Multi-Channel OFDR Strain Sensor Based on Wavelength/Space Division Multiplexing Weak FBG Arrays

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***Abstract*—A multi-channel OFDR strain sensor was demonstrated based on femtosecond-laser-inscribed wavelength/space division multiplexing weak fiber Bragg grating array (WFBGA) in standard SMF. At a sensing spatial resolution of 3 mm, the number of channels and the measurement strain range were eight and 9000 $\mu\varepsilon$, respectively. The reflection spectral of each WFBG for each channel were successfully captured using spectral splitting method based on OFDR, thereby achieving strain demodulation for each channel. Compared with WDM WFBGAs, the maximum strain was only 1000 $\mu\varepsilon$ based on two-channel SMF.**

***Index Terms*—Distributed strain sensor, FBG arrays, multi-channel, wavelength/space division.**

I. Introduction

OPTICAL frequency domain reflectometer (OFDR) has been widely used in industrial field due to its high spatial resolution, such as in pipeline monitoring and early warning [1], [2]. Multi-channel measurement has always been a significant research focus in various applications [3], [4]. For example, a distributed multi-channel OFDR sensor for simultaneous measurement of relative humidity and temperature with a gauge length of 10 mm was proposed based on spatial-domain time-delayed multiplexing [5]. Moreover, a two-channel strain sensor with a measurement range of 3000 $\mu\varepsilon$ based on chirped fiber grating loop ring-down structure and time division multiplexing (TDM) technology was also proposed [3]. In addition, an eight-channel ultrasound sensor was achieved using a switchable fiber Bragg grating filter built into an Erbium-doped fiber laser [6]. Obviously, multi-channel fiber-optic sensors are mostly implemented using fiber Bragg gratings (FBG) combined with multiplexing technology. Recently, multiplexing technologies such as TDM, space division multiplexing (SDM), and wavelength division multiplexing (WDM) based on FBG have been studied in the field of large-capacity fiber optic sensing [7], [8], [9]. To achieve larger capacity, a method of fabricating large-scale weak FBG arrays (WFBGAs) on-line with the optical fiber drawing tower has been proposed, where the WFBG was written by UV phase mask [10]. But the Bragg wavelength of the obtained WFBG was fixed when using a type of phase mask. In 2023, FU et al. used femtosecond lasers to fabricate FBG to measure large strains, and FBG provided physical positioning

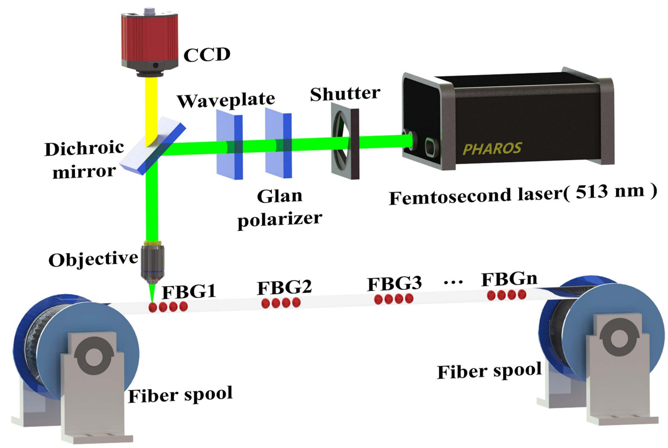

Fig. 1. (a) Schematic diagram of automatic fabrication of weak FBG arrays (WFBGAs) in single mode fiber (SMF) using point-by-point technology and reel to reel dragging system; (b) Schematic of wavelength/space division multiplexing WFBGAs. Channel1 (CH_1) corresponded to $WFBGA_1$ with Bragg wavelength of 1482.5 nm, and so on, Channel8 (CH_8) corresponded to $WFBGA_8$ with Bragg wavelength of 1605.0 nm. Note that each WFBGA included 25 WFBGs, i.e., $WFBG_{i\text{-}1}$, $WFBG_{i\text{-}2}$, ..., and $WFBG_{i\text{-}25}$. The length and spacing of each WFBG were 0.5 mm and 2.5 mm, respectively.

