

Article

A Faraday Anomalous Dispersion Optical Filter Based on Rubidium Hollow-Cathode Lamp

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Abstract: Using a hollow-cathode lamp (HCL) to build a Faraday anomalous dispersion optical filter (FADOF) is a new method to realize narrow linewidth optical filters. In contrast to other atomic optical filters based on saturated vapors, which work at a relatively high temperature to maintain the atomic density, the HCL device using sputtered particles can work at a much lower temperature. In this work, a rubidium HCL-based FADOF (HCL-FADOF) working at 780 nm is established and carefully tested. With 20 mm cathode length, the transmittance can reach 29% under 18 mA discharge current and 260 G magnetic field at room temperature, which is equivalent to the performance of a saturated vapor-based FADOF (VC-FADOF) at more than 60 °C. This work provides a direct comparison of the performance of the HCL-FADOF and the VC-FADOF, which is of great benefit to further studies of atomic filters at normal temperature.

Keywords: hollow-cathode lamp; atomic filter; atomic density

The atomic filter is a kind of ultra-narrow bandwidth optical filter, which takes advantage of the narrow linewidth of the atomic resonance line. Up to now, most atomic filters are realized in alkali metal saturated vapor cells and cover some specific wavelengths from visible to near infrared, such as 589 nm in sodium [1]; 532 nm, 770 nm in potassium [2,3]; 776 nm, 780 nm, 1529 nm in rubidium [4–9]; 455 nm, 852 nm in cesium [10,11]. Such atomic filters exhibit important applications in LiDAR [12,13], optical communication [14,15] and quantum physics [16,17].

Methods of atomic filters develop from early types of atomic resonance filters (ARFs) based on frequency conversion [18], to recent Faraday anomalous dispersion optical filters (FADOFs) structure based on magneto-optical birefringence [19] and other types. However, what remains unchanged is the use of atomic saturated vapor cells and the requirement of the high atomic density. The higher atomic density means the higher pressure and therefore the higher temperature. This leads to two problems: (i) it is necessary to heat the saturated vapor cell, sometimes higher than 200 °C even for alkali metals [16,20], which could be very inconvenient in some cases; (ii) the saturated vapor pressure for lots of elements, such as alkali earth metals, is so low that it is necessary to heat them to an extremely high temperature. For example, the rubidium atomic density in a saturated vapor cell is about $1.56 \times 10^{16} / \text{m}^3$ at 27 °C. However, strontium vapors must be heated to about 280 °C to achieve the same atomic density. Since the requirement of the high temperature for saturated vapors of many elements is so hard to meet, the temperature problem of atomic saturated vapor cells becomes one of

the main difficulties in expanding wavelengths of atomic filters. Therefore, other methods beyond saturated vapor cells are proposed.

In 2016, we proposed a new kind of atomic filter based on a hollow-cathode lamp (HCL) and demonstrated a strontium HCL-based FADOF (HCL-FADOF) working at 461 nm [21]. Unlike the saturated vapor cell, the HCL generates atomic vapors in a “sputtering” way as following [22]: (i) the buffer gas in the HCL, such as Ne, Xe, is ionized by the high voltage between the anode and the cathode of the HCL; (ii) the positively charged ions are then attracted by and accelerate toward the negatively charged cathode, which is made by the metal(s) of interest; (iii) the ions strike the surface of the cathode on arrival at the cathode; (iv) if they have sufficient energy, the ions cause atoms of the cathode to be ejected. In our early work in the strontium HCL-FADOF, the transmittance exceeded 60% at room temperature, corresponding to the strontium atomic density at about 300 °C in a strontium saturated vapor cell [21]. However, because of the lack of the strontium saturated vapor cell-based FADOF (VC-FADOF) working at the same wavelength, the comparison between the HCL-FADOF and the VC-FADOF has not been completed.

Because the 780 nm is the commonly used wavelength of the FADOFs [6,7], we establish a rubidium HCL-FADOF working at 780 nm to compare with a rubidium VC-FADOF working at the same wavelength. Thanks to the open-source software program ElecSus, which is very accurate in simulating the transmittance spectrum of the ground state rubidium FADOF under weak signal [23,24], we do not really need to build a new VC-FADOF.

