A low noise optical frequency synthesizer at 700–990 nm

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(Received 12 August 2016; accepted 10 September 2016; published online 27 September 2016)

Optical frequency synthesizers can generate single-frequency laser light with high precision and accuracy at any desired wavelength over a wide optical region. Here, we demonstrate such an optical frequency synthesizer, which yields coherent light at any wavelength within 700–990 nm with more than 500 mW of power. The relative fractional frequency instability and uncertainty between the output light and the reference light of the optical frequency synthesizer are $6 \times 10^{-19}$ at 1 s averaging time and $2 \times 10^{-21}$, respectively. This synthesis noise is two orders of magnitude better than the frequency stability and accuracy provided by optical clocks, supporting optical frequency synthesis from the most accurate optical clocks. When the optical frequency synthesizer is referenced to a cavity-stabilized laser at 1064 nm, the output of the optical frequency synthesizer is tested to have an average linewidth of 1 Hz and frequency instability of $1.5 \times 10^{-15}$ at 1 s, limited by the reference laser. Published by AIP Publishing. [http://dx.doi.org/10.1063/1.4963690]

Frequency synthesizers from audio frequency to the microwave region have been widely used in technology and scientific research. However, in the optical region there is no such frequency synthesizer, which can generate single-frequency, coherent light at any desired wavelength over a wide optical region with high precision on demand. Optical atomic clocks can serve as the ultimate reference for an optical frequency synthesizer (OFS). Recently, the fractional frequency instability and uncertainty of optical clocks have been reduced to the level of $10^{-18}$ [1–4]. The unprecedented frequency stability and accuracy provided by optical clocks have been opening new applications, such as searching for possible variations of fundamental constants, tests of fundamental physics, precision spectroscopy, and redefinition of the international system of time [5–9]. It is necessary to use an OFS to convert the superior performance of the optical clocks at specific wavelengths to a broad optical and microwave region without degrading their frequency stability, accuracy, and coherence.

The invention of the optical frequency comb [10,11] paved the way to the OFS [12,13]. A comb can transfer the coherence and frequency accuracy of a high performance laser as a reference to all the comb teeth over a wide region with uncertainty at the $10^{-19}$ level [14]. However, all the comb teeth are typically in the same light beam and each tooth has very little light power (nW ~ μW range). For this reason, combs cannot meet the requirements directly in many applications that demand single-frequency coherent light at a desired frequency with ample power. By employing an additional wavelength-tunable, single-frequency continuous-wave (c.w.) laser with the useful power to inherit the coherence and frequency accuracy of a reference light, this challenge can be overcome. This c.w. laser is the output of an OFS.

There are two ways to phase-lock the OFS output laser to a reference laser through a comb. First, by phase-locking a comb tooth to the reference laser tightly, the properties of the reference laser are transferred to all the comb teeth [14–18]. Then a c.w. laser is phase-locked to a frequency-stabilized comb tooth near its frequency. A relative linewidth of millihertz and frequency transfer instability of a few $10^{-15}$ at 1 s averaging time have been achieved [15]. In an alternative approach, the properties of a reference laser are directly transferred to a c.w. laser with a free-running comb as a transfer oscillator. [19,20] In this method, the error signal for phase-locking the c.w. laser is derived from the heterodyne signals by beating the reference laser and the c.w. laser against the comb, where the comb frequency noise is removed. Coherence transfer from 1064 nm to 1542 nm with relative frequency instability of $4 \times 10^{-18}$ at 1 s has been demonstrated [21].

As a step toward the OFS, we have used the second approach to construct an accurate optical frequency divider (OFD). The OFD is demonstrated to have a division noise (the relative frequency fluctuation between the input and output light) of $6 \times 10^{-19}$ at 1 s and division uncertainty at the $10^{-21}$ level [22].

Here, an OFS has been constructed based on the OFD. The OFD accurately converts the frequency and transfers the coherence from a reference laser to a Ti:sapphire c.w. laser as the output of the OFS. Consequently, the OFS outputs coherent light at any desired wavelength within 700–990 nm with more than 500 mW of power. The frequency synthesis instability and uncertainty of OFSs are demonstrated to be $6 \times 10^{-15}$ at 1 s and $2 \times 10^{-21}$, respectively.

Figure 1(a) shows the diagram of the OFS. A single-frequency, Ti:sapphire c.w. laser with more than 1 W of power over the tuning range of 700–1000 nm is used as the output of the OFS with frequency $f_{\text{out}}$. First, a computer coarsely sets $f_{\text{out}}$ to a targeted frequency with an uncertainty of ±30 MHz via network connection with a wave meter and the controller of the Ti:sapphire c.w. laser. The laser frequency is coarsely adjusted by tuning a birefringence filter inside the laser cavity.

