Ultrahigh Resolution Fiber Bragg Grating Sensors for Quasi-Static Crustal Deformation Measurement

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Abstract—Recently developed ultrahigh resolution optical fiber grating sensors provide powerful tools for crustal deformation monitoring thanks to their unique advantages such as high resolution, low cost, easy deployment, and capability of remote and multiplexed sensing. This paper reviews the development of several types of fiber-optic sensors with ultrahigh resolution in quasi-static domain, including a fiber Bragg grating sensor interrogated with a narrow-linewidth wavelength-sweeping laser, a fiber grating based Fabry–Perot interferometer sensor by using Pound–Drever–Hall technique, sensors interrogated with sideband interrogation method, and the realization of time division multiplexed ultrahigh resolution fiber sensors. The implementation of fiber grating sensors for in situ measurement of crustal deformation are also introduced.

Index Terms—Fiber Bragg grating, strain sensor, time division multiplexing, ultrahigh resolution.

I. INTRODUCTION

PRECISE measurement and modeling of crustal deformation in quasi-static domain allow us to probe the rheology of rocks deep in Earth, and the measurement involves extremely small strain variation with a rate of $10^{-12}$ s$^{-1}$ [1]. The Global Positioning System has shown its ability in measurement of surface motions over large area and longtime coverage. Meanwhile, to study geophysical phenomena such as movement of magma and slow earthquake dynamics requires monitoring the spatially-resolved and temporally-continuous crustal deformation information with high spatial resolution and fast time response [2], [3]. Conventional sensors for these purposes include extensometers and laser interferometers installed underground [4]–[6]. For example, a strain resolution of $4 \times 10^{-10}$ was achieved with laser interferometer in 800-m evacuated tube with heavy insulation from the surroundings and active temperature control [4]. Those types of sensors, however, are difficult to be widely installed due to their high cost and large size ranging from several tens to hundreds of meters in length. Moreover, because such sensors can only give integrated strain information over their lengths, no spatially resolved deformation information can be obtained.

On the other hand, fiber Bragg grating (FBG) strain sensors have well-known advantages such as small size, low cost, easy installation, high stability, and good linearity over a large strain range. Especially, they can be multiplexed for spatially resolved sensing. They have already been widely adopted in applications like smart materials and structural healthy monitoring. Naturally, they are also very attractive for geophysical applications if they can provide the required strain resolution in quasi-static domain.

Even though FBG sensors have realized even better than picostain (pc) resolution for dynamic strain sensing [7]–[12], the performance of conventional fiber sensors is not so satisfactory for quasi-static strain measurement. A quasi-static strain signal exhibits as a random arbitrary signal in a given observation period, and environmental disturbance such as temperature variation is also in the quasi-static region. To guarantee the long-time stability of a quasi-static strain sensor, an extra reference is required, making it more challenging than a dynamic sensor. The spectroscopic frequency associated with an atomic or molecular transition has been a popular reference for static strain sensing [13]–[15], but this type of reference cannot compensate the output drift of the sensor owing to environmental interference, and that it works only at a specific wavelength corresponding to the atomic or molecular transition also limits the dynamic range of the sensor. In contrast, a strain-isolated FBG with the same temperature sensitivity as the sensing head, the FBG for sensing, is an ideal reference to compensate the long-term drift of both laser source and the sensor head, if the FBGs for sensing and reference are under exactly the same temperature [16]. Fortunately, the variance of crustal temperature is very slow within a small range, and the temperature difference between the sensing and reference FBGs can be ignored if they are carefully installed with proper packaging.

In this paper, we review the recent researches on FBG based quasi-static strain sensors for crustal deformation measurement, including an FBG sensor interrogated with a narrow-linewidth wavelength-sweeping laser, an FBG based Fabry–Perot interferometer sensor by using the Pound–Drever–Hall (PDH) technique, sensors interrogated with sideband interrogation method, and the realization of time-division multiplexed ultrahigh

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resolution fiber sensors. With the proposed sensors, the crustal strain caused by ocean tide was clearly observed at Aburatsubo Bay, Japan, and the seismic waves were also recorded. Those work show that ultrahigh resolution FBG sensors have great potential as powerful tools for geophysical science.

II. PRINCIPLE OF FBG SENSORS

FBGs are fabricated by introducing periodic variations in the refractive index of the core of an optical fiber [17]. Fig. 1(a) shows the internal structure of an optical fiber with a grating written inside. When lightweight propagates through the grating, at a particular wavelength named Bragg wavelength $\lambda_B$, reflected lightwave at different position will be in phase and enhanced. The Bragg wavelength $\lambda_B$ is given as [18]:

$$\lambda_B = 2n_{\text{eff}} \Lambda$$  

(1)

where $n_{\text{eff}}$ is the effective index of refraction of the FBG, and $\Lambda$ is the grating period. When the FBG experiences a strain or temperature change, the Bragg wavelength $\lambda_B$ will shift accordingly. The relative change in Bragg wavelength is expressed as:

$$\Delta \lambda_B / \lambda_B = (\alpha + \xi) \Delta T + (1 - p_e) \varepsilon$$  

(2)

where $\Delta T$ is the temperature change, $\varepsilon$ the longitudinal strain, $\alpha$ the thermal expansion coefficient, $\xi$ the thermo-optic coefficient, and $p_e$ the effective elasto-optic constant of the fiber material, respectively. Equation (2) shows that the Bragg wavelength is sensitive to both strain and temperature linearly.

An FBG sensor consists of both the FBG as sensing head and the interrogation system. The typical configuration of an FBG sensor is shown in Fig. 1(b). The lightweight from the source is partly reflected by the FBG, and then demodulated to obtain the Bragg wavelength shift of the FBG, hence getting the information of strain/temperature. The resolution of strain/temperature is determined by the interrogation method, or in other words, the precision in the measurement of the Bragg wavelength shift of the FBG. Although broadband sources have been widely adopted for FBG sensors [19], this type of source is not suitable for high resolution applications. Due to the limited power spectrum density of broadband source, there is a trade-off between narrow bandwidth and high optical power of the reflected lightwave of the FBG. Up to date, all the ultrahigh resolution strain sensors are based on narrow linewidth laser sources.

