Laser-induced scattering structures for metrology and distributed sensing

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ABSTRACT

Femtosecond laser irradiation allows to modify the optical properties of transparent materials with high accuracy. In many applications, optical scattering produced by the laser irradiation is one of the major limiting factors. However, there are situations when the scattering is responsible for the basic principle of operation of the optical element. This report reviews two research directions where laser-induced scattering can be successfully exploited.

First, spectroscopic measurements can be performed by analyzing the speckle patterns created by the scattering medium. The measurements are made possible by the strong dependence of the speckle pattern on the wavelength of light. A scattering chip created thanks to a femtosecond laser makes allows addressing the stability problem faced by many scattering spectrometers. The volumetric scattering centers are induced in silica substrate via micro-explosions caused by the focused laser beam. Such a spectrometer can be successfully used for interrogating fiber Bragg gratings or interferometers.

Second example is found in optical reflectometry. This technology allows turning an optical fiber into a distributed microphone or thermometer. A single optical fiber can monitor a stretch of several tens of kilometers with an accuracy of several meters. Such systems have wide range of applications in civil engineering, geosciences and other fields. Reflectometry measurements are performed by observing the back-scattered light produced by the glass medium of the optical fiber. Femtosecond laser writing allows effectively increase backscattered light whilst introducing minimal additional losses. In this way, the sensitivity of reflectometric systems can be increased or their range can be extended.

Keywords: femtosecond laser writing, silica glass, optical fiber, spectrometry

1. INTRODUCTION

Sub-picosecond light pulses allow efficient modification of glasses that are otherwise optically transparent under normal conditions. Femtosecond laser pulses are already being successfully exploited for a variety of industrial applications, such as inscription of waveguides[1,2] and diffraction elements[3,4], optical data storage[5–7], and ion toughened glass cutting. One of the main properties of a transparent medium, when exposed to a short pulse of light, is the change in refractive index. In the case of quartz glass, both an increase and a decrease in the refractive index can be achieved depending on writing conditions. Material irradiated with femtosecond laser pulses undergoes a rapid thermal quenching resulting in glass structure which corresponds to elevated temperatures frozen in the laser exposed regions. Some glasses, notably quartz glass, exhibits an anomalous behavior becoming denser at higher temperatures[8]. Even illuminated with relatively weak pulses (100-200 nJ), the quartz glass compacts due to the increased fictive temperature, which results in a partial increase of the refractive index. Additionally, defects are induced in the glass, which also contribute to the increase in the refractive index due to the absorption lines in the UV region[9–11]. When writing waveguides or diffractive elements, the laser beam scans the volume of the material in a raster way. Since the written structure essentially consists of a large number of overlapping points, the written structure will be inhomogeneous. Additional inhomogeneity can be introduced by nano-pores occurring in the regime of nanograting formation[12]. These inhomogeneities in the linear mode of light-material interaction cause Rayleigh or Mie scattering depending on the characteristic dimensions of the inhomogeneities.

2. DISTRIBUTED ACOUSTIC SENSING

Frequently, optical scattering is one of the key aspects for which experimental parameters are optimized to reduce losses. However, in some cases, optical scattering can be successfully exploited and made a reference feature for the performance of an optical element. One of the best uses for scattering is distributed acoustic sensing (DAS), where backscattered light is used to detect acoustic signals. Operation of the DAS system is based on the sensitivity of backscattered light (intensity and phase) to the acoustic wave. By exploiting this technology kilometers of an optical fiber can be turned into a distributed sensing system, which requires just a one end access. A typical DAS system couples a nanosecond light pulse into the optical fiber, fluctuations of the refractive index give rise to the scattered light. Part of this light backpropagates and is collected by the interrogator. The most successful and commonly used DAS architecture is phase-sensitive optical time domain reflectometry (φ-OTDR)[13]. This configuration allows to turn optical fiber into distributed strain sensor operating over distances of 10 to 40 kilometers and are successfully exploited for vertical seismic profiling and borehole monitoring. However, a range of applications, such as sub-sea power cable monitoring and perimeter security, require DAS systems with operational range exceeding 100 kilometers due to limited access or cost-efficiency.