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TABLE I
WAVELENGTH/SPACE DIVISION MULTIPLEXING WFBGAS PARAMETERS, AND STARTING/ENDING WAVELENGTH OF 8 CHANNELS IN STRAIN DEMODULATION USING SPECTRAL SPLITTING METHOD

Channel Number	Bragg Wavelength	Starting Wavelength	Ending Wavelength
CH_1 ($WFBGA_1$)	1482.5 nm	1480.0 nm	1497.5 nm
CH_2 ($WFBGA_2$)	1500.0 nm	1497.5 nm	1515.0 nm
CH_3 ($WFBGA_3$)	1517.5 nm	1515.0 nm	1532.5 nm
CH_4 ($WFBGA_4$)	1535.0 nm	1532.5 nm	1550.0 nm
CH_5 ($WFBGA_5$)	1552.5 nm	1550.0 nm	1567.5 nm
CH_6 ($WFBGA_6$)	1570.0 nm	1567.5 nm	1585.0 nm
CH_7 ($WFBGA_7$)	1587.5 nm	1585.0 nm	1602.5 nm
CH_8 ($WFBGA_8$)	1605.0 nm	1602.5 nm	1620.0 nm

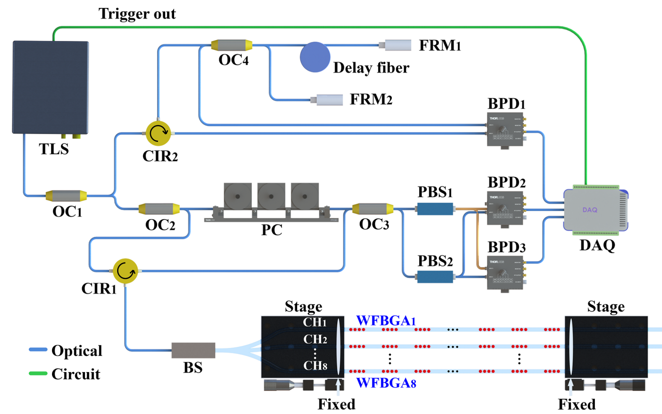

Fig. 2. Experimental setup for wide-range strain sensing based on OFDR using wavelength/space division multiplexing WFBGAs, i.e., WFBGA1, $WFBGA_2$, …, and $WFBGA_8$. TLS: Tunable laser source; OC: Optical coupler; PC: Polarization controller; FRM: Faraday rotation mirror; BPD: Balanced photodetector; PBS: Polarization beam splitter; CIR: Circulator; DAQ: Data acquisition card.

for position correction [11]. But the strain measurement was done on only one fiber. And various demodulation techniques including wavelength demodulation based on optical time-domain reflectometry (OTDR) [12] and phase demodulation based on phase-sensitive OTDR [13], as well as OFDR [14] were also demonstrated. In addition, the OFDR and WDM was also proposed to improve the capacity of multiplexed FBGs [15].

In this letter, eight-channel OFDR strain sensor was demonstrated based on WDM and SDM femtosecond-laser-inscribed WFBGAs in standard SMF using spectral splitting method. The maximum measurable strain for each channel was 9000 $\mu\varepsilon$, where the sensing spatial resolution was 3 mm. The process of fabricating eight WFBGAs with different Bragg wavelengths was introduced. The method of using spectral splitting to achieve multi-channel strain demodulation has been studied. Moreover, the performance of multi-channel strain sensing based on WFBGAs were further investigated.

II. EXPERIMENTAL SETUP AND DISSCUSSIONS

As shown in Fig. 1, a WFBGA automatic fabrication system consisting of an optical path section and a reel to reel dragging section was constructed. The optical path section was composed of a shutter, a Glan-prism, a half-wave plate, a dichroic mirror, and an objective. The detailed process of fabricating WFBGA in SMF (SMF-28e, Corning) using point-by-point technology was as follows. Firstly, the fiber spools at both ends were synchronously rotated to the right to the processing region by driving the stepper motor. Secondly, the image of the fiber core was captured in real-time by CCD. Thirdly, the first WFBG, i.e., $WFBG_1$, was fabricated using automatic-focusing algorithm based on fiber core image recognition, which utilizing the brightness and darkness changes of the fiber core boundary [16]. By repeating the above process, WFBGA, i.e., consisting of $WFBG_1$, $WFBG_2$, …, and $WFBG_n$, was automatically fabricated.

