Optics Letters

Large-scale multiplexed weak reflector array fabricated with a femtosecond laser for a fiber-optic quasi-distributed acoustic sensing system

MENGSHI WU,[1,†] CHI LI,[2,†] XINYU FAN,[1,*] CHANGRUI LIAO,[2,3] AND ZUYAUN HE[1]

[1]State Key Laboratory of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, Shanghai 200240, China
[2]Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education and Guangdong Province, College of Physics and Optoelectronic Engineering, Shenzhen University, Shenzhen 518060, China
[3]e-mail: cliao@szu.edu.cn
*Corresponding author: fan.xinyu@sjtu.edu.cn

Received 20 April 2020; revised 24 May 2020; accepted 25 May 2020; posted 26 May 2020 (Doc. ID 395725); published 29 June 2020

In this Letter, we propose a large-scale multiplexed weak reflector array fabrication method by using a femtosecond laser with relatively high reflectivity and low transmission loss. This kind of weak reflector array can be used in a quasi-distributed acoustic sensing system as sensing fiber instead of single-mode fiber (SMF) to achieve an ultrahigh signal-to-noise ratio (SNR). An automated fabrication system is designed, and a reflector geometric structure with high reflectivity and low scattering loss is designed based on this system. As a prototype to demonstrate the performance, one thousand weak reflectors are written on the SMF with an interval of 10 m, a reflectivity around −42 dB, and a transmission loss of 0.34 dB/km. In comparison to the method of using SMF as the sensing fiber, at least 15.8 dB enhancement to the SNR can be achieved by using the reflector array as the sensing fiber.

https://doi.org/10.1364/OL.395725

The fiber-optic distributed acoustic sensing system (DAS) [1,2] can be used to measure and locate acoustic signals along a fiber of several kilometers. Therefore, it is widely studied and adopted in many large-scale monitoring applications, such as pipeline monitoring, reservoir monitoring, and safeguarding purposes. Among all the DAS systems, the phase-sensitive optical time domain reflectometer (Φ-OTDR) is mostly studied because it can achieve a long sensing range as well as an acceptable signal-to-noise ratio (SNR). Based on this system, several key techniques have been proposed to enhance the SNR. The coherent detection technique [1] uses a strong light wave to interfere with the signal light wave, which can enhance the SNR to the shot-noise limitation. On the other hand, the pulse compression technique [3] enables the system to use a probe pulse longer than the spatial-resolution-restricted length and therefore to have a high signal power. Besides, the distributed amplification technique [4] can be adopted into the system to enhance the signal power of a long-distance system. With these techniques, the Φ-OTDR system can be used in many real applications with good performance. Further, researchers are trying to apply the Φ-OTDR system to some high-end applications, such as underwater acoustic signal monitoring since this system has great advantages in the aspect of multiplexing scale, which is highly needed for this application. However, the system SNR is still insufficient, even using all the techniques described above.

Recently, the method of adopting reflectivity enhanced fiber has become another effective way to improve the system SNR and has been widely studied. Until now, three approaches of reflectivity enhanced fiber have been proposed. The first one is the Rayleigh backscattering (RBS) enhanced fiber [5]. This approach may increase the RBS power by exposing a single-mode fiber (SMF) under ultraviolet rays, which brings about 10 dB enhancement to the backscattering power while maintaining the fully distributed sensing capability. However, a high scattering means a large scattering loss, which makes it impractical for long-distance sensing. The second approach is to write the weak fiber Bragg grating (FBG) array along a fiber [6] by using an ultraviolet laser and a phase mask. A reflectivity of −17 dB can be achieved at maximum, which gives a very large enhancement to the signal power. This technique is well developed and has been used in the real applications [7,8]. However, the presented works have not concentrated on the power utilization efficiency, which considers the reflectivity and the transmission loss of the FBG simultaneously. Additionally, the annealing effect and the sensitivity of the spectrum to the temperature and strain may make the reflectivity unstable. The third approach is to write the weak reflector array [9] along a fiber. This approach uses a femtosecond laser to inscribe a serial of reflectors in the SMF, which has not been thoroughly studied yet.

