Closed-loop Interrogation Techniques for Temperature Measurement using Fibre Bragg Gratings

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Abstract: Closed-loop schemes which maintain the amplitude of the reflected light from the FBG sensors at a constant level are proposed to implement interrogators for FBG temperature sensors. Two systems are presented: a very low-cost system where a thermoelectric cooler is used to tune a DFB laser, and a more complex multi-point system with a broadband laser where *n* tracking FBGs located inside the interrogator are tuned by *n* thermoelectric modules. The variation of the laser wavelength with temperature (or the variation of the tracking FBGs with the temperature) is used to perform the measurements. Since the values of temperature in these devices are uniquely associated with the sensing FBG reflected wavelength, if the temperature behaviour of the FBG sensor is known, by measuring the temperature in the laser (or in the tracking FBGs) it is possible to accurately calculate the temperature in the FBG sensors. A single-point sensor prototype was constructed to validate the technique and a very high resolution of ± 0.08 m°C was measured in a 100°C temperature range.

1 INTRODUCTION

Fiber Bragg Gratings (FBG) optical sensors became very popular since they are relatively easy to interrogate. Since applying a strain that stretches a FBG causes a change in its gratings period, the strain results in a change in wavelength of the light reflected by the FBG. Thus, to interrogate a FBG, it is necessary to measure the variation of the centre wavelength of the FBG, usually called the Bragg shifts (Hill and Meltz, 1997).

However, due to the small dependency of the Bragg shifts with temperature for a naked FBG, interrogators with very high resolutions wavelength measurement are required. For example, since a typical naked FBG presents a $\Delta\lambda/\Delta T \approx 10$ pm.°C^{-1} (Othonos and Kalli, 1999), the interrogator should present a 1 pm resolution if a resolution of 0.1 °C is required in the measurement system. Furthermore, techniques which employ sophisticated optical components in the interrogation system are usually very expensive (Othonos and Kalli, 1999) and cannot be used in low-cost applications. In this paper we present two interrogation techniques: a single-point interrogation technique which uses a narrow band DFB laser and presents very high resolution and low-cost, and a multi-point closed-loop electronics interrogation technique which employs a broad band laser and has a very fast interrogation speed.

2 THE PROPOSED TECHNIQUE

2.1 Principle of Operation

The basics of the proposed closed-loop interrogation technique is shown in the block diagram of Figure 1, where a closed-loop interrogation system with a DFB narrow band laser is shown. The FBG sensor is illuminated by a DFB laser with wavelength λ_0 through optical coupler OC_1. The reflected light by the FBG is sent to the photodiode D_1 and the photodiode current is converted to voltage in the transimpedance amplifier A_1. To show the principle of operation of the system it will be assumed that when the laser wavelength is at the FWHM (Full Width at Half Maximum) of the FBG, the output voltage of the transimpedance amplifier will be equal to V_0.

In (Dias et al., 2008), a feedback control of the operating point of a FBG was proposed, in order to allow for the interrogation of ac signals around the operation point. In this paper a similar approach is used, and a feedback loop is implemented in order to force the laser's output wavelength track the changes

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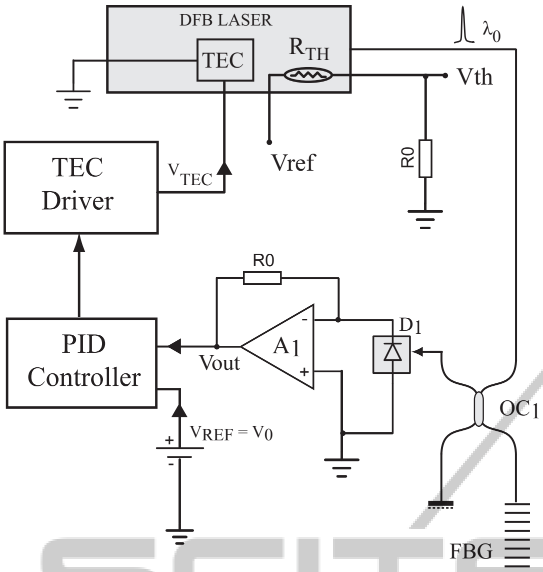

