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RF Modulated Fiber Optic Sensing Systems and Their Applications

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ABSTRACT

A fiber optic sensing system with an intensity sensor and an RF modulated source has been shown to have sensitivity and resolution much higher then a comparable system employing low modulating frequencies or DC mode of operation. Also the RF modulation with an appropriate configuration of the sensing system provides compensation for the unwanted intensity losses.

This paper describes the basic principles and applications of a fiber optic sensing system employing an RF modulated source. In addition the paper discusses various configurations of the system itself, its components, and modulation and detection schemes. Experimental data are also presented.

2. INTRODUCTION

Fiber optic sensing systems (FOSS) are finding more and more applications due to such properties of fibers as immunity to electro-magnetic interference, smaller size and weight, and high modulation bandwidth. Among different configurations of FOSS, systems employing RF modulated source and detection are attractive because they also provide built-in referencing to compensate for unwanted variations in the light intensity, high sensitivity, and can adopt any intensity modulating sensor.

The basic principle of RF modulated FOSS can be found in a number of papers.[1-4] The system is shown schematically in Fig. 1. It consists of a fiber optic (FO) subsystem, RF modulation, RF detection, and readout units. The FO subsystem is comprised of an imbalanced FO interferometer with an incorporated intensity sensor and fiber optic cables connecting the interferometer with a source and a photodetector. The light source, either a light emitting diode or a laser diode, is modulated at frequencies corresponding to destructive and constructive interferences that occur at the length of the imbalance. The measured parameter affects the intensities of the interfering signals producing a resultant signal which carries information about the measured parameter. This signal is detected by the photodetector and preprocessed by a signal processing unit. As a part of the signal processing, the signal carried at the lower modulating frequency is divided by the one carried at the higher frequency. The resultant signal then is sent to a readout unit either to be displayed, stored, or used for computing. This signal exhibits a high sensitivity to changes in the measurand and immunity to intensity losses in the fiber cables, the source, and the photodetector.

Depending on applications, various configurations of RF modulated FOSS can be constructed.

3. FIBER-OPTIC SYSTEM

The imbalanced FO interferometer with an intensity sensor forms a sensing head.[1] The sensing head can be constructed to operate in either transmission or reflection modes. The sensing head in the transmission mode has low back reflections but operates at lower frequencies and requires multiple fiber optic links. On the other hand, the reflection mode offers higher frequency operation at the same physical length of the imbalance and one common fiber optic link but suffers from back reflections and higher coupling losses. Figure 2 shows typical examples of FO systems with sensing heads in transmission and reflection modes and the configuration of the system with the sensing head used in the experiments.

The traditional configuration of the FO system generally makes use of one arm of the FO interferometer as a reference arm and the other arm, with the sensor in it, as a signal arm. Such a configuration, however, can be modified by placing intensity sensors in both arms of the interferometer and subjecting them to the same disturbance. The sensors should be designed in such a way that the same disturbance would lead to a decrease in the intensity of the light propagating in one arm of the interferometer and an increase in the intensity of the light propagating in the other arm. Such a configuration may enhance the sensitivity of the system.

4. MODULATION-DETECTION SCHEMES

The simplest modulation-detection scheme is based on continuous modulation and continuous parallel detection. Such a scheme has been previously used and involves continuous modulation of the light source at two frequencies. A block diagram of this scheme is shown in Fig. 3. A signal generator (SG) produces a signal modulated at frequency f_1. The signal then is split into two parts, one part is sent to a frequency doubler (FD) to generate a signal modulated at a frequency $f_2 = 2f_1$, and the other part is left untouched. Thus two signals modulated at frequencies f_1 and f_2 have been generated. The two signals are combined using a frequency combiner (FC) and applied to the source (SO) along with the DC current bias via a bias-tee (BT). A photodetector (PD) senses the signals at both frequencies simultaneously and sends them to a frequency separator (FS) where they are separated into low and high frequency channels. An RF detector (RFD) in each channel converts the RF modulated signal into a DC signal. A divider (D) takes a ratio of the DC signals generated in the low and high frequency channels.