In our previous work [10], we proposed a quasi-distributed acoustic sensing system with a weak reflector array. By using the array as the sensing fiber, this system shows an ultrahigh SNR. However, the weak reflector array used in this work has some problems not suitable to be used in the real applications. First, the transmission loss of the prototype is high, which is

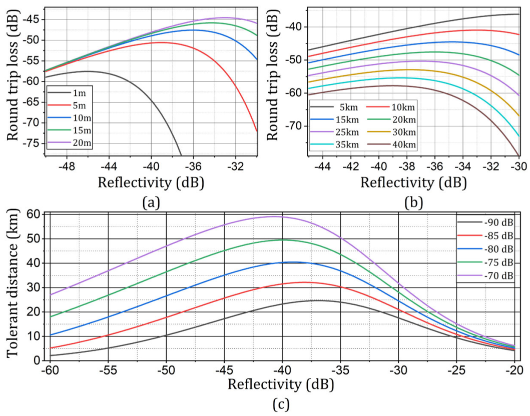

Fig. 1. Relationship between the round trip loss with the reflectivity for (a) different reflector spacing with a fiber length of 20 km and (b) different fiber lengths with a reflector spacing of 10 m. (c) Relationship between the tolerant distance with the reflectivity for different tolerated noise levels with a reflector spacing of 10 m.

about 1.1 dB/km and cannot satisfy the requirements for the long-distance sensing. Therefore, the geometric structure of the reflectors should have an optimized design to reduce the scattering loss of each reflector. On the other hand, the weak reflector array cannot be produced with a large multiplexing scale since it is difficult to make the fabrication process automatable. The focusing operation of the inscribing process requires a complicated manual control. It not only hinders by producing a weak reflector array with a large scale but also hinders the technical iteration to reduce the scattering loss. As the scattering loss of each reflector is very low, a large-scale multiplexed reflector array is needed to analyze the scattering loss of each reflector accurately.

In this Letter, we demonstrate the fabrication of a prototype of a weak reflector array, which has a length of 9.8 km, a reflector interval of 10 m, a reflectivity around −42 dB, and a transmission loss of 0.34 dB/km. This prototype is used as the sensing fiber, and it demonstrates that the weak reflector array approach can be used in Φ-OTDR system to achieve an ultrahigh SNR and a long sensing distance simultaneously with an equivalent spatial resolution of 10 m, which can be used in some high-end applications such as underwater acoustic sensing. An automatic femtosecond laser fabrication system is proposed to produce this prototype. Additionally, in order to optimize the performance, the reflector structure is carefully designed to make it have a high reflectivity and a low scattering loss.

In order to achieve an optimum performance of the system, an appropriate reflectivity of the reflectors should be calculated in advance. For this system, since the probe light wave is mainly reflected by the reflector instead of by RBS, the reflected signal power is much higher than the method of using SMF. Considering that a high reflectivity brings a high signal power but a large transmission loss simultaneously, the signal power reflected by the reflector at the far end may be not high. Here, we define the round trip loss as the power attenuation of the light wave reflected by the reflector at the far end that then transmits back. In order to achieve a low round trip loss, the reflectivity should be carefully designed not too high or too low. Figures 1(a) and 1(b) show the round trip loss in different conditions. The round trip loss is calculated as the summation of the transmission loss and the reflection loss,

$$\mathrm{loss}_{\mathrm{total}} = \mathrm{loss}_{\mathrm{fiber}} + \mathrm{loss}_{\mathrm{reflection}}, \tag{1}$$

where the transmission loss is set to be 0.18 dB/km, which is a traditional value of the commercial SMF, and the reflection loss is calculated to be the loss brought by the reflection. The tolerant distance for the array with different reflectivity is also calculated and shown in Fig. 1(c). This parameter is defined as the maximum sensing distance of the system to achieve a predetermined noise level, which can be calculated according to [10]