The efforts to extend operational range of fiber DAS systems lasts for almost one decade. Most of the proposed solutions rely on active signal amplification within the fiber using Raman amplification or pumping fiber doped with rare-earth ions[14,15]. There were also attempts to find passive solutions by reaching the right balance between signal strength and sensing range. Presence of the scattering results in exponential decrease of the propagating light and at some point the signal drops below detectable level. One can increase amount of back-scattered light by increasing scattering, but in this case, signal is stronger at the beginning, where signal to noise ratio is already sufficiently good[16]. The remote end of the fiber, however, suffers from increased decay of the signal and results in reduction of the detection range. Long faint gratings is another path for increasing backscattered signal[17]. However, this approach requires very high inscription precision to satisfy resonant conditions over all distance of the grating. As a result, demonstration of this technology has been limited to only few meters length fiber. In this case the signal to noise ratio can be significantly improved at a cost of added losses and reduced bandwidth of operation. Recently, an alternative approach based on femtosecond laser writing was proposed for improving signal to noise ratio in DAS systems[18]. Highly localized micro-reflectors are imprinted into the bulk of the fiber allowing to increase the backscattered signal by up to two orders of magnitude. At the same time the added losses introduced by the micro-reflectors are minimal allowing to significantly improve operating range of the DAS system. Attaching such fiber to the far end of the DAS system allow to recover the signal and effectively extend operational range[19]. Recently a 10-kilometer DAS system has been demonstrated containing micro-reflectors inscribed every 10 meters[20]. For this demonstration the standard telecom fiber has been modified using an automated laser inscription system that included fiber rewinder, positioning and focusing system. The ability to control reflectivity of each micro-reflector by adjusting writing conditions allows to compensate decay of the signal achieving equal strength of the signal from all reflectors. Total measured losses of this fiber were less than 0.3 dB/km indicating minimal losses added by the micro-reflectors. This demonstration clearly indicates feasibility of inscribing large number of micro-reflectors with high consistency necessary for long range DAS systems.

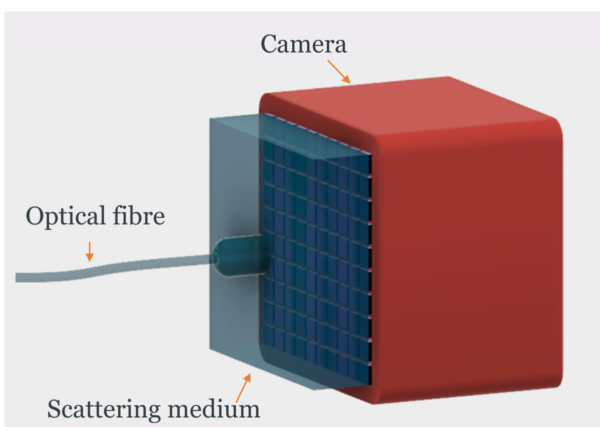

Figure 1. Schematic layout of a scattering spectrometer. The light is delivered via a single mode fiber, which acts as a spatial filter. The light is then scattered by glass containing nano-voids and collected by CMOS sensor.

3. SCATTERING SPECTROMETER

A coherent light propagating through the scattering medium forms so called speckle-patterns, which are result of complex interference occurring from multiple scattering sources. At first glance, these patterns might appear completely chaotic and absent of any useful information. However, using appropriate measurement and data processing techniques optical scattering can also be successfully exploited for analyzing light characteristics such as spectral composition[21,22]. The basic idea relies on the fact that each component of light carrying different spectral or polarimetric information will propagate via unique path through the scattering medium. As a result, the observed speckle pattern is a superposition of multiple light components. Essentially scattering medium can act as a spatial mapping device where light is redistributed based on its spectral characteristics. Spectral information can be extracted by comparing recorded speckle pattern against calibration database, which is obtained using a tunable laser source. In fact, scattering spectrometer can be calibrated not only to wavelength, but also directly to the measured quantities (stress, polarization, chemical concentration, etc), if they uniquely alter spectrum of the light used for the interrogation. This approach eliminates need for a dedicated calibration system. The in-situ calibration of the system improves SNR and enables direct measurements with simplified data processing.

