Review of Optical Fiber Sensing Technology and Principle

Jinze Shi[1]

[1] *Shanghaitech University, School of Physics Science and Technology(SPST), Pudong new east area, CHN*
[*] *shijz@shanghaitech.edu.cn*

Abstract: Distributed Optical fiber sensor (DOFS) has developed greatly in precise measurement. OTDR and OFDR are two most significant techniques in DOFS. This paper reviewed scattering theory and principles of OTDR, OFDR system and their derivative system. Advantages and drawbacks of OTDR and OFDR are proposed especially with respect of spatial resolution and sensing range. Improvement methods on above crucial parameters and recent practical application scenario are also referred.

1. Introduction

As information technology and industry developed further, optic fiber based sensors has achieved great applications in many areas such as aerospace industry, precision instrument design, military facilities and so on. It also appears increasingly larger commercial potential and market shares especially for distributed sensors(Figure.1). Optical fiber sensors are usually divided into four categories([1]): 1.Point sensors, which is carried out by a single detect point in measurement space, based on devices like Fabry-Perot sensors and single Fiber Bragg Grating(FBG) sensors; 2.Quasi-distributed sensors: which utilized fixed number measuring points on fiber, such as multiplexed FBG sensors; 3.Integrated sensors, measuring a average information of some physical quantity in a certain spatial region, but only a single value is provided; 4. Distributed sensors: provide a certain spatial resolution measurement with any points along a fiber cable. Distributed optical fiber sensors (DOFS) is able to capture various distributedly parameters which is coupled with refractive index along fiber under test, such as strain, stress, temperature, etc. In contrast to extrinsic optical fibers, which are utilized for transferring information and obtaining light signal generated on the sensing point, distributed optical fiber sensors belongs to intrinsic optical fibers and converting information resulted by environmental changes which modulate signals' phase, intensity and frequency. Intrinsic backscattering including Rayleigh, Raman and Brillouin scattering are three mainly researched and used physical process on DOFS. Detailed comments are reviewed in section 2. In terms of time domain or frequency domain, DOFS are classified as optical time domain reflectometry (OTDR) and optical frequency domain reflectometry (OFDR). Back-scattering light intensity decays in fibers as sensing range increases, so spatial resolution and sensing range are in balance, therefore SNR is crucial to DOFS system. OTDR has already achieved huge commercial value, series of technology such as ϕ-OTDR, B-OTDR, C-OTDR, P-