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Frequency stabilization of a tunable erbium-doped fiber laser

S. L. Gilbert

National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80303

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A single-frequency Er-doped fiber laser that is tunable from 1.52 to 1.58 μm has been constructed. The laser linewidth was determined to be less than 1.6 MHz FWHM by observing the spectrum of the beat between the fiber laser and a 1.523-μm He–Ne laser. The frequency of the fiber laser was locked to several absorption lines of acetylene near 1.53 μm. This research demonstrates the inherent stability of fiber lasers and their potential for use in a wavelength standard for optical communications.

Wavelength standards in the 1.5-μm region are important for many of the proposed optical communication schemes that involve frequency-division multiplexing and coherent heterodyne detection. In addition to these optical communications applications, absolute frequency measurement of reference lines in this region would be useful for frequency-standard metrology and high-precision spectroscopy. Fiber lasers, in which the active medium is a dopant in an optical fiber core, are attractive candidates for use in a wavelength standard because of their potential for narrow-linewidth operation. This Letter describes an experimental investigation of the frequency stability of a single-longitudinal-mode Er-doped fiber laser. It is found that the laser has short-term ($f \geq 5$ Hz) frequency fluctuations of less than 1 MHz rms, and these fluctuations are reduced to less than 500 kHz rms by stabilizing the laser to an absorption line in acetylene. It is concluded that fiber lasers show excellent potential for use in a highly accurate wavelength standard with a linewidth and reproducibility of better than 100 kHz.

Research on frequency stabilization of lasers in the 1.5-μm region has concentrated on stabilizing the frequency of diode lasers to various atomic (krypton,[1] neon,[2] and rubidium[3]) and molecular (ammonia,[4,5] water,[4] and acetylene[6,7]) lines. The frequency noise spectrum of diode lasers, however, can extend well beyond 1 GHz. This causes inherent difficulties in obtaining narrow linewidths. A fiber laser's frequency fluctuations, on the other hand, are dominated by mechanical motion of the cavity elements and thermal drift. The spectrum of the fluctuations is therefore confined to low frequencies, where they can be easily removed by an electronic servo loop.

Single-longitudinal-mode operation of Er-doped fiber lasers has been demonstrated in two different cavity configurations: a fiber Fox–Smith resonator[8] and a fiber ring resonator.[9] The Fox–Smith cavity experiment reported a linewidth of less than 8.5 MHz, which was the resolution of the optical spectrum analyzer used. The ring laser linewidth was characterized using a delayed self-heterodyne technique that indicated a linewidth of $\leq$60 kHz. This is a good measurement of the laser noise at high ($\geq$10 kHz) frequencies. However, since a 25-km delay line (0.1 msec) was used, the measurement was not sensitive to the low-frequency (less than or equal to a few kilohertz) components of the fluctuations. It was found here that the dominant noise components in a fiber laser are confined to this lower-frequency regime.

An acetylene absorption line was chosen as a reference for several reasons. Of the molecular absorbers identified to date, acetylene has the strongest lines in this region. Acetylene is also relatively immune to perturbations from electric and magnetic fields since it is a symmetric molecule (no permanent dipole moment) and is not paramagnetic. This lack of sensitivity to the environment is an important characteristic for a reproducible standard. In optogalvanic spectroscopy of atomic lines, however, Zeeman shifts of greater than 10 GHz/T (1 MHz/G) have been observed on some transitions.[10] Another advantage of molecular absorption bands is that they are made up of a number of lines, each of which can be used as a reference point for frequency-division multiplexing. The $\nu_1 + \nu_3$ vibrational–rotational spectrum of the $^{12}C_2H_2$ acetylene molecule has a clean spectrum containing approximately 40 clearly distinguishable lines with spacings of ~70 GHz ($\approx$0.6 nm) between 1.51 and 1.54 μm.[11] A similar spectrum shifted ~8 nm toward longer wavelengths can be obtained from $^{13}C_2H_2$.[7] If additional lines are required, the $^{12}C^{13}CH_2$ spectrum[12] could also be used.

