Alternative laser system for cesium magneto-optical trap via optical injection locking to sideband of a 9-GHz current-modulated diode laser

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Abstract: By optical injection of an 852-nm extended-cavity diode laser (master laser) to lock the + 1-order sideband of a ~9-GHz-current-modulated diode laser (slave laser), we generate a pair of phase-locked lasers with a frequency difference up to ~9-GHz for a cesium (Cs) magneto-optical trap (MOT) with convenient tuning capability. For a cesium MOT, the master laser acts as repumping laser, locked to the Cs $6S_{1/2}$ (F = 3) - $6P_{3/2}$ (F' = 4) transition. When the + 1-order sideband of the 8.9536-GHz-current-modulated slave laser is optically injection-locked, the carrier operates on the Cs $6S_{1/2}$ (F = 4) - $6P_{3/2}$ (F' = 5) cooling cycle transition with −12 MHz detuning and acts as cooling/trapping laser. When carrying a 9.1926-GHz modulation signal, this phase-locked laser system can be applied in the fields of coherent population trapping and coherent manipulation of Cs atomic ground states.

OCIS codes: (140.3520) Lasers, injection-locked; (140.3518) Lasers, frequency modulated; (140.3320) Laser cooling; (270.0270) Quantum optics

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1. Introduction

The most obvious approach to provide the cooling/trapping and repumping beams for alkali metal atoms magneto-optical trap (MOT) [1–4] is to use two independent lasers, which demand two corresponding frequency locking systems to improve the frequency stability, and need acousto-optic modulator (AOM) and offset locking to set the appropriate frequency detuning of the cooling/trapping laser. All of these points make the whole system complicated. To simplify the alkali metal atoms MOT, alternative laser systems were introduced using only one single frequency diode laser with radio-frequency (RF) modulation directly applied to the injection current [5,6], or applied to an external high-frequency phase-type electro-optical modulator (EOM) [7] to generate modulation sidebands. Because of the very weak response of the diode laser to RF modulations at several GHz of frequency [8], the generated first-order sidebands are normally much weaker than the carrier, so one of the first sidebands serves as the repumping laser while the strong carrier serves as the cooling laser [5–7]. Although a vertical-cavity surface-emitting laser (VCSEL) [9,10] principally has a higher response frequency, the single-mode output power of the state-of-art VCSEL is limited to below ~mW level, which therefore limits its application. Also, offset locking should be implemented to set the cooling/trapping laser's detuning in the above methods, which is required by the MOT mechanism. If an alternative laser system for the alkali metal atoms MOT can simplify the control scheme of the cooling/trapping laser's detuning, and also plays more roles in relevant experiments, it would be much appreciated for practical applications.

We propose an alternative approach here to generate two phase-locked coherent 852-nm laser beams with a frequency difference of up to ~9 GHz and moderate laser power (several tens of mW). There are various methods to generate two phase-locked laser beams, such as the use of optical phase-lock loops [10], or the use of a high-frequency phase-type EOM [11] or a high-frequency AOM [12] to modulate the output beam of a single-frequency laser, or even directly adding RF modulation onto the injected current of a single-frequency diode laser [9,13,14]. Some of the above schemes require a Fabry-Perot (FP) filter cavity to remove the unwanted modes [13,14] which makes the laser system more complicated. In our approach, the optical injection of an 852-nm extended-cavity diode laser (ECDL, master laser) to lock the + 1-order sideband of a ~9-GHz-current-modulated slave laser is adopted and is applied in atom cooling/trapping. We note that locking of the + 1-order sideband of a ~3-GHz current-modulated slave laser has been reported in ref [15] and the carrier of a ~8.4 GHz current-modulated slave laser has been optically injection locked by a master laser in ref [16]. In our case, the + 1-order sideband has been injection-locked by the master laser when the modulation frequency is extended to the hyperfine splitting of cesium (Cs) ground states (~9.19263177 GHz). It should be stressed here that the modulation response is very weak at 9-GHz level and only several percent of the slave diode laser's total power is distributed to the + 1-order sideband. However, this is already enough for the + 1-order sideband to be injection locked and a larger modulation index is absolutely not necessary. We use the laser system directly for the Cs MOT. When the master laser is locked to the Cs $6S_{1/2}$ (F = 3) - $6P_{3/2}$ (F' = 4) hyperfine transition, the carrier of the slave laser with more than ~90% of total power is used as the cooling/trapping beam and the master laser is used as the repumping beam. This

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has the advantage that we cannot only conveniently and independently change the power of the cooling/trapping and repumping laser beams, but also can conveniently change the detuning of the cooling/trapping laser by only adjusting (or even scanning) the RF modulation frequency. Also, as the two lasers are phase-locked, this laser system can be used to study Cs coherent population trapping (CPT) and coherent manipulation of atomic ground states [13,14] via the stimulated Raman adiabatic passage (STIRAP) scheme in Λ-type atomic system, which requires phase-locked laser beams with a frequency difference of exact hyperfine splitting of the Cs ground state (two-photon resonant but one-photon detuning is several GHz or more.

