Fast and reliable interrogation of USFBG sensors based on MG-Y laser discrete wavelength channels

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Abstract

In this letter, we propose to use discrete wavelength channels of a single chip MG-Y laser to interrogate an ultra-short fiber Bragg grating with a wide Gaussian spectrum. The broadband Gaussian spectrum of USFBG is sampled by the wavelength channels of MG-Y laser, through which the center of the spectrum. The measurement inherits the important features of a common tunable laser interrogation technique, namely its high flexibility, natural insensitivity to intensity variations relative to common intensity-based approaches. While for traditional tunable laser methods, it requires to sweep the whole spectrum to obtain the center wavelength of the spectrum, for the proposed scheme, just a few discrete wavelength channels of laser are needed to be acquired, which leads to significant improvements of the efficiency and measurement speed. This reliable and low cost concept could offer the good foundation for USFBGs future applications in large scale distributed measurements, especially in time domain multiplexing scheme.

Keywords: Fiber sensor; Ultra-short FBG; interrogation.

1. Introduction

Ultra-Weak fiber Bragg grating (FBG) based quasi-distributed sensors have an important function in the large civil construction, the manufacturing industry, defense industry and so on [1-3]. The low reflectivity of the sensing FBGs, especially for a large-scale FBGs sensing network, is an essential feature which ensures a low crosstalk level among identical sensors in an array. Generally, the low reflectivity for an FBG, can be realized by a small perturbation to the effective refractive index or by using a short length of the grating. The ultra-short fiber Bragg grating (USFBG) is a type of weak FBGs with typical grating lengths scaled to only hundreds or even tens of microns with significantly broaden reflection spectra, typically several (or even tens of) nm [4]. However, due to their inherent broad spectra which are unfavorable for many spectral interrogation techniques, such USFBGs have rarely been used as sensors. Even so, several important advantages can be envisaged if USFBGs can be used as grating sensors, especially for distributed measurements [5]. Recently, we have introduced USFBGs potentials as weak sensing units and have demonstrated an identical USFBG based distributed microwave-photonic sensing system [6]. However, a major problem in the practical application is the complexity and, hence, expensiveness of the sensing system. Therefore, it is expedient to develop intensity-based approaches to the detection of FBG signals, which will substantially simplify the measurement system at the cost of a possible decrease in the measurement accuracy. One of the most successful FBG's signal tracking techniques with the greatest commercial success, is based on tunable lasers. The laser wavelength is swept continuously, and the reflected spectrum is measured using a high-speed photodiode so that the peak wavelength is estimated by fitting the measured reflected spectrum; since the output of the swept light source has a narrowband spectrum, it can take more advantage for long distance and multiplexing measurement than the method using a broadband source [7, 8]. However, this type of systems is inherently limited in its speed due to laser scanning rate and especially the data acquisition speed [9]. In this paper, we experimentally demonstrate a low cost and fast USFBG interrogation system by employing a single chip Modulated Grating Y-branch (MG-Y) as the light source. Based on high speed electronic tuning control of the laser lines, our proposed system avoids the need for a tunable laser light source, standard continuous sweeping through the entire spectrum, and all the associated limitations, such as ultra-high sampling requirements, and can relieve the cost of the interrogation system. The sensor measurement range can be largely extended by simply increasing the number of wavelength channels and scheme takes advantage of the intensity modulation of narrow spectral bandwidth light.

2. Ultra-short FBGs interrogation principle

FBG is a special Bragg grating photo-imprinted within the optical fiber core by ultraviolet (UV) light irradiation. The key parameters of an FBG are period, chirp rate, length, and depth of index of refraction modulation. In the formation of USFBGs, a typical depth of index of RI modulation will be applied during the grating writing on an ultra-short part of the fiber core. The fabrication of USFBGs is similar to that of common uniform FBGs, and therefore can be cost-effective and efficient. By placing a tunable slit between the phase mask and the fiber, ultra-short grating lengths can be easily obtained by carefully adjusting the slit width. The spectral response for the uniform FBG is given by:

$$R(\lambda)=\frac{-\kappa\sinh\left(\sqrt{\kappa^2-\sigma^2 L}\right)}{\sigma\sinh\left(\sqrt{\kappa^2-\sigma^2 L}\right)+i\sqrt{\kappa^2+\sigma^2}\cosh\left(\sqrt{\kappa^2-\sigma^2 L}\right)}$$

(1)

Where L is the grating length, $\kappa = 2\pi\Delta n/\lambda$ is the “AC” coupling coefficient, proportional to amplitude of the refractive index (RI) change Δn, and σ is “dc” self-coupling coefficient. From equation (1) a low-reflectivity Bragg grating should contain a low value of κL to satisfy $\kappa L << 1$. This can be either approached by very weak RI change Δn, as is conventionally done, or an ultra-short grating length (typically hundreds of μm), which also yields a wide reflection spectrum (typical bandwidth ~1.0-3.5 nm) [10].

