208km ultra-long single span hybrid BOTDR and Φ-OTDR with ROPA technology

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Abstract: Ultra-long single span hybrid BOTDR and Φ-OTDR system with ROPA technology is proposed. Using double heterodyne detection configuration, high order Raman amplifiers, cascaded RGUs, 208km unrepeatered real time simultaneous temperature and vibration measurement is achieved.

OCIS codes: (060.2370) Fiber optics sensors; (230.4480) Optical amplifiers

1. Introduction

Distributed sensing systems can transform an optical fiber cable into an array of sensors, with the advantages of ultra-high sensitive, long-distance passive measurement and the immunity to electromagnetic interference. Multi-parameter measurement, such as vibration, temperature,and strain etc. can comprehensively monitor the health status of optical fiber, which is of great demand in submarine networks and ultra high voltage(UHV) ac power grid. The hybird systems of BOTDR(for temperature and strain measurement) and Φ-OTDR(for vibration measurement) have been developed intensively[1-2]. Most of the systems' sensing distances are limited to 50km, due to the detection pulse power is limited by undesired nonlinear effect in the fiber. Distributed Raman amplification, which can provide the probe pulse a distributed gain along the fiber to avoid nonlinear effect, has been used to extend sensing distance to over 100km[3-4]. However, it still cannot meet the requirement of UHV networks, whose unrepeatered transmission span is usually above 200km. Remote pumped optical amplifier(ROPA) is another key technology to increase the sensing distance for unrepeatered systems. By inserting a small section of Erbium-doped fiber(EDF) into remote end of the sensing fiber, while its pump power is injected from detection end, the sensing signal can then be remotely amplified without relay[5]. However, few attempts to use ROPA assitance in distributed optical fiber system have been developed.

In this paper, a ultra-long single span hybrid BOTDR and Φ-OTDR system based on ROPA technology is proposed. Brillouin signals and Rayleigh signals are divided into two beams and detected separately by two coherent receivers. By applying high order Raman amplifiers, cascaded RGUs and ultra low loss G654E fiber, the vibration and temperature information at the distance of 208km is detected, which is highest unrepeatered sensing distance to the best of our knowledge. The SNR of the recoverd 100Hz vibration signal is 35dB, and the measurement uncertainty of BOTDR during the last 1km length is 1.05MHz.

2. Experimental setup

The simplified schematic of our proposed system is shown in Fig.1. A 1550nm narrow linewidth laser(NLL) with 15dBm output power and 400Hz linewidth is used as the light source, whose output is divided into local light and probe light through a 90:10 coupler. The continuous-wave probe light passes through the Acousto optic Modulator(AOM), which generate the probe pulse with 300ns width and 2.5ms repetition period. After being amplified by Erbium doped fiber amplifier(EDFA), the probe pulse is launched into the test fiber through the circulator. The local light is divided into two parts through a 70:30 coupler. The lower power branch serves as the reference light for Φ-OTDR, and is connected to an Integrated coherent receiver(ICR) with 250MHz bandwidth. The other branch is modulated by an Electro optic Modulator(EOM), driven by a microwave source, which generates about 10.8GHz frequency shift to the reference light of BOTDR. By optimizing the splitting ratio of the loacl light, the performances of the BOTDR and Φ-OTDR are balanced. Another ICR with 500MHz bandwidth is used for heterodyne detection of Brillouin signal and eliminating the dependence of the Brillouin gain on polarization. The IF signals from the ICR of BOTDR are amplified by a low noise amplifier(LNA) with 30dB gain and filtered by a 10MHz bandwidth bandpass filter(BPF). The reflected optical signal from circulator includes Brillouin signals and Rayleigh signals, and are pre-amplified by an EDFA with 100GHz filter. Brillouin signals are seperated with Rayleigh signals by a 50:50 coupler and narrowband Fiber Bragg Grating(FBG). The data is synchronously collected by a Data Acquisition Card(DAQ) with sampling rate of 125MSa/s.

The ROPA system consists of two parts: remote pumping unit(RPU) and remote gain unit(RGU). RGU consists of a section of EDF, and receives the pump light from RPU to amplify the probe pulse. The test fiber is assembled with G.654E fiber, which has an average loss(including splices) of 0.157dB/km and effective area of

130μm^2. The fiber link consists of four parts, divided by three RGUs. These RGUs are located at about 100km、143km、178km respectively. The dedicated pump path is used to provide residual pump power for the farthest RGU, and is adjusted to 178km, using the same fiber with the probe path. The 2nd order RPU modules have 2 wavelengths of 1340nm, 1360nm to realize Raman amplification for 1st order pump wavelengths. The 1st order RPU modules of probe path have 4 wavelengths ranging from 1425nm to 1480nm to realize both raman amplification for porbe pulse and provide residual pump power for RGUs. The 1st order RPU modules of dedicated pump path have 3 wavelengths to maximize residual pump power of 1480nm.

