Fiber DFB Lasers for Sensor Applications

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Abstract

Fiber distributed feedback (DFB) lasers have been studied theoretically and experimentally, with emphasis on properties that are of importance for the use of these lasers in sensor applications, either as sensing elements or as sources for interrogation.

In the first part of the thesis we demonstrate a method for characterization of fiber DFB lasers which is based on scanning a heat-induced index perturbation along the cavity and recording the induced laser frequency shift. The experimental results reveal that the sensitivity of fiber distributed-feedback laser sensors with frequency read-out is highly localized near the grating phase-shift position. It is shown theoretically that the measurements give a good indicator for the intensity distribution in the cavity. Use of the characterization data to determine the grating coupling parameter κ, the polarization dependence of κ, and birefringence non-uniformities as well as identification of the order of longitudinal mode operation are discussed and demonstrated experimentally. Asymmetrically phase-shifted lasers with a highly directional output power are also investigated.

The second part deals with laser stability and noise. The measured laser frequency modulation noise ranges from 20 Hz/$\sqrt{\text{Hz}}$ at 1 kHz to 1.3 Hz/$\sqrt{\text{Hz}}$ at 1 MHz, with a sharp peak at the relaxation oscillation frequency near 220 kHz. $1/f$ noise is observed below 1 kHz. Negative feedback to the pump from a monitor detector reduces the intensity noise to the detection noise level, and removes the relaxation oscillation noise from the laser frequency. By comparing measured intensity and frequency fluctuations, we estimate the effective linewidth broadening factor at the relaxation oscillation frequencies of the investigated lasers to be between 2.1 and 3.8, as compared to typically between 3 and 7 for semiconductor lasers. The noise performance of four serially multiplexed fiber DFB lasers are found to be similar to that of the free running single lasers. We have also investigated the tolerance of fiber DFB lasers to external back-reflections before the onset of instabilities. The tolerable reflection coefficient is found to decrease with increasing external cavity lengths up to a few hundred meters, and to be proportional to the relative linewidth (quality factor) of the relaxation oscillation resonance. The tolerable length of Rayleigh backscattering fiber varies from 37 to 278 m. UV-induced saturable absorbers seem to play a role in degrading the laser stability.

The third part is devoted to a theoretical and experimental study of the polarization modes of the fiber DFB laser. A comprehensive model for steady state analysis of polarization mode competition (PMC) is presented. Effects of polarization dependent grating strength, back reflections, polarization dependent grating non-uniformities, twist, Faraday rotation, cross-saturation from serially multiplexed lasers, pump polarization fluctuations, as well as spatially and polarization dependent gain hole-burning are covered by the model. Regimes of single and dual polarization operation are identified and the modal output powers and differential gain contributions are investigated versus different types of polarization imperfections in the cavity. An experimental investigation of how the PMC and polarization beat frequency depend on localized transverse force perturbations, back reflections, and changes in pump polarization state is also carried out. Good agreement is obtained between the experiments and the simulation model. The noise fluctuations in the polarization beat frequency is also investigated. Use of a dual polarization laser as a transverse force sensor with a resolution in the order of 1–100 $\mathrm{nN}/\sqrt{\mathrm{Hz}}$ for interrogation frequencies above 20 Hz is demonstrated.

In the forth part we demonstrate the application of the fiber DFB laser for simultaneous static temperature and strain measurements, and as a hydrophone for the $0.1-1$ MHz frequency range. By measuring both the wavelength of one laser polarization modes and the polarization beat frequency we are able to determine the strain and temperature with accuracies of $\pm 3\mu\varepsilon$ and $-0.04°\mathrm{C}$, respectively. These accuracies are limited by the accuracies of the equipment used to calibrate the sensor. For the fiber DFB laser hydrophone we demonstrate a noise equivalent pressure of $\sim$ 93 dB $\mu\mathrm{Pa}/\sqrt{\mathrm{Hz}}$. The angular responsivity at 800 kHz has a central lobe with a 3-dB width of 6.4°. This corresponds to an effective sensitive length of approximately 6mm, which is much shorter than the DFB grating length of 5 cm.

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Chapter 1
Introduction

1.1 Background

The fiber sensor technology has developed during the past few decades much as a result of the rapid technological advances made for the telecommunication industry. Fiber compatible components and tools have become available, such as diode lasers, fusion splicers, fiber connectors, couplers, and amplifiers. The erbium doped fiber amplifier (EDFA) [1, 2] is often referred to as the most important single invention that has boosted the deployment of optical fiber technology for communication purposes. More recently, the fiber Bragg grating (FBG) technology [3, 4, 5, 6, 7] has developed to a commercial level. Due to their high degree of wavelength selectivity and simple in-fiber design, the FBG technology is expected to become essential in future wavelength division multiplexed (WDM) communication systems. FBGs are also attractive for broadband applications, such as dispersion compensation and EDFA gain flattening.

