Frequency locking of an erbium-doped fiber ring laser to an external fiber Fabry–Perot resonator

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An all-fiber, single-frequency, erbium-doped ring laser has been frequency locked to a resonance peak of an external fiber Fabry–Perot resonator by the Pound–Drever technique. In addition, feedback to the mode selection filter in the laser resonator eliminates occasional mode hopping completely, resulting in frequency-locked, stable, single-frequency operation of the laser for periods of several hours.

There have been several demonstrations of frequency stabilized lasers operating in the important 1.5-μm telecommunications window. Techniques include absolute frequency stabilization using atomic lines[1] and frequency locking to the resonance peak of a reference cavity using either the transmitted laser field[2] or the reflected laser field.[3,4] For application to wavelength-division-multiplexed systems, the Pound–Drever approach (i.e., the reflected field method) is attractive since it provides evenly spaced multiple resonance peaks that can be shared by several lasers and since the reflected wave approach provides response to laser phase fluctuations that is not limited by the reference resonator lifetime.[3,4]

We have recently demonstrated an all-fiber erbium-doped ring laser whose characteristics include quantum-limited intensity noise operation,[5] narrow linewidth (<4 kHz),[6] large sidemode suppression (>60 dB), and large tuning range.[7] This device is based on a novel tandem fiber Fabry–Perot (FFP) concept in which a first, narrow-bandwidth Fabry–Perot (free spectral range 6 GHz, bandwidth 50 MHz) provides mode selection while a second, broadband device (free spectral range 4 THz, bandwidth 26 GHz) provides tuning (see Ref. 8 for a discussion of FFP technology). Although it is quite stable, this device does exhibit periodic mode hops on a time scale of minutes and experiences slow frequency shifts because of thermal drift of the resonator. In this Letter, we demonstrate an all-fiber stabilization scheme based on the Pound–Drever approach, which eliminates mode hopping altogether and locks the lasing frequency to an external FFP resonator. The resulting device is stable for periods of several hours and opens up the possibility of locking multiple fiber ring lasers to a single reference. Such a system is inherently compatible with optical fiber and could be of potential use in a fiber link employing wavelength-division multiplexing, in a fiber sensing network, or as a spectroscopic source.

The laser setup and the electrical schematic for the error signal generation are shown in Fig. 1. The laser includes broadband and narrow-band FFP's for tuning and mode selection, a Corning FiberGain module with a 980-nm pump diode, polarizers and a phase modulator with a polarization controller, metal-clad fiber (MCF) for laser cavity-length control, and isolators for unidirectional operation and isolation from external reflections. All the components were fiber pigtailed and assembled by using either a mechanical splicer or a fusion splicer. Lasing emission was coupled out by a 3-dB fiber coupler. The laser cavity length was 65 m (free spectral range 3 MHz). The laser was housed in a styrofoam box to provide shielding from room microphonics, which cause mode hopping.

The stabilization system consists of two independent control circuits. The first causes the internal mode-selection FFP filter to track the lasing frequency as it drifts or shifts owing to tracking provided by the second control circuit. This first circuit eliminates mode hopping. The second circuit causes the lasing frequency to track a particular resonance of the external FFP reference. Both circuits utilize the Pound–Drever method.

For the first circuit, we obtained the frequency deviation error signal between the lasing mode and

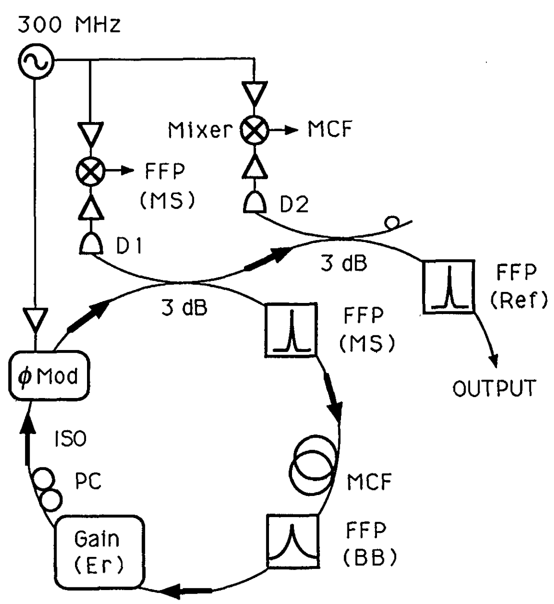

Fig. 1. Erbium-doped fiber ring laser with stabilization setup. ISO, isolator; MS, mode selection; BB, broadband; PC, polarization controller; D1, D2, photodiodes.

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the internal mode-selection FFP filter by placing an electro-optic phase modulator inside the ring, immediately before the output coupler and internal mode-selection FFP filter as illustrated. The phase modulator was driven at 300 MHz. At this frequency the phase modulation sidebands were well outside the FFP bandwidth of 50 MHz, ensuring nearly full reflection of the sidebands. Full reflection also prevents any possibility of unintentional mode locking by the phase modulator. The fully reflected sidebands of the lasing field and the partially reflected lasing field were coupled out of the ring by the bidirectional coupler as illustrated and then photomixed at the photodiode (D1). The magnitude and the phase of the reflected lasing field depend on the frequency deviation of the reflected field relative to the transmission peak of the FFP cavity, so that the demodulated photomix signal at the mixer output gives the sign and the magnitude of the deviation.[3] Radio-frequency bandpass filters were employed before the mixer to improve the signal-to-noise ratio. Frequency tracking was then attained by processing this error signal through a proportional-integral-differential control circuit and feeding it back to the controlling voltage of the mode-selection FFP filter.