Figure 1: Block diagram of the basic closed-loop interrogation technique.

of the FBG (caused by an external strain, in this case a temperature variation) so that the output voltage of the transimpedance amplifier will always be at V_0. This is done by entering the output of the transimpedance amplifier and a reference voltage (numerically equal to V_0) in a PID controller which output will drive the thermoelectric cooler (TEC) normally found in DFB lasers (Cremonezi et al., 2012).

If a characterization of the laser's wavelength as a function of the laser's temperature is performed using the internal thermistor available in the DFB laser's package, by measuring the voltage V_{TH} in a voltage divider made with the thermistor, it is possible to know the wavelength of the laser and, consequently, the temperature of the FBG.

2.2 Multi-Point FBG Sensing with Narrow Band DFB Lasers

The proposed technique can be used to interrogate multiple FBGs. However, if the system is illuminated with a narrow DFB laser and the sensors are chained in a series configuration, there is a trade-off between temperature range and number of points possible to interrogate. Low-cost lasers usually can be tuned over a 2 nm range when heated/cooled by its internal thermoelectric cooler, resulting in a temperature scanning range of approximately 200 °C. This results in a serious limitation because, if, for example, four FBGs are to be inserted in the same optical fibre, each FBG will be allowed to have an excursion of only approximately 50 °C or overlapping of the spectra will occur.

If a low excursion range is acceptable, a very simple and low-cost interrogation can be implemented, as shown in Figure 2. A single microcontroller controls the whole system, and also implements a digital PID controller, which is the core of the interrogator. The system is initialized by forcing the laser to its minimum temperature, which leads to the minimum wavelength in the laser's output. Then an analogue class AB power amplifier A_2, controlled by a microcontroller's internal DAC, drives the TEC (heating it) while the output of the transimpedance amplifier V_{out} is monitored by an A/D converter also internal to the microcontroller.

When the value of V_{out} reaches 10% of V_0, (that is, when the laser wavelength is beginning to enter the FBG spectrum), the output of the DAC is disconnected from the TEC driver and the the output of the PID controller is fed into the input of the TEC power driver A_2. The PID circuit acts and the system reaches its steady state value, with $V_{out} = V_0$. The A/D converter checks if the system is stable while another channel of the A/D converter measures the voltage at the thermistor V_{TH}. Since V_{TH} is uniquely related to the lasers wavelength output, the exact position (and consequently the temperature) of the FBG can be easily calculated.

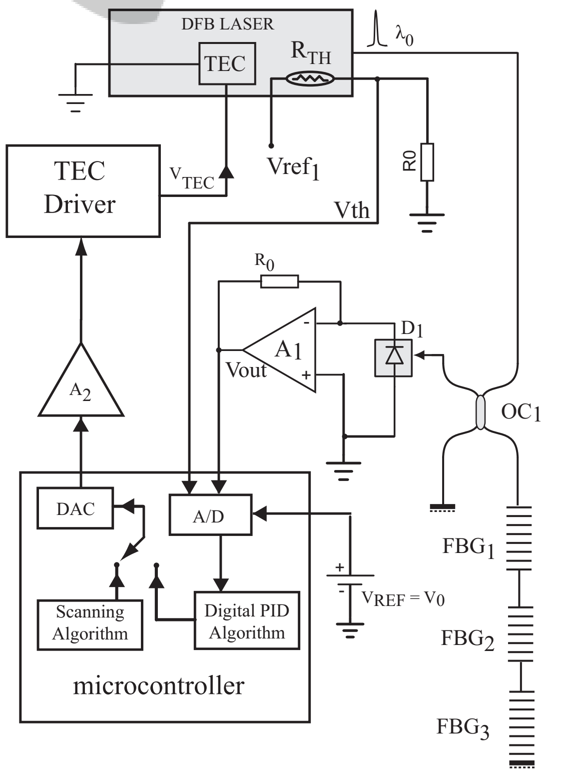

Figure 2: Block diagram of the DFB laser single-point closed-loop interrogator.

