Linewidth and frequency jitter measurement of an erbium-doped fiber ring laser by using a loss-compensated, delayed self-heterodyne interferometer

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The single-mode linewidth of an erbium-doped, single-frequency, fiber ring laser has been measured by using a newly developed loss-compensated delayed self-heterodyne interferometer that has a resolution of less than 600 Hz. The natural linewidth is determined to have an upper bound of less than 2 kHz. In addition, frequency jitter was found to be dominant over the natural linewidth, yielding an effective linewidth of approximately 4 kHz.

Linewidth and frequency stability of laser oscillators are critical parameters for certain applications, including coherent communication systems and coherent sensing systems. There is increasing interest in erbium-doped fiber lasers owing to a number of advantages that they have, including inherent compatibility with optical fiber. Recently we demonstrated an all-fiber, erbium-doped ring laser (EDFRL) using a tandem fiber Fabry–Perot (FFP) filter concept. The device exhibits stable single-frequency operation, characterized by large side-mode suppression (greater than 48 dB) as well as quantum-limited intensity noise at high frequency.[1-3] In this Letter we describe measurement of the linewidth and frequency jitter of this device with the use of a new loss-compensated version of the recirculating delayed self-heterodyne interferometer[4] (RDSHI).

The experimental setup for the EDFRL and the loss-compensated RDSHI is shown in Fig. 1. Optical gain for the EDFRL was provided by a Corning FiberGain module pumped with a temperature-controlled 980-nm laser diode. The tandem FFP filter in the laser structure makes possible a large tuning range as well as good longitudinal-mode stability.[1] The total cavity length was approximately 50 m with a corresponding free spectral range of 4 MHz. Approximately 1 mW of output power from the EDFRL was coupled to the loss-compensated RDSHI. The performance characteristics of the loss-compensated RDSHI are described in Ref. 5. Briefly, they are similar to those of the optical recirculating DSHI first introduced by Tsuchida[4] but with an erbium-doped fiber amplifier (EDFA) introduced into the recirculating loop to provide loss compensation.

90% of the optical power incident upon the RDSHI is sent directly to the fast photodiode (15-GHz corner frequency, Ortel Corporation), while 10% of the power is coupled into the loop. In addition to the EDFA, the loop consists of 11 km of standard transmission fiber and an acousto-optic modulator (10% efficiency, operated at 140 MHz). Each pass through the recirculator thereby delays the optical beam in time and introduces a 140-MHz frequency shift. After completion of a pass, 10% of the light is coupled out of the loop and heterodynes with the directly transmitted wave at the detector. The other 90% is recoupled into the loop for further delay and frequency shifting. Spectrum analysis of the detected photocurrent therefore shows a series of frequency-shifted peaks that correspond to photomixed beat notes produced by the directly transmitted wave mixing with increasingly delayed frequency-shifted waves. Those beat notes corresponding to time delays greater than the coherence time of source make possible measurement of the source linewidth. Previously, only two or three passes through the recirculator have been observable by using this approach.[4] The loss-compensation technique greatly extends the useful delay of the interferometer, thereby extending its resolution limit.

A FFP bandpass filter (bandwidth 42 GHz, finesse 100) and a pigtailed optical isolator are also included in the RDSHI to reduce the recirculating amplified spontaneous emission and to inhibit loop oscillation. By adjusting the pump power of the RDSHI gain

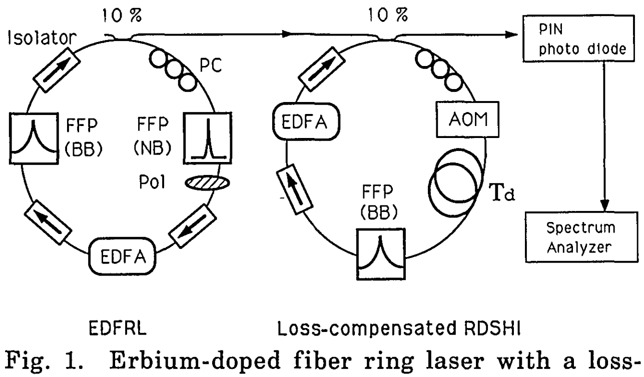

Fig. 1. Erbium-doped fiber ring laser with a loss-compensated delayed self-heterodyne interferometer. EDFA, erbium-doped fiber amplifier module; PC, polarization controller; NB, narrow band; BB, broadband; Pol, polarizer; AOM, acousto-optic modulator.