The main disadvantage of this modulation-detection scheme is the heating of the source due to high frequency signals continuously applied to it. Heating of the source can result in a number of problems, the most significant of which is a shortening of the source lifetime. To avoid this disadvantage another technique has been proposed. It is based on burst modulation and sequential detection. Figure 4 depicts the scheme. In this scheme a source (SO) is burst modulated sequentially at two frequencies f_1 and $f_2 = 2f_1$ using a signal generator (SG), switches (SW), a frequency doubler (FD), and a triggering circuit (T). The triggering signal has a repetition rate of about 2 kHz and a duty factor of 50 percent. The response from a photodetector (PD) is analyzed sequentially by an RF detector (RFD) and a synchronizing circuit (SC) using corresponding signals from the triggering circuit (TC). Two DC signals exiting the synchronizing circuit have levels proportional to amplitudes of the signals at corresponding modulating frequencies. These DC signals are divided by a divider (D) with the result of the division being sent to a readout unit. Such a modulation-detection scheme has been implemented using modular components, an LED, and modulating frequencies of 100 and 200 mHz. The dynamic range of the scheme is limited by the repetition rate of the triggering signal. In order to use this scheme in a sensing system for detection of rapidly changing measurands, appropriate changes should be made to increase the repetition rate of the triggering signal and the bandwidth of the following electronics.

5. APPLICATIONS

The RF modulated FOSS that have already been demonstrated employ a simple displacement sensor[4] and a displacement-based pressure sensor.[5] The system, however, can accommodate any intensity modulating sensor. Sensors that have recently been tried include a temperature sensor and a linear variable density filter. Also for evaluation purposes a Ronchi ruling has been used in place of the sensor. These components were incorporated in sensing systems that used 100/140 μm fiber, 50 and 100 MHz modulating frequencies, and the continuous modulation - continuous parallel detection scheme. In the course of the experiments the modulation depth of the signals impinging on the source has been approximately 10 percent.

The temperature sensor is a pellet of polished Nd_2O_3 doped glass with one of the faces coated with a reflective coating. The absorption of Nd^{+3} ions tends to increase with temperature. Thus, placed in the system described above, the sensor responds to a temperature change by changing the relative intensities of the interfering signals. The resultant intensity is related to the temperature. In the FOSS used in the experiment, the temperature sensor is incorporated in one of the interferometric sensing heads described in Fig. 2 with an imbalance of 1 m. Continuous modulation at 50 and 100 MHz applied to the source causes destructive and constructive interference to occur at the corresponding modulating frequencies. Figure 5 shows the average signal that exits the divider D (See Fig. 3) as a function of temperature over the range 100 to 220 °C. These data are obtained by taking the signal from the divider at a rate of 10 times per minute and using the oven with a temperature ramp of 1 °C/min. The data is averaged over every degree of temperature and then averaged over five runs. The standard deviation of the resultant data is less than 1 percent.

A linear variable density filter has been used in the conventional configuration of the sensing head with the filter being placed in one, signal arm of the interferometer and a reflector in the other, reference arm (see Fig. 2(c)). The system with such a sensor can find applications as a device to measure the displacement or distance in a direction normal to the direction of the light propagation. The system can be also used to measure reflection and transmission coefficients as well as thickness of thin films. Two variable density filters have been also used to implement the configuration described in Section 3 above with sensors in both arms. Such a system has been built by positioning the two filters as shown in Fig. 6 with an opaque separator between and the reflective surfaces facing out. This system has shown sensitivity almost twice that of the conventional one. The dynamic range, however, is correspondingly lower.

To demonstrate the high sensitivity of the RF modulated system and performance of the system in a dynamic mode, the linear density filter has been replaced by a Ronchi ruling. In this setup the ruling is moving with a constant speed of about 10 μm/sec in front of the optical window of the FO system. Thus different portions of the ruling with different grating periods are viewed by the system. As a result, a corresponding time dependent signal that describes the profile of the ruling is observed. Conventional methods have allowed us to resolve Ronchi rulings with periods up to 20 lines/mm. However, with utilization of the technique described in this paper the resolution of the system is greater than 110 lines/mm. This approach may find applications in, for example, surface quality control analyses or production quality control of components with periodic structures, such as Ronchi rulings and precise threads.

6. ACKNOWLEDGMENT

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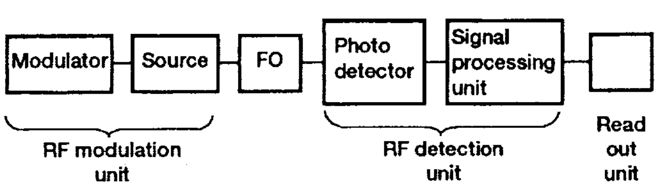
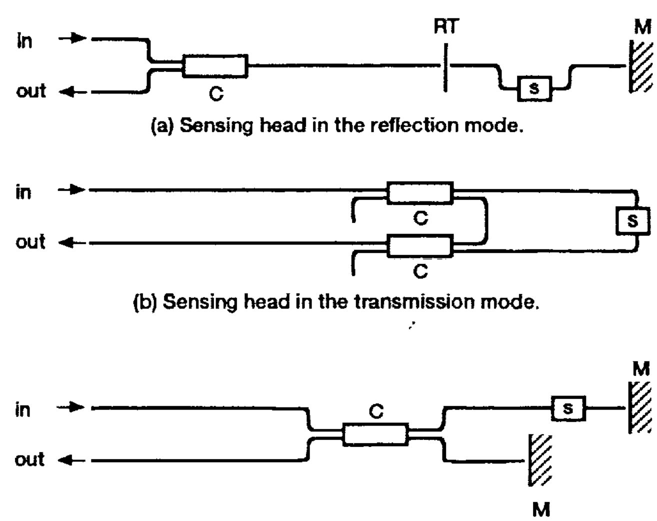


Figure 1.—Block diagram of RF modulated fiber optic sensing system.