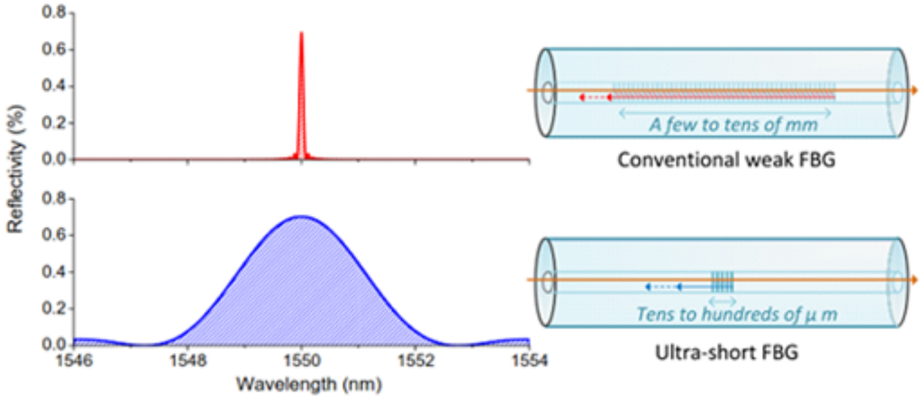

Fig.1. Weak FBGs and USFBGs typical reflection spectra [6].

The simulation shows that the R(λ) becomes closer to a Gaussian profile as the grating is weaker. For example Gaussian fitting are performed over the main lobes of USFBGs with L=0.2mm, $\kappa L = 0.05$ and Δn of 1.3 ×10-4 an extremely high quality of fit (R2> 0.999) is obtained and Gaussian functions may well approximate at least the peak region of the spectrum of the light reflected by an USFBG. Figure 1 illustrates the characteristic comparison between USFBGs and the conventional weak FBGs [6].

In practical FBG based measurements, for example, structural health monitoring applications with events such as multiple damage states in composite material and transverse cracks, usually the sensing transducer is under a non-uniform strain distribution. Such a long grating length could make the FBG sensor very easily exposed to no-uniform distribution of strain or temperature, which could distort the spectrum considerably and thus affect the measurement accuracy [11]. Nevertheless the USFBG's ultrashort lengths could fundamentally solve the mentioned non-uniform measurement problem and more importantly, they could provide significant benefits in terms of the central wavelength tracking in the Gaussian data fitting procedure because of their ideally Gaussian shape reflection spectrum. The principle of our proposed USFBG interrogation is based on the USFBG Gaussian shape spectrum reconstruction. Fig. 2. shows a typical USFBG is sampled by a variable number of sampling wavelengths. Due to a measurand change, the sensor answer is spectrally moving to higher/lower wavelength depending on the gradient of the measurand change.

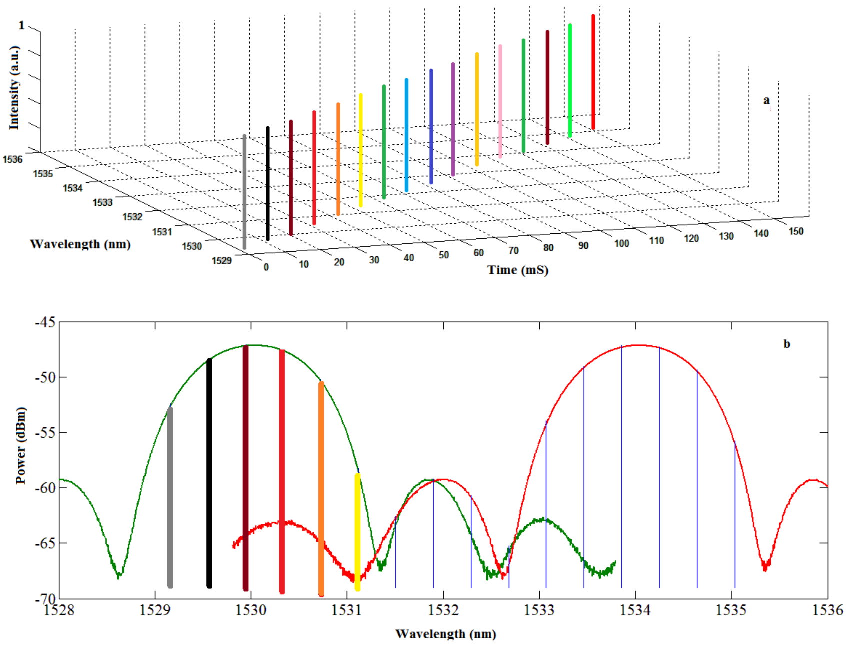

Fig.2. (a) Switched channels of MG-Y laser lines with 10ms intervals, (b) the USFBG (FWHMs of ~1.36 nm) reflection spectrum, which reconstructed by laser lines during 150ms integration time over 4 nm Bragg wavelength shift.