The experimental setup is shown in Figure 1. A 780 nm laser passes through an isolator (ISO) and an iris diaphragm (ID). After that, the laser passes through the first Glan–Taylor prism (GT1) to improve the degree of polarization and then passes through the rubidium HCL (HAMAMATSU L2783 series). A pair of permanent magnets (M1 and M2) on both sides of the HCL generate a magnetic field along the laser propagation direction. Because of the Faraday effect, the polarization of the laser near resonance rotates when passing through the HCL. By setting a proper magnetic field and discharge current, the polarization rotates 90° after passing the HCL. However, the Faraday effect does not occur at other wavelengths, so the polarization of the non-resonant laser does not rotate. The second Glan–Taylor prism (GT2) is used to select the polarization of the laser which rotates 90°. The intensity of the laser after the GT2 is then recorded by a photodetector (D). Unlike the saturated vapor cell, the effective length of the HCL is the cathode length, which is only 20 mm here, because the discharged buffer gas in the HCL limits the range of atoms or ions sputtered from the cathode [22]. It should be noted that the HCL is 1

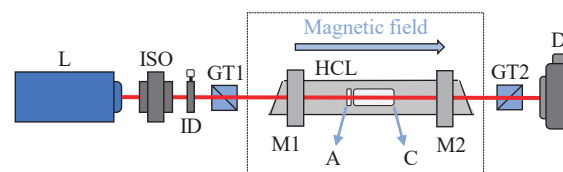


Figure 1. The experimental setup. L: 780 nm laser; ISO: 780 nm isolator; ID: iris diaphragm; GT1 and GT2: Glan–Taylor prisms; HCL: rubidium hollow-cathode lamp; A: the anode of the HCL; C: the cathode of the HCL; M1 and M2: a pair of permanent magnets; D: photodetector.

The transmittance spectra of the HCL-FADOF at different discharge currents and magnetic fields are measured. The transmittance spectra are calculated as follow (the absorption of optical devices are ignored): (i) when the GT2 is perpendicular to the GT1 and the HCL is on, we record the laser power variation with laser wavelength on the D as $P_1(\lambda)$; (ii) when the GT2 is parallel to the GT1 and the HCL is off, we record the laser power variation with laser wavelength on the D as $P_2(\lambda)$; (iii) when the GT2 is perpendicular to the GT1, the laser is off and the HCL is on, we record the light power of the HCL at different discharge currents on the D as P_3 ; (iv) the transmittance spectra of the HCL-FADOF can be calculated by $Tr = [P_1(\lambda) - P_3]/P_2(\lambda)$. Some typical transmittance spectra at

different magnetic fields and discharge currents are shown in Figure 2. To examine the performance of the HCL-FADOF more clearly, we focus on peak transmittances and check them under different discharge currents (maximum of 20 mA as allowed for our HCL) and magnetic fields, as shown in Figure 3. It is clear that with the discharge current increasing until 18 mA, the peak transmittances at different magnetic fields increase. The maximum transmittance can reach 29 % at the discharge current of 18 mA and the magnetic field of 260 G. It is obvious that the higher discharge current leads to the higher atomic density and the higher transmittance. However, when the discharge current increases to 20 mA, transmittances slightly decrease. The performance of this HCL-FADOF at 18 mA discharge current in detail is further studied. The transmittance spectra at different magnetic fields and the discharge current of 18 mA in contour form are shown in Figure 4. With the magnetic field increasing, the center frequency of the transmittance spectrum decreases.