A standing-wave single-frequency Er-doped fiber laser has been built. The 40-cm optical path length of the laser cavity produces a longitudinal mode spacing of ~375 MHz. Single-longitudinal-mode operation is accomplished as follows: Feedback from a diffraction grating confines the lasing to a region of ~5 GHz around the central wavelength. Two pieces of Er-doped optical fiber (2.8 and 1 cm long) form coupled cavities, within the 40-cm cavity, with 3.6- and 10-GHz free spectral ranges, respectively. The overlap of the transmission peaks of these cavities with the laser cavity modes forces the laser to operate in a single longitudinal mode.

A schematic diagram of the laser is shown in Fig. 1(a). The fiber is end pumped through mirror M1 (99% reflectivity at 1.55 μm, 56% transmissivity at 528.7 nm), with 528.7-nm light from an Ar^+ laser. This mirror is in contact with one end of the 2.8-cm-

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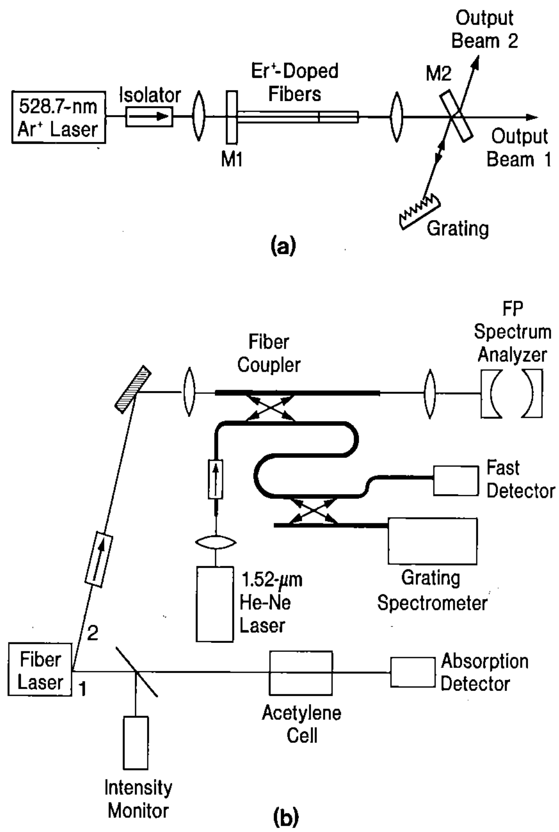

Fig. 1. (a) Schematic diagram of the Er-doped fiber laser. (b) Diagram of the apparatus for measuring the beat spectrum between the fiber laser and the 1.523-μm He–Ne laser and for detecting absorption lines of acetylene. The second fiber coupler operates as a beam splitter for the mixed signal.

long, Er-doped fiber (0.22 mol % Er^{3+} in a SiO_2–Al_2O_3 core, single transverse mode at 1.5 μm). The 1-cm piece of fiber is attached to the longer piece by using a demountable splice fiber connector. The output of this fiber is collimated with a lens and reflected by mirror M2 (77% reflectivity at 1.54 μm) onto a 1200-groove/mm grating set for Littrow conditions. The first-order diffraction from the grating then follows the reverse path. The laser output consists of the two beams that are transmitted through mirror M2. Coarse tuning of the wavelength is done by manually tilting the diffraction grating, and fine tuning (over 2 GHz) is accomplished by translating and tilting the grating with a piezoelectric transducer (PZT) and stretching the 2.8-cm fiber with another PZT. The entire apparatus is mounted on a table that is not vibrationally isolated.

