High Speed Measurement in Spectral Drill using Q-plate and Camera

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Abstract: We have proposed a method to scan resonance modes in a Fabry-Pérot cavity applying a geometric phase shifter, named as spectral drill. When the geometric phase shifter consists of two quarter wave plates and a half wave plate sandwiched by them is put into a cavity, the resonance modes can be scanned by the rotation of the half wave plate. Since a mechanical rotation stage has been used for scanning the cavity in our prior works, the scanning rate was limited by the rotational speed of the stage. In this work, by replacing the half wave plate to a q-plate with removing the mechanical stage and by taking transmission images by a camera, we succeeded in 720 times faster acquisition of the transmission spectrum of the spectral drill.

1 INTRODUCTION

Regular separation of resonance modes of a Fabry-Pérot (FP) cavity in the spectral region has been used as a spectral ruler and has been applied to a frequency marker for the fine spectroscopy and the essential principle of a frequency comb(Del'Haye et al., 2009). Since the frequency separation between the resonance modes depends on the cavity length d, the resonance frequency can be scanned by changing the cavity length. The maximum scanning frequency range in the FP cavity is restricted by physical limitations of the cavity mirror position or by the tunable range of physical properties defining the effective light path length within the cavity. For instance, one of cavity mirrors is supposed to be mounted on a piezo manipulator for scanning along optical axis. In such case, the scanning length is limited to only micron order. It may be enough length for visible light, but short for the IR range, in which the wavelength becomes longer than one micron. Other problem for piezo scanner is on its hysteresis. For the precise measurement, one has to take care about the reproducibility of the frequency axis because of a piezo hysteresis.

A geometric phase experienced by a light whose polarization state moves on a Poincaré's sphere is understood as the analogy of the Berry phase experienced by the wave-function of electron propagating in a vector field. The geometric phase of a light had been investigated by Puncharatnum in old days(Pancharatnam, 1956). As an application of the geometric phase of a light, a geometric phase shifter (GPS) consists of a simple series of phase plates has been also proposed by some groups for precise control of the optical phase(Yang et al., 2010) and the THz-wave phase(Kawada et al., 2016). Recently, the geometric phase has attracted many researches because the metasurface technology can control such geometric phase of a light by designing artificial structures(Huang et al., 2012).

We have previously reported an optical configuration named "*spectral drill*," in which a GPS is put into a FP cavity. In the spectral drill, the resonance frequency of the FP cavity can be swept continuously with seamless manner by rotating a phase plate consisting the GPS(Ohno, 2018). The motion of resonance modes moving on the spectral region with rotating the phase plate looks like apparent motion of grooves on a drill with the rotation. This behavior is responsible for the name of spectral drill. Since, in our previous system, the phase plate was mounted on an auto-rotational stage, the scanning speed of the resonance modes was limited by the rotational speed of the mechanical movement. In this paper, we propose a method to break this limitation by replacing a phase plate with a q-plate and using a camera.

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We believe this method will open new spectroscopic applications of a spectral drill.

2 SPECTRAL DISTRIBUTION

A GPS consists of the series of one quarter wave plate (QWP), a half wave plate (HWP), and another QWP. The fast axis of two QWPs are respectively tilting by $+/-45$ degrees from the polarization direction of an incident light. In a usual GPS setup, HWP can be rotated with mounting on a rotational stage(Yang et al., 2010; Kawada et al., 2016; Ohno, 2018). When the rotational angle of the HWP is α, the light experiences the geometric phase delay of 2α. Consequently, a GPS within a FP cavity makes the confined light get the phase delay of 4α per one round trip. In this case, the transmission intensity of the cavity can be given as (Ohno, 2018),

$$I/I_0 = \left[1 + \frac{4R}{(1-R)^2}\sin^2(kd+2\alpha)\right]^{-1}, \quad (1)$$

where, I_0, k, d, and R are the intensity and wavenumber of the incident light, the cavity length, and reflectance of the cavity mirrors, respectively. Note that we assumed all of the reflectance of the cavity mirrors are the same to be R. When the values of reflectance are different and/or the cavity has energy loss by some reasons, $1-R^2$ can be treated as the effective loss in a round trip within the cavity. Now, we consider to replace the HWP in the GPS with a q-plate. A q-plate is made of anisotropic molecules, like a liquid crystal or its polymerized material. It partially works as a HWP, but the fast axis is gradually rotated $m/2$ times around the center of the optics, and is usually used for generating an optical vortex beam with the topological charge of m(Marrucci, 2013; Sanchez-Lopez et al., 2018). When such GPS is introduced into the FP cavity, the transmission intensity distribution in the polar coordinates (r,θ), whose origin is set onto the center of the q-plate, can be derived through modifying Eq.(1) as,