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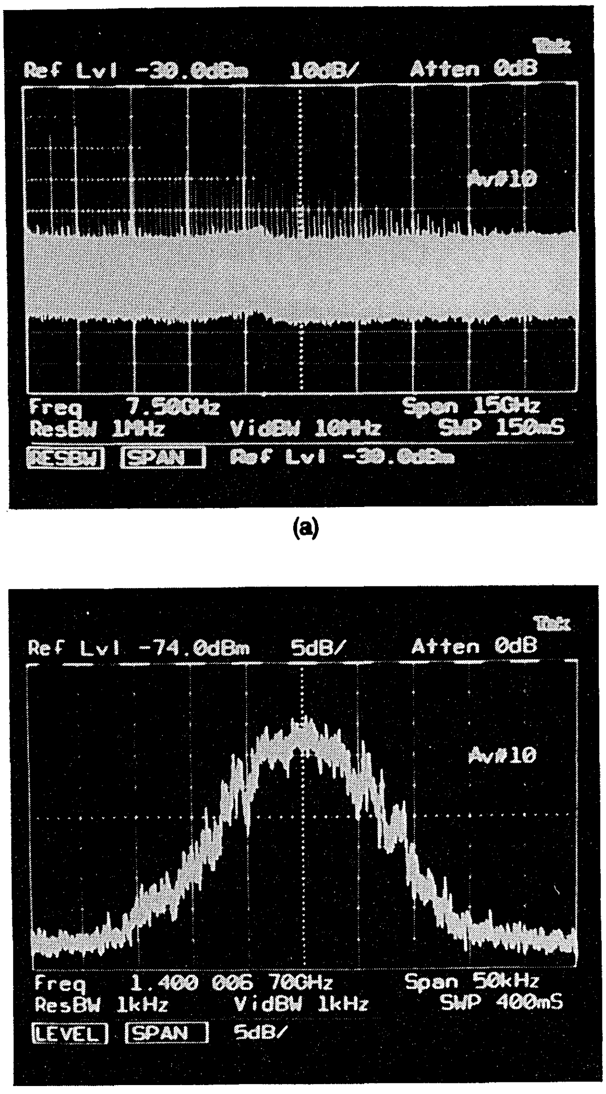

Fig. 2. (a) Detected beat-note spectrum between the undelayed laser beam and the delayed beam showing over 70 beat notes (full span 15 GHz, detector bandwidth 15 GHz). (b) Typical spectrum of the delayed self-heterodyne interferometer at 10th order.

module and matching the bandpass filter wavelength of the RDSHI to the ring laser wavelength, it was possible to detect the recirculated beam delayed as many as 70 round trips through the loop [Fig. 2(a)] without any unintentional recirculator oscillation.[5] Since the measured spectral broadening that is due to the EDFA was smaller than the RDSHI resolution for as many as 30 round trips for an 11-km spool,[5,6] the loss-compensated RDSHI has an effective delay line of 330 km (for 30 orders) and a resulting resolution of 600 Hz.

We measured the linewidth of the EDFRL between the wavelengths of 1531 and 1538 nm using the 10th order of the loss-compensated RDSHI (corresponding resolution of 1.2 kHz). The beat spectrum [Fig. 2(b)] was taken in the averaging mode of the spectrum analyzer (Tektronics Model 2782) over several seconds with the resolution bandwidth setting at 1 kHz. The FWHM was calculated from the 3- and 6-dB points of these spectra assuming a Lorentzian line shape. An upper bound on the natural linewidth was 2 kHz as given by the intersection of interferometer resolution and data plots in Fig. 4 below. There was no noticeable dependence on the laser wavelength (Fig. 3), laser power, RDSHI loss compensation, or codopant of the erbium fiber used in the EDFRL. This suggests that an extrinsic noise source is dominant over the observed linewidth of this laser. (The Schawlow–Townes linewidth, for example, has an inverse dependence on the laser power and has a theoretical subhertz value for the EDFRL at these power levels.) We attribute this to frequency jitter of the detected beat

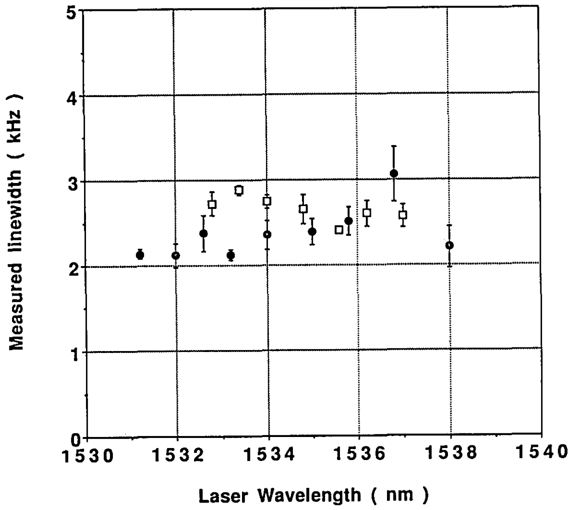

Fig. 3. Measured linewidth of the EDFRL between wavelengths of 1531 and 1538 nm. Circles, aluminum-codoped erbium fiber in the EDFRL; squares, germanium-codoped erbium fiber in the EDFRL.

