A Study of FMCW Technique for Optical Sensor Application

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学位論文要旨

Abstract In this work, an optical FMCW (frequency modulated continuous wave) sensor system fed by a current-modulated semiconductor laser is analyzed theoretically and experimentally. The frequency-tuning nonlinearity of the laser diode and its effect on the sensor system are considered. For a current-frequency modulation with a linear function, effects from the frequency dependence and the current dependence of the FM efficiency of the laser diode are taken into account. Theoretical and experimental results obtained show good agreement. As an improvement approach, a new, linearly frequency-tuning light source is proposed. The linear frequency tuning is achieved by a frequency comparison and a feedback control to the current modulation signal. Applications of the sensor system for characterizations of optical waveguide devices are discussed and measured results are demonstrated. Good improvements in the spatial resolution and the detection sensitivity of the sensor system are obtained.

Chapter 1 Introduction

The optical FMCW technique as a useful frequency modulation technique has been widely utilized in files of the optical communication and the optical sensor. Developed Optical FMCW sensor systems possess a very simple constitution and an easily adjusting detection range for satisfying various sensing needs whether in basic physical measurements or in the optical internal diagnosis. As active utilization of the current-frequency modulation characteristic of the laser diode and the coherent heterodyne detection, with the adoption of high-coherent laser diode with a very wide frequency-tuning range, optical FMCW sensor systems are of very great potential in optical internal diagnosis applications where a high spatial resolution, high sensitivity detection will be required. A critical element in FMCW sensor systems is its light source which can determine the achievable spatial resolution and detection range. In optical FMCW sensor systems, the frequency-tuning nonlinearity of the light source is an important problem, which results mainly from large thermal response time constants in the laser module and a current dependence of the FM efficiency of the laser diode. This nonlinearity can directly induce a broadening of the detection signal spectrum and a noise floor rising, which degrade the spatial resolution and the detection sensitivity of the FMCW sensor system. Our study purpose is to resolve this problem, meanwhile to develop a high-performance, linearly frequency-tuning FMCW sensor system for optical internal diagnosis applications.

Chapter 2 Optical FMCW Sensor System

In this chapter, the basic FMCW technique and its applications in optical sensor systems will be mentioned. With a optical FMCW sensor system, we measure the absolute and relative distances of the object under test. By an analysis, we know that in the measurement of the absolute distance, the maximum detection, distance will be determined by the coherence length of the light source, and in the measurement of the relative distance, detection errors are induced mainly from the phase noise of the light source. A large frequency tuning range in FMCW sensor system will be necessary not only to improve the spatial resolution, but also to enhance the measurement procision.

The frequency and current dependence of the FM efficiency of laser diode used in our study, as well as its spectral linewidth under a large-amplitude current modulation condition are measured. Measured results illustrate that (a) the FM efficiency will change with the modulation frequency and the bias current (injection current), which can cause the frequency tuning nonlinearity even using a linear modulation current, and (b) a linewidth increasing with the modulation current amplitude, which will generate large phase noises in the output spectrum of the beat signal, causing large measurement errors.

The operation principle of balanced heterodyne detection scheme is mentioned. An analyzed results on the SNR of the sensor system indicates that the balanced detection scheme allows one to attain a shot noise detection limitation as using a large local optical power, and a slight inequality in optical characteristics of detection components will immediately lead to a substantial degradation of the SNR.

Chapter 3 Optical Internal Characteristic Diagnosis

In this chapter, we first introduce a nonlinearity compensation technique in the FMCW sensor system using a frequency equalizer to modify the triangular current modulation signal. The principle of this method is through an enhancement of the high-frequency components in the current modulation signal to compensate the decrease of the FM efficiency in high-frequency regions. This technique can effectively improve the spatial resolution and the detection sensitivity of the sensor system.

