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Optical memory effect from polarized Laguerre–Gaussian light beam in light-scattering turbid media

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ABSTRACT

Propagation effects of polarized Laguerre–Gaussian light with different orbital angular momentum (L) in turbid media are described. The optical memory effect in scattering media consisting of small and large size (compared to the wavelength) scatterers is investigated for scattered polarized light. Imaging using polarized laser modes with a varying orbital strength L-parameter was performed. The backscattered image quality (contrast) was enhanced by more than an order of magnitude using circularly polarized light when the concentration of scatterers was close to invisibility of the object.

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1. Introduction

The propagation and scattering of light in an optical dense turbid medium has significant interest in connection with communication, remote sensing and imaging of an object hidden in the scattering medium. Scattering media blur coded information and images. Using the salient properties of light: wavelength, coherence, and polarization one can improve images and coded information traveling in free space inside fog, clouds, smoke, and tissue as well as in fiber optic waveguides. Over the years, several methods have been used to discriminate the signal and improve the quality of an object image from the noise of scattered light. The problem to extract an image propagating through or located in a scattering medium was investigated theoretically and experimentally over the past 20 years [1–9]. Soon there will be a bottleneck in communications due to the vast encoded data stream. Continuous and exponentially growing demand on optical fiber information capacity is exhausting state of the art methods to maintain information capacity levels [10]. The corresponding information capacity limits are a direct result of wavelength division multiplexing conflicting with high bit rate signal formats. This is due in great part to detrimental non-linear optical phenomena that arise from the tight confinement of the light signal in a single mode optical fiber core [11–13]. To prevent an impending optical fiber "bottleneck," new methods to increase information capacity that circumvent optical non-plane waves and non-linear effects are required.

One potential method is the exploitation of light's unused spatial degrees of freedom via the higher-order modes in multimode optical fibers [14]. The properties of higher-order modes are rich and include optical angular momentum [15], vector polarization [16], and span a complete, orthogonal, and higher-dimensional Hilbert space using SU(N) [17] allowing them to serve as separate and non-mixing information channels. Encoding light signals onto each higher-order mode as an additional information channel, analogous to wavelength division multiplexing, is referred to as mode division multiplexing (MDM). MDM can increase information capacity in optical fiber transmission in an amount proportional to the number of modes used. One key and simple approach to improve image quality and information flow was to show that the vector nature of light can play a key role in the process of the light scattering. Using a polarized laser beam, it was shown that the intensity of forward and backscattered light significantly depends on the size of the scattering particles, their concentration in a turbid medium and on the polarized state of the incident light beam [18–23]. Three key length parameters important to characterize light propagating in scattering media are: the scattering length (L_s), transport length (L_{tr}) and absorption length (L_a) [8,24]. The L_s is the mean distance between scatterers, L_{tr} is the distance traveled to change the directions of incoming photons, and L_a is the distance travelled before the photons are absorbed. These lengths are the inverse of the scattering coefficients: μ_s, μ_{tr} and μ_a, respectively. The scattering from small particles are more random in direction after a scattering event, while from large particles the photons are more

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forwarded scattered. The sizes of scattering particles (d) are compared to wavelength of light: small size scatterers ($d < \lambda$) and large size particles ($d > \lambda$). The polarization techniques have been advanced to improve the imaging of an object hidden inside a highly optically dense turbid medium [22–24]. It was shown experimentally [24] that the image contrast of an object can be enhanced by linearly polarized light because the parallel component of the polarization vector is highly reflected off the front surface and overwhelms any imaging information from below the surface in backward scattering imaging. The perpendicular component blurs an image and travels deeper to give information from below the surface. An alternative method using circularly polarized light [25,26] gives the possibility to significantly improve imaging in higher concentration (multi-scattering events) media and mainly in the case of large size scatterers ($d > \lambda$, Mie scattering). In this case of scattering from a high concentration of large size particles, the backscattered light was shown to predominantly retain the same state of polarization as the incident light for both polarizations (linear and circular). This phenomenon is known as the optical memory effect (OME) and was described in a number of articles [19,20,24–28] where Gaussian light beams were incident onto a scattering medium. An additional new and novel encoding method to transfer more data is to use the twist of light associated with the non-planar wave front of a Laguerre–Gaussian (LG) beam, which uses the property of orbital (L) and spin angular momentum (SAM) parameters. The parameter L is a measure of orbital angular momentum (OAM) and the strength of the optical vortex of the LG-beams. The strength L is associated with the vortex of the wavefront twist and SAM is associated with the circular vector of polarization.

