246km Long Distance fiber optic DAS System Based on Multi-Span Bidirectional EDFAs and Cascaded AOMs

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Abstract: A long-distance DAS system based on multi-span bidirectional erbium-doped fiber amplifier was proposed. Assisted with high ER pulse from cascaded AOMs, 246km sensing distance was realized using four-segment relays.

1. Introduction

Due to the advantages of ultra-high sensitive, long-distance passive measurement and the immunity to electromagnetic interference, fiber optic distributed acoustic sensing (DAS) technology based on phase sensitive optical time domain reflectometry (φ-OTDR) has been applied in many areas [1]. In DAS system, the detection pulse power is limited by nonlinear effect, which leads to a weak scattering signal and limits the application in the field of ultra-long detection range, such as pipeline safety monitoring and railway safety monitoring. A common method to extend the sensing distance is distributed Raman amplification, which can provide a smoother power distribution to avoid nonlinear effect and has realized 103km vibration detection [2]. However, the sensing distance is also limited because of the limited pump efficiency. Therefore, the multi-span relay amplification technology based on Erbium-doped fiber amplifier (EDFA) was also widely studied [3]. The Er-doped fibers were used to amplify the bidirectional light signal and the sensing length can reach up to 100km. However, owing that the power of forward probe pulse is much larger than that of backscattering light, most of the carriers are consumed by forward probe light. Therefore, the backscattering light will not be magnified effectively, which limits the span distance. What's more, because the EDFA will bring the amplified spontaneous emission(ASE) noise and degrade the extinction ratio of light pulse, both length and number of span are limited, which hinders the further improvement of sensing length.

In this work, a long-distance DAS scheme based on cascaded acousto-optic modulators (AOMs) and multi-span relay was proposed, where the bidirectional EDFA module is designed as relay module to amplify both the probe light and backscattered light. The noise model of multi-span bidirectional EDFAs is established firstly, where a high pulse extinction ratio(ER) is needed for a long sensing distance. Furthermore, a coherent detection based DAS system with high ER and multi-span relay amplification are established and tested. The acoustic signals at 246km are detected and recovered with a high signal-to-noise ratio(SNR) of 14dB, which is highest sensing distance to the best of our knowledge.

2. Design and optimization of bidirectional EDFA relay for multi-span DAS

In order to extend span distance, a bidirectional EDFA amplifier module is designed as shown in Fig. 1(a). The amplifier module consists of two EDFAs (EDFA1 and EDFA2) and two circulators (C1 and C2). The forward probe pulse is amplified by EDFA1 through the path A and the backscattering light is amplified by EDFA2 through the path B. Compared with single EDFA, the module can set the pump current of two EDFAs separately and achieve the best relay performance.

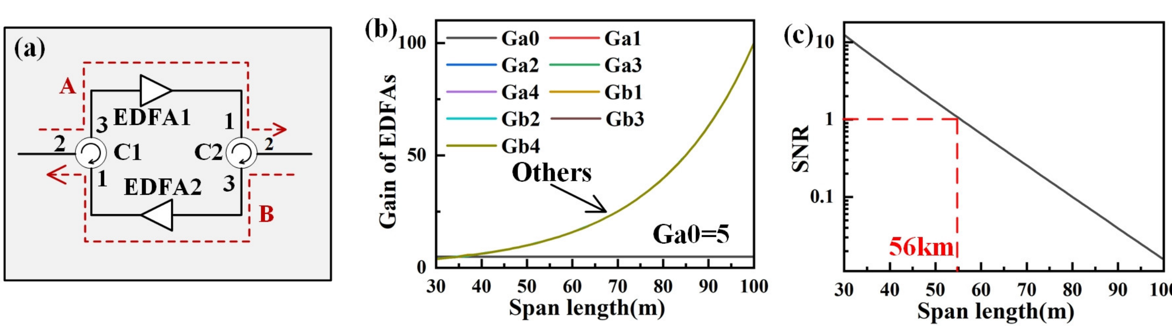

Fig. 1. (a) bidirectional EDFA amplifier module. (b)The optimal EDFA gain allocations and (c)SNR of Rayleigh scattering at the end of span under different span length.