Traditional spectrometers rely on angular dispersion obtained using a prism or diffraction grating. As spatial separation between spectral components increases linearly with distance large distance is required to achieve sufficient spectral resolution. Scattering process allows to solve this problem as multiple scattering events effectively folds the optical path. In addition, each scattering event contributes to spatial separation of the spectral components. Spectrometers based on chaotic light redistribution were demonstrated to achieve sub-femtometer spectral resolution[23]. Such systems have also extremely simple setup consisting just of scattering medium and image detection device such as a CMOS imaging sensor (Fig. 1). Simplicity of scattering spectrometer can potentially provide low-cost and ruggedized interrogation solution for optical sensing systems such as fiber Bragg gratings.

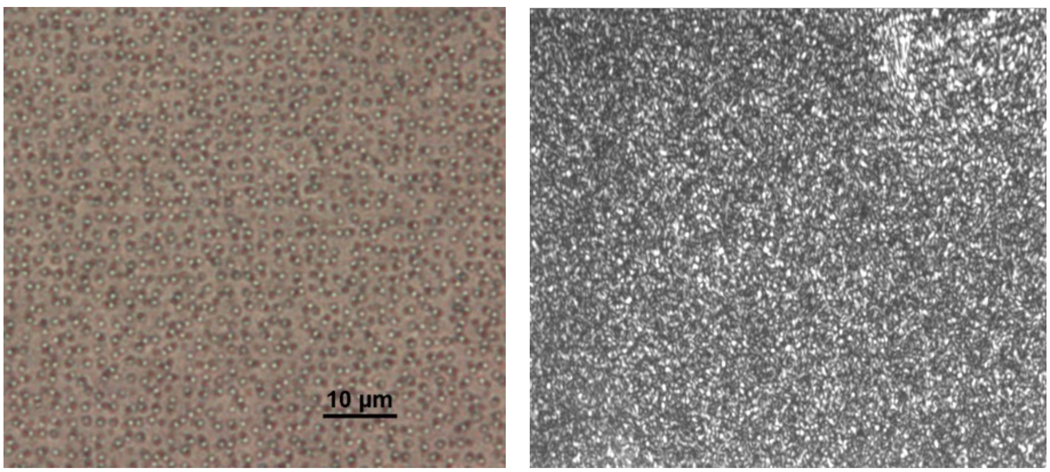

Figure 2. (Left) Image of the laser written scattering medium. Individual nanovoids can be seen randomly distributed across 1 x 1 mm area. (Right) Speckle pattern produced by laser written scattering medium.

One challenging task operating scattering spectrometer is ensuring that scattering medium does not drift with time, otherwise calibration database is rendered useless. The drift can occur due to thermal or mechanical fluctuations which alter distribution of the scattering centers and result in modification of speckle patterns. In order to minimize environmental influence, the scattering medium should be implemented in mechanically stable substance and minimized in its spatial dimensions eliminating complex thermal gradients. Femtosecond laser writing is able to satisfy these requirements. It is well known that tightly focused femtosecond laser pulse can produce a nano-voids in the bulk of transparent material as a result of micro-explosion. Such nano-voids allow to achieve relatively high refractive index contrast and act as scattering centers. By inscribing a large number of these nano-voids one can achieve a tailored scattering medium what is embedded in a uniform glass matrix providing additional protection from the environmental elements (Fig. 2).

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