1083 nm Ytterbium doped tunable fiber laser for $^3$He pumping applications

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1. Introduction

Hyperpolarized $^3$He is used in a variety of research fields and for various applications like neutron spin filters and magnetic resonance imaging of human lungs. Both require either very high nuclear polarization, or large amounts of gas and high production rates [TAS, 00]. The most efficient method among the polarization techniques is metastability exchange optical pumping (MSEOP), which involves the $^2S$-$^2P$ transition at 1083nm [NAC, 85]. The ideal source consists of a laser with a linewidth <2GHz in order to avoid absorption saturation of one speed class. With a fiber laser technology, this is achievable with a source exhibiting a great quantity of modes (multimode envelop) at the same time with a linewidth quite the same as the atomic Doppler width (~1.8 GHz). For this purpose a new and powerful (up to 10W output power achievable) 1083nm fiber laser has been developed in a master oscillator power fiber amplifier configuration (MOPFA). As this laser is dedicated to $^3$He pumping, the power must be shared out among the multimode envelop at the scale of lifetime of He atoms (0.1 µs). Gain is obtained by means of Ytterbium doped double clad (DC) fiber pumped by broad stripe laser diodes.

2. Principle of operation

The principle of operation is presented on the figure below (Fig. 1). Spin polarized $^3$He is produced by direct optical pumping from its metastable $^2S_1$ state populated in a low pressures (~1mbar) discharge. The polarization is transferred with large cross section trough metastability exchange collisions to the nuclei of the ground state atoms.

![Figure 1: 1083nm $^3$He principle of excitation](image-url)

To be pumped permanently, the optical pump signal at 1083nm must have a continuous fund at the time scale of lifetime of $^2P$ level. This means that we have to characterize the laser signal during this time scale (0.1µs) and in terms of average power. To fulfill the optical characterization of the laser, we make measurements with a fast photodiode.
(700MHz bandwidth). The set up consists on a fast photodiode connected to an electrical spectrum analyzer (HP8590A). This measurement gives many information on the laser:
- the frequency of the relaxation oscillation
- the Free Spectral Range (FSR)
- the beat frequency of the longitudinal modes when they are present [HEA,97]: intensity noise measurement

Analysis of this measurement is presented in one of the next following sections. Other techniques are possible depending on the material available. For example, we can mentioned the use of a fixed Fabry-Pérot etalon with a FSR of 1.5GHz and a finesse of 100. The method we use at Keopsys is an intensity noise measurement.

3. 1083nm laser architecture

![Figure 2: 1083nm tunable fiber laser architecture. Gain is obtained using VSP®](image)

The optical oscillator is based on a Fabry-Pérot cavity closed by a high reflective (HR) mirror and a tunable low reflective (LR) FBG as shown on Fig. 2. The gain section consists of an Yb$^{3+}$ doped double clad (DC) fiber pumped by a broad stripe laser diode emitting at 975 nm. Injection of pump power is possible by means of imbedded V-groove directly formed into the side of an optical fiber (V-groove side pump technique (VSP®)). Laser light is totally reflected on the fiber sidewall and 90% coupling efficiency can be achieved [RIP, 95]. The inner cladding has as star shape profile ensuring efficient mode mixing. A couple of all glass silica fibers, single mode at 1µm, are spliced at both ends of the DC fiber. As dedicated for a particular application, the laser has to regroup a certain number of functionalities or intrinsic properties.

- **Tunability:** In order to match with all absorption lines of $^3$He, the laser has to be tunable over more than 60GHz (typically between 1082.9 and 1083.3 nm (in air)). A FBG piezo electrical control allows fine tuning of the wavelength to the $^3$He resonance lines beyond 80GHz as shown in Fig. 3.

![Figure 3: Optical SNR of the 1083nm fiber laser (resolution = 0.07 nm). The insert corresponds to wavelength tunability.](image)
- **Polarization:** For the particular application of Helium pumping, the analyze is made for a nuclear polarization (M) generally equal to 0. Thus, a circular polarization of the laser signal at 1083 nm has to be achieved [LED, 98]. To achieve good level of polarization, a polarizer is inserted at the output of the laser cavity. The association of this polarizer with a polarization controller allows reaching any state of polarization. Extinction ratio (E.R.) better than 20dB is obtained commonly. The linear state of polarization at the output of the benchtop associated with a quarter wave plate gives a circular state of polarization, ideal to analyze the atomic response of an Helium cell at M=0.