As an important optical sensor application, we developed an optical FMCW diagnosis system (see Fig. 1) for characterizations of various optical waveguide devices. In practice, we have diagnosed some optical waveguide devices which included two glass-based optical waveguides (see Fig. 2), the optical fiber and the fiber coupler (see Fig. 3) for measurements of internal reflections, loss estimations and so on. We also measured the bending and splice losses in optical fibers. These results demonstrate that this diagnosis system has satisfactory detection performances in optical internal diagnosis applications.

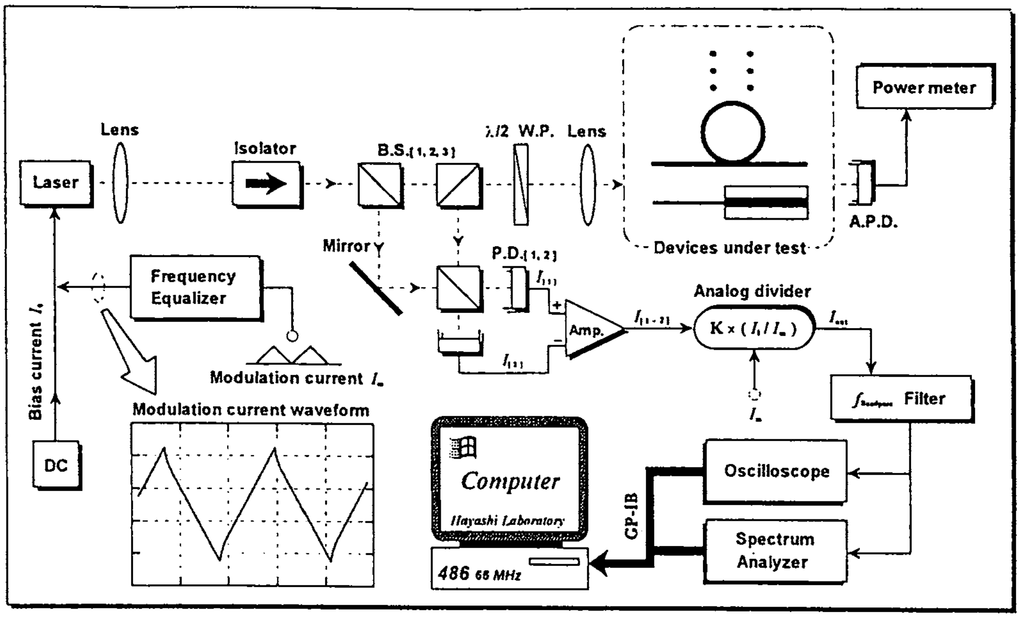

Fig. 1 Optical diagnosis system configuration.

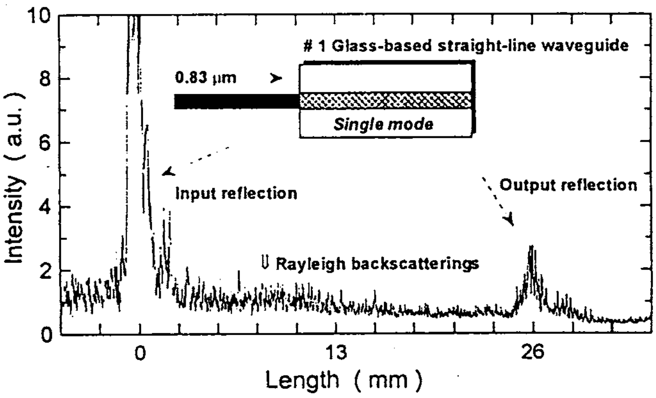

Fig. 2 Internal reflection distribution in an optical waveguide.