To achieve larger capacity sensing, eight WFBGAs, i.e., $WFBGA_1$, $WFBGA_2$, $WFBGA_3$, $WFBGA_4$, $WFBGA_5$, $WFBGA_6$, $WFBGA_7$ and $WFBGA_8$, with Bragg wavelengths of 1482.5, 1500.0, 1517.5, 1535.0, 1552.5, 1570.0, 1587.5, and 1605.0 nm, were firstly fabricated, as shown in Table I and Fig. 1(b). The corresponding pitches were 1.025, 1.037, 1.049, 1.061, 1.073, 1.085, 1.097, and 1.109 μm, respectively. Note that each WFBGA was consisted of 25 identical WFBGs, i.e., $WFBG_{i\text{-}1}$, $WFBG_{i\text{-}2}$, …, and $WFBG_{i\text{-}25}$, as shown in Fig. 1(b). The length and spacing of each WFBG were 0.5 mm and 2.5 mm, respectively. To achieve multi-channel sensing simultaneously, eight WDM WFBGAs were spatially multiplexed, as shown in Fig. 1(b). In other words, $WFBGA_1$ was deployed on channel1 (CH_1), $WFBGA_2$ was deployed on CH_2, and so on, $WFBGA_8$ was deployed on CH_8.

To measure the spectrum of WDM WFBGAs, a conventional OFDR system was built, as shown in Fig. 2. The light from the tunable laser source (TLS, N7776C, Keysight) was divided into two parts through an optical coupler (OC_1), where the sweeping range and sweeping rate of the TLS were 140 nm, i.e., from 1480 to 1620 nm, and 80 nm/s, respectively. One part of the light was injected into a Michelson structure consisting of two Faraday rotating mirrors (FRMs) and delay fiber, and the signal generated was served as an external clock of data acquisition card (DAQ, M2p. 5966, Spectrum) to sample the beat signal from balanced photo-detectors (BPDs, PDB480C-AC, Thorlabs). Another part of the light was injected into a Mach-Zehnder structure consisting of polarization controller (PC) and WDM WFBGAs. The reflected signals of WDM WFBGAs were entered into Mach-Zehnder structure. Note that eight WDM WFBGAs were spatially multiplexed through a beam splitter (BS). Two polarization beam splitters (PBSs), i.e., PBS_1 and PBS_2, as well as two BPDs, i.e., BPD_2 and BPD_3, was employed to reduce the polarization fading effects.

To achieve subsequent strain demodulation, the frequency domain spectra of eight WDM WFBGAs were firstly measured separately. In other words, only one WFBGA was connected to the BS at a time. As shown in Fig. 3(a), each WFBGA has 25 Rayleigh backscatter (RBS) amplitude enhancement peaks, corresponding to 25 WFBGs. Note that the number of WFBGs for a WFBGA was dependent on the reflectivity of the WFBG and multiple crosstalk [17]. And the positions of the first gratings of $WFBGA_1$, $WFBGA_2$, $WFBGA_3$, $WFBGA_4$, $WFBGA_5$, $WFBGA_6$, $WFBGA_7$, and $WFBGA_8$ were slightly different,

