Chapter 10

Conclusion

This chapter summarizes the most important implications of the results reported with respect to the use of Er-doped fiber DFB lasers as sensing elements or interrogation sources.

An index perturbation method for characterization of fiber DFB lasers has been demonstrated. Besides being useful for investigation of laser characteristics, such as the order of longitudinal mode operation, modal intensity distributions, grating strength, and the polarization dependence of the grating strength, the method and the associated theory reveals that the effective sensitive length of a fiber DFB laser sensor is typically only 1/5 to 1/12 of the total grating length, depending on the grating strength and the distribution of the grating phase-shift region. This allows for sensor element designs with small dimensions. The measured sensitive lengths vary between 4 and 7 mm for a grating length of 50 mm.

An important motivation for using fiber DFB lasers as sensor elements is the high resolutions obtainable in measurements of quantities that modulate the fiber strain, refractive index, or birefringence. The laser frequency and polarization beat frequency noise levels demonstrated in this thesis correspond to resolutions that are 3 to 4 orders of magnitude better than what has been achieved in the laboratory with passive sensors with comparable sensitive lengths, such as fiber Bragg gratings [1, 2]. The laser frequency and beat frequency noise measurements are summarized in Table 11.1, along with the obtained sensitivities to different measurands.

To exploit the high resolutions in practical sensor implementations it is necessary to minimize the sensitivity to disturbances that one do not want to mea-

		Laser frequency	Beat frequency
Noise floor:	@ 2 Hz	$400\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$	—
	@ 20 Hz	$140\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$	$100\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$
	@ 200 Hz	$50\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$	$30\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$
	@ 2 kHz	$20\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$	—
	@ 20 kHz	$15\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$	$3\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$
	@ 500 kHz	$1.6\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$	—
Sensitivity:	temperature	-1 MHz/mK	1.6 kHz/mK
	strain	-150 MHz/$\mu\varepsilon$	8 kHz/$\mu\varepsilon$
	hydrostatic pressure	900 Hz/Pa	(low)
	birefringence ($\Delta n/n$)	—	200 Hz/10^{-12}
	lateral force	(-1.3 ± 0.8 Hz/nN)	1.6 Hz/nN

Table 11.1. Measured fiber DFB laser frequency and polarization beat frequency noise densities, as well as sensitivities to different measurands. The polarization beat frequency of the investigated lasers were about 1 GHz.

sure, such as (depending on the application) temperature changes, vibrations, and effects of strain and bending in flexible probes. Simultaneous interrogation of the optical frequency and the polarization beat frequency from a dual polarization laser seems to be a powerful technique for reducing this problem. Careful design of the sensor housing and fiber coatings are also believed to be important in order to minimize the sensitivity to unwanted disturbances.

Instabilities due to external back reflections from discrete reflectors Rayleigh scattering in the lead fiber seems to be a potential problem for the application of fiber DFB lasers as remote sensor elements positioned far ($\gtrsim 100$ m) from the pumping and interrogation unit. In many cases, this problem can be overcome by inserting optical isolators or non-reflective wavelength selective attenuators in the lead fiber near the sensor laser. A more preferable solution would be to develope fiber DFB lasers that are more tolerable to external reflections. Important parameters in this respect are the grating reflectivity, the linewidth enhancement factor, and saturable absorber defects in the gain-medium.

The observation that single polarization fiber DFB lasers can be multiplexed along a single fiber without significant degradation of the noise performance is promising for the possibility of performing multiple point distributed sensing with fiber DFB lasers. Simulation results have also shown that the polarization mode competition at steady state is not affected significantly by serial multiplexing. It should be noted, however, that the dynamic behavior of dual polarization lasers in serially multiplexed systems still needs to be investigated.

We have focused mainly on 1480-nm pumped fiber DFB lasers with moderate output powers in the $< 500\ \mu$W range. The low laser efficiency is due to low pump absorption in the short Er-doped fiber. Considerably higher output powers can be obtained by pumping Er-Yb co-doped lasers at 980 nm, because of a much higher pump absorption. However, the high pump absorption per laser in this case does not allow for serial multiplexing of lasers. Moreover, the increased self heating associated with high power laser operation can disturb the sensor performance [3]. The output power obtained with 1480-nm pumping should be more than sufficient for accurate sensor interrogation. Sources with higher output powers can be made by using the residual pump power to pump an erbium doped fiber amplifier in an master oscillator power amplifier (MOPA) configuration.