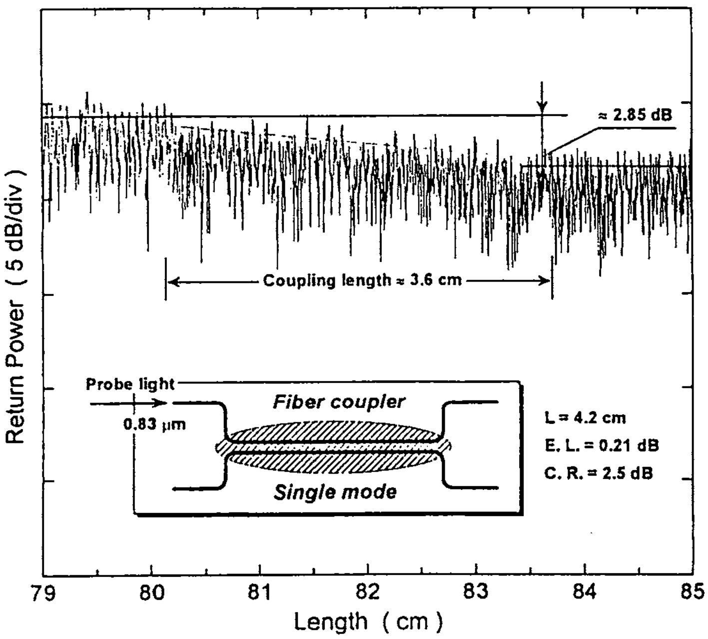

Fig. 3 Return power distribution in a fiber coupler.

Chapter 4 Theoretical and Experimental Investigations on Optical Frequency Tuning Nonlinearity

In this chapter, we will present some theoretical investigations on reasons of the frequency-tuning nonlinearity, as well as nonlinearity effects on the detection signal in FMCW sensor systems. A simple calculation model is proposed (see Fig. 4) and analyses was taken in the time domain. We first investigate the thermal response process of the laser model with a large-amplitude step modulation current and a fiber polarimetric interferometer (see Fig. 5). By measurements, we found four thermal response time constants existing in our laser module. These thermal response time constants basically determine the behavior of the current-frequency modulation of the laser diode. With these time constants, we constituted a temporal impulse response function h(t) for this laser module.

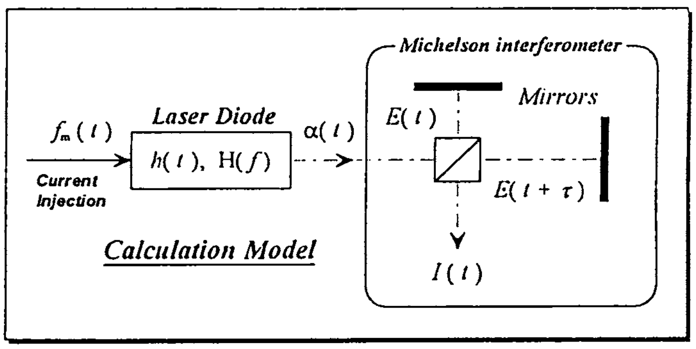

Fig. 4 Calculation model.

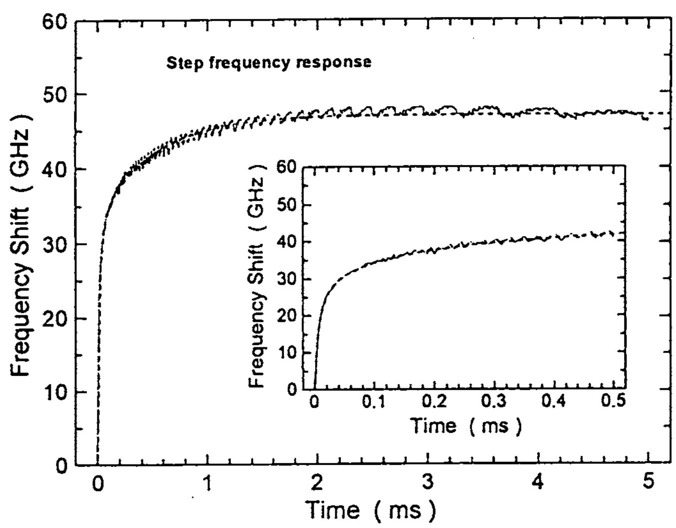

Fig. 5 Step current response of laser diode.