Assuming a linearized reflection curve of the FBG, the reflected power is a linear function of the Bragg wavelength shift of FBG when the FBG is interrogated using a narrow-linewidth frequency-locked laser. With frequency-locked laser, a strain sensitivity of 1.2 $\text{nm}$ at 1.5 Hz is achieved by directly measuring the reflected optical power [13]. To suppress the influence of the power fluctuation of the laser source, PDH readout scheme is employed in Ref. [15] with a gas absorption line for reference, resulting in a strain resolution of $6 \text{pm}$ at 10 Hz and $2 \text{pm}$ down to 0.01 Hz. Since the strain resolution is directly related with the linewidth of the laser, even higher resolution of $350 \text{fs}$ at 5 Hz was reported by stabilizing a diode-laser against a quartz-disciplined optical frequency comb [20]. The measurement range of the sensors with frequency-locked laser, however, is limited by the linear range of the response curve, either the spectrum of FBG or the PDH readout signal. Using an FBG with a moderate reflection slope can extend the measurement range, but the cost is strain resolution degeneration.

Since the quasi-static strain measurement involves interrogation of both the sensor head and reference element and comparing their frequency difference, an alternative method is to detect the frequency difference directly. The measurement range is no longer restricted by the linear range of response curve. To do so, the grating sensor head and reference element can either be sequentially interrogated by a narrow-linewidth wavelength-sweeping laser, or simultaneously interrogated by two different laser beams. In our recent work, a series of fiber grating interrogation techniques with ultrahigh resolution in quasi-static domain have been developed, and they are introduced in the following sections.

III. FBG SENSORS WITH ULTRAHIGH RESOLUTION

Since quasi-static strain measurement involves interrogation of both the FBG sensor head and reference element, a narrow-linewidth wavelength-sweeping laser can be used to get the spectra of both the sensor head and reference elements, with a high resolution and large measurement range.

A. Direct Spectrum Detection

The typical configuration of the FBG sensor system is shown in Fig. 2. The system consists of a pair of identical FBGs; one is for the sensing of strain and the other is strain-free working as a reference. The two FBGs are close mounted to experience the same temperature change. As a result, the relative Bragg wave-
length change indicates the strain information on the sensing FBG. A narrow-linewidth wavelength-sweeping laser is used to interrogate the FBGs, and the lightwave reflected from the FBGs is detected by photodetectors. While the wavelength of the tunable laser sweeps over the principal peaks of the FBGs' reflective spectra, their reflectivity are sampled at a discrete sequence of wavelengths $\lambda_i$ with a step of $d\lambda$. The reflectivity of the sensing FBG is labeled as $R(\lambda_i)$, while the reflectivity of the reference FBG is labeled as $R_R(\lambda_i)$.

Assuming the two FBGs have the same shape spectrum when the sensing FBG experiences strain variation, which is widely accepted, the reflectivity satisfies:

$$R_R(\lambda_i) = R(\lambda_i + \Delta \lambda) = R(\lambda_{i+\delta})$$  

(3)

where $\Delta \lambda$ is the wavelength shift caused by strain, and $\delta = \Delta \lambda/d\lambda$ is the corresponding index shift. A cross-correlation algorithm can be used to demodulate the differential wavelength shift $\Delta \lambda$ from the measured spectra between the reference FBG and the sensing FBG, because this algorithm is proved to have very good resolution compared with other algorithms such as the centroid detection algorithm and the least square fitting algorithm [21], [22]. The cross-correlation product is:

$$C(\delta) = \sum_{i=-N}^{N} R(\lambda_{i+j}) R_R(\lambda_{i+\delta}).$$  

(4)

In (4), it is assumed that both $R(\lambda_i)$ and $R_R(\lambda_{i+\delta})$ are zero if the indices lie outside their ranges. This assumption is acceptable as long as the sampling range covers the whole principal peaks of both FBGs. $C(\delta)$ has the maximum at $\delta = \delta_0$, where the two spectra overlap completely, so $\delta$ is demodulated from the index when $C(\delta)$ is at its maximum. Although the index of maximum $C(\delta)$ falls into an integer which is the nearest to $\delta$, $\delta$ can be precisely calculated either by interpolation or by curve-fitting around the maximum.

Due to the random errors in the measured reflectivity, the retrieved $\delta$ deviates from the actual strain, and the deviation range is the resolution of the sensor. There are two main origins of the random errors in measured reflectivity: one is the intensity noise of the photodetector as well as the laser, and the other is laser wavelength repeatability, as shown in Fig. 3.

The intensity noise in the measurement of optical power includes the shot noise of the light, the noise of the photodetector, and the quantization noise in the A/D convert process. The wavelength repeatability is the random uncertainty of the measured wavelength in repeating sweeps. The uncertainty of the measured wavelength can be converted into an error in reflectivity, and the converting coefficient is the differential of the FBG’s spectrum.

Because of the random noise described above, the measured spectrum is actually the sum of real spectrum $R(\lambda_i)$ and the random noise $N(\lambda_i)$. The correlation product is then modified to be:

$$C' (\delta) = \sum_{i=-N}^{N} R(\lambda_{i+j}) R(\lambda_i) + \sqrt{2} \sum_{i=-N}^{N} R(\lambda_{i+j}) N(\lambda_i)$$  

$$= C_R(\delta) + C_N(\delta).$$  

(5)

Here the sum of random noise is written as $\sqrt{2} N(\lambda)$ because they are independent, and $\delta = 0$ is assumed to simplify the analysis without any influence on the resolution. The first term $C_R(\delta)$ in (5) is the auto-correlation curve of the real spectrum without noise, as shown in Fig. 4 (the black dashed line). It has a peak (labeled $P$ in the figure) at $j = 0$ and declines when $j$ diverges from 0. The second term $C_N(\delta)$ is the cross-correlation term of the real spectrum and the random noise. It makes the actual cross-correlation curve $C'(\delta)$ fluctuate, and one example of $C'(\delta)$ is shown as the red line in Fig. 4. Because only the relative amplitude is concerned with the position of the maximum, $C'(\delta)$ can be vertically shifted to pass through point $P$ to simply analysis, as shown as the dashed red line in Fig. 4.