FBG lasers combine the EDFA and FBG technologies. There is a potential for the FBG lasers to become an important alternative as light sources for the telecommunications industry. They offer very narrow linewidths, low temperature dependence of the wavelength, and easy setting of the laser wavelength during production, and a large tuning range, which is favorable for dense WDM applications. The facts that they are in-fiber devices and that multiple FBG lasers can be pumped by a single pump laser may also be favorable.

FBG lasers can be divided into two categories depending on the grating geometry. The fiber distributed feedback (DFB) laser consists of a continuous Bragg grating written into an optical fiber containing a gain medium, such as

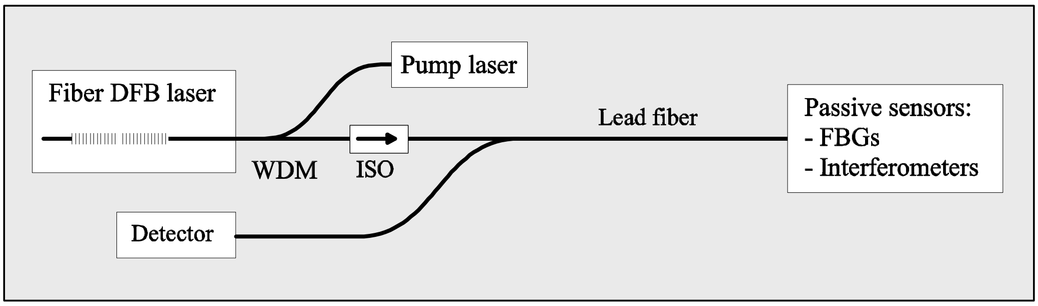

Figure 1.1. Fiber DFB laser used as source for interogation of passive fiber sensors. WDM, wavelength division multiplexer discriminating between the pump and laser wavelengths; ISO, optical isolator; FBGs, passive fiber Bragg gratings.

Er^{3+} ions [8]. This integration of the gain medium into the grating contrasts to the distributed Bragg reflector (DBR) geometry where two separate Bragg grating reflectors are separated by a gain section. If the spatial separation of the DBR gratings is comparable to or longer than the optical penetration depth into the gratings, there will be multiple cavity resonances within the grating reflection bandwidth. It is therefore known that DBR lasers tend to have problems with multiple longitudinal mode hopping or multimode operation, a problem that can be reduced by reducing the distance between the gratings. A DFB laser is essentially a DBR laser where the grating separation has been reduced to zero [9]. By introducing a π grating phase-shift at the center of the grating, the grating resonance is moved to the center of the grating reflection band, and the resulting DFB laser can operate very robustly in a single longitudinal mode.

This thesis is mainly focused on developing an understanding of Er-doped fiber DFB lasers with emphasis on their properties of importance for fiber-optic sensor applications.

Fig. 1.1 illustrates how a fiber DFB laser could be applied as a source for interrogation of passive FBG sensors or interferometric sensors. The very narrow linewidth combined with potentially very accurate strain or temperature tuning allows for interrogation of passive sensors over a large (several nm) optical wavelength range with high resolution.

Fiber DFB lasers can also be used as a sensor elements on their own [10, 11], as illustrated in Fig. 1.2. If the lasers are designed in such a way that the pump absorption per laser is not too high, multiple laser sensors (labelled DFB1 through DFBn in the figure) can be multiplexed in series on a single fiber. The interrogation system would usually monitor variations in the laser frequency, which gives a measure for strain and refractive index variations in the laser fiber. If the laser operates in two polarization modes the beat frequency