After the temperature of the first FBG is read, the PID controller is disconnected from the TEC power driver and the microcontroller DAC starts to heat the TEC, in order to the laser reach the next FBG. Again, when the output of the transimpedance amplifier indicates that the laser wavelength is at the beginning of the spectrum of next FBG, the same procedure done with the first FBG is repeated (the DAC is disconnected, the PID takes control of the system, etc.). This is repeated until the last FBG in the chain is measured, when the system begins to travel backwards (by cooling the laser), in the direction of the first FBG.

The only difference when measuring the FBGs during the returning path (cooling the laser) is that now it is necessary to drive the TEC until the laser crosses the whole FBG spectrum and the condition $V_{out} = 0.9V_0$ is reached, that is, the laser wavelength is at the left side of the FBG so that the PID takes control of the system always at the same point. It is important to notice that this system is relatively slow, since the measurements cannot be performed simultaneously and the time required to scan four FBGS (heating/cooling time, PID time necessary to stabilize the system) can take up to 2 minutes.

2.3 Multi-Point FBG Sensing with Broad Band Lasers

Implementing a closed-loop interrogator using a broad band laser leads to a system which can accept a large number of sensing FBGs and a extremely very fast measurement time, typically in the order of a few microseconds for each FBG. A block diagram of the interrogation system using a broad band laser is presented in Figure 3. In this scheme, the number of optical components is proportional to the number of FBGs sensing elements, and the final cost of an interrogation system with input for more than 3 FBG temperature sensors is dominated by the cost of the optical components (tracking FBGs, couplers and photodiodes).

The broad band laser illuminates the chain with *n* FBGs sensing elements through a optical circulator $Circ_1$. The reflected light from the chain of FBG sensing elements is fed into a series of optical couplers. Each optical coupler let 95% of the incoming light goes to the next coupler, and 5% of the light is directed into a small circuit called Signal Tracking Block (STB_i. In each STB there is one FBG (called tracking FBG, which is glued to a Zn substrate), one photodiode, one thermoelectric cooler, one semiconductor temperature sensor and one microcontroller with its the electronic circuitry. Although it is not necessary that the tracking FBGs be matched to the sensing FBGs, it is easier to design the system if the FBGs in each pair of tracking/sensing FBGS have their centre λ close. The basic schematic of each STB block is presented in Figure 4,

