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Nonlinearity Compensation of the Fiber Bragg Grating Interrogation System Based on an Arrayed Waveguide Grating

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***Abstract*—In this paper, we report on nonlinearity compensation for a solid-state fiber Bragg grating (FBG) sensor interrogation system based on an arrayed waveguide grating (AWG) device. A lookup table with calibration data is used to improve system linearity. A reduction in the absolute value of the measurement error from 120 μstrain or 15 °C to 4.8 μstrain or 0.6 °C, respectively, is experimentally demonstrated.**

***Index Terms*—Arrayed waveguide grating (AWG), fiber Bragg grating (FBG), linearization, nonlinearity, sensors.**

I. Introduction

FIBER BRAGG grating (FBG) sensors have been widely used as temperature, strain, or pressure sensors. Their small size, light weight, electromagnetic immunity, chemically inert nature, and other benefits render these sensors extremely useful for implementation in civil and mechanical engineering. FBGs can be easily multiplexed using wavelength-division multiplexing; thus, an array of sensors can be addressed with one optical fiber. Being spectrally encoded, FBGs are immune to optical signal intensity modulation, which offers the advantage of high accuracy when extended distance monitoring is required.

A number of FBG interrogation techniques have been reported in the literature [1], [2]. The most successful ones include scanning filters, tuning lasers, and charge-coupled-device spectrometers. However, these systems are not suitable for interrogating large arrays of sensors at high speed.

Commercially available FBG interrogation systems usually use tunable filters based on piezoelectric actuators that permit relatively low scanning speeds of 50–100 Hz. Such scanning rates are insufficient to monitor dynamically changing signals, and thus, the application of such systems is limited to monitoring slowly changing temperature or strain parameters.

An interrogation system for FBG and Fabry–Pérot sensors using an arrayed waveguide grating (AWG) has previously been reported [3]–[5]. The main benefit of this solution is that the interrogator is solid state (no moving parts); hence, the speed of operation can be very high. However, due to the discrete character of the device, its response is not linear. The extent of the nonlinearity depends on the sensor spectral bandwidth and AWG channel width and spacing. At a given AWG channel spacing, the errors of the system decrease as the sensor bandwidth increases [3]. However, it is preferable to use sensors with a narrow bandwidth to raise the number of sensors used within the AWG spectral window.

Previously, we demonstrated that to improve the system linearity, it is necessary to either increase the sensor bandwidth (not an ideal solution as explained above) or use an AWG with denser channel spacing (associated with the system cost increase).

In this paper, we propose that the system linearity can be significantly improved by using a "universal" lookup table with a prerecorded simulated sensor response in the wavelength domain. This can be used to accurately compute the actual FBG peak position.

II. Solid-State Sensor Interrogation System

The system architecture based on a broadband light source and a commercial 16-channel AWG device is shown in Fig. 1 [3].

In this approach, an FBG sensor is illuminated by a superfluorescent source (SFS), and the AWG device is used to analyze the spectrally encoded information reflected from the sensor. The conversion of the optical signals to electrical signals is performed by photoreceivers connected to each AWG channel. The detectors' outputs are sampled using a data acquisition (DAQ) board, and the FBG spectrum is recovered on a personal computer (PC) by using discrete information from the channels.

III. Software Simulation

The proposed interrogation system was previously modeled in Labview software (National Instruments) [3]. The program enables the modeling of an AWG with Gaussian passbands and was matched to the specific device that was available for this research. The available grating had a 100-GHz channel spacing, which is equivalent to approximately 0.8 nm, whereas the full-width at half-maximum (FWHM) of the individual AWG channels was equal to approximately 0.4 nm. Eight channels of the AWG were simulated and monitored.

Fig. 2 depicts the user interface of the simulation program. The screenshot was taken during a simulation of the interrogation of an FBG having 1-nm FWHM with a center wavelength of 1549 nm.

