Faraday laser at Rb 1529 nm transition for optical communication systems

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We experimentally demonstrate a Faraday laser at Rb 1529 nm transition by using a performance-improved Rb electrodeless-discharge-lamp-based excited-state Faraday anomalous dispersion optical filter as the frequency-selective element. Neither the electrical locking scheme nor the additional frequency-stabilized pump laser are used. The frequency of the external-cavity diode laser is stabilized to the Rb 1529 nm transition, and the Allan deviation of the Faraday laser is measured by converting the optical intensity into frequency. The Faraday laser can be used as a frequency standard in the telecom C band for further research on metrology, microwave photonics, and optical communication systems.

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External-cavity diode lasers (ECDLs) are increasingly popular in fundamental research and practical applications due to their compactness and reliability[1]. In an extremely broad range of applications of laser spectroscopic measurements and metrology[2], both the frequency-stabilized lasers and frequency stabilization with long-term stability are essential[3,4]. In particular, laser frequency-stabilization techniques at the telecommunication wavelengths have been extensively investigated, and much effort is presently devoted toward the realization of practical laser frequency standards in the telecommunication region (1528–1563 nm) for the field of multi-wavelength optical communications[5,6].

However, in conventional 1529 nm optical frequency standards, the method of utilizing an optically pumped Rb vapor cell, which exhibits resonances at 1529 nm, made the whole system costly, bulky, and complex[7–10]. Moreover, electrical locking schemes are usually implemented to stabilize a diode laser by using methods of atomic or molecular absorption line[11], including frequency-modulation spectroscopy[12], polarization spectroscopy[13], modulation transfer spectrum[14], etc. For example, in the Pound–Drever–Hall technology, either the resonator or the laser frequency must be modulated to generate an error signal for feedback to the laser current and/or its temperature[15]. The laser should be compatible for fast enough actuation to achieve efficient feedback. While this is a robust and widely used technique, it is not to be ignored that the feedback circuit frequently generates noise peaks in the frequency spectrum of the locked laser. Therefore, it is highly desirable to devise an approach where excited-state frequency standards do not depend on a frequency-stabilized laser as well as electrical locking. One promising solution to this problem is to use an Rb electrodeless discharge lamp (EDL)-based excited-state Faraday anomalous dispersion optical filter (LESFADOF)[16,17] to limit the laser frequency to Rb 1529 nm transition.

Since Faraday anomalous dispersion optical filter (FADOF) technology was introduced in 1956[18], different kinds of applications of FADOF have been carried out for its advantages of high transmission, ultra-narrow bandwidth, and high noise rejection[18–23], such as laser communications[24], remote sensing[25], lidar systems[26], and Faraday laser[27–30]. So far, FADOFs operating on a variety of wavelengths in the ultraviolet, visible, and near-infrared have been reported[31–33]. Although both the original Rb LESFADOF operating on the Rb $5P_{3/2} - 4D_{5/2}$ transition (1529.4 nm in a vacuum) without an additional frequency-stabilized pump laser[17] and the Faraday laser lasing on 780 nm ground-state transition have been previously reported[27], unfortunately, the excited-state Faraday laser has never been realized due to the low transmittance of the LESFADOF.

In the present work, we combined an ECDL and a performance-improved LESFADOF into a portable LESFADOF-based Faraday laser at Rb 1529 nm transition. The narrower bandwidth and higher transmission provided a better locking signal, and, therefore, the Faraday laser can be stabilized to a higher precision. With the help of Faraday anomalous dispersion effects[18], we presented a nonlinear LESFADOF with higher transmission than that previously reported[17]. A cavity mirror provided optical feedback with a free spectrum range (FSR) of 300 MHz; hence, the LESFADOF successfully limited the laser frequency to the excited-state $5P_{3/2} - 4D_{5/2}$ of the Rb 1529 nm transition. The improved peak transmission corresponding to the transition in the LESFADOF was 46% with a filter bandwidth of 600 MHz. The Allan deviation of the Faraday laser was about 3×10^{-9} at 100 s.

Furthermore, a new type of Faraday laser was also realized by utilizing an antireflection-coated laser diode (ARLD)[34], and the measured results proved that the wavelength of the Faraday laser was stabilized to Rb 1529 nm transition during a period of 24 h with an Allan deviation of 1×10^{-7} at 10,000 s. The Faraday laser at Rb 1529 nm transition would be widely used in metrology, microwave photonics, and the optical communication field[5,6].

The Faraday laser setup is schematically shown in Fig. 1(a). The length of the external cavity of the Faraday laser is 60 cm (and, hence, the FSR is 300 MHz). The laser beam emitted from a 1529 grating ECDL is sent into the LESFADOF, which is composed by a pair of Glan–Taylor prisms (G1 and G2) with an extinction ratio of 1×10^{-5}, a pair of permanent magnets (M1 and M2) supplying static axial magnetic field of 500 G, and an EDL with a radio-frequency (RF) amplifier; the vapor cell of the EDL is 3 cm long and contains natural Rb and 2 Torr Xe buffer gas. Electrons and ions in the vapor cell are accelerated when the RF power (250 MHz) is turned on[16,17], where due to the collision of the buffer gas, more electrons and ions are generated simultaneously. Therefore, the Rb atoms are pumped from the $5S$ ground state to the $5P$ excited state by high-energy-state buffer gas atoms. The laser frequency is scanned across the $5P_{3/2} - 4D_{5/2}$ transition [1529.4 nm in vacuum; see Fig. 1(b)] by using a piezoceramic actuator. Rc is a coated mirror with reflectivity of 80% and the transmission of 20% for the 1529 nm laser. The laser beam is polarized by the Glan–Taylor polarizer and turned into the linearly polarized light before going through the EDL in a static axial magnetic field of 500 G. Then, it goes through G2 before finally being received by the photodetector (PD). When the polarizing direction of G1 and G2 is parallel, the absorption spectrum is detected; however, the transmission spectrum is detected when the polarizing direction of G1 and G2 is orthogonal.

The measured transmission spectrums of the LESFADOF with different cell temperatures are depicted in Fig. 2.

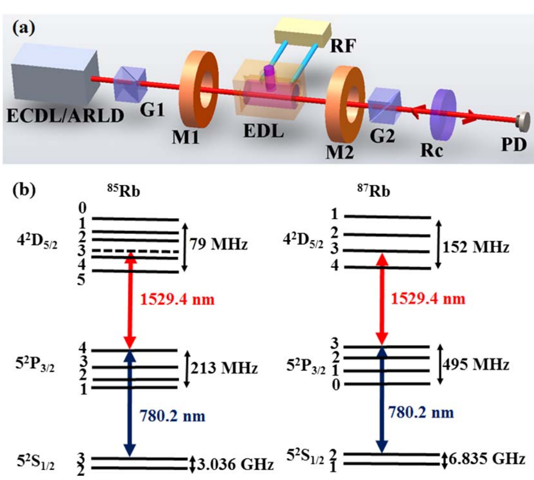

Fig. 1. (a) Experimental setup of the two types of Faraday laser. (b) Relevant energy level diagram.

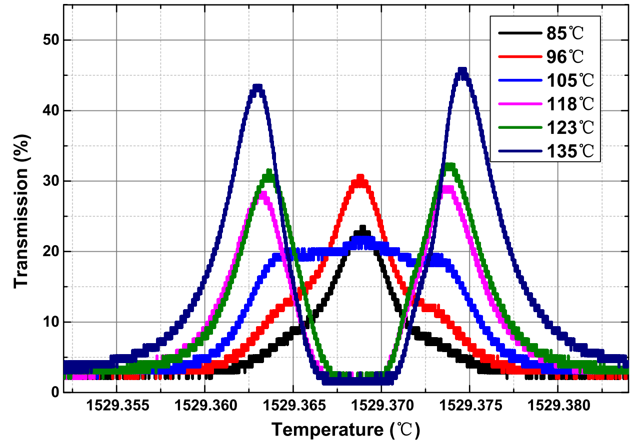

Fig. 2. (Color online) Measured transmission spectrums of the LESFADOF with different cell temperatures in a static axial magnetic field of 500 G.

With the cell temperatures of 85°C, 96°C, 105°C, 118°C, 123°C, and 135°C, the transmittance of the LESFADOF is 22%, 31%, 21%, 28%, 33%, and 46%, respectively. The lineshape of the transmission spectrum varies with the changes of the cell temperature in a static axial magnetic field of 500 G.

The measured absorption spectrum of the LESFADOF is shown in Fig. 3(a). In order to certify the scheme of the Faraday laser when the temperature of the vapor cell is 135°C, hence, the transmittance of the transmission

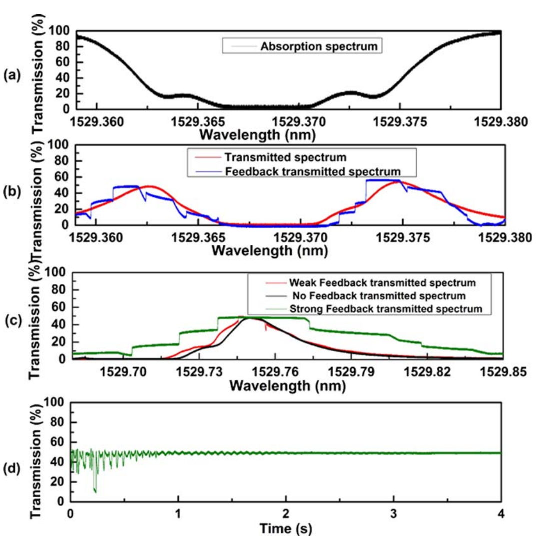

Fig. 3. (Color online) (a) Measured absorption spectrum of the LESFADOF. (b) The measured transmission spectrum (black curve) of the LESFADOF with transmittance of 46% and the measured transmission spectrum (red curve) with strong optical feedback by Rc. (c) The measured transmission spectrum with maximum transmittance of 46% of the LESFADOF with no optical feedback (black curve), weak optical feedback (red curve), and strong optical feedback (green curve) by Rc. (d) The optical signal of the laser frequency being stabilized to the peak of the transmission spectrum detected by a PD when the optical bread board is beaten.

spectrum is 46%, and the light transmitted from the LESFADOF is fed back into the ECDL by adjusting cavity mirror Rc. Therefore, the transmission spectrum of the LESFADOF with optical feedback is measured, as shown in Fig. 3(b) (blue curve), and the transmission spectrum of the LESFADOF without optical feedback is shown in Fig. 3(b) (red curve). The transmission spectrums with different feedback intensities are measured mainly by adjusting cavity mirror Rc. Figure 3(c) shows the measured transmission spectrums with maximum transmittance of 46% of the LESFADOF with no optical feedback (black curve), weak optical feedback (red curve), and strong optical feedback (green curve), respectively. The ladder-type transmission spectrum (green curve) is measured when the cavity mirror Rc provides strong optical feedback. The optical signal of the Faraday laser with the frequency not being scanned by a piezoceramic actuator detected by a PD with strong optical feedback is shown in Fig. 3(d). The amplitude of the signal is equal to the peak of the transmission spectrum with a maximum transmittance of 46% of the LESFADOF, and it is proved that the frequency of the Faraday laser is absolutely stabilized to the excited-state $5P_{3/2} - 4D_{5/2}$ of the Rb 1529 nm transition. The fluctuations of the signal result from the vibration of the optical bread board due to the beating, which illustrates that the frequency of the Faraday laser is stabilized to the Rb 1529 nm transition.

In order to measure the Allan deviation of the Faraday laser, we assume that the lineshape of the Doppler transmission spectrum is the Lorenz lineshape[35],

$$I = \frac{(\Gamma/2)^2}{(\Gamma/2)^2 + \Delta^2}, \tag{1}$$

where Δ is the frequency detuning, Γ is the linewidth of the transmission spectrum, and I is optical intensity. Equation (2) is the differentiation of Eq. (1), hence, Eq. (7) is derived by using Eqs. (3)–(5) at the condition of Eq. (6):

$$\delta I = \frac{-(\Gamma/2)^2 2\Delta\delta\Delta}{(\Gamma/2)^4 + 2(\Gamma/2)^2\Delta^2 + \Delta^4}, \tag{2}$$

$$\Delta^2 \to 0, \tag{3}$$

$$\Delta^4 \to 0, \tag{4}$$

$$2\Delta \approx \delta\Delta, \tag{5}$$

$$\Delta \to 0, \tag{6}$$

$$\delta I = \frac{-(\delta\Delta)^2}{(\Gamma/2)^2}, \tag{7}$$

$$\delta\Delta = \left(\frac{\Gamma}{2}\right)^2 \times \sqrt{|\delta I|}. \tag{8}$$

Therefore, the approximate differential equation between optical intensity and frequency of the Faraday laser can be described by Eq. (8) derived from Eq. (1) by using decomposition and calculating the differential. Consequently, Eq. (8) is valid for the condition of Eq. (6). Hence, we obtain the frequency stability by converting the output voltage signal into laser frequency. The self-evaluated Allan deviation of the frequency stability of the Faraday laser realized by the ECDL is shown in Fig. 4. The Allan deviation of the frequency stability of the Faraday laser is about 3×10^{-9} at 100 s. One option for improving the frequency stability is to use an optical fiber to increase the length of the cavity[29].

In addition, a new type of Faraday laser is realized by using the ARLD (Toptica LD-1550-0050-AR-2) instead of the ECDL, as shown in Fig. 1(a)[34]. The Rb LESFADOF is the key element of the Faraday laser. The principle of how the LESFADOF works is very similar to a conventional FADOF[18]. The laser beam is polarized by the Glan–Taylor polarizer and turned into linearly polarized light before going through the EDL in a static magnetic field of 500 G. Due to the Faraday anomalous dispersion effect, the light with frequency corresponding to the transition spectrum of the LESFADOF is transmitted when the polarizing direction of G1 and G2 is orthogonal. Consequently, the light emitted from the ARLD (Toptica LD-1550-0050-AR-2) is filtered by the LESFADOF and fed back into the ARLD by cavity mirror Rc. We carried out a set of frequency measurement experiments continuously during a period of 24 h by using a PD and a digital multimeter (Agilent 34401A) to measure the long-term frequency stability of the Faraday laser. The measured optical intensity fluctuations of the Faraday laser realized by the ARLD during 24 h and the self-evaluated Allan deviation of the frequency stability of the Faraday laser realized by the ARLD are shown in Fig. 5. Therefore, it is proved that the laser frequency is stabilized in the center of the Rb 1529 nm transition for a long time.

In conclusion, we develop two types of proof-of-principle Faraday lasers with intrinsic atomic feedback, reducing the need for external optics and expertise that is usually required to frequency-stabilize an ECDL operating on the excited-state $5P_{3/2} - 4D_{5/2}$ of the Rb 1529 nm transition[7–10]. With the current design, both the Faraday

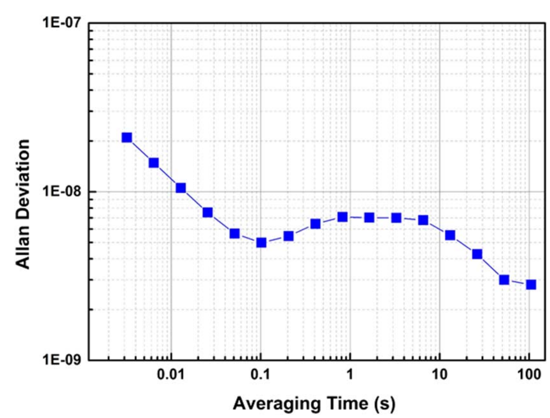

Fig. 4. Self-evaluated Allan deviation of the frequency stability of the Faraday laser realized by the ECDL.

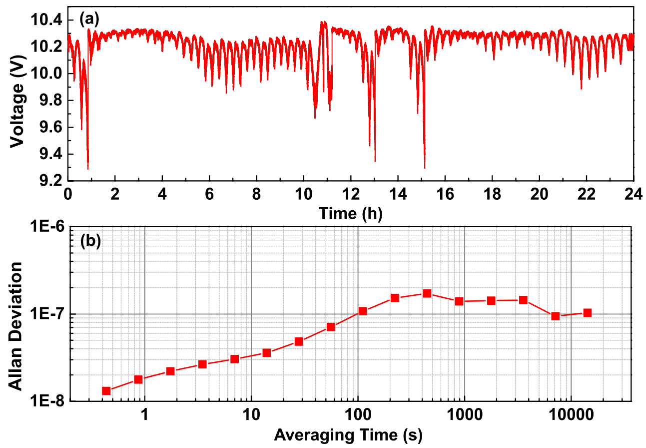

Fig. 5. (a) Measured optical intensity fluctuations of the Faraday laser realized by the ARLD during 24 h. (b) The self-evaluated Allan deviation of the frequency stability of the Faraday laser realized by the ARLD.

laser by using ECDL and the Faraday laser by using ARLD[34] are achieved. Although the two types of Faraday lasers have different performance, both of them integrated with reflection-coated fiber as an extended optical cavity have the potential for substantial reduction of frequency fluctuations[29]. The Faraday laser is appreciated for its frequency, corresponding to the Rb atom excited-state 1529 nm transition, while it utilizes an EDL instead of a frequency-stabilized laser as a prerequisite to prepare Rb atoms from the 5S to the 5P excited state. Hence, the light emitted from the Faraday laser can be used for further research on metrology, microwave photonics, and optical communication systems[36,37]. In addition, this method does not employ any electrical locking schemes, thus, it is small in size and greatly low in complexity. Furthermore, due to the extraordinarily rich spectra of the EDL[38], this scheme provides a highly innovative approach for laser frequency stabilization. Similar high-transmission Faraday filters can be engineered for alternate operating wavelengths for the other alkaline-earth metal atoms[30], so, in principle, this type of design is generally applicable to all alkaline-earth elements. Moreover, the successful development of the LESFADOF-based Faraday laser predicts potential possibilities for the implementation of a Faraday laser based on a hollow-cathode-lamp-based FADOF[32]. Therefore, this scheme can greatly expand the application of other wavelengths corresponding to atomic transitions of about 70 kinds of elements, including high melting point metals[32].

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