Figure 2(a) shows the error signal obtained with and without the feedback loop in operation. Without the feedback (lower curve), the acoustically unshielded laser gives frequent mode hops, resulting in an error signal of ~10 MHz (corresponding to 3–4 longitudinal modes). Once feedback is engaged, a significant reduction of the error signal is apparent. We confirmed the resulting mode-hop-free operation of the laser by monitoring the lasing spectrum, using a Newport Super-Cavity scanning interferometer. Without any acoustical shielding of the laser and with introduction of intentional acoustic disturbances, no mode hops were observed over periods of several hours.

To lock the laser frequency to the external FFP cavity, an additional 3-dB fiber coupler and the reference FFP cavity (closely matched with the internal mode-selection FFP) were added after the output port of the ring laser as illustrated. Even though the laser output was modulated at 300 MHz, after the external 50-MHz-bandwidth FFP the sidebands at 300 MHz were 20 dB smaller than the main carrier. The partly reflected field from the reference FFP cavity was then detected at photodiode D2, processed as described for the first servo loop, and then converted to a current used to resistively heat the MCF (1.5 m long, 2-Ω resistance) making up part of the laser ring. This has the effect of controlling the overall laser ring optical path length. The tuning range possible by resistive heating alone was approximately 200 MHz with a corresponding maximum current of 500 mA. This range and the MCF response time of 4 ms were sufficient to compensate for the relative drift of the external reference FFP cavity and laser frequency caused by thermal variations.

Once the laser frequency was locked, it was possible to observe laser wavelength tracking of the transmission peak of the external reference FFP cavity, either by observing the optical spectrum, using the Super-Cavity scanning interferometer, or by monitoring the applied voltage on the mode-selection FFP filter inside the cavity. Within the limited tracking range of 200 MHz, owing to the limited applied current on the MCF, the laser wavelength varied linearly with the external FFP tuning voltage. Figure 2(b) shows the error signal obtained from the external FFP cavity servo loop with and without the feedback loop engaged. Error signal reduction is again apparent for the case of the loop engaged.

To summarize, we have locked the lasing mode of a single-frequency, erbium-doped fiber ring laser to an external FFP cavity by implementing the Pound–Drever technique. Limited tracking of 200 MHz was possible as we tuned the external reference FFP cavity. An additional tracking circuit was also implemented to control the internal Fabry–Perot mode-selection filter, thereby eliminating mode hopping completely. The complete system attains stable, frequency-locked operation of the laser for several hours. Further improvements to the system will include the locking of multiple lasers to the same reference FFP cavity and the possible introduction of

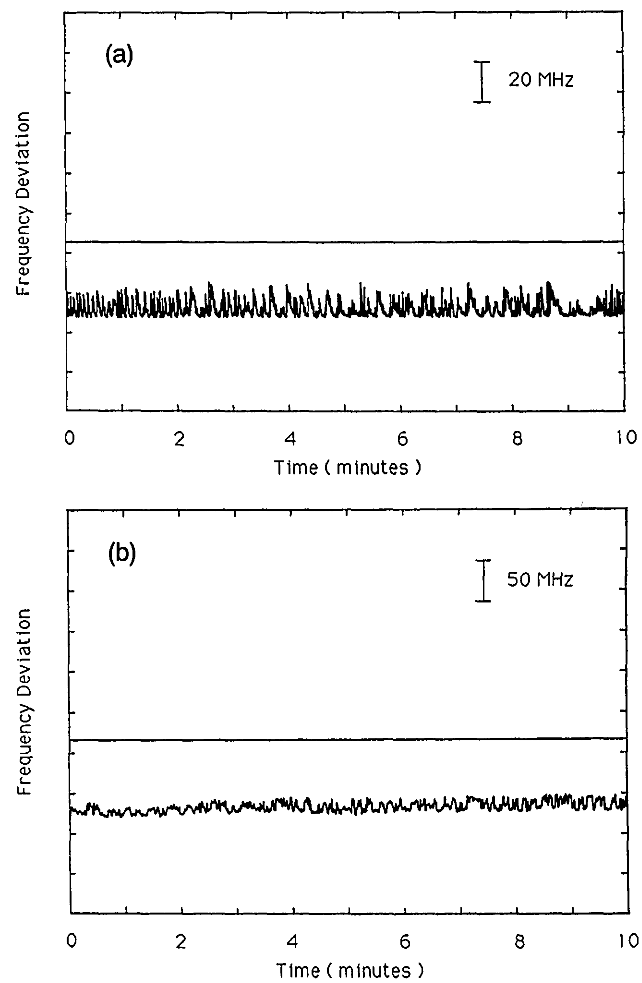

Fig. 2. (a) Error signals from the internal mode-selection filter locking circuit: upper curve, with feedback; lower curve, without feedback. (b) Error signals from the external reference cavity locking circuit with feedback activated on the internal mode-selection filter: upper curve, with feedback; lower curve, without feedback.

an absolute frequency reference based on an atomic reference.

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