The FBG spectral response is displayed on the background of the AWG channels in the bottom window of the user

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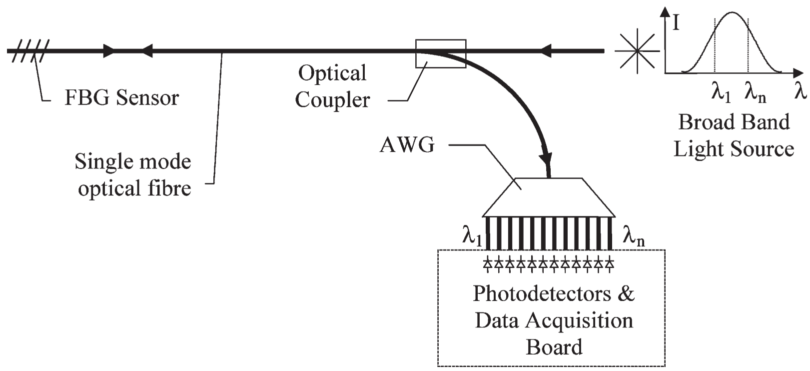

Fig. 1. Functional block diagram of the FBG–AWG measurement system.

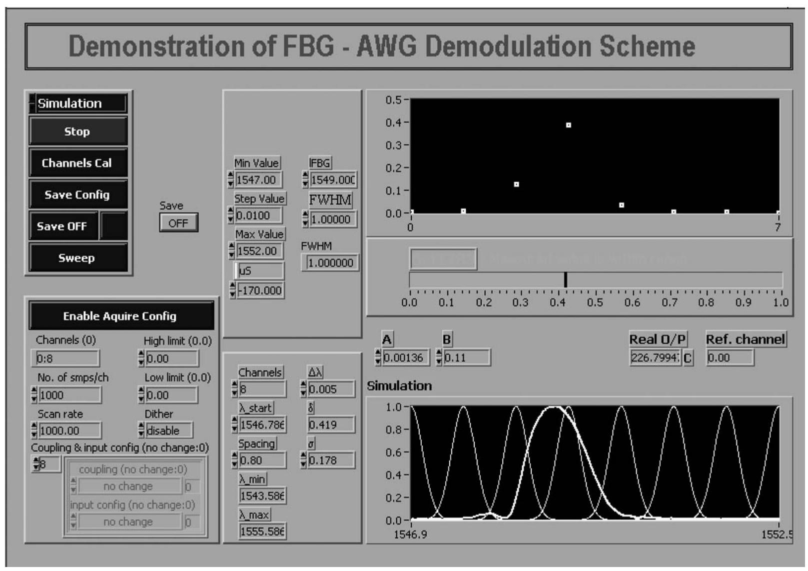

Fig. 2. Labview simulation of the AWG interrogation system.

interface (Fig. 2). The top window represents the outputs from the photoreceivers. The FBG reflection was captured using an optical spectrum analyzer and stored in a data register in the simulation software. The software allowed this register to be shifted by a specified wavelength step. This allows the FBG wavelength shift to be simulated. Note that the spectra of the AWG channels and the FBG sensor were normalized to one. The FBG peak position shifts across the AWG channels as the measurand changes. By tracking this position, the information about the measurand is obtained. Peak detection is realized by fitting a parabolic function into the three points located around the maximum channel output and computing the position of the function maximum.

The system requires calibration in terms of wavelength, strain, or temperature before the real measurement can take place.

IV. System Errors

As highlighted in the introduction, the major limitation of the AWG is its nonlinearity caused by the discrete nature of the device. The light source spectrum is divided into a number of narrow-band components equal to the number of device channels.

The optical power in the channel is equal to the integral of the reflected sensor spectrum modified by the AWG channel passband shape. If the FBG spectral width is too narrow compared to the AWG channel spacing, the spectral shape recovered from the photodetectors' outputs may look somewhat different from the actual FBG spectrum (see Fig. 2, top window). This results in roughly sinusoidally varying system errors.

The software platform described in the previous section was used to quantify these errors. The system operation and the sensor response were modeled by scanning the FBG spectral characteristic across the AWG channels within the range of about 5 nm. The sensor output was normalized over the AWG channels, and its response is shown in Fig. 3.

It should be noted that although noise generated by the individual photoreceivers, the quantization error due to analog-to-digital conversion, and temperature and long-term drifts influence the final measurement in the real system, they are less pronounced than the error introduced by the system nonlinearities. Therefore, these quantities were not taken into consideration during simulation.

As can be seen in Fig. 3, the system nonlinearity is significant. However, using the sensor response characteristic, it is possible to create a lookup table, which can be used to linearize the response.

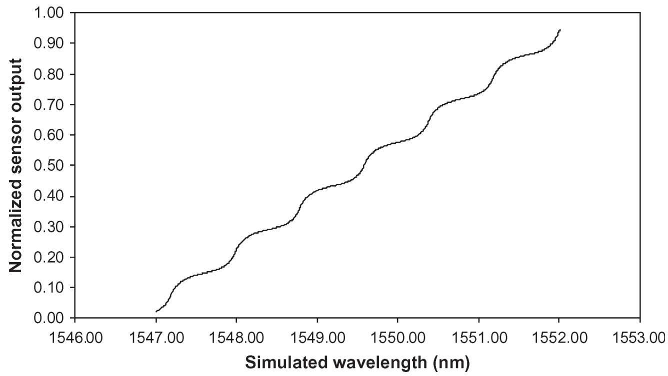

Fig. 3. Sensor response characteristic with 100-GHz AWG and 1-nm FWHM FBG.

For this reason, the simulated characteristic shown in Fig. 3 was stored in a data file. As the peak wavelength shifted across the AWG channels, the equivalent wavelength was derived from the lookup table. To obtain the actual wavelength values, quadratic interpolation was applied for the values falling between the data points stored in the lookup table.

Results of the experimental testing of this linearization method are presented in the following section.

V. Experimental Evaluation

The measurement system, as shown in Fig. 1, was set up in the laboratory. The sensing FBG was illuminated through a 50/50 optical coupler using an SFS. The reflected signals were analyzed using a prototype AWG (manufactured by KYMATA) and the AWG channel monitor, which was specially designed for this purpose. The photodetector outputs were monitored using a 12-bit DAQ board (National Instruments), and the acquired signals were analyzed on a PC. Signal processing was performed in the Labview software. The AWG channels were thermally stabilized using a TEC controller. All optical components were interconnected using a single-mode fiber, which was spliced or terminated with polished contact connectors.

Two FBG sensors were permanently attached to a cantilever beam in close proximity to one another using epoxy adhesive (Epotek 353 ND). One FBG was illuminated by the SFS, and the reflected signal was analyzed using the AWG interrogator (as shown in Fig. 1). The beam allowed an application of strain, which was sufficient to shift the tested FBG peak across the spectral window covered by approximately four AWG channels. The second FBG was used as a wavelength reference measured using a commercial FBG interrogation system.

Two experiments were carried out. The first was based on the lookup table with the data from the simulated system as described in the previous section. The second experiment was performed using the lookup table that contains the data collected from the real sensor system. The results of these experiments are shown in Figs. 4–7.

As can be seen from the results, the system linearity was significantly improved after implementing the proposed solutions. The absolute value of the maximum error was decreased to about 8 pm when using the lookup table derived from the simulation. This error is equivalent to a resolution of

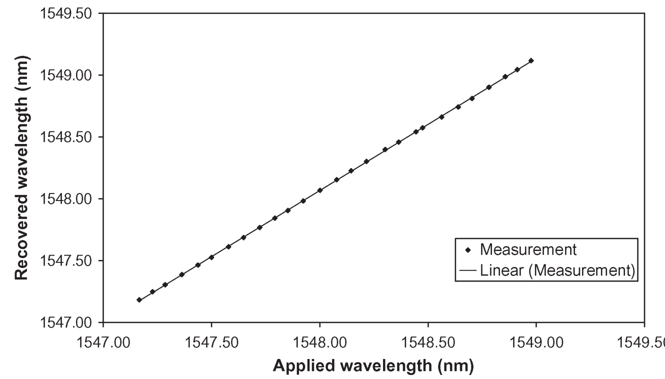

Fig. 4. Sensor response characteristic for a 100-GHz AWG using a lookup table based on FBG simulation.

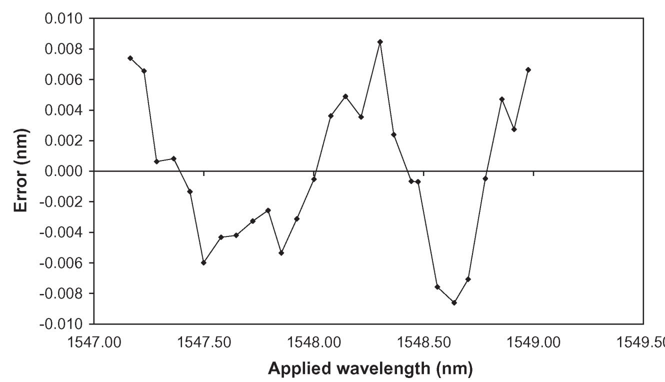

Fig. 5. Measurement error for a 100-GHz AWG using a lookup table based on FBG simulation.

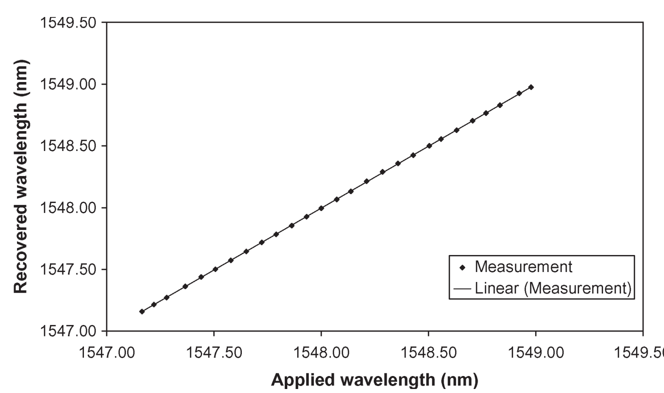

Fig. 6. Sensor response characteristic for a 100-GHz AWG using a lookup table based on the direct calibration of an FBG.

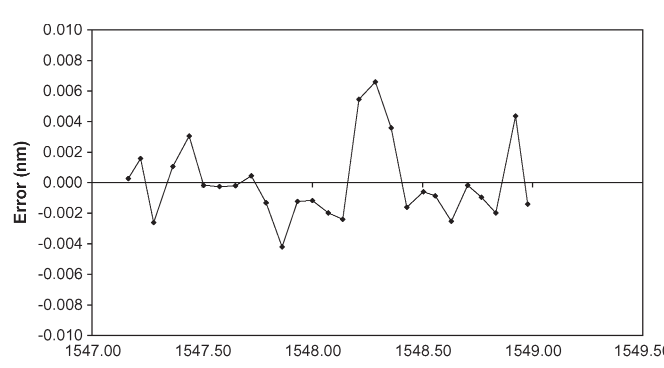

Fig. 7. Measurement error for a 100-GHz AWG using a lookup table based on the direct calibration of an FBG.

6.4 μstrain or 0.8 °C, with a measurement range of 1450 μstrain or 181 °C. Further linearity improvement was achieved when the lookup table was obtained from the direct sensor calibration and resulted in the maximum error of approximately 6 pm, which is equivalent to 4.8 μstrain or 0.6 °C. In contrast, the system maximum error previously reported for the same AWG and FBG [3] exceeded 100 μstrain.

VI. Conclusion

In this paper, we have demonstrated the successful nonlinearity compensation of the nonlinear behavior of the FBG interrogation system based on an AWG. This was achieved through the implementation of a lookup table that contains the FBG sensor response data. The linearization method has been evaluated in the laboratory. The nonlinearities introduced due to the discrete nature of the AWG were quantified using the software model of the measurement system. Using a 100-GHz channel spacing AWG and an FBG with 1 nm FWHM, the system nonlinearity was reduced to below 9 pm when a lookup table was derived from the simulation. The error is further reduced below 7 pm when the lookup table is derived from direct sensor calibration.

It should be noted that the sensor bandwidth can be narrowed if an AWG with 50-GHz channel spacing is used. This would allow for a better use of the interrogator spectral window.

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