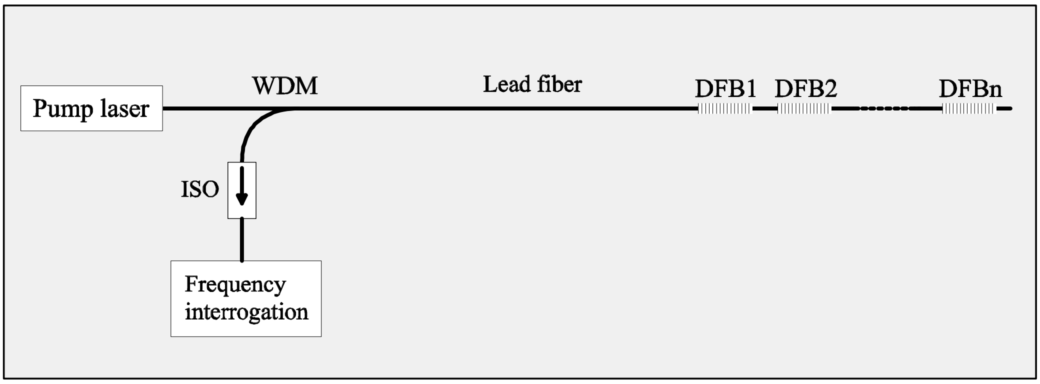

Figure 1.2. Fiber DFB lasers used as sensor elements. WDM, wavelength division multiplexer discriminating between the pump and laser wavelengths; ISO, optical isolator; DFB1 trorough DFBn, serially multiplexed fiber DFB sensor elements.

between the polarization modes can also be monitored, producing a measure of the birefringence in the laser cavity. The possibility of forming a true single point two-parameter sensor by combining laser frequency and polarization beat frequency interrogation is also attractive. For instance, this approach can be used to remove unwanted temperature dependence from the sensor readout.

The first single longitudinal mode fiber Bragg grating sensor lasers demonstrated in the literature were DBR lasers [12, 13, 14]. An important advantage of DFB over DBR sensor lasers is that the DFB lasers are less reluctant to longitudinal mode hopping due to non-uniform strain perturbations of the cavity. In many applications the shorter sensitive length of the fiber DFB laser will also be an desirable.

Fiber DFB laser sensors have many advantages in common with passive FBG sensors [15], such as compact in-fiber design, a highly localized sensitive region, and wavelength multiplexing capabilities. Both sensors types are based on interrogation of a shift in the FBG resonance frequency. The reflection bandwidth of a passive FBG may typically be in the order of 10 GHz, while the emission linewidth of fiber DFB lasers is typically in the order of $1 - 10$ kHz. Intuitively, this allows for an improvement of the interrogation accuracy by several orders of magnitude.

1.2 Thesis Outline

This thesis is divided into four parts with a total of 10 chapters. All chapters except for Chapters 1, 3, and 10 are reproductions of articles or papers that have been submitted to or are published in journals and conference proceedings. Each chapter should therefore be self contained, with its own abstract, introduction and conclusion.

In Part I a method for characterization of the longitudinal dependence of the sensitivity of the fiber DFB laser frequency to refractive index perturbations is investigated theoretically and experimentally. We show that the characterization results can reveal important information about the laser, such as the intensity distribution along the laser cavity, the grating strength, and the longitudinal mode of operation.

Part II is devoted to the investigation of laser noise and stability. Knowledge of the typical spectral distributions of the relative intensity noise and frequency noise of fiber DFB lasers is necessary in order to estimate the obtainable dynamic resolution of sensor systems employing these lasers. An understanding of the origins of the laser noise is essential if one wants to reduce the noise level further. We have found that external back reflections due to Rayleigh scattering or weak discrete reflections in the lead fiber may lead to instabilities in fiber DFB laser sensors that are connected to a long lead fiber like in Fig. 1.2.

In Part III the conditions for single or dual polarization mode operation of fiber DFB lasers is investigated. A comprehensive simulation model is introduced, which covers effects of gain hole-burning, several types of polarization dependent grating imperfections, as well as external back reflections. Simulation results are shown that illustrate the magnitudes of different types of polarization imperfection that can be tolerated in order to maintain dual polarization operation. Experimental results are presented which were obtained by applying polarization dependent external reflections to a dual polarization fiber DFB laser, and by applying a localized transverse force to the DFB phase-shift position which modifies the phase-shift birefringence. By monitoring the polarization beat frequency versus the transverse force, we demonstrate that the laser can be used as a very sensitive transverse force sensor. We also investigate the sensitivity of the polarization beat frequency to external back reflections, and the polarization beat frequency noise spectrum is measured.

In Part IV we demonstrate two applications of the fiber DFB laser as a sensor. The first application is of a dual polarization laser for simultaneous static strain and temperature measurements by interrogating both the laser wavelength shift and the polarization beat frequency shift. By using this technique we show that it is possible to eliminate the temperature sensitivity from the strain measurements and vice versa with a high degree of accuracy. The second application demonstrated is of a fiber DFB laser hydrophone for use in the $0.1 - 1$ MHz range. We investigate the sensitivity and angular directivity of the sensor, and compare the angular directivity with the spatial sensitivity distribution obtained with the characterization method introduced in Part I.

Finally, some concluding remarks are given in Chap. 10.

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