Full Link SNR Equalization DAS System over 80km Based on Gradient Discrete Scattering Enhanced Fiber

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Abstract: We proposed a full-link SNR-equalization DAS based on gradient discrete scattering enhanced fiber with backscattering rates increase gradually according to optical loss. The experimental results show a $15\text{p}\varepsilon/\sqrt{Hz}$ strain resolution over 80km.

1. Introduction

Fiber optic distributed acoustic sensing (DAS) technology based on phase sensitive optical time domain reflectometry (φ-OTDR) has been applied in many fields [1], and the applications in multiple fields bring forward new demands for DAS, where long-distance high-quality equalization acoustic detection is one of the most urgent one. In DAS system, the optical transmission loss brings a low optical power and a large noise in the far end, which limits the application in the field of long-distance detection, such as pipeline and railway safety monitoring. A common method to improve the far end signal-to-noise ratio(SNR) is amplification. The Erbium-doped fiber amplifier (EDFA), distributed Raman amplification and distributed Brillouin amplification has been widely studied, and the detection range can reach over 108km without any relays [2]. However, the signals detected by far-end are much worse than near-end, leading to large noise and more sensing blind areas induced by low optical power. Another method is using scattering enhanced optical fiber(SEF). A specific section of scattering enhanced fiber in far-end is utilized to replace the ordinary single mode fiber to improve SNR and realized high quality acoustic detection at 125km [3]. However, the scattering enhanced fiber will greatly consume light power, which can only improve SNR within a short range [4].

In this paper, a full link SNR equalization DAS system over 80km was demonstrated based on the proposed gradient discrete scattering enhanced fiber (GDSEF). With a series of discrete scattering enhanced points (SEP) inscribed along the axial direction, GDSEF can enhance the SNR of the backscattering signal. Particularly, the backscattering rates of SEPs are specially designed by the power distribution of the probe light: scattering rates of near-end SEPs are relatively weak enhanced for less power loss, while the far-end SEPs have a stronger scattering rates for SNR improvement, and thus the SNR equalization can be realized. The simulation results show that the proposed method can realize over 80km full link distributed SNR Equalization acoustic detection. Further, to verify our method, a GDSEF composed of four different backscattering rates SEFs is fabricated. To simulate the loss caused by longer distance GDSEF, three 25km single mode fibers (SMFs) are connected with the four SEFs. The results show that DAS system based on GDSEF can recover acoustic signal over 80km with the extremely high quality, whose strain resolution can be less than $15\text{p}\varepsilon/\sqrt{Hz}$(@10Hz) with an 88.1% probability, indicating a great far-end sensing performance which is close to the near-end of the traditional DAS system.

2. Principle and simulation analysis

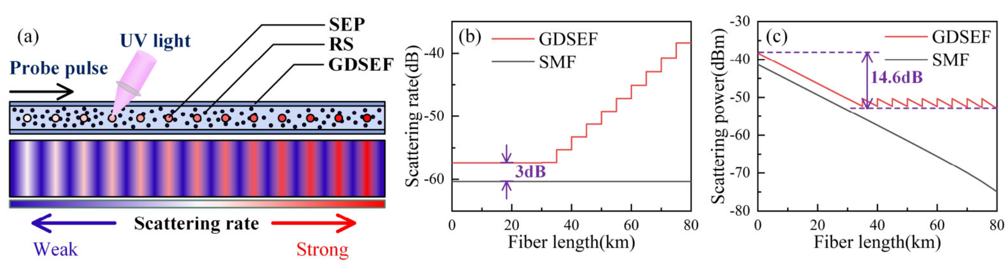

Fig. 1. (a) Diagram of GDSEF DAS. RS: Rayleigh scattering. UV: Ultraviolet. Simulation results: (b) Scattering rate of SMF DAS and GDSEF DAS; (c) Scattering power of SMF DAS and GDSEF DAS.

The scheme of DAS based on GDSEF is shown in Fig. 1(a). In long distance DAS, the signal quality in far-end is limited by low backscattering power, leading to a deterioration of the sensing signal which is affected by optical noise. Besides, the large power difference between near end and far end will also bring much noise. For example, a 100km fiber will bring a 40dB power difference. Therefore, the far-end signal might be completely submerged in PD noise to ensure that the near-end signal is not saturated, which is limited by the dynamic range of PD. To obstacle the problem, a series of discrete SEPs are inscribed in the sensing fiber, and their backscattering rates are specially designed according to the light power distribution: the near-end SEPs have a weak backscattering enhancement and far-end SEPs have strong backscattering enhancement for higher backscattering power and less power difference. It is noted that the backscattering rates need to be set carefully since SEP with a high backscattering rates will greatly consume light power.

