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This paper must be cited as:

Min, R.; Korganbayev, S.; Molardi, C.; Broadway, C.; Hu, X.; Caucheteur, C.; Bang, O....
(15-1). Largely tunable dispersion chirped polymer FBG. *Optics Letters*. 43(20):5106-5109.
<https://doi.org/10.1364/OL.43.005106>



The final publication is available at

<https://doi.org/10.1364/OL.43.005106>

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Additional Information

Largely tunable dispersion chirped polymer FBG

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Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX

We demonstrate a largely tunable dispersion fiber Bragg grating (FBG) inscribed in microstructured polymer optical fiber (mPOF). The bandwidth of the chirped FBG (CFBG) was achieved from 0.11 to 4.86 nm, which corresponds to a tunable dispersion range from 513.6 to 11.15 ps/nm. Furthermore, thermal sensitivity is used to compensate the wavelength shift due to the applied strain. These results demonstrate that CFBG in POF is a promising technology for future optical systems.

OCIS codes: (140.3490) Polymer optical fibers, fiber Bragg gratings, dispersion devices, optical systems.

<http://dx.doi.org/10.1364/OL.99.099999>

Chirped fiber Bragg gratings (CFBGs) in silica fibers are attractive components which have been implemented for a variety of applications, such as long distance dispersion compensation [1], optoelectronic oscillator [2], mode locked fiber laser [3], accelerometer [4] or biomedical sensing [5]. Furthermore, microwave photonics is also a promising application area where dispersive elements are required, which includes beamforming for phased array antenna [6], signal generation [7] or reconfigurable transversal filters [8] amongst others. Indeed, CFBGs based on silica fiber is a very mature technology and several techniques have been demonstrated for fabricate and tuning, such as temperature gradient [9], strain gradient [10], varying the period of the grating [11] and tuning with ferrofluidic defects in microstructured optical fiber [12]. However, polymer optical fibers (POFs) show higher thermo-optic coefficient, larger elongation before breakage and lower Young's modulus compared with silica fiber. Accordingly, a broader tuning range under temperature and strain, easy handling due to its low stiffness and lower installation costs are some of their main advantages [13], besides its biocompatibility. During the last decade,

the use of polymer optical fiber (POF) has been increasing for short reach applications such as home networks [14-15] and low cost interconnects in datacenters [16] or sensors [13], which leads to current growing interest in novel fiber wavelength sensitive components.

Since the first fiber Bragg grating (FBG) in POF was reported in 1999 [17], FBGs in POF have become attractive devices for optical communication and sensing. Examples of them are phase-shifted FBG [18], tilted FBG [19] or FBGs in low loss cyclic transparent amorphous fluoropolymers (CYTOP) POFs [20-21], as reported in recent literature. CFBGs in POF were theoretically proposed for tunable dispersion in 2005 [22] by applying both strain and temperature, showing a potential large dispersion tuning range from 110 to 2400 ps/nm. However, experimentally, the first CFBG in POF was successfully fabricated by using a chirped phase mask in 2017 [23] as well as CFBGs have been recently fabricated in POF at 850 nm by using a uniform phase mask and non-uniform tapered fibers [24].

In this letter, we present the first dispersion experimental demonstration of largely tunable dispersive FBGs in POF, where a dispersion range from positive 11.15 to 513.6 ps/nm and negative 490.60 to 15.90 ps/nm has been achieved, therefore, CFBGs in POF are confirmed as very promising dispersive devices for a variety of applications.

The use of tapered silica fibers in 1996 [25] allowed to demonstrate variable group delay slope of the CFBG by applying different strain values. *Liu et al* [22] provided simulation results for a similar approach in polymer fibers. In this paper, we present a tunable dispersion CFBG inscribed in an endlessly single-mode benzyl dimethyl ketal (BDK)-doped poly (methyl methacrylate) (PMMA) microstructured POF (mPOF) [26], which was fabricated in DTU Fotonik by using the center hole doping technique. In order to remove any residual stress of the fiber from the drawing process,

the fiber was pre-annealed at 80°C for 24 hours. A 20 cm long fiber sample was connected to a ferrule, cleaved with a portable cleaver [27] and polished with sand paper to enhance the end face quality. As explained in [28], acetone can be employed to obtain POF etching. In our experiment, prior to the inscription process, the fiber section was immersed in acetone while a constant speed automatic translation stage was used to shift the fiber during the etching process, resulting in a non-uniform etching time for different fiber sections. Consequently, a linear tapered section, as shown in Fig. 1 (a), is obtained with high reliability and repeatability, the tapered fiber diameter has been measured along the taper of two points separated by 10 mm as 65 μm and 55 μm , lead to a linear taper profile of 1 $\mu\text{m}/\text{mm}$. The tapered fiber was subjected to 1% strain during exposure by a single pulse (with duration of 15 ns) with 2.5 mJ energy from a 248 nm KrF laser at 248 nm where a 10 mm long uniform phase mask of 1064 nm period was used, delivering a 10 mm long CFBG. The laser beam profile was measured as a rectangular Tophat function of 6.0 \times 1.5 mm² size and 2 \times 1 mrad² and a slit of 10 mm width sets the length of the grating. It was focused onto the fiber core utilizing a plano-convex cylindrical lens (Newport CSX200AR.10) with focal length of 20 cm. Additional details can be found in [24].

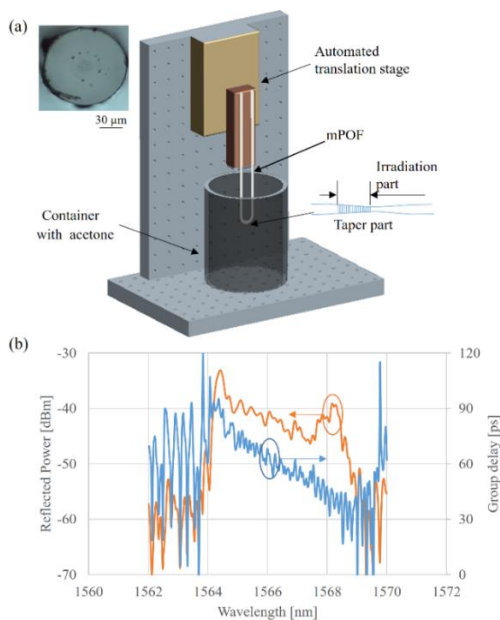


Fig. 1. (a) Taper setup for mPOF; inset: end face of mPOF. (b) Reflected spectral power and group delay after fabrication and strain released.

Given that microstructuring is typically known to scatter circa 20% of the incident light during a successful inscription, some inhomogeneities may exist in the fibers refractive index profile. In symmetric microstructured fibers, inscription is successful provided no capillaries are in the light path of the inscription laser beam. Oppositely, in the worst case, the FBG profile is affected and the fiber is directionally sensitive. However, work by Broadway et al. has shown that for He-Cd inscription of PMMA mPOF, lateral directivity appears mechanically homogeneous over a 20-degree

arc, even at pressures as low as 1kPa [29]. An optical backscatter reflectometer (LUNA 4600) with wavelength resolution of 33 μm was used to measure the reflected power and group delay. Fig. 1 (b) shows the reflected spectral power and the group delay of the fabricated CFBG after strain release, performing similarly to taper CFBG in silica fibers [30]. The maximum bandwidth was 4.86 nm, corresponding to a chirp of 0.486 nm/mm and a dispersion value around 11.15 ps/nm.

A 5 cm long POF including a 1 cm long CFBG was subjected between two fiber clamps (Thorlabs HF001) fixed on the translation stage, as shown in Fig. 2, which shifts every 10 μm step (0.005%). Figs. 3 (a) and (b) show the strain dependence of the reflected spectral power and group delay of the grating. It is clearly shown that chirped grating response strongly varies with the applied strain. The slope of the group delay vs wavelength (i.e. grating dispersion) varies according to the bandwidth change since the maximum grating delay is given by the grating length. The group delay shows a positive slope for strain levels higher than 1% and a negative when strain decreases from the value employed during the grating inscription. The reason for that is due to stress optic effect, which is opposite to the lengthening effect [30] and a chirp cancellation occurs. As expected, the central wavelength of the grating shifts to longer wavelengths when strain increases. Fig. 3 (c) shows a strain sensitivity of $1.26 \pm 0.02 \text{ pm}/\mu\epsilon$, similar to uniform POFBG in the same material at 1530 nm ($\sim 1.3 \text{ pm}/\mu\epsilon$) [31].

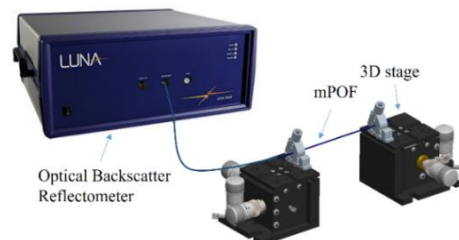


Fig. 2. Experimental setup for strain measurements.

