We present an all-optically stabilized, erbium-doped mode-locked fiber laser with an optically pumped ytterbium-doped fiber. The mode-locked fiber laser has two frequency-control actuators that are pump laser powers for erbium-doped and ytterbium-doped fibers. We investigate the frequency-control characteristics of the mode-locked laser and find that the fixed points for the two actuators are sufficiently apart from each other, realizing the simultaneous phase locking of the repetition and carrier envelope offset frequencies. We describe a long-term frequency measurement of an acetylene-stabilized laser at 1542 nm using an all-optically stabilized frequency comb. © 2015 The Japan Society of Applied Physics
We evaluated the independence of the two frequency control actuators of the frequency comb to determine whether it is possible to stabilize two frequency degrees of freedom simultaneously.

The $N$-th mode frequency in the comb is well known as

$$\nu(N) = N \cdot \nu_{\text{rep}} + \nu_{\text{ceo}}$$  \hspace{1cm} (1)

When we adjust the frequency-control actuator, there is a fixed point\(^{13}\) that results from canceling the changes in $\nu_{\text{rep}}$ and $\nu_{\text{ceo}}$. At the fixed point, Eq. (1) is

$$\nu(N_{\text{fix}}) = N_{\text{fix}} \cdot \nu_{\text{rep}} + \nu_{\text{ceo}}.$$  \hspace{1cm} (2)

We obtain the following equation by differentiating both components of Eq. (2) by $\nu_{\text{rep}}$:

$$\frac{d\nu(N)}{d\nu_{\text{rep}}} \bigg|_{N=N_{\text{fix}}} = \frac{d\nu_{\text{ceo}}}{d\nu_{\text{rep}}} = 0,$$  \hspace{1cm} (3)

$$N_{\text{fix}} = \frac{d\nu_{\text{ceo}}}{d\nu_{\text{rep}}}. $$  \hspace{1cm} (4)

Therefore, $-d\nu_{\text{ceo}}/d\nu_{\text{rep}}$ corresponds to the mode number at the fixed point. Here, we consider the two fixed points $N_{\text{fix}}^{YDF}$ and $N_{\text{fix}}^{YDF}$ when we change the pump powers to the EDF and YDF, respectively. To characterize the independence of the two frequency control actuators, we consider the changing ratio $N_{\text{fix}}^{YDF}/N_{\text{fix}}^{YDF}$ which corresponds to the ratio of fixed-point frequencies. The changing ratio should not be close to 1 if we are to control both frequencies independently.

First, to measure the $N_{\text{fix}}^{YDF}/N_{\text{fix}}^{YDF}$ ratio, we investigate a tunable pump-power range for which we can observe the $\nu_{\text{ceo}}$ signal by increasing the pump power to the EDF and YDF individually. We then choose 6 individual pump-power points as typical powers within the tunable power ranges to the EDF and YDF. Next, we observe $\nu_{\text{rep}}$ visually with a frequency counter and $\nu_{\text{ceo}}$, with a spectrum analyzer while increasing the pump power to the EDF from minimum to maximum (6 points) with the pump power to the YDF fixed (measurement #1). We also measure $\nu_{\text{rep}}$ and $\nu_{\text{ceo}}$ while increasing the pump power to the YDF with the pump power to the EDF fixed (measurement #2). Figure 2 shows the $\nu_{\text{ceo}}$ deviation versus the $\nu_{\text{rep}}$ deviation when each of the pump powers to the EDF and YDF is changed. To reduce the long-term frequency-drift effect during the observation, we use data of measurements #1 and #2 for the plots in Figs. 2(a) and 2(b), respectively. $N_{\text{fix}}^{YDF}$ and $N_{\text{fix}}^{YDF}$ at different pump powers are calculated from Figs. 2(a) and 2(b), respectively. Furthermore, fixed points in the optical frequency range can be derived from $N_{\text{fix}}^{YDF}$ or $N_{\text{fix}}^{YDF}$ using Eqs. (2)-(4).

