Intrinsic Spectrum Analysis of Laser Dynamics Based on Fractional Fourier Transform

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Abstract—The intrinsic spectrum that results from the coupling of spontaneous emission in a laser cavity can determine the energy concentration and coherence of lasers, which is crucial for optical high-precision measurements. To date, it has been difficult to analyze the intrinsic spectrum in high-speed laser dynamics processes, especially under the condition of fast wavelength sweeping. In this work, a new method to analyze the laser intrinsic spectrum is proposed with laser energy decomposition into a series of chirp-frequency signals, which is realized by fractional Fourier transform (FRFT) of the coherently reconstructed laser waveform. The new understanding of the energy distribution of lasers contributes to accurate characterization of laser dynamic parameters in the time-frequency domain. In a proof-of-concept experiment, the time-frequency dynamic process of a commercial wavelength-swept laser is tested for different wavelength-scanning speeds, and the most suitable measurement time window width required for the narrowest FRFT-based spectrum is also explored. The proposed analysis method of laser dynamic parameters will promote the understanding of laser dynamics and benefit optical precision measurement applications.

Index Terms—Fractional Fourier transform, intrinsic spectrum, laser dynamics, linewidth measurement, wavelength-swept laser.

I. INTRODUCTION

HIGH-PERFORMANCE lasers with dynamic time-frequency parameters, such as wavelength-swept lasers and chirped ultrashort pulse lasers, have been widely used in the fields of optical precision measurement, such as in precision spectroscopy [2], [3], optical frequency domain reflectometer (OFDR) distributed fiber sensing [4], [5], and swept-source optical coherence tomography (SS-OCT) [6]. The time-frequency analysis of lasers is crucial for characterizing the performance parameters, including the energy concentration and sweep speed. For laser applications, the energy concentration of lasers in the time-frequency domain, commonly described by the linewidth, characterizes the laser coherence and spectral purity, which determines the maximum measurement distance and depth of FMCW lidar, OFDR fiber sensing and SS-OCT. The frequency sweep speed determines the response time of the optical precision measurement system and needs to be accurately measured for frequency comparison. For the operation of a dynamic time-frequency laser, the spontaneous emission couples with the laser longitudinal mode back and forth in the laser cavity and induces random amplitude and phase modulation, which causes broadening of the intrinsic spectrum of the laser [7], [8], [9]. Therefore, the dynamic measurement of the intrinsic spectrum induced by spontaneous emission is of great importance to optimize the laser structure for improvement of the energy concentration and coherence of dynamic time-frequency lasers.

To date, the concept of energy distribution refers to the frequency-domain linewidth when decomposing the laser waveform into a series of fixed-frequency signals. On this basis, the current methods for measuring the dynamic time-frequency laser linewidth mainly include direct spectrum scanning, roll-off measurement and coherent detection. The direct spectrum scanning method obtains the transient spectrum of lasers by scanning a narrow-band filter such as a Fabry-Perot (FP) cavity [10] to measure the laser linewidth. The roll-off method [11], [12] measures the attenuation relationship between the interference spectrum intensity and the arm length difference of the interferometer and obtains the coherence length and coherence time of the dynamic time-frequency laser, which can be used to deduce the average linewidth. The coherent detection method mainly includes three techniques of coherent receiver detection [13], delayed self-heterodyne/homodyne detection [14], [15], [16], [17], [18] and 3×3 coupler interferometry [19], [20], which can reconstruct the laser amplitude and phase. The transient laser linewidth and noise can be further obtained by Fourier transform of the reconstructed optical waveform. However, in the case of high-speed laser frequency scanning, the concept of fixed-frequency decomposition of the laser energy cannot reflect the intrinsic energy width of the frequency-swept laser. It is well known that there is a compromise between the Fourier spectrum resolution and time window, that is, the Fourier spectrum resolution is the reciprocal of the time window. When using fixed-frequency decomposition to analyze a frequency-swept

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laser, if the time window is shortened to reduce the number of frequency components, then the spectral resolution will not be sufficient to analyze narrow linewidth lasers. If the time window is enlarged to increase the spectral resolution, then this will increase the number of frequency components in the time window such that the observed laser linewidth is not the intrinsic laser linewidth but the width of the laser frequency tuning. For example, when the sweep speed is 1 MHz/μs, a time window width of less than 1 μs will result in a spectral resolution of greater than 1 MHz, so it is impossible to demodulate linewidths below 1 MHz. If the time window is set to be larger than 1 μs, then the frequency tuning range will exceed 1 MHz, so the demodulated linewidth cannot be less than 1 MHz either. That is, when the sweep speed reaches 1 MHz/μs, the narrowest linewidth obtained by conventional fixed-frequency decomposition is approximately on a 1 MHz order of magnitude. Therefore, an intrinsic laser linewidth of less than 1 MHz, which could be induced by phase noise, cannot be accurately obtained by conventional fixed-frequency decomposition under a sweep speed of larger than 1 MHz/μs. Thus, conventional fixed-frequency energy decomposition cannot reflect the signal purity and noise intensity of a fast-swept laser with low noise. It is necessary to redefine the energy decomposition waveform according to the intrinsic features of frequency sweeping. It is worth noting that the fractional Fourier transform (FRFT) can decompose the wave energy with the frequency-swept waveform as the basic component signal, which has been widely used in optics [21], signal processing [22], [23], radar [24], communication [25], and so on.

In this work, we propose to analyze the intrinsic energy distribution of a dynamic time-frequency laser by decomposing the laser energy with the chirp-frequency waveform signal as the basic component, which is realized by fractional Fourier transform (FRFT) of the coherently reconstructed laser waveform. In a proof-of-concept experiment, the intrinsic energy distribution and linewidth of a commercial wavelength-swept laser as a typical dynamic time-frequency laser are tested for different scanning speeds, and the appropriate measurement time window width required for the FRFT-based linewidth is also explored. With the new decomposition idea for dynamic time-frequency lasers, the laser spectral purity measurement resolution is no longer limited by the laser wavelength-scanning speed. In theory, the spectral linewidth resolution is inversely proportional to the measurement time window. The new understanding of the energy distribution of dynamic time-frequency lasers proposed in this work will contribute to accurate characterization of laser dynamics under fast and broadband frequency sweeping and benefit optical precision measurement applications.

II. FRFT THEORY AND SIMULATION

The comparison of the energy spectrum distribution between the traditional Fourier transform (FT) and fractional Fourier transform (FRFT) is shown in Fig. 1. For a fixed single-frequency laser signal, the traditional FT can accurately analyze the frequency domain information of the signal, as shown in
Fig. 3. Simulation of the fractional Fourier transform with different rotation angles. (a) Intensity distribution of the FRFT with different rotation angles. (b) Definition of the linewidth for a specific rotation angle.

Fig. 4. Delayed self-heterodyne coherent detection system and data analysis process. C1 and C2: Couplers; AOM: Acousto-optic modulator; PD: Photodetector.

Fig. 1(a). As the center frequency remains constant, the decomposition of the signal into the fixed-frequency components can reflect the intrinsic energy width of the laser. However, for a dynamic time-frequency laser signal at a certain time, such as that from a wavelength-swept laser, the fixed-frequency decomposition of the laser signal cannot reflect the intrinsic energy bandwidth of the frequency-swept laser, as shown in Fig. 1(b). Different from the traditional FT, the decomposition component of the FRFT is the chirp-frequency waveform signal, which can coincide with the wavelength-swept laser signal and is promising for obtaining a spectrum-concentrated energy distribution, as shown in Fig. 1(c). In the demodulation process based on the FRFT, the frequency sweep rate can be tuned by choosing different rotation angles (or fractional domain orders) to obtain the narrowest energy spectrum distribution for wavelength-swept lasers.

The FRFT [22], [23] is a generalization of the Fourier transform with additional free angle parameters. It can be interpreted as a rotation by an angle $\alpha$ in the time-frequency plane [21]. The FRFT of a function is defined as [22]

$$
F_\alpha(u) = F_\alpha \{ f(t) \} (u) = \frac{1}{\Delta} \int_{\mathbb{R}} f(t) K_\alpha (u, t) \, dt, \quad (1)
$$

where $F_\alpha$ denotes the FRFT operator, $\alpha$ is the rotation angle in the time-frequency plane, $u$ denotes the fractional-domain...
frequency, and the kernel function $K_\alpha (u, t)$ is given by

$$K_\alpha (u, t) = \begin{cases} A_\alpha e^{\frac{1}{2} \alpha^2 - j \frac{1}{2} - t u \cot \alpha}, & \alpha \neq m\pi \\ \delta (t - u), & \alpha = 2m\pi \\ \delta (t + u), & \alpha = (2m - 1)\pi \end{cases}$$

where $A_\alpha = \sqrt{(1 - j \cot \alpha)/2\pi}$, $\delta$ is the delta function, and $m \in \mathbb{Z}$. It is worth noting that $F^{2m}$ is the identity operator for any integer $m$, and $F_\alpha$ has the property of $F^{\alpha + \beta} \{ f(t) \} = F_\alpha \{ F_\beta \{ f(t) \} \}$. For $\alpha = \pi/2$, (1) is reduced to the traditional Fourier transform. The inverse FRFT is given by

$$f(t) = F^{-\alpha} \{ F_\alpha(u) \} = \int_{-\infty}^{\infty} F_\alpha(u) K_\alpha(u, t) du,$$  

which means that the inverse FRFT can be regarded as the FRFT with rotation angle $-\alpha$. We can see that the original function $f(t)$ is decomposed into the superposition of a series of kernel functions. This series of kernel functions is the complex conjugate of the kernel functions defined by (2), which is also a series of sweep signals. Different $\alpha$ values correspond to different initial angular frequencies of the sweep signal as $\omega = u \csc \alpha$. At this time, the fractional domain shows the intensity distribution of the sweep signal with different initial frequencies but the same sweep slope.

We can assume that a typical wavelength-sweep laser signal to be analyzed satisfies the form of $e^{j \omega_0 t^2 + j \omega t + \varphi_0(t)}$, where $\omega_0$ is the frequency tuning rate, $\omega_0$ is the initial frequency, and $\varphi_0(t)$ is the phase noise. When $\alpha$ is specially chosen so that $\cot \alpha = -k_0$, the quadratic factor $e^{j \frac{1}{2} \omega_0 t^2}$ of the FRFT can accurately offset the frequency sweep of the signal, and the linear factor $e^{-j \alpha \cot \alpha}$ of the FRFT is equivalent to the traditional FT of the remaining phase part $e^{j \omega_0 t + \varphi_0(t)}$, with the variable $\omega = u \csc \alpha$ as the Fourier frequency. Therefore, the laser linewidth of the wavelength-sweep laser, which can reflect the laser noise $\varphi_0(t)$, can be defined as

$$\Delta f = \frac{1}{2\pi} \Delta u \csc \alpha,$$

where $\Delta u$ is the half energy spectral width of the laser signal decomposed by the FRFT at the rotation angle, which satisfies

$$\int_{u_0 - \Delta u/2}^{u_0 + \Delta u/2} F_\alpha(u) F^*_\alpha(u) du = \frac{1}{2} \int_{-\infty}^{\infty} F_\alpha(u) F^*_\alpha(u) du,$$

where $u_0$ is the fractional domain center frequency, defined as $u_0 = \int_{-\infty}^{\infty} u F_\alpha(u) F^*_\alpha(u) du / \int_{-\infty}^{\infty} F_\alpha(u) F^*_\alpha(u) du$.

For the calculation of the FRFT, T. Erseghe et al. [26] proposed the FRFT decomposition structure shown in Fig. 2. When $\alpha \neq m\pi$, from (1) and (2), the FRFT can be expanded as

$$F_\alpha(u) = \sqrt{(1 - j \cot \alpha)} e^{\frac{1}{4} \frac{t^2}{\alpha^2} - j \frac{1}{2} \alpha^2} \frac{1}{\sqrt{2\pi}}$$

$$\times \int_{-\infty}^{\infty} \left( f(t) e^{j \frac{1}{2} \frac{t^2}{\alpha}} \right) e^{-j \alpha \cot \alpha} dt.$$

Therefore, in Fig. 2, $\tilde{f}(t) = f(t) e^{j \frac{1}{2} \frac{t^2}{\alpha}}$, $\tilde{F}(u \csc \alpha) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \tilde{f}(t) e^{-j \alpha \cot \alpha} dt$, where the function $\tilde{F}(\omega)$ is the Fourier transform of $\tilde{f}(t)$, and the frequency domain variable is further replaced by $u \csc \alpha$, i.e., $\omega = u \csc \alpha$. The core of the algorithm is the FT, and two chirp operators are used for the input signal and output signal.

We simulate the energy distribution of a wavelength-swept laser signal based on the FRFT, as shown in Fig. 3. Based on the basic properties of the FRFT, the rotation angle $\alpha$ represents the angular frequency sweep speed $k$ of the chirp component in the inverse FRFT, with $k = -\cot \alpha$. When the rotation angle $\alpha$ is scanned from 0 to $2\pi$, the energy distribution can be concentrated at a specific angle, as shown in Fig. 3(a). The intensity in Fig. 3(a) is the square modulus of the FRFT of the chirped signal. When the angle changes, the intensity distribution will also change accordingly. Specifically, the spectral distribution with a typical rotation angle is shown in Fig. 3(b). From the half energy bandwidth of the FRFT, which can be varied by the rotation angle, we can obtain the linewidth of the swept laser. Therefore, for the narrowest measurement of the linewidth, one should search for the optimal rotation angle.

### III. COHERENT DETECTION CONFIGURATION

A delayed self-heterodyne coherent detection system is utilized to measure the transient frequency and phase of the wavelength-swept laser, as shown in Fig. 4. The system consists of two couplers $C_1$ and $C_2$, an acousto-optic modulator (AOM), an AOM driver, a 10 m delay fiber, a photodetector (PD), a data acquisition system and a computer. The AOM provides a frequency shift for the laser signal, and the delay fiber provides a time delay $\tau$ for the detection system.

Based on the delayed self-heterodyne coherent detection system, the wavelength-swept laser signal can be expressed as

$$E = A e^{j (\omega_1 t + k_1 t^2/2 + \phi(t))},$$

where $A$ is the laser amplitude, $\omega_1$ is the initial frequency, $k_1$ is the sweep rate, and $\phi(t)$ is the phase noise. The laser signal passing through the AOM can be expressed as

$$E_1 = A_1 e^{j ((\omega_1 + \omega_2) t + \frac{1}{2} k_1 t^2 + \phi(t))},$$

where $A_1$ is the laser amplitude through the AOM, and $\omega_2$ is the frequency shifted by the AOM. The laser signal passing through the delay fiber can be expressed as

$$E_2 = A_2 e^{j (\omega_1 (t-\tau) + \frac{1}{2} k_1 (t-\tau)^2 + \phi((t-\tau)))},$$

where $A_2$ is the laser amplitude through the delay fiber and $\tau$ is the time delay. The beat signal obtained at coupler $C_2$ can be expressed as

$$I = |E_1 + E_2|^2 = A_1^2 + A_2^2 + 2A_1 A_2 \cos (\omega_1 t + \omega_\tau + k_1 t \tau - k_1 t^2/2 + \phi(t - \tau) - \phi(t - \tau)).$$

By demodulating the signal, we can obtain the phase $\phi_0(t)$ of the beat signal, i.e., $\phi_0(t) = \omega_0 t + \omega_\tau + k_1 t \tau - k_1 t^2/2 + \phi(t - \tau) - \phi(t - \tau)$. Additionally, the phase $\phi_0(t)$ is $\omega_0 t$ of the RF driving signal of the AOM can also be demodulated according to
the synchronously recorded waveform. Therefore, the demodulated laser phase noise-related term $\phi_0(t)$ satisfies

$$
\phi_0(t) = \phi_b(t) - \phi_d(t) = k\tau t + \varphi(t) - \varphi(t - \tau) + \omega \tau - k\tau^2/2, \tag{10}
$$

where $k\tau$ can be regarded as the linear fitting slope of the demodulated phase $\phi_0(t)$ over time, $\varphi(t) - \varphi(t - \tau)$ denotes the residual noise after the linear fitting of $\phi_0(t)$ over time, and $\omega \tau - k\tau^2/2$ denotes the initial phase of $\phi_0(t)$. Under the condition of a short time delay $\tau$, the derivative of the phase noise can be written as

$$
\frac{d\varphi}{dt} \approx \frac{\varphi(t) - \varphi(t - \tau)}{\tau} = \frac{\phi_0(t)}{\tau} - kt - \omega + \frac{k\tau}{2}, \tag{11}
$$

The wavelength-swept laser phase $\Psi(t)$ can be reconstructed as

$$
\Psi(t) = \omega t + \frac{k}{2} t^2 + \varphi(t) = \int \left( \omega + kt + \frac{d\varphi}{dt} \right) dt \\
\approx \int \left( \frac{\phi_0(t)}{\tau} + \frac{k\tau}{2} \right) dt = \frac{1}{\tau} \int \left( \phi_0(t) + \frac{k\tau^2}{2} \right) dt \\
= \frac{1}{\tau} \int \phi_0(t) dt, \tag{12}
$$

where the initial phase $\phi_0(t)$ is hard to demodulate; it has to be set as an arbitrary value, which will induce an arbitrary initial frequency offset for the wavelength-swept laser. Based on the algorithm shown in Fig. 2, we can further obtain the FRFT of
Fig. 7. (a) Reconstructed phase for different sweep speeds. (b) Measured linewidths for different sweep speeds under different time windows. (c) Fractional domain spectrum of the minimum linewidth. (d) Minimum linewidth at different sweep speeds.

the reconstructed wavelength-swept laser as

\[ F_\alpha(u) = \sqrt{\frac{1 - j \cot \alpha e^{\frac{u^2}{2 \cot \alpha}}}{2\pi}} \int_{-\infty}^{+\infty} A e^{j\Phi(t)} e^{j\frac{u}{2 \cot \alpha}} \alpha dt, \tag{13} \]

where \( u \) is the fractional frequency and \( \alpha \) is the rotation angle.

As mentioned above, when the rotation angle is tuned, the fractional domain spectrum will show different energy concentrations, based on which we can judge the best fractional domain order. From (10), we can obtain the estimated sweep slope \( k \) of the wavelength-swept laser, and the optimal rotation angle should satisfy \( k = -\cot \alpha \). After the above steps, we can demodulate the wavelength-swept laser signal into a series of chirp-frequency components and then obtain the intrinsic spectrum information, which is determined by the laser phase noise.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

As a proof of concept, we measure the dynamic parameters of a commercial wavelength-swept laser (Luna Phoenix 1202) as a typical dynamic time-frequency laser. In the experiment, we reconstruct the phase and measure the linewidth for different sweep speeds by the FRFT. For each group of signals, we first use IQ demodulation to obtain the differential phase \( \phi_0(t) = \phi_b(t) - \phi_d(t) \) and use linear fitting to obtain the reference sweep speed \( k \) related to the rotation angle \( \alpha \), as shown in Fig. 5(a). The reconstructed phase can be further obtained by integrating the differential phase, as shown in Fig. 5(b). With the optimal rotation angle \( \alpha \), the distribution of the energy concentration is obtained by FRFT of the reconstructed laser signal, as shown in Fig. 5(c). The frequency axis is rewritten in the fractional domain with \( f = \frac{u \csc \alpha}{2\pi} \), which can reflect the laser spectrum induced by laser phase noise. To characterize the linewidth of the laser signal in the fractional domain, we use the half energy width as the linewidth. The area of the shaded part is half of the overall energy, and its width is the half energy width. Fig. 5(d) shows the integrated energy \( E(\delta u) \) curve under the condition of different integration bandwidths, which is calculated as

\[ E(\delta u) = \int_{u_0 - \delta u/2}^{u_0 + \delta u/2} F_\alpha(u) F_\alpha^*(u) du, \]

where \( u_0 \) is the fractional domain central frequency and \( \delta u \) is the fractional domain integration bandwidth. The integration bandwidth is rewritten in the form of frequency, i.e., \( \delta f = \frac{\delta u \csc \alpha}{2\pi} \). Considering the random error during the calculation, each signal is calculated 10 times and averaged to obtain the linewidth.

Considering that the FRFT is a generalized extension of the traditional Fourier transform, we explore the influence of the time window width of the FRFT, as shown in Fig. 6. It is worth noting that the narrowest measured linewidth could be obtained with a suitable time window width. When the width of the time window is too short, due to the insufficient sampling time, the frequency analysis resolution is insufficient to show the laser noise. When the width is too long, the measured linewidth is broadened due to the 1/f frequency noise of the laser cavity, which has also been widely discussed regarding fixed single-frequency lasers [27].

The linewidths for different sweep speeds from 0.93 nm/s to 1000.03 nm/s are further measured, as shown in Fig. 7. The sweep speeds are directly set by the control program of the
commercial wavelength-swept laser. Based on the reconstructed phases in Fig. 7(a), the linewidths under different time windows could be measured with suitable rotation angles, as shown in Fig. 7(b). The optimal time windows for different sweep speeds are very close, and the narrowest linewidths are almost equal, which means that the sweep speed nearly does not change the intrinsic linewidth of the laser. However, when the time window is enlarged, the faster the frequency sweep speed is, the broader the linewidth measured, which is mainly induced by the nonlinear sweeping of the laser frequency. Therefore, the narrowest linewidth can only be measured in the appropriate time window width for wavelength-swept lasers.

To show the influence of the rotation angle for the FRFT of the reconstructed laser signals, we set up different fractional orders to measure the laser linewidth at the same sweep speed of 10.02 nm/s, as shown in Fig. 8(a). The front five curves are the fractional domain spectra near the optimal rotation angle, and the last one is the spectrum with $\alpha = \pi/2$, i.e., the traditional FT spectrum. It is worth noting that a deviation from the optimal rotation angle will induce spectral broadening. Specifically, we further compare the spectra obtained by FRFT and FT under different time window widths, as shown in Fig. 8(b). The narrowest linewidths calculated by the FRFT and FT are 0.14 MHz and 0.84 MHz, respectively. The yellow curve is the increasing frequency width of the laser signal corresponding to the time window. Under the condition of satisfying the Fourier resolution, the linewidth demodulated by the Fourier transform is relatively close to the increased width from the frequency sweeping, which further indicates that the real linewidth cannot be observed due to the change in the laser frequency. The use of the fractional Fourier transform can reduce the influence by several orders of magnitude. The black curve is the spectral resolution due to the corresponding time window. Neither the FRFT nor FT can break this resolution, which is limited by the time window. The results show that the linewidth measured by the traditional FT cannot reflect the intrinsic linewidth of the laser with a high-speed frequency sweep rate. Meanwhile, the narrowest linewidth measured by the FRFT remains relatively constant with the chirp-frequency waveform as the decomposition component, which demonstrates that the FRFT can break through the measurement resolution limitation of the traditional FT and has a higher accuracy in the decomposition of wavelength-swept laser signals.

V. CONCLUSION

In summary, we propose a new concept to analyze the intrinsic energy distribution of the laser dynamics during fast and wide-range frequency sweeping by decomposing the laser energy with the chirp-frequency waveform signal as the basic component, which is realized by fractional Fourier transform (FRFT) of the coherently reconstructed laser waveform. In the proof-of-concept experiment, the intrinsic energy distribution and linewidth of a commercial wavelength-swept laser as a typical dynamic time-frequency laser are tested for different scanning speeds from 1 nm/s to 1000 nm/s. The sweep speed and intrinsic spectrum can be simultaneously reconstructed, and the optimal demodulation time window of signals with different sweep speeds is also verified. With the new decomposition idea for dynamic time-frequency lasers, the laser spectral purity measurement resolution is no longer limited by the laser wavelength-sweeping speed, which can be utilized to characterize the coupling strength between the spontaneous emission and the laser energy in a fast frequency tuning process. In theory, the spectral linewidth resolution is inversely proportional to the measurement time window. The new understanding of the energy distribution of dynamic time-frequency lasers proposed in this work will contribute to accurate characterization of laser dynamics under fast and broadband frequency sweeping and benefit optical precision measurement applications.

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