Single frequency erbium fiber external cavity semiconductor laser

W. H. Loh,[a)] R. I. Laming, and M. N. Zervas
Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, United Kingdom

M. C. Farries
GEC-Marconi Materials Technologies, Caswell, Towcester, Northants, NN12 8EQ, United Kingdom

U. Koren
AT&T Bell Laboratories, Crawford Hill Laboratory, Holmdel, New Jersey 07733

(Received 6 March 1995; accepted for publication 26 April 1995)

A novel external cavity configuration for stable single frequency operation of the semiconductor laser is demonstrated. By using an erbium doped fiber as the external cavity, longitudinal mode-hopping is suppressed, ensuring single frequency operation. Employing a 3 m long fiber cavity, resolution-limited optical linewidths of a kHz are obtained. © *1995 American Institute of Physics.*

External cavity semiconductor lasers have long been considered an attractive way to achieve narrow linewidth single frequency operation, as the linewidth is expected to vary inversely as the square of the cavity length.[1] In this regard, single mode fibers have often been employed as the basis of the external cavity,[2–7] as they offer a compact and reasonably robust way of forming long cavity lengths. To achieve stable single frequency operation, however, a frequency selective element is normally required to discriminate against other external cavity (EC) modes to prevent them from lasing. With cavity lengths of a few tens of cm or longer, the mode spacings come down to the order of several hundred MHz or less, and it has been difficult so far to find suitable intracavity filters with sufficient resolution capable of suppressing neighbouring EC modes.

In this letter, we demonstrate a simple solution to this problem, which is to use erbium-doped single mode fibers rather than conventional undoped low-loss fibers to form the external cavity. The laser configuration is shown in Fig. 1. The 1530 nm laser diode has its anti-reflection coated (AR) facet facing the erbium fiber, and the fiber end is tapered and lensed to couple directly to the diode. The other end of the erbium fiber is spliced to a 25 cm length of undoped fiber which terminates in a photorefractive Bragg grating, forming the end reflector of the external cavity. The Bragg grating is 80% reflecting at 1535 nm, and has a bandwidth of 0.2 nm. 3 m of Er^{3+} fiber (with a single pass small signal absorption of 3 dB at 1535 nm) was used, resulting in an EC mode spacing of just 30 MHz. The Bragg reflector thus does not discriminate between individual EC modes (there are $\sim$1000 such modes falling within the bandwidth of the reflector), but it ensures that the lasing wavelength falls within the Er^{3+} absorption band. In contrast, with a broadband mirror as the end reflector instead of the Bragg grating, the lasing wavelength shifts to $\sim$1515 nm to avoid the Er^{3+} absorption, losing the advantage of using an Er^{3+}-fiber cavity.

Figure 2 shows the light-current characteristic of the laser. There is a sharp rise in the output power at threshold, which we attribute to the saturable loss in the Er^{3+} fiber. At maximum bias, the laser output power is 7.5 mW, and the lasing spectrum observed on an optical spectrum analyser with 0.1 nm resolution is shown in Fig. 3, indicating a side mode suppression ratio of $\sim$35 dB. Note however that this analyser does not resolve EC modes, and the modes observed here are due to the laser diode alone with its imperfect AR coating. To monitor the EC modes, a Newport Supercavity scanning interferometer (FSR = 6 GHz, resolution 1 MHz) was used. With proper adjustment of the fiber polarisation state, we find that single frequency operation could be obtained, which was typically stable for tens of minutes without any mode-hops. Instead of mode-hopping, the lasing frequency smoothly drifts back and forth with time, usually over several tens of MHz. The laser would also remain in the same EC mode as the bias current was varied from maximum to threshold, without a mode-hop. The linewidth was measured using a delayed self-heterodyne technique with a 25 km delay line, and the result is shown in Fig. 4. From the width of the rf spectrum, an optical linewidth of about 1 kHz could be inferred; however, this corresponds to a coherence time longer than the delay time. The laser linewidth is thus actually resolution-limited by the measurement setup, but is likely to be sub-kHz. It should also be mentioned that the laser stability observed here seems particularly notable since the entire experiment was conducted simply on a small optical bench without vibration isolation, and no attempt was made to shield any part of the laser cavity from air currents, etc. By comparison, when the Er^{3+} fiber was replaced by an equivalent length (3 m) of undoped standard telecom fiber, stability was found to be poor, with single mode operation typically lasting only for a few seconds at most before mode-hopping rapidly amongst several adjacent EC modes.

A physical basis for the stabilizing effect of the Er^{3+}-

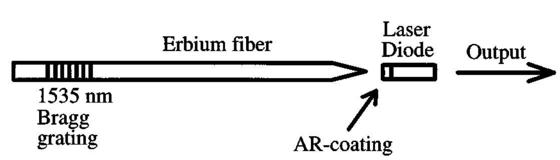

FIG. 1. Schematic of external cavity laser configuration.