Figures 3(a) and 3(b) show maps of the fixed points in the optical frequency range considered, and Fig. 3(c) indicates the ratio of the fixed points for the two actuators, calculated from the experimental results shown in Fig. 2. The ratio of the fixed points does not indicate a strong dependence on the pump powers to the EDF and YDF. The calculated ratios are always sufficiently smaller than that obtained when we adjust the pump powers to the EDF and YDF in this experiment. We consider the entire pump power region to be appropriate for the simultaneous phase locking of two degrees of freedom of the optical frequency comb.

We utilized UTC (NMIJ), a frequency standard based on a hydrogen maser at NMIJ, as a frequency reference for the all-optically controlled frequency comb. We used a universal

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*Fig. 1. Experiment setup for the optical frequency measurement of a 1542 nm acetylene-stabilized laser by using the all-optically stabilized frequency comb. PD, photodetector; O.I., optical isolator; P, polarizer; Q, quarter-wave plate; H, half-wave plate; WDM, wavelength division multiplexing coupler; OBPF, optical bandpass filter; O.C., output coupler.*

operates in the stretched-pulse\(^{11}\) regime from the spectral shape and roughly estimated total cavity dispersion. The mode-locked laser behaves stably, and the mode locking starts without any initiating triggers.

In this study, we changed the pump power into the YDF from 27 to 95 mW since we could observe the $\nu_{\text{ceo}}$ signal in this power range. We observed a significant change in spectral shape when we increased the pump power into the YDF. The spectral shape changed from the typical shape of a stretched pulse to the distinct shape of a similariton,\(^{12}\) which suggests that the pump power changes the cavity dispersion.

Figure 1 shows the experimental setup that we used to observe $\nu_{\text{rep}}$, $\nu_{\text{ceo}}$, and the beat note between the comb and a 1542 nm acetylene-stabilized laser using the above-mentioned mode-locked laser. We used 1% of the laser output to monitor the laser spectrum, and we divided the other 99% of the output into two equal parts. One of the two parts was further divided into two branches. The first branch was used to detect the $\nu_{\text{ceo}}$ signal by employing an $f$–$2f$ interferometer, and the second branch was used to detect a beat note with the 1542 nm laser. The power to the EDF was approximately 670 µW and it was optimally amplified to 90 mW at the first branch.\(^{13}\) The amplified pulse train was spectrally broadened with a highly nonlinear fiber (HNLF),\(^{14}\) and guided to the $f$–$2f$ common-path interferometer. As a result, we obtained a signal-to-noise ratio of 35 dB for the $\nu_{\text{ceo}}$ signal at a 300 kHz resolution bandwidth. In this experiment, we found no negative effect on the $\nu_{\text{ceo}}$ detection in terms of obtainable S/N when we inserted the YDF into the oscillator.

The spectrum of the mode-locked laser contained sufficiently strong 1542 nm components, and we obtained a signal-to-noise ratio of 40 dB at the resolution bandwidth (RBW) of 300 kHz for a heterodyne beat note between the laser and the comb without the HNLF.
signal generator (Keysight 33622A) to synthesize the reference frequencies for $f_{\text{rep}}$ and $f_{\text{ceo}}$. We employed a frequency mixer and an 8-bit digital phase comparator\(^{16}\) as the phase discriminators to phase-lock $f_{\text{rep}}$ and $f_{\text{ceo}}$, respectively. The 8-bit phase comparator can discriminate a phase difference of up to $\pm 128 \pi$, which facilitates appropriate phase locking without cycle slips. As a result of trials at every pump power level, we succeeded in phase-locking $f_{\text{rep}}$ and $f_{\text{ceo}}$ simultaneously.

We have measured the optical frequencies of an acetylene-stabilized laser\(^{17}\) using our all-optically stabilized frequency comb. Figure 4 shows measurement results for $f_{\text{rep}}$ and $f_{\text{ceo}}$ and the beat note between the comb and the stabilized laser. The Allan deviation of $f_{\text{rep}}$ improves with the inverse of the averaging time, which is the resolution limit of the frequency counter we used. The deviation of $f_{\text{ceo}}$ also improves with the inverse of the averaging time, which is limited by residual phase noise, indicating its appropriate phase locking. We consider that the Allan deviation of the beat frequency between the comb and the acetylene-stabilized laser is limited by the frequency stability of the stabilized laser, in the averaging time range above 10 s since the stabilities are adequate for the stabilized laser, and the stability improves with the inverse of the square root of the averaging time. In the regime below 10 s, the relative frequency stability of the function generator (Keysight 33622A) used as the reference for $f_{\text{rep}}$ might constitute a frequency stability bottleneck.