Further, the noise model of bidirectional EDFA relay based multi-span DAS is established. In the multi-span DAS, two kinds of optical noise need to be considered, which are the turn off noise caused by light leakage of detection pulse and the ASE noise of EDFA. The power of light leakage can be expressed as $P_{leak} = P_{pulse}/ER$, where P_{pulse} is the peak value power of probe pulse and ER is extinction ratio. Because light leakage is continuous, the turn off noise in the receiving end is superposition of light leakage's Rayleigh scattering during the whole optical fiber link. While the probe signal in the receiving end is the superposition of pulse's Rayleigh scattering, whose superposition length is the pulse's duty ratio(DR) times the turn off noise. Therefore, a higher ER is needed for DAS. If the ER can much larger that $1/DR$, the turn off noise can be ignored. Another optical noise is ASE noise of EDFA, which will be larger when the gain of EDFA is larger as $P_{ASE}(G) = n_{sp} \cdot h\nu \cdot (G-1) \cdot \Delta\nu$, where n_{sp} is the spontaneous emission coefficient, h is Planck constant, ν is the optical frequency, G is the gain of EDFA and $\Delta\nu$ is the optical bandwidth. Therefore, the pump of EDFA should be optimized according to the following aspects. If the pump power of EDFA is too small, the optical signal cannot travel far enough. While if the pump power of EDFA is too large, the additional ASE noise will be accumulated.

Here, a DAS system with five spans is analyzed as an example, where the pulse wide and peak power are set as 200ns and 8mW, ER is set as 100dB and nonlinear threshold power is set as 40mW. Firstly, the optimal EDFA gain allocations are solved under different span length, whose results are plotted in Fig. 1(b) where the forward amplifier's gain before the first span is expressed as G_{a0}, and the forward and backward EDFAs' gain after nth span is expressed as G_{an} and G_{bn} respectively. It can be seen that G_{a0} needs to be 5 to enlarge the peak power up to nonlinear threshold power and other EDFAs' gains are same as each other. Further, the SNRs of Rayleigh scattering signal at the end of span under optimal EDFA gain allocations are calculated and shown in Fig. 1(c). Owing that more fiber loss, the longer span will bring the poorer SNR. When SNR is less than 1, the noise will draw up the signal and the sound waves cannot be recovered. Therefore, the longest span is 55km, corresponding to 275km sensing distance.

3. Experimental Setup and Results

In order to verify the method, bidirectional EDFA module for multi-span relay amplification is employed to build a prototype system. The configuration is shown in Fig. 2, where coherent detection and polarization diversity reception are employed [4]. The cascaded AOMs modulate light signal into pulse synchronously for a high ER pulse with >82dB. Further, four amplifier modules are used as remotely gain units(RGU), and the distance between each other is 49.4km, 49.4km, 49.5km, 49.5km, respectively. Moreover, a section of fiber(FUT5) with the length of 48.7km is connected to the fourth RGU and the far-ends of five FUTs are wrapped around piezoelectric transducers(PZTs), corresponding to the sensing distance of 49.4km, 98.8km, 148.3km, 197.8km and 246.5km, respectively.

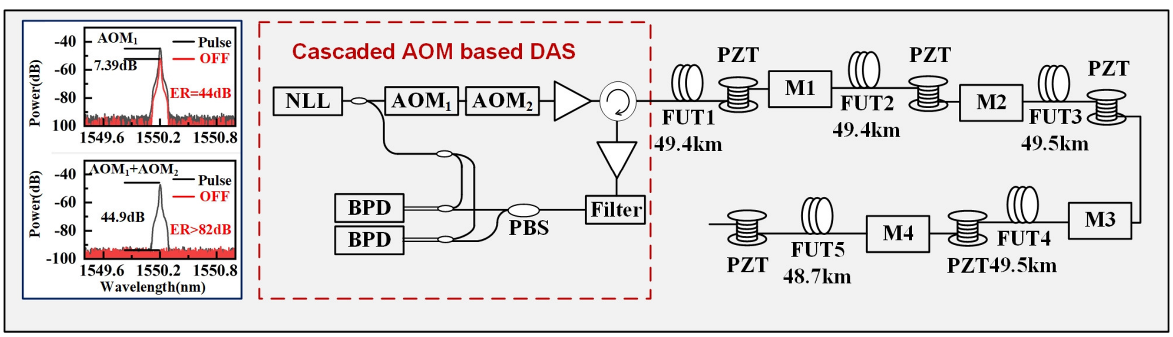

Fig. 2: Multi-span relay amplification based DAS system. M1-M4: the bidirectional EDFA amplifier module.