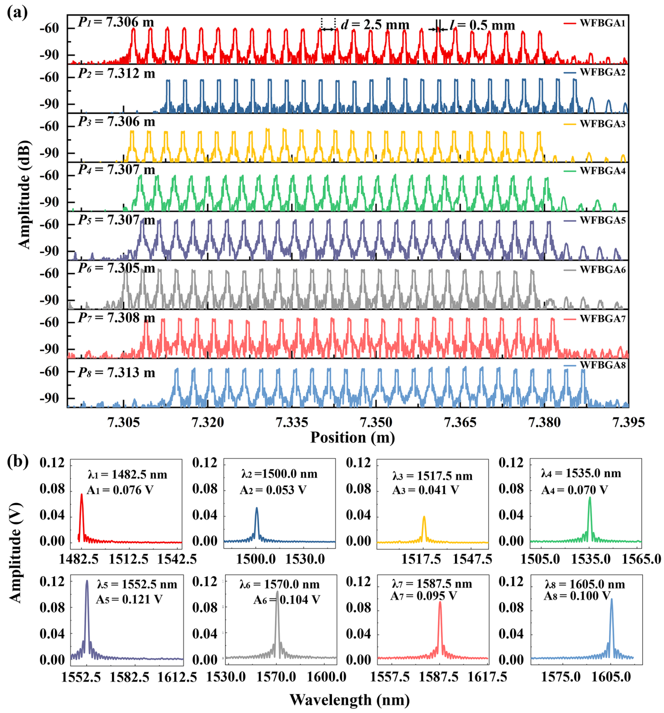

Fig. 3. (a) Frequency domain spectra of eight WDM WFBGAs obtained through separate measurements, where the positions of the first gratings were located at 7.306, 7.312, 7.306, 7.307, 7.307, 7.305, 7.308, and 7.313 m, respectively; (b) Reflection spectrum of eight WFBGAs, corresponding to Bragg wavelength of 1482.5, 1500.0, 1517.5, 1535.0, 1552.5, 1570.0, 1587.5, and 1605.0 nm.

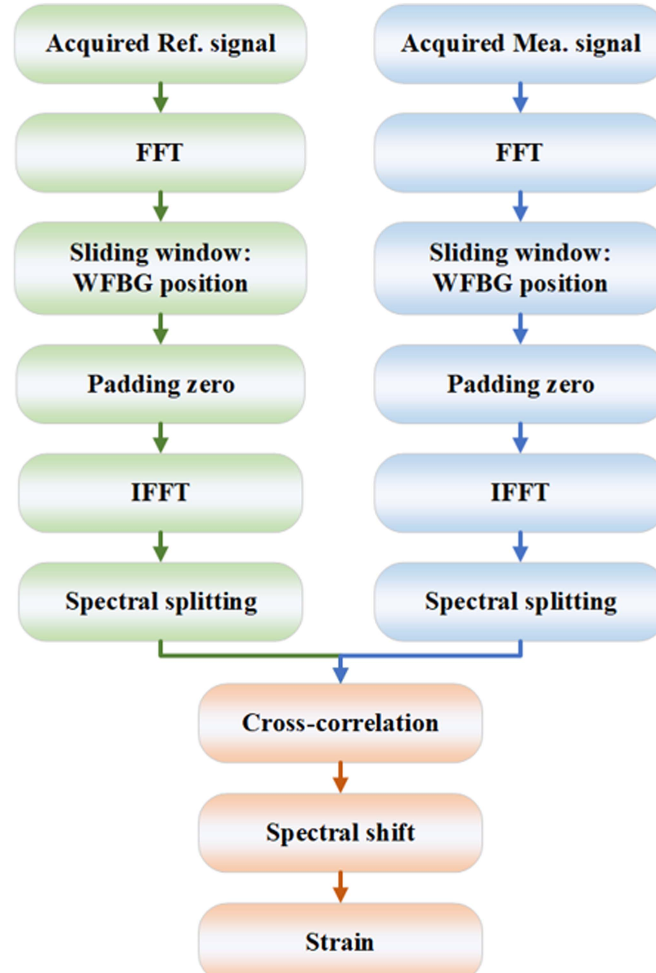

Fig. 4. Flow diagram of the OFDR strain demodulation based on WDM/SDM WFBGAs. Ref. signal: reference signal; Mea. signal: measurement signal; FFT: Fast Fourier Transformation (FFT); IFFT: inverse FFT.

located at 7.306, 7.312, 7.306, 7.307, 7.307, 7.305, 7.308, and 7.313 m, respectively. The measured length and spacing were consistent with the settings. Moreover, the Bragg wavelength of each WFBGA were also matched with the Table I. And the amplitude (A) was fluctuated around 0.9 V, as shown in Fig. 3(b). Note that the subsequent multi-channel strain demodulation was not affected by the amplitude difference of the WFBGA.