Fig. 4 shows the bandwidth dependence and the dispersion with the applied strain. In Fig. 4 (a), the negative slope region shows a bandwidth decrease with strain of 5.01 nm/%, whereas higher values of strain than 1% lead to an increase of 8.71 nm/%. Fig. 4 (b) shows the dependence of the grating dispersion with the strain, where a dispersion increase from 11.15 to 513.60 ps/nm is achieved by increasing the strain up to 1.04 %. Negative dispersion of 490.60 ps/nm is measured for strain values of 0.94 % and it decreases to 15.90 ps/nm when 1.5% strain is applied. During 0.94% to 1.04 % strain, two opposite sign dispersion appeared due to the process of the conversion of the group delay slope. Since the grating is inscribed under 1% strain, the chirp is caused because of the stress-optic effect (i.e. strain gradient along the fiber). However, in this case, the grating pitch is not varying over the taper. After release, the chirp due to the stress-optic effect disappears, but another chirp appears due to different parts of the taper relax differently from the initial strain gradient (reversely to the lengthening effect [30]). Therefore, larger chirps can be created and the chirped grating can be packaged strain-free [24]. Detailed theory is provided following

the analysis of r (radius) and L (fiber length) in chirped gratings using the transfer matrix method [32].

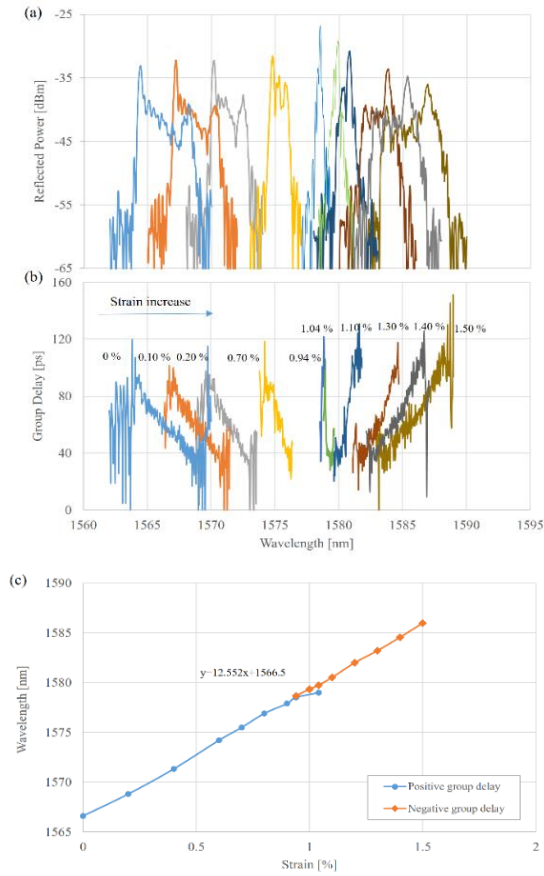


Fig. 3. (a) Reflected spectrum vs strain. (b) Group delay vs strain. (c) Central wavelength shift vs strain.

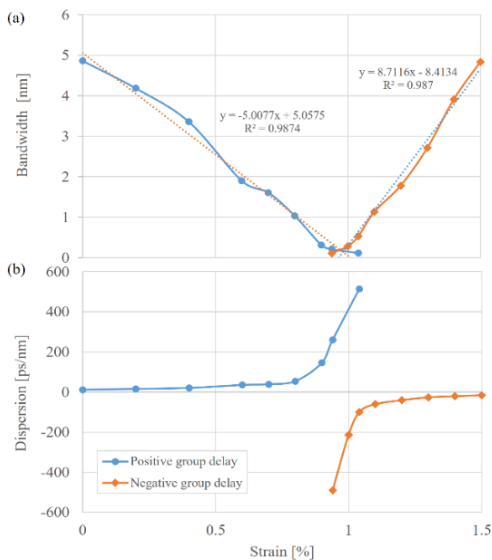


Fig. 4. Characterization of the CFBG response: (a) bandwidth vs strain. (b) Dispersion vs strain.

Fig. 3 (c) shows the central wavelength shift with the applied strain, which we propose to be compensated with the effect of temperature. Consequently, we characterized the CFBG response between 30 and 52°C. The grating was placed on a Peltier plate with the temperature maintained by an electronic temperature controller. Figs. 5 (a) and (b) show the obtained reflected spectral power and the group delay measurements. Fig. 6 shows a linear dependence of the central wavelength with the temperature, yielding a sensitivity of 0.0719 nm/°C. We can, therefore, conclude that we can achieve a 1.6 nm tuning range over 22 °C temperature tuning. Note that this value is larger than the 1.3 nm achieved in silica FBG when 100°C temperature change is applied [33].