In order to verify our method and provide theoretical basis for the GDSEF fabrication, a simulation analysis is conducted for optimal SEP settings whose result is shown in Figs. 1(b) and 1(c). In the simulation, the spacing between SEPs is set 5m and the backscattering power dynamic range is set as 15dB to obtain large backscattering signals in the full-link. In the near end, owing to the strong enough Rayleigh backscattering power, the SEPs provide only 3dB backscattering enhancement to avoid the coherent fading of SMF and reduce power consumption. With the increase of distance, the backscattering power will be decreased. When the backscattering power exceeds the 15dB limit, the SEPs with stronger backscattering enhancement have to be used to obstacle the limit. As shown in Fig. 1(c), with the specially designed backscattering enhancement, the far-end backscattering power is exactly 15dB smaller than the near-end to save the optical power. Consequently, the simulation result demonstrates that our method can realize SNR equalization over 80km with a 5m spatial resolution.

3. The fabrication of GDSEF

To realize the fabrication of the GDSEF, the energy of laser, the stability of tension and the speed of servo motor for fiber winding should be controlled with high precision, which can ensure accurate gradient discrete scattering enhanced of SEP. Here, the on-line automatically inscription system is set up, which contains a program logic control (PLC) grating fabrication platform and the UV-transparent coating optical fiber (UV-TCF), as shown in Fig. 2(a). The UV-laser is 248nm KrF Excimer laser (IPEX-700) with up to 300mJ energy output and 20ns pulse duration. The SEPs are directly inscribed into UV-TCF through single pulse exposure, in which the fiber owns a high UV transmissivity coating. The winding system can work at the continues and trigger working modes, which can realize precise spacing control. Then, a phase mask is employed to produce periodic interference pattern which determines the wavelength region of enhanced scattering. The scattering intensity of SEF can be precise controlled by adjusting inscription condition, such as laser spot length, pulse energy, the focusing degree of the laser spot and so on.

In this work, the fiber winding speed is set as 60m/min, the laser pulse frequency is modulated to 0.2 Hz, and the laser pulse energy are respectively set as 150mJ/200mJ/250mJ/300mJ for the four SEFs. Besides, the four SEF are fabricated with the lengths of 2.1km/2.2km/4km/2.2km respectively, and the spacing of each SEF is 5m. Fig. 2. (b) illustrates the OTDR traces of SEF1~ SEF4, indicating that each SEP is fabricated successfully without any omissive grating. Compared to the SMF, the scattering enhancement of SEF1~SEF4 are stepped increased with 7.5dB/10dB/12.5dB/15dB respectively. Besides, the scattering intensity fluctuation of SEP is only within 3dB by optimizing the fabrication parameters such as the control of tension, and the slight fluctuation is mainly caused by the instable laser energy.

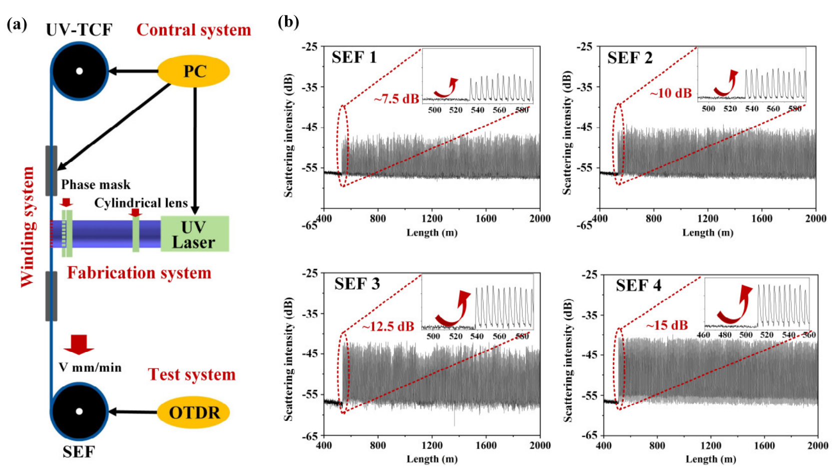

Fig. 2. (a) SEF on-line automatically inscription system. (b) the OTDR trace of SEF1~ SEF4.

