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Further study of spectral ripple with a laser scattering measurement apparatus

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ABSTRACT

To study the spectral effect further, which exists in fold-type cavity ring-down or enhanced absorption spectrometer, a set of laser scattering measurement apparatus was presented and applied to evaluate the surface status of high-reflectivity coatings. Based on this apparatus and another set of optical-feedback cavity ring-down spectrometer with the equivalent noise absorption coefficient of 9.0×10^{-9} cm^{-1}, some experiments are carried out to inspect some analyses about the effect's mechanism. It is determined that the spectral ripple originates from the interference fringe's movement of resonance light beams along the surface of folding mirror, which causes the folding mirror's loss to change with the laser wavelength's scanning. Based on this conclusion, the potential application and the processing methods of spectral ripple are proposed and discussed.

1. Introduction

Optical-feedback cavity ring-down spectroscopy (OF-CRDS) is a novel and high-performance spectroscopic technique, and it was first proposed and demonstrated by D. Romanini and his partners in 1999 [1]. OF-CRDS often uses a V-shaped optical resonator as the absorption cell, and the optical-feedback from the folding mirror of absorption cavity is applied to increase the continuous-wave CRDS apparatus's performance in term of acquisition rate, dynamical range, precision and cost [2,3]. Especially in 2014, a new near-shot-noise limited technique called as optical feedback frequency stabilized cavity ring-down spectroscopy (OFFS-CRDS) was introduced [4], and it could achieve the absorption detection sensitivity of 5×10^{-13} cm^{-1} Hz$^{-1/2}$ with the kilohertz resolution. The optical-feedback effect of V-shaped cavity has also been applied in cavity enhanced absorption spectroscopy (CEAS), and the actual applications of optical-feedback CEAS (OF-CEAS) with different types of lasers have even been demonstrated [5–8]. In recent years, some other OF-CEAS techniques with other cavity structures, such as linear or ring cavity, have also been reported [9–11].

In the applications of OF-CRDS or OF-CEAS with a V-shaped optical resonator, a subtle effect called as the spectral ripple has even been described and studied [8,12–14]. For example, in mode-by-mode OF-CRDS apparatus with a symmetric cavity, this effect was observed as a doubling of the ring down spectrum, with data points lying alternatively on two parallel spectra, and it made the shot-to-shot variations of the ring down time 10–100 times larger than the standard deviation from the fit of a single ring down event [12]. In 2010, anther OF-CRDS scheme is applied to investigate this effect further. In which, the laser's resonance in fold-type cavity was realized by modulating the cavity's length, so its spectral resolution was no longer confined to the Free Spectral Range (FSR) of cavity [15], and could achieve ~0.003 cm^{-1} with the noise-equivalent absorption coefficient of 2.6×10^{-8} cm^{-1} Hz$^{-1/2}$. With this apparatus, the ripple's period was measured as about two times of FSR of V-shaped cavity, and its amplitude was previously known as mainly relating with the surface status of folding mirror. Unfortunately, some more intensive studies were not carried out for lacking the measurement means. To explore the induced mechanism of spectral ripple, various loss items of fold-type cavity have been analyzed and discussed, especially those loss items associated with the light distribution in the fold-type optical resonator. It is generally recognized that the resonance light field's variation on folding mirror, such as the node and the anti-node appear alternately with the spectral scanning, is the main reason for the spectral ripple, but these analyses have not been confirmed by some direct experiments as far as we know.

In this paper, to study the spectral ripple further, various contrast experiments are carried out with our developed OF-CRDS apparatus, and a set of laser scattering measurement device is built specifically to observe the surface state of mirrors [16]. Some analyses about the ripple effect will be inspected experimentally, and a simple model based on two-beam interference will be built and used to explore some applications with this effect.

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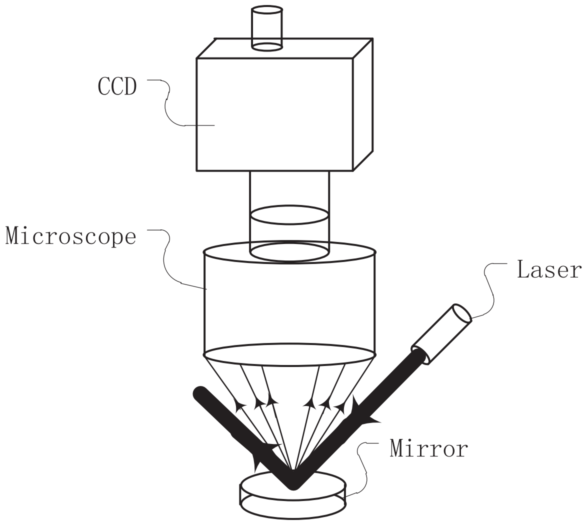

Fig. 1. The sketch of laser scattering measurement apparatus.

2. Experimental methodology

Previous experimental studies have preliminarily demonstrated some relations between the ripple effect and the surface state of folding mirror. In particular, it was found that the ripple phenomenon disappeared when the folding mirror was cleared, but some detailed studies about the corresponding relation between the surface status of folding mirror and some characteristics of ripple effect, such as its period and amplitude, were not investigated for the lack of some necessary means of measurement. Therefore, to study the spectral ripple further, an apparatus used to evaluate surface status of mirrors and a high-performance OF-CRDS system are essential.

