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Measurement of frequency sweep nonlinearity using atomic absorption spectroscopy

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A B S T R A C T

A novel scheme to determine frequency sweep nonlinearity using atomic saturated absorption spectroscopy is proposed and demonstrated. The frequency modulation rate is determined by directly measuring the interference fringe number and the frequency gap between two atomic transition peaks of rubidium atom. An experimental setup is established, and test results show that the frequency sweep nonlinearity is ~10%, with an average frequency modulation rate of ~1.12 THz/s. Moreover, the absolute optical frequency and optical path difference between two laser beams are simultaneously determined with this method. This low-cost technique can be used for optical frequency sweep nonlinearity correction and real-time frequency monitor.

1. Introduction

Diode lasers are widely used in scientific and civil fields ranging from wireless communication [1,2] , inverse synthetic aperture lidar detection [3,4], to atomic experiment [5–7]. However, during the frequency sweep process, undesirable nonlinearity occurs and results in significant measurement errors [8,9]. Therefore, precise measurement and feedback control of frequency sweep nonlinearity is quite important for high-precision applications.

Self-heterodyne interferometry is often used to measure frequency sweep nonlinearity [10–12]. However, radio frequency signals along with optical modulator and long fiber delay line are needed. On the other hand, wavelength meters, Fabry–Pérot etalon (FPE) or frequency comb can be used to monitor the laser frequency and measure the sweep rate of the diode laser [13–16], but the tuning of the laser must be much larger than the free spectral range of the FPE and only gives frequency information at discrete intervals. Another method uses an environmentally isolated reference interferometer to actively correct the frequency sweep nonlinearity [17–19]. Nonlinearity can also be compensated by externally triggering time domain sampling or using post-processed resampling algorithms [20,21]. However, all these measurement methods need expensive and complicated frequency reference, which limits potential application in low-cost fields.

For high-precision applications, tunable diode lasers are usually frequency locked using atomic saturated absorption spectroscopy (SAS) technique [22], which has excellent frequency stability and accuracy. In this paper, we propose and demonstrate a novel and low-cost scheme for the measurement of frequency sweep nonlinearity based on the SAS technique. This scheme has several advantages. First, this measurement can be accomplished with conventional laboratory equipment, and does not rely on expensive and bulky wavelength measurement devices to monitor the frequency, thus greatly reducing system complexity and cost. Moreover, this method enables simultaneous determination of frequency sweep rate, absolute optical frequency, and optical path difference (OPD) between two beams for one single measurement. This simple technique has potential application in fields such as frequency sweep nonlinearity correction and real-time optical frequency monitor.

2. Measurement principle

For simplicity, the period of the triangular-wave signal used to modulate the laser frequency is defined as $2T_m$. Each period is divided into two parts, the rising period and the falling period, as shown in Fig. 1. The solid curve in upper trace represents the frequency of the signal wave, the dashed curve stands for the frequency of the reference wave, the middle trace is atomic saturated absorption spectroscopy signal, and the solid curve in lower trace corresponds to the periodic beat signals. When the reference wave and the signal wave interfere, the beat signal can be written as [23]

$$I(t) = I_0\left[1 + \eta \cos\left(2\pi\alpha\tau t + 2\pi\nu_0\tau - \pi\alpha\tau^2\right)\right], \tag{1}$$

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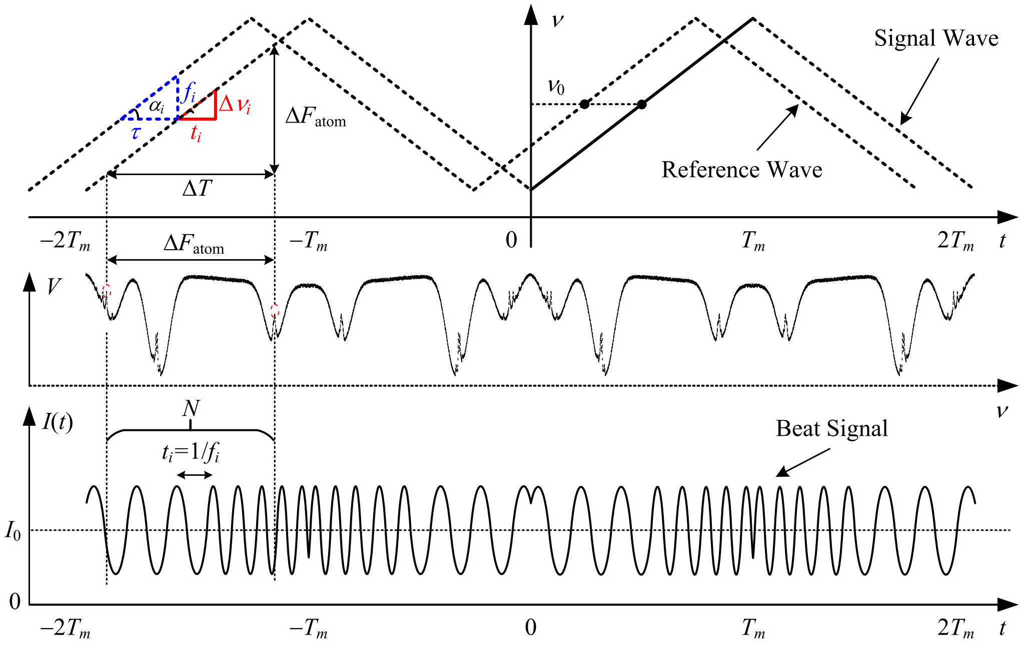

Fig. 1. (Color online). Measurement principle of the laser system: upper trace—scanning waves; middle trace—atomic SAS signal of rubidium atom, where V is the measured voltage and ν the absolute optical frequency; lower trace—beat signals.

where I_0 is the average optical intensity of the beat signal; η the interference fringe contrast; t the sweep time; α the frequency modulation rate; τ the group time delay given by $\tau = L/c$, where L is the OPD and c is the speed of light; and ν_0 the average optical frequency during the frequency sweep process. The first term in bracket of Eq. (1) represents the beat signal with the beat frequency of $\alpha\tau$, while the last two terms in bracket of Eq. (1) contribute to systematic measurement errors.

The beat frequency of the ith interference fringe can be written as

$$f_i = \alpha_i \times \tau \ \ (i = 1, 2, \ldots, N), \tag{2}$$

where N is the fringe number, $\Delta T (\Delta T < T_m)$ the sweep time corresponding to two transition peaks in Fig. 1, and α_i the frequency modulation rate during time interval t_i. If N is large enough, it is reasonable to assume that the modulation rate is constant for each time interval t_i with the relation $\sum_{i=1}^{i=N} t_i = \Delta T$. On the other hand, for each time interval t_i, the optical frequency increases by $\Delta\nu_i = \alpha_i \times t_i$. By adding each minor frequency increment during ΔT yields $\sum_{i=1}^{i=N} \Delta\nu_i = \Delta F_{atom}$, where ΔF_{atom} is the fixed frequency gap of the two transition peaks of alkali atoms. Note that for certain atoms, ΔF_{atom} is a constant value and can be precisely known. This typical value is on the order of GHz and immune to environmental perturbations.

The fringe number N of the beat signal is measured with peak finding algorithms, and each beat frequency can be determined using the atomic peak location related scanned time. Consequently, the frequency modulation rate and absolute optical frequency can be calculated as:

$$\begin{aligned} \alpha_i &= f_i \times \Delta F_{atom}/N \\ \nu_i &= \nu_0 + i \times \Delta F_{atom}/N. \end{aligned} \tag{3}$$

Furthermore, the delay time and OPD can also be determined as follows:

$$\begin{aligned} \tau &= N/\Delta F_{atom} \\ L &= cN/\Delta F_{atom}. \end{aligned} \tag{4}$$

The spatial OPD resolution is $\Delta L = c/\Delta F_{atom}$, consistent with that reported in [21]. As can be seen from Eqs. (3) and (4), measurement resolution of the modulation rate and absolute optical frequency is inversely proportional to the fiber delay length (fringe number), while resolution of the OPD is constant regardless of the fiber delay length. Therefore, when measuring the modulation rate and absolute optical frequency, a shorter fiber length is preferred in low-precision and small-size applications and vice versa. To further increase the OPD resolution, larger scanned frequency range is a good option. For experimental plans aim at OPD determination, fiber length of several meters long is enough to achieve ~ cm resolution.

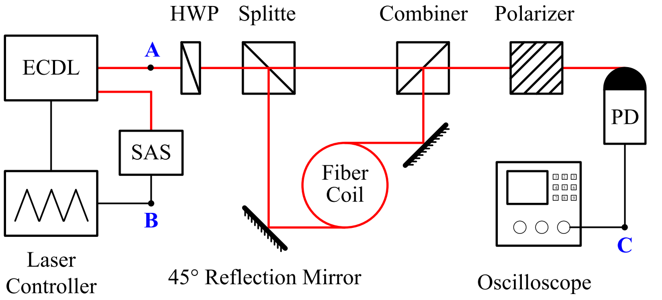

Fig. 2. (Color online). Schematic of experimental apparatus: red line—optical signal; black line—electronic signal. The points B, and C represent measurement locations of atomic SAS signal and beat signal respectively, while frequency modulation rate and absolute optical frequency at point A are calculated based on measured data at points B and C.

3. Experimental setup and results

According to the measurement principle described in Section 2, schematic of the experimental apparatus is depicted in Fig. 2 to measure the frequency sweep nonlinearity. The tunable laser is an external cavity diode laser (ECDL, Toptica DL Pro) operating at 780.24 nm, which corresponds to resonant transitions of rubidium (Rb) atom. In principle, any two of the transition peaks can be used as an absolute frequency reference, and two transitions of $5S_{1/2}F = 2 \rightarrow 5P_{3/2}F' = 2, 3$ crossover and $5S_{1/2}F = 2 \rightarrow 5P_{3/2}F' = 3$ (the scanned frequency range ΔF_{atom} is 4.235 GHz) is used in this experiment, where F and F' denote the ground state and excited state, respectively. The laser frequency is modulated with a triangular wave by driving the piezoelectric transducer (PZT) with a repetition rate of 100 Hz and a peak-to-peak sweep voltage of 13 V, corresponding to an overall scanned frequency range of 5.666 GHz.