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Phase-coherent addition of laser beams with identical spectral properties

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Abstract

We coherently add two beams from separate diode lasers with identical frequencies to obtain a single coherent beam (degree of coherence $\simeq 1$) with well-defined polarization. The frequencies of the two sources are simultaneously injection locked to a third laser oscillator. The laser beams are merged at a polarizing beam splitter cube with an active stabilization of the relative phase against acoustic noise and thermal drifts. Different schemes to control the relative phase are investigated. The system can easily be extended to coherently add a large number of laser sources.

Keywords: Injection-lock; Seeding; Coherent addition; Diode lasers; Phase lock

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1. Introduction

Laser sources are technologically limited in the maximal output power. Phase-coherent addition of laser beams from separate sources offers a way to overcome this limitation. The ultimate goal is to attain an output beam which is indistinguishable from a beam originating from a single laser source. To this purpose several schemes have been realized. A lossless beam combiner for laser sources with slightly different frequencies is described in [1]. For sources with equal frequencies addition can be achieved by injection locking the laser sources to a master oscillator and combining the laser beams interferometrically by means of a simple beam splitter [2–4]. Alternative combination methods for phase locked laser beams with equal frequencies are realized by means of a binary phase grating [5] or a birefringent element [6]. An electro-optic beam combiner with an integrated phase modulator based on a Ti:LiNbO$_3$ waveguide has been realized in [7].

In this paper we demonstrate a simple method for the coherent combination of two laser beams in order to obtain a laser beam with added intensity at a single frequency. To obtain an output beam that is indistinguishable from the laser beam emitted by a single laser source the two initial laser

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beams should have exactly the same frequency with a constant phase relation and well matched phase fronts. In order to satisfy the first two conditions, we use the method of injection locking [8–12]. Two laser diodes (slave lasers) are seeded by a reference laser (master laser) in order to force the slave diodes to emit laser light with spectral properties that are identical to those of the reference laser. The phase fronts are matched by coupling the beams into an optical fiber.

The basic setup is shown in Fig. 1. The master beam enters the slave diode setup through an optical isolator. The master beam is split into two components at a polarizing beam splitter cube (PBC) in order to simultaneously seed two slave lasers. The beams of the injection-locked slave lasers are superposed on the PBC and the resulting beam passes through the optical isolator in reverse direction. The output beam emanates from the second port of the optical isolator. If the relative phase is equal to zero, linear polarization is attained after the PBC. To maximize the output of the optical isolator, the polarization of the superposed laser beam is adjusted by means of the half-wave plate (HWP). Thermal expansion and acoustic noise can lead to drifts and fluctuations of the relative phase which in turn cause fluctuations in the polarization of the superposed beam. Therefore a monitor beam emanating from the second port of the PBC is used as input for a stabilization scheme which controls the phase of S2 with the aid of a phase shifting element. We achieve an output beam with low intensity noise and a power equivalent to the sum of the powers of the individual slave diodes. The combined beam is coupled into a single-mode polarization maintaining optical fiber with the same efficiency as a beam originating from a single laser source (74%).

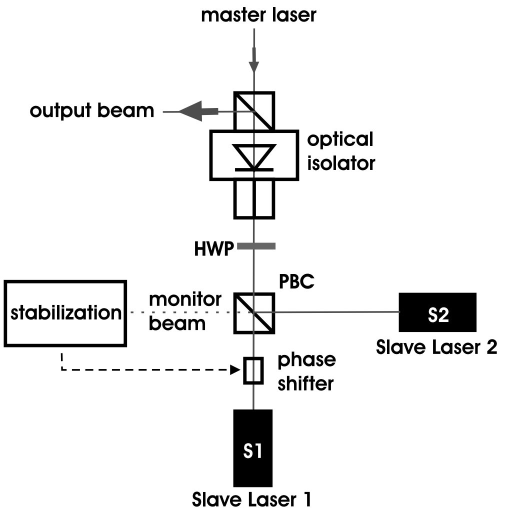

Fig. 1. Sketch of the system to combine laser sources of equal frequencies.

The major advantage of our setup is simplicity, stability and cost efficiency. Our stabilization scheme does not require any modulation technique to attain a bipolar error signal. As a consequence the output beam is free from additional frequency components that would be caused by phase modulation techniques as realized in [2–4]. The methods described in these references realize the stabilization of the relative phase of the merged beams through a slight modulation of the phases which produces a bipolar error signal. With our setup we achieved high addition efficiency and a nearly perfect degree of coherence for the output beam.