In the experiment, the probe pulse with 200ns pulse width and 2.5ms pulse repetition period is injected into the FUT. Due to the limitation of distance bandwidth product, the longest detection distance is 250km, which is just suitable for the system of Fig. 2. According to the discussion in part 2, the pump currents of forward EDFAs are set as 100mA and that of backward EDFAs are set as 100mA. PZT are driven by sinusoidal wave with the amplitude of 0.5V and the frequency of 60Hz. Firstly, the back scattering signal of a probe pulse is detected and presented in Fig. 3(a). It can be seen that the bidirectional EDFA modules can amplify signal effectively, and the beat frequency can be distinguished from the ground noise. Finally, the acoustic signal of PZT is demodulated by the dual-polarization vector superposition demodulation algorithm [5]. As shown in Figs. 3(b)- 3(g), the sinusoidal waves at different locations can be recovered successfully, whose fluctuation of amplitude is caused by interference fading. Notably, 246.5km is the highest sensing length to the best of our knowledge, in which SNR can reach 14.1dB.

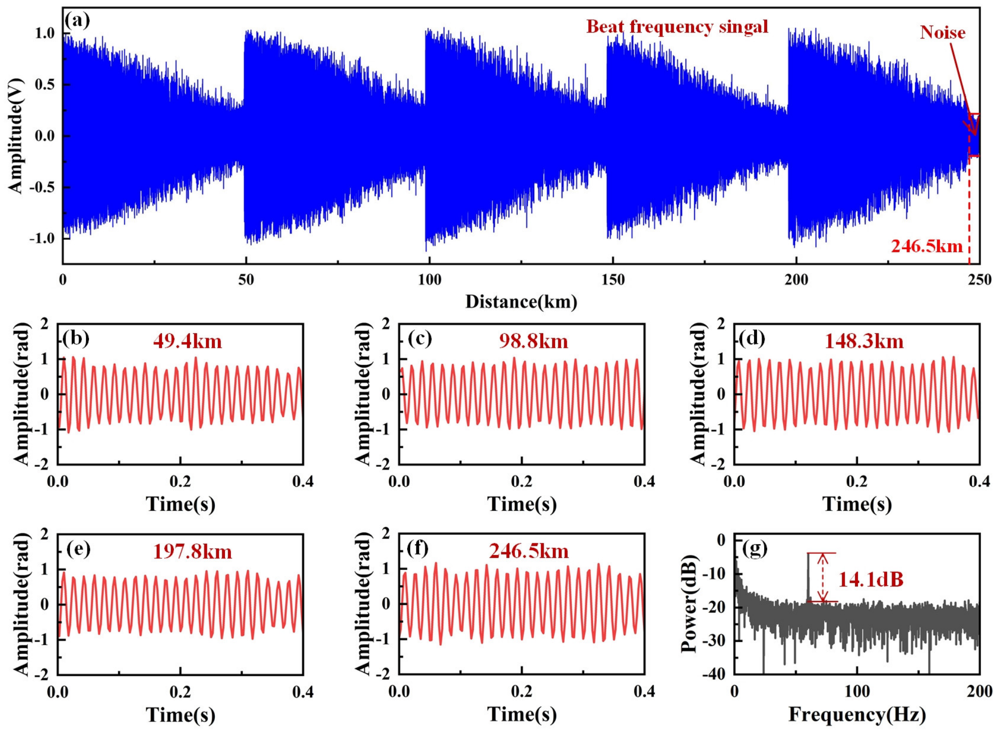

Fig. 3. The experiment result. (a)The back scattering signal of a probe pulse. (b-f) Time domain signals at (b)49.4km, (c)98.8km, (d)148.3km, (e)197.8km and (f)246.5km. (g) Frequency domain signal at 246.5km.

4. Conclusions

In summary, we have proposed and verified a long-distance DAS system. Firstly, a bidirectional EDFA module is designed which can amplify both forward and backward optical signal. Then the noise model of the EDFA module based multi-span DAS is established, where a high pulse extinction ratio(ER) is needed for a longer sensing distance. Furthermore, a prototype system with four-segment relays is built with a sensing distance up to 246 km and a 14dB SNR, which is highest sensing length to the best of our knowledge. The scheme greatly expands the application scope of DAS, especially in the fields requiring long distances measurement such as railway monitoring and tunnel safety monitoring.

5. Acknowledgements

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