$$I(r,\theta) = G(r)\cdot\left[1 + \frac{4R}{(1-R)^2}\sin^2(kd+2\alpha(\theta))\right]^{-1}, \quad (2)$$

where, $G(r)$ is the beam power distribution in radial direction. $\alpha(\theta)$ is the tilting angle of the fast axis at the partial area at the azimuthal position θ on the q-plate. In mth-order q-plate, the tilting of the fast axis is distributed as $\alpha(\theta) = \frac{m}{2}\theta$. This means that the resonance condition of $kd + m\theta = n\pi$ with an integer value n can be satisfied $2m$ times around the center of the q-plate. Hence, when we measure the transmission image around the optical axis of this system, we will observe $2m$ fringes in the azimuthal direction around the center.

3 EXPERIMENT

3.1 Experimental Setup

The experimental setup is depicted in Fig.1. A beam from a single mode external cavity diode laser (ECDL), wavelength of 1.55 μm, was incident to a FP cavity. In the front of the FP cavity, the beam was gradually diverged via a lens with a short focusing length of 5 cm. In the presenting spectral drill, a GPS consisting of two QWPs and a q-plate (Thorlabs, WPV10L-1550, m=1) between them was allocated within the cavity. Behind the cavity, the transmitted beam pattern was measured by an InGaAs camera, which has sensitivity for 1.55 μm. The spectral information can be measured without any mechanical rotation of the HWP, whereas, in our prior works, we have required a rotational stage for the HWP in order to sweep the geometric phase.

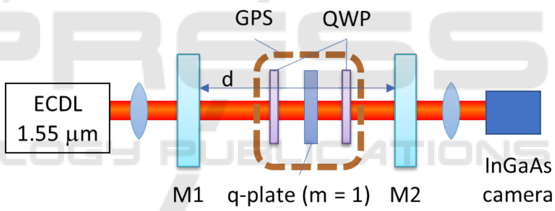

Figure 1: Experimental setup. A geometric phase shifter (GPS) using a q-plate is put within a FP cavity. GPS: geometric phase shifter, M1 and M2: cavity mirror, QWP: quarter wave plate, ECDL: external cavity diode laser.

3.2 Results

A measured image under the condition of the cavity length d of 3.2 cm is shown in Fig.2. A couple of bright arms are observed in the image and the trajectory of them draws spiral pattern from the center to the outer part of the image. These bright curves are respectively corresponding to the resonance of the cavity. The number of bright arms of two is just corresponding to our expected number of $2m$ since the value of m in the q-plate was unity. The spiral shape of the fringes is due to the slight longer cavity length at the outer side from the center part considering a gradually diverging beam within the cavity. Although it is not shown here, we have also confirmed the arms gradually rotate with increasing the wavelength or cavity length as expecting from Eq.(2).

Here, we estimate the frequency sensitivity of this system when one obtains the frequency change of a light source from the image. When $d = 3.2$ cm, the free spectral range (FSR) of the cavity is derived as 4.7 GHz. The angle of view for a bright area on a arm from the center position, denote with β, is obtained as around 20 degrees. Consequently, the sensitivity for the frequency change can be roughly estimated to $(\mathrm{FSR}) \cdot \beta/(2\pi/2m) = 0.5$ GHz.

In the presenting system, the acquisition rate of a spectral image was determined by the frame rate of the InGaAs camera of 60 Hz. In our prior spectral drill, we used an auto-rotational stage in order to rotate a HWP. Comparing with the rotational speed of the stage of 30 deg./sec., we considered that 720 times faster acquisition rate was achieved.

We consider that this acquisition time is sufficiently fast for feedback applications, for example we are expecting the frequency locking of a single mode laser within sub-GHz order frequency by performing image analysis to every acquired image. For more precise frequency locking, the improvement of q-value of a cavity or a long cavity length will be necessary.

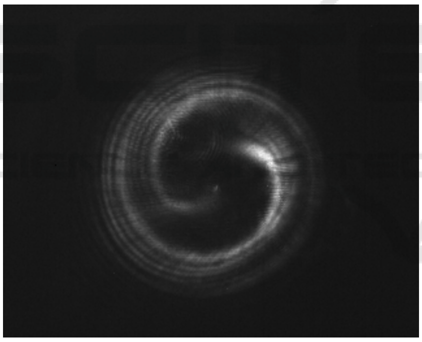

Figure 2: A measured transmission image when cavity length d = 3.2 cm.

4 CONCLUSIONS

In a spectral drill, we replaced a HWP on a rotational stage with a q-plate and took the FP spectral image using a camera for the high speed measurement. We succeeded in 720 time faster acquisition of the spectra than the prior spectral drill. It will open the new methodology to control the laser frequency and its applications.

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