2. Experimental setup

Optical injection locking has the advantage of transferring the master laser's special characters, such as the narrow linewidth and good frequency stability to the slave laser, and maintaining phase locking between the master and slave lasers. In our experiment, we optically inject the master laser's partial output to lock the + 1-order sideband of the direct-current-modulated slave laser by using a ~9-GHz RF modulation signal. The master laser is an 852-nm home-made grating extended-cavity diode laser (ECDL) in which a single-mode FP-type 9-mm-can-packaged AlGaAs diode laser (JDSU-5411-G1) is inserted into a blazed grating extended cavity in the Littrow configuration (the diffraction efficiency of the grating is ~12%). The typical output power of the ECDL is ~70 mW, and the linewidth is ~500 kHz (50 ms). The slave laser is another single-mode FP-type 9-mm-can-packaged AlGaAs diode laser with moderate output power (~100 mW).

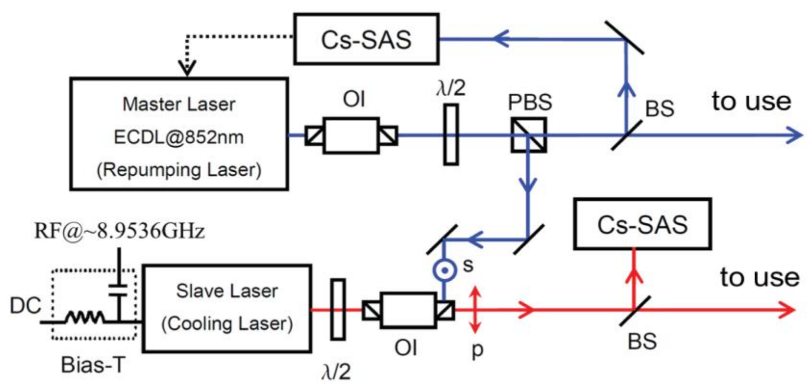

Fig. 1. Experimental setup for our optical-injection-locking scheme. Keys to the figure: ECDL: grating extended-cavity diode laser; OI: optical isolator; Cs-SAS: cesium saturation-absorption spectroscopic device; BS: beam splitter plate; PBS: polarization beam splitter cube; RF: radio frequency signal; λ/2: half-wave plate; s: s polarization; p: p polarization.

A schematic diagram of our optical-injection-locking system is shown in Fig. 1. The output laser beams of the master (repumping) laser and slave (cooling) laser first pass through optical isolators (OI) to avoid optical feedback, respectively. Then the master laser's beam is split into two parts where the s-polarized beam with the power of ~100 μW (measured after the injection beam passed through the slave laser's OI) is injected into the slave laser and overlapped with the output beam of the slave laser for locking of the + 1-order sideband. The master laser is stabilized to the Cs $6S_{1/2}$ (F = 3) - $6P_{3/2}$ (F' = 4) hyperfine transition by using a saturation-absorption spectroscopic (SAS) scheme. A ~9-GHz RF modulation signal is added directly to the slave laser's injection current via a bias-tee (Picosecond Pulse Labs, Model 5547 with typical bandwidth of ~15 GHz). When the + 1-order sideband of the slave laser is optically injection locked by the master laser, the carrier of the slave laser and the master laser have a frequency difference of ~9-GHz, which can be send out for other experiment.

For operation of a Cs MOT, the cooling/trapping laser is normally locked to the Cs F = 4 - F' = 5 cooling cycle transition with a certain red detuning D_c, while the repumping laser is

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normally locked to the Cs F = 3 - F' = 4 transition to pump the atoms accumulated on the F = 3 ground state back to the cooling cycle transition. In our approach, the master laser serves as the repumping laser and the carrier of the slave laser modulated by the RF signal ν_{RF} serves as the cooling/trapping laser. The RF modulation frequency ν_{RF} can be expressed as: ν_{RF} = 9.192 GHz - (251 MHz + D_c) (when red detuning, D_c<0). We can conveniently change the detuning D_c of the cooling/trapping laser by adjusting (or scanning) ν_{RF} and can still make sure the slave laser is injection locked. When ν_{RF} changed from 8.946 GHz to 8.971 GHz, D_c correspondingly changed from −5 MHz to −30 MHz, now the offset locking and AOMs are no longer needed to set or scan the detuning D_c. Furthermore, this laser system can be extended to the applications of CPT and coherent manipulation of Cs ground states via STIRAP scheme in in Λ-type atomic system since the frequency difference between the master laser and the carrier of slave lasers can be swept continuously around 9.19263177 GHz with the slave laser injection locked.