4. Experimental setup and results

In order to verify our method, the four SEFs are sorted by backscattering rate and connected. It is noted that although only four SEFs are used in the test to perform theoretical verification, our method can realize full link backscattering enhancement. As shown in Fig. 3(a), to simulate the longer distance GDSEF loss, three 25km SMFs is spliced with the four SEFs. In the experiment, the self-developed DAS system based on coherent detection and polarization diversity reception is used as interrogator [5], which connects to GDSEF and sends probe pulses into the fiber with a 100Hz pulse repetition frequency. As shown in Fig. 3(b), the SEFs can amplify signal effectively and the far end backscattering signal have a good SNR. Then, the signal quality of GDSEF DAS and SMF DAS is compared. The noise floor in 473 sensing channels of the SEF2 are recorded under a quiet environment, and further the strain resolution is calculated. Similarly, the quiet environment signals are recorded by an 85km SMF, and 473 sensing channels at the same location are used for contrast. The strain resolution distribution of two systems is presented in Figs. 3(c) and 3(d). It can be seen that GDSEF DAS have a better noise floor and the strain resolution can be less than $15\mathrm{p}\varepsilon/\sqrt{Hz}$(@10Hz) with an 88.1% probability for the whole 473 channels, while the SMF DAS only has 30.5% probability. Furthermore, we wrapped 3m optical fiber of SEF4 around a piezoelectric transducer(PZT) to applied a sinusoidal wave with the amplitude of 10V and the frequency of 10Hz. As presented in Fig. 3(e), the sine signal is recovered with high fidelity whose fitting coefficient R^2 is 0.999. The results show that GDSEF DAS can realize full-link high quality acoustic detection over 80km.

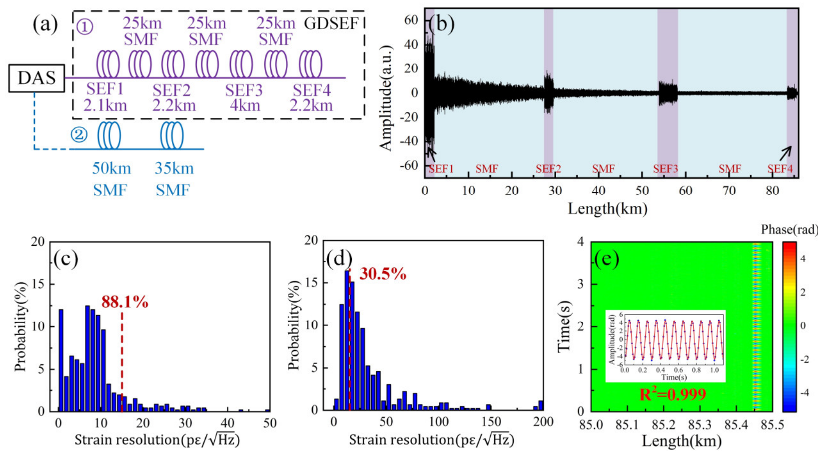

Fig. 3. Experimental setup and results. (a) Experimental setup of GDSEF DAS; (b) The back scattering signal of GDSEF; (c) The strain resolution distribution of GDSEF DAS; (d) The strain resolution distribution of SMF DAS; (e) Temporal and spatial distribution pattern of signal at the far end; Inset: temporal signal from PZT.

5. Conclusion

In summary, we have proposed and demonstrated a full link SNR equalization DAS system based on the proposed GDSEF. A series of discrete SEPs are inscribed into GDSEF along the axial direction whose backscattering rates are specially designed according to the power distribution of the probe light. The simulation demonstrates that the proposed method can realize over 80km full link distributed acoustic sensing with an 5m spatial resolution. Further, a GDSEF composed of four different backscattering rates SEFs is fabricated and used for acoustic detection. The results show that DAS system based on GDSEF can recover acoustic signal over 80km with the high fidelity, whose strain resolution can be less than $15\mathrm{p}\varepsilon/\sqrt{Hz}$(@10Hz) with an 88.1% probability, indicating a great far-end sensing performance which is close to the near-end of the traditional DAS system. Our method can realize full link SNR-equalization acoustic detection over ~80km, which greatly expands the application scope of DAS, especially in the fields requiring long-distance and high-fidelity measurement such as railway and pipeline monitoring.

6. Acknowledgements

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