(a) Sensing head in the reflection mode.

(b) Sensing head in the transmission mode.

(c) Sensing head used in the experiments.

Figure 2.—Fiber optic systems.

C - coupler
S - sensor
M - reflective mirror
RT - semireflective-semitransparent mirror.

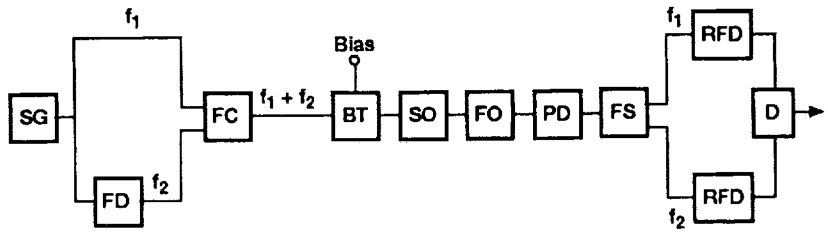


Figure 3.—Scheme using continuous modulation and continuous parallel detection.

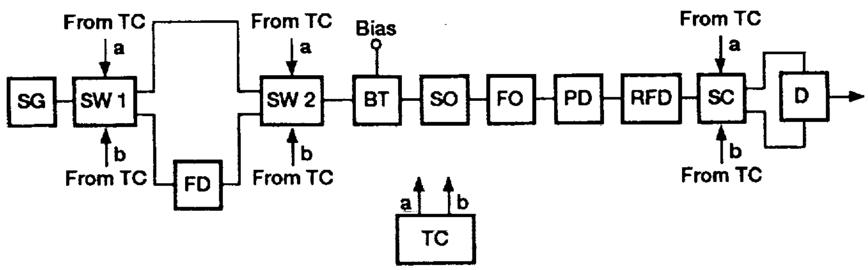


Figure 4.—Scheme using burst modulation and sequential detection.

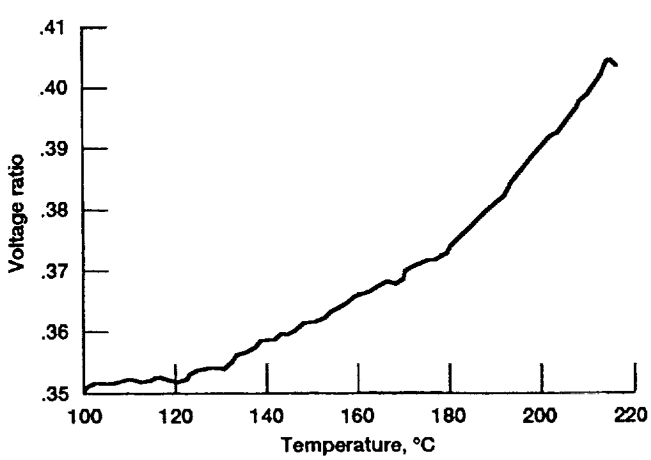


Figure 5.—Response of RF modulated thermometer as a function of temperature.

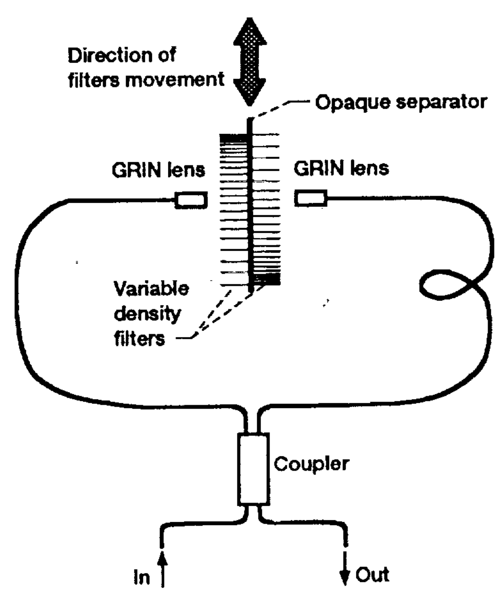


Figure 6.—Sensing head with sensors (variable density filters) in both arms of FO interferometer.

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