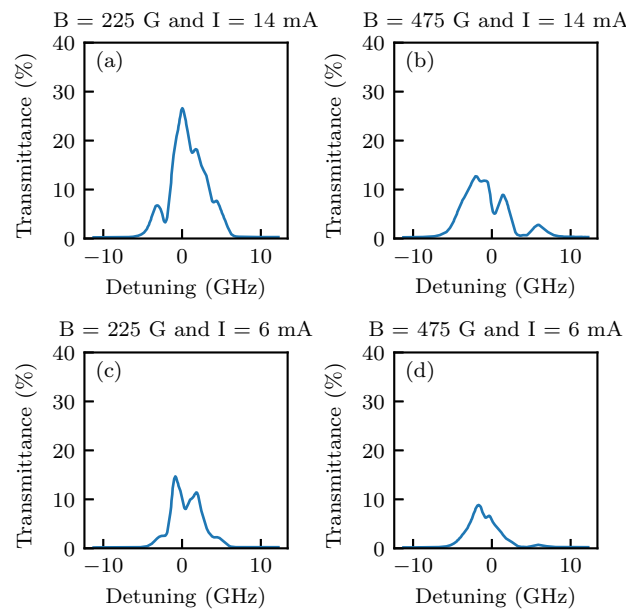


Figure 2. Some typical transmittance spectra of the HCL-FADOF. (a) The transmittance spectrum at the magnetic field of 225 G and the discharge current of 14 mA; (b) the transmittance spectrum at the magnetic field of 475 G and the discharge current of 14 mA; (c) the transmittance spectrum at the magnetic field of 225 G and the discharge current of 6 mA; (d) the transmittance spectrum at the magnetic field of 475 G and the discharge current of 6 mA.

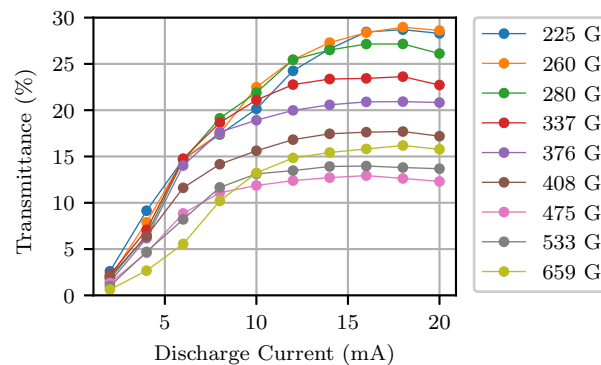


Figure 3. The peak transmittances at different magnetic fields versus various the discharge current of the HCL. The maximum transmittance is 29% at the discharge current of 18 mA and the magnetic field of 260 G.

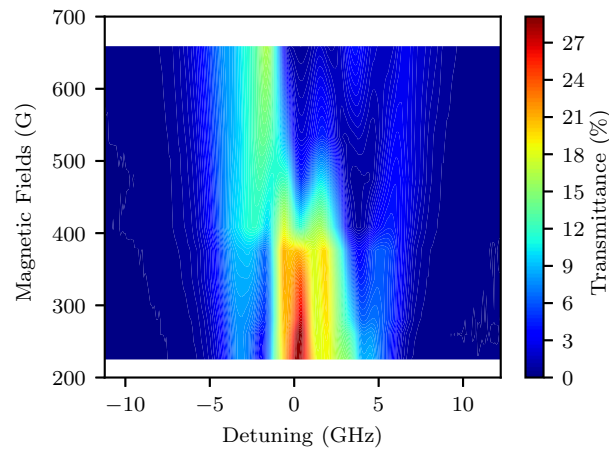


Figure 4. All the transmittance spectra for various magnetic fields and the discharge current of 18 mA.

To compare the performance of the HCL-FADOF and the VC-FADOF, all transmittance spectra have been fitted in ElecSus software, using its own fitting function. Several fitted transmittance spectra are shown in Figure 5 and the fitted parameters (the equivalent temperature and the magnetic field) are listed in each subfigure. All the fitted temperatures at different discharge currents are shown in Figure 6. The fitted results show that the atomic density in the rubidium HCL of this experiment corresponds to that of a rubidium saturated vapor cell at the temperature of more than 60 °C when the discharge current exceeds 15 mA. It is straightforward to think that the equivalent temperature, which is determined by the atomic density as we mentioned at the beginning, is decided by the discharge current of the HCL. The atomic density can be calculated according to the equivalent temperature using Equation (1) [25,26]:

$$\rho_N = \frac{10^{A+\frac{B}{T}}}{kT} \quad (1)$$

in which k is Boltzmann's constant, T is the temperature in K, ρ_N is the atomic density of rubidium in ground state in $/\text{m}^3$, A and B are constants that depend on the elements. For rubidium, $A = 9.316$, $B = -4040$ below 321 K and $A = 9.861$, $B = -4215$ above 321 K. Although the atomic density can be calculated according to the gas discharge theory [27], an empirical formula, which describes the relationship between the atomic density and the discharge current, is more useful and convenient in the experiment. To obtain the empirical formula, the relationship between the equivalent temperature and the discharge current is further fitted under the assumption that the empirical formula can be expressed by Equation (2):

$$\rho_N = \frac{aI}{1 + bI} \quad (2)$$

in which I is the discharge current of the HCL in mA and a , b are the coefficients to be fitted. a represents the conversion coefficient of the discharge current and the atomic density, and b is related to the saturated discharge current of the HCL. Please note that the I in Equation (2) must be no more than 20 mA. The fitted curve of the relationship between the equivalent temperature and the discharge current is also shown in Figure 6. The fitted result show that $a = 4.003 \times 10^{16} /(\text{mA} \cdot \text{m}^3)$, and $b = 0.047 / \text{mA}$. The curve of Equation (2) is shown in Figure 7. With the discharge current increasing, the atomic density increases but the increasing rate becomes slow.

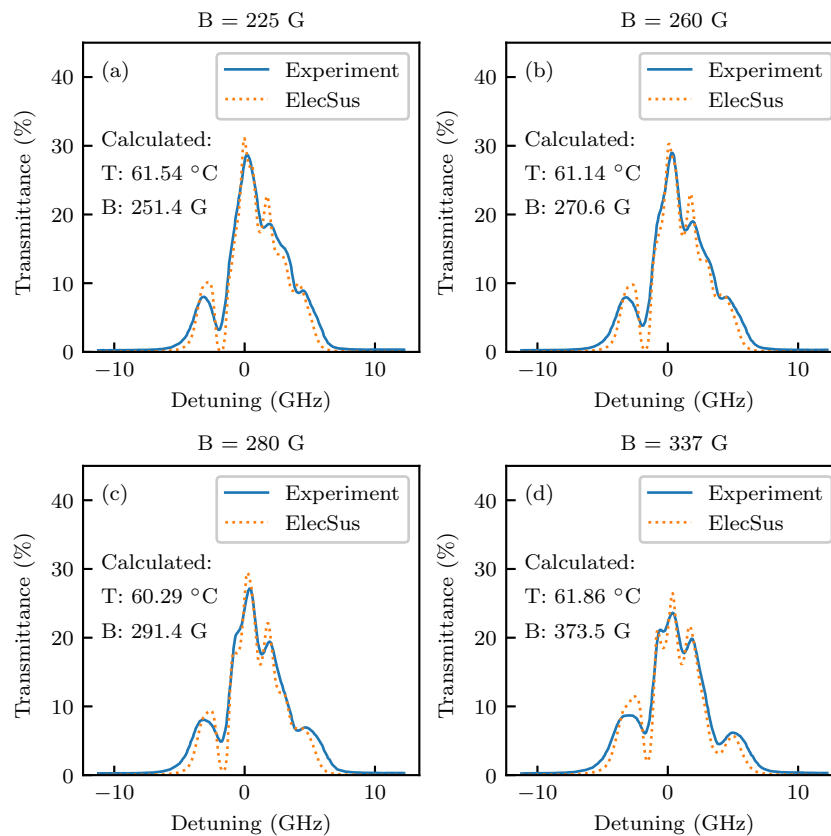


Figure 5. The measured transmittance spectra (blue, solid) and the fitted transmittance spectra (orange, dashed) at the discharge current of 18 mA and the magnetic field from 225 G to 337 G. The fitted equivalent temperatures (T) and magnetic fields (B) are listed on each subfigure. (a) The measured and the fitted transmittance spectra at the magnetic field at 225 G, and the fitted equivalent temperature is 61.54 °C and the fitted magnetic field is 251.4 G; (b) The measured and the fitted transmittance spectra at the magnetic field at 260 G, and the fitted equivalent temperature is 61.14 °C and the fitted magnetic field is 270.6 G; (c) The measured and the fitted transmittance spectra at the magnetic field at 280 G, and the fitted equivalent temperature is 60.29 °C and the fitted magnetic field is 291.4 G; (d) The measured and the fitted transmittance spectra at the magnetic field at 337 G, and the fitted equivalent temperature is 61.86 °C and the fitted magnetic field is 373.5 G.