[a)]Electronic mail: whl@orc.soton.ac.uk

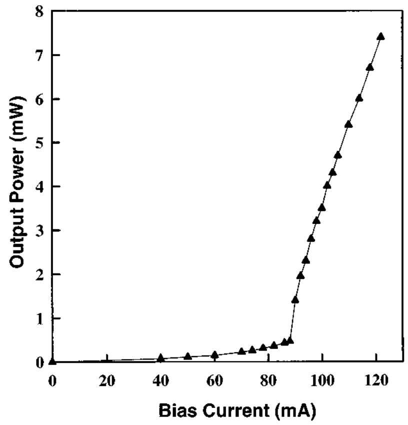

FIG. 2. Light-current characteristic of 3 m long Er^{3+}-fiber external cavity laser.

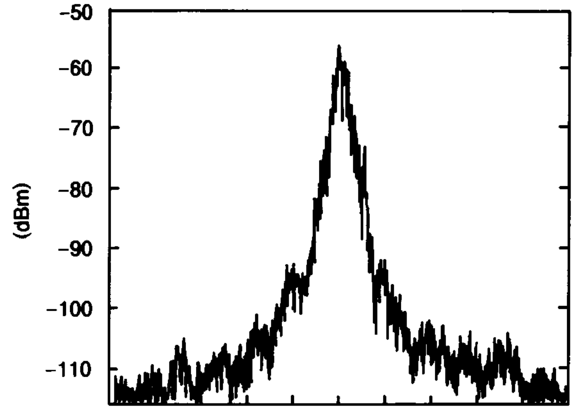

FIG. 4. Delayed self-heterodyned beat spectrum of 3 m long Er^{3+}-fiber external cavity semiconductor laser. (Horizontal axis is 10 kHz/div, centre frequency 100 MHz.)

fiber cavity based on spatial hole burning[8] may be outlined as follows. When single frequency operation is established in the laser, the resulting intensity standing wave formed in the cavity imposes a spatial hole-burning pattern on both the Er^{3+} fiber (loss saturation) and the laser diode (gain saturation). Thus, within the Er^{3+} fiber, regions of high optical intensity coincide with regions of low (saturated) loss, and vice versa. Within the laser gain medium, similar behaviour would be expected, with regions of high optical intensity coinciding with lower (saturated) gain. However, because the gain region is extremely short relative to the entire cavity, and placed at the end reflector, neighbouring EC modes would all share the standing wave pattern and hence the same spatial gain distribution (at an end reflector, all standing waves terminate as a node). In fact, with the 500 μm long laser diode, it would require another mode over 0.5 nm away to see a substantially different gain distribution from the original lasing frequency, but such a mode would not be excited since the bandwidth of the Bragg reflector is narrower than that (0.2 nm). Furthermore, carrier diffusion would also tend to smooth out the spatial hole-burning pattern.[9] The result is that spatial hole burning in the gain medium has minimal destabilising effects. The Er^{3+} fiber, on the other hand, spans much of the cavity, and the spatial loss pattern formed will discriminate even against adjacent EC modes, since at some point(s) along the cavity length, the standing wave patterns of different modes will be out of phase with each other. Effectively, a narrow-bandpass filter with bandwidth on the order of an EC mode spacing is burned into the Er^{3+} fiber by the lasing mode, which then serves to reinforce that lasing frequency. The self-written nature of this filter also allows the lasing frequency to shift smoothly to accommodate slow drifts/perturbations (on time scales longer than the Er^{3+} lifetime of $\sim$10 ms) without having to modehop, as has been observed, which is another potentially useful feature from a tunability point of view. Absorbing Er^{3+} fibers have previously been employed in fiber lasers to establish single mode operation[10] and long term mode stability in a loop laser;[11] its incorporation here in an external cavity semiconductor laser is particularly effective and advantageous due to the nature of the diode gain medium as explained above.

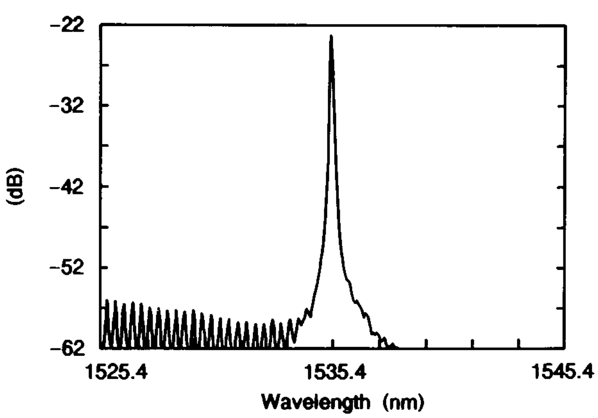

FIG. 3. Optical spectrum of laser at maximum bias.

