Optical pumping of Rb by Ti:Sa laser and high-power laser diode

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We present a laser system based on a tunable Titanium:Sapphire (Ti:Sa) laser optimized for maximum efficiency of the optical pumping process of Rb atoms. The system represents the first and crucial part of the HpG (hyperpolarized gasses) production process. It was designed for laboratory purposes where the expensive and complicated Ti:Sa laser is justified because of its variability, narrow linewidth and easy tuning of the wavelength. The system consists of a modified commercial Ti:Sa laser pumped by a Nd:YAG laser, beam-forming and polarizing optics, and heated interaction cell attached to a vacuum manifold and gas containers placed in homogeneous magnetic field generated by a set of Helmholz coils. Furthermore we describe another laser system based on a high power semiconductor laser. It is designed to operate in medical and industrial applications to come. We concentrated on the lased diode emission linewidth reduction because of the efficiency of the optical pumping process. The emission linewidth was reduced approximately from 1 THz to 100 GHz.

1. Introduction

Hyperpolarized noble gasses (HpG) have found a steadily increasing range of applications in nuclear magnetic resonance imaging. They can be regarded as a new class of magnetic resonance contrast medium or as a way of greatly enhancing the temporal resolution of the measurement of processes relevant to areas as materials science and biomedicine [1].

The hyperpolarized xenon ^{129}Xe plays a major role in the study of microsporous materials like zeolites. The study and application is based on the chemical shift in Xenon gas. At very low hyperpolarized Xenon pressures and at the room temperature, the chemical shift is sensitive to the interaction of xenon atoms with the walls. It leads to the study of microsporous materials [1].

The production of HpG, predominantly the Xenon ^{129}Xe, became attractive for its potential applications in medicine as well. The powerful technique of magnetic resonance imaging of human body has a limited ability to examine organs with low water content and/or with air spaces, such as colon or lungs. An introduction of a highly contrasting ingredient would significantly extend its potential. Gaseous Xenon is normally not present in the body, so the experiments do not suffer from unwanted background signals. More, the hyperpolarized Xenon acts as a source of very strong nuclear magnetic resonance (NMR) signal which can even lead to introduction of specialized simple MRI apparatuses with significantly less powerful magnets. These applications show that HpG may

become a useful tool for non-invasive investigation of human lung ventilation, giving access to static imaging during breathhold, dynamics of inspiration/expiration, and functional imaging.

The phenomenon of angular momentum transfer by the exchange of spin between optically pumped Rb atoms and nuclear spins of ^{3}He was first reported by [2] and theoretically described in [3]. With the higher efficiency of the polarization process that the spin-exchange technique namely of ^{129}Xe can offer, this technique became the mainstream in HpG production and experiments [4]. The first experiments with optical pumping of Rb vapor employed a Rb lamp or dye lasers. When the first commercially available Titanium-Sapphire (Ti:Sa) lasers appeared, they proved to be a useful replacement for dye lasers in many spectroscopic applications. We employed a commercial Ti:Sa laser for our experiments for its easy wavelength tuning and narrow linewidth.

The Ti:Sa laser output radiation is linearly polarized and this is absorbed by both magnetic substates m=±1/2 of the Rb 5s $^2S_{1/2}$ ground state. Unlike for the production of hyperpolarized noble gasses (namely ^{129}Xe) the light absorption by the one magnetic substate is necessary. This is ensured by the circularly polarized light which can be generated by introduction of a quarter-wave plate. For example, right circularly polarized light selectively excites population from the m=-1/2 ground state to the m=1/2 excited state. Relaxation of the exited state brings population down to both ground states, m=1/2 and m=-1/2. Under continuous radiation, the m=-1/2 ground state will

be depleted and population will subsequently accumulate in the m = 1/2 ground state, leaving the Rb electrons spin-polarized. The Rb polarization is subsequently transferred to ^{129}Xe nuclear spins through spin-exchange collisions. For Zeeman splitting of ground state to substates m = ±1/2 is necessary to apply a homogenous magnetic field, which is generated by a set of Helmholz coils.

The optimum matching of the laser emission to the absorption line of the Rb vapor is important for achievement of the best efficiency of the pumping process. The laser optical frequency should be stabilized by an electronic servo-loop to the center of the Rb absorption line. The linewidth of the laser can be modified by introduction of one or more etalons into the resonator as well as the absorption linewidth varies with temperature (pressure) of the Rb vapor and more significantly by the pressure of the gas mixture.

