Active sub-Rayleigh alignment of parallel or antiparallel laser beams

Holger Müller, Sheng-wey Chiow, Quan Long, Christoph Vo, and Steven Chu

Physics Department, Stanford University, Stanford, California 94305

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We measure and stabilize the relative angle of parallel and antiparallel laser beams to 5 nrad/$\sqrt{\text{Hz}}$ resolution by comparing the phases of radio frequency beat notes on a quadrant photodetector. The absolute accuracy is 5.1 and 2.1 μrad for antiparallel and parallel beams, respectively, which is more than 6 and 16 times below the Rayleigh criterion. © 2005 Optical Society of America

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Lasers are universal tools as high-precision rulers, i.e., references of length, time, or spatial direction. Examples are the definition of the meter, experiments in fundamental physics,[1,2] and precision inertial sensing. Extremely high accuracy, both in terms of frequency and phase[3] as well as pointing stability, is demanded in atom interferometry,[4–6] which is applied for atomic clocks and inertial sensing for the measurement of Newton's constant G, the local gravitational acceleration g, and the ratio of the Planck constant to the mass of an atom $\hbar/M$. In atom interferometers that use two-photon transitions driven by counterpropagating laser pulses as beam splitters,[7,8] the phase of the matter waves is measured against the effective wave vector $|\mathbf{k}_{\text{eff}}|=|\mathbf{k}_1|-|\mathbf{k}_2|\cos\alpha$, where $\alpha\simeq\pi$ is the angle between the individual wave vectors $\mathbf{k}_{1,2}$. Present precision atom interferometers, such as the measurement of $\hbar/M$ to a few 10^{-9} absolute accuracy, require the same level of accuracy in $|\mathbf{k}_{\text{eff}}|$,[9] and further improvements are expected. For an accuracy goal of 10^{-10}, initial misalignment, vibration, or creep in the counterpropagation angle α must be kept below 20 μrad. However, creep of conventional optics setups leads to a systematic error of the order of 10^{-9} in $|\mathbf{k}_{\text{eff}}|$ in current experiments.[9] Therefore, we developed an active control system to stabilize the alignment of parallel and antiparallel laser beams.

The power of optical systems to resolve a small angle β between light rays is often given in terms of the Rayleigh criterion $\beta\gtrsim\beta_R\equiv\lambda/a$, where λ is the wavelength and a the aperture.[10] Even for the large beam diameters common in atom interferometry (in our setup, $\lambda=0.852\ \mu$m and the beam waist $w_0\approx a/\pi\approx0.8$ cm, which implies $\beta_R\approx34\ \mu$rad), sub-Rayleigh alignment is necessary for a 10^{-10} precision in $|\mathbf{k}_{\text{eff}}|$. Conventional methods of measuring the angle β are not well suited for this purpose: for example, a pair of pinholes is often used to test the alignment, but it does not indicate the direction of a misalignment. Active alignment is facilitated by using a corner cube to retroreflect one of the beams and testing the parallelity afterward. [Hollow corner cubes that are certified to have subarcsecond ($\approx5\ \mu$rad) alignment errors are commercially available.] High sensitivity is achieved by using the interference fringes between the beams to indicate the relative alignment.[11–13]

In this Letter we report a system that solves the problem of beam-pointing fluctuations in optics setups such as the laser systems used in atom interferometry. We detect the relative angle by a beat note measurement on a quadrant photodetector (QD) (Fig. 1) by using radio frequencies above the technical $1/f$ noise floor of lasers. A servo tracks the pointing of one beam relative to the other. The high absolute accuracy of our method is confirmed by a detailed study of the systematic effects.

Whenever two overlapped electromagnetic waves having a frequency difference of ω are detected (by using a photodiode, for example), interference causes an oscillating component (beat note) at ω. For an infinitely small detector area, the beat note's phase is equal to the phase difference ϕ of the waves at the location of the detector. For parallel beams, ϕ is constant on the cross section of the beams. If the beams are misaligned by an angle $\beta\ll1$, however, $\phi=2\pi r\beta/\lambda$ is a function of the distance r from the center on the plane of incidence (Fig. 1). Thus, measuring $\phi(r)$ at different locations reveals the angular alignment. For separately measuring the two relevant angles, we measure the phases between two pairs of detectors. Therefore, we split off an $\sim$1% intensity sample by using a residual reflection from a polarizing beam splitter (PBS), where the polarizations are set for maximum transmission (Fig. 1). The sample beams are directed to a QD, one by retroreflection from the corner cube.

For calculating the phase differences for a QD of finite radius R, we calculate the interference pattern

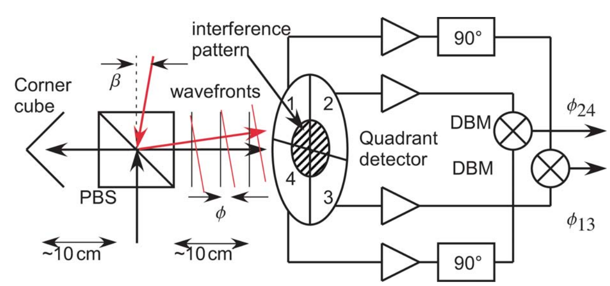

Fig. 1. (Color online) Schematic of the setup for antiparallel beams.

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due to two Gaussian beams within the Rayleigh range (where the wavefronts are essentially flat), tilted relative to each other by an angle $\beta \ll 1$. The beat note is given by the intensity integrated over the area of one quadrant,

$$I_1 = 2|E_1E_2| \int_0^R \int_{-\pi/4}^{\pi/4} r \exp(-2r^2/w_0^2) \times \cos(\beta kr \cos\theta - \omega t)\mathrm{d}\theta \mathrm{d}r, \quad (1)$$

where r and θ are cylindrical coordinates on the QD's surface and $k=2\pi/\lambda$. The integration is carried out to the first order in β by decomposing the outer cosine according to $\cos\alpha=(e^{i\alpha}+e^{-i\alpha})/2$ and then using $\exp(iz\cos\theta)=\Sigma_{n=-\infty}^{\infty} i^n J_n(z)e^{in\theta}$. We write the result as $I_1=\text{constant}+N\cos(\omega t+\phi_1)$, where N is the amplitude of the beat note and $\tan\phi_1=(w_0/\lambda)s(\eta)\beta$ its phase. The function $s(\eta)=2[\sqrt{\pi}\Phi(\eta)-2\eta e^{-\eta^2}]/[1-\exp(-\eta^2)]$ depends on the ratio $\eta=\sqrt{2}R/w_0$ [$\Phi(\eta)=(2/\sqrt{\pi})\int_0^{\eta}\exp(-t^2)\mathrm{d}t$ is the probability integral]. For $w_0=0.8$ cm, $R=0.5$ cm, the phase difference between opposite quadrants $\phi_{13}=\phi_1-\phi_3=2\phi_1 \sim 6.6\times10^4\beta$.

Since the beat is completely determined by the interfering radiation, its phases are quite insensitive to the arrangement of the detection system. Thus, $\phi_{13}=\phi_{24}=0$ indicates counterpropagation, regardless of the orientation of, e.g., the detector, the corner cube, or the PBS with respect to the beams (assuming no corner cube errors and that the setup is small compared with the wavelength of the beat frequency). Also, if the interfering beams are parallel, but not accurately overlapped, the phase shift between the quadrants remains zero, even if additionally the center of the QD is off the center of the interference pattern. Also note that ϕ_{13} and ϕ_{24} are independent of the ω and that imbalances in photodetector sensitivity or area should not offset the zero of the phase measurement. This insenitivity to systematic effects and the linear dependence of the signal (rf phase difference) on the counterpropagation angle β make our method well suited for reaching sub-Rayleigh absolute accuracy.

The method directly stabilizes the relative orientation of the wavefronts, which is the quantity that matters in atom interferometry. As long as the detector is close to the atom interferometer, different radii or positions of the waists can be tolerated: if for each beam both the QD and the atoms are within z_R/n distance to the waist and centered to within w_0/m, then the error will be $\lesssim \beta_R/(nm)$. For the above beam parameters and n,m at least 5 (which is easy to achieve), $\beta_R/(nm)=1.5$ μrad.

The optical setup is built on a (floating) optical table, using standard lens holders and mirror mounts. The signals from the quadrants are amplified by transimpedance amplifiers in the cascode transistor configuration,[11] using LM7171 operational amplifiers. The amplifier bandwidth of 40 MHz reduces their phase shifts to 40 mrad at $\omega=2\pi\times1$ MHz, corresponding to a 0.4 μrad offset in β; this, however, cancels out if the amplifiers are alike.

The amplified signals are converted to emitter-coupled logic signals by four comparators (type AD96687). This reduces the influence of laser power variations on the subsequent stages. Double-balanced mixers (DBMs), type LPD-1 by Mini-Circuits, are used as phase detectors. Since double-balanced mixers produce zero average output voltage when driven by quadrature signals, we shift ϕ_1 and ϕ_4 by 90° by using critically damped second-order low-pass filters before the comparators. Using broadband 90° shifting networks such as quadrature power splitters can yield a frequency range of about 2:1 (also removing the need for trimming). Using sample-and-hold-type phase detectors would eliminate the need for a phase shifter and could have a several gigahertz bandwidth. The dc output of the mixers is low-pass filtered to an ~10 kHz bandwidth and is amplified by a factor of 10 to the ±12 V range. The sensitivity of this circuit to the rf phase difference is measured to be 10.9 mV/mrad for the X channel and 10.2 mV/mrad for Y, corresponding to a sensitivity to the beam misalignment angle β of 0.72 and 0.67 V/μrad, respectively.

For testing and trimming the electronics, one could rotate the QD around its axis, which should cause no error in the counterpropagation angle. A simpler method, however, is to use two laser beams separated by 1 MHz in frequency and overlapped in a common single-mode fiber as a copropagation reference. After an initial trim of the phase shifters, the drift is below 0.15 μrad beam alignment error over several weeks. Reducing the intensity of the beams by a factor of up to 8 causes an error below 0.7 μrad. (Further reduction causes errors, as the beat notes become too weak for accurate phase measurement.) Thus the overall long-term error of the electronics is estimated as <1 μrad.

We also study the influence of the optical elements on the accuracy. Two counterpropagating beams are aligned to produce zero misalignment error signals. Setting an iris in front of the QD then causes no offset larger than 0.5 μrad for diameters of 5–10 mm.

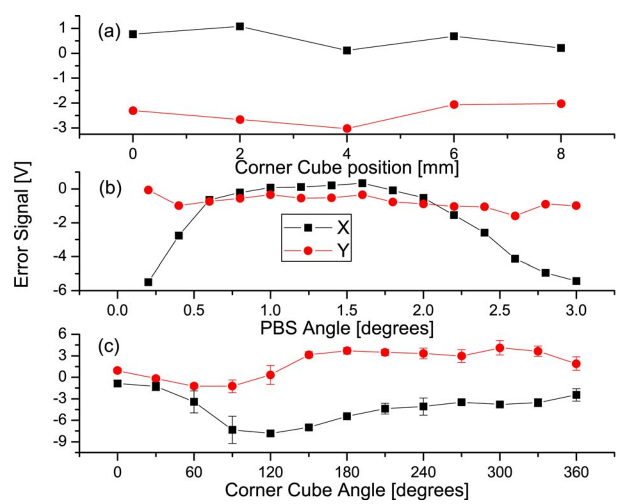

Fig. 2. (Color online) Tests for systematic influences: (a) parallel shift of the corner cube, (b) PBS alignment, (c) rotation of the corner cube.