3. Experimental results and discussions

For the FP-type diode laser, the response to RF modulation signal with a frequency of several GHz is normally extremely weak [8], and it will dramatically decrease when the modulation frequency increases, unless operating in the relaxation oscillation peak around ~3 GHz. Typically when the carrier of ~9-GHz-modulated slave laser is injection locked by the master laser (with the injection beam power of ~80 μW), the power of the + 1-order sideband has a proportion of several percent of total power, which is enough to be injection locked by the master laser. The modulation sidebands increase with modulation index following the square of Bessel function [17,18]. If the modulation index is too large, the first sidebands will contain too much energy and higher-order sidebands will appear [17]. We have studied the range where there are no more upper sidebands generated.

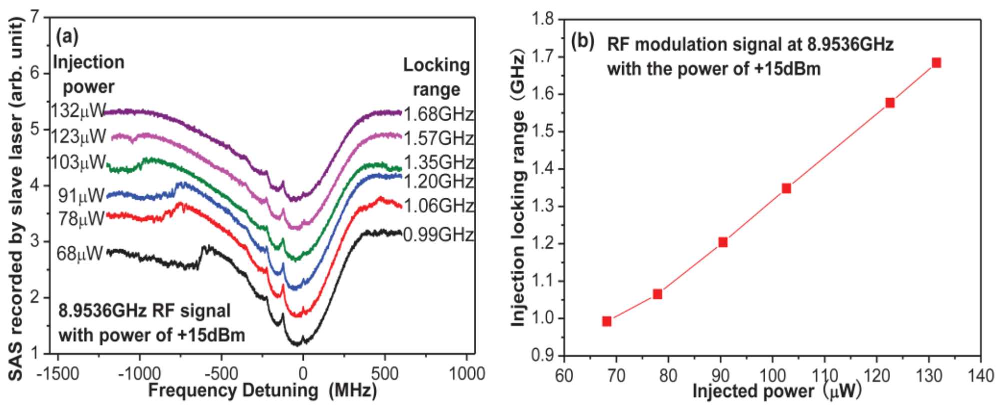

Fig. 2. Influence of the power of the injected beam on the injection locking range of the slave laser when the + 1-order sideband is injection locked by the master laser. (a) The SAS of the slave laser at difference injection beam power. (b) The injection locking range data derived from Fig. 2(a) vs the injected beam's power.

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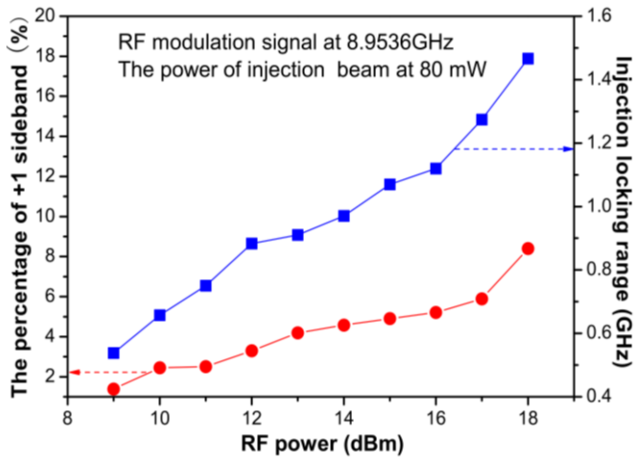

Fig. 3. Influence of the power of the RF modulation signal on the proportion of the + 1 sideband and the injection locking range of the slave laser when the + 1-order sideband is injection locked. The proportion of + 1 sideband (red circles) and the injection locking range (blue squares) are increased with the RF power.

When the RF modulation frequency keeps at 8.9536 GHz, the proportion of the + 1-order sideband is affected by the power of the injection beam and by the power of the modulation signal. When fixing the RF modulation power at 15dBm, Fig. 2 shows the injection locking range of the slave laser as a function of the injected beam power. With the injection power fixed at 80 μW, Fig. 3 shows the proportion of the + 1 sideband (by measuring the transmission spectrums of F-P cavity) and the injection locking range of the slave laser (by measuring the SAS) as a function of the RF modulation signal power. According to the Fig. 2 and Fig. 3, when the + 1-order sideband is injection locked, the locking range of slave laser is increased with the proportion of the + 1-order sideband which is affected by the injection beam power and the RF modulation signal power.

