Lasers for the Axion-like Particle Search

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DOI: http://dx.doi.org/10.3204/DESY-PROC-2008-02/matthias_hildebrandt

A couple of promising experiments on the axion-like particle search (ALPS) are currently ongoing, reaching a level of high interest in the field of light particle research. In all kind of these experiments lasers are used to directly produce ALP or detect indirect ALP effects like polarization changes. For the direct production the number of produced ALP scales with the number of photons interacting with a strong magnetic field. Therefore, high power laser systems are needed to produce a detectable number of ALP. Laser parameters like wavelength, beam quality and operation regimes (cw or pulsed) directly effect the experiments sensitivity. The design considerations for different laser systems as well as some suitable laser systems for the ALPS will be presented.

1 Introduction

In recent years several research groups have addressed the search for theoretically predicted light particles such as ALP. In principle, laser light propagating through a magnetic field B undergoes a conversion and reconversion from photons to ALPs. These light particles are not supposed to interact with dense matter and can therefore hardly be detected directly. However, the so called "shining light through a wall" experiments take advantage of this phenomenon. After a certain interaction length l a beam-block is placed inside the magnet. ALPs that propagate through this barrier get reconverted to photons in a second magnetic field. This regenerated light can then be detected with low-noise photo-detectors. A second predicted effect that accompanies the ALP conversion process is a slight rotation between the incident and regenerated light polarization which can be detected to provide evidence for the generation of these particles.

$$P_{\gamma\to a} = \frac{4B_{ext}^2\omega^2}{M^2 m_a^4}\sin^2\left(\frac{m_a^4 l}{4\omega}\right) \tag{1}$$

$$R = (P_{\gamma\to a})^2\left(\frac{P_l}{\omega}\right)\eta \tag{2}$$

The conversion probability and regeneration rate are described by Eq. 1 and 2 for light polarized parallel to the magnetic field ($E||B$) with the inverse axion coupling coefficient M and the axion mass m_a [1]. Parameters that are related to the laser source being used are the photon energy ω, detector efficiency η and the optical power P_l. The laser power inside the magnetic field determines the number of photons that can possibly be converted.

Nowadays, fiber based lasers with 400 W of output power in linear polarized continuous-wave (cw) operation are commercially available with nearly diffraction limited beam quality at a wavelength around 1 μm [2]. Although CO_2 gas lasers with even more output power and good beam quality are on the market, the emission wavelength of 10.6 μm would not allow for a straightforward detection. Fiber and solid-state lasers can deliver significantly more output power up to several kW, with degraded beam quality and unpolarized output [3]. The beam quality does not directly effect the ALP conversion efficiency, but is of some concern when mechanical apertures formed by magnet tubes limit the maximum size and divergence of the laser beam and small focus spots of only a few μm diameter on the photo-detector array are needed. Continuous-wave laser sources with up to 18 W have been installed in ALPS experiments with single- and multiple passes through the magnet [1, 4]. These were argon-ion based gas lasers emitting at 514 nm. An emission in this wavelength range is favorable for ALPS experiments due to smaller costs and better performance of photo-detectors available for this wavelength. Pulsed lasers offer significantly lower average powers and consequently a relatively low time-integrated photon flux. Still they have been applied very successfully in ALPS experiments [5]. Commercial systems deliver a few hundred mJ pulse energy in the infrared and offer an excellent conversion efficiency into visible and ultraviolet wavelength ranges [6]. A temporal synchronization of laser pulses and detector exposure-time increases the signal to noise ratio.

