Interrogation Laser for a Strontium Lattice Clock

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***Abstract*—We report on the setup and characterization of a 698-nm master–slave diode laser system to probe the $^1S_0-^3P_0$ clock transition of strontium atoms confined in a 1-D optical lattice. A linewidth on the order of about 100 Hz of the laser system has been measured with respect to an ultrastable 657-nm diode laser with 1-Hz linewidth using a femtosecond fiber comb as a transfer oscillator. The laser has been used to measure the magnetically induced $^1S_0-^3P_0$ clock transition in ^{88}Sr, where a linewidth of 165 Hz has been observed. The transfer oscillator method provides a virtual beat signal between the two diode lasers that has been used to phase lock the 698-nm laser to the 1-Hz-linewidth laser at 657 nm, transferring its stability to the 698-nm laser system.**

***Index Terms*—Atomic clocks, frequency control, laser stability, optical phase-locked loops (PLLs), semiconductor lasers.**

I. Introduction

Optical lattice clocks with strontium have reached relative uncertainties of below 10^{-15} [1]–[6]. Their stability is ultimately limited by the quantum projection noise, which, for uncorrelated 10^6 atoms and a Fourier-limited linewidth of 1 Hz, would result in an Allan deviation of the relative frequency fluctuations of $\sigma_y(\tau) \approx 10^{-18} \cdot \tau^{-1/2}$. However, to reach this short-term stability, even better stability from the clock laser is needed. Therefore, an improved optical source, which is phase stable during the required interrogation time of a few seconds, represents a key technology for optical frequency metrology [7]–[9]. Until a few years ago, the investigation of the instability of a laser system was only possible by comparison with a similar system operating at the same wavelength. With the development of the frequency comb technology [10]–[13], it is now possible to measure the instability and linewidth of an ultranarrow laser by comparison with another laser system operating at a different wavelength [2], [3]. In addition, the use of frequency combs can be combined with a phase-locking technique to stabilize a laser system with a large intrinsic linewidth to a reference laser with an ultranarrow linewidth [3]. This way, the stability of a reference laser can be transferred to any other laser system. Thus, the task of designing a clock laser system for a certain frequency standard can be split into two parts: 1) the design of an ultrastable reference laser at a wavelength that allows for ultimate stability and reliability and 2) the transfer of this stability to a less-sophisticated laser system operating at the desired wavelength.

This paper is organized as follows: After a short description of a master–slave diode laser system designed for probing the 698-nm clock transition of strontium atoms confined in a 1-D optical lattice (Section II), we discuss the characterization of this laser system by comparing its frequency with that of a 1-Hz linewidth laser at 657 nm used in a Ca clock [1] (Section III). In Section IV, we present the results of the magnetically induced spectroscopy of the $^1S_0-^3P_0$ clock transition of the bosonic strontium isotope ^{88}Sr. The virtual beat signal derived with the transfer oscillator method is used to phase lock the 698-nm laser system to the 1-Hz-linewidth laser. We discuss this phase-locking method in Section V.

II. Setup of the Clock Laser System

For probing the $^1S_0-^3P_0$ strontium clock transition, we have set up a 698-nm cavity-stabilized master–slave diode laser system, as shown in Fig. 1. The cavity and laser setup follows the design of the 657-nm laser [1]. To reduce seismic noise, the cavity is placed on a vibration isolation platform inside an acoustic isolation box. Because of limited space and to avoid disturbing the isolation system, both lasers are placed on a separate breadboard measuring 60 cm × 90 cm. A short polarization-maintaining single-mode optical fiber of 1.5-m length links the master laser with the cavity setup. As shown in the similar setup of the 657-nm laser, the vibrational and thermal fiber noise does not limit master laser stability at the level of 1-Hz linewidth [1].

The master laser is an extended cavity diode laser in Littman configuration operated at a diode temperature of 44 °C with an output power of 4 mW. Its output frequency is locked to a high-finesse optical cavity using the Pound–Drever–Hall [14] stabilization technique. An acoustooptic modulator (AOM) introduces a frequency offset for tuning the laser. The cavity consists of a 100-mm-long spacer made of ultralow expansion glass. The optical axis of the cavity is horizontally oriented. A cavity finesse of 330 000 has been measured, corresponding to a linewidth of 4.5 kHz. The cavity is mounted in a temperature-stabilized vacuum chamber at a residual pressure of 10^{-7} mbar.

To minimize the sensitivity against vertical vibrations, the cavity is supported at four points near its horizontal symmetry plane [15]. The support design is slightly different from that

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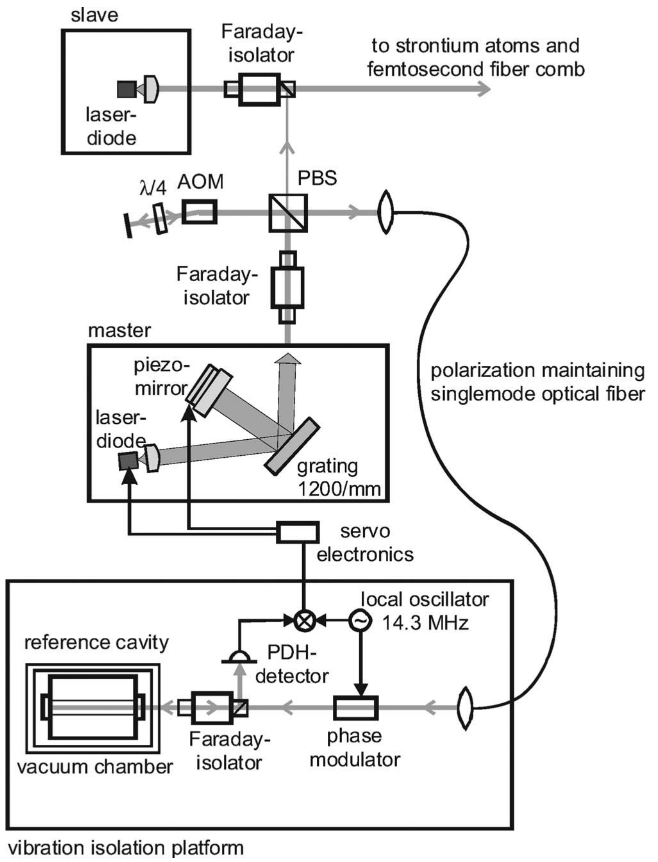

Fig. 1. Setup of the master–slave diode laser system for probing the strontium clock transition.

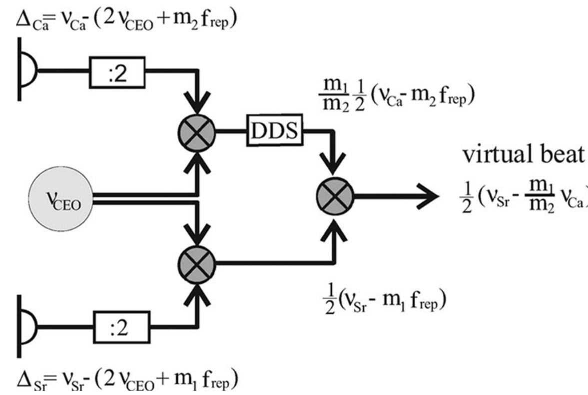

Fig. 2. Schematic of the RF electronics for generating a virtual beat signal between the strontium and the calcium laser. The fs comb acts as a transfer oscillator. Thus, the virtual beat is independent of the fluctuations of the repetition rate $f_{\rm rep}$ and the carrier envelope offset frequency $\nu_{\rm CEO}$ of the fs fiber comb.

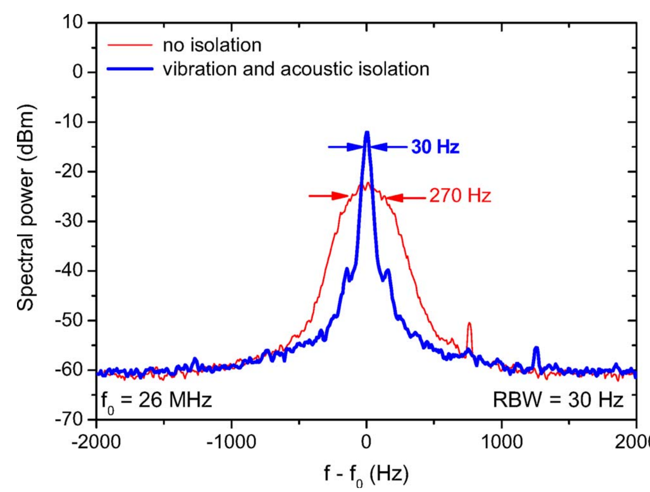

Fig. 3. Frequency spectrum of the virtual beat between the 698-nm Sr laser and the Ca reference laser. The spectrum obtained without any isolation (270-Hz linewidth) was averaged over ten sweeps of 0.135 s. The spectrum measured with a passive vibration isolation table and acoustic isolation (30-Hz linewidth) was averaged over 100 sweeps.

used in the 657-nm laser. In place of four holes drilled in the cylindrical cavity spacer, we glued small drilled invar plates on the spacer surface and used Viton cylinders to support the cavity. A sensitivity to vertical vibrations of about 140 kHz/ms^{-2} was measured, which is far greater than that calculated from a finite-element analysis. A difference of 1 mm from the optimal support point positions would result in a residual sensitivity of less than 8 kHz/ms^{-2}. Thus, the observed sensitivity cannot be explained by tolerances of the support point positions. We therefore attribute the discrepancy to the spacer touching the surrounding heat shield. This will be corrected in the near future.

The injection-locked slave laser delivers an output power of 23 mW. The laser remains injection locked over several days without manual resetting and adjustment. Its light is sent to the strontium atoms and the femtosecond (fs) fiber-laser comb by two optical fibers with provisions to cancel the noise acting on the fiber length [16].

III. Characterization of the Probe Laser System

A commercial fs fiber-laser comb was used to characterize the laser system. We used the fs laser as transfer oscillator [2], [3], as shown in Fig. 2, to compare the optical frequencies $\nu_{\rm Ca}$ and $\nu_{\rm Sr}$ of the 657-nm Ca laser and the 698-nm Sr laser. For each laser, the beat signal $\Delta_{\rm Ca}$ and $\Delta_{\rm Sr}$ with the neighboring comb line is detected. These beats are generated with the frequency-doubled output of the comb. Thus, the frequencies of the comb lines are given by the product of integer mode number m and repetition rate $f_{\rm rep}$ plus twice the carrier envelope offset frequency $2\nu_{\rm CEO}$, which is measured with an $f{-}2f$ interferometer using the original fs-laser output. Each beat signal is preprocessed by a tracking oscillator and digitally divided by two. Then, $\nu_{\rm CEO}$ is removed from both signals by multiplying them with $\nu_{\rm CEO}$ in a mixer and selecting the sum frequency. The signal frequency in the calcium branch is multiplied by m_1/m_2 using a direct digital synthesizer (DDS). After subtracting the frequencies from each other, one gets a signal that corresponds to a virtual beat of the two optical frequencies $\nu_{\rm Sr}/2$ and $\nu_{\rm Ca} \cdot m_1/2m_2$. This signal follows the frequency fluctuations of both lasers with a bandwidth of several tens of kilohertz, which is limited by the bandwidth of various phase-locked loops (PLLs) used to track the intermediate frequencies. This virtual beat has a frequency of about 26 MHz. Since it is independent of $f_{\rm rep}$ and $\nu_{\rm CEO}$, it is not degraded by fluctuations of these two quantities within the tracking bandwidth.

Monitoring the beat signal with a spectrum analyzer provides an excellent tool for a real-time analysis of the Sr clock laser. We use this setup to characterize and improve the 698-nm laser with respect to the 657-nm reference laser. Fig. 3 shows the

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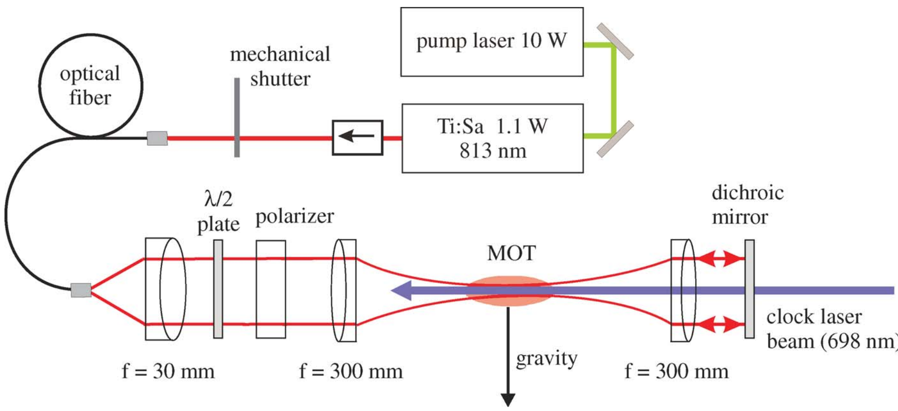

Fig. 4. Setup of the 1-D optical lattice at 813 nm. The 1-D lattice is directed perpendicular to gravity and to the axis of the MOT coils.

measured power spectral density of the virtual beat. Without any isolation of the reference cavity from seismic vibrations and acoustic noise, the virtual beat note shows a linewidth of about 270 Hz. Using a vibration isolation platform and an additional box for acoustic noise reduction narrows the linewidth by a factor of ten, resulting in a linewidth of 30 Hz. The virtual beat is observed at half the frequency of the Sr laser. Depending on the spectrum of frequency fluctuations, the linewidth of the laser is between twice and four times the measured virtual beat linewidth [17], i.e., from this measurement, we deduce a laser linewidth between 60 and 120 Hz.

IV. Spectroscopy of the Strontium Clock Transition

Using the 698-nm laser system with the cavity on the vibration isolation table but without the acoustic isolation box, we investigate the single-photon excitation of the $^1S_0{-}^3P_0$ clock transition in bosonic ^{88}Sr. The strontium atoms are confined in a 1-D optical lattice. To load the atoms into the optical lattice, we cool the strontium atoms to a few microkelvins using a two-stage cooling process.

In the first cooling stage, the atoms are captured from a Zeeman-slowed atomic beam and cooled to 2 mK in a magnetooptical trap (MOT) operating on the broad $^1S_0{-}^1P_1$ transition at 461 nm [18], [19]. This MOT works with a magnetic field gradient of 7.4 mT/cm, a $1/e^2$ laser beam diameter of 10 mm, and a total laser intensity of 21 mW/cm^2. The cooling laser is detuned 54 MHz below the $^1S_0{-}^1P_1$ transition frequency. After 200 ms, $3 \cdot 10^7$ atoms are trapped in the MOT. For further cooling, a MOT working at the spin-forbidden $^1S_0{-}^3P_1$ transition at 689 nm with a $1/e^2$ laser beam diameter of 5.2 mm is employed [18], [19]. To cover the Doppler shift of the atoms from the first cooling stage and to compensate the limited velocity capture range of the 689-nm MOT, the laser spectrum is broadened by modulating the laser frequency at 50 kHz with a peak-to-peak frequency excursion of 3 MHz. For this phase of the 689-nm MOT, a magnetic field gradient of about 0.7 mT/cm, a total intensity of 33 mW/cm^2, and a detuning of 1.6 MHz below the $^1S_0{-}^3P_1$ transition is used. Within a 70-ms-long broadband cooling interval, the atoms were cooled down to 15 μK. Finally, the frequency modulation is switched off, and the cooling laser is operated at a single frequency detuned 400 kHz below the $^1S_0{-}^3P_1$ transition. With an intensity of 440 μW/cm^2 and a 70-ms-long cooling interval, this process leads to $8 \cdot 10^6$ atoms at a temperature of 3 μK.

During the whole cooling process, the atomic cloud is superimposed with the horizontally oriented 1-D optical lattice operated at 813 nm. At this wavelength, the light shift of the $^1S_0$ and $^3P_0$ states cancels, and the clock transition frequency becomes independent of the laser intensity [20], [21]. As shown in Fig. 4, the 1.1-W output beam of the Ti:sapphire lattice laser is coupled into a polarization-maintaining optical fiber and passes through polarization optics before being focused at the center of the atom cloud. The beam is linearly polarized, with its polarization perpendicularly oriented to gravity. A dichroic mirror is used to retroreflect the 813-nm laser beam and, hence, to establish the 1-D optical lattice. With a beam radius of 30 μm and a power of 600 mW, a trap depth of 120 μK is realized. After switching off the 689-nm MOT, up to 10^6 atoms at 3 μK are trapped in the lattice. This corresponds to a transfer efficiency from the 461-nm MOT into the lattice of up to 3%. A shorter loading time of the 461-nm MOT results in fewer atoms in the lattice. For the spectroscopy of the $^1S_0{-}^3P_0$ transition, we choose a loading time of 13.5 ms, resulting in $1.2 \cdot 10^5$ lattice-trapped atoms to avoid collision broadening of the clock transition. The light of the 698-nm slave laser is superimposed with the 1-D optical lattice. The beam has a waist radius of 40 μm.

To enable the $^1S_0{-}^3P_0$ clock transition in bosonic ^{88}Sr, which is forbidden for any single-photon transition, we follow the proposal by Taichenachev *et al.* [22] and apply a dc magnetic field for mixing a small and controllable fraction of the nearby $^3P_1$ state to the $^3P_0$ state. This method has successfully been employed by Barber *et al.* with neutral ^{174}Yb [23] and Baillard *et al.* with ^{88}Sr [24]. The magnetic field is oriented parallel to the linear polarization of the interrogation laser beam. For spectroscopy of the $^1S_0{-}^3P_0$ transition, the coupling magnetic field of 2.3 mT is turned on, and a 200-ms-long pulse of the 698-nm interrogation laser with an intensity of 3.2 W/cm^2 excites a fraction of the atoms into the $^3P_0$ state. The 461-nm MOT beams are then used to detect the remaining ground state atoms by their fluorescence.

Fig. 5 shows the variation of the fluorescence signal with respect to the interrogation laser frequency. The cycling time of the frequency scan is given by the duration of the cooling

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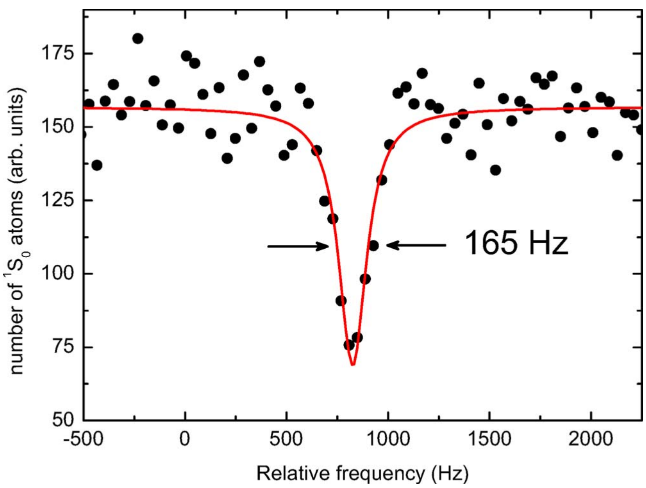

Fig. 5. Magnetically induced $^1S_0-^3P_0$ clock transition of ^{88}Sr. Each data point corresponds to a single measurement cycle of 640 ms. The frequency axis is determined from the offset between the reference cavity and the interrogation laser (twice the AOM frequency). It is corrected for the cavity drift and shifted by an arbitrary frequency to obtain small numbers.

stages, the probe pulse, and the fluorescence detection, which sums up to 640 ms.

With a Lorentzian line fit to the measured spectrum, we get a full-width-at-half-maximum linewidth of 165 Hz. The difference to the laser linewidth deduced from the virtual beat is most likely due to different environmental conditions, e.g., no acoustic isolation box was used during the spectroscopy. To achieve better resolution in future measurements, it is necessary to improve the probe laser linewidth. This is achieved by phase locking the laser to the 657-nm reference laser, as described in the next section.

V. Phase Lock

To perform a phase lock of the 698-nm diode laser system to the 657-nm reference laser, the virtual beat signal between both lasers is compared with the output of a radio frequency (RF) synthesizer by a phase and frequency comparator (Φ; see Fig. 6). The RF synthesizer is referenced to a 100-MHz signal derived from an H-maser. The comparator output drives a high-quality surface-acoustic-wave 400-MHz voltage-controlled oscillator (VCO). A DDS is used to transform this signal to the frequency of 266 MHz, driving the double-pass AOM between the Sr master laser and the reference cavity. The RF frequency at the AOM controls the Sr laser frequency and, therefore, the virtual beat frequency, thus closing the PLL.

Fig. 7 shows the spectrum of the virtual beat at 26 MHz, with the PLL of the 698-nm Sr laser open and closed, respectively. Without the PLL, the laser showed a linewidth of a few hundred hertz, which is caused by seismic and acoustic vibrations of the reference cavity; with open PLL, we observe the frequency noise of the free-running VCO. When the PLL is closed, the virtual beat signal narrows down to a δ function. The measured linewidth of the virtual beat of 1 Hz is then limited by the resolution bandwidth of the spectrum analyzer. The virtual beat signal between the phase-locked lasers is an in-loop signal and does not show possible additional phase noise from the fs fiber

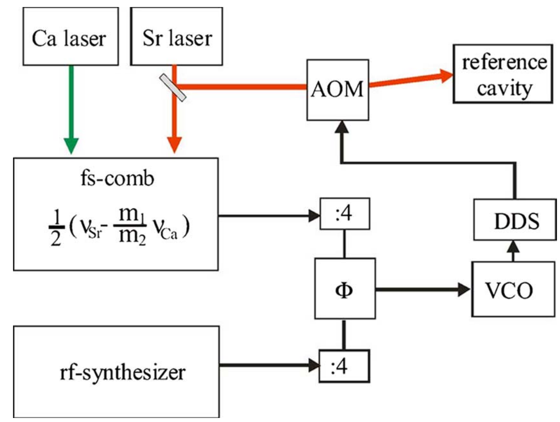

Fig. 6. Schematic of the phase lock of the 698-nm Sr laser to the 657-nm Ca laser serving as a reference.

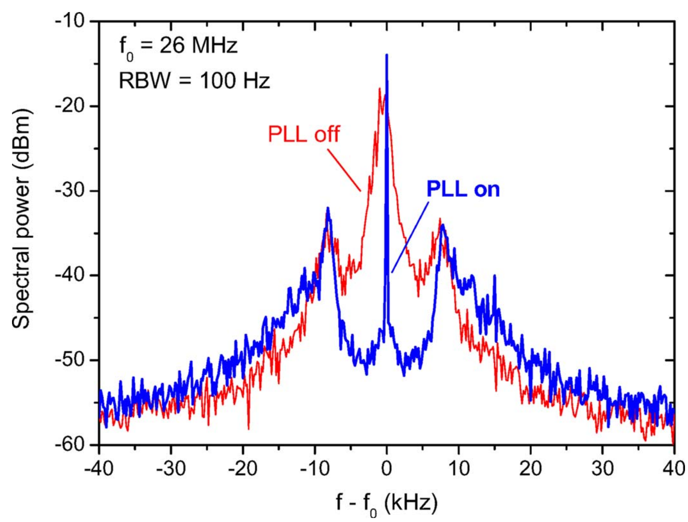

Fig. 7. Virtual beat between the Sr and Ca lasers with the PLL open and closed. With the PLL open, the noise of the free-running VCO is dominating. Both spectra are averaged over ten sweeps with a sweep time of 80 ms.

comb, electronic components, and uncompensated fiber links. Previous tests of the transfer method using two independent combs have confirmed that a linewidth of less than 1 Hz can be achieved [3]. Further spectroscopy on the Sr clock transition, including fiber noise cancellation [16], could be used to test the laser linewidth. So far, different technical problems concerning the experimental setup have not allowed spectroscopy on the clock transition using the phase-locked laser.

VI. Conclusion

We have set up a 698-nm laser system to investigate the clock transition of bosonic ^{88}Sr induced by a magnetic field. The laser was characterized relative to an ultranarrow linewidth reference laser at 657 nm using an fs fiber comb as a transfer oscillator. The comparison is unaffected by fluctuations in the repetition rate and the carrier envelope frequency of the comb and provides a real-time virtual beat between the two lasers with a large frequency bandwidth. As the measured linewidth of the clock transition had been limited by the interrogation laser linewidth, we have narrowed the laser linewidth by phase locking the

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virtual beat to a stable RF reference. With this method, the stability and linewidth of a given reference laser can be transferred to a second laser at an arbitrary wavelength within the spectral range that is accessible by the frequency comb.

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