$$S(f) = \frac{et_r}{RP_s t_w}, \tag{2}$$

where e stands for the elementary charge, t_r stands for the repetition rate of the probe pulse, R stands for the responsiveness of the power detector, P_s stands for the signal power reflected by the last reflector, and t_w stands for the pulse width of the probe pulse. This simulation is calculated under the condition that the system uses a weak reflector array with a spacing of 10 m, and the probe pulse has a 6.4 μs width and a 5 dBm peak power. Since the pulse compression technique can be used in the system, the pulse width is not restricted by the reflector spacing. The repetition period of the probe pulse is calculated equal to the round trip time along the weak reflector array. The return loss is calculated with Eq. (1). In experiments, we found that the scattering loss of the reflector does not have obvious relationship with the reflectivity. Its variation is mainly related with the fabrication process. Therefore, even though the scattering loss may not be neglected in the actual condition, it does not influence the simulation of the relationship between the return loss and the reflectivity. According to Fig. 1, the optimum reflectivity for the typical applications is mostly in the range from −45 dB to −35 dB. By designing a new structure of reflector, we demonstrate that the weak reflector array can be inscribed in SMF with a reflectivity in this optimum range with a low scattering loss.

According to mode coupling theory, the light wave reflected by a reflector can be described as the contra-directional interaction between the forward and backward propagating waves along the fiber, which is affected by the perturbation of the waveguide refractive index. The degree of this interaction, which reflects the magnitude of the reflectivity, is represented by the coupling coefficient [11], which is associated with the modulation depth and the overlap area between the refractive index modulated area and the mode field. Note that using a high modulation depth but a small modulated area may bring a high scattering loss, as point shape and line shape [12] modulated area will generate Mie scattering when illuminated by the light wave. Therefore, a plane shape reflector to fully cover the mode field may be the best geometric structure as it can realize a high reflectivity and a low scattering loss simultaneously. Actually, there was a work report about FBGs inscribed by using a "plane-by-plane" method [13]. This method can be used to inscribe a refractive index modulated plane in the fiber by reshaping the focus into a cylindrical shape with a cylindrical lens and then scanning the focus. However, the plane inscribed by this method is not big enough to cover the fiber core and has a small index modulation depth, making the reflectivity not high. In order to realize a larger modulated area and a larger modulation depth, we design the structure to be a plane composed by several parallel lines with a dense distribution. The structure is shown in Fig. 2.

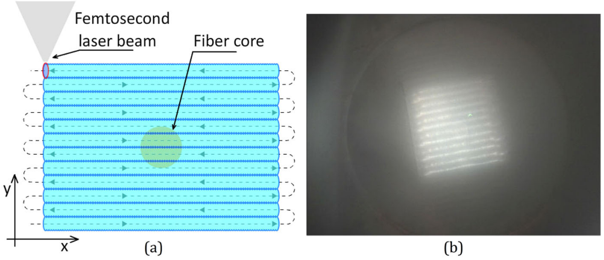

Fig. 2. Structure of the reflector surface. (a) Designed structure, where the red lined area stands for a single index modulated point caused by a femtosecond laser pulse. The reflector is inscribed by moving the laser focus along the dashed line in the arrowed direction. (b) Reflector surface captured by a microscope.

The setup of the femtosecond laser processing system is shown in Fig. 3. A coiling system is designed to supply and gather the fiber. It is necessary to measure the fiber length getting through in this system. The fiber is input into the system by the feeding spool and output from the system to the take-up spool. The moving force for the fiber is supplied by the motor attached to the take-up spool. It also controls the moving speed of the fiber. The fiber tension in the system is controlled by a brake attached to the feeding spool. A tension sensor is used in the coiling system to measure the fiber tension in real-time. The controller reads the tension from the sensor and adjusts it by controlling the output torque of the brake with a negative feedback. An optical encoder is attached to the counter wheel to measure the rotation angle, which corresponds to the fiber length getting through the system. The counter wheel has a perimeter of 0.25 m, and the optical encoder outputs 2000 signal pulses for each turn. Therefore, the accuracy of the length measurement is about 0.125 mm, which is also the minimum allowable reflector spacing of this method because the coiling motor is controlled by the feedback data of the coder. In each producing cycle of a reflector, the coiling system moves the fiber along the z axis with a length of 10 m and then stops to wait for the femtosecond processing system to write a reflector in the fiber. A semiactive fiber clamp is placed on the displacement platform to control the position of the focus point on the fiber. The main part of the clamp is a V-groove, which can clamp the fiber along x and y axis. The clamp does not affect the moving of the fiber along the z axis. In order to fix the relative position of the fiber core with the focus along x and y axis, the fiber tension is required to be controlled convergent to a constant value. The laser beam is generated by a femtosecond laser (Spectra-Physics, Solstice) with a wavelength of 800 nm, a pulse width of 100 fs, a repetition rate of 1 kHz, and a pulse energy of 4 mJ. Then the laser is attenuated by rotating a half-wave plate followed by a Glan-polarizer and focused by an x100 oil-immersed objective lens. The matched oil between the fiber and the objective lens can eliminate the aberration introduced by the cylindrical shape of the fiber.

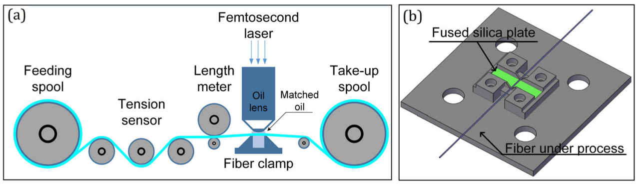

Fig. 3. (a) Setup of the femtosecond laser processing system. (b) The designed fiber clamp.

The reflector plane is composed of several refractive index modulated lines. Each line is inscribed by scanning the focus along the x axis with a predetermined speed. The scanning speed is fast so that the focus position is different when each femtosecond laser pulse arrives. Therefore, the modulated line is composed of several modulated points, which are generated by different laser pulses. The row spacing, which is the spacing of two neighboring points along the x axis, can be adjusted by controlling the scanning speed. After one modulated line inscribed, the focus is then moved up along the y axis to the initial inscribing point of the next line. The line spacing can be adjusted by controlling the moving distance along the y axis. Considering that the step size of the displacement platform is 1 μm, the resolution of the line spacing adjustment is restricted. The inscribing sequence of these lines is designed from the bottom to the top along the y axis to avoid the laser being refocused by the modulated area. As the fiber clamp cannot completely fix the fiber along the x and y axis when the fiber is getting through along the z axis, the focus location has a little variation for each reflector when being inscribed. Therefore, the reflector is designed to have an x-axis dimension of 50 μm and a y-axis dimension of 48 μm, which is big enough to ensure the modulated area covers the mode field despite of the focus variation. The size of the point modulated by each femtosecond laser pulse along the x axis and z axis are 1 μm. The reflector has a z-axis length of 1 μm, which is same as a single modulated point. The reflector is very short and cannot form a stable transmission mode. Therefore, it does not affect the mode field of the fiber. Considering the short reflector length and the long reflector spacing, the reflectors may bring little birefringence to the fiber. Figure 2(b) shows the photograph of an inscribed reflector surface. This inscribing method can realize a relatively large modulated depth since the laser power density in the focus is high. However, negative index modulation is also introduced because of the high laser power, which causes the scattering loss and deteriorates the reflectivity. In order to mitigate the effect of negative index modulation, the line spacing, the row spacing, and the laser power need to be carefully adjusted.