In a second step, using an OFD [22], the output light frequency is precisely set as $f_{\text{out}} = f_{\text{ref}}/R$, where $R$ is a preset...
The frequency of a Ti:sapphire c.w. laser, as the output of the OFS, is coarsely set by a computer with the aid of a wave meter, and is accurately fine-tuned via an oscilloscope. A second FPU (Fig. 1b) is set to fine-tune f_{out} by 10 MHz via tuning the frequency synthesizer (SYN) crystal to PD0. The signal of f_{out} is then phase-locked to a stable RF signal by controlling the pumping power of the fs laser. Consequently, both f_{out} and f_{ref} fluctuate within ±1 mHz measured on a frequency counter with a gate time of 1 s.

The beat note f_{sb2} between f_{out} and its nearest comb tooth with frequency f_{N2} is detected on a frequency counter with a gate time of 1 s. In a frequency process unit (FPU), we use the beat notes f_{b1} and f_{b1*} between f_{ref} and the comb to synthesize an RF signal directly from f_{ref}. The signals f_{b1} and f_{b2} are extracted from f_{out} and f_{out*} using DBMs and direct digital synthesizers (DDS), whose divisors are set as K_{1}/K_{2} = N_{1}/(N_{1} + 1). Then the resulting signal is sent to a third DDS with divisor K_{3} to synthesize a self-referenced time base at nearly 10 MHz as

\[ f_{\text{tune}} = \frac{f_{b1} + f_{\text{ref}}}{K_{1}} + \frac{f_{b2} - f_{\text{ref}}}{K_{2}} \left( \frac{f_{\text{ref}}}{K_{1}} - \frac{f_{\text{ref}}}{K_{2}} \right) \frac{1}{K_{3}} = \frac{f_{\text{ref}}}{K}, \]

where \( K = K_{0}/(1/K_{1} - 1/K_{2}) \). Then an RF signal f_{tune} is synthesized as f_{tune} = f_{ref} / K on an RF SYN with time base of f_{tune}. Here, K is a number depending on the setting of the DDSs and RF SYN.

In a similar manner as described above, a second FPU generates an error signal

\[ \Delta = \frac{f_{b1} + f_{\text{ref}}}{M_{1}} - \frac{f_{b2} + f_{\text{ref}}}{M_{2}} - \frac{f_{\text{ref}} - f_{\text{out}} - f_{\text{tune}}}{M_{1}} - \frac{f_{\text{out}} - f_{\text{tune}}}{M_{2}}, \]

which is also free from comb frequency noise by setting the divisors of two DDSs to meet the requirement of M_{2}/M_{1} = N_{2}/N_{1} on the computer via RS 232 cables. The values of N_{1}, N_{2}, and f_{tune} are calculated in advance based on the values of f_{ref}, f_{b1}, and f_{b2} measured on frequency counters and the values of f_{ref} and f_{out} measured on the wave meter. With this error signal \( \Delta, f_{\text{out}} \) is phase-locked to f_{ref} by tuning the driving frequency of a double-passed acoustic-optic modulator (AOM, fast servo) at the output of the Ti:sapphire c.w. laser and the voltage applied on a PZT inside the laser cavity (slow servo). Finally, f_{out} is related to f_{ref} with an accurate ratio \( R = 1/(M_{2}/M_{1} + 1/K) \). Profiting from the techniques of the transfer oscillator scheme based on our optically referenced frequency comb, the self-referenced time base, and

\[ f_{\text{ref}} = M_{1}/N_{1} + f_{\text{sb1}}. \]
careful elimination of light path fluctuation, the division noise and uncertainty of the OFD are \(6 \times 10^{-19}\) at 1 s and \(1.4 \times 10^{-21}\), respectively, by comparing the division ratio of the OFD against the frequency ratio between the fundamental and the second harmonic of a laser.\(^{22}\)

The optics for the OFS are sealed in a box to reduce the light path fluctuation due to airflow turbulences. The laser light from the reference laser and that to the wave meter are transferred through optical fibers. After the output light from the Ti:sapphire c.w. laser double-passes the AOM, the power of the first order diffraction light of the AOM (OFS output light) is about 500 mW.

To switch \(f_{\text{out}}\), to a completely new wavelength, we need to follow the above procedure. By now, manual intervention includes grating rotation, determination of the divisors of the DDSs and \(f_{\text{tune}}\), and laser phase locking. It is possible to foresee all the manual intervention can be replaced by using a motor-driven rotation stage for \(G_2\) and digital phase lock loops.