It is interesting to note that stability is not necessarily improved with shorter Er^{3+}-fiber cavities. This is perhaps not too surprising since the Er^{3+}-based filter bandwidth varies inversely with the length, thus longer lengths yield better frequency selectivity, which compensates for the potentially greater destabilising effects arising from closer EC mode spacings. We removed the 3 m long erbium fiber and replaced it with a 17 cm length of a higher concentration Er^{3+} fiber with a small signal absorption loss of 2.2 dB. The total fiber cavity length was 0.43 m, including the 25 cm section of undoped fiber attached to the Bragg grating. In this case, the laser could also operate stably for tens of minutes without mode-hopping, but the lasing frequency now tends to drift over a wider range (several hundreds of MHz). This could be directly due to perturbations associated with the laser diode having a greater impact (through gain/index fluctuations or shifts in the diode-fiber coupling—the fiber lens tip is simply held in free space), since it now constitutes a larger fraction of the entire cavity. In this respect, longer Er^{3+}-fiber cavities would thus seem more advantageous in reducing medium term frequency drift. For this shorter cavity, the laser linewidth measurement is shown in Fig. 5. Assuming a Lorentzian profile, the optical linewidth is deduced to be 8 kHz (from the -20 dB rf spectrum width of 150

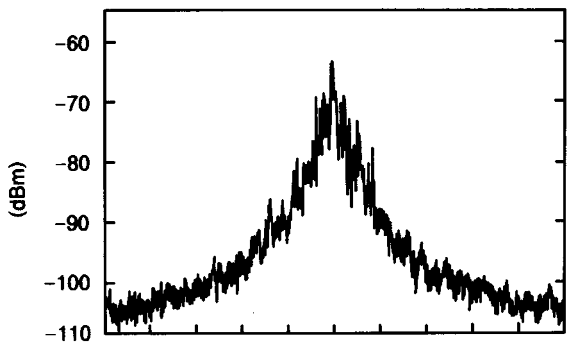

FIG. 5. Delayed self-heterodyned beat spectrum of 0.43 m long external cavity laser with 17 cm length Er^{3+} fiber. (Horizontal axis is 50 kHz/div, centre frequency 100 MHz.)

kHz). Indeed, if we now take this broader, and hence more reliable, linewidth to estimate the corresponding linewidth for a 3 m cavity based on the $1/(\text{length})^2$ dependence, a linewidth in the region of 200 Hz would be expected, which supports the earlier assertion that the linewidth was actually sub-kHz for the 3 m long EC laser constructed.

As a last check, we replaced the 17 cm length of Er^{3+} fiber with an equal length of undoped fiber, thus forming a conventional 0.4 m fiber external cavity. Single mode stability was still poor with this shorter cavity. Closer examination showed that single mode operation is invariably upset whenever the mode drifts by ~200 MHz, the EC spacing for this laser, usually resulting in a modehop back to the previous EC mode. This is in contrast to the Er^{3+}-fiber EC laser, which can maintain uninterrupted single frequency operation in spite of frequency drifts over several mode spacings, another indication of the increased robustness achievable with this new external cavity configuration.

In conclusion, we have demonstrated that an erbium fiber based external cavity semiconductor laser represents a significant improvement over conventional undoped fiber external cavity lasers. The self-stabilising effects of spatial hole burning in the Er^{3+} fiber allows long cavities to be constructed without incurring severe penalties in single mode stability, thus enabling very narrow linewidths to be easily achieved. Together with the well-known advantages of fiber Bragg gratings to be fabricated to close wavelength tolerances, this advance offers attractive prospects for realising large numbers of stable compact single frequency lasers at specific wavelengths for WDM applications.

We would like to thank L. Reekie for providing the photorefractive fiber grating. R. I. Laming acknowledges the Royal Society for the provision of a Research Fellowship.

[1] C. H. Henry, J. Lightwave Technol. **LT-4**, 288 (1986).
[2] E. Brinkmeyer, W. Brennecke, M. Zurn, and R. Ultrich, Electron. Lett. **22**, 135 (1986).
[3] C. A. Park, C. J. Rowe, J. Buus, D. C. J. Reid, A. Carter, and I. Bennion, Electron. Lett. **22**, 1132 (1986).
[4] K. Y. Liou, Y. K. Jhee, G. Eisenstein, R. S. Tucker, R. T. Ku, T. M. Shen, U. K. Chakrabarti, and P. J. Anthony, Appl. Phys. Lett. **48**, 1039 (1986).
[5] M. S. Whallen, K. L. Hall, D. M. Tennant, U. Koren, and G. Raybon, Electron. Lett. **23**, 313 (1987).
[6] D. M. Bird, J. R. Armitage, R. Kashyap, R. M. A. Fatah, and K. H. Cameron, Electron. Lett. **27**, 1115 (1991).
[7] P. A. Morton, V. Mizrahi, T. Tanbun-Ek, R. A. Logan, P. J. Lemaire, H. M. Presby, T. Erdogan, S. L. Woodward, J. E. Sipe, M. R. Phillips, A. M. Sergent, and K. W. Wecht, Appl. Phys. Lett. **64**, 2634 (1994).
[8] A. E. Siegman, *Lasers* (University Science, Mill Valley, 1986), Chap. 12.
[9] H. Statz, C. L. Tang, and J. M. Lavine, J. Appl. Phys. **35**, 2581 (1964).
[10] M. Horowitz, R. Daisy, B. Fischer, and J. Zyskind, Electron. Lett. **30**, 648 (1994).
[11] Y. Cheng, J. T. Kringlebotn, W. H. Loh, R. I. Laming, and D. N. Payne, Opt. Lett. **20**, 875 (1995).