To investigate the strain property of the WDM/SDM WFBGAs, two ends of $WFBGA_1$, $WFBGA_2$, …, and $WFBGA_8$, corresponding to CH_1, CH_2, …, and CH_8, were fixed on two linear translation stages via AB glue, as shown in Fig. 2. The flowchart of strain demodulation was shown in Fig. 4. Firstly, the reference (Ref.) signal without strain and measurement (Mea.) signal with strain of eight WFBGAs were acquired, respectively. Note that the Ref./Mea. signal are signals acquired from 8-channles simultaneously, i.e., mixed signals of 8-channles WDM/SDM WFBGAs. Secondly, fast Fourier transform (FFT) operation was performed to transform into the spatial domain to obtain the mixed frequency domain spectra. As shown in Fig. 5, the RBS amplitude enhancement peaks of the mixed 8-channles WFBGAs was overlapped together and located between 7.305 and 7.387 m. Thirdly, the Ref. and Mea. signal of the FUT were divided into multiple parts by the sliding window (SW). Note that the length of SW is the grating length and spacing, i.e., 3 mm. Taking $WFBGA_1$ as an example, the position of the first SW was located at 7.305 ∼ 7.308 m according to the position of

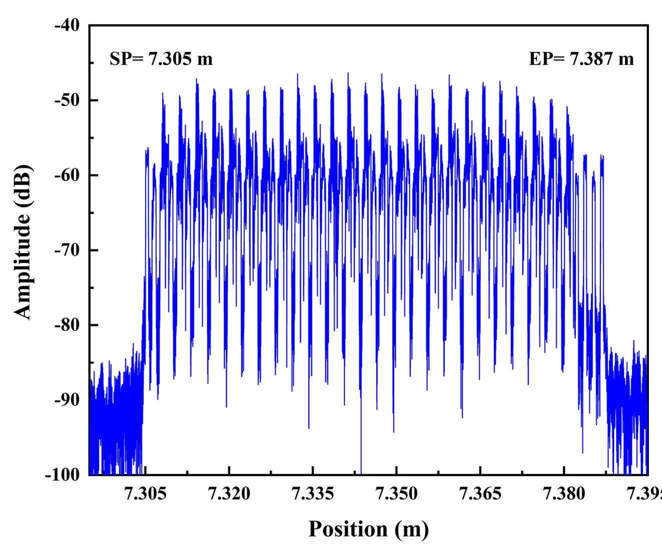

Fig. 5. Mixed frequency domain spectrum of eight WDM WFBGAs, i.e., eight-channel, located between 7.305 and 7.387 m. SP: Starting position; EP: Ending position.

