A frequency-stabilized pump laser for wavelength conversion in long distance quantum communication

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Abstract: We demonstrate a compact frequency-stabilized laser at 1.06 μm for wavelength conversion. The achieved frequency stability is sufficient to connect the nitrogen-vacancy center in diamond and the telecommunication wavelength for long distance quantum communication.

1. Introduction

Quantum communication has been expected to realize unconditionally secure communications. For long distance quantum communication, development of quantum repeaters is necessary. In the quantum repeater system, quantum memories are used to transfer the quantum states of propagating photons to electron or nuclear spin states of the memory material.

The wavelengths of the photons depend on the quantum memories, which lie around visible range. On the other hand, the photons at the telecommunication wavelength are suitable for low loss propagation in optical fibers. Therefore, to realize long distance quantum communication based on the quantum repeaters, visible-to-telecommunication wavelength conversion is inevitable and has been intensively studied [1, 2]. In the wavelength conversion process, a pump laser fulfilling energy conservation is used. For efficient coupling with the linewidth of quantum memories, frequency stabilization of the pump laser is necessary for long term stable operation. In the case of Nitrogen-vacancy (NV) center in diamond, one of the most promising quantum memory, the wavelength of photons is 637.2 nm and the linewidth is around 10 MHz.

In this paper, we demonstrate the frequency stabilization of a compact pump laser (1064 nm) by using Doppler-free spectroscopy of molecular iodine, aiming to control the linewidth and the drift of the laser frequency under 10 MHz. The pump laser used in the present experiment is compact and low cost and emits high power of hundreds of mW. Therefore, the laser meets the requirements of the wavelength conversion in the experiment of the NV centers in diamond. However, the laser contains no piezoelectric elements and very few input ports for frequency control. By using the driving current of pump diode in the solid-state laser as a control port, we successfully locked the laser frequency without using any external frequency modulators such as an acousto-optic modulator (AOM). This has resulted a compact pump laser system for loaded in the quantum repeater nodes.

2. Experimental setup

Figure 1 shows a schematic diagram of the compact iodine-stabilized laser. This laser consists of a laser controller and a laser head, in which a diode laser pumps a solid-state laser. The dimensions of the compact laser are 95 mm × 28 mm × 37 mm (length × width × thickness). A periodically-poled potassium titanyl phosphate (PPKTP) crystal was used for second harmonic generation at 532 nm. The 532 nm beam was separated from the fundamental light by a dichroic mirror. The fundamental light can be used for possible applications or laser frequency measurement. On the other hand, the 532 nm beam was sent to a saturated-absorption spectrometer with a 40 cm-long iodine cell. The spectroscopy of molecular iodine was performed based on the third-harmonic technique by applying a frequency modulation on the compact laser

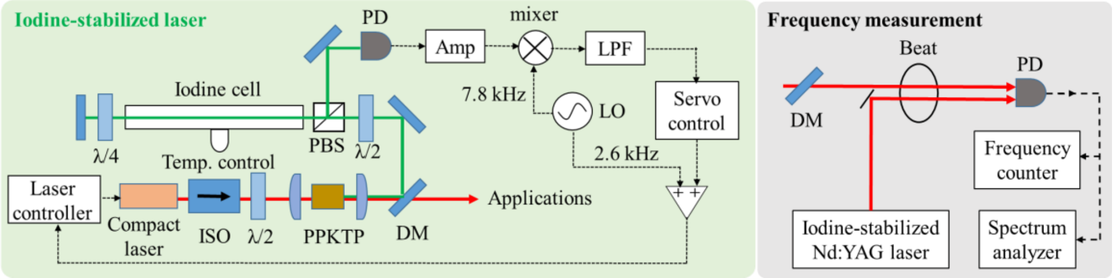

Fig. 1. Setup of a compact frequency-stabilized laser. Optical and electrical paths are shown as solid and dashed lines, respectively. ISO: Isolator, PPKTP: Periodically poled potassium titanyl phosphate, DM: Dichroic mirror, PBS: Polarization beam splitter, PD: Photodetector, LO: Local oscillator, LPF: Low-pass filter.