As shown in Fig. 1, a simple digital measuring system is built based on the light scattering method. This apparatus takes a semiconductor laser (30 mW, 635 nm) as the light source, and its collimated laser with the diameter of ~ϕ10 mm irradiates the mirror's surface in a dark surrounding. The scatter light of mirror surface is then collected by a microscope with the magnification of about ×40, and its scatter image with the region of ~1.8×2.4 mm is then digitized by a CCD camera with the resolution of 12Bit. In this case, the laser's power distribution in ~1.8×2.4 mm can be considered as uniform. By means of this system, it is easy for us to obtain the particle pollution level of mirror' surface in OF-CRDS or OF-CEAS apparatus by analyzing its scatter images. Especially according to the light scatter theory, the average and variance value of the scattering image's gray can be used to describe the mirror surface's average scatter loss and its inhomogeneous performance, respectively.

OF-CRDS system used in this experiment is developed from our previous apparatus, as described in some literatures [14,15], it uses a V-shaped glass ceramic block with the ultra-low expansion coefficient as the optical resonator, and three high-reflectivity mirrors (R≈99.99% at 1548 nm) are fixed on its polished surfaces with the optical glue technique. This installation is beneficial to the replacement of the mirrors and keeping the laser's resonance status in V-shaped cavity. To reduce the influence of the strong absorption of water vapor in the atmosphere, 1568 nm DFB laser is used as the light source. During OF-CRDS measurement, V-shaped cavity's length is modulated by a PZT actuator to realize the laser's resonance, and the fast modulation of DFB laser's current achieves the laser's switch in the tens of nanoseconds. A near-infrared photo-detector (PDA400, Thorlabs) is applied to capture the decay transient signal; the signal is then digitized by a high-speed A/D card (CS320A, CleverScope) and fitted with a single exponential function in a computer. In the actual experiments, the typical decay time of V-shaped cavity at 6375.7 cm^{-1} is determined as ~9.72 μs. Combined with the cavity length of 491 mm, the single-pass loss of this cavity is calculated as ~171×10^{-6}, and five repeated measurements show that the standard deviation of measured CRDS data is ~0.27×10^{-6}. DFB laser's wavelength was tuned in the spectral range of 6375.7–6376.9 cm^{-1} by setting its temperature at 22.5 ℃ and scanning its current in the range of 20–80 mA, and V-shaped cavity's loss spectrum in this spectral region was then measured, the results show our OF-CRDS apparatus's equivalent noise absorption coefficient is ~9.0×10^{-9} cm^{-1}. In fact, it is found that there were still some weak periodic noises in the measured results after these OF-CRDS data were analyzed.

3. Experimental results

In the uncontaminated conditions, the typical CRDS or OF-CRDS of V-shaped cavity is smooth curve as shown in the under-line of Fig. 2 (right), in which, an obvious absorption line-shape can be observed, and it may be the absorption spectral line of water vapor at 6376.1319 cm^{-1} with the intensity of 4.196×10^{-26} cm^{-1}/(molecule×cm^{-2}) according to the Hitran databases [17]. To observe a clear ripple phenomenon, the folding mirror was first removed from V-shaped cavity and exposed in dry weather conditions for a period of time, and its surface absorbed some of the dust in the atmosphere. The contaminated surface of the folding mirror was then placed under the light scattering measurement apparatus, and its scattering photo observed by a microscope was taken by CCD as shown in Fig. 2 (left). It is found that the coating surface of the folding mirror has been polluted by some small particle, and their size can be calculated on the order of microns. Furthermore, the gray's mean and standard deviation value of scattering image are calculated as 1.05 and 11.89, respectively. After re-adjusted and fixed the contaminated folding mirror on V-

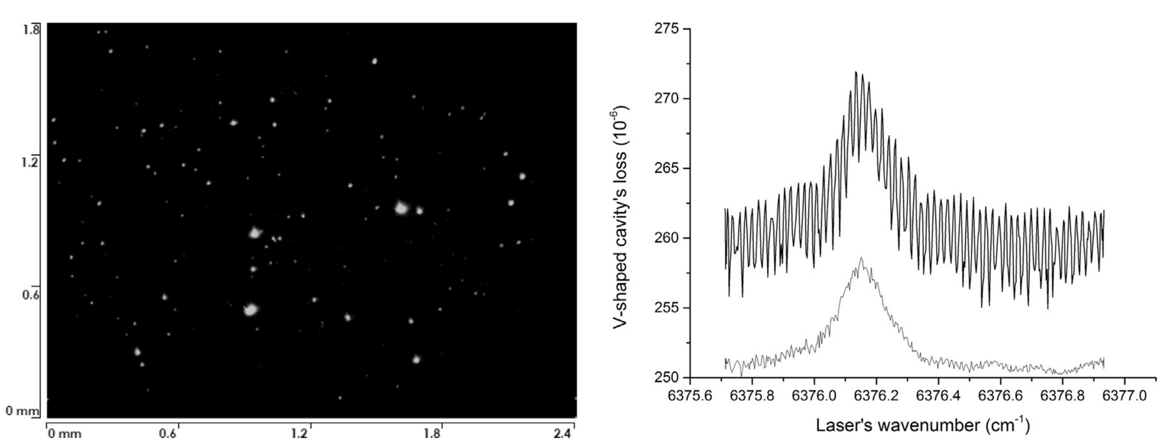

Fig. 2. Light scatter image of slight polluted folding mirror (left) and measured CRDS curves in this case (right).