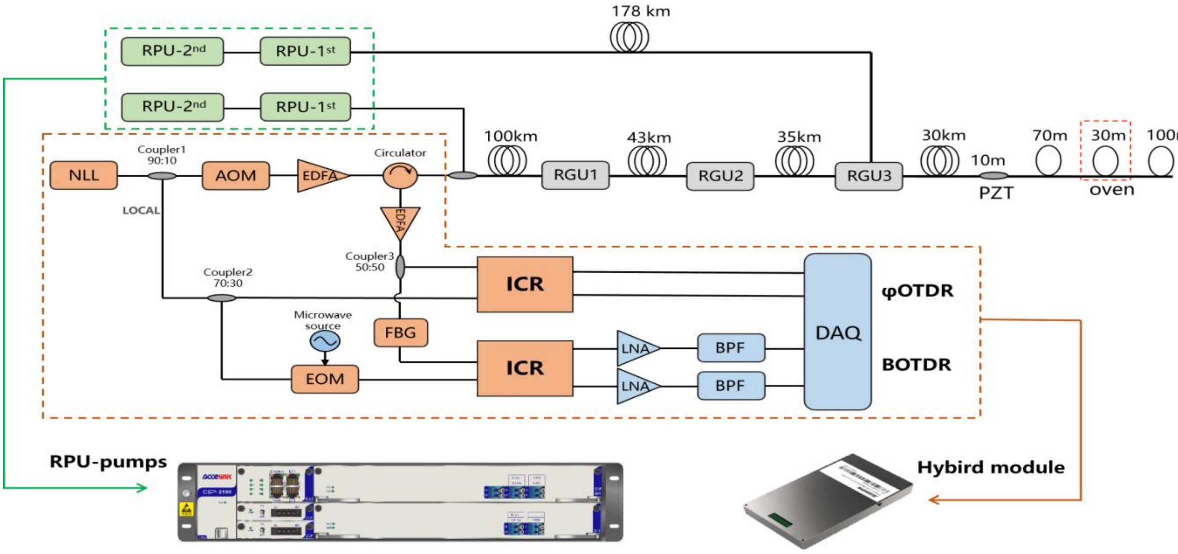

Fig.1. Experimental setup. NLL: narrow linewidth laser; AOM: acousto-optic modulator; EDFA:Erbium Doped Fiber Amplifier; ICR: Integrated coherent receiver; EOM: electro-optic modulator; FBG: Fiber Bragg Grating; LNA: low noise amplifier; BPF: band-pass filter; DAQ: data acquisition card; RPU: remote pumping unit; RGU:remote gain unit; PZT: piezoelectric transducer;

3. Experimental results and discussion

In this paper, the total length of test fiber is about 208km, with 32.6dB loss (including the loss of all connection points and fusion points of the line). Temperature and vibration measurement experiments are carried out to check the performance of the hybird system. As shown in Fig.1, a piezoelectric transducer(PZT) of 10m wrapped fiber is used for vibration test. And an oven with 30m fiber loop inside is used for temperature test. To realize an ultra-long sensing distance, the power of probe pulse and Raman pumps should be carefully optimized. The probe pulse power launched in the fiber is 16.3dBm. The probe path pump power launched is 2430mW, with 10dB forward on-off Raman gain, and the residual pump powers reaching at RGU1 and RGU2 are 14.1mW and 1.8mW. The dedicated pump power launched is 2935mW, with the residual pump power reaching RGU3 is 1.4mW. The time domain Rayleigh trace is shown in Fig.2(a). The probe pulses are successively amplified by three RGUs, whose EDF length is optimized to achived the maximum gain, with the peak pulse output powers are 18.9dBm, 16.9dBm and 15dBm respectively.

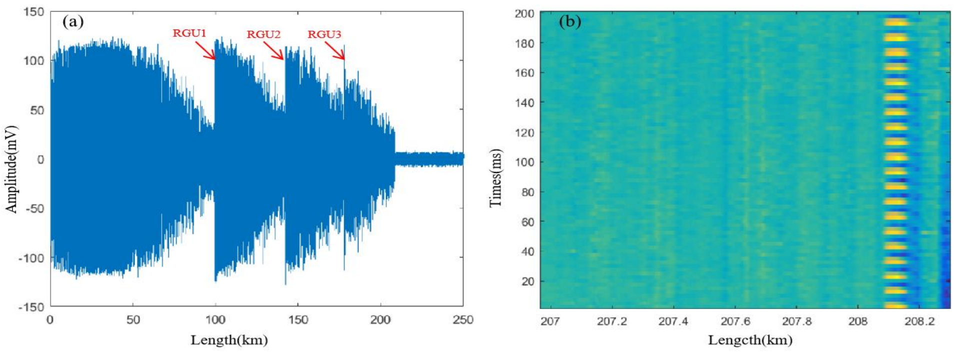

Fig. 2. (a) Time domain traces of Rayleigh trace; (b) 3D map of the distribution of the vibration.

