A Power Efficient Faraday Laser at 780nm Rb Transition

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***Summary*—we report on the development of a power efficient Faraday laser working at 780nm Rb transition using an atomic vapor Faraday filter as a frequency-selecting element. In the routine linear-cavity of Faraday laser, a partial reflectivity cavity mirror was used as output coupler. In this work, a high-reflection mirror (R>99.98%) replaces the partial reflectivity cavity mirror, the transmitted light of the Faraday optical filter is fully used as feedback beam and for frequency selection, while the light with polarization perpendicular to the transmitted part from the second polarizing beam splitter (PBS2) of Faraday anomalous dispersion optical filter (FADOF) is output. Single frequency laser is obtained at 780 nm Rb transition over a range of laser diode (LD) current from 60 to 140 mA. Such a single-frequency laser will be an excellent optical frequency standard by frequency stabilization technique.**

***Keywords*—Faraday anomalous dispersion optical filter (FADOF); faraday Laser; single-longitudinal-mode.**

I. INTRODUCTION

Stable external-cavity diode laser (ECDL) with narrow linewidth is getting more important for atomic physics experiments [1,2]. Common ECDL using a diffraction gratings for wavelength selection requires precise alignment and is sensitive to acoustic and mechanical disturbances [3,4]. Another way to reach the desired laser is to use a narrowband interference filter (IF) placed in a linear cavity as a frequency-selective component [5,6], but mode hopping is still easy to occur and wavelength drifts is serious because of 0.45 nm filter bandwidth. The faraday laser [7,8,9] using Faraday anomalous dispersion optical filter (FADOF) as mode-selection element is immune to the current and temperature fluctuation of laser diode, the frequency long term stability (<1MHz) was proved in reference [10]. In addition, a cesium Faraday laser utilizing modulation transfer spectroscopy for suppressing frequency drifts has been realized, frequency stabilization of which can reach 10^{-15} orders of magnitude at short term and long term [11].

The transmission bandwidth of FADOF is generally in the order of GHz, it is very suitable to select the lasing mode in the resonator. However, its transmittance is very difficult to reach 100% in most cases, that is, the part of the light is lost, which reduces the laser output power and results in multiple light outlets. In references [9,10], cavity mirror with the partial reflectivity（80% and 90%）served as output coupler, not only was the light exit from the partial reflectivity cavity mirror, but the light lost by the atomic filter would be output from the reflection port of the second polarization element. If the light reflected by the second polarization element is used as output and the transmitted light as feedback for frequency selection, the output power of the laser will be increased and the structure will be optimized. In principle, the FADOF parameters will affect both the laser frequency and the output coupling efficiency.

In this work, we demonstrate an extended cavity Faraday laser system consists of the antireflection-coated laser diode (ARLD), an aspheric collimating lens, FADOF and high-reflection mirror. The second polarizing beam splitter (PBS2) in FADOF acts as an output coupler, single-frequency laser is achieved by adjusting the temperature of the atomic cell. Under the anomalous Faraday effect of atomic vapor in axial magnetic field, if the rotation angle of polarization direction of the exit light from atomic vapor is not equal to 90° relative to the incident light, the transmitted light of the filter can be used for feedback and frequency selection, the loss light is reflected by PBS2 as the output of the laser.

II. EXPERIMENTAL SETUP

The experimental setup of the FADOF transmitted spectra measurement in Fig. 1(a). A 780 nm external cavity diode laser (ECDL) can be tuned to cover all of the Rb $5^2S_{1/2} \rightarrow 5^2P_{3/2}$ transitions. The laser beam is divided into two parts by BS1. One is used for saturated absorption spectrum (SAS) and the other as a probe laser. The saturated absorption spectra of a natural Rb cell is detected by PD2 and the transmitted spectrum of a natural Rb FADOF is detected by PD1. The shape of the Rb cell in FADOF and in SAS is a cylinder with diameter of 15 mm and length of 30 mm. PBS 1 and PBS 2 are a pair of crossed polarizers with an extinction ratio of 3×10^{-3}. The temperature of the Rb cell in FADOF are controlled by a home-made temperature controller with precision of 0.01℃. The magnetic field is produced by four pieces of permanent magnets, the static axial magnetic strength of which is 300 G with the inhomogeneity of the magnetic field of less than 7%. The transmission T of FADOF is defined as the intensity of light transmitted through the second polarizer PBS2 (I_x) divided by the initial intensity PBS1 (I_0) before the cell. Light out of the passband frequency is rejected at the second polarizer.

Fig. 1(b) shows schematic of the extended cavity Faraday laser. The light emitted from the 780 nm ARLD (Eagleyard EYP-RWL-0780- 02000-1300-SOT12-0000) is collimated by an aspheric collimating lens with focus of 4.51mm and NA of 0.55. The collimating beam is sent through the first polarizing beam splitter (PBS1), then the polarization of the light after passing through the vapor cell is changed. The transmitted light is reflected by HR-Mirror with reflectivity of 99.98% and fed back to ARLD, while the light reflected by BPS2 is used as output. The optical cavity length of the Faraday laser is about 20 cm, which has a free spectrum range of 750MHz. The transmission bandwidth of FADOF is generally in the order of GHz, so a single-frequency operation is expected. By adjusting the filter temperature parameter, the feedback ratio of laser can be modulated to achieve the optimal laser output.

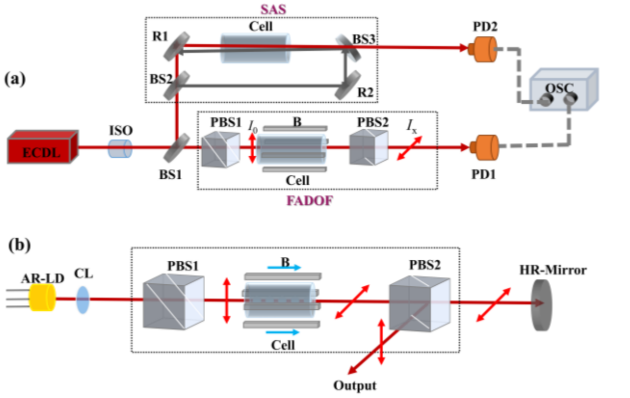

Fig. 1. (a) Schematics of the FADOF transmitted spectra measurement. ECDL, 780 nm external cavity diode laser; ISO, isolator; BS, beam splitter; PBS1 and PBS2, a pair of polarizing beam splitter; R, 45°high-reflection mirror for 780 nm; PD, photodetector; OSC, oscilloscope. (b) Schematic of the extended cavity Faraday laser. ARLD, anti-reflection coated laser diode; CL, collimating lens; HR-Mirror, 0°high-reflection mirror for 780 nm.

III. RESULTS AND DISCUSSION

Theoretical work on atomic filters has been extensively reported [11,12], and the corresponding computational software (ElecSus) is available [13,14]. All studies show that the filter transmission spectrum is related to magnetic field intensity, cell length, and temperature. However, it has been found in recent years that the incident light intensity also has a great influence on the transmittance of the filter [15]. When the filter is put into the cavity as a frequency-selecting element, the intra-cavity intensity will gradually be stronger with the increase of bias current, which means that the transmittance of the filter is not constant. Under the condition of constant magnetic field intensity and cell length, the influence of cell temperature and incident light intensity on the transmittance of atomic filter was investigated experimentally, as shown in Figure 2. Since the laser spot is difficult to estimate accurately, we directly replace the incident light intensity with the incident power entering into the atomic filter. Moreover, the collimation spot size in Faraday laser is almost equal to the incident spot (1mm*2mm) in the FADOF transmitted spectra measurement. When the incident light power was 1mW, 3mW and 10mW, respectively, the transmission rises with the temperature increasing at first. Around 85°C, the transmission achieves a maximum. Then, the transmission drops with the temperature increasing. The maximum transmittance of the atomic filter is as high as 90% at 3mW. The temperature at the maximum transmission peak of the FADOF is slightly different under different incident light intensity. In the case of laser resonance, changing the filter temperature is actually adjusting the laser feedback ratio and effective coupling output efficiency. It should be noted that the transmittance of the FADOF here includes the optical loss of the cell windows which is not coated in the inner surfaces.

At the same temperature, the transmittance of the FADOF with different incident light power is compared. Figure 3

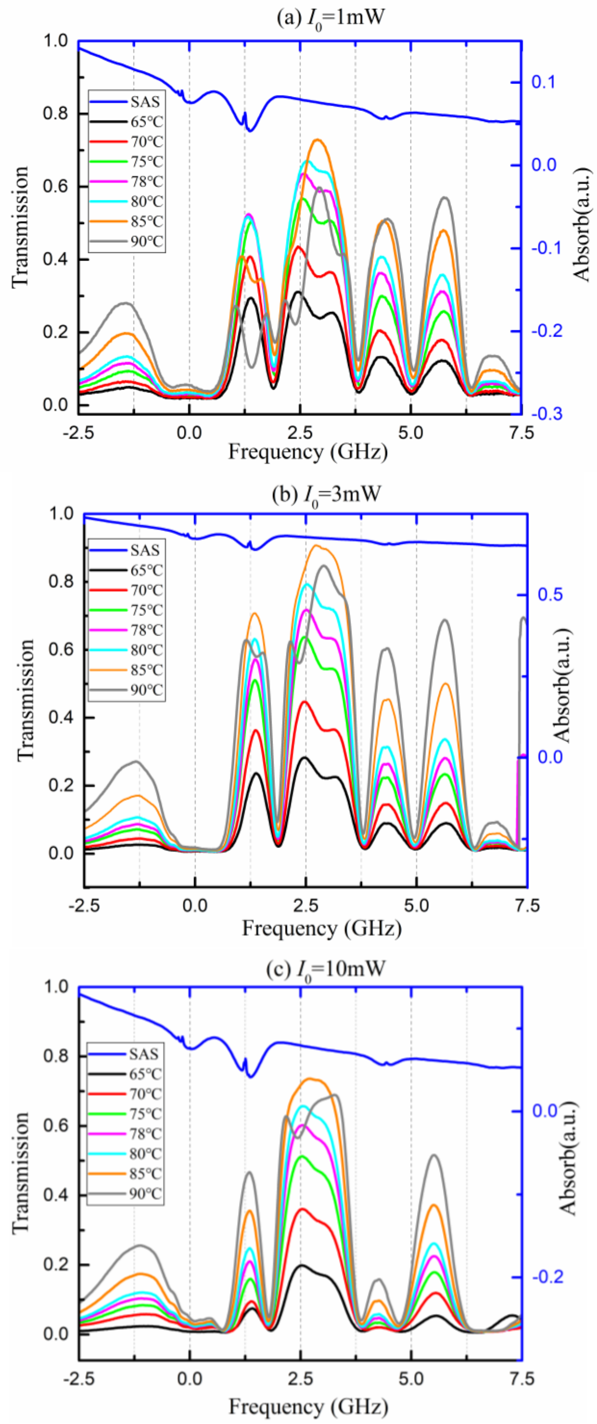

Fig.2. Transmitted spectra of the naturally abundant Rb FADOF at temperatures of 65 °C,70 °C ,75 °C,78 °C, 80 °C,85 °C and 90 °C in different incident powers in the line-center mode.(a) 1mW, (b) 3mW, (c) 5mW. The reference position $\nu = 0$ corresponds to 87Rb 52S1/2 F=2 → 52P3/2 F=3 transition frequency.

shows the transmitted spectra with 1mW, 3mW and 5mW at 78 °C. The nonlinear relation between transmittance and incident light intensity is clearly shown and the transmittance difference is about 10%. If the incident light intensity continues to increase, the difference will be enlarged. When all the parameters of the filter are fixed, the transmission spectrum of the filter will be changed by adjusting the laser diode bias current, which means that the ratio of the external cavity feedback and the effective output coupling efficiency of the laser are dynamic and nonlinear. It can be predicted that the output power-current curve of the laser is also nonlinear. Although the main transmission peak decreases at high power incidence, the sideband transmission peak is effectively suppressed, which is beneficial for single frequency laser.

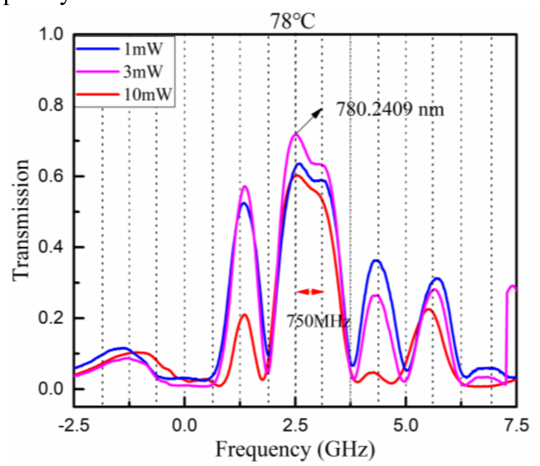

Fig.3. Transmittance spectra of the naturally abundant Rb FADOF with incident power of 1mW, 3mW and 5mW at thesame temperatures of 78 ° C .

When the temperature of FADOF is set at 65 ℃, laser only works within a small range of current. The working current range and laser output power increase with the temperature increasing. It found that the laser performance is optimal when the filter temperature is set at 78℃. When the temperature exceeds 78℃, the output power of the laser decreases and the mode is unstable.

We investigate the output power of the Faraday laser, the number of the longitudinal modes and laser wavelength at the temperature 78℃ of FADOF. Fig. 4 shows the output power of the Faraday laser versus driven current. The laser threshold is about 60 mA, the maximum output power 46 mW. Power does not increase linearly with current, which attributes the influence of the intracavity light intensity on the transmittance of FADOF.

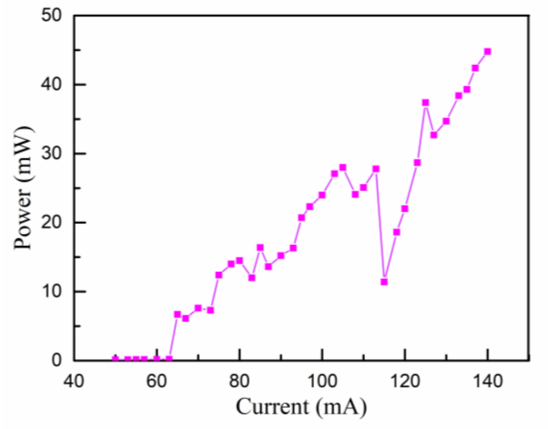

Fig.4. Output power versus driven current.

A scanning Fabry-Perot interferometer (Thorlabs SA210-5B) with a free spectrum range (FSR) of 10 GHz and resolution of 67 MHz was employed to record the signature of the lasing modes over the entire current range, as shown in Fig.5. The upper trace (the blue line) is the interferometer ramp voltage and the lower trace (the purple line) is the voltage of the detector measuring the Faraday laser transmission through the Fabry–Perot scanning interferometer. The absence of any peaks between the main resonances of the interferometer clearly indicates operation at a single frequency. When current increases from threshold to 140 mA, the Faraday laser is always in single-longitudinal-mode operation.

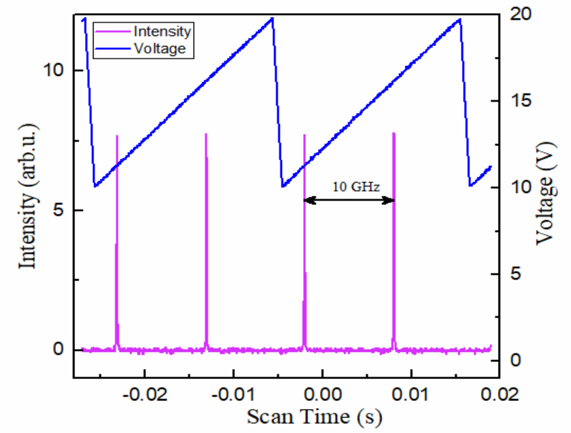

Fig.5 Output spectrum of single-longitudinal-mode operation measured by Fabry-Perot scanning interferometer.

The laser wavelength is measured by a wavelength meter (Bristol 671A). When the current of LD is set at 80mA, wavelength meter has recorded wavelength values of 12 hours at a sampling rate of 1Hz, as shown in Fig.6. The output wavelength of the Faraday laser fluctuates between 780.2418nm and 780.2398nm, corresponding to the main peak of the transmission spectrum of the filter. The wavelength fluctuation indicates that the laser has been operating within the transmission band of the filter.

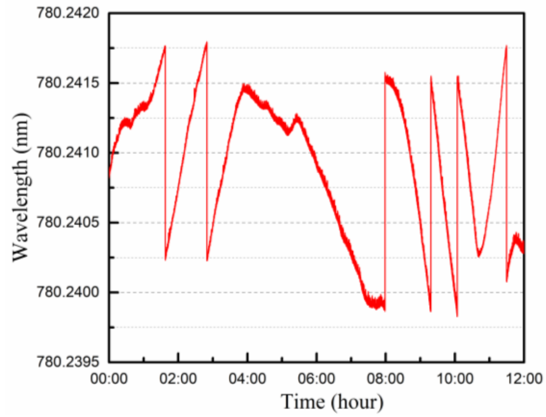

Fig.6 The measured wavelengths of the faraday laser as a function of time (12 hours).

To measure the linewidth of the 780 nm Faraday laser, we carry out a heterodyne beating experiment between the laser and the other Faraday laser operating near 780.246nm. The power spectrum of the heterodyne signal is shown in Fig.7. The actual power spectrum shows a single clear peak within the detection bandwidth (9.5GHz), indicating that both lasers were exhibiting single mode behaviour. The full-width at half-maximum (FWHM) of the Lorentz fit arrives at 36.4 kHz. Therefore, the linewidth of the 780 nm Faraday laser is approximate 25.7 kHz. This linewidth is small enough to be useful for many atomic physics experiments where the laser linewidth should be ideally be less than the natural linewidth of the D lines (~ 6MHz).

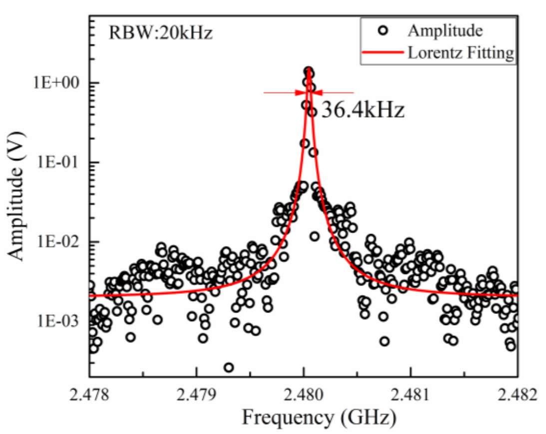

Fig.7 Spectrum of beat signal between two Faraday lasers. The sweet time of the spectrum analyzer is 30 ms, the resolution bandwidth is set to 20 kHz. The FWHM of the Lorentz fit is 36.4 kHz.

IV. Conclusions

In conclusion, we realize an extended cavity Faraday laser system using the ARLD as gain the medium and a naturally abundant Rb Faraday optical filter as a frequency selective device. The output power of laser is 46 mW at driven current of 140mA. The laser operates in single-longitudinal-mode over a range of laser diode (LD) current from 60 to 140 mA. The laser wavelength is well kept within the highest transmission peak of FADOF and the laser linewidth arrives at about 25.7 kHz. In the future, the output wavelength of the laser will be shifted to the Rb atomic Doppler broadened line by means of electro-optical modulation, then adopting the modulation transfer spectroscopy as described in [16], this Faraday laser will be easily locked on Rb atomic sub-Doppler transition lines, which can be widely used in atomic physics experiments.

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