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Directional gated imaging in a turbid medium using an ultrafast optical Kerr gate

Yuhu Ren[a], Wenjiang Tan[a,*], Yipeng Zheng[a], Xiaojing Liu[a], Junyi Tong[b]

[a] Key Laboratory for Physical Electronics and Devices of the Ministry of Education & Shaanxi Key Lab of Information Photonic Technique, School of Electronics & information Engineering, Xi'an Jiaotong University, Xianning-xilu 28, Xi'an, 710049, China
[b] Departments of Applied Physics, Xi'an University of Technology, Xi'an, 710048, China

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ABSTRACT

Directional gated imaging of hidden objects in scattering media is demonstrated using an ultrafast optical Kerr gate (OKG), in which the gating and imaging beams are focused by utilizing a cylindrical lens and a convergent lens, respectively. Owing to the spatial transmission characteristics of the directional gate, a rectangular aperture stop is formed, which leads to different resolution limits for vertical and horizontal structures of an object. By implementing directional gated imaging, the directional feature can be extracted from an original image.

1. Introduction

Oriented linear or piecewise linear patterns are common phenomena in nature, which forms an important class of images [1]. An effective technique for extracting the directional feature from an original image is based on Fourier transform analysis because it enables the separation of their different spatial frequencies. Directional filters in the Fourier domain are used in different applications, such as image coding [2], design of fan filters [3], and texture discrimination [4]. Many directional filters are also used for digital image processing to extract the directional feature from an original image [5–7]. Compared to the directional filter used by the digital imaging processing method, a full optical directional filter enables immediate processing. Notable examples of the optical directional filters used by the optical Fourier transform have been used for defecting detects in textured materials [8,9].However, most studies on extracting the directional feature from an original image were conducted in a non-scattering environment.

Optical imaging of targets embedded in highly scattering media, such as biological tissues [10–13], fog [14], or diesel sprays [15,16] is a challenging problem because multiple scattering of light by the turbid media scramble optical information for imaging. Moreover, the image quality is often degraded because of the noise that arises from the multiple scattering in a scattering medium. Light transmitted through a turbid medium comprises ballistic, snake, and diffuse components [17]. The difference in the transit time can be exploited to sense objects [18,19] hidden in a scattering medium by detecting only the ballistic component but excluding delayed scattered photons. Among available time gating techniques, optical Kerr gate (OKG) has been investigated widely because of its advantages, such as no need for the satisfaction of the phase-matching condition or the capability to acquire a time-sliced true 2D spatial image for both incoherent and coherent optical signals [20–24]. However, most studies on OKG imaging give little information on the directional feature from imaging of hidden objects in a scattering medium. For example, liquid/gas interfaces in a high-pressure spray cannot be clearly seen only using OKG imaging without a digital image post-processing algorithm [25]. Therefore, the development of a directional gated imaging system which is an all-optical system is helpful for extracting gas/fuel jet interfaces in sprays.

* Corresponding author.
E-mail address: tanwenjiang@mail.xjtu.edu.cn (W. Tan).

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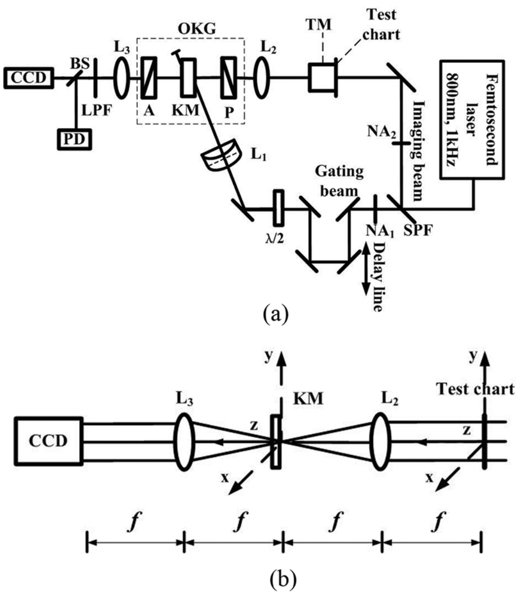

Fig. 1. (a) Experimental setup of the directional gated imaging system. (b) Schematic of the 4*f* imaging system. L_1: cylindrical lens; L_2, and L_3: lenses; SPF: short pass filter; λ/2: half-wave plate; P: polarizer; A: analyzer; NA: neutral attenuator; LPF: long pass filter; TM: turbid medium; KM: Kerr medium; BS: beam splitter; OKG: optical Kerr gate; and f: focal length of lenses L_2, and L_3.

In this paper, we demonstrate a directional gated imaging through a turbid medium by use of an ultrafast OKG, in which the gating and imaging beams are focused by utilizing a cylindrical lens and a convergent lens, respectively. A sequence of directional gated images of a test chart hidden behind a highly turbid medium was obtained by means of the directional filter technique. Owing to the spatial transmission characteristics of the directional gate, a rectangular aperture stop was formed, which led to different resolution limits for vertical and horizontal structures of an object. Using directional gated imaging, the directional feature of an original image can be extracted and the contrast of directional gated images can be enhanced significantly.

2. Experimental setup

The schematic of the directional gated imaging system is shown in Fig. 1 (a). A Ti:sapphire laser was used to provide light pulses with a central wavelength of 800 nm, full width at half maximum of 50 *f*s, and repetition rate of 1 kHz. The laser beam was split into a gating beam centered at 780 nm and an imaging beam centered at 800 nm by a short pass filter (SPF). The intensities of the gating and imaging beams were adjusted by neutral attenuators NA_1 and NA_2, respectively. The imaging beam was first modulated by a 1.41-line-pair/mm resolution chart (a chromium-coated glass U.S. Air Force resolution chart) and then introduced to a turbid medium. The transmitted light from the turbid medium was first focused by lens L_2 and then introduced into the OKG. The OKG consists of a pair of crossed polarizers and a CS_2 cell. The gating beam was first linearly polarized at 45° with respect to the polarization of the imaging beam for the optimal efficiency using a half-wave (λ/2) plate. The gating beam was focused by cylindrical lens L_1 with focal length $f_1 = 150$ mm into the Kerr medium of CS_2 filled in a quartz cell of thickness 5 mm. This is the main difference from the conventional OKG [26–30], in which the gating beam is focused by a convergent lens. The cylindrical lens is used to adjust the shape of the gating beam. The magnification of circular light by a cylindrical lens can be different for two perpendicular directions [31].

The cylindrical lens L_1 was used to change circular light into rectangular light. Convergent Lenses L_2 and L_3 both with focal lengths $f = 150$ mm formed a 4*f* imaging system as shown in Fig. 1 (b). In this imaging system, the imaging pulse was spatially overlapped with the gating pulse in the Kerr medium which was placed at the back focal plane (Fourier-transform spectrum plane) of lens L_2. When the two pulses were spatially and temporally overlapped, the imaging pulse polarization was rotated owing to the birefringence of the Kerr media induced by the gating pulse. Then a part of the imaging pulse passed through an analyzer, which was synchronously detected by a charge coupled device (CCD) camera and a photodiode (PD).

The turbid medium was composed of a polystyrene microsphere solution contained in a cubic cuvette with inside dimensions of 50 mm × 50 mm × 10 mm. The cuvette thickness along the optical axis was 10 mm. The diameter of the polystyrene microsphere was 3.13 μm. The refractive indices of the background medium n_b and the polystyrene microspheres n_p were 1.33 and 1.58, respectively. The absorption of the turbid medium was low enough to be neglected. The value of the optical depth (OD) of the sample was 9.9.