2 Single-frequency laser for cavity-locking

In recent years the highest output power demonstrated from a laboratory fiber laser with linear polarization and close to diffraction limited beam quality was 633 W [7] showing the current limitation to increase the ALP detection sensitivity by scaling the laser power. An attractive alternative for ALPS experiments are Fabry-Pérot cavities installed inside the magnet that provide a large resonant power buildup [8, 9]. These cavities can either be operated with an active laser material placed inside the resonator or as passive high finesse cavities with a frequency coupling to an external laser, also referred to as injection-locking. The intra-cavity power in standing wave laser cavities depends on the mirror transmission and additional parasitic losses, the available laser gain and the saturation intensity of the laser material [10]. Intra-cavity powers of several kW should be feasible with minimized cavity losses and high laser gain. The power buildup in passive Fabry-Pérot cavities and their application for ALPS experiments is reviewed in detail by T. Meier *et al.* [11]. For an efficient resonant coupling of a laser to the fundamental transverse mode of a Fabry-Pérot cavity a laser source with diffraction limited beam quality and a stable narrow-linewidth emission spectrum is needed. Narrow-linewidth laser emission has been demonstrated from distributed feedback or external-cavity semiconductor lasers, ytterbium and erbium doped fiber lasers with integrated fiber Bragg gratings and solid-state micro-chip or non-planar ring oscillators (NPRO). Stable single-frequency operation with only one resonant longitudinal laser mode and a minimization of external and internal noise sources enable a free-running operation with a linewidth of only a few kHz. With a linewidth of 1 kHz (measured over 100 ms) and a frequency stability of less than 1 MHz per minute, NPROs provide one of the most stable single-frequency laser emission with typically 2 W of output power at 1064 nm [12]. NPROs have been installed in large-scale interferometers for gravitational-wave detection. These interferometers also comprise Fabry-Pérot cavities to enhance laser power and improve detector sensitivity. For the next stage Laser Interferometer Gravitational-Wave Observatory (Advanced LIGO) a power buildup to 830 kW was proposed [13]. Such high intra-cavity powers are obtained by resonantly coupling a single-frequency laser with 200 W of output power, linear polarization and nearly diffraction limited beam quality to a series of high finesse cavities. Due to thermo-optical restrictions, this output power can not be extracted directly from a NPRO. The Advance LIGO laser system comprises a four-stage Nd:YVO amplifier, delivering 35 W of output power, and a Nd:YAG based laser oscillator resonantly coupled to the NPRO master-oscillator [14]. This laser system is perfectly suited for an application in ALPS experiments and is currently installed up to the amplifier stage at DESY in Hamburg, for an ongoing "light shining through a wall" experiment named "ALPS" with a HERA dipole magnet [15]. A schematic representation of the laser system is shown in Fig. (1). The NPRO emission is passed through a pair of wave-plates to

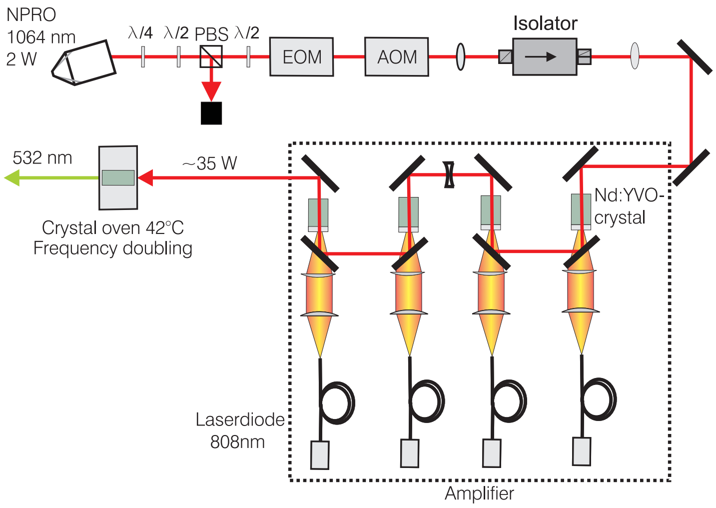

Figure 1: Schematic setup of the single-frequency laser system installed at ALPS (DESY). (PBS polarizing beam splitter, EOM electro-optic modulator, AOM acousto-optic modulator.

linearize the elliptical polarization. Electro-optic and acousto-optic modulators are installed for frequency and amplitude stabilization and a Faraday isolator protects the NPRO against backward propagating radiation. The amplifier consists of four Nd:YVO crystals pumped by four fiber-coupled laser diodes. An amplified output of more than 35 W with a fundamental mode TEM_{00} content of more than 95% is obtained with excellent long term stability. For the ALPS experiment the 1064 nm emission is frequency doubled in a periodically poled KTP crystal. Currently in single-pass configuration 0.8 W at 532 nm are achieved. With a resonant cavity for power enhancement, conversion efficiencies of 40-50% are expected.
An alternative amplification scheme for single-frequency radiation has been presented in the past using ytterbium doped large mode-area (LMA) fibers. Although nonlinear effects such as Brillouin scattering exacerbate the amplification of narrow-linewidth signals due to the long interaction length and small core size, impressive results have been obtained with 402 W of output power with linear polarization and good beam quality [16]. Extremely high gain allows for single-pass amplification to high power levels with good efficiency. Ytterbium doped fiber amplifiers are very promising candidates for future single-frequency laser applications with more than a kW of optical power.

3 Summary

We have presented considerations on the selection of laser sources and parameters for axion-like particle search experiments. Depending on the experimental approach different parameters such as emission wavelength, output power and pulsed or continuous-wave operation come into consideration. The use of resonantly coupled Fabry-Pérot cavities to enhance the laser power inside the dipole magnets has been studied intensely in the past. This approach includes the need for single-frequency laser radiation. Nonplanar ring oscillators offer extremely frequency stable radiation which can be amplified using solid-state or ytterbium doped fiber amplifiers and used as input sources for resonant cavity-locking.

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