2. Experimental arrangement with Ti:Sa laser

As a source of optical power we used a manually tunable cw Ti:Sa laser. A small amount of the output radiation was coupled into a wavemeter for coarse adjustment of the laser wavelength. The diameter of the beam is expanded by a telescope and a circular polarization of the light is generated by a retardation quarter-wave plate. The output laser beam width of approximately 0.3 mm (FWHM) was expanded to the width matching the diameter of the absorption cell (35 mm) by Galileo telescope consisting of diverging and converging lenses (Fig. 1).
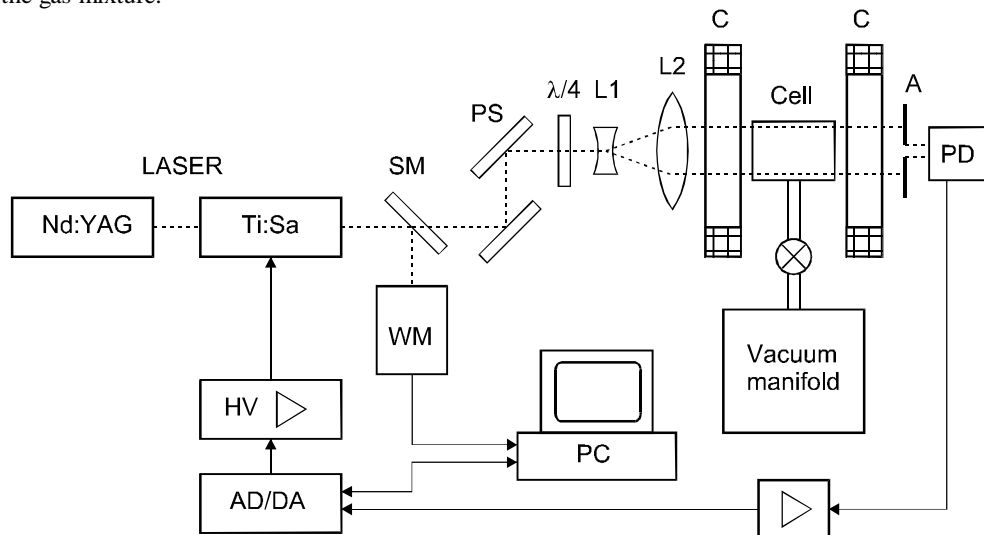

Fig. 1. Experimental set-up for optical pumping of rubidium. SM – semireflecting mirror; PS – periscope; λ/4 - quarter-wave retardation plate; L1, L2 – lenses of the telescope; C - Helmholz coils; A – aperture; PD – photodetector; WM – wavemeter; AD/DA – analog/digital and digital/analog converter unit; HV – high-voltage amplifier; PC – personal computer.

Our commercial Coherent Ti:Sa laser, model 899-01, is a flexible, convertible ring laser that can operate as a conventional dye ring laser, or a solid state ring laser using titanium:sapphire as the gain medium. Pumping is done by solid-state diode-pumped, frequency-doubled Nd:Vanadate (Nd:YVO$_4$) Coherent Verdi V-6 laser that provides single-frequency green (532 nm) output at power levels greater than 6 Watts. Wavelength of the Ti:Sa laser is tunable in a wide range (680 nm - 1025 nm) by birefringent filter while the useful output varies with the wavelength and is close to 1 W. The birefringent filter is controlled manually by micrometer adjusting system. To keep the continuous pumping process running for a longer time electronic control of the lasing wavelength was necessary. We extended the tuning screw by a piezoelectric element. This allowed us to tune the laser resonator length electronically over 0.25 nm which exceeds by far thermal wavelength drifts. A great sensitivity of the laser to dust particles led us to place it in

a separate clean box slightly over-pressurized by nitrogen generated by evaporation from a liquid state.

The target cell used for measurement was a simple cylinder 9.2 cm long. The cell is made of borosilicate glass with flat windows. It was enclosed in a teflon box to allow thermostabilization by a hot-air flow. The box with target cell was placed in a Helmholtz coils system designed to generate a homogeneous 10 mT magnetic field with homogeneity 2.18×10^{-4}. The cell is attached to a vacuum manifold by non-magnetic vacuum components. A small amount of Rb was moved into the cell under vacuum conditions and a mixture of gasses could be fed into the cell through separate valves. The main part of the evacuation system was Turbomolecular Drag Pumping Station TSH 071 E by Pfeiffer Vacuum GmbH. The whole evacuation system allowed evacuation down to a pressure of 8×10^{-5} Pa.

3. Control electronics and software

In our laboratory arrangement, we designed the tuning and wavelength control of the Ti:Sa laser by a PC (personal computer), an AD/DA converter card, and high voltage amplifier driving piezo transducer. Control of the system is performed by a special software written in LabVIEW environment. The communication between a personal computer and AD/DA converter card is ensured by CAN bus. The program works in two different modes. The first one allows manual search of the desired absorption line of rubidium by manual coarse screw tuning. Than the triangular-signal generator is used for matching of the line into the center of tuning range and the stabilization loop is activated. The second mode allows automatic detection of the absorption line. In the second regime after a manual coarse tuning, the program monitors the variations in detected signal and if the absorption line is found out, the stabilization loop is activated automatically. In both of this cases the Ti:Sa laser wavelength is stabilized on the center of the absorption line of rubidium at the wavelength 794.76 nm to achieve the maximum efficiency of the optical pumping process. For the frequency locking of the Ti:Sa laser, we employed a technique with wavelength modulation and the first harmonics detection. All of the parameters and constants can be set and modified during running of the program. Important values of measurement are recorded to a text file.

4. Experimental results

During the optical pumping and spin-exchange process, to achieve the maximum efficiency the optical frequency of the pumping laser beam should be tuned close the center of the Rb transition. At the same time the linewidth of the pumping laser radiation should be fitted approximately to the linewidth of the selected Rb transition.
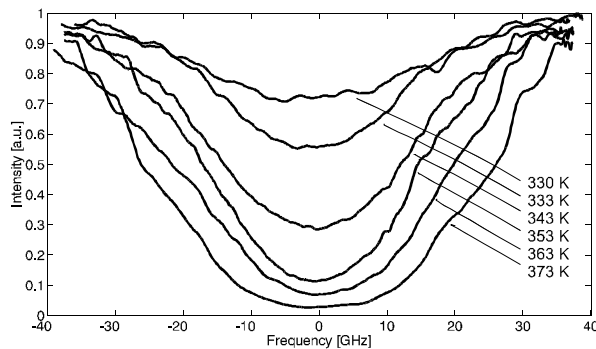

Fig. 2. Detected absorptions in the Rb vapor under presence of He buffer gas for various temperatures of the mixture.

The measurement of linewidth of the laser was based on the detection of contrast of interference fringes in a Michelson interferometer assembly. The coherence length was 12 mm which corresponds to the linewidth of 25 GHz. The laser linewidth reduction by inserting etalons into the resonator led to discontinuities in the laser tuning and detection of the Rb transition became impossible. With the presence of gas mixtures of certain pressures in the cell necessary for the spin-exchange process the linewidth of the absorption line in Rb may be significantly increased. In our first experiment we started with increasing of the cell pressure by He in the role of a buffer gas. A sealed absorption cell was filled with approximately 2 mg of Rb and certain amount of He close to the atmospheric pressure. The whole cell was heated by a flux of a hot air and the pressure of Rb vapor and He increased. In this configuration the line broadening of Rb is dominated by the pressure of the buffer gas and the level of absorption is given predominantly by the pressure of Rb vapor. The detected absorption line for a set of temperatures and corresponding pressures is given in Fig. 2 and the measured values in Tab.2.

Table. 2. Values of He and Rb pressure in the cell and corresponding FWHM linewidth and absorption of the Rb absorption line.

T	$\Delta\nu$	p_{3He}	p_{Rb}	A
K	GHz	Pa	Pa	%
330	30	1,00E+05	3,99E-04	28
333	31	1,01E+05	5,32E-04	45
343	33	1,04E+05	1,60E-03	72
353	35	1,07E+05	3,99E-03	89
363	43	1,10E+05	1,33E-02	93
373	48	1,13E+05	1,73E-02	97

The optimum value of the He pressure of approximately 1.13×10^5 Pa was extrapolated to match the emission linewidth of 25 GHz of the laser. Suitable partial pressure of Rb vapor which corresponds to nearly 100% absorption of the incident laser radiation in our cell is at the temperature 373 K. The effect of thermal drift of the pumping laser without the stabilization servo lock shows drifting away from the absorption line center in the range of tenths of minutes is shown in Fig. 3.
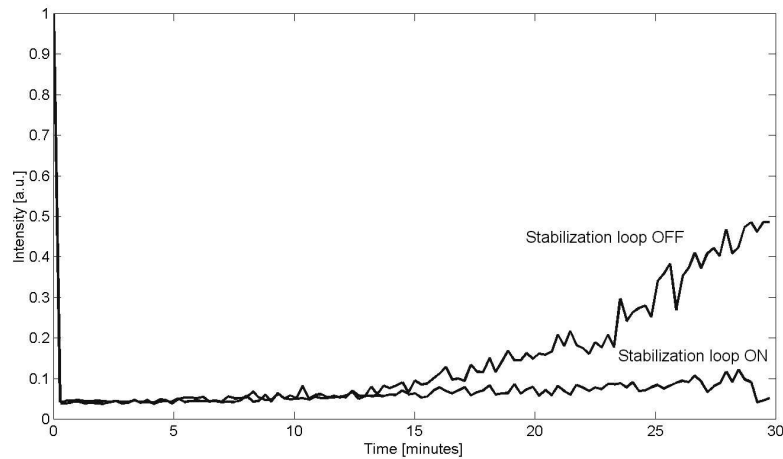
Fig. 3. Tuning into and rifting away from the absorption line center with stabilization OFF and the effect of the servo loop.