We simulate a current-frequency modulation process of the laser diode, in which the thermal response time and the current dependence of FM efficiency are considered (see Fig. 6). The calculated result indicate that the large time delay between the modulation current and optical frequency changes will cause an obvious nonlinear frequency tuning. Calculated results for the beat frequency indicate that maximum beat frequency deviations will occur at turning points of the triangular current modulation signal, where there is a large current change (see Fig. 7). Owing to this nonlinearity, the beat spectrum will be degraded and become broadening. Also the beat spectrum will become more broadening as the detection distance

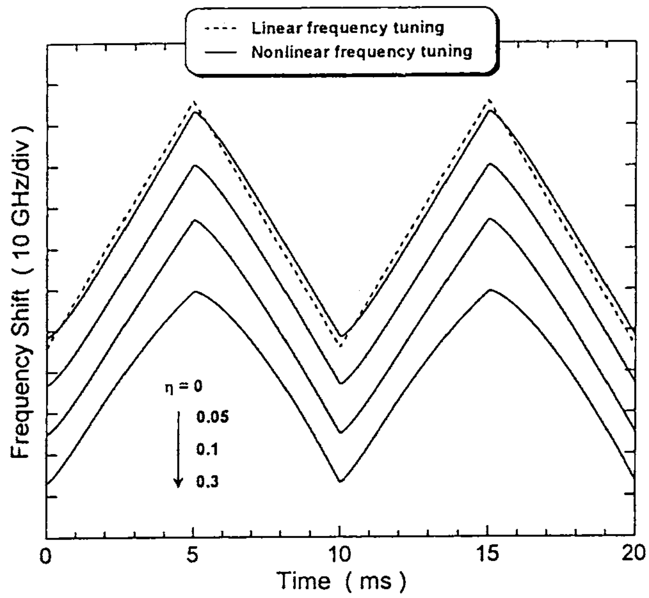

Fig. 6 Optical frequency shift under current modulation.

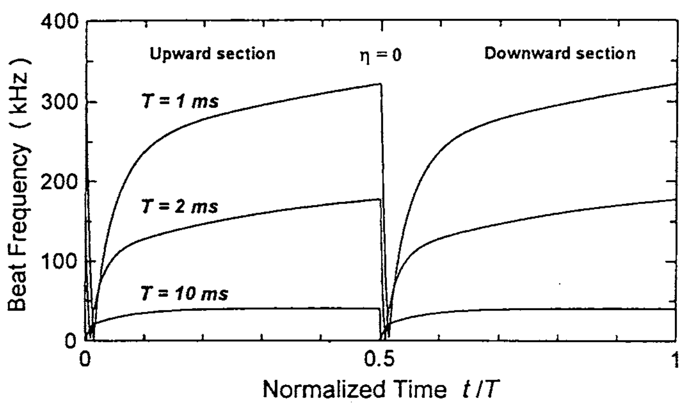

Fig. 7 Beat frequency deviation.

L increases, because the nonlinearity including in the beat signal was proportional to t/T, thus to L/cT. The calculation results above are in fair agreement with those obtained from experimental measurements.

Chapter 5 Linearly Frequency-Tuning Optical FMCW Sensor System

We propose a new light source configuration based on an optical-electrical PLL operation principle. This light source with an automatic detection and compensation capacity for the frequency-tuning nonlinearity, is very suitable for FMCW sensor systems. The light source configuration comprises an auxiliary fiber interferometer and an electrical feedback control loop (see Fig. 8). The nonlinearity elements in the beat frequency are picked out as a frequency error signal through a phase comparison operation. Then this error signal is negatively fed to the current modulation signal. With this, the time-frequency change rate $\delta f/\delta t$ of the laser diode is controlled to keep constant, consequently, a linear frequency tuning is obtained.