A large portion of this work has been devoted to a theoretical and experimental investigation of polarization mode competition in fiber DFB lasers. A simple method for obtaining robust single polarization operation seems to be manipulation of the polarization dependence of the grating coupling coefficient κ, thus introducing polarization dependent losses in the laser cavity. This can be obtained by controlling the polarization of the UV light used for the grating inscription [4]. If UV post-processing is used to make the grating phase-shift, an alternative approach is to introduce a polarization dependence in the grating phase-shift [5, 6], which also leads to polarization dependent cavity losses. Pump polarization fluctuations, external back-reflections, and grating birefringence non-uniformities will also affect the laser polarization mode competition.

Sufficient control with the above mentioned parameters is also necessary to obtain robust dual polarization lasers. The results presented in Chap. 7, and also experience from other dual polarization experiments, makes us confident that this is possible. In cases where mechanically induced changes in the birefringence are to be measured, it is however important to design the force transducer mechanism carefully so that a sufficient uniform birefringence distribution is maintained along the laser length.

The low level of frequency noise and potential strain and temperature tuning capabilities of fiber DFB lasers makes them promising as sources for passive fiber Bragg grating sensor interrogation, interferometric sensor interrogation, high resolution spectroscopy, and for optical device characterization purposes. Compared to other sources with comparable frequency noise characteristics, the fiber DFB lasers have the advantages of a compact in-fiber design, easy and accurate wavelength selection during production, a large tuning range without mode-hopping, and the possibility of creating multiple wavelength sources that are pumped from a single diode pump laser, either through serial laser multiplexing, or by Moiré grating techniques [7].

The easiest method to obtain strain-tuning is by applying a tensile strain. The mechanical strength of the fiber limits the possible tuning range to ~ 10 nm in this case, corresponding to a strain of ~ 8 mε. Compression tuning allows for a larger tuning range, and mode-hop free compression tuning of a fiber DBR laser over 32 nm has already been demonstrated in the lab [8]. Major challenges in the development of a commercial compression tuned device are expected to be to ensure a sufficient uniform strain distribution to avoid longitudinal mode hopping, and at the same time avoid mechanical degradation of the fiber (due to friction or buckling). Because of the short effective cavity length, fiber DFB lasers are generally expected to be more tolerant to non-uniform strain and less prone to mode-hopping than DBR lasers.

References

[1] A. Arie, B. Lissak, and M Tur, "Static Fiber-Bragg Grating Strain Sensing Using Frequency-Locked Lasers", J. of Lightwave Technol., Vol. 17, pp. 1849–1855, 1999.

[2] B. Lissak, A. Arie, and M Tur, "Highly sensitive dynamic strain measurements by locking lasers to fiber Bragg gratings", Opt. Lett., Vol. 23, pp. 1930–1932, 1998.

[3] O. Hadeler, M. N. Zervas, E. Rønnekleiv, and M. Berendt, "Temperature distribution along DFB fibre lasers", *IEE colloquium digest on Optical Fibre Gratings*, (IEE, Box 96, M. Faraday House, Stevenage, Herts. SG1 2SD, UK), 1999.

[4] M. Ibsen, E. Rønnekleiv, G. J. Cowle, M. O. Berendt, O. Hadeler, M. N. Zervas, and R. I. Laming, "Robust high-power (>20 mW) all-fiber DFB lasers with unidirectional and truly single polarization outputs" in *Proc. to Conference on Lasers and Electro-Optics (CLEO) 1999*, pp. 245–246, paper CWE4, Baltimore, USA, 1999.

[5] H. Storøy, B. Sahlgren and R. Stubbe, "Single polarization fibre DFB laser", El. Letters, Vol. 33, pp. 56–8, 1997.

[6] J. I. Philipsen, M. O. Berendt, P. Varming, V. C. Lauridsen, J. H. Povlsen, J. Hübner, M. Kristensen, B. Pálsdóttir, "Polarisation control of DFB fibre laser using UV-induced birefringent phase-shift", El. Letters, Vol. 34, pp. 678-9, 1998.

[7] M. Ibsen, E. Rønnekleiv, O. Hadeler, G. J. Cowle, M. N. Zervas, and R. I. Laming, "Stable multiple wavelength generation in all-fibre DFB laser" in *Topical Meeting on Bragg Gratings, Photosensitivity, and Poling in Glass Waveguides*, paper FA4, Florida, USA, 1999.

[8] G. A. Ball and W. W. Morey, "Compression-tuned single-frequency Bragg grating fiber laser", Opt. Lett., Vol. 19, pp. 1979–1981, 1994.