The returned signal power of each discrete line of laser on photo detector is mathematically proportional to the overlap integral of the spectrum function of the laser source and the reflectance distribution of the fiber Bragg grating [12]:

$$I_n = \int_0^\infty R(\lambda - \lambda_B)\, S(\lambda - \lambda_n)\, d\lambda \tag{2}$$

Where, $S(\lambda-\lambda_n)$ and $R(\lambda-\lambda_B)$, are the laser and the USFBG spectrum. Since the spectral width of the laser is much narrower than the USFBG bandwidth, by considering ‘S’ as a delta function, and assuming USFBG spectrum is ideal Gaussian approximated, total reflected power of n’th wavelength laser channel can be expressed as:

$$I = SR_m \exp\left[-(4\ln 2)\left(\frac{\lambda_n - \lambda_B}{\Delta\lambda_B}\right)^2\right] \tag{3}$$

Where R_m, λ_B and $\Delta\lambda_B$ are the peak reflectivity, Bragg wavelength, and bandwidth of the sensing FBG, respectively.

By switching the laser channels, and using a Gaussian fitting algorithm over the PD signals, a best-matching Gaussian function is calculated and its central position is assigned as the corresponding Bragg wavelength of the sensing grating. The adjusted Gaussian function is:

$$G(\lambda - \lambda_B') = Gaussian\_fit\ \{I_1, \ldots, I_n\} = R_m' \exp\left[-(4\ln 2)\left(\frac{\lambda - \lambda_B'}{\Delta\lambda_B'}\right)^2\right] \tag{4}$$

Where R_m', λ_B', $\Delta\lambda_B'$ are the adjusted parameters, amplitude, center and deviation; theoretically these three parameters can be derived from random groups of value from I_n.

In practice, when the strain changes, not only will the wavelength of the USFBG shift, but also the peak intensity may change, but the spectral shape remains approximately the same as the original one ($\Delta\lambda_B' = \Delta\lambda_B$). The $G(\lambda-\lambda_B')$ can be reconstructed by using a pairs of any I_n values. To eliminate the reflectivity of the USFBG’s side lobes, it is reasonable to use the largest value of three groups of value. Obviously, center of adjusted Gaussian function is insensitive to any intensity fluctuations resulted by bending loss of the fiber, light source variations. In other words, this will give it a self-referencing capability, making the system even more attractive for large-range and harsh environment sensing.

3. Experimental results and discussion

The proposed interrogation system was carried out in the case of applied strain under USFBG, which was glued to a micrometric translation stage with a resolution of 2 µm as shown in Fig. 3. The primary components of the system: a 5MHz MG-Y laser as a narrowband light source; InGaAs avalanche photo-detector (bandwidth of DC-100MHz), and a computer/DAQ for data processing, aggregation and transmission. Both of the MG-Y laser and APD can all be controlled and monitored by the computer. MG-Y-Branch tuned laser is one of the most interesting semiconductor lasers which is generally used solely for telecommunication applications. The MG-Y laser wavelength channels are chosen from the ITU grid containing 89 channels at 50 GHz spacing by means of tuning three currents listed in a look-up table (LUT). It can control by using the high speed electronic tuning, and address any discrete wavelength channel in the C-band to switch across the wavelength channels of interest. An USFBG with ultra-short lengths of <500 µm and Bragg resonance of near 1544:9 nm, was written along a single mode fiber; the reflectivity is

~1.37 %, and FWHM is >1.541 nm. The source wavelength was controlled from 1543.9 nm to 1547.5 nm with 0.4 nm increments via serial port, and the sensing signal was tracked by using 10 wavelength channels in every 100ms. In the proposed setup, the interrogation speed is only limited by the wavelength switching time of the MG-Y laser. There is a trade-off between the measurement range of the sensor and maximum sampling frequency. The sampling rate of sensor can be increased by using fewer wavelength channels.