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Due to the random noise, the shifted cross-correlation curve deviates from the auto-correlation curve. The deviation is a function of the index $j$:

$$\Delta_N(\lambda_j) = \sum_{i=-N}^{N} \sqrt{2} R(\lambda_{i+j}) N(\lambda_i) - \sum_{i=-N}^{N} \sqrt{2} R(\lambda_{i-j}) N(\lambda_i)$$  

$$= \Delta_{N,elec}(\lambda_j) + \Delta_{N,\lambda}(\lambda_j).$$  

(6)

Here $\Delta_{N,elec}$ and $\Delta_{N,\lambda}$ are the noise terms caused by the relative intensity noise and the wavelength inaccuracy, respectively. The mathematical expectation of $\Delta_N$ is zero, and its standard deviation is:

$$\sigma(\Delta_N) = \sqrt{\sigma^2(\Delta_{N,elec}) + \sigma^2(\Delta_{N,\lambda})}.$$  

(7)

The gray zone in Fig. 4 illustrates the fluctuation range of the shifted cross-correlation curve due to noises. The index $j$ of the maximum $C'$ indicts the detected strain, which deviates from zero due to noises, and it satisfies:

$$C_R(\delta) + \frac{\sigma(\Delta_N(\lambda_j))}{2} \geq C_R(\delta).$$  

(8)
The factor of 1/2 in (8) is because only the positive $\Delta \lambda (j)$ causes the peak deviating from $j = 0$ while the negative value does not. Once the expressions of $C_R(j)$ and $\sigma (\Delta \lambda (j))$ are obtained, the wavelength resolution can be calculated from (8).

For FBGs with smooth spectrum profile, the resolution of the sensor is deduced [21] after proper numerical approximation:

$$\lambda_R = \sqrt{\Delta \lambda} \cdot \sqrt{0.80 \cdot \lambda_{\text{width}} \cdot \sigma^2 (\Delta R_{\text{elec}}) + 1.75 \cdot \sigma^2 (\delta \lambda) / \lambda_{\text{width}}}$$

where $\lambda_R$ is the wavelength resolution of the sensor, $\Delta \lambda$ the wavelength sweep step of the laser, $\sigma (\Delta R)$ the standard deviation of the relative intensity noise, $\sigma (\delta \lambda)$ the standard deviation of wavelength accuracy, respectively. From the wavelength resolution, the strain resolution can be simply deduced by the strain-wavelength coefficient of FBG, which is about 1.2 pm/mm.

According to (9), the optimized bandwidth of FBG is determined by the wavelength accuracy of the laser and the relative intensity noise of the photodetectors:

$$\lambda_{\text{width, opt}} = \frac{1.48 \sigma (\delta \lambda)}{\sigma (\Delta R_{\text{elec}})}.$$  

Equations (9)-(11) give the guidelines to achieve ultra-high resolution for narrow-linewidth wavelength-sweeping laser based FBG sensors. It also predicts the achievable resolution with the given devices, agreeing well with previous experimental results [21].

B. Interrogation of FFPI Sensor with PDH Technique

According to the analysis on the resolution of FBG sensors, the laser’s wavelength repeatability during sweeping has considerable influence on the strain resolution of the sensor. The bandwidth of a practical FBG ranges from tens to hundreds of pm, and the wavelength-sweeping laser has to cover the spectra of both the FBG for strain sensing and the FBG for reference, requiring a large tunable range up to several nm. Further improvement of the laser wavelength repeatability is very difficult for lasers with such a large tunable range. The Bragg grating based fiber Fabry–Perot interferometers (FFPI) is potential candidate for the sensor head because of its extremely narrow resonance bandwidth [23].

The FFPI is formed by placing two identical high reflection FBGs in one fiber. It has the same strain/temperature sensitivity as the FBG, while it has a series of resonances with bandwidth on the order of MHz, much narrower than that of FBG’s. Furthermore, to suppress the intensity noises in interrogation of FFPI, PDH technique is employed.

The principle of PDH technique [24], [25] is shown in Fig. 5. The lightwave from the laser source is phase-modulated with a phase modulator (PM) driven by a sinusoidal waveform, and thus two groups of sidebands (the 1st order sidebands usually play the dominant role) are generated besides the carrier. When these lightwaves are reflected by an FFPI, they experience different amplitude reflections and additional phase shifts, causing an intensity modulation in the reflected lightwave. By demodulation of this intensity modulation with a multiplier (Mul) and a low pass filter (LPF), an output signal, i.e., the PDH signal is obtained, which is a function of the frequency deviation between the laser and the resonance of FFPI. The PDH signal is immune to the intensity fluctuation of the laser source and the residual reflection from fiber components along the lightwave path.

The schematic configuration of the proposed FFPI sensor is shown in Fig. 6. It consists of a pair of identical FFPIs; one is for the sensing of strain, and the other is strain-free working as a reference and a temperature sensor. Each FFPI, fabricated by Fujikura Ltd., is formed by writing two identical FBGs 20-cm distant in a single mode fiber. The parameters of the FBGs are: nominal center wavelength 1549.85 ± 0.04 nm, high reflection spectrum range 0.25 nm, and peak reflectivity 99.5%. The free spectral range (FSR) and the bandwidth of the FFPIs are 4.1 pm and 0.9 MHz, respectively. A narrow linewidth tunable fiber laser (NKT, E15) is used to interrogate the FFPIs with the PDH technique, and the...
output signal after demodulation is a function of the frequency deviation between the laser and the resonance of the FFPI.