This paper is organized as follows: In the next section the simultaneous injection locking of two diode lasers is described. The coherent superposition of the beams is characterized in Section 3. In Section 4 different methods are compared regarding the stabilization of the relative phase against thermal drifts and acoustic noise. The last section describes a possible extension of the setup to a larger number of laser sources.

2. Simultaneous injection lock of two lasers

A more detailed diagram of our setup is shown in Fig. 2. The reference laser for the injection lock consists of a temperature- and current-stabilized diode laser (Hitachi HL7851) whose spectral width is reduced by an external grating resonator [13,14]. The elliptical transverse profile is transformed into a circular profile by an anamorphic prism pair (AP1). The optical isolator rotates the polarization of the master beam by 45°. With the anamorphic prism pair the transverse mode of the master beam is matched with the profiles of the slave beams.

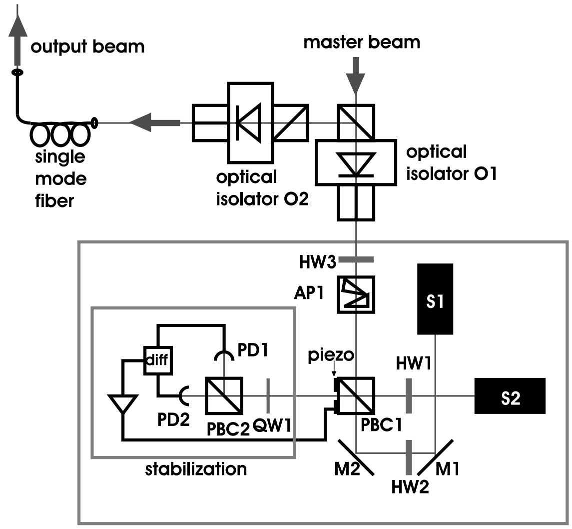

Fig. 2. Detailed view of the coherent laser beam combiner.

Additionally, AP1 provides for a circular shape of the output beam. PBC1 splits the master light for injection locking of the two slave diodes (S1 and S2). The slave beams are emitted by two laser diodes (DL7140-201, Sanyo) which are temperature- and current-stabilized. These two diodes are axially rotated in such a way that their elliptical beam profiles are equally oriented. If the master beam and the slave beams are spatially well overlapped, and if the temperature and the supply current are adequately chosen, the light fields of both slave diodes identically follow the spectral properties of the master laser.

The injection lock is best characterized by the locking range, i.e. the frequency range of the master laser over which the slave diodes follow the master laser. The locking range depends on the overlap and mode matching between the beams of master and slave. It increases with the intensity of the master laser that is coupled into the slave diode. Under optimal conditions in our setup the minimal master-beam intensity for stable injection locking of both slaves was measured to be as low as 20 μW. The range is given by $\Delta\nu_{\text{lock}} = \frac{\gamma_e}{\pi}\sqrt{\frac{P_{\text{master}}}{P_{\text{slave}}}}$ [8], with P_{master} and P_{slave} denoting the powers of the master and slave respectively, and γ_e the energy loss rate of the resonator. One therefore expects a square root functional dependence of the locking range versus the injected power. Fig. 3 shows the measured locking range as a function of the master intensity monitored on a Fabry-Perot cavity into which both slave lasers are coupled. The locking range of the combined setup is equal to the locking range of one laser diodes. The data was fitted with $\Delta\nu = A\sqrt{P_{\text{master}}}$ with $A = (1090 \pm 30)\ \text{MHz}/\sqrt{\text{mW}}$ (dashed line).

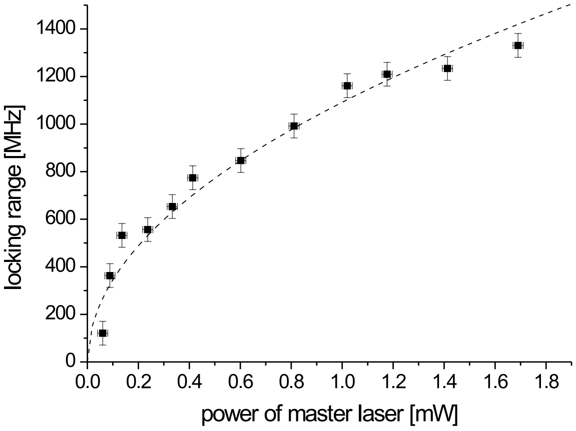

Fig. 3. Locking range for the combined slave laser as a function of the injected power. The dashed curve is a square root function fitted to the data.