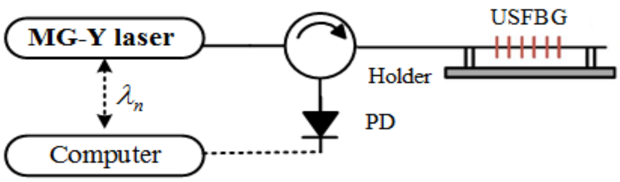

Fig.3. Schematic strain sensing setup.

Fig. 5 (a, b, c and d) shows the evolution of the USFBG reconstructed spectrum as the applied strain increases, and Fig. 5 (e) shows the wavelength shifts of the sensing FBG at different strains. A linear behavior could be found for each measurement. The strain sensitivity of USFBG was calculated by linear curve-fitting. The fitted coefficient of the under strain USFBG (FWHM ~1.541nm) is ~0.26pm/µℇ, and a typical measurement of proposed interrogator with 10 laser channel was obtained with a relatively wide linear range of >10000 µℇ. The performance of power detection interrogation systems for fiber Bragg grating sensors can be optimized in terms of their sensitivity.

To evaluate the FBG's FWHM relation with the sensing sensitivity, similar measurements were performed on the strain-turned grating with FWHM of 1.0 nm. Fig 4. Shows the sensing sensitivity and measurement range for 1 and 1.54 nm bandwidths which reconstructed just over two fixed laser lines. As expected, increasing the laser line wavelength spacing to the FBG's bandwidth ratio, will result in higher sensitivity. However, this operation would also lead to a decrease of the operational range. This can be explained by noting that when this ratio increases, the shift range of the grating spectrum which is located within the effective spectral range, which is higher than floor noise, will decrease. But in this setup, we have used several lines of lasers for FBG spectrum reflection reconstruction, and then its peak wavelength shift is only related to strain-optic constant of FBG.

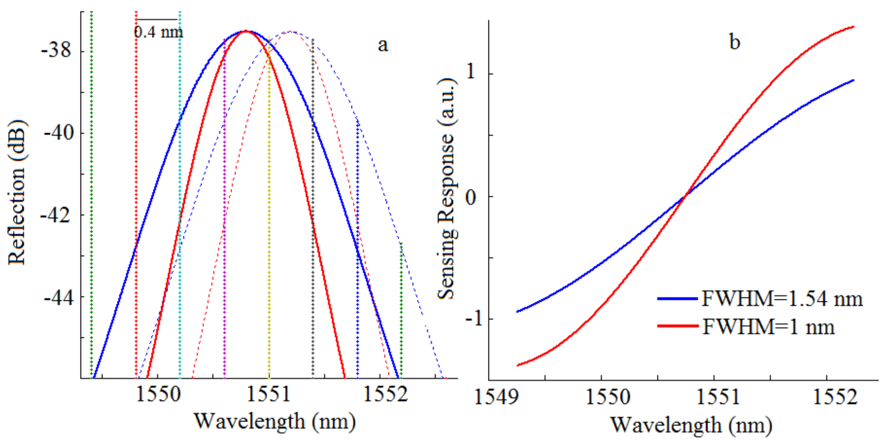

Fig.4 USFBGs spectrum and their shifts (b) Response curve of two grating.

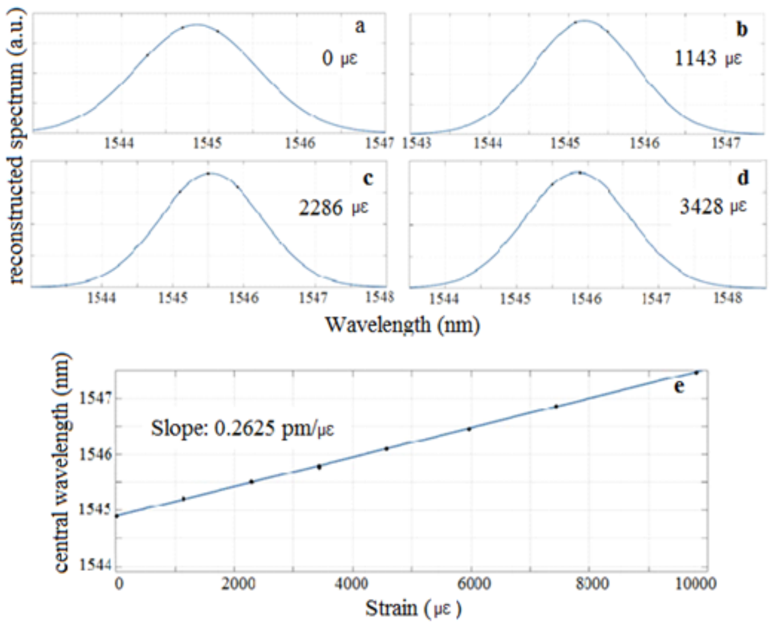

Fig.5 Grating reconstructed power spectra under (a) strain free, (b) 1143 μƐ, (c) 2286 μƐ, (d) 3428 μƐ and (e) measured Bragg wavelength shift versus strain.