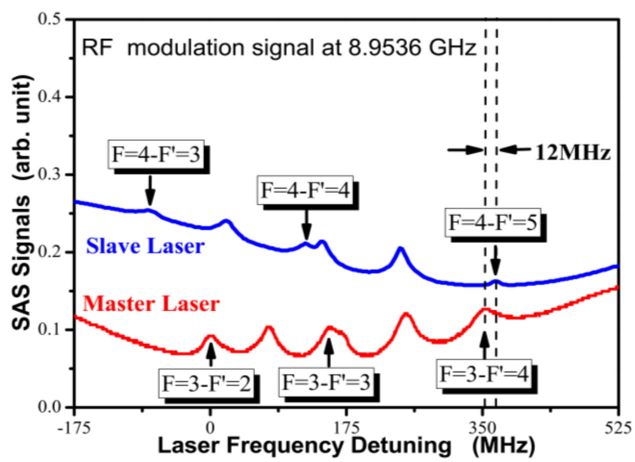

Fig. 4. SAS signals for both the master and slave lasers. The slave laser is directly modulated at 8.953613177 GHz. When the master laser used for the repumping laser of Cs MOT is scanned to the Cs F = 3 - F' = 4 transition, the carrier of the slave laser with the + 1-order sideband injection locked used for the cooling/trapping laser of Cs MOT now is detuned by −12 MHz relative to the Cs F = 4 - F' = 5 cooling cycle transition.

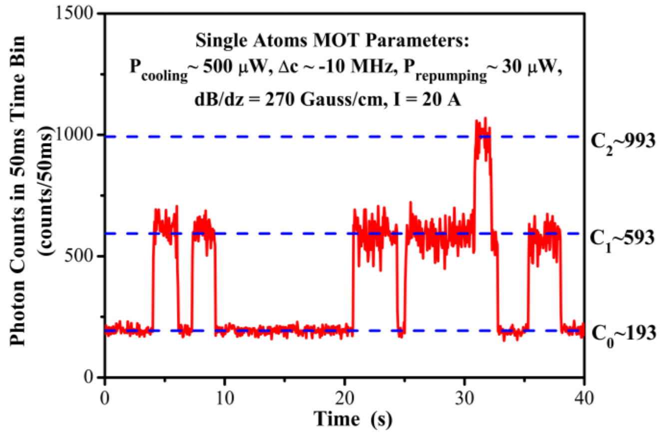

Fig. 5. Typical LIF photon-counting signals for individual Cs atoms trapped in our large-magnetic-gradient MOT under optimized conditions. The three LIF photon-counting levels of C_0, C_1 and C_2, indicate no atom, one atom and two atoms are trapped in the MOT, respectively. The time bin is set to 50 ms.

Our laser system can be applied to a standard MOT [1,13,14] as well as a single-atom MOT [2–4]. To explain the extension of our laser system and to illustrate the subsequent experimental program, we take the single-atom MOT as an example. Figure 4 and Fig. 5 show the use of this laser system for laser cooling/trapping when the modulation frequency is 8.9536 GHz. We can see from Fig. 4 that when the master laser is locked to the Cs F = 3 - F' = 4 transition and thus can be used as the repumping laser, the slave laser's carrier operates on the Cs F = 4 - F' = 5 transition with red detuning Δ_c of 12 MHz, and thus can be used as the cooling/trapping laser. Figure 5 shows that using this laser system we can trap a few atoms or even a single atom in our MOT. Typical laser induced fluorescence (LIF) photon-counting signals of trapped atoms detected by an avalanche photodiode (APD). Relevant experimental parameters are given in the caption of Fig. 5. The discrete steps indicate that an atom randomly enters or leaves the trap. Because each atom contributes the same quantity (~400 counts/50 ms) of LIF photons, the number of atoms trapped in the MOT can be recognized directly from the step level.