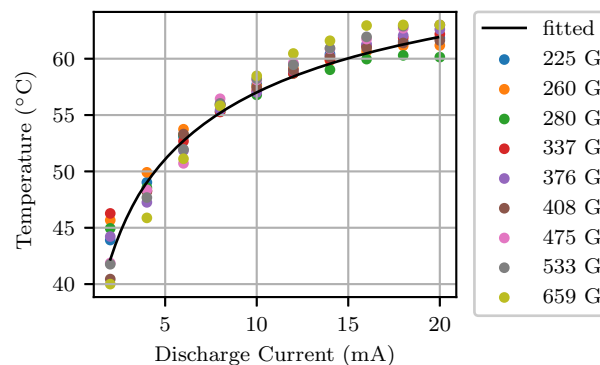


Figure 6. The fitted equivalent temperatures of the HCL at different magnetic fields versus the discharge current (color dots) and the fitted curve (black line) of the equivalent temperature of the HCL versus the discharge current.

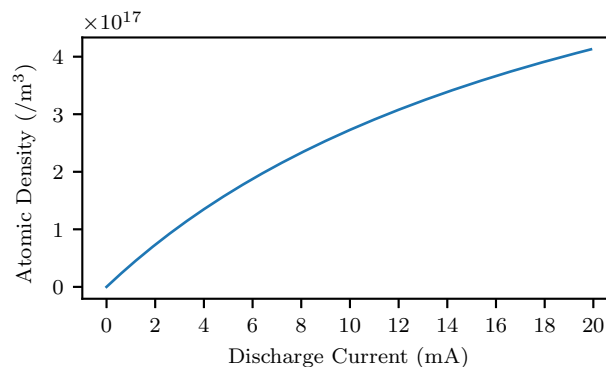


Figure 7. The atomic density in the rubidium HCL versus the discharge current calculated using Equation (2).

This experiment shows that the HCL can really improve the atomic density at room temperature. This can help us to expand the wavelengths of atomic filters and decrease the requirement of ambient temperature for using FADOF. However, there are also slight differences between the HCL-FADOF and the VC-FADOF. The broadening and the overlap of the HCL-FADOF, which broaden the bandwidth of the HCL-FADOF, are more serious than those of the VC-FADOF. And the peak transmittances of the HCL-FADOF are lower 1–2% than those of the VC-FADOF. These are contrary to the design goal (high transmittance and narrow bandwidth) of the atomic filters. The first reason may be the collision between the rubidium atoms and the ions. As mentioned before, the positively charged ions strike the surface of the cathode under the acceleration of the electric field between the anode and the cathode. Simultaneously, the atoms or ions sputtered from the cathode are also struck by the positively charged ions. The second reason may be the Stark effect. Unlike the saturated vapor cell, there is a large electric field, which could cause the Stark effect, between the anode and the cathode. Hence there is not only the Zeeman effect but also the Stark effect in the HCL-FADOF. The impact of the Stark effect in an HCL-FADOF deserves further study.

In conclusion, a rubidium HCL-FADOF working at 780 nm was established and carefully tested. The transmittance reaches 29% under the discharge current of 18 mA and the magnetic field of 260 G with the cathode length of only 20 mm. A direct comparison of two kinds of FADOFs shows that the performance of the HCL-FADOF under the discharge current of 15–20 mA is equivalent to a VC-FADOF with a 20 mm long saturated vapor cell which is heated to 60–65 °C. However, the peak transmittances of the HCL-FADOF are lower 1–2% than that of the VC-FADOF and the FWHM (full width at half maxima) of the HCL-FADOF is larger than that of the VC-FADOF. These further prove that the HCL can be used to increase the atomic density for building up a FADOF at room temperature. Moreover, an empirical formula, which indicates the relationship between the atomic density and the discharge current of the HCL, is fitted. This empirical formula can be convenient for us to estimate the atomic density of the HCL under a certain discharge current.

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