Measured results on the sideband suppression (see Fig. 9), the linearity and the long-term frequency stability (see Fig. 10) of the beat signal demonstrate that this light source has

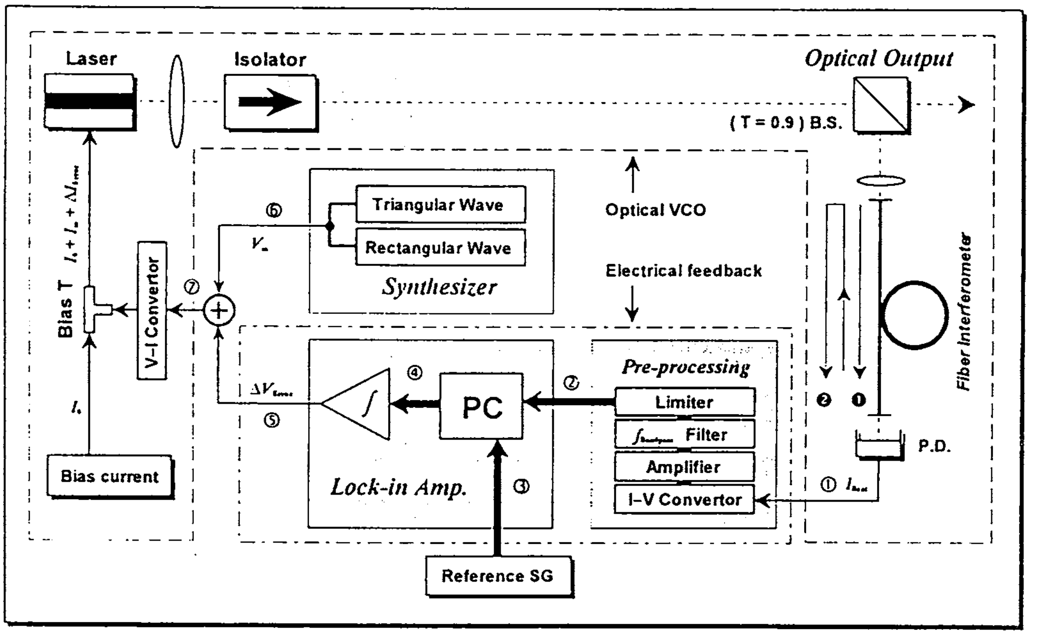

Fig. 8 Linearly frequency-tuning light source configuration.

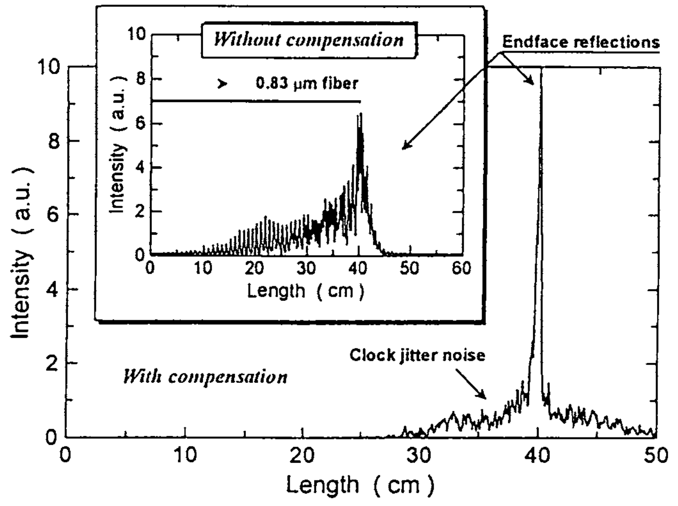

Fig. 9 Measured beat spectrum.

a very good frequency-tuning linearity and stable operation performances.

With this light source configuration, we constitute a new, linearly frequency-tuning FMCW sensor system. Several internal diagnosis results demonstrated that improvements both in the frequency-tuning linearity and the beat frequency stability, finally led to a lot of substantial enhancements and improvements in detection performances of the sensor system, especially in the spatial resolution and the detection sensitivity (see Fig. 11).