In order to characterize the quality of the injection lock we measured the frequency spectrum of the output beam by recording the beat note between the master beam and the slave laser with a fast photodiode. The master beam was shifted by about 140 MHz with an acousto-optical modulator (AOM). The measured width of the beat signal was less than 1 kHz thus completely determined by the resolution bandwidth of the spectrum analyzer. The center frequency of the beat note drifts over a range of about 1 kHz on a time scale of several seconds which reflects a drift of the voltage controlled oscillator in the driving electronics of the AOM. There are no indications for incoherent contributions to the beat signal.

3. Coherent superposition and interference

Exact matching of both slave beams after PBC1 is crucial for obtaining an added beam indistinguishable from a beam of a single laser source. The electric field vector of the coherently added beam is given by $\vec{E} = (1/\sqrt{4\epsilon_0 c})\mathrm{e}^{-\mathrm{i}\omega t}\begin{pmatrix}\sqrt{I_1}\\ \sqrt{I_2}\mathrm{e}^{\mathrm{i}\phi}\end{pmatrix} + \text{c.c.}$ with I_1 and I_2 denoting the individual intensities of S1 and S2, respectively. Thus, the polarization depends on the relative phase ϕ and on I_1 and I_2. Linear polarization is achieved for $\phi = 0$. For $I_1 = I_2$ the polarization is along $\binom{1}{1}$, for $I_1 \neq I_2$ the polarization is rotated. The half-wave plate HW3 is thus necessary to orient the polarization along $\binom{1}{1}$ in order to maximize the output of the optical isolator O1. Relative phases different to zero lead to circular light components in the added beam which are transformed into intensity losses by the polarizers of the optical isolator O1. In order to adjust the relative phase between S1 and S2, PBC1 can be moved towards S1 by a piezo electric actuator, which varies the relative optical path between the beams from S1 and S2. The output beam is coupled into a single-mode polarization maintaining optical fiber to filter the beam spatially and attain perfect mode matching. We achieved a transmission of 74% for the combined laser beam. A second optical isolator O2 is inserted before the fiber as the phase stabilization is extremely sensitive to feedback of light from the fiber.

Fig. 4 shows a measurement of the power transmitted through the fiber while the piezo voltage was scanned periodically. From the visibility of the interference pattern $\eta = (P_{\max} - P_{\min})/(P_{\max} + P_{\min})$ one can deduce the degree of coherence $\gamma = \eta(P_1 - P_2)/(2\sqrt{P_1 P_2})$ [15]. The powers were measured to be $P_1 = 34.8(5)$ mW, $P_2 = 32.8(5)$ mW, $P_{\max} = 68.4(5)$ mW, $P_{\min} = 0.89(3)$ mW, from which the visibility $\eta = 0.974(1)$ and the degree of coherence $\gamma = 0.975(1)$ are obtained. This shows the excellent phase correlation between the slave diodes. The output beam after the fiber indeed behaves like a beam originating from a single laser source. The slight deviation from perfect coherence might be accounted for by supply current noise of the slave laser diodes and incomplete seeding.

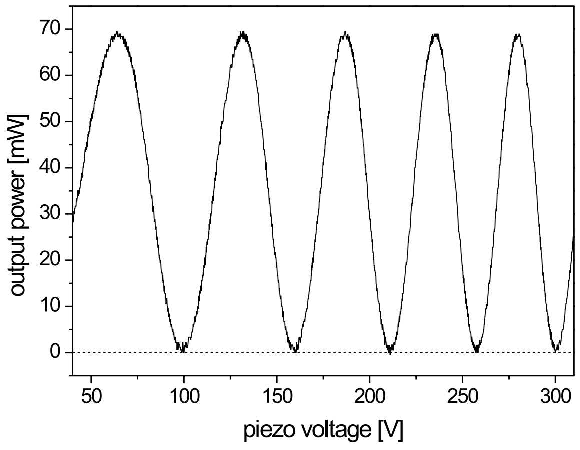

Fig. 4. Power of the output beam as a function of the piezo voltage which determines the difference between the optical paths of S1 and S2.

4. Stabilization of the relative phase

The relative phase is subjected to drifts due to thermally caused variations in the relative optical path length or fluctuations due to acoustic noise. This leads to fluctuating circular light components in the added laser beam. To guarantee a fixed linear polarization of the combined laser light which maximizes the throughput of the optical isolator, the relative phase has to be stabilized. A monitor beam is split from the merged slave beams by slightly rotating the polarizations of the two slave beams with the help of half-wave plates HW1 and HW2 (see Fig. 5). As a consequence, a small amount of laser light leaves PBC1 through the second port. Polarimetric measurements on the monitor beam are performed to obtain a bipolar error signal which is proportional to $\sin(\phi)$, where ϕ denotes the relative phase between S1 and S2. HW1 and HW2 should be adjusted in such a way that they contribute equally to the intensity of the monitor beam.

