Realization of 16-channel digital PGC demodulator for fiber laser sensor array

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Abstract. This paper describes a 16-element DFB FL (distributed feedback fiber laser) sensor array system interrogated by NI-PXI-based (PCI extensions for Instrumentation) digital PGC (phase generated carrier) technique. The lasing wavelengths of the DFB FLs are changed by the external strains or temperatures, and hence they can be used as sensors by detecting the wavelength shifts. An unbalanced MI (Michelson interferometer) is employed in the sensor array system to amplify the wavelength shifts of DFB FL sensors to detectable phase shifts. The output phase signals of the MI are separated into different channels by a DWDM, and then detected by a low-noise photodiode array. The digital PGC algorithm is realized on a PXI platform (NI, National Instruments), which consists of three FPGA (Field Programmable Gate Array) modules and a high performance system controller. The normalization of the interference fringe is proposed and realized in this paper to reduce the influence of the light intensity fluctuations, and a trigger mechanism is introduced into the digital multi-channel PGC demodulation scheme to synchronize the date among different channels. A 16-element DFB fiber laser sensor array system has been set up in the experiment and the demodulated results have demonstrated a minimum detectable wavelength shift of $1 \times 10^{-6}$ pm/$\sqrt{\text{Hz}}$, a linearity of as high as 0.9994, and a dynamic range of 110dB@100Hz.

1. Introduction
With the development of optical fiber sensor techniques, fiber sensor networks have been widely studied for the applications in the fields of petroleum seismic exploration, earthquake prediction, and security. The DFB FL sensor has attracted considerable research interests for its many unique advantages, including small size, light weight, high sensitivity, and especially the intrinsic ability to be wavelength division multiplexed along a single fiber [1]. In 1995, K P Koo and A D Kersey achieved a two fiber laser sensors array system using phase-locked demodulating technique [2]. In 2007, a four-element fiber laser hydrophone array was reported with the demodulation by a 3×3 coupler [3].

Among the various demodulation schemes adopted in optical fiber sensor system, the PGC technique has been widely used for its advantages of high resolution, large dynamic range and high stability. However, the application of the traditional analog-circuit-based PGC technique is limited by the characteristics of the electronic device, and it has the disadvantages as the difficulty of changing parameters, the sensitivity to environmental noise, and the instability. Compared with the analog-PGC, the digital PGC technique is much easier to be realized, and it is insensitive to the environmental interference, so it is more suitable for demodulating large scale WDM fiber laser sensors array. But on the other hand, the digital PGC algorithm needs relatively complex calculations to recover the phase signals [4]. It requires a high performance demodulation system to carry out the great amount of
real-time calculations. In fact, it is difficult to realize the PGC algorithm on a personal computer for the simultaneous demodulation for a DFB FL sensor array system.

The NI-PXI system is a commercialized digital signal processing system produced by the National Instrument Corporation. It is based on the FPGA modules and a powerful system controller, which provides high performance and reliability. A 16-element fiber laser sensor array system is set up using the digital PGC demodulation technique based on the NI-PXI system and corresponding LabVIEW software in this paper. The system has achieved a high performance demodulation of 16-channel PGC signals in a real-time manner. And the simultaneous demodulation of the 16-element DFB fiber laser sensor array system with a high wavelength resolution is also confirmed by the experiments in this paper.

2. Principle

2.1. The principles of PGC algorithm

The lasing wavelength of a DFB FL sensor will be changed by the external strains or temperatures. An unbalance Michelson interferometer is employed to amplify the wavelength shift of DFB FL sensor into the detectable phase shift of the MI [5].

\[
\Delta \phi = -\frac{2\pi n \Delta L}{\lambda^2} \Delta \lambda
\]  

where \( \Delta \phi \) is the phase shift of the MI, \( \Delta \lambda \) is the wavelength shift of laser, \( n \) is the refractive index of fiber, and \( \Delta L \) is the path difference of the two arms of the unbalance MI. In the PGC technique a large amplitude phase modulation carrier at a higher frequency out of the signal band is introduced into one arm of the interferometer, and hence eliminates the signal-fading caused by the initial phase drifts of the MI. The output signal of the MI can be expressed as:

\[
I = A + B \cos \left( C \omega t + \varphi_i(t) + \varphi_{env} \right)
\]  

where the constant \( A \) and \( B \) are proportional to the incident light intensity, \( B \) also correlates with the visibility of the interferometric signal, \( C \) is the modulation depth, \( \omega \) is the angular frequency of the carrier, \( \varphi_i(t) \) is the signal of interest, and \( \varphi_{env} \) is the initial phase of the MI with the external disturbance.

The output phase signal of the MI is mixed with \( G \cos \omega_1 t \) and \( H \cos(2\omega)t \) to produce two channels of signals, respectively. After the following operations as shown in figure 1, including LPF (low-pass filtering), differential, cross-multiplying, integrating, and HPF (high-pass filtering), the recovered sensing signal of interest can be obtained as:

\[
B^2G\text{H}J_1(C)J_2(C)\varphi(t)
\]  

where \( J_1(C) \) and \( J_2(C) \) are Bessel functions.

