Published in final edited form as:

Opt Lett. 2018 September 01; 43(17): 4232–4235. doi:10.1364/OL.43.004232.

Multimode interference dynamic light scattering

J. R. Guzman-Sepulveda, A. Dogariu*

CREOL, The College of Optics and Photonics, University of Central Florida, 4304 Scorpius St., Orlando, Florida 32826, USA

Abstract

When dealing with dynamic scattering systems, being able to collect strong signals while maintaining a high signal-to-noise ratio (SNR) is critical. It is well known that a spatially coherent measurement provides the largest SNR, while a partially coherent one provides better means for proper spatial averaging. In this Letter, we present a robust implementation of a fiber-based, single-mode, common-path interferometer assisted by multimode interference. We show that light can be efficiently collected from larger coherent regions while keeping a high SNR that is comparable to that of a pure single-mode arrangement. Additionally, our implementation allows having both a stable local oscillator encoding information on the fiber-medium interface and a linear dependence on scattering density. These two attributes, in turn, permit accessing the effective optical properties of the dynamic complex system.

OCIS codes:

(280.4788) Optical sensing and sensors; (060.2370) Fiber optics sensors; (120.3180) Interferometry; (070.6760) Talbot and self-imaging effects

Optical methods are ideally suited to measure the structural dynamics of complex media. In particular, light scattering techniques such as dynamic light scattering (DLS) are of interest because of their flexibility and potential noninvasiveness [1]. Practical implementations, however, are limited not only because of the multiple scattering or the strong attenuation encountered in optically dense media, but also because of the inability to collect light efficiently while maintaining a high signal-to-noise ratio (SNR).

Interferometric schemes are not the exception. Moreover, the interferometric detection of optical signals requires spatial coherence in order to provide the largest contrast. In this context, it is well known that a spatially coherent measurement results in the largest SNR, while a partially coherent one can provide stronger signals and better means for proper spatial averaging, at the expense of the signal quality [2]. Traditionally, in fiber-based implementations of different interferometers, such as optical coherence tomography (OCT) for instance, the spatial coherence is inherently preserved by the use of single-mode fibers (SMFs), which play the role of a small aperture for spatial filtering and, at the same time, permit coupling the scattered energy onto a single propagating mode. However, when using SM interferometers, the signal is practically collected only from a small volume, which is

*Corresponding author: adogariu@creol.ucf.edu.

determined by the fiber core and the spectral properties of the light source. This imposes some limitations on the strength of the signals measured, especially in situations where weak scattering is generated by “inefficient” scatterers, or by low particle number densities, which, additionally, limits the applicability of the traditional statistical tools for signal analysis, e.g., the central limit theorem. Conversely, when using multimode (MM) arrangements, one enhances the collection efficiency but, due to the larger detection area, the measurement is inherently noisier. Simply put, one would like to operate under intermediate conditions in which the SNR and the collection efficiency are more balanced. For this, one could think of hybrid SM–MM configurations in which the SM spatial filtering and the MM larger detection are both, somehow, preserved.

Examples of practical situations where such an intermediate configuration can be advantageous include not only the above-mentioned scenarios related to weak scattering or noisy backgrounds, but also those where scattering is suppressed by absorption or where long, anisotropic scattering objects with large aspect ratio, e.g., cytoskeletal filaments, are involved. In this case, a pure SM implementation would be suitable to resolve fast dynamics, but it would not provide means for proper ensemble averaging.

In this Letter, we report on the use of multimode interference (MMI) phenomena to create the intermediate configuration desired. Specifically, we present a variant of the SMF-based DLS, which is assisted by MMI effects. Our experimental realization consists of a fiber-based common-path interferometer, built around SMFs and operating in reflection, where larger detection regions are generated in which spatial coherence is preserved. In our new design, the MMI mechanism allows (1) spreading the initially well-confined SMF energy over larger coherent areas at the distal end of the MMF, (2) interacting and collecting light over extended areas due to the larger core of the MMF, and (3) means to back-propagate the collected light to the small aperture (SMF core). We experimentally demonstrate that the proposed SM–MM hybrid architectures provide, simultaneously, the best features of both pure SM and MM setups. Additionally, our implementation allows having both a stable local oscillator at the fiber–medium interface and a linear dependence on scattering density. These two features were inaccessible in a DLS measurement until now.

The self-imaging phenomenon was first observed by Talbot [3] in the context of the diffraction from gratings, was later on explained by Rayleigh [4], and its understanding has been consolidated [5–8]. Self-imaging phenomena are not restricted to free space and can also be observed in waveguides supporting multiple modes [9,10]. Self-interference phenomena are used not only to optimize the transmission through fiber links, but also in functional devices such as tunable fiber lenses [11] and band-pass filters [12], as well as in a wide variety of sensors and tunable lasers [13].

Here, we propose to use a MMI device at the tip of a SMF-based DLS setup operating in reflection, as shown schematically in Fig. 1. Light from the low-coherence source, a superluminescent diode of 7 nm bandwidth centered at 670 nm (Superlum BLM-S-670-G-I-4; coherence length of about 30 μm in aqueous media), was launched into a SMF and then coupled into a 50/50 SM coupler. The fibers used in the experiments are commercially available SM-600 and 62.5/125 MMF. The light source is pigtailed to a SM-600, which

actually supports a single mode at 670 nm. Thus, the single mode excitation of the MMF can be ensured for a clean MMI process.

In this configuration, the portion of the (dynamic) field that is scattered by the complex system and is coupled back to the MMF, $E^{(s)}(t)$, can be measured through the heterodyne amplification resulting from its interference with a (static) reference field, $E^{(r)}$, which in turn results from the inherent Fresnel reflection at the end-facet of the fiber [14,15]. The inset in Fig. 1 shows a sample cross section and its corresponding radial cut (red continuous line), of the intensity distribution that can be used for illumination for a length of MMF of $L = 0.7$ mm. The length of the MMF has been chosen arbitrarily in order to simply show that a much larger area of detection can be covered as compared to the case when only a SMF is used (dashed black line). Additionally, the use of low-coherence radiation will limit the maximum depth, L_c , from which coherent scattering can be collected. Effectively, the optical signals come from a picolitter-sized volume where single scattering amply dominates.

The self-imaging conditions can be assessed in a simple way as follows. For the case of symmetric interference, single images of the input field are produced at effective distances $L_{\text{eff}} = p(3L_\pi/4)$, where $p = 1, 2, 3, \dots$, and L_π is the so-called beating length between the two lowest-order modes [9]. This beating length can be estimated as $L_\pi \approx 4n_{\text{eff}} W_{\text{eff}}^2(3\lambda_0)$, with n_{eff} and W_{eff} being the effective refractive index and effective optical diameter, respectively, of the lowest-order mode, and λ_0 the free-space wavelength.

In a zeroth-order approximation, the effective refractive index can be taken as that of the MMF core i.e., $n_{\text{eff}} \approx n_{r\text{MMF}}$, and the effective optical diameter as the physical diameter of the MM waveguide i.e., $W_{\text{eff}} \approx W_{\text{MMF}}$. If the refractive index of the core of the MMF is taken as 1.45 and its diameter 62.5 μm , one can verify that the single replicas appear at integer multiples of the so-called Talbot distance $L_{\text{eff}} = z_T \approx 8.45$ mm, which corresponds to $p = 1$.

For a more complete description of the characteristics of our MMI device, we simulated our structure by following Refs. [11,16]. The simulations were performed at $\lambda_0 = 670$ nm for a SMF–MMF consisting of a SMF with core diameter of $d = 6$ μm and numerical aperture of $\text{NA} = 0.12$, and a MMF with $d = 62.5$ μm and $\text{NA} = 0.22$. These are typical values of the commercial-grade fibers used here. Briefly, our MMI configuration pertains to a case of symmetric, restricted interference in which only the radially symmetric (LP_{0m}) modes are involved. From the simulations, one can construct the field distribution at an arbitrary propagation distance, $E(r, z) = \sum_m c_m F_m(r) \exp(-i\beta_m z)$, as shown in Fig. 1, where $F_m(r)$ the field distribution of the m th radially symmetric mode, c_m is the field excitation coefficients of each mode, which can be calculated by the overlap integral between $F_m(r)$ and the

excitation field, $E^{(\text{in})}(r, 0)$, $c_m = \frac{\int_0^\infty E^{(\text{in})}(r, 0) F_m(r) r dr}{\int_0^\infty F_m(r) F_m(r) r dr}$, and β_m is the corresponding propagation

constant of each of those modes. More importantly for our purpose, one can also assess the spatial correlation characteristics by means of the field autocorrelation function (ACF),

$$C(\rho, z) = \frac{\int_0^\infty E(r) E^*(r - \rho) dr}{\int_0^\infty E(r) E^*(r) dr}, \text{ from which a characteristic correlation length can be estimated}$$

e.g., through the full-width half-maximum of the ACF. By doing so, it can be shown that the correlation length extends practically over the whole radius of the MMF at any propagation plane regardless of how fine the features in the interference pattern are. This should result in a large contrast of the intensity fluctuations, because the spatial coherence is preserved even though the field extends over larger areas.

In our context, it is desirable to maintain a short MMF while still operating at useful self-imaging replicas in order to minimize the losses associated to the interference process in the MMF and the spatial filtering of the SMF. Thus, we designed for fractional replicas [7], in the range $p \leq 1$, as suggested in Fig. 1.

Traditionally, in a DLS experiment, the only parameter of interest is the characteristic correlation time of the light intensity fluctuations, τ , which provides the hydrodynamic information of the diffusing scattering centers. In our approach, on the other hand, two optical descriptors can be followed: (1) the time-averaged total power, which is determined mainly by the local oscillator ($E^{(r)} \gg E^{(s)}$) and provides information on the Fresnel reflection at the fiber-medium interface i.e., $\langle I_t \rangle \approx \langle |E_t|^2 \rangle_t \propto |r|^2$, and (2) the total energy in the power spectrum the light intensity fluctuations, which relates to the contrast of the fluctuations and provides information on the scattering density, i.e., $\beta = \int_0^{+\infty} P(f) df \propto \sigma N$.

In our experiments, we first verified that a performance similar to that of a purely SM scheme can be achieved. In this first set of experiments, we measured the Brownian dynamics of an aqueous suspension of polystyrene beads (ThermoFisher; nominal size of 360 nm and deviation $\sim 3\%$; 1.0 wt% concentration). This colloidal system provides a relatively high scattering and allows a clear assessment of the influence of the MMF length of these fractional MMI devices.

The power spectra of light intensity fluctuations, $P(f)$, which is the frequency-domain equivalent of the time-domain intensity ACF typically measured in a DLS experiment, were recorded in the frequency range from 1 Hz to 10 kHz with a resolution of 1 Hz and integration time of 30 s over a total duration of 5 min (10 spectra per measurement; New Focus 2001-FC photo-receiver), for devices with different lengths of the MMF.

Figure 2(a) shows the total scattered power, β , for the different devices tested. The error bars represent the standard deviation over the collection of raw spectra measured per data point. This result helps to clearly identify the conditions under which $P(f)$ can be properly measured, as it verifies that the length of the MMF cannot be arbitrarily chosen. As expected, the useful lengths of the MMF (resonant locations) correspond to the fractional replicas $p = 1/4, 1/2$, and 1. The typical resonant behavior shown in Fig. 2(a) is equivalent to the filter-like response observed in spectrally operated MMI devices [12,13]. As far as we know, our results are the first experimental demonstration of the filtering properties of a MMI device in the direct domain, i.e., length.

Figure 2(b) presents the average power spectra (averaged over the collection of raw spectra) measured at the resonances shown in Fig. 2(a), which correspond to values of $p = 1/4, 1/2$, and 1. The power spectrum measured with a purely SM scheme ($p = 0$), as well as that measured

with a length of MMF outside the resonance, are plotted for reference. It can be seen that, even when measured at the same detector gain, the amplitude of $P(f)$ for a length of 2.0 mm is two orders of magnitude smaller than the slightly different length of 2.1–2.2 mm [see also Fig. 2(a)]. This is precisely the hallmark of MMI devices—due to the large number of modes involved in the interference process, the net result is strongly sensitive to small variations in the effective geometrical and optical parameters of the device, which can actually make them ideal for high-sensitivity sensing.

The slope of -2 in the logarithmic scale in Fig. 2(b) indicates the asymptotic limit of a Lorentzian spectrum, which is associated to a process of normal diffusion. It is important to note that, even though the system under study is the same in all cases (particles in water), operating in conditions where the intensity fluctuations have low contrast can misguide the interpretation of DLS results.

In our example, for a length of 2 mm, the asymptotic slope of the spectrum is about -1.4 , which could be associated to a sub-diffusive process, e.g., particle diffusion in strong confinement.

In a second set of experiments, we evaluate the performance of a fractional MMI device in a range of weakly scattering situations. In these experiments, we used colloidal suspensions of polystyrene beads with nominal size of 102 ± 3 nm (size standard Thermo Fisher 3100A) at different concentrations. Throughout these experiments, the same MMI device was used for the measurements (length of 2.2 mm; $p \approx 1/2$). In this case, we also followed the total power measured in order to evaluate the balance between the signal's strength and quality.

Figure 3 shows the total power detected and scattered as a function of the concentration of particles. From the total power [Fig. 3(a)], it can be seen that the pure SM arrangement is more sensitive to the small variations of the Fresnel reflections, while in the SM–MM hybrid configuration, the local oscillator remains stronger and more stable, irrespective of the concentration of particulates. Consequently, in the pure SM scheme, the total scattered power also varies due to the more unstable local oscillator used for heterodyning, i.e., the intensity fluctuations actually result from the amplification of the scattered field through the interference with the reference field, as opposed to the hybrid SM–MM [Fig. 3(b)].

In Fig. 3, the balance between the signal's strength and its quality is obvious. Nevertheless, we emphasize that the most important benefit is that, aside from the dynamic information, one can infer the effective optical properties of the complex medium. This has deeper implications, since the optical parameters of the complex system, which are now accessible, have not been available in DLS measurements before.

In conclusion, we demonstrated that, by providing a SMF-based DLS setup with MMI capabilities, the ensemble dynamics of complex systems can be measured over effectively larger regions while maintaining a high SNR. The interference of multiple modes in the MMF sensing tip generates larger detection regions where the spatial coherence is preserved. This mechanism also provides means to back-propagate the collected light to the core of the SMF, such that the spatial filtering of the SMF is also preserved and effectively used. In this way, the proposed architecture insures that the best features of both SM and MM setups are

achieved simultaneously. We assessed the performance of one of these SM–MM hybrid structures in the context of weak scattering and demonstrated that, as opposed to a purely SM implementation, the signal can be measured independently of the concentration of particulates. Finally, we demonstrated that, aside from better balance between strength and quality of the signal, our device permits retrieving information on the effective optical properties of the medium. This is a unique feature that was not available in traditional DLS until now. It opens the possibility to fully characterize, mechanically and optically, inhomogeneous media in conditions of weak scattering, noisy backgrounds, and anisotropic scattering. These are circumstances commonly encountered in biological systems or gel-like materials [17]. In such complex systems, it is critical to detect stronger signals with large SNR, while providing means for proper ensemble averaging.

Funding.

National Heart, Lung, and Blood Institute (NHLBI) (5R21HL124486).

REFERENCES

1. Berne BJ and Pecora R, Dynamic Light Scattering: With Applications to Chemistry, Biology, and Physics (Courier Corporation, 1976).
2. Salem M and Dogariu A, J. Modern Opt 51, 2305 (2004).
3. Talbot HF, London Edinb. Philos. Mag. J. Sci 9, 401 (1836).
4. Lord R, Philos. Mag 11, 196 (1881).
5. Winthrop JT and Worthington CR, J. Opt. Soc. Am 55, 373 (1965).
6. Montgomery WD, J. Opt. Soc. Am 57, 772 (1967).
7. Berry MV and Klein S, J. Mod. Opt 43, 2139 (1996).
8. Saastamoinen T, Tervo J, Vahimaa P, and Turunen J, J. Opt. Soc. Am. A 21, 1424 (2004).
9. Soldano LB and Pennings EC, J. Lightwave Technol 13, 615 (1995).
10. Okamoto K, Fundamentals of Optical Waveguides (Academic, 2010).
11. Mohammed WS, Mehta A, and Johnson EG, J. Lightwave Technol 22, 469 (2004).
12. Mohammed WS, Smith PW, and Gu X, Opt. Lett 31, 2547 (2006). [PubMed: 16902614]
13. May-Arrioja DA, Antonio-Lopez JE, Sanchez-Mondragón JJ, and LiKamWa P, Advanced Lasers (Springer, 2015), pp. 19–33.
14. Popescu G and Dogariu A, Opt. Lett 26, 551 (2001). [PubMed: 18040382]
15. Popescu G and Dogariu A, Eur. Phys. J. Appl. Phys 32, 73 (2005).
16. Wang Q, Farrell G, and Yan W, J. Lightwave Technol 26, 512 (2008).
17. Torquato S, Random Heterogeneous Materials: Microstructure and Macroscopic Properties (Springer, 2013), Vol. 16.

Fig. 1.

Schematic of the SM common-path interferometer assisted by MMI capabilities. The inset shows a sample cross section of the field amplitude distribution and its corresponding radial cut (red continuous line), for a length $L = 0.7$ mm. The length of the MMF has been chosen arbitrarily in order to illustrate that the energy can be spread out controllably over much larger areas as compared to when only a SMF is used (dashed black line).

Fig. 2.

(a) Total power scattered, β , for different lengths of the MMI device. (b) Sample power spectra measured for lengths of MMF around the resonances in (a). Spectra of the purely single-mode scheme and for a length of MMF outside the resonance are plotted for reference.

Fig. 3.

(a) Total power measured and (b) total power scattered, β , as a function of concentration of particles. The same MMI device was used throughout the measurements (length of 2.2 mm; $p \approx 1/2$).