The fiber laser is tunable from 1.52 to 1.58 μm, with the highest power operation at ~1.545 μm. At this wavelength the laser has a threshold of 30 mW (pump power coupled into the fiber) and a slope efficiency of 10% for the combined outputs. At 1.523 μm the threshold is 60 mW and the slope efficiency is 5%. The frequency spectrum of the laser was monitored on a Fabry–Perot (FP) spectrum analyzer with a 1.5-GHz free spectral range and a transmission bandwidth of 8 MHz. The frequency jitter on the side of the spectrum analyzer's transmission peak indicated that the short-term frequency fluctuations ($f \geq 5$ Hz) of the fiber laser were less than 2.5 MHz peak to peak (<1 MHz rms). Figure 2 shows a spectrum of this noise from 0 to 1 kHz. A spectrum covering frequencies out to 25 kHz showed no structure beyond 1 kHz. Fiber laser intensity fluctuations contributed less than 0.3 mV throughout this spectral range, but fluctuations in the spacing of the FP spectrum analyzer mirrors may significantly contribute to the spectrum in Fig. 2. The peaks at harmonics of 60 Hz are probably due to Ar^+-laser intensity noise, which cause changes in the index of refraction of the fiber core owing to temperature changes in the fiber. This interpretation is consistent with the observation in this study of significant modulation of the fiber laser frequency when the Ar^+-laser intensity was deliberately modulated. The fluctuations of an unstabilized 1.523-μm He–Ne laser were also observed using the same technique. The He–Ne laser's fluctuations were ~30% smaller than those of the fiber laser, and the spectrum was also confined to low frequencies but was not dominated by 60-Hz harmonics. Since the frequency fluctuation spectrum of the fiber laser is confined to frequencies below 600 Hz, removal of this noise should be straightforward with a relatively low-frequency (a few kilohertz) feedback loop and an appropriate error signal.

The laser frequency fluctuations were also measured by recording the spectrum of the beat between the fiber laser and the 1.523-μm He–Ne laser. The setup for this experiment is shown in Fig. 1(b). Light from output beam 2 of the fiber laser was coupled into one port of a 2 × 2 fiber coupler. The He–Ne laser light was coupled into the other input port of the coupler, and the combined signals were sent to the FP spectrum analyzer, a 0.1-nm resolution grating spectrometer, and a fast InGaAs detector. Optical isolators were used on both inputs of the fiber coupler to avoid optical feedback to the lasers. The fiber laser was tuned within 3 GHz of the He–Ne laser, and a beat note was observed on a rf spectrum analyzer. Single scans of the beat spectrum had linewidths of between

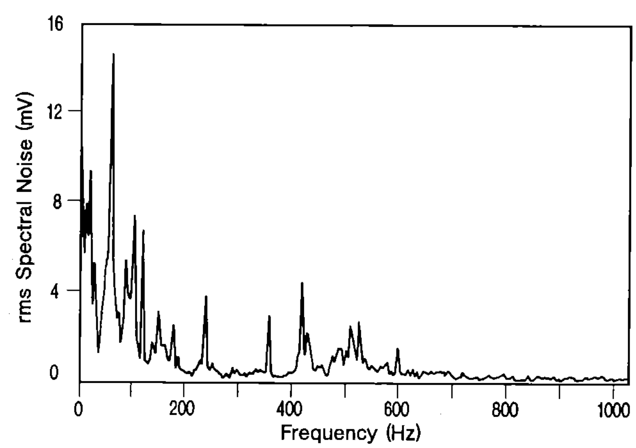

Fig. 2. Spectrum of the frequency fluctuations of the free-running fiber laser using the side of the FP spectrum analyzer transmission peak as a frequency discriminant. A 10-mV change in transmission through the FP spectrum analyzer corresponded to a laser frequency change of approximately 200 kHz.