The stabilization is achieved by means of a simple proportional integral derivative (PID) servo loop on the piezo electric actuator at PBC1.

To characterize the noise, the frequency spectrum of the intensity was measured with a resolution bandwidth of 10 kHz. The relative intensity noise of the merged beam shows a uniform distribution over a range of about 1 MHz and equals −40 dB. The relative noise expected by incoherent addition of both slave diodes would be −43 dB.

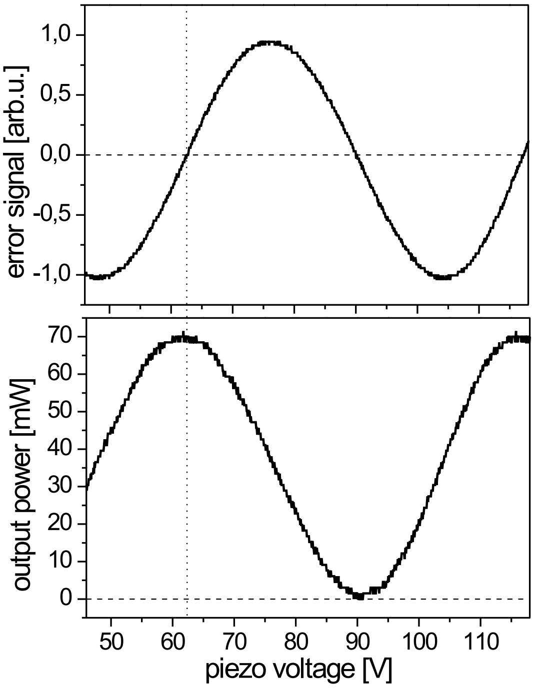

Fig. 5. Error signal and the corresponding output power as a function of the piezo voltage. The vertical line shows the piezo voltage at which the system is stabilized for maximum output power.

The slight increase in intensity noise is accounted for by the fact that the intensity of the merged beam is sensitive to fluctuations in the relative phase which are generated by high frequency current fluctuations in the supply current and technical noise of the interferometer.

Instead of using a piezo-electric actuator the relative phase between the slave laser fields can be influenced by an electro-optical modulator or another phase shifting element in one of the optical paths of the slave diodes. The relative phase can also be changed by modulating the master frequency if there is a difference in the optical path between S1 and S2. In Fig. 6 the dependence of the error signal on the master frequency detuning is shown. Between −600 and 800 MHz both slave lasers are phase locked. If the frequency is scanned beyond the locking range, the injection lock breaks down. This results in a sudden change of the error signal. Within the locking range the error signal is proportional to $\sin(4\pi\Delta x(\nu - \nu_0)/c)$, with Δx denoting the difference in the optical path between S1 and S2, ν denoting the laser frequency, ν_0 denoting the reference frequency (D2 transition of ^{87}Rb) and c denoting the speed of light. By means of a fit Δx is determined to be 6.5(1) cm which is in accordance with the actual path length difference.

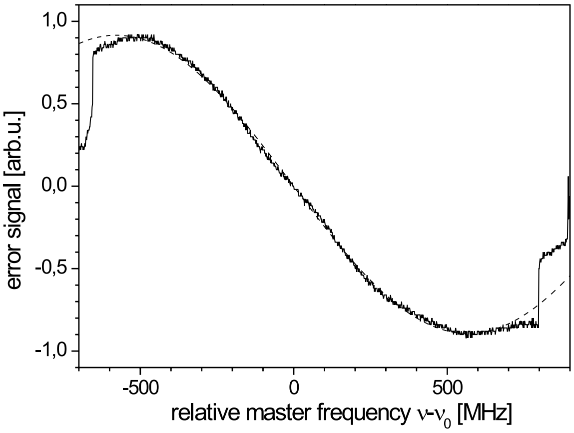

Fig. 6. Error signal as a function of the detuning of the master laser. The reference frequency ν_0 is given by the D2 transition of ^{87}Rb. Due to a difference in the optical path lengths of S1 and S2 the relative phase ϕ is changed. The error signal is proportional to $\sin(\phi)$. The dashed curve is a sinusoidal fit to the error signal.