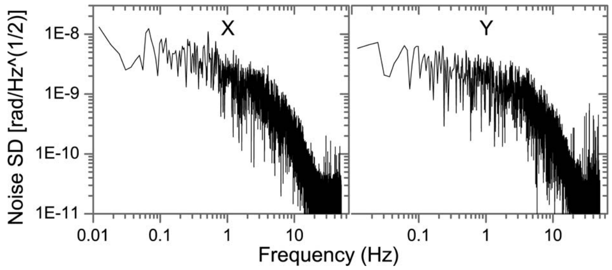

Fig. 3. Noise spectral density (SD) of the angle measurement.

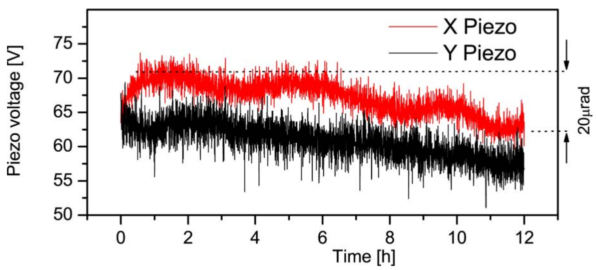

Fig. 4. (Color online) 12 h operation of the system.

(For smaller diameters, errors arise due to insufficient signal amplitude.) Shifting the corner cube orthogonally to the sample beam directions by up to 8 mm causes an error below 1.4 μrad; see Fig. 2(a). We test rotating the PBS away from its optimum position. For rotations below $\sim 0.8°$, the error is below 1.3 μrad; see Fig. 2(b). Larger rotations cause strongly reduced signal amplitude: a 1° rotation offsets the centers of the beams on the QD by 3.3 mm from each other and by 5 mm—the QD's radius—from the QD (Fig. 1). Thus this measurement also demonstrates the low influence of beam displacement. The error ϵ in the retroreflection angle of the corner cube is tested by rotating the corner cube around the beam axis, which should cause a modulation of 2ϵ peak to peak in the X and Y alignment error signals. The data shown in Fig. 2(c) shows a peak deviation of $\epsilon = 4.6$ μrad (including an ~ 2 μrad drift of the beam alignment during the measurement), within the manufacturer's specification of $\epsilon \lesssim 5$ μrad. We also test the resolution by using two beams from a single-mode fiber as a stable copropagation reference. The noise spectral density of both channels (Fig. 3) is essentially white at $\lesssim 5$ nrad/$\sqrt{\text{Hz}}$ between 0.01 and 1 Hz.

For active control of the alignment by a proportional-integral feedback, we use a pair of mirrors that can be tilted by about 200 μrad with piezo actuators with a sensitivity of ~ 2 μrad/V and a resonance frequency of 1.2 kHz. This works reliably, as demonstrated by the 12 h time trace shown in Fig. 4. The servo corrects for short and long term alignment fluctuations of the order of 20 μrad with ~ 3 nrad/$\sqrt{\text{Hz}}$ residual noise in the error signals. In actual atom interferometry applications, parts of the optics may be mounted on a floating vibration isolator, whose creep would considerably increase the long-term errors without active stabilization. We plan to operate the beam stabilization for about 1 s every few minutes and store the applied correction. This should be sufficient for keeping the error below 15 μrad at all times.

We have demonstrated a system for measuring and maintaining the counterpropagation of laser beams, based on retroreflecting one beam and comparing the phase of beat notes between them on a quadrant photodetector. We reach a resolution of 5 nrad in 1 s integration time. Tests for systematic influences indicate an overall absolute accuracy of better than 5.1 μrad, six times below the Rayleigh criterion of 34 μrad. If the setup is used for copropagating beams, the corner cube inaccuracy is eliminated, giving 2.1 μrad absolute accuracy.

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