Fig. 7 shows that the bandwidth and dispersion of the CFBG are stable when the temperature varies in the range 30-52°C. The dispersion is estimated as 26.2 ± 0.4 ps/nm and keeps constant within the margin of error. The measured blue shift of the central wavelength with temperature can be employed to compensate the wavelength shift obtained when external strain is applied for the sake of dispersion tunability, which makes this dispersion device even more flexible. Fig. 4 shows a large range of dispersion, from 145.8 ps/nm at 0.9% strain to 513.6 ps/nm at 1.04% strain under a central wavelength shift of 1.76 nm.

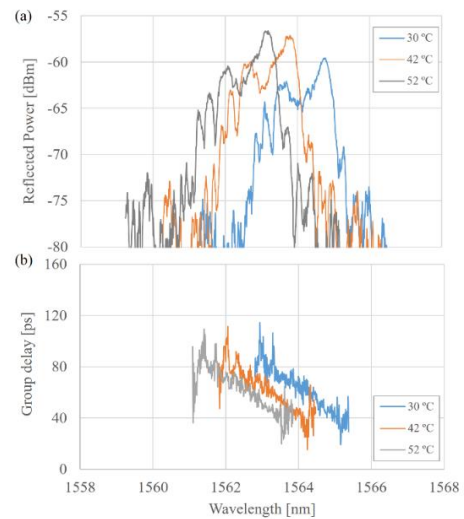


Fig. 5. CFBG response characterization at different temperatures: (a) Reflected spectral power vs wavelength, (b) Group delay vs wavelength.

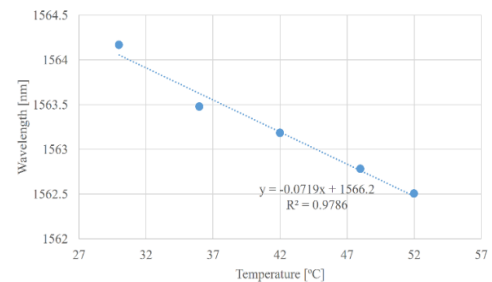


Fig. 6. Linear dependence of the central wavelength under different temperatures.

For example, to offset the center wavelength increase induced by 0.14% applied strain, the required temperature rise is 24 °C, which is suitable for the temperature range for POFBG technology. In silica FBG, the temperature and strain sensitivities are 11.3 pm/°C and 1.06 pm/με, so 132 °C temperature change would be required to compensate the wavelength shift due to 0.14 % applied strain, which is not practical for real application [33].

In conclusion, for the first time to our knowledge, the tunable dispersion of a chirped fiber Bragg grating inscribed in POF by using non-uniform tapered fibers technique has been demonstrated. We also propose to employ temperature in order to compensate the central wavelength shift due to the applied strain, and therefore, promising tunable CFBG devices are presented for future optical systems.

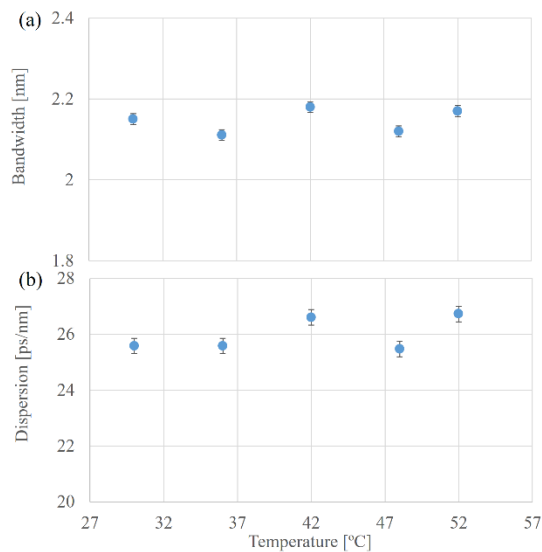


Fig 7. (a) Bandwidth vs Temperature. (b) Dispersion vs Temperature.

Funding. FCT through the fellowship SFRH/BPD/109458/2015, program UID/EEA/50008/2013. D. Tosi and S. Korganbayev are supported by ORAU grant LIFESTART (2017-2019). This work was also supported by the Research Excellence Award Programme GVA PROMETEO 2017/103 Future Microwave Photonic Technologies and Applications and Science Foundation of Heilongjiang Province of China (F2018026).

Acknowledgment. The authors acknowledge the support of Azat Abdullayev for strain setup outline.

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