In experiments, both FFPIs are strain-free packaged to ascertain the performance of the interrogation system. The laser wavelength sweeps within the overlapped high reflection region of the FFPIs. The tunable range is 5 pm, larger than the FSR of the FFPI to necessarily reveal at least one complete resonance peak for both FFPIs. A group of typical demodulated PDH signals during one wavelength sweep are shown in Fig. 7(a). Due to the existence of two polarization-mode in the FFPI, the strong PDH signal is companied with a residual signal for each FFPI even after polarization controlling. This residual signal is digitally removed during data procession, and this problem can be completely solved if polarization maintaining fiber (PMF) based FFPIs are used.

The cross-correlation algorithm is employed to extract the resonance frequency difference from the two demodulated resonance curves to get the strain information, as shown in Fig. 7(b). Once the PDH signals for the two FFPIs are obtained after one sweep of the laser, the cross-correlation product of the first pair of complete resonance peaks is calculated, and the index of maximum indicates the resonance difference between the two FFPIs. The evolution of the resonance difference between the two FFPIs against time is monitored and logged 2 times per minute. Fig. 8(a) plots the detected resonance wavelengths of both FFPIs, and the extracted resonance difference between the two FFPIs is shown in Fig. 8(b). The jump in the figures indicates the resonance mode switch due to the resonance frequencies slipping caused by environmental temperature change. The amplitude of the jump exactly equals to the FSR of FFPIs. Since the FSR can be precisely measured, and the direction of the resonances’ slip is logged, the jump can be removed in data processing. As a result, this sensing system has very large dynamic range of hundreds of $\mu\varepsilon$, as long as the high reflection ranges of both the FFPIs remain overlapped portion under applied strain. Irrespective of the resonance mode switch, the standard deviation of the measured resonance difference between the two FFPIs is 5.4 fm after temperature compensation, corresponding to a strain resolution of 4.5 n$\varepsilon$ with a strain sensitivity of 1.2 pm/$\mu\varepsilon$.

Since only a small tunable range is required for the FFPI based quasi-static strain sensor, narrow-linewidth laser with external frequency modulation can also be used as the laser source. In Ref. [26], a single sideband modulator is employed to perform the wavelength sweep with excellent linearity, and a strain resolution up to 0.67 n$\varepsilon$ was realized in laboratory with this configuration.

C. Simultaneous Interrogation With Sideband Interrogation Technique

For the laser wavelength-sweeping based fiber gratings sensors as mentioned above, the tunable range of laser must be large enough to cover the resonances of both the sensing and reference gratings, and the large tuning range restricts the measuring rate of the sensor. To avoid the large wavelength sweeping range, a sideband interrogation technique was proposed to interrogate the sensing and reference elements simultaneously with very small tunable range [27]. Furthermore, the laser sweeping can be avoided when the sideband interrogation technique is combined with feedback control loops [28].

The schematic setup of the sensor system is shown in Fig. 9. A pair of identical FFPIs are used as the sensing and reference elements, similar to the sensor head in previous section. The lightwave from a narrow linewidth laser source is split into two paths to interrogate the two FFPIs respectively. The reference FFPI is interrogated with one path of lightwave by using PDH.
where $\omega$ is the initial lightwave frequency (the carrier frequency), $\Omega_M$ is the RF signal frequency, $\beta$ is the maximum phase shift of the PM, and $J_1(\beta)$ is the first order Bessel coefficient. High harmonics are omitted here because their response in demodulation is similar in shape but weak in amplitude compared with the first order sidebands. When the modulated lightwave is reflected by the reference FFPI, the three components experience different amplitude reflections and additional phase delays respectively, which cause an intensity modulation on the reflected lightwave. By demodulating this intensity-modulated lightwave the PDH signal is obtained.

On the other hand, the sensing FFPI is interrogated by the other path of light modulated with an intensity modulator (IM) driven by the sum of three RF signals as following:

$$F(t) = \cos(\Omega_S t) + \cos(\Omega_M t) - \cos(\Omega_S t - \Omega_M t)$$

(13)

where $\Omega_S$ is radio frequency which is much larger than $\Omega_M$. After the intensity modulation, the lightwave has the form of:

$$\exp(\imath \omega t) [1 + kF(t)]$$

$$= A \exp(\imath \omega t)$$

$$+ 0.5k \exp(\imath (\omega + \Omega_S) t) \times [1 + \exp(\imath \Omega_M t) - \exp(-\imath \Omega_M t)]$$

$$+ 0.5k \exp(\imath (\omega - \Omega_S) t) \times [1 - \exp(\imath \Omega_M t) + \exp(-\imath \Omega_M t)]$$

(14)

where $k$ is the intensity modulation depth of the IM. Besides of the carrier, two groups of sidebands appear in (13). Each group of sidebands has similar form as (11) with the same modulation frequency of $\Omega_M$, but their center frequencies are shifted from the carrier by $\Omega_S$. This characteristic enables us to utilize one group of the sidebands to interrogate the sensing FFPI, which has a resonance frequency different from the carrier frequency. The demodulation for the sensing FFPI is exactly the same as that for the reference FFPI.

In one measurement, the frequency of the narrow linewidth laser source is tuned to sweep around a resonance frequency of the reference FFPI, as the PM light shown in Fig. 10. Meanwhile, $\Omega_S$ is adjusted to approximate the resonance frequency difference between the two FFPIs. When the laser frequency is swept around the resonance of the reference FFPI, one group of sidebands is shifted to sweep around the resonance frequency of the sensing FFPI simultaneously, as the IM light shown in Fig. 10. The beams reflected by the FFPIs are demodulated respectively to extract output signals. During one wavelength sweep of the laser, the demodulated signals from the two FFPIs are similar in shape but staggered in horizontal position.

Then a cross-correlation algorithm is employed to calculate the frequency difference between the demodulated signals.

The other group of sideband has no interference in the demodulation, as long as its frequency is far away from any resonance frequency of the sensing FFPI. With this configuration the dynamic range of the sensor is about half of the FSR of the sensing FFPI. A further improvement of the configuration is to replace the sensing FFPI with a PMF based $\pi$-phase-shifted FBG, which has unique resonance frequency. In this case the interference of the other sideband is avoided and larger dynamic range can be achieved [29].