![Figure 1. The schematic algorithm of PGC technique.](image)
Because the final demodulated result is proportional to $B^2$. $B$ is decided by the light intensity and the visibility of the MI, the recovered signal will change with the fluctuation of the light and external disturbance. So the system cannot get the desired signal of interest. To eliminate the influence of the variations of light intensity, the peak-to-peak normalization is introduced into the digital PGC algorithm. The basic principle of the normalization is shown as follows:

$$y = \frac{x - x_{\text{min}}}{x_{\text{max}} - x_{\text{min}}}$$

where $y$ is the result of the normalization of $x$, $x_{\text{max}}$ and $x_{\text{min}}$ is the maximal value and the minimum value of the sampled date. By adopting the normalization scheme, the demodulation result can be expressed as $GHJ_{(C)}J_{(C)}\varphi(t)$, so the influence of light intensity has been eliminated.

2.2. The realization of PGC on NI-PXI

PXI is a modular instrumentation platform originally introduced in 1997 by National Instruments as a basis for building electronic test equipment or automation systems. And the platform always combines a signal system controller and various kinds of modules to set up a real measurement system. On account that the PC-based (personal computer) PGC demodulation scheme can not afford the great amount of calculations, three high performance FPGA modules are selected to build up the PXI platform to realize the simultaneous PGC demodulation for the 16-element DFB fiber laser sensor array system in this paper. The PGC algorithm is mainly programmed on the FPGA except for the band-pass filtering on the duo-core system controller, as shown in figure 2. And the programme is achieved by a graphical development environment: NI LabVIEW, which can help to save developing time.

![Figure 2](image)

**Figure 2.** The structure of the program of PGC algorithm realized on the FPGA modules and the system controller.

In order to realize the PGC technique on FPGA, three key techniques have been adopted in the program. Firstly, the program should be developed as parallel execution to make sure that the PGC technique could be carried out simultaneously for different channels, and the PXI could demodulate the signals from the multiplexed DFB laser sensor system. Secondly, the algorithm is processed digitally one point by one point on the FPGA module. It means that the program will not allow new samples until the processing of a former point has been finished. Therefore, the PGC technique should be separated into several sections, as shown in figure 2, so as to ensure a high sampling rate [6]. At last, a trigger mechanism, as shown in figure 3, must be employed in the program for the synchronization between different channels to ensure the validity of the demodulated results. When the demodulation system starts to work, a trigger signal is sent by a master FPGA module at first, and then the other two FPGA modules receive the trigger, which is an order as to begin to sample. Such a trigger mechanism can assure the synchronization of all the FPGA modules.
The program on the system controller is also completed using LabVIEW. Its main function is to carry out the process of band-pass filtering and the fast Fourier transform (FFT), and to display the demodulated results both in the time domain and in the frequency domain. The interface of the program is shown in figure 4.

![Figure 4](image_url) **Figure 4.** The interface of the demodulation program on the system controller.

### 3. Experiment and result

The schematic diagram of the proposed 16-element DFB fiber laser sensor array system is shown in figure 5.
Figure 5. The Schematic diagram of the proposed 16-element DFB FL sensors array system.

Sixteen DFB fiber lasers were pumped by a 980nm semiconductor laser. They were stuck parallelly on a rectangular piezoelectric transducer (PZT). A sinusoidal test signal was given to the sensors by electrical modulating the PZT. The path difference of the MI was 5 m. Two faraday rotator mirrors were incorporated at the end of the MI arms to make the interferometer polarization insensitive. The output phase signals of the MI were separated into different wavelength channels by DWDM, and the detected analog electronic signals were converted into digital signals. Then the PGC algorithm was processed on the three I/O FPGA modules. The sampling rate of A/D converter is 100 kS/s and the frequency of the carrier is 10 kHz. The test signal is 100Hz and the demodulated results of sixteen sensors are demonstrated in time domain as shown in figure 6. The minimum detectable wavelength shift of the system is determined by the noise level, which is $1 \times 10^{-6}$ pm/$\sqrt{\text{Hz}}$, as shown in figure 7. The linearity between the test signal and the demodulated results can reach as high as 0.9994 at each test frequency, as the linearity at 100Hz shown in figure 8. A dynamic range of 110dB@100Hz has been achieved by the PGC demodulation scheme in this system, as shown in figure 9.

Figure 6. The demodulated results of 16 channels in time domain.
4. Conclusion
In this paper, a 16-element DFB fiber laser sensor array system is demonstrated using PGC demodulation scheme. The key techniques of the high performance real-time 16-channel PGC demodulation based on a NI-PXI platform have been introduced. Experimental system has been set up in the laboratory. And the demodulation results show that a minimum detectable wavelength shift of $1 \times 10^{-6}$ pm/$\sqrt{\text{Hz}}$, a linearity of as high as 0.9994, and a dynamic range of 110dB@100Hz.

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