Transverse Doppler Effect using Engineered Optical Beams

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Abstract: When a light beam with a transverse spatially-varying phase is considered for optical remote sensing, in addition to the usual longitudinal Doppler frequency shift of the returned signal induced by the motion of the scatter along the beam axis, a new transversal Doppler shift appears which is due to the motion of the scatterer in the plane perpendicular to the beam axis [1]. With engineered light, light scattered by a particle at a particular location is associated with a specific value of the phase of the incident field at that point. As the particle move across the beam, it produces an echo that is dependent on the phase of the incident field. By noting the change of the phase of the echo (Doppler Effect), the movement can be measured. We discuss here how this new effect can be used to enhance the current capabilities of optical remote sensing systems, adding the capacity to detect more complex movements of scatters.

Laser remote sensing systems are widely used to monitor the location and velocity of moving targets. When a laser beam illuminates an observation region, the interaction of the light beam with the target can modify the phase of the signal reflected back to the receiver, a change that can be used to extract information about the location and velocity of the target. For instance, in a monostatic standard laser remote system, if the target is moving with velocity $\vec{v}$, the reflected signal will show an optical frequency shift $\Delta f_L = |\vec{v}| \cos\theta/\pi$, where θ is the angle between the velocity of the target and the direction of propagation of the light beam. This is the usual longitudinal Doppler shift.

The classical Doppler scheme only allows the direct detection of the target velocity component along the line- of-sight, and does not provide any information about the components of the velocity perpendicular to the direction of propagation of the light beam. However, the capability to detect transverse velocities is of great interest in fields as diverse as biology microfluidics, micro-organism motility [2], optical coherence tomography medical imaging [3], atmospheric and oceanic turbulence remote sensing [4], and fluid aerodynamics [5].

Up to now, the only option to measure these velocities was to use signal-processing techniques based solely on Doppler measurements along the line of sight for a large set of directions. If the scatterer is in motion, the frequency of the scattered radiation will be different in each direction. Due to the diverse nature of the data sources, post-processing is required to analyze and correlate the data and, in general, accuracy and spatiotemporal resolution of the measurement are poor.

Here, we present a new method for measuring directly the transverse components of the velocity [1]. The key point of the technique proposed here is to make use of a light beam where each point of the transverse plane is associated with a particular value of the phase of the field (structured light). The phase of the light reflected back to the receiver from a moving target will contain information about the location of the target at each instant, producing a Doppler shift associated to the change of transverse position. The observation of the transverse Doppler shift makes use of a stationary structured beam and a fixed detector. Since the target is moving, the light reflected back to the detector changes its phase in accordance to the particular location of the target at each instant. The movement of the target produces effectively a time-varying phase that mimics the phase of the structured field. Spatial light modulators allow to generate complex spatial phase and amplitude light patterns and to modify them in a prompt and efficient manner.

We will show that an optical beam with an appropriately designed phase gradient yields a new Doppler frequency shift induced by the transverse velocity of the scatterer $\Delta f_T = \vec{\nabla}\Phi(\vec{r}) \cdot \vec{v}/2\pi$ which is proportional to the velocity component of the scatterer along the phase gradient $\vec{\nabla}\Phi(\vec{r})$ of the transmitted signal. Contrary to the longitudinal Doppler frequency shift, this new transverse Doppler component is not sensitive to the operating optical frequency band. For illustrative purposes, we analyze the Doppler changes induced by some basic transverse motions of scatterers, i.e. uniform translation and rotation, in some simple optical sensing scenarios. Note that, in most practical situations, Doppler optical echoes are composites of signals from a dense array of single scatterers, each of which can be considered moving with identical velocity.