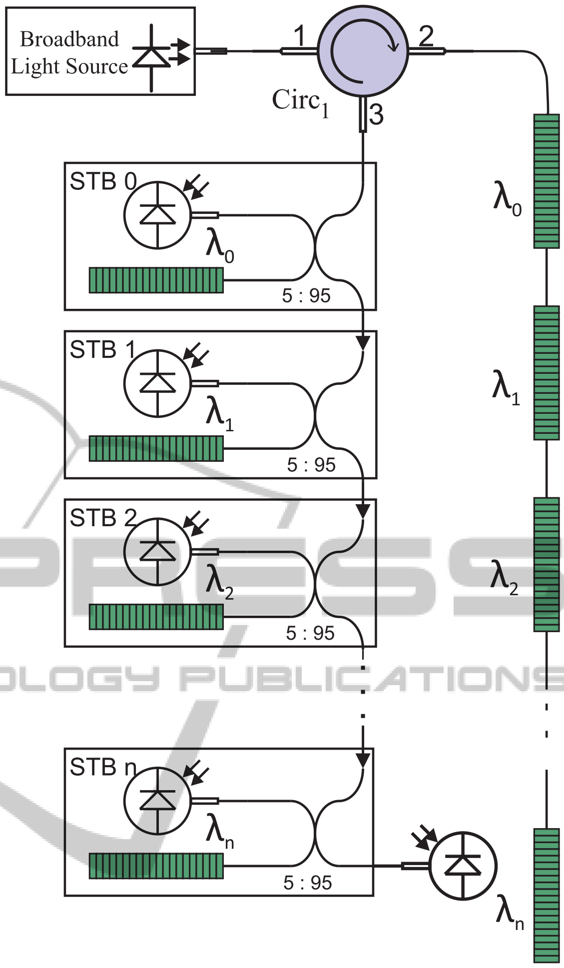

Figure 3: Block diagram of the broad band laser multi-point closed-loop interrogator.

The STB electronics circuits drive the TEC while the microcontroller acquires the output of the transimpedance amplifier, which value is equal to the convolution between the sensing and the tracking FBGs. A PID algorithm executed in the microcontroller controls a DAC and a TEC driver circuit, forcing the value of this convolution (output voltage of the transimpedance amplifier V_{out}) to be equal to a reference value V_{ref}. If the temperature behaviour of the tracking FBG was previously characterized, measuring its temperature it is possible to determine the centre λ of the tracking FBG. Knowing the centre λ of the tracking FBG and remembering that, in the same FBG profile (one has to choose to operate on the left or on the right side of the FBG profile) the convolution value is uniquely related to the centre wavelength of sens-

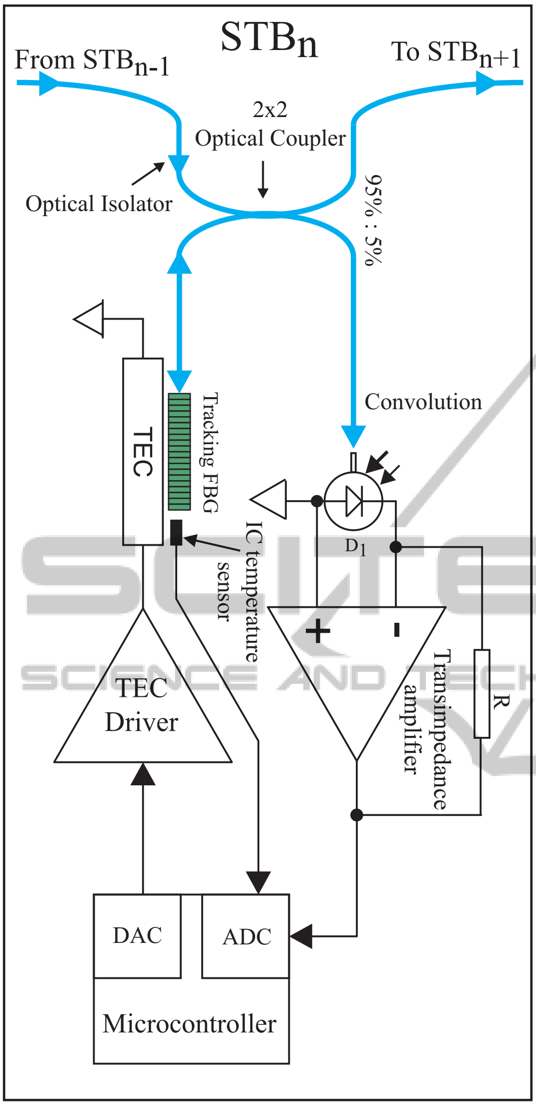

Figure 4: Schematic of the Signal Tracking Block - STB.

ing FBG, the temperature of the sensing FBG is easily calculated.

The system may require up to one minute to have all STBs in steady state, due to the slow heating/cooling which is used to control the tracking FBGs. However, once the steady state is reached, all the signal processing for the stabilization of the *n* sensing FBGs is done in parallel, and it requires only a few microseconds to interrogate each one of the *n* channels, since all that has to be done is to convert the analogue voltage V_{out} to digital.