Using an OFS, we are able to accurately synthesize optical signals at any wavelength within 700–990 nm from the best optical clocks. OFSs based on a single frequency comb can link several optical clocks for frequency comparisons. To simulate this, we used OFSs in series to connect optical frequencies, as shown in Fig. 2(a). For a two-step optical frequency synthesis, OFS\(_1\) was employed to synthesize laser light with frequency \(f_\text{Ti}\) from a cavity-stabilized 1064 nm laser\(^{24}\) \((f_\text{1064–1})\) with a preset division ratio \(R_1\). Therefore, \(f_{\text{T1}} = f_{\text{1064–1}}/R_1\). Then OFS\(_2\) used \(f_{\text{T1}}\) as the reference to synthesize light from a second independent 1064 nm laser \((f_{\text{1064–2}})\) as \(f_{\text{T2}} = f_{\text{T1}}/R_2\). The beat frequency \(f_b\) between \(f_{\text{1064–2}}\) and \(f_{\text{1064–1}}\) is measured on a counter with the time base of \(f_{\text{tune}} = f_{\text{1064–2}}/k\). The product of the frequency ratios, \(R = R_1 \times R_2\), can be determined according to \(f_b = f_{\text{1064–1}} - f_{\text{1064–2}}/(R_1 \times R_2) = A \times f_{\text{1064–1}}/(k \times 10^7)\). Here, \(A\) is the reading number in hertz on the counter.

As shown in Fig. 2(b), the fractional instability of \(R\) (blue squares) follows \(6 \times 10^{-19}/\tau\) \((\tau\) is the averaging time). The noise is from servo systems, DDSs, and residual light path fluctuation. It is close to the noise floor of \(4 \times 10^{-19}/\tau\) when \(f_{\text{1064–2}}\) are phase-locked to \(f_{\text{1064–1}}\) without using any OFS (green circles), where the noise comes from a servo and light path fluctuation. The measured instability of \(R\) implies that during optical frequency synthesis the relative frequency instability between the OFS output and input light is two orders of magnitude better than that of the most stable lasers,\(^{25–29}\) adding a negligible noise onto the output of the OFS. The linewidth of \(f_b\) was measured on a fast Fourier transform (FFT) spectrum analyzer, as shown in the inset of Fig. 2(b). It is a RBW-limited linewidth of 1 mHz, indicating that the coherence has been faithfully transferred from \(f_{\text{1064–1}}\) to \(f_{\text{1064–2}}\) via the OFSs. In the three-step frequency synthesis, OFS\(_3\) was appended. The relative fractional instability corresponding to \(R = R_1 \times R_2 \times R_3\) is slightly higher, as shown with red triangles in Fig. 2(b).

The product of the ratios, \(R\), has been measured in sixteen different days over five months. Figure 2(c) shows the deviation of \(R\) from the setting value. During the measurement, the wavelength of the Ti:sapphire c.w. laser varied from 700 to 990 nm, and \(R_1\) and \(R_2\) varied accordingly. Each data point results from averaging over a roughly 5000 s measurement time. Blue squares (red triangles) denote the measurement in the two-step (three-step) frequency synthesis. Using standard statistical methods, we combine 22 sets of data (total measurement time of \(10^5\) s) to calculate the fractional deviation of \(R\) to be \((1.5 \pm 2.0) \times 10^{-21}\) (99% confidence level).\(^{30}\) The synthesis uncertainty of the OFSs here is three orders of magnitude better than the most accurate optical clocks.\(^{3,4,11}\) limited mainly by the OFD.\(^{21}\)

When the OFS is referenced to a 1064 nm laser frequency-stabilized to a 7.75-cm-long cavity \((f_{\text{1064}})\),\(^{24}\) the performance of the OFS output light at 778.6 nm is measured.
and the SHG of $f_{1557}$ with a SNR of 40 dB in 300 kHz RBW was measured on a counter. As shown in Fig. 3(b), the fractional frequency instability is $1.7 \times 10^{-15}$ at 1 s, limited by $f_{1064}$ and extra noise from the EDFA and a piece of noise-uncompensated optical fiber connected between the EDFA and the 1557 nm laser. After subtracting the contribution of $f_{1557}$, the frequency instability of the OFS is $1.5 \times 10^{-15}$ at 1 s.

In conclusion, an OFS has been constructed. It outputs coherent light at any desired wavelength within 700–990 nm with more than 500 mW of power. Benefiting from the high output power of the OFS, it is possible to broaden the output wavelength range with nonlinear optical processes. The relative frequency instability and uncertainty during optical frequency synthesis are demonstrated to be $6 \times 10^{-19}$ at 1 s and $2 \times 10^{-21}$, respectively. It supports the optical frequency synthesis from the most accurate optical clocks. When the OFS is referenced to a cavity-stabilized laser at 1564 nm, the output of the OFS is tested to have an average linewidth of 1 Hz and frequency instability of $1.5 \times 10^{-15}$ at 1 s, mainly limited by the reference laser. We expect such a frequency synthesizer in the optical region will be instrumental in precision spectroscopy-based applications.

This research was supported by the National Natural Science Foundation of China (11334002, 91636214 and 11374102), Shanghai Rising-Star Program (15QA1401900), and Program of Introducing Talents of Discipline to Universities (B12024).

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