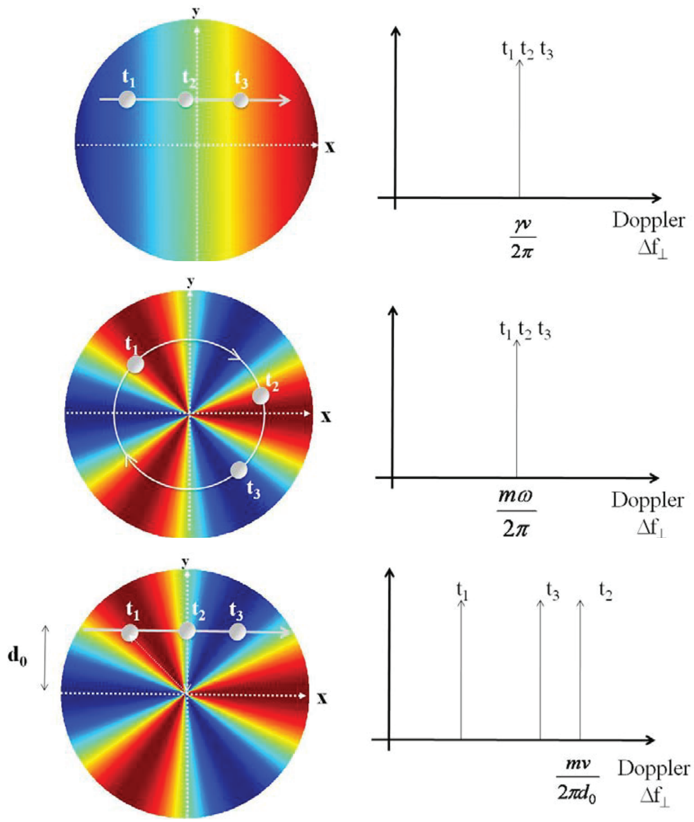

Fig. 1. Sketch of the movement of a target (white solid line) in a beam with a spatially varying phase-gradient (as indicated by color scales), and the corresponding Doppler shift of the returned signal for three different times $t_1 < t_2 < t_3$. Upper row: A target with constant velocity moves v in a constant phase gradient γ, induces a time-independent Doppler shift of value $\gamma v/2\pi$. Middle row: The target rotates with angular velocity ω in a LG beam with azimuthal mode m, and induces a time-independent Doppler shift of value $m\omega/2\pi$. Lower row: Doppler shift induced by the uniform movement of a scatterer on a twisted LG beam. The frequency shift depends on time (t_1, t_2, t_3...) as the scatterer moves across the LG beam.

As a first example, we consider a small scatterer that move with constant transverse velocity v along an arbitrary direction x, as shown in Fig. 1 (upper row). To measure this velocity, we can make use of a transversal phase γx with a constant gradient γ. As a second example, we use a Laguerre-Gauss LG beam, one of the simplest light beams showing a phase gradient, to detect a rotating scatterer, as shown in Fig. 1 (middle row). LG modes, which appear naturally in laser cavities and have well-known propagation properties, have been recently the subject of interest for new applications that makes use of complex beams. Generally speaking, when a LG beam with azimuthal index m illuminates a single scatterer, the phase $m\varphi$ of the backscattered signal depends on the cylindrical azimuthal angle φ. If the single target would move on a LG beam with a uniform movement (as shown in Fig. 1, lower row), a variable in time Doppler shift would be observed.

Experimental verification has used the setup shown in Fig. 2. Setup considers a simple heterodyning system configured as a Mach-Zehnder interferometer with lab controlled conditions for target and light beam alignment. Structured light beams are efficiently generated using a spatial light modulator. Moving target is defined using a small reflector in a piezo motor driven optical mount. The interference is detected by a photodetector attached to a digital oscilloscope for storage and processing.

Figure 3 shows the Doppler effect that accompanies the movement of a particle in a plane transversal to the optical beam axis. In this experiment, the particle describes a circular trajectory and it is moving with constant angular velocity. The particle is illuminated by a LG beam with azimuthal mode m=3. Doppler shift can be clearly observed