To investigate how to select pairs of I_n values, here we used four peaks pairs of measured I_n to USFBG spectrum reconstruction. Fig. 6 shows the exact reflection spectrum and resolved Gaussian spectrum of the under test USFBG. The experimental results show the adjacent center of the 4 resolved spectra are almost the same, and any two maximum of measured I_n can be used for USFBG central wavelength tracking.

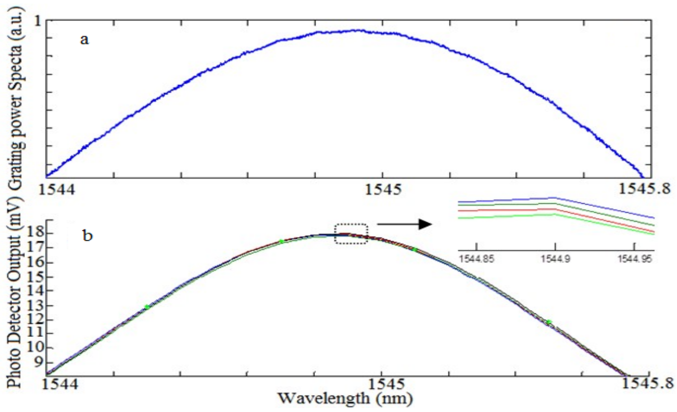

Fig.6. (a) USFBG reflection power spectra, measured by OSA, (b) its resolved spectrum with four sets of PD maximum groups.

During the stationary physical (temperature/strain) conditions measurement, the Bragg wavelength shift should be zero. But the actual sensing signals are affected by the systematic errors such as the intensity noise of the laser and the PD. This measurement noise includes the shot noise of the light, the electronic noise of the PD, and the quantization noise in the A/D conversion process. It mainly leads to some fluctuations in the PD output signal, which strongly depends on the USFBG's reflectivity. These systematic error can be regarded as the system resolution. To investigate the sensing system stability/resolution, the measurement was repeated several times under the same condition. The actually detected wavelength shifts are affected by the systematic error, as system resolution. The measurements show that the system has less than 0.05 nm wavelength shifts on the strain free, as shown in Fig.7. This systematic error is mainly caused by the APD output signal fluctuations, it can be improved by using higher signal-to-noise ratios (SNRs) of the USFBGs.

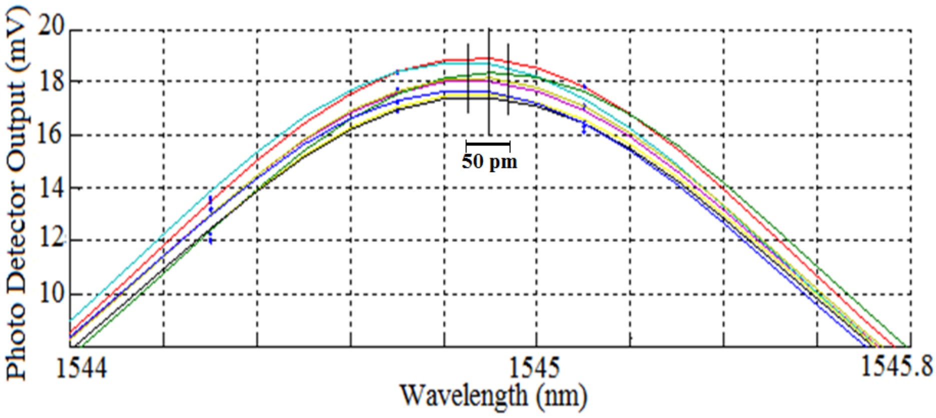

Fig.7. Grating, strain free, reconstructed power spectra versus PD output signal fluctuations.

4. Conclusion

A reliable and practical intensity-based interrogation of USFBGs is proposed and implemented by reflectometry of multi-wavelength channels of single chip MG-Y laser. By sampling the USFBG's reflection peaks, the grating reflection spectrum has been reconstructed. It exhibits several important features of high flexibility, fast speed, inherent insensitivity to power fluctuations, relatively wide linear measurement range of near 10000με and good potential for large scale sensing network interrogation. Future work will focus on extending the current setup to interrogate the large scale time domain multiplexed identical USFBG sensing network [13].

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