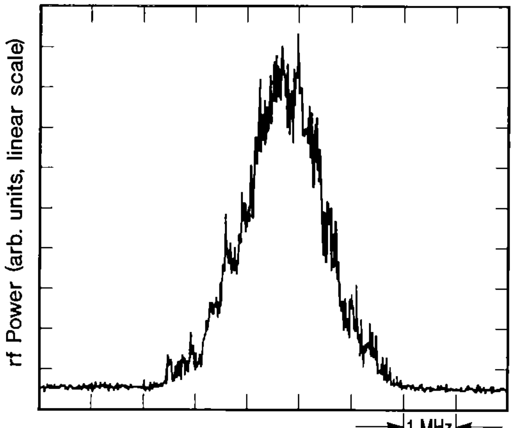

Fig. 3. Heterodyne beat spectrum between the fiber laser and the He–Ne laser averaged over twenty 50-msec samples with a 100-kHz resolution bandwidth. The beat spectrum is centered at 468 MHz and has a FWHM of 1.6 MHz.

1.7 and 2.0 MHz FWHM. To obtain a better signal-to-noise ratio by averaging several scans, it was necessary to reduce the drift of the fiber laser frequency. This was accomplished by loosely locking (unity gain at ~150 Hz, gain of ≈100 at 1.5 Hz) its frequency to the side of the FP spectrum analyzer's transmission peak. This reduced the fiber laser's fluctuations to roughly the same amplitude as those of the He–Ne laser, as observed on the FP spectrum analyzer. Figure 3 shows the spectrum of the beat between the lasers taken under these conditions and averaged over 20 samples. The 1.6-MHz linewidth (FWHM) is a combination of the fiber laser and He–Ne laser frequency fluctuations.

The fiber laser was locked to the sides of several different $^{12}C_2H_2$ lines near 1.53 μm. As shown in Fig. 1(b), output beam 1 of the laser was sent through a 30-cm-long acetylene cell, and the transmission signal through the cell was monitored by a photodiode. Another photodiode (the intensity monitor) was used to monitor the laser power. With the cell filled to a pressure of 270 Pa (2 Torr), we observed 58%, 65%, and 68% absorption of the laser light on the $P(5)$, $P(7)$, and $P(9)$ lines of the $\nu_1 + \nu_3$ vibrational band. These lines had a FWHM of 550 ± 75 MHz due primarily to Doppler broadening. An error signal for stabilization was obtained by tuning the laser frequency to the side of one of these lines and adjusting the absorption signal amplification so that its magnitude matched that of the signal from the intensity monitor detector. The resultant subtracted signal was then near 0 V, with fluctuations predominantly due to the laser frequency changes. This error signal was sent to the grating PZT to lock the laser frequency and reduce the short-term fluctuations. The unity-gain frequency of this locking was approximately 1 kHz, and the locked fiber laser linewidth was limited by residual intensity fluctuations in the error signal. Unfortunately, it was not possible to observe a beat between the stabilized fiber laser and the He–Ne laser because there are no strong acetylene lines within 3 GHz (the fast detector bandwidth) of the He–Ne frequency. By observing the fluctuations of the laser frequency with the FP spectrum analyzer, it was determined that the short-term fluctuations were reduced to less than 1.3 MHz peak to peak (<500 kHz rms). The long-term frequency drift was reduced dramatically, but it was difficult to evaluate this quantitatively because of the FP spectrum analyzer's drift. The stabilization error signal showed deviations that correspond to a change in the central frequency of less than 200 kHz over a period of 30 min. It is risky to draw any firm conclusions about the stability of the laser from the behavior of the error signal, however, since it was contaminated by residual intensity changes and, perhaps, noise or drift in the electronics.

In summary, a single-longitudinal-mode, Er-doped fiber laser that has short-term frequency fluctuations of less than 1 MHz rms has been constructed. Long-term frequency stability by locking the laser frequency to the $P(5)$, $P(7)$, and $P(9)$ lines of the $\nu_1 + \nu_3$ band of the $^{12}C_2H_2$ molecule has been achieved. This research demonstrates that fiber lasers have desirable qualities for use in a wavelength standard. In the future, significant improvements in the laser stabilization can be made by using more sophisticated techniques such as Doppler-free saturated absorption spectroscopy. In addition, a compact, rugged version of this fiber laser could be built that utilizes diode laser pumping (980 nm or 1.48 μm) and fiber gratings.

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