If the frequency of the output beam is to remain fixed the relative phase between the two diode lasers can be controlled by changing the injection current of S1 or S2. The phase of the slave laser field changes with current since the refractive index increases linearly with the amount of electrons injected into the laser active volume. This effect can be seen in Fig. 7. The error signal is plotted versus ΔI, the difference of the supply currents of S1 and S2. We varied the injection current of S1 and S2 in opposite directions in order to double the phase shift over the locking range. If ΔI is less than 0.4 mA the error signal shows a sinusoidal dependence on the current since it is proportional to $\sin(\phi)$ with the phase $\phi = (\partial\phi/\partial I)\Delta I$ where $\partial\phi/\partial I$ is denoting the derivative of the phase with respect to the current. Out of a fit we obtained $\partial\phi/\partial I = 4.5(1)\ (\mathrm{mA})^{-1}$. If ΔI is scanned beyond 0.4 mA the injection lock breaks down causing a sudden change in the error signal. With our setup, the phase could be changed by $\pm\pi/2$. This

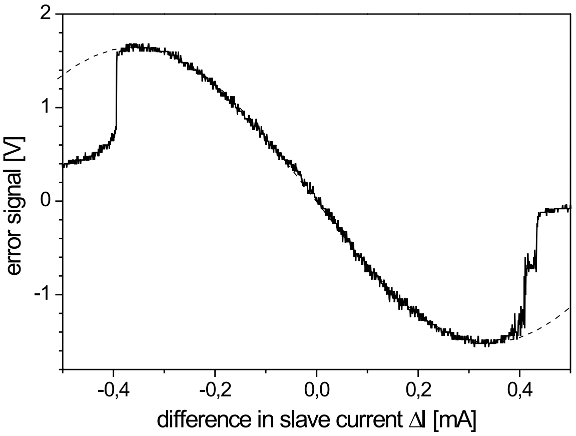

Fig. 7. Error signal as a function of the difference in supply current of S1 and S2. The currents for S1 and S2 are scanned in opposite direction. The dashed line is a sinusoidal fit to the error signal.

provides a high-speed method for phase locking which can be used to improve the stability.

5. Outlook

We have shown that two independent slave diodes can be seeded simultaneously by one master and added coherently to obtain a beam with doubled intensity, indistinguishable from a beam of a single laser source. We use this system as a stable laser source for a magneto-optical trap. The stability of the setup allows us to drive the magneto-optical trap continuously over several hours. The concept can be applied to coherently add the output of several laser amplifiers. Adding laser power from separate sources becomes particularly important if one wants to drive nonlinear processes. For example, the output power of a frequency doubling setup is quadrupled if supplied with a combined laser beam of doubled power.

Fig. 8 shows how the setup can be upgraded to obtain an output beam with four times the power of a single laser. The dashed boxes contain the laser combination setup for two laser sources as shown in Fig. 2. Their output beams are combined with orthogonal polarization on a PBC to obtain an output beam with four times the power of a single laser diode. The phase is stabilized via the same polarimetric method used for the combination of two laser sources. All slave laser diodes are injection locked by the same master laser. Note, that only one optical isolator is needed. As this device is usually the most expensive part of the setup, high-intensity coherent beams can be obtained at low cost. The system can be further extended in a tree-like manner. For N source lasers, $(N-1)$ stabilization setups are needed.

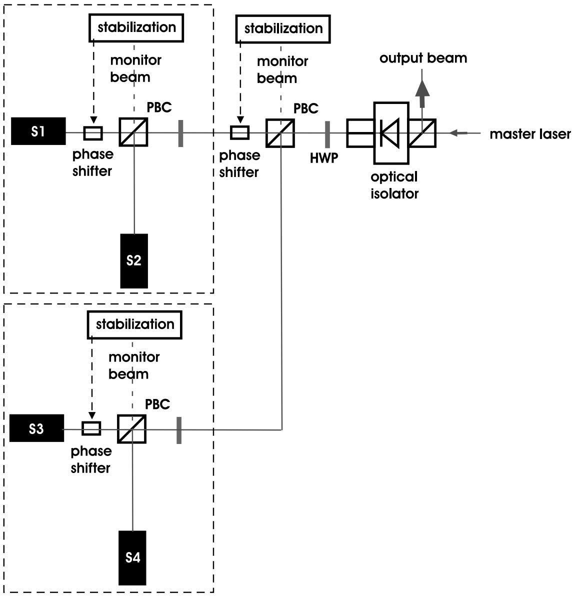

Fig. 8. The setup can be extended by successively adding blocks of dual laser beam combiners (dashed boxes) in a tree-like manner and stabilizing the relative phases between these blocks.

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