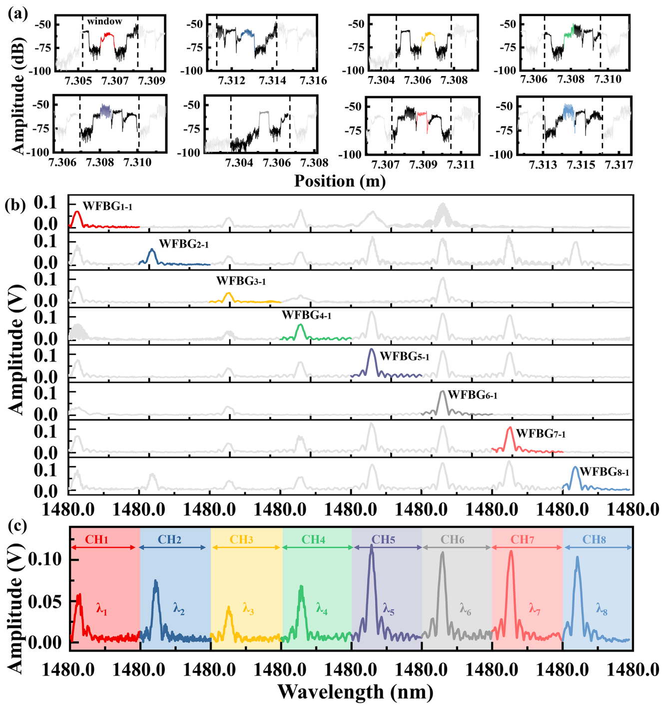

Fig. 6. (a) Schematic diagram of the specific position of the first sliding window (SW) of each WFBGA, i.e., each channel; (b) Reflection spectra of $WFBGA_{1-1}$, $WFBGA_{2-1}$, …., and $WFBGA_{8-1}$ recovered from the corresponding SWs; (c) Concatenated reflection spectra captured from each channel using spectral splitting.

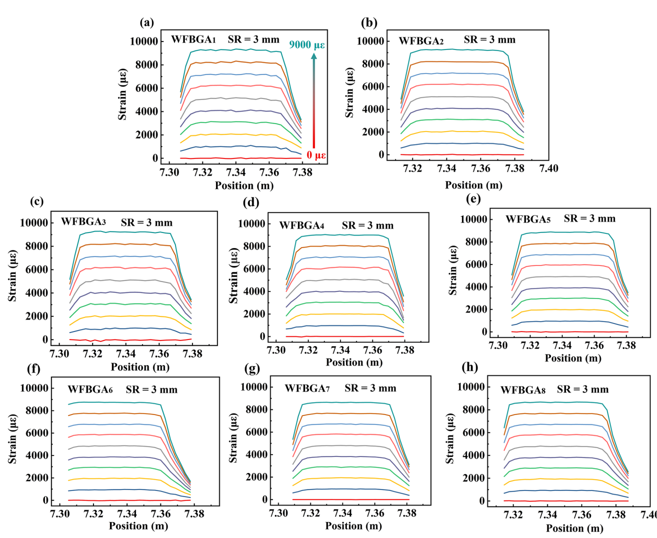

Fig. 7. Demodulated strain profiles of $WFBGA_1$, $WFBGA_2$, $WFBGA_3$, …, and $WFBGA_8$, corresponding to CH_1, CH_2, CH_3, …, and CH_8, when the applied strain was increased from 0 to 9000 $\mu\varepsilon$ under a spatial resolution of 3.0 mm.

the first WFBG, i.e., $P_{1\text{-}1} = 7.306$ m in Fig. 3, as shown in the first figure of Fig. 6(a). Similarly, the position of the first SW of the other seven WFBGAs were also determined based on the position in Fig. 3. Obviously, only the colored curve portion in the SW was corresponded to the distance domain spectrum of the WFBGA, while the other curve portions should be cut. Fourthly,

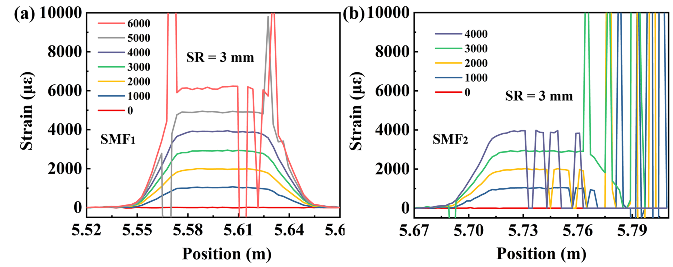

Fig. 8. Demodulated strain profiles of two-channel multiplexed, i.e., (a) CH_1, (b) CH_2, based on standard SMF under the spatial resolution (SR) of 3 mm.