In laboratory experiments, both FFPIs are placed under strain-free condition to ascertain the performance of the sensor system. A fiber laser (NKT, E15, linewidth 1 kHz) with integrated piezo tuner is used as the light source. The frequency of the laser is finely tuned via a piezo-driver (PI, E-625) directly controlled by a computer. The laser frequency sweeping speed is 37 MHz/s and the sweeping range is only 46 MHz, a little larger than the resonance bandwidth of the FFPI but much smaller than the FSR. The PM is driven by a 2-MHz RF signal from FG1 (NI, PXI-5421). In this experiment $\Omega_S$ was set to 67 MHz, and the IM is driven by the sum of three RF signals with frequencies of 65 MHz, 67 MHz and 69 MHz from FG2 to FG4 (NI, PXI-5422), respectively. All the 4 FGs are synchronized to maintain the frequency and phase relationship of the RF signals. Since two groups of resonance modes exist for each FFPI due to polarization modes in the SMF, a polarization controller (PC) is used to suppress the unwanted group of resonance modes. The lightwaves reflected by the FFPIs are detected by high speed photodetectors (New Focus, 2503) via circulators. The outputs of photodetectors together with the driving signal for PM are sampled by a high speed analog to digital convertor (NI, 5761R) and then processed in digital domain. A field programmable gate array (FPGA) module (NI, PXI-7965R) is employed to assist data processing for enhancing the speed. Compared with analog circuits, the digital processing has smaller low frequency noise, finer control of the phase match for demodulation and more flexible design of the low pass filter.

The extracted frequency difference from the demodulated signals over 2 hours is shown in Fig. 11. The fluctuation range (standard deviation) is 94 kHz, which determines the frequency resolution of the sensor system. The strain sensitivity of the
FFPIs is tested to be 116 MHz/με; thus, a corresponding strain resolution of 0.8 με is achievable with the sensor system, if the sensor head is designed properly.

The realization of the sub-με static strain resolution is based on the precise measurement of the resonance frequency difference between the two FFPIs. First, the resonance difference is approximately compensated by the frequency of accurately generated sideband. Then, the residual difference between the resonance frequencies is precisely measured with the RF demodulation technique and the cross-correlation algorithm. By replacing the sensing FFPI with a π-phase-shifted FBG, and adjusting the Ωs to track the variation in resonance frequency difference, large dynamic range is expectable without resolution degradation.

D. Sideband Interrogation With Dual Feedback Loops

For the wavelength-sweeping based fiber grating sensor, the measurement speed is mainly limited by the sweeping speed of the laser. In addition, the nonlinearity of the frequency sweeping also reduces the strain resolution of the sensor [21]. Since the PDH signal is proportional to the frequency deviation between the laser and the FFPI resonance frequency around the resonance bandwidth, and it crosses zero if the laser frequency exactly lies on the resonance frequency, the PDH signal can be used as an error signal to lock the laser to the resonance. By respectively locking the carrier and one sideband to the sensing and reference FFPIs with two individual feedback loops, the resonance frequency difference can be retrieved from the modulation frequency of the sideband with a quick sensing speed and high resolution [28].

In the sensor configuration, a piece of π-phase-shifted FBG (π-PSFBG) on PMF is used as the sensing element. The π-PSFBG is a type of FBG with a phase shift of π introduced in the middle of grating, which results in a narrow transmission at the center of the high-reflection spectrum. An FFPI based on the same type of PMF works as the reference. Both the π-PSFBG and the FFPI have the same strain/temperature sensitivity as ordinary FBGs.

A phase-modulated narrow-linewidth lightwave is used to interrogate the FFPI using the PDH technique, as shown in Fig. 12(a). The FFPI has many transmission peaks (resonance references) within a broad frequency range, and the transmission peak near the π-PSFBG resonance frequency is selected for interrogation. The frequency of phase modulation is much smaller than the FSR of the FFPI, so the rest of transmission peaks do not respond to the probe lightwave. The extracted signal by PDH technique indicates the frequency mismatch between the laser frequency and the selected resonance frequency of the FFPI, and it is then used as the error signal to lock the laser to the selected resonance frequency.

In the other path, the phase-modulated narrow-linewidth lightwave is then intensity modulated by an IM for the interrogation of the π-PSFBG. The intensity modulation spectrum of π-PSFBG is flat except for a single narrow transmission peak within its high reflection band. Therefore, when the selected 1st order sideband is aligned to the narrow transmission peak via a feedback loop, the other frequency components (the carrier, the symmetrical 1st order sideband and high-order sidebands) will have no influence on the extracted PDH signal from the selected 1st sideband.

When the laser carrier and one 1st sideband are locked to the reference FFPI and sensing π-PSFBG with two individual feedback control loops, the resonance frequency difference between the FFPI and π-PSFBG will be exactly the frequency difference between the laser carrier and sideband, i.e. the frequency of intensity modulation. When temperature fluctuation occurs, the spectra of both the FFPI and π-PSFBG will shift with the same amount, so the temperature fluctuation induced adjustment of the reference loop does not affect the sensing feedback loop.

On the other hand, if the strain applied to the π-PSFBG varies, its transmission peak will shift correspondingly. The sensing feedback loop adjusts the intensity modulation frequency to align the 1st sideband to the π-PSFBG resonance frequency. This modulation frequency adjustment does not affect the laser frequency, so the sensing feedback loop does not interfere with the reference feedback loop. The two feedback loops operate at a relatively fast speed, making sure that the laser and the sideband are separately aligned to the transmission peaks of the FFPI and π-PSFBG. The intensity modulation frequency is
Fig. 13. System configuration for dual feedback; VCO: voltage-controlled oscillator (from Ref. [28]).

The measured power density spectra of the three strain signals with different frequencies are shown in Fig. 14. The narrow peaks at 1 Hz, 10 Hz, and 100 Hz in each curve correspond to the applied strain signals. The amplitudes of the peaks are in good agreement with the applied strain, indicating that the sensor system has flat response in this frequency range. Considering the 20 kHz operating frequency of the feedback loops, the sensor could have a frequency range up to several kilohertz by using a quicker RF counter. The noise power density from 0.01 to 250 Hz band is also given in the figure. The noise behaves a 1/f distribution below 30 Hz, and the strain resolution at 10 Hz is about $10^{-11} \cdot \varepsilon/\text{Hz}^{1/2}$. For the frequency above 30 Hz, the noise power density generally reaches an upper bound of $10^{-12} \cdot \varepsilon/\text{Hz}^{1/2}$ except for several noise peaks.

The tuning range of the VCO is 1 GHz (from 1.0 GHz to 2.0 GHz), so the direct measuring strain range of the proposed sensor is about 7 $\mu$ε. However, the reference FFPI has a series of resonance frequencies with constant frequency interval (FSR) of the FFPI. When the transmission peak of the sensing $\pi$-PSFBG is shifted beyond the 1–2 GHz range due to strain variance, the sensor can automatically select a nearby resonance of the FFPI as the reference. The strain is then calculated from the frequency of the VCO with an offset of the FSR. In this configuration, the measurement range can be up to 300 $\mu$ε, mainly limited by the working bandwidth of the FFPI (about 0.3 nm). Considering the strain resolution of 0.01 $\mu$ε, the dynamic range of the sensor is up to 149 dB at 10 Hz.

IV. MULTIPLEXED HIGH RESOLUTION SENSORS

In order to obtain the full information of the geological tectonic process, dense array of strain sensors is required for the measurement of strain field and strain tensor. Multiplexed strain sensors can greatly reduce the cost of the system. Generally, the multiplexing techniques of ultrahigh resolution fiber grating sensors mainly include the wavelength-division multiplexing (WDM) technique, and the time-division multiplexing (TDM) technique. The fiber grating sensors using broadband light sources are inherently compatible with the WDM technique, but they can’t realize the required strain resolution. Using a narrow-linewidth wavelength-sweeping laser, the fiber gratings sensors...
Fig. 15. The TDM scheme. (a) The incident pulse is reflected by \( \pi \)-PSFBGs respectively, which forms a train of pulses without overlap. (b) The interrogation system. AOM: acousto-optic modulator; and PCs: polarization controllers.

with different wavelength can be interrogated, and the capability of multiplexing is proportional to the tunable range of laser [30]. However, the linewidth-laser with large tuning range is very expensive, and the sweeping repetition rate limits the sensing rate to several samples per second or even lower. Pico-strain FBG sensor array with WDM was reported [31], in which each sensing channel includes an independent laser, photodetector and other attachments for frequency locking. Actually, the same WDM method can be applied to the single-channel ultrahigh resolution FBG sensors by using individual laser for each sensor head with proper wavelength interval. The disadvantage is the cost and complexity, which increases linearly with the scale of the sensor array, restricting the practicality of such schemes.

Based on the PDH technique and sideband interrogation method, recently the TDM technique is adopted to realize multiplexed sensing with ultrahigh resolution [32]. All the sensing channels have similar parameters, and share the same laser and photodetector to reduce the total cost of the sensor.

The principle of TDM is shown in Fig. 15(a). A group of \( \pi \)-PSFBGs with the same nominal wavelength are used as the sensor heads. They are connected to one fiber coupler in parallel with different fiber delay lines. The probe lightwave is cut into pulses by a modulator. When the pulse incidents to the optical fiber coupler, each \( \pi \)-PSFBG reflects the pulse with different time delay due to the different optical path lengths, and a pulse train without overlap could be received by the photodetector.

The systemic configuration is shown in Fig. 15(b). A narrow-linewidth fiber laser generates the lightwave with constant frequency and power. A PM driven by a 10-MHz sinusoidal signal is used for frequency mismatch discrimination as in the PDH technique. After the PM, an IM driven by an RF signal generator is employed to generate the sideband. Then, an acousto-optic modulator (AOM) driven by a pulse generator cuts the modulated laser into pulses for TDM. The \( \pi \)-PSFBG array consists of 4 \( \pi \)-PSFBGs, 4 polarization controllers (PCs), and 3 fiber rolls with different lengths.

Fig. 16. Experimental results. (a) Testing states for the \( \pi \)-PSFBG. (b) The power density spectra (partly from Ref. [32]).

The \( \pi \)-PSFBGs are interrogated in turn, and one incident pulse interrogates a certain \( \pi \)-PSFBG only. When a certain \( \pi \)-PSFBG is under detection, only the corresponding segment of reflected lightwave is taken out according to the fiber roll introduced time delay and the incident pulse duration. The demodulation of the segment is the same as the typical PDH technique, and the output signal indicates the frequency mismatch between the \( \pi \)-PSFBG and the sideband. In one sensing cycle, a group of frequency mismatches is recorded, and they are used to adjust the sideband frequencies for next sensing cycle. For each \( \pi \)-PSFBG sensor, an individual feedback control process ensures that the corresponding sideband is locked on its resonance.

In the experiment, one of the \( \pi \)-PSFBG (the #4 \( \pi \)-PSFBG) is used as the reference for temperature compensation, and the other 3 \( \pi \)-PSFBGs work as strain sensors, as shown in Fig. 16(a). A 1 Hz, 45 n\( \varepsilon \) sinusoidal strain is applied to #3 \( \pi \)-PSFBG by a nano-positioning stage, while constant strain is applied to \( \pi \)-PSFBG #1 and #2.

The power density spectra of the strain signals for the sensing \( \pi \)-PSFBGs are shown in Fig. 16(b). A sharp peak at 1 Hz appears in the frequency domain curve of channel 3, which agrees well with the calibration signal. In frequency higher than 0.1 Hz region, the noise power densities of all the three sensing channels have an upper bound of 0.8 n\( \varepsilon \)/Hz\(^{1/2}\), corresponding to a strain resolution result better than 0.8 n\( \varepsilon \) in the 0.1 Hz to 50 Hz band. At frequencies lower than 0.1 Hz, the power density of each channel is still in the n\( \varepsilon \) scale.

The sensor array can be easily expanded by inserting additional \( \pi \)-PSFBGs, couplers and delay fiber rolls. The optical power loss caused by the couplers can be compensated by adding an amplifier before the photodetector. Thanks to the sweeping-free structure and the quick tuning speed of the RF
Field experiments of the ultrahigh resolution FBG sensors were carried out at the Aburatsubo Crustal Deformation Observatory, Earthquake Research Institute, The University of Tokyo. As shown in Fig. 17, the observatory locates at the tip of the Miura Peninsula, about 60 km southwest to Tokyo, Japan.

In the field experiments, one vault with several sections is previously built on the coast. Extensometers with length of 38 m are set in one of the sections for crustal deformation measurement. The fiber grating strain sensors are installed in another section (Sect. B in the figure). When the ocean tide level varies, the pressure applied to sea bottom changes accordingly, resulting in the deformation of rock mass. This phenomenon provides a good reference load to verify the performance of the fiber sensors.

### V. Field Experiments

Field experiments of the ultrahigh resolution FBG sensors were mounted inside Section B of the vault in 2010. The nominal Bragg wavelengths are 1535 nm and 1555 nm for the FBGs in the two units (No. 1 and No. 2), respectively. All of the four FBGs have bandwidth of 0.22 ± 0.02 nm. Each sensor unit consists of a commercially available FBG strain gauge (Micron Optics, os3600) and a reference FBG (fabricated by Fujikura Ltd.). The 1-m long os3600 is mounted between two steel anchors fixed about 30-cm deep into the rock bed. The reference FBG is strain-free to distinguish the slowly varying strain signal from environmental disturbance such as thermal drift.

As illustrated in Fig. 18, a narrow linewidth laser scans the two sets of sensor units sequentially using WDM technique. The whole sensor system was controlled by a LabVIEW program running on a personal computer. Continuous strain measurement can be performed for several months without maintenance. Part of the in situ experimental results over one week (June 6–13, 2011) is shown in Fig. 19.

Fig. 19(a) and (b) illustrates the oceanic tide level and the measured strain by FBG sensors, respectively. The measured strains by FBGs have similar shape to the oceanic tide level, showing that the oceanic tide induced crustal deformation is clearly observed. The different amplitudes between the two sets of FBG sensors in Fig. 19(b) probably reflect differences in deformation at the FBG mounting locations. If so, the results suggest the feasibility of measuring the distribution of rock mass deformation with high spatial resolution and low cost.

### A. Measurement With Tunable Laser Based FBG Sensor

In the first experiment, a narrow-linewidth wavelength-sweeping laser based FBG sensor is used for the crustal deformation measurement. The system configuration is shown in Fig. 18. It is very similar to the configuration in Fig. 2, except that two sets of FBG sensors are installed and interrogated via WDM [30]. Each sensor consists of a pair of similar FBGs with the same nominal Bragg wavelength for sensing and reference, respectively. The sensing FBG is mounted on the rock bed, and the reference FBG is strain-free, working as reference to distinguish the slow varying strain signal for the environmental noises such as temperature drift, affecting both the laser source and the sensor head. The fiber grating sensors are mounted in enclosure vault underground with very slow thermal variation (<0.5 °C/year), and the sensing and reference FBGs are places close to each other, so that they always experience the same temperature.

The wavelength of the narrow linewidth tunable laser sweeps to interrogation the spectra of the FBGs. A polarization scrambler (PS) is employed to eliminate the influence of polarization instability. About 10% of the power from the laser source is diverted by a coupler (CP1) as a power reference for ratio power detection to eliminate the source power variation during the wavelength sweeping. For either sensor unit, strain information is obtained from the Bragg wavelength difference between the spectra of the sensing and the reference FBGs. The two FBGs have similar spectra, especially the same nominal Bragg wavelength. With this configuration the sensor is immune to the long-term wavelength drift of the laser, and the influence of wavelength nonlinearity during laser wavelength sweeping is also eliminated. The maximum reflection of the FBGs is chosen around 70%, considering both bell-shaped spectral shape and high reflection.

The two FBG sensor units were mounted inside Section B of the vault. The measured strain information is slightly different between the extensometer and the FBG sensors due to their different mounting spots and methods, the data given by the extensometer can be used to evaluate the resolution of the FBG sensors. Fig. 19(d) plots the comparison of the measured strain given by FBG No. 2 over one day and that by the extensometer. The strain amplitude of extensometer is scaled by a factor of 2011) is shown in Fig. 19.

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Fig. 19(c) is the data from the 38-m-long extensometer. Although the measured strain information is slightly different between the extensometer and the FBG sensors due to their different mounting spots and methods, the data given by the extensometer can be used to evaluate the resolution of the FBG sensors. Fig. 19(d) plots the comparison of the measured strain given by FBG No. 2 over one day and that by the extensometer. The strain amplitude of extensometer is scaled by a factor of 0.76, and the offset is also adjusted for comparison. The measured strain by the FBG sensor fluctuates against that by the extensometer with a standard deviation of 9.8 με, showing that
a 10-με strain resolution is demonstrated. This is the first in situ measurement of 10-με static strain resolution with FBG sensors.

B. Measurement With Sideband Interrogation Technique

The tunable laser based FBG sensor was later replaced by the sideband interrogation technique based sensor for higher strain resolution and quick response in 2012. The interrogation setup is shown in Fig. 20. A π-phase shifted FBG on PMF is used as the sensing element, while a fiber ring on PMF is employed for reference. The fiber ring has a series of resonance frequencies like an FFPI, but it is simpler in structure and the working bandwidth is much larger. An improved sideband interrogation technique is proposed to measure the resonance frequency difference between the π-phase shifted FBG and the fiber ring [29].

The fiber ring resonator is interrogated with the PDH technique. The phase modulated lightwave is used to interrogate the fiber ring, and the returning lightwave is demodulated to extract the PDH signal digitally. Meanwhile, a branch of the modulated lightwave is intensity-modulated by an IM, which is driven at a radio frequency Ω. The intensity modulation generates two sidebands from the carrier, and both sidebands have the same pattern of phase modulation as the carrier, but with a frequency shift of Ω. Either of the sidebands can be used for the interrogation of the π-phase shifted FBG, just as the interrogation of the fiber ring. Compared with Ref. [27], this new configuration is more compact and only one radio frequency signal generator (RFSG) is required.