5. Experimental arrangement with high power laser diode

In our laboratory, we realized the experimental arrangement for optical pumping of Rb atoms based on the high power laser diode. The block diagram of the workplace is shown in Fig. 4. The main part of the experimental setup is a high power laser diode S-λ-3000C-200-H. The maximum output CW power is approximately 3 W and the central wavelength is about 797 nm. The output beam is collimated with aspheric, high NA lens and the elliptic profile of the beam is adapted to the circular profile with anamorphic prism pair. The remaining part of the experimental setup is similar to the experimental arrangement with Ti:Sa laser apart from the diverging lens in optical telescope which had to be replaced by another one because of the different diameter of the input laser beam.
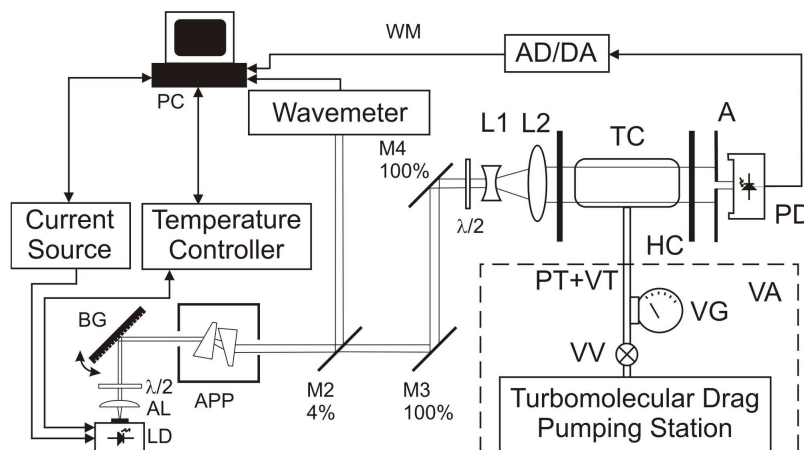

Fig. 4. Experimental set-up for optical pumping of rubidium based on high power laser diode. LD – laser diode; AL – aspheric lens; $\lambda/2$ – half-wave retardation plate; BG – diffraction grating; APP – anamorphic prism pair; M2 – semireflecting mirror; M3, M4 – periscope; $\lambda/4$ - quarter-wave retardation plate; L1, L2 – lenses of the telescope; HC – Helmholz coils; A – aperture; PD – photodetector; WM – wavemeter, VA – vacuum Apparatus.

To achieve the maximum efficiency of the optical pumping process based on high power semiconductor laser, only the pressure broadening of the Rb absorption line is insufficient. Hence the laser emission linewidth should be reduced too. We do it with diffraction grating which is used as a laser diode selective feedback. The first experimental result is shown in Fig. 5. It is obvious that the laser diode emission linewidth was significantly reduced from 1 THz to 100 GHz. The optical power loss is about 60%.
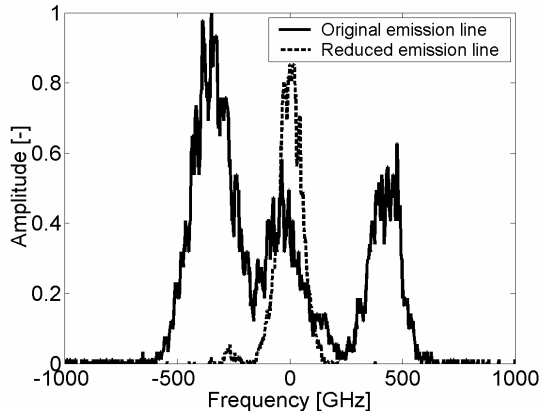
Fig. 5. High power laser diode emission lines.

6. Conclusion

We modified the commercially available Ti:Sa laser for the ability to automatic tuning by PC and AD/DA converter. For control the tuning process was created the special software in LabVIEW programming system. The laser linewidth was determined by the coherence length measurement and the value is 25 GHz. For this value we calculated ([5], [6]) the optimum pressure of He (1.13×10^5 Pa at 373 K) for the collision-broadening of Rb absorption line. Thereafter the laser was used for optical pumping of the mixture of Rb under presence of He buffer gas. The absorption of nearly 100% of the incident laser radiation was reached at 373 K (Fig. 2). The designed stabilization loop for the frequency locking of the Ti:Sa laser on the top of absorption line was tested too (Fig. 3).

We also realized the experimental workplace for optical pumping of Rb atoms with high power laser diode. We reduced the laser diode emission linewidth from 1 GHz to 100 MHz with the optical power loss about 60%. Now we prepare the special measurement control software and in near future first experiments with optical pumping of Rb will be conducted.

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