The relationship between the fixed point $N^{\text{Yb}}_{\text{ax}}$ and the YDF length should be investigated as the next step, although it is outside the scope of this study. The fixed point may be able to be managed by changing the YDF length.

Table I shows the frequency control characteristics of the frequency control mechanisms. We do not consider the above-mentioned mechanisms to have any serious problems for long-term durability, severe environments, or mechanical stability as actuators. Nevertheless, a silica-based YDF is notably superior to other actuators in terms of robustness. In particular, the wide tunability of $f_{\text{ceo}}$ using the new actuator (pump power to the YDF) is significant. In this experiment, we tuned $f_{\text{ceo}}$ more than two times than $f_{\text{rep}}$ at least. Further optimizations (e.g., total dispersion of the oscillator cavity, pump current setting, and polarization setting) will enable us to tune $f_{\text{ceo}}$ over an even greater range. The $f_{\text{rep}}$ tunability is sufficiently wide, although long-term $f_{\text{rep}}$ stabilization requires temperature control. The bandwidth of the new actuator is of great interest, and is yet unclear because this experimental setup is not specialized for fast servo. We expect the servo bandwidth to be several hundred kHz since the $f_{\text{ceo}}$ phase locking of an ytterbium-doped fiber-based comb is easily achieved with a similar servo bandwidth.\(^{20}\)

Fig. 2. $f_{\text{ceo}}$ deviation versus $f_{\text{rep}}$ deviation when the pump powers to (a) erbium-doped and (b) ytterbium-doped fibers are changed.

Fig. 3. (a) Fixed points in optical frequency range derived from $N^{\text{Er}}_{\text{ax}}$. (b) Fixed points in optical frequency range derived from $N^{\text{Yb}}_{\text{ax}}$. (c) Frequency ratio of the fixed points ($N^{\text{Yb}}_{\text{ax}}/N^{\text{Er}}_{\text{ax}}$).

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[16] Frequency comparator

[17] Acetylene-stabilized laser

[18] Typical values

[19] CIPM-recommended value

[20] Servo bandwidth
Fig. 4. Measurement results for (a) $f_{\text{rep}}$, (b) $f_{\text{cw}}$, and (c) beat frequency between the comb and the 1542 nm acetylene-stabilized laser. The Allan deviations are normalized by dividing them with the optical frequency of the 1542 nm laser.

Table I. Comparison of control mechanisms for mode-locked erbium-doped fiber laser-based frequency comb.

| Frequency control mechanism | PZT | EOM | AOM | Pump control to EDF | Pump control to YDF |
|----------------------------|-----|-----|-----|--------------------|--------------------|
| High-speed controllability | Passable to Good | Very good | Good | Good | Promising |
| (Bandwidth) | $\sim 180\,\text{kHz}$ | $\sim 4\,\text{MHz}$ | $\sim 300\,\text{kHz}$ | $\sim 500\,\text{kHz}$ | |
| Wide tunability of $f_{\text{cw}}$ | Not available | Not available | Passable | Good | Very good |
| Wide tunability of $f_{\text{rep}}$ | Passable | Passable | Not available | Good | Good |

Remark
- a) When using a fiber-attached PZT, the fiber is mechanically stretched and becomes slow; when using a free-space PZT, independent PZTs are needed to obtain a broad bandwidth and a passable tunability simultaneously.
- b) A fast high-voltage amplifier is needed to obtain a broad bandwidth and a passable tunability simultaneously.

An all-optically stabilized frequency comb is realized. It is cost-effective and robust, and has wide $f_{\text{ceo}}$ tunability. It is an evolutionary configuration of the mode-locked fiber laser for an optical frequency comb and might become a mainstream comb if a narrow-linewidth comb can be realized by all-optical stabilization in the near future.

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