Publication List

Journal Publications

1. E. Rønnekleiv, "Sagnac sensor for location of a disturbance", Appl. Opt., Vol. 36, pp. 2076–2083, 1997 .
2. E. Rønnekleiv, M. N. Zervas and J. T. Kringlebotn, "Modeling of Polarization Mode Competition in Fiber DFB Lasers", IEEE J. Quantum Electron., Vol. 34, pp. 1559–69, 1998.
3. E. Rønnekleiv, M. N. Zervas and J. T. Kringlebotn, "Correction to "Modeling of Polarization Mode Competition in Fiber DFB Lasers"", IEEE J. Quantum Electron., Vol. 35, pp. 1097–1100, 1999.
4. O. Hadeler, E. Rønnekleiv, M. Ibsen and R. I. Laming, "Polarimetric fiber distributed feedback laser sensor for simultaneous strain and temperature measurements", Appl. Opt., Vol. 38, pp. 1953–1958, 1999.
5. E. Rønnekleiv and O. Hadeler, "Stability of an Er-Yb-doped fiber distributed-feedback laser with external reflections", Opt. Lett., Vol. 24, pp. 617–619, 1999.
6. E. Rønnekleiv, M. Ibsen, M. N. Zervas, and R. I. Laming, "Characterization of fiber distributed-feedback lasers with an index perturbation method", Appl. Opt., Vol. 38, pp. 4558–4565, 1999.
7. S. W. Løvseth, J. T. Kringlebotn, E. Rønnekleiv and K. Bløtekjær, "Fiber DFB Lasers Used as Acoustic Sensors in Air", Appl. Opt., Vol. 38, pp. 4821–4830, 1999.
8. E. Rønnekleiv, M. Ibsen, and G. J. Cowle, "Polarization Characteristics of Fiber DFB Lasers Related to Sensing Applications", accepted (Dac. 1999) for publication in IEEE J. Quantum Electron.

Conference Proceedings

1. E. Rønnekleiv, K. Bløtekjær, and K. Kråkenes, "Distributed fiber sensor for location of disturbances," in *9th International Conference on Optical Fiber Sensors* (National Research Council of Italy, Florence, 1993), postdeadline paper PD7.

2. E. Rønnekleiv, M. Ibsen, M. N. Zervas and R. I. Laming, "Characterization of intensity distribution in symmetric and asymmetric fiber DFB lasers", in *CLEO'98, Tec. Digest,* Vol. 6, CTuE6, San Francisco 1998.

3. O. Hadeler, M. N. Zervas, E. Rønnekleiv, and M. Berendt, "Temperature distribution along DFB fibre lasers", *IEE colloquium digest on Optical Fibre Gratings*, (IEE, Box 96, M. Faraday House, Stevenage, Herts. SG1 2SD, UK), 1999.

4. E. Rønnekleiv and S. W. Løvseth, "Stability of Distributed Feedback Fiber Lasers with Optical Feedback", in *13th International Conference on Optical Fiber Sensors*, Proceedings of SPIE Vol. 3746, pp. 466–469, 1999.

5. D. Thingbø, E. Rønnekleiv and J. T. Kringlebotn, "Intrinsic Distributed Feedback Fibre Laser High Frequency Hydrophone", in *Topical Meeting on Bragg Gratings, Photosensitivity, and Poling in Glass Waveguides*, paper ThE4, pp. 57–59, Florida, USA, 1999.

6. M. Ibsen, E. Rønnekleiv, G. J. Cowle, M. O. Berendt, O. Hadeler, M. N. Zervas, and R. I. Laming, "Robust high-power (>20 mW) all-fiber DFB lasers with unidirectional and truly single polarization outputs" in *Proc. to Conference on Lasers and Electro-Optics (CLEO) 1999*, paper CWE4, pp. 245–246, Baltimore, USA, 1999.

7. M. Ibsen, E. Rønnekleiv, O. Hadeler, G. J. Cowle, M. N. Zervas, and R. I. Laming, "Stable multiple wavelength generation in all-fibre DFB laser" in *Topical Meeting on Bragg Gratings, Photosensitivity, and Poling in Glass Waveguides*, paper FA4, pp. 149–151, Florida, USA, 1999.

Presentations

1. E. Rønnekleiv and K. Bløtekjær, "Sagnac sensor system for location of disturbance", in *Norwegian Electro-Optics Meeting*, Fefor, Norway, 1993.

2. E. Rønnekleiv, "Modeling polarization mode competition in fiber DFB-lasers", in *Norwegian Electro-Optics Meeting*, Geiranger, Norway, 1997.

3. E. Rønnekleiv, D. Thingbø and J. T. Kringlebotn, "Frequency and Intensity Noise of Er-doped Fiber DFB Lasers", in *Norwegian Electro-Optics Meeting*, Balestrand, Norway, 1999.

4. S. W. Løvseth and E. Rønnekleiv, "Stability of Distributed Feedback Fiber Lasers with Optical Feedback", in *Norwegian Electro-Optics Meeting*, Balestrand, Norway, 1999.