[3]. The laser beam transmitted through the iodine cell (pump beam) was reflected back to the cell by using a plane mirror. The reflected beam (probe beam) was overlapped with the pump beam. A quarter wave plate ($\lambda/4$) was set between the iodine cell and the mirror, which rotated the polarization of the probe beam by 90° so that the probe beam was reflected by a polarization beam splitter (PBS) and sent to a photodetector (PD).

Usually, the third-harmonic technique is operated with a relatively high modulation frequency of hundreds of kHz to obtain a low-noise signal. However, this laser does not accept such a high-speed modulation. Therefore, we aimed to experimentally overcome this challenge. The original laser frequency was modulated by adding a sinusoidal signal of 2.6 kHz to the injection current of the pump laser in the solid-state laser and the obtained signal was demodulated at 7.8 kHz. Then we successfully obtained a third derivative signal of molecular iodine with a good signal-to-noise ratio. This signal was fed back to the injection current through a servo controller.

3. Results

We observed the hyperfine transitions of the R(86)33-0 line of molecular iodine at 532 nm. The cold-finger temperature of the iodine cell was held at 7 °C, corresponding to an iodine pressure of 8 Pa. The temperature of the cell body was matched to a controlled room temperature of 24 °C. The modulation width was set at Ω = 1 MHz which is shown in Figure 2(a). The frequency of the compact laser was locked to one of the hyperfine transitions, a_{10}. To evaluate the stability of the laser frequency, we measured the beat frequency between the compact laser and an iodine-stabilized Nd:YAG laser using the fundamental light. The frequency stability of the iodine-stabilized Nd:YAG laser is smaller than 10^{-13} at an averaging time τ of 1 s [4]. Therefore, the frequency stability of the observed beat frequency is mainly dominated by the compact laser. Figure 2(b) shows the Allan standard deviation calculated from the measured beat frequencies. The dashed line shows the frequency stability requirement from the linewidth of the NV centers in diamond (< 1/10 of the linewidth). The frequency stability of a free-running compact laser is 1.6×10^{-9} at $\tau = 1$ s corresponding to frequency stability of 4.5×10^{4} Hz in the laser frequency and getting worse as the averaging time increases. The frequency stability of the stabilized compact laser is 2.6×10^{-12} at $\tau = 1$ s and reached 8.7×10^{-13} at $\tau = 100$ s, corresponding to frequency stabilities of 0.72 kHz and 0.25 kHz, respectively. The achieved laser frequency stability is about three orders of magnitude better than the requirement of the NV centers in diamond.

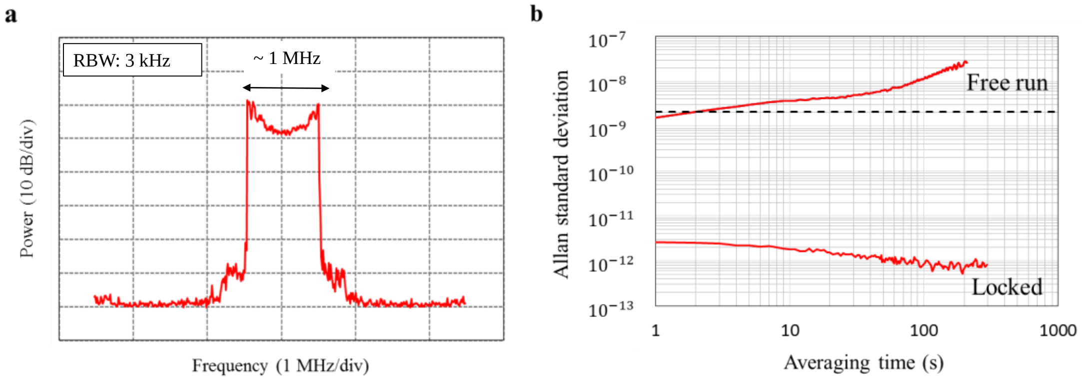

Fig. 2. (a) Spectra of the beat frequency between iodine-stabilized Nd:YAG laser and the compact laser. (b) Allan standard deviation calculated from measured beat frequency between iodine-stabilized Nd:YAG laser and the compact laser

4. References

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