The adjusting parameters of the line spacing and row spacing are shown in Table 1, where the line spacing and row spacing are independent variables, while the laser power in each experimental group is a dependent variable. It is the optimum value for these experimental groups to achieve the highest reflectivity. In each experimental group, the prototype has a length of 100 m and a reflector spacing of 10 m. The transmission loss is measured from the OTDR trace of the prototype by calculating the intensity difference of the RBS between the beginning section

Table 1. Adjusting Parameters of the Point Spacing

No.	Line Spacing μm	Row Spacing μm	Power μW	Reflectivity dB	Transmission Loss dB/km
1	1	0.1	150	−55.08	3.1
2	1	1	220	−42.31	1.0
3	2	1	220	−37.24	0.8
4	2	0.5	200	−35.16	0.6
5	3	0.5	180	−41.99	0.4
6	4	0.5	190	−41.12	0.3

and the ending section of the prototype. This measurement has a deviation of about 0.1 dB as the measured prototype is short and the noise of the OTDR is relatively high. The reflectivity is measured by calibrating the mean intensity of the peak values of the reflectors on the OTDR trace with the intensity of the end face reflection peak, which is created by cutting the end of the prototype with a fiber cleaver and has a reflectivity of 4%. As shown in Table 1, among all the experimental groups, the sixth group shows a minimum transmission loss and a relatively high reflectivity. This performance can demonstrate the advantages of using the weak reflector array. Although a lower transmission loss was not achieved in this experiment, it may be realized by using a displacement platform with a smaller step size or adjusting the dimension of focus much more carefully, which is difficult to be implemented in our lab with current equipment.

A prototype of the reflector array is fabricated to demonstrate the system performance. This prototype is made under the configuration of experimental group 6 in Table 1, with a distance of 9.8 km and a reflector spacing of 10 m. An OTDR trace of the prototype is measured and shown in Fig. 4. By calibrated to the end face reflection shown in Fig. 4(d), the reflectors are measured to have a reflectivity varying from about −45 dB to −40 dB despite that there are some sections with large reflectivity variations. The averaged moving speed is about 8 m/min. It also takes about 5 s to inscribe a reflector. Therefore, the processing time of fabricating the prototype is about 20 h. During that time, many disturbances may apply to the system, making the uniformity of the reflectivity poor. Here, we show the section with the best reflectivity uniformity in Fig. 4(b). We believe that by optimizing the fabrication system, the uniformity can be further improved. Moreover, in the experiment, we found that good uniformity brings low scattering loss, and has potential to further reduce the transmission loss. In order to measure the transmission loss of the prototype fiber, two sections of SMF with a length of 100 m are fused at the near end and the far end of the prototype. As shown in Figs. 4(c) and 4(d), considering that the averaged reflectivity of RBS at the near end SMF is −63.92 dB and at the far end is −70.72 dB, the transmission loss is 0.34 dB/km. Considering that the SMF has a transmission loss of about 0.18 dB and a RBS ratio of about −60 dB when being probed by a 100 ns long pulse, this prototype brings a 15.8 dB enhancement to the signal power at the far end of the fiber, which is a significant improvement of the system performance. The transmission loss introduced by each reflector is calculated to be 0.0016 dB. We used a reflector array with 49 line shape reflectors in our previous work [10], which have a reflectivity of about −40 dB and a transmission loss of 0.018 dB for each reflector. In comparison to the line shape reflector having the similar reflectivity, the transmission loss of the reflector written with the new method is greatly reduced. Since the transmission loss of the array is mainly determined by the reflectors, the reflector array inscribed by the new method can achieve a larger multiplexing scale than the line shape method. Additionally, the OTDR used in the experiment uses DFB lasers with center wavelengths of 1310 nm, 1450 nm, 1550 nm, and 1650 nm and linewidths of about 1 nm as the light sources. The OTDR traces measured with different wavelengths show good consistency except the transmission losses are different for different wavelengths, which means that the reflection spectra are nearly flat.

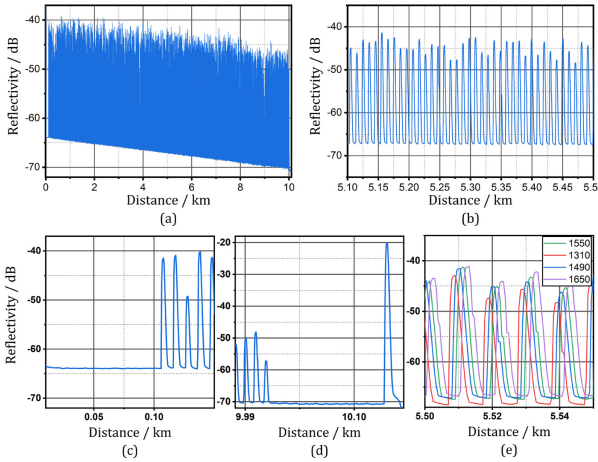

Fig. 4. OTDR trace of the prototype reflector. (a) The full trace of the prototype. (b) Trace of the section with the best reflectivity consistency. (c) The beginning part of the trace. (d) The ending part of the trace. (e) Traces measured with a light wave of different wavelengths.

In conclusion, a new fabrication method of a weak reflector array is proposed in this Letter. The weak reflector array can be used in the quasi-distributed acoustic sensing system to achieve an ultrahigh SNR and a long sensing distance simultaneously. In order to produce a large-scale multiplexed array and facilitate the technical iteration, we propose an automated fabrication system. Based on this system, the transmission loss and the reflectivity are optimized by carefully designing and adjusting the reflector structure. The prototype using the designed geometric structure with a length of 9.8 km and a reflector spacing of 10 m is demonstrated, realizing a reflectivity around −42 dB and a transmission loss of 0.34 dB/km, which is the optimum parameter for the quasi-distributed acoustic sensing system.

Funding. Ministry of Science and Technology of the People's Republic of China (2017YFB0405500); National Natural Science Foundation of China (61735015, 61620106015, 61775132).

Disclosures. The authors declare no conflicts of interest.

[†] These authors contributed equally to this Letter.

REFERENCES

1. Y. Lu, T. Zhu, L. Chen, and X. Bao, J. Lightwave Technol. **28**, 3243 (2010).
2. G. Yang, X. Fan, S. Wang, B. Wang, Q. Liu, and Z. He, IEEE Photon. J. **8**, 6802412 (2016).
3. D. Chen, Q. Liu, and Z. He, Opt. Express **25**, 8315 (2017).
4. Z. N. Wang, J. J. Zeng, J. Li, M. Q. Fan, H. Wu, F. Peng, L. Zhang, Y. Zhou, and Y. J. Rao, Opt. Lett. **39**, 5866 (2014).
5. S. Loranger, M. Gagné, V. Lambin-Iezzi, and R. Kashyap, Sci. Rep. **5**, 11177 (2015).
6. H. Guo, J. Tang, X. Li, Y. Zheng, H. Yu, and H. Yu, Chin. Opt. Lett. **11**, 030602 (2013).
7. S. Liu, G. He, Z. Zheng, L. Ding, A. Zhou, H. Guo, C. Zhou, and D. Jiang, J. Lightwave Technol. **38**, 1900 (2020).
8. L. Xin, Z. Li, X. Gui, X. Fu, M. Fan, J. Wang, and H. Wang, Opt. Express **28**, 6794 (2020).
9. Z. Chen, L. Yuan, G. Hefferman, and T. Wei, Opt. Lett. **40**, 320 (2015).
10. M. Wu, X. Fan, Q. Liu, and Z. He, Opt. Lett. **44**, 5969 (2019).
11. T. Erdogan, J. Lightwave Technol. **15**, 1277 (1997).
12. K. F. Ren, G. Gréhan, and G. Gouesbet, J. Opt. Soc. Am. A **14**, 3014 (1997).
13. P. Lu, S. J. Mihailov, H. Ding, D. Grobnic, R. B. Walker, D. Coulas, C. Hnatovsky, and A. Y. Naumov, J. Lightwave Technol. **36**, 926 (2018).