An important character of our laser system is that the master and slave lasers are phase coherent, as shown in the beat-note spectrum of Fig. 7. This laser system can thus not only be used in atom cooling/trapping in the MOT, but can also be used in the coherent manipulation of the ground states of a single Cs atom, and in CPT of Cs atoms by changing the RF modulation frequency to 9.19263177GHz. Figure 6 shows that when the + 1-order sideband of the 9.19263177-GHz-modulated slave laser is injection locked, the master laser is locked to the Cs F = 3 - F' = 3(4) transition, and this yields that the slave laser's carrier operates on the Cs F = 4 - F' = 3(4) transition exactly. Figure 7 shows the beat-note spectrum at 9.293 GHz when the master laser was shifted by + 100 MHz by using an AOM. The AOM is used to distinguish the beat-note signal of the master laser and the slave laser's carrier from that of the slave laser's first sidebands and the carrier. The −3dB linewidth is ~1Hz, which means that the two lasers are phase coherent. These two lasers can be coupled to a three-level Cs Λ-system for CPT research [10] if the RF signal is swept around 9.19263177 GHz, and can also be used in coherent manipulation of the Cs ground state through STIRAP scheme [13,14] when the master laser is far detuned to the Cs $6P_{3/2}$ state (GHz and even more). For realization of coherent Rabi flopping and operation of an atomic quantum bit (qubit), the STIRAP scheme can be adopted to coherently manipulate the ground states of a long-lived single Cs atom that is trapped in a far-off-resonance optical tweezer [3].

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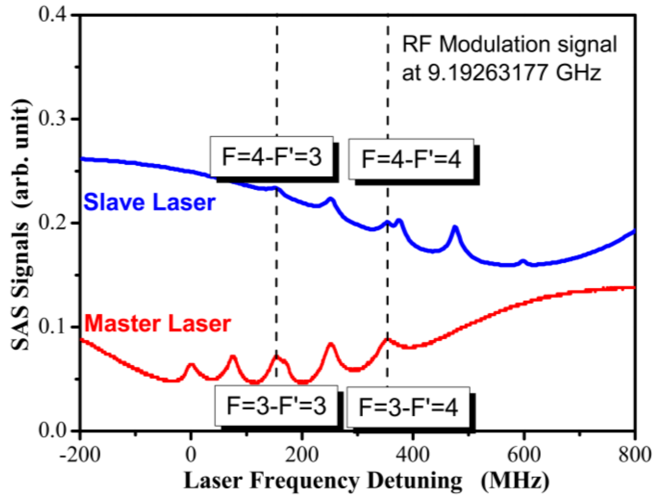

Fig. 6. The slave laser is modulated at 9.192613177 GHz. When the master laser is scanned to the Cs F = 3 - F’ = 3(4) transition, and the carrier of the slave laser with the + 1-order sideband injection locked is exactly resonated to the Cs F = 4 - F’ = 3(4) transition.

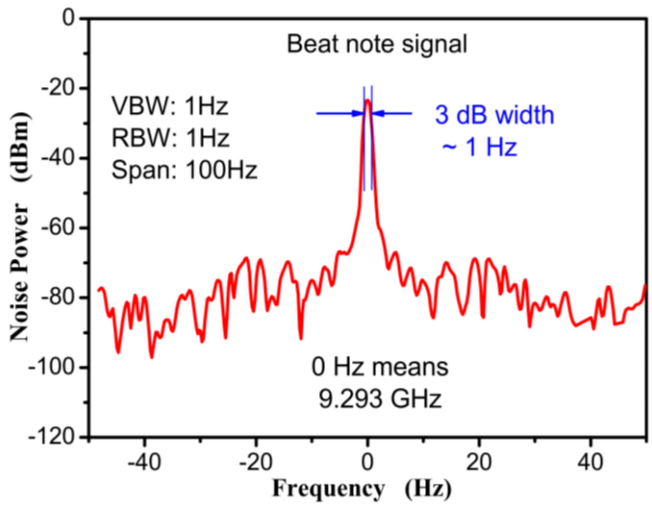

Fig. 7. Beat-note signal at 9.293 GHz measured by using a fast photodiode and the RF spectrum analyzer (Agilent E4405B) which is set as follows: the frequency span is 100 Hz, and the resolution bandwidth (RBW) and the video bandwidth (VBW) are both 1 Hz.

4. Conclusions

In conclusion, a convenient method to produce two phase-coherent lasers with a frequency difference of up to ~9 GHz has been demonstrated experimentally by optical injection locking to the modulated sideband of the slave laser. Using this laser system, an alternative approach for the cooling/trapping and repumping lasers has been implemented in our single-atom Cs MOT. The frequency detuning of the cooling/trapping laser can be changed conveniently by adjusting or scanning the RF modulation frequency, and the offset frequency locking and AOM frequency-shifting systems are not necessary. The master laser and the carrier of the slave laser are phase-locked, and their frequency difference can be adjusted exactly to the hyperfine splitting (9.19263177 GHz) of the Cs ground state, which can therefore be used for CPT experimental research. Also, if the master laser is detuned to the Cs $6P_{3/2}$ state by several GHz and even more, this laser system can be used to implement STIRAP scheme with a Λ-

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type three-level system, which can be adopted to coherently manipulate the ground states of a long-lived single Cs atom trapped in an optical tweezer to serve as qubit.

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