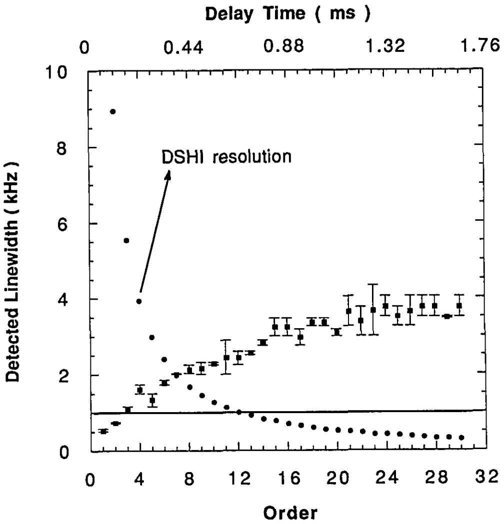

Fig. 4. Measured FWHM of the beat-note spectrum plotted versus the delay line length (lower axis) and the delay time (upper axis). The solid line is the spectrum analyzer resolution bandwidth setting, the circles denote the resolution of the RDSHI, and the squares denote the measured linewidth of the EDFRL. DSHI, delayed self-heterodyne interferometer.

note induced mainly by acoustic or thermal cavity length fluctuations of the EDFRL.

Testing this idea requires a long delay line to give enough time for the laser to exhibit full root-mean-square frequency variation between the directly transmitted beam and the delayed beam. If the delay line is not long enough, then only a fraction of the full root-mean-square jitter will be measured. For this experiment, the beat spectrum was measured at every order (up to the 30th) to determine the dependence of the line shape FWHM on the delay line length change (this is another advantage of the loss-compensated RDSHI compared with the conventional method in which the length of the delay is fixed[7]). The FWHM was again measured and calculated from the 3- and 6-dB points of the beat spectrum, assuming a Lorentzian line shape. As expected, the mean FWHM of the beat spectrum saturated to a constant value of approximately 4 kHz after the 22nd order, and increasing deviation from the Lorentzian line shape was evident (Fig. 4).

To confirm that this broadening was from the laser, the experiment was repeated in three different cases: with acoustic isolation on the laser only, on the RDSHI only, and both on the laser and the RDSHI. The results showed no detectable difference in FWHM linewidth with acoustic isolation on the RDSHI. However, the acoustic isolation on the laser resulted in a narrower FWHM linewidth, which indicates that the laser frequency jitter is from cavity length fluctuations that are due to acoustic noise.

To summarize, we measured the linewidth and frequency jitter of a single-frequency, erbium-doped fiber ring laser with a newly developed loss-compensated, delayed self-heterodyne interferometer. The improved RDSHI has a peak resolution of 600 Hz with only 11 km of delay fiber (the resolution is wavelength dependent since the EDFA loss compensation has a dependence on the wavelength). The linewidth of the EDFRL has an upper bound of less than 2 kHz, showing a flat dependence with respect to the oscillation wavelength and the output power of the laser. The measured frequency jitter was approximately 4 kHz. We attribute the frequency jitter to laser cavity length fluctuation from various perturbations such as thermal and acoustic noise. The time scale of this fluctuation is approximately 1–2 ms. Further research will be focused on active frequency stabilization of the EDFRL.

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References

1. N. K. Park, J. W. Dawson, C. Miller, and K. J. Vahala, Appl. Phys. Lett. **59,** 2369 (1991).
2. J. W. Dawson, N. K. Park, C. Miller, and K. J. Vahala, in *Digest of Conference on Optical Fiber Communication* (Optical Society of America, Washington, D.C., 1992), paper WA5.
3. N. K. Park, S. Sanders, J. W. Dawson, and K. J. Vahala, in *Digest of Conference on Lasers and Electro-Optics* (Optical Society of America, Washington, D.C., 1992), paper CWE5; S. Sanders, J. W. Dawson, N. K. Park, and K. J. Vahala, Appl. Phys. Lett. **60,** 2583 (1992).
4. H. Tsuchida, Opt. Lett. **15,** 640 (1990).
5. J. W. Dawson, N. K. Park, and K. J. Vahala, IEEE Photon. Technol. Lett. **4,** 1063 (1992).
6. H. Okamura and K. Iwatsuki, Electron. Lett. **26,** 1965 (1990).
7. D. A. Smith, M. W. Maeda, J. J. Johnson, J. S. Patel, M. A. Saifi, and A. Von Lehman, Opt. Lett. **16,** 387 (1991).