each SW was padded with zeros and then transformed back to frequency domain through inverse FFT (IFFT). As shown in Fig. 6(b), the reflection spectra of $WFBGA_{1\text{-}1}$, $WFBGA_{2\text{-}1}$, …., and $WFBGA_{8\text{-}1}$ were recovered. To cut off the excess distance domain signals, the sweeping range of the TLS was uniformly divided into 8 parts, as shown in Table I. In this way, the starting and ending wavelengths of CH_1, i.e., $WFBGA_1$, were 1480 and 1497.5 nm. Taking $WFBGA_{1\text{-}1}$ as an example, five reflection peaks were recovered at the sweeping range of the TLS, i.e., 1480-1620 nm, corresponding to wavelengths of 1482.5, 1517.5, 1535.0, 1552.5 and 1570.0 nm. At this time, spectral splitting was performed at the range of 1480 $\sim$ 1497.5 nm to capture the corresponding spectral segment of CH_1, i.e., the reflection peak at the wavelength of 1482.5 nm, as shown by the red peak in Fig. 6(b). Similarly, only the reflection peak at the range of 1497.5 $\sim$ 1515 nm was captured for $WFBGA_{2\text{-}1}$. In this way, the grating reflection spectra captured from each channel were concatenated together, as shown in Fig. 6(c). Obviously, the number of recovered reflection peaks for each WFBGA was different attributing to the different starting positions of each WFBGA in Fig. 3(a). Take the 6th row as an example, the sliding window in the distance domain was included three WFBGs, i.e., $WFBG_{6\text{-}1}$, $WFBG_{1\text{-}1}$, and $WFBG_{3\text{-}1}$. Therefore, the recovered reflection spectra exhibited three peaks. And the amplitudes of $WFBG_{1\text{-}1}$ and $WFBG_{3\text{-}1}$ were weaker than that of $WFBG_{6\text{-}1}$. The reason is that the $WFBG_{6\text{-}1}$ was completely contained within the sliding window, while $WFBG_{1\text{-}1}$ and $WFBG_{3\text{-}1}$ were only partially included. Finally, the cross-correlation was performed on the Ref. and Mea. signal of the same channel to obtain the spectral shift, i.e., Δf, of the corresponding channel. Then the applied strain of each channel could be obtained according to the spectral shift.

When the strain was increased from 1000 to 9000 $\mu\varepsilon$ with a step of 1000 $\mu\varepsilon$, the strain sensing property of eight-channel WFBGAs were studied. As shown in Fig. 7, the applied strains to $WFBGA_1$, $WFBGA_2$, $WFBGA_3$, …, and $WFBGA_8$ were successfully demodulated using spectrum splitting. Note that the demodulated strain in Fig. 7(f) is caused by incomplete overlap between the WFBGA position and the applied strain area. This indicated that multi-channel large strain sensing could be achieved using the combination of WDM/SDM WFBGAs and OFDR spectral splitting method. The number of sensing channels could be further expanded by reducing the strain measurement range. Note that the sensing spatial resolution is 3 mm, i.e., the length plus spacing of WFBG. Moreover, SMF was also employed to achieve 2-channel distributed strain sensing. When the applied strain was greater than 4000 $\mu\varepsilon$, the wrong points induced by lower signal-to-noise ratio (SNR) were appeared for CH_1 under the spatial resolution of 3 mm, as shown in Fig. 8(a). For CH_2, it is not possible to successfully demodulate strains greater than 1000 $\mu\varepsilon$.

III. Conclusion

In conclusion, a multi-channel, i.e., eight-channel, OFDR strain sensor was demonstrated based on femtosecond-laser-inscribed WDM WFBGAs in standard SMF, where the sensing spatial resolution was 3 mm. eight WFBGAs with Bragg wavelengths of 1482.5, 1500.0, 1517.5, 1535.0, 1552.5, 1570.0, 1587.5, and 1605.0 nm were fabricated and spatially multiplexed into eight channels, each consisting of 25 identical WFBGs. The reflection spectral of each WFBG for each channel were successfully captured using spectral splitting method based on OFDR. The strain profiles of each channel were successfully and clearly demodulated, when the applied strain was increased from 1000 to 9000 $\mu\varepsilon$. Compared with WDM WFBGAs, the maximum strain was only 1000 $\mu\varepsilon$ based on two-channel SMF. More channels would be multiplex by broadening the sweeping range of the tunable laser source and increasing the length of WFBG.

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