Chapter 6 Conclusions

In this chapter, we give some conclusions for our study work in developing the optical FMCW sensor technique and its applications in the optical sensor field.

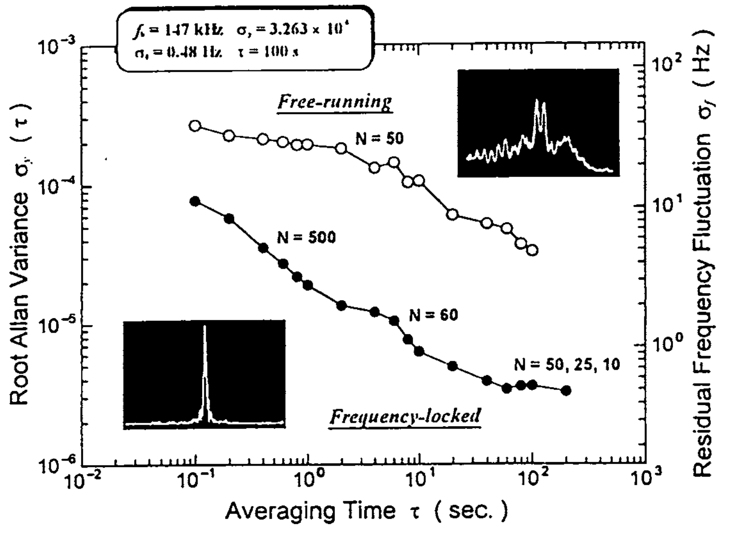

Fig. 10 Long-term beat frequency stability.

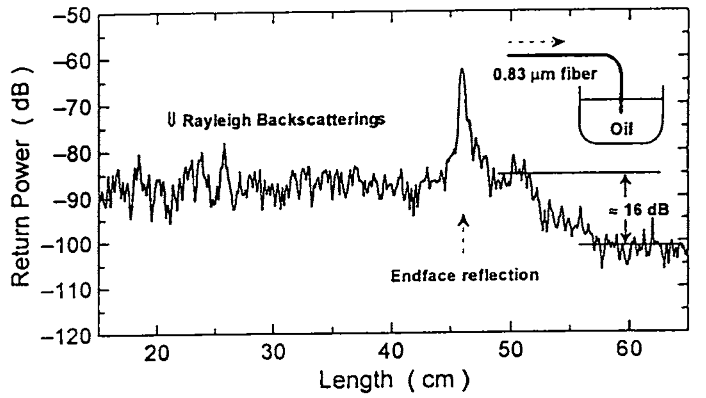

Fig. 11 Rayleigh backscatterings in a fiber.

学位論文の審査結果の要旨

学位論文審査委員会は第１回審査会を平成７年１月30日に開催し面接審査を行った。さらに２月10日の口頭発表後に開催した最終審査で慎重に審議した結果，以下の通り判定した。

本論文は光学素子の内部診断に有用なFMCW（frequency modulated continuous wave）反射計法の光源の必要条件及びその実現について論じたものである。本法は光源の光周波数を変えることによって素子の内部位置を周波数軸上に投影し，診断するものであり，次の成果を得ている。

(1) 光源の必要条件は光周波数が時間に正確に比例して掃引すること，その掃引全幅が大きいこと，発振線幅が狭いこと等であることを明らかにしている。

(2) 光源として半導体レーザを用いると，直接注入電流変調により簡易に光周波数掃引が得られるが，半導体レーザの熱特性等により時間比例掃引ができないことを論じている。

(3) 半導体レーザの熱特性から変調波形を補正する方法及び基準干渉計を用いたfeedback法による２種類の改善方法を開発・実現し，１桁以上の診断性能の向上を達成している。

以上のように，本論文は光ＩＣ回路の開発・発展に不可欠の内部診断技術にいくつかの重要な設計指針を与えるものであり，博士論文に値すると判定する。