In this paper, the OME-effect, previously described by Ni and Alfano [24–26] using a Gaussian laser mode ($L=0$), is experimentally extended using the polarization states and the OAM of Laguerre–Gaussian beams [29–31]. The scattering and imaging is investigated with different OAM-states (L) for scattering media with small and large scattering particles. The LG complex laser beams adds a new dimension to light's spatial degrees of freedom for light propagating in turbid media. This includes helical shaped and twisted wave fronts, singularities in electric fields and spatial vector polarization states of the beam profile. These twisted special light forms opens a new renaissance era in optics called “complex vector light”. This complex vector light can possess both spin angular momentum (SAM) which is associated with optical circular polarization and OAM, which is associated with the helicity of non-planar wave fronts. The angular momentum of spin and orbital properties appear separately and do not interact in paraxial beams. Coupling can occur by the spin–orbit interaction (SOI) of SAM and OAM in non paraxial beams, highly focusing, scattering in inhomogeneous and anisotropic media. The theory of OMA and SAM propagation and scattering of polarization and singularities of complex light is not considered here.

The LG laser beam has an optical vortex (phase singularity) at the center of the beam and carries an orbital angular momentum (OAM: $l = \pm L\hbar$, $L = 0, \pm 1, \pm 2, \ldots$) and a spin angular momentum (SAM: $\sigma = \pm 1$). The total angular moment is equal to:

$$\gamma = (L+1)\hbar\Omega/2. \tag{1}$$

The phase singularity (optical vortex) at the center of the beam is the point (area) of zero intensity and such a beam has a spatial profile of a ring and has been called a “donut” beam.

Two experimental geometrical arrangements were investigated in this study: the scattering at 90° and the backscattering (180°) for different orbital angular momentum modes (L) and states of polarization of the vortex LG beams. The polarized LG (donut) beams are used for investigation of scattering and imaging in the turbid medium with scattering particles of different sizes and concentrations (volume fraction of scatterers) in water suspension. Small size scatterers ($d < \lambda$, the case of Rayleigh scattering) and large size particles ($d > \lambda$) at different concentrations were studied to understand the possible influence of the OAM L-effects on the OME-phenomena.

2. Experimental methods

Three methods are described in this section: (1) 90°-angle scattering, (2) Backscattering, and (3) Imaging using polarized LG-beams of different L.

2.1. The experimental arrangement for linear-polarized LG beam with OAM values from $L=0$ to $L=5$ scattered at 90°

The setup of this experiment is shown in Fig. 1. The LG-beam scattered at 90° was used with the linear polarization technique with OAM parameters varying from $L=0$ to $L=5$. The He–Ne laser ($\lambda = 0.633\ \mu$, 5 mW output power) was used as a source of light. The laser output with a Gaussian mode (beam diameter around 1 mm) was expanded five times and then transformed to a polarized LG-beam by using the holographic Spatial Light Modulator (SLM).

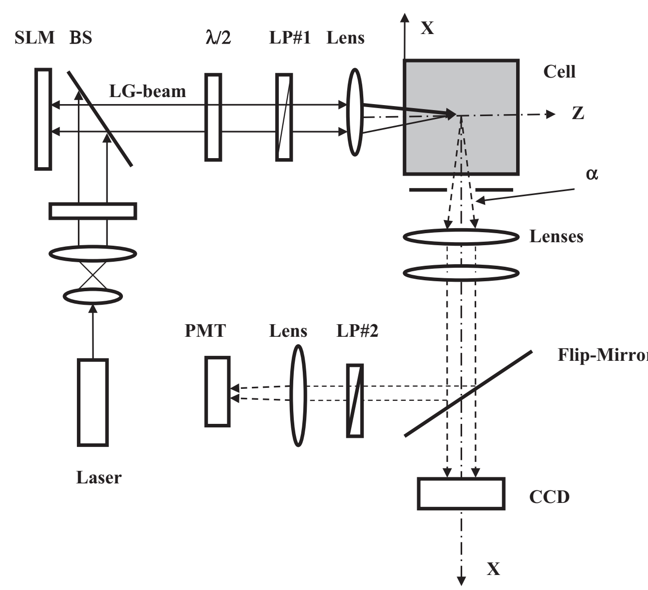

Fig. 1. Experimental setup for LG-beams scattered at 90° by turbid media.

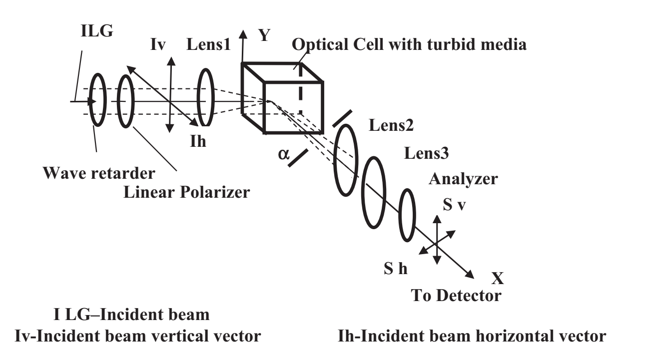

Fig. 2. Diagram of polarizing measurements of Laguerre–Gaussian beams scattered at 90° by turbid media.

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