large area, providing a better average across the sample. Note also that the alignment and position of the sample under test are not critical for this geometry.

To prove the potential of this technique for ballistic light measurement, we performed experiments on suspensions of polystyrene microspheres of different particle sizes and concentrations placed in cuvettes of 1-cm thickness. Figure 2 shows the transmission results for scattering media with three particle sizes, 0.121, 0.356, and 3.135 μm, for which the scattering cross sections σ_s are 9.78×10^{-14}, 5.0×10^{-11}, and 2.83×10^{-7} cm^2, respectively. Each data set was normalized with respect to the value of transmission through deionized water placed in the same cuvette to account for the effect of absorption in water, which has a constant value for all the samples. As can be seen in Fig. 2, the experimental decay sharply ends at the noise level of the device, indicating that the filtering of scattered light is virtually complete owing to both the coherence and the angular gating. However, a disagreement can be observed between the experimental data and the expectation of the Lambert–Beer law, denoted by dashed lines in Fig. 2. Note that the deviation from the negative exponential behavior becomes more important for samples of smaller particle size. This particle-size dependence of the ballistic light attenuation is unexpected, and an interpretation more refined than the conventional Lambert–Beer law is needed. As opposed to the

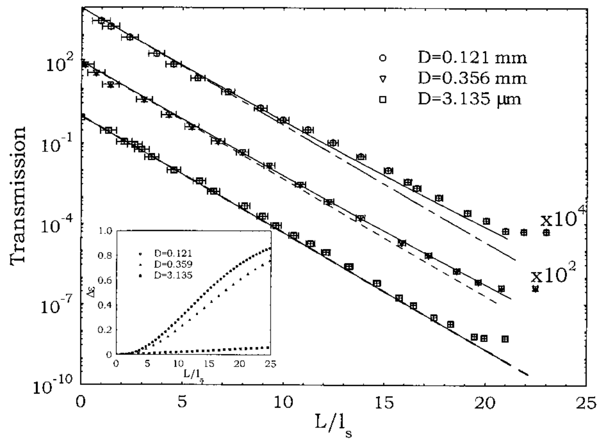

Fig. 2. Ballistic attenuation for suspensions of different particle sizes. The data are scaled as indicated; the dashed lines represent negative exponentials, whereas the solid lines are given by Eq. (3). The inset shows the relative difference between the transmission given by Eq. (3) and that of the Lambert–Beer law as a function of optical thickness L/l_s.

monochromatic case described by the Lambert–Beer law, the spectral density in our measurements approaches a Gaussian with a FWHM of ~60 nm, centered at $\lambda_0 = 1.33$ μm. In this case, the transmission coefficient, defined as the ratio between the transmitted and the incident power, takes the form

$$T_{\Delta\lambda}(\lambda_0) = \int_{-\infty}^{+\infty} S_{\Delta\lambda}(\lambda - \lambda_0)\exp[-N\sigma_s(\lambda)L]\mathrm{d}\lambda. \quad (3)$$

Equation (3) asserts that the overall transmitted light is given by the summation of the contributions from all the frequency components, weighted by the initial optical spectrum, and it takes the form of a convolution between the Lambert–Beer transmission and the incident spectral density $S_{\Delta\lambda}(\lambda - \lambda_0)$, of central frequency λ_0 and width $\Delta\lambda$. It is easily seen in Fig. 2 that the dependence of Eq. (3), which is indicated by continuous lines, describes much better the experimental results for all the particle sizes. As shown in the inset of Fig. 2, where the relative difference $\Delta\varepsilon = (T_{\Delta\lambda} - T_0)/T_0$, with T_0 being the Lambert–Beer transmission function, is plotted as a function of optical density, the correction brought to the Lambert–Beer law by Eq. (3) has increasing importance as the particle size decreases and becomes negligible for large particles. The reason is that the scattering cross section depends more strongly on the size parameter $2\pi R/\lambda$ for smaller values of the particle radius R. Therefore, in this range of size parameters, the particles are characterized by different scattering cross sections corresponding to each frequency component of the optical spectrum. For large particle sizes, the cross sections associated with individual spectral components do not change significantly over the incident spectrum, and thus the overall attenuation approaches the negative exponential decay, as in the case of monochromatic light.

Time-gated measurements can also provide the path-length selectivity necessary to isolate the ballistic light component.[13] However, note that even in this case one uses practically broadband emission spectra for which the correction to the ballistic transmission as described in Eq. (3) should become important.

In conclusion, we have introduced a new technique for measuring the ballistic component of light propagating through optically opaque media. Compared with the confocal configuration, the present geometry has the advantage of the coherence gate, which allows isolating the early-arriving ballistic light. The heterodyne detection provides a considerable dynamic range; the decay of the ballistically transmitted light is limited only by the noise level of the device and not by the diffusive component of light. We emphasize that the dynamic range available in our particular experiments does not represent a fundamental limit; the interferometer performance is still far from the shot-noise limit.[13] We found that, owing to the broad spectrum, the ballistic transmission data deviate from the Lambert–Beer law with an increasing amount for smaller scatterers. The experimental results are explained very well by considering that the propagating light is a superposition of monochromatic components that attenuate at different rates. Note that the quantitative analysis in low-coherence imaging techniques relies heavily on the validity of conventional Lambert–Beer attenuation for light propagating toward and scattering back from a target surrounded by a turbid medium.[20] The technique proposed in this paper should find application in the characterization of random media as well as for medical and biological investigation.

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