- **Power:** Various applications can be aimed by this type of 1083 nm fiber laser: image of the lungs for medical application, polarized $^3$He Neutron spin filters (NSF) … These applications all tend through the same goal: be able to produce a great quantity of hyperpolarized $^3$He with a good efficiency. It then clearly appears that the power of the pumping source is a very important parameter. From then on, we can point out that these applications can benefit from a formidable combination of the highest technical standards in the field of fiber optic communication. Rare earth that could be used to emit in the 1 micron range are Ytterbium, Neodymium, Praseodymium. Ytterbium is, through its simple quantum energy level, offering the best laser efficiency (>70%). Moreover, its peak absorption at 977nm makes it possible to be pumped by high output power and cheap laser diodes that have emerged with the fast progress made in the last decade for the Telecommunication market. In parallel to the development of these low cost laser diodes, the process to produce rare earth doped DC fibers has been controlled. For the fabricant of fiber, it is nowadays quite as easiest to produce DC than simple clad rare earth doped fibers. The association of these two crucial components (semiconductor laser diodes and DC rare earth doped fiber) as lead to the development of pumping techniques directly trough the doped first clad of these DC fibers. Keopsys has developed the V-groove side pump technique (VSP®) to propose a various range of rare earth doped fiber amplifier. For Ytterbium amplifiers, 10W saturated output power amplifiers are currently obtained. Developed in a Master Oscillator Power Fiber Amplifier (MOPFA) configuration the 1083nm laser for helium pumping is a state of the art product that perform to all highest technical standards. The oscillator delivers few tens of mW, high enough to saturate the high power booster (Fig. 4).

![Graph 1](image1.png)

![Graph 2](image2.png)

**Figure 4:** Left: Output power of the 1083 nm laser oscillator versus launched pump power. Right: Output power with 25mW input power at 1083 nm versus the pump current of the booster stage.
In the standard MSEOP conditions, excitation to the metastable $^2S$ state is obtained with a weak radio frequency (R.F.) discharge in a low pressure He gas cell at room temperature. The 1083nm adsorption lines are Doppler broadened (1.98GHz FWHM for $^3$He). For a selected component the optical transition rate is determined by the number of resonant laser modes actually emitted on a time scale of the order of 0.1µs, corresponding to the $^2P$ state radiative lifetime. With high output power, saturation of the absorption in a gas cell may appear. To preserve a good efficiency at high power, the optical pumping must concern maximum of the atoms present at the same time in the cell. If we consider that the Doppler distribution of resonance frequencies results of the thermal distribution of gas speeds, we can point out that the pumping light must be as less selective as possible. Then, intrinsically, the pumping signal at 1083 nm emitted by a all fibered MOPFA laser must have a multimode envelope under a linewidth corresponding to the Doppler width of $^3$He in the standard conditions of pressure (~1 mbar).

4. Dynamical behavior and multimode operation

Dynamical behavior and multimode characterization of the laser are both presented. The results show that the laser operates in CW regime.

The figures listed below are the result of measurements using a fast photodiode (700MHz bandwidth) connected simultaneously to a digital oscilloscope and an electrical spectrum analyser. Temporal power evolution and corresponding intensity noise spectrum have been measured as shown on Fig. 5. Intensity noise measurement gives information on the number of modes present at the same time in the cavity [HEA, 97]. In fact, the observation of many peaks simultaneously visible on the spectrum analyser is the consequence of multiple longitudinal modes under the multimode envelope of the laser beating together [HUM, 93]. The response of the spectrum analyser is a comb of peaks which witnesses that a lot of modes are present at the same time into the cavity.

**Figure 5:** Temporal trace and frequency dynamic (laser modes), $P_{\text{pump}} = 1167\,\text{mW}$, CW operation. For the right curve, resolution bandwidth = 1MHz (Insert 10-150MHz, Res BW : 3MHz).

Analyzing results listed above we can see that the behavior of the multimode envelope of the laser well suited Helium pumping application. In fact, the left curve shows an average power non equal to zero, and moreover not at the time scale of lifetime of $^3$He. The right curve proves that the number of modes present in the cavity, at the same time, under the envelope of the linewidth of the laser is important. In this case, the intensity noise
spectrum is composed of a comb of peaks separated by the cavity FSR. The oscillator, with a multimode envelope is the ideal source as long as in the same time the linewidth is quite the same as the atomic Doppler width (~1.98 GHz) in order to avoid absorption saturation of one speed class. This is the case of the Keopsys 1083 nm high power fiber laser dedicated to this application.

5. Conclusion
We have demonstrated that an all fiber tunable laser with a central wavelength of 1083nm could represent the best choice as a source for $^3$He pumping application. In parallel, the laser linewidth, the temporal and modal behavior have been presented. An important effort has been devoted at Keopsys on the development and the optimization of the intrinsic properties of the 1083 nm fiber laser.

References:


