A DFB Fiber Laser Sensor System Using NI-Compact-RIO-based PGC Demodulation Scheme

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ABSTRACT

An eight-channel distributed feedback fiber laser (DFB FL) sensor system using phase generated carrier (PGC) demodulation scheme is described in this paper. This system employs an unbalanced Michelson interferometer to convert the measurands-induced laser wavelength shifts into the phase shifts. The digital PGC algorithm is realized on the Field Programmable Gate Array (FPGA) module of the commercialized NI-Compact RIO. The influence of the time delay between the interferometric signal and the PGC carrier is then investigated. Finally, the experimental system is setup to validate the analysis above.

Key words: DFB fiber laser sensor, digital PGC demodulation, NI CompactRIO, phase difference

1. INTRODUCTION

Distributed feedback fiber laser (DFB FL) sensors exhibit great advantages including small size, light weight, immunity to electromagnetic interference, and the ability to be wavelength division multiplexed along a single fiber [1]. Among various demodulation schemes adopted in optical fiber sensor system, the PGC technique has been widely used, because this method has the advantages of high stability, large dynamic range and high resolution [2]. However, this technique needs relatively complex calculations [3]. So, a high performance real-time PGC demodulation system is needed, especially for multiplexed optical fiber sensors. It is difficult to complete the great amount of calculations for PGC algorithm within a short time, using software on the personal computer (PC). Besides, the PC-based PGC demodulation scheme can not provide a reliable and steady performance. The NI Compact RIO is a commercialized low-cost reconfigurable control and acquisition system, which provides high performance and reliability. The system integrates an open embedded architecture with small size, extreme ruggedness, and hot-swappable industrial I/O modules. It is powered by reconfigurable I/O (RIO) FPGA technology. The NI Compact RIO can provide a convenient and stable way to realize those calculations for PGC algorithm in the embedded system because it adopts techniques which can be explored by the graphical software—LabVIEW. Besides, as Compact RIO could be explored in a relatively short period with LabVIEW, time and energy can be saved to focus on other aspects of the system. The Parallel code was designed to realize the PGC algorithm in the FPGA module of Compact RIO. The demodulated results with high wavelength resolution are confirmed by the experiments in this paper.

2. BASIC PRINCIPLE OF THE PGC TECHNOLOGY

The central wavelength of the DFB Fiber Laser will be changed by the external strains or temperatures [5]. The unbalanced interferometer will convert the wavelength shift into the phase shift of the interferometer.

$$\Delta\varphi = -\frac{2\pi n\Delta L}{\lambda^2}\Delta\lambda \tag{1}$$

Where $\Delta\varphi$ is the shift of the phase, $\Delta\lambda$ is the shift of the wavelength, n is the refractive index, and ΔL is the path difference of the two arms of the interferometer. In the PGC scheme, a large-amplitude sinusoidal signal $C\cos\omega_c t$ at a frequency out of the signal band is introduced as the phase modulation to eliminate the fade caused by the initial phase drifts of the interferometer. The light detected at the output of the interferometer can be expressed as:

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$$I = A + B\cos(C\cos\omega_c t + \varphi(t) + \varphi_0) \quad (2)$$

Where constant A and B are proportional to the input optical power, B also depends on the visibility of the interferometric signal. $\varphi(t)$ contains the signal of interest and φ_0 includes the initial phase difference of the two arms of the interferometer and the phase shift for environmental effects. The interferometric signal is mixed (2) with signal $G\cos\omega_c t$ and $H\cos(2\omega_c)t$, respectively. And then, by low pass filtering the high frequency items, two channel of signals are produced. After the following operations (Fig.1), including differential, cross-multiplying, integrating, and high pass filtering, the signal of interest $B^2GHJ_1(C)J_2(C)\varphi(t)$ can be obtained, where $J_1(C)$ and $J_2(C)$ are Bessel functions.

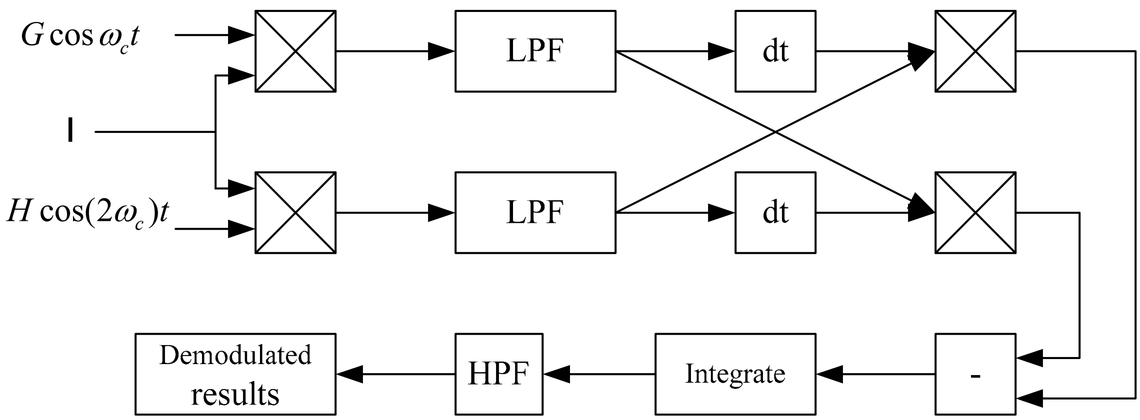

Fig.1 The frame of the PGC technique

3. EIGHT-ELEMENT DFB FL SENSORS SYSTEM DESCRIPTIONS

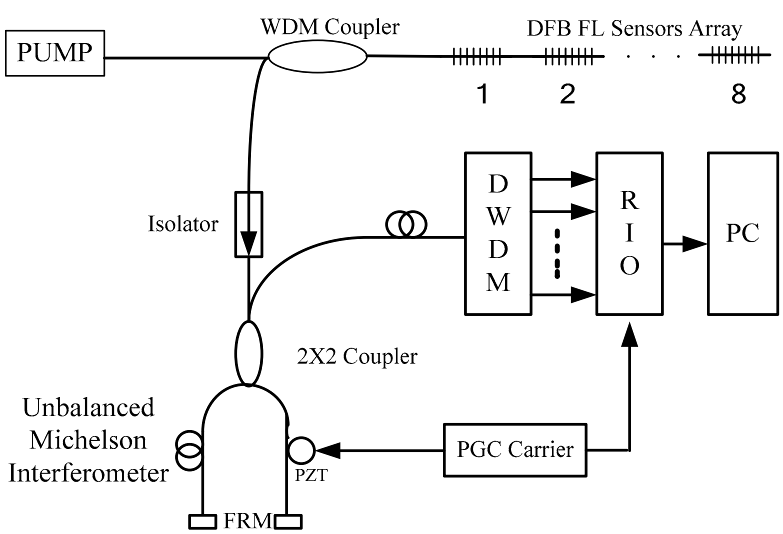

Fig.2 Schematic diagram of the proposed Eight-elements DFB FL sensors array system

A schematic diagram of the proposed eight elements DFB FL sensors array system based on digital PGC demodulation is shown in Fig.2. A laser diode at 980nm is used to pump the array of eight DFB FL sensors with central wavelength λ1, λ2, …, λ8. A wavelength division demultiplexer (WDM) is used to separate the returned fiber laser C band light from the 980 nm pump laser light. An optical isolator is inserted to suppress feedback-induced noise in the system. Then, the sensor output is coupled into an unbalanced interferometer. The wavelength-shifts of the DFB FL Sensor are converted to phase-shifts simultaneously using an unbalanced Michelson interferometer. A dense wavelength division demultiplexer (DWDM) is adopted to split off the individual DFB FL Sensor signals as a wavelength filter. The signal of each channel is detected by a low-noise p-i-n photodiode and an amplifier circuit. The analog outputs of the photo-detectors and the carrier signal are then sent to the NI-Compact RIO to perform the PGC demodulation algorithm. The demodulation results are transmitted into a personal computer (PC) to be displayed and stored.

4. THE REALIZATION OF THE PGC TECHNIQUE ON COMPACT RIO

4.1 Structure of Compact RIO

NI-Compact RIO is a kind of embedded system, which adopts real-time and FPGA technologies to deliver high-performance in a small, rugged industrial control and acquisition platform. Compact RIO is consisted of a reconfigurable I/O FPGA core, a real-time embedded processor, and industrial hot-swappable I/O modules.

(1) The reconfigurable I/O FPGA core provides the reliability of professional hardware circuitry and the performance of true parallel execution in silicon;

(2) The real-time embedded processor for stand-alone and distributed deterministic operation with a built-in web-based human-machine interface;

(3) The industrial hot-swappable analog and digital I/O modules can be connected to industrial sensors and actuators directly.

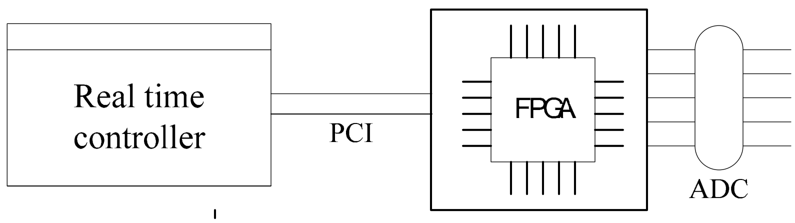

Fig.3 The structure of Compact RIO

4.2 The realization of the PGC algorithm on FPGA

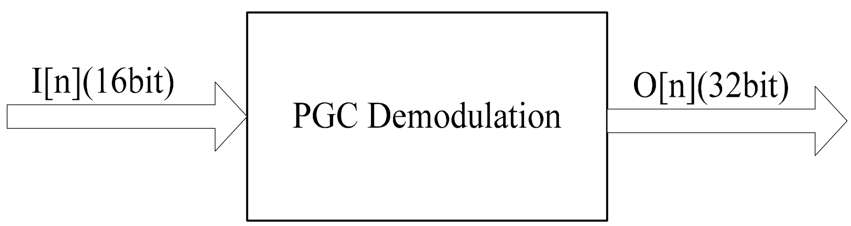

Fig.4 Top module of PGC algorithm

The PGC algorithm can be realized on FPGA because of its own characters. We can see the flow chart of the PGC algorithm in Fig.1, which can be simplified into Fig.4. This module can be realized in a pipelining at rate of the sampling rate. In each sampling period, the input port receives a data and the output port gives a demodulation result. And the wavelength resolution of the demodulation should also be considered in the digital signal processing when using FPGA. Based on the PGC modulation and demodulation theory, the amplitude of the demodulated signal is in a fixed range, which can be forecasted. Then we simulate the whole demodulation progress using 16 bits fixed point operation (only few processing and the output data are 32bits), the results show that the resolution can satisfy the wavelength resolution requirement of the sensor system.

In order to realize the PGC technique on FPGA, two key points should be emphasized: First, the program should be developed as parallel execution to make sure PGC technique could be carried out simultaneously for different channels, thus Compact RIO could demodulate signals from multiplexed DFB laser sensor system. Second, the digital signal processing is done one point by one point on FPGA which means the program will not allow the analog to digit converter to sample until the former point has been processed, therefore PGC technique should be separated into several parts (Fig. 5) to perform so as to ensure a high sampling rate.

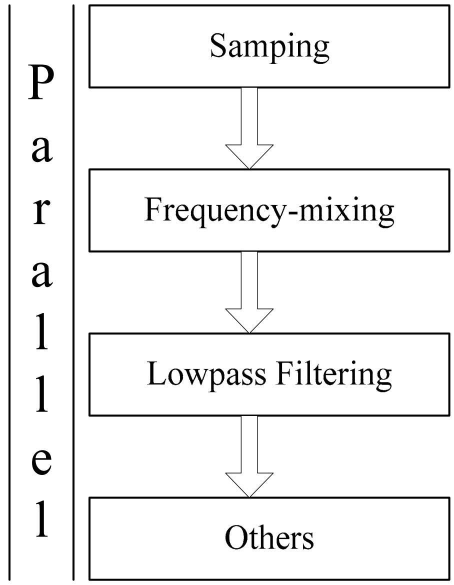

Fig.5 The steps of the processing

5. THE TIME DELAY ANALYSIS

As shown in Fig.2, the PGC carrier has two different paths to transmit. One is the modulating carrier, which is used to modulate the Michelson interferometer. The other is the demodulating carrier, which is connected to Compact RIO for demodulation. As a result, they have different transmitting time, which can be described as phase difference Δ. If we suppose the modulating carrier is $C\cos\omega_c t$, then the demodulating carrier $G\cos\omega_c t$ can be expressed as $G\cos(\omega_c t+\Delta)$ and the item $H\cos 2\omega_c t$ changes to be $H\cos(2\omega_c t+2\Delta)$ .The signal item is $I = A + B\cos(C\cos\omega_c t+\varphi(t)+\varphi_0)$. In this situation, the demodulation result will be got after these following operations:

Mixing1: $I = [A + B\cos\left(C\cos\omega_0 t+\varphi(t)\right)]\times G\cos(\omega_0 t+\Delta)$

Mising2: $I = [A + B\cos\left(C\cos\omega_0 t+\varphi(t)\right)]\times H\cos(2\omega_c t+2\Delta)$

Lowpass filtering1: $-GBJ_1(C)\sin\varphi(t)\cos\Delta + GBJ_1(C)\sin\varphi(t)\sin\Delta$

Lowpass filtering2: $HBJ_2(C)\cos\varphi(t)\cos 2\Delta - HBJ_2(C)\cos\varphi(t)\sin 2\Delta$

Differential1: $GJ_1(C)B\cos\varphi(t)(\sin\Delta-\cos\Delta)\varphi^{'}(t)$

Differential2: $HBJ_2(C)\sin\varphi(t)(\cos 2\Delta-\sin 2\Delta)\varphi^{'}(t)$

Cross-multiplying1: $GHJ_1(C)J_2(C)B^2\sin^2\varphi(t)(\cos 2\Delta-\sin 2\Delta)(\sin\Delta-\cos\Delta)\varphi^{'}(t)$

Cross-multiplying1: $-GHJ_1(C)J_2(C)B^2\cos^2\varphi(t)(\cos 2\Delta-\sin 2\Delta)(\sin\Delta-\cos\Delta)\varphi^{'}(t)$

Subtracting: $-GHJ_1(C)J_2(C)B^2(\cos 2\Delta - \sin 2\Delta)(\sin\Delta - \cos\Delta)\varphi'(t)$

Integrating: $-GHJ_1(C)J_2(C)B^2(\cos 2\Delta - \sin 2\Delta)(\sin\Delta - \cos\Delta)\varphi(t)$

High pass filtering: $GHJ_1(C)J_2(C)B^2(\cos\Delta - \sin 3\Delta)\varphi(t)$

Compared with the theoretical result shown in part 2, the experiment result has a multiplication item $(\cos\Delta - \sin 3\Delta)$, which has a relationship with the phase difference Δ. The phase difference is a fixed value in a real system, so we can get the signal of interest $\varphi(t)$. This analysis demonstrates the feasibility of the experiment's setting up.

6. EXPERIMENTS AND RESULTS

The eight-channel DFB fiber laser sensor array system was tested in a water tank, and a loudspeaker was adopted as the signal source. The sampling rate of the analog signal to digit signal converter was 100 kHz and the frequency of the carrier was 5 kHz. A test tone of 100Hz was applied to the sensor. The demodulation results of the 8 sensors are demonstrated in the time domain, as shown in Fig.6. And the corresponding frequency spectrum of one sensor is shown in Fig. 7. The minimum detectable wavelength shift of the digital PGC demodulator is determined by the noise level, which is 1×10^{-6} pm/√Hz(@1kHz), as shown in Fig.8. The dynamic range of the system can reach 120 dB@100 Hz, the linearity between the signals applied to the sensor and the PGC demodulation results can reach 0.9995 at each test frequency. Fig.9 plots the linearity at the frequency of 100Hz.

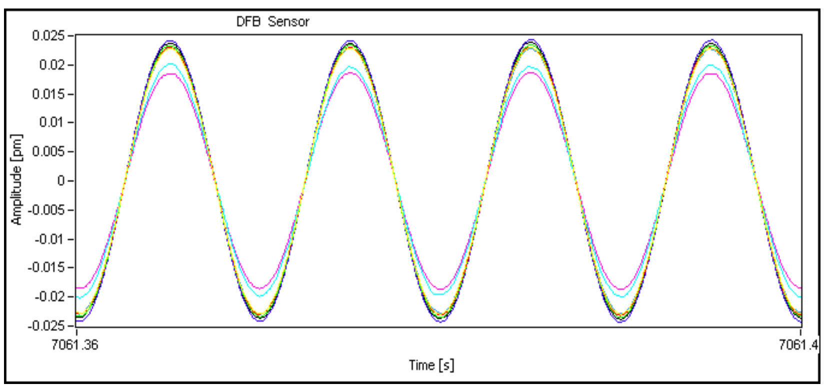

Fig.6 The demodulated result in time domain

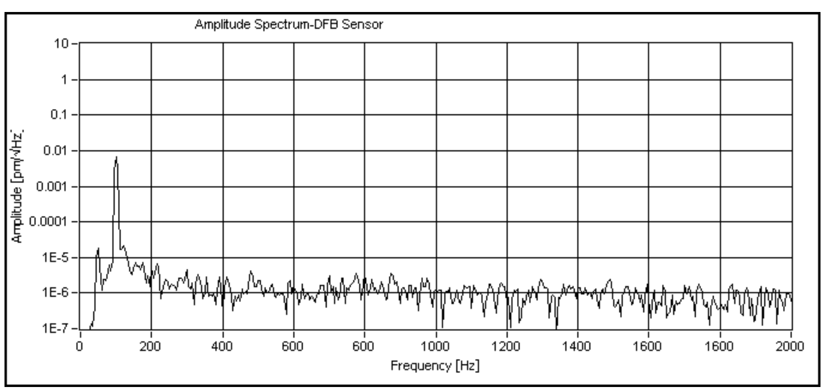

Fig.7 The demodulated result in frequency domain

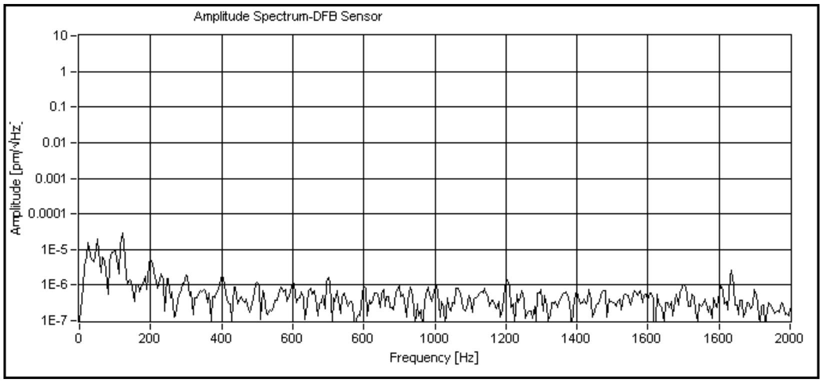

Fig.8 The figure of the noise level

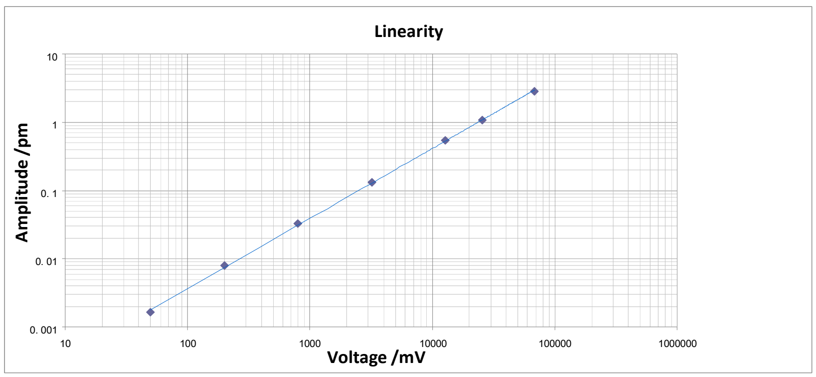

Fig.9 The linearity at the frequency of 100Hz

7. CONCLUSIONS

In this paper we have demonstrated an eight channel DFB fiber laser sensor system using PGC demodulation scheme. The key factors of FPGA-based PGC demodulation have been analyzed, and the PGC demodulation system based on NI-Compact RIO has been realized. The final experiment shows that a noise level of 1×10^{-6} pm/√Hz and a system dynamic range of 120 dB@100 Hz have been achieved.

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