At the end of the fiber, the PZT is driven by sinusoidal wave with the amplitude of 1.5V and the frequency of 100Hz. Piezoelectric constant is 200μm/V. The phase information of the vibration can be extracted through IQ demodulation,with 30m gauge length for processing differential phase. Fig.2(b) shows the waterfall of the PZT area, it can be seen that the vibration is clearly recognized. As shown in Fig.3(a), the 100Hz sinusoidal waves can be recovered successfully, whose fluctuation of amplitude is caused by interference fading and the limit of the unwrapping algorithm. The power spectral is presented in Fig. 3(b), and the SNR of the 100Hz signal can reach 35dB.

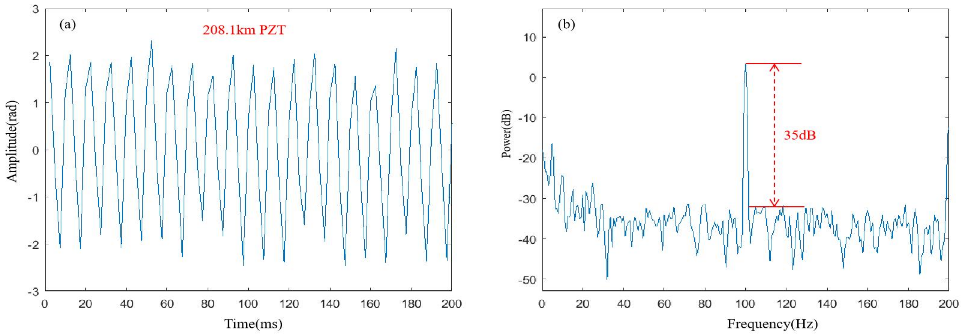

Figure.3. (a) Demodulated 100Hz phase signal at 208.1km PZT; (b) The spectra of the demodulated phase signal.

BFS distribution of the total fiber, as shown in Fig. 4(a) is obtained by sweeping the frequency of the Microwave source from 10.4GHz to 10.8GHz with the step of 2MHz. 1000 average times are applied towards the Brillouin trace to enhance the SNR. And then the Lorentz fitting method is used, without any denoise process. As presented in Fig. 4(b), when the 30m loop fiber in oven is heated from 30℃ to 40℃, the BFS at the point rise about 9MHz, which is consistent with the applied change of temperature, within the tolerance of experimental error. By calculating the standard deviation of the last 1km data, the measurement uncertainty obtained is 1.05MHz.

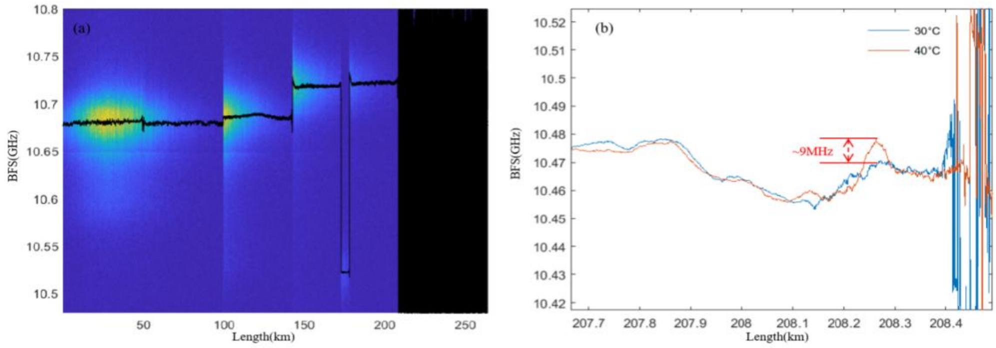

Figure.4. (a) BFS distribution of the total fiber; (b) BFS distribution change of heating oven.

4. Conclusion

In summary, we have experimentally demonstrated a ultra-long single span hybrid BOTDR and Φ-OTDR system to realize simultaneous temperature and vibration sensing based on ROPA technology. Thanks to the combination of double coherent detection, high order Raman amplifiers, and cascaded RGUs, 208km sensing range is achieved, which is highest single span length to the best of our knowledge. The 100Hz sinusoidal vibration signal is recovered successfully by Φ-OTDR, with 35dB SNR in Frequency domain. At the same time, the measurement uncertainty of BOTDR is calculated to be 1.05MHz. The scheme greatly expands the unrepeatered sensing distance for BOTDR and Φ-OTDR system, and is hope to be used at such as submarine networks and ultra high voltage ac power grid.

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