3 EXPERIMENTAL RESULTS

A prototype of a single-point FBG interrogator using a 1550 nm DFB laser (Eudyna Devices USA, 2004) was implemented to validate the principle of the closed-loop technique. In the developed prototype (block diagram shown in Figure 4), an analogue PID controller was used, and the microcontroller was responsible only for scanning the system during start-up and for reading the voltage V_{TH} at the thermistor.

The system was tested in the temperature range of -20°C to 80°C, and the resolution obtained was very high since, after reaching the steady-state, the output voltage of the transimpedance amplifier presented a maximum fluctuation which was less than 10μV, in an output signal of 2.5 V. The edge of the sensing FBG profile has a width of approximately 400 pm and a variation from 0% to 100% of the FBG reflected light reaching the photodiode causes a voltage variation equal to 5 V in the output of the transimpedance amplifier. Therefore, the slope of the FBG profile is about 40 pm/V. Since a voltage change of 20μV can be measured, it means that a variation of 800.10^{-6} pm can be detected. This result indicates that the developed closed-loop single point interrogator using a DFB laser presents a resolution of 0.08m°C for a typical naked FBG with $\Delta\lambda/\Delta T = 10$ pm.°C^{-1}.

A plot of the measured data in the prototype for the temperature range of 30°C to 47°C is shown in Figure 5, where it is presented the thermistor voltage measured as a function of the temperature in the FBG sensor, acquired with a precision AD590M (Timko, 1976) temperature transducer.

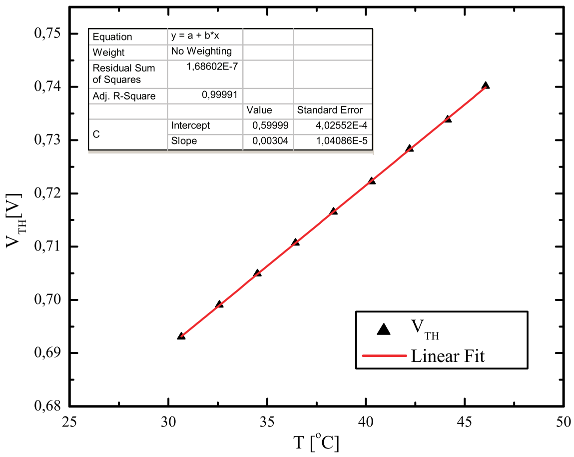

Figure 5: Plot of the thermistor voltage V_{TH} as a function of the temperature measured with an AD590M temperature transducer.

4 DISCUSSIONS AND CONCLUSIONS

Three techniques for the implementation of closed-loop interrogators for FBG temperature sensing applications were presented. A very low-cost single-point interrogator can be constructed with only three optical components, a DFB laser, an optical coupler and a photodiode. This interrogator has an extremely high resolution (80 μ°C for a naked FBG sensor) and with a 2 nm tunable DFB laser it can measure temperatures over a 200°C range.

The DFB laser technique can also be used in multi-point temperature measurements, but the system presents limitations: the interrogator is slow (up to two minutes can be necessary to measure FBGs which are at the extreme points of the temperature range), and there is a trade-off between the number of sensing FBGs and the maximum temperature range that each FBG can measure. Nevertheless, the system presents a very high resolution and is extremely cheap, since the cost of all components necessary to implement the interrogator is around 300 Euro at the time of writing.

A multi-point closed-loop interrogator scheme that uses a broad band laser was also presented. This technique is extremely fast and each FBG sensing element can be interrogated in a few microseconds. The system is modular and can be easily built to operate with a custom number of channels. Since part of the optical power is lost in the series of the optical couplers inside the equipment, it is expected that the maximum number of channels would be limited to 30-40. The multi-point closed-loop interrogation technique is much more expensive than the technique which uses the DFB laser because each interrogation channel requires one FBG, one optical coupler and one photodiode. The electronics circuits, TECs and IC temperature sensors which are necessary to implement the interrogator are only a fraction of the cost of the optical components and, therefore, the cost of the interrogator is basically given by the optical components.

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