Fig. 21(a) illustrates the working principle of the sensor. First, the frequency of the narrow linewidth tunable laser source is tuned close to one resonance of the fiber ring, as the reference lightwave shown in Fig. 21(a). Meanwhile, one of the sidebands is set close to the resonance frequency of the π-phase shifted FBG by adjusting Ω. Next, the frequency of the narrow linewidth laser source is swept around the resonance of the fiber ring. At the same time, one sideband sweeps around the π-phase shifted FBG. Both the fiber ring resonator and the π-phase shifted FBG will produce a PDH signal respectively, as shown in Fig. 21(b). It should be pointed out that the carrier and other sidebands has no contribution in interrogation of the π-phase shifted FBG, because the corresponding PDH signal approach zero as long as they are far away from the resonance frequency of the π-phase shifted FBG. A cross-correlation algorithm is employed to calculate the frequency difference between the demodulated signals with high resolution, which has good capability to suppress random noise. The extracted frequency difference plus Ω is the actual resonance difference between the fiber ring and FBG, and this frequency is then used to adjust Ω for the next laser sweep.

With the above feedback controls, the center frequency of laser is locked to one resonance of the fiber ring, and one sideband is locked to the resonance frequency of the π-phase shifted FBG. The resonance difference between the fiber ring and the π-phase shifted FBG is exactly Ω. If a large strain is applied to the π-FBG, the center frequency of the laser can be locked to a different resonance frequency of the fiber ring, which is close to the resonance frequency of π-phase shifted FBG, so that the Ω is tuning within the available region of the RFSG. Since the fiber ring has constant resonance frequency interval of FSR, the real strain-induced resonance difference will be Ω + N×FSR, where N is the number of FSR corresponding to the reference resonance frequency change during the measurement. The measurable strain range of the proposed sensor is only limited by the tunable range of the laser.

During the in situ demonstration, two piers with distance of 1 m are inserted into the rock bed 30-cm deep and fixed. The π-
phase shifted FBG is mounted between the piers with pre-strain. A strain-isolated fiber ring is placed close to the \( \pi \)-phase shifted FBG. The vault is enclosed with very stable temperature and the strain measurement is unattended. A distributed feedback (DFB) diode laser is used as the laser source with frequency tuned via current. The frequency tuning range of the laser is about 1 GHz (\( \sim 8 \) pm), covering several FSR of the fiber ring. The PM is driven by a function generator (NI, 5412) with a frequency of 10 MHz, while the IM is driven by a radio frequency signal generator (NI, 5651). The reflected lightwaves are detected by high speed photo detectors (New Focus, 3503). The demodulation is achieved with a dual channel I/Q demodulator. Both the I and Q channels are sampled by a high speed analog-to-digital converter, and then the two channels combine to produce the PDH signal. The sensing speed is about 100 samples per second.

Fig. 22(a) shows the measured strain by \( \pi \)-phase shifted FBG and the oceanic tide level over one week during September 1–7, 2014. The oceanic tide level is sampled every 30 seconds. The strain of \( \pi \)-FBG is obtained by averaging the raw data to 1 sample per 10 seconds and the offset is adjusted for easier observation (the \( \pi \)-phase shifted FBG is tensioned with a large pre-strain for installation, so only the change of measured strain relates to the actual crustal deformation). The very similar shapes of the two curves show that the oceanic tide induced crustal deformation is clearly measured. Fig. 22(b) is the comparison of the measured strain by the \( \pi \)-phase shifted FBG and one nearby extensometer (Ext) with 38-m baseline. The two curves have different amplitude, which is caused by the different position and baseline length (the baseline of installed \( \pi \)-phase shifted FBG sensor is 1 meter). The extensometer can only provide the averaged strain over its length of baseline (38 m), while the \( \pi \)-FBG sensor provides the average strain over a distance of only 1 meter.

The length of baseline determines the spatial resolution of the strain sensor, which plays an important role in geophysical research. For example, as shown in Fig. 22(a), the measured strain by the \( \pi \)-FBG sensor has a phase shift compared with the tide level, while the two curves in Fig. 22(b) are almost in phase. The phase difference is relates with the propagation of crustal deformation in rock, which is an important issue in geophysical researches. The FBG strain sensor provides meter-order spatial resolution on the measurement of deformation distribution, which is almost impossible for traditional extensometers.

Seismic waves were also recorded thanks to the fast measurement speed of the sensor. Fig. 23 shows the raw data of the strain sensor around an earthquake (M3.9, at 23:48, March 17, 2015, JST) in Chiba, Japan. Traditional seismometers are based on acceleration measurement and can only record dynamic signals like seismic wave, while the \( \pi \)-phase shifted FBG sensor records both dynamic (seismic wave) and quasi-static (oceanic tide induced deformation) strain deformation. Here, the \( \pi \)-phase shifted FBG sensor shows the great potential of covering the whole frequency region that geophysical research involves.

VI. CONCLUSION

In this paper, we reviewed our recent work on the ultra-high resolution optical fiber strain sensors in quasi-static region. The resolution of FBG sensor interrogated by narrow linewidth tunable laser is theoretically analyzed, and the guidelines for the sensor design are discussed. FFPI and PDH technique are adopted for ultra-high resolution sensing. With the FFPI sensor interrogated by a sideband method, sub-nano order strain resolution is obtained based on wavelength sweeping. Both the strain resolution and measuring speed are markedly improved with a dual-feedback-loop configuration, and a strain resolution of \( 10^{-11} \) with dynamic range up to 149 dB is achieved at 10 Hz. With the proposed fiber grating sensors, crustal deformation and seismic wave were successfully recorded in field experiments with a strain resolution on the order of \( \pi \varepsilon \). Combined with the common advantages of fiber sensors, those work show that optical FBG sensors have great potential in applications of geophysical researches.
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