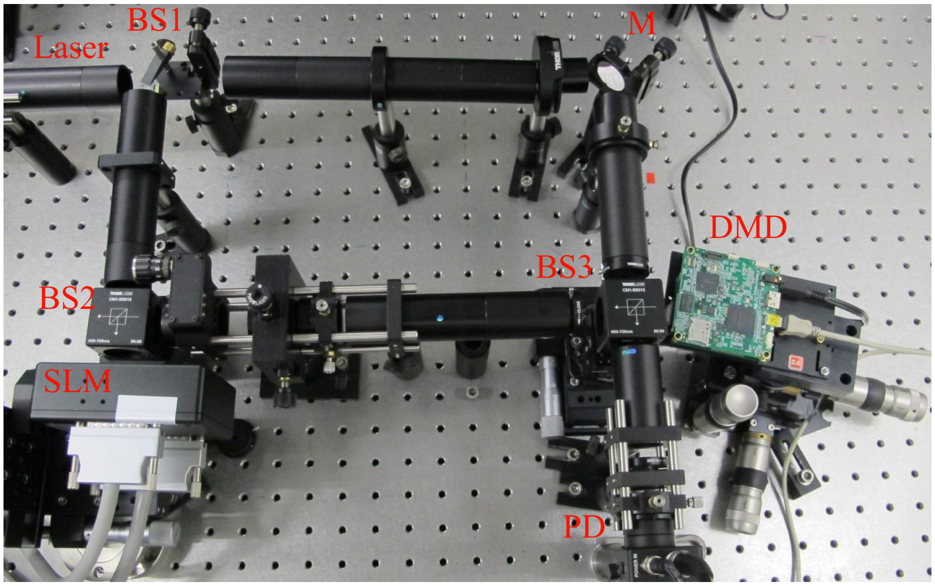

Fig. 2. The experimental setup considers a simple heterodyning system configured as a Mach-Zehnder interferometer with lab controlled conditions for target and light beam alignment. Structured light beams are efficiently generated using a spatial light modulator (SLM). Moving target is defined using a small Digital Micromirror Device (DMD) which uses an array of micromirrors that can be used for high speed, efficient, and reliable spatial light modulation. The interference is detected by a photodetector (PD) attached to a digital oscilloscope for storage and processing.

in the return signal (left plot) and the corresponding power spectrum (right). The maximum of the spectral density occurs at the expected Doppler frequency. More details of our analysis and results will be presented at the meeting.

References

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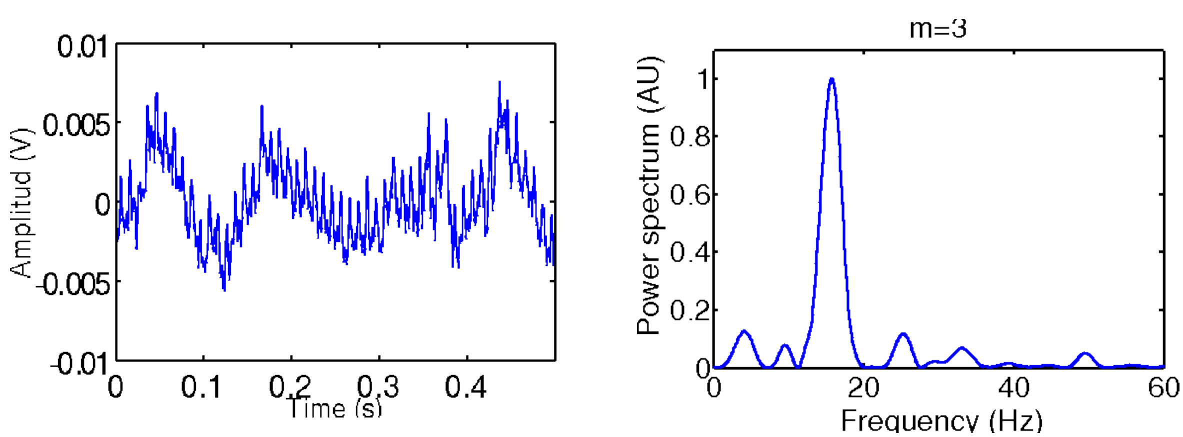

Fig. 3. Example processing of a input Doppler signal. Both the amplitude of the signal (left) and its power spectral density function (right) are shown. Detector return signal and their corresponding spectrum are a particle moving in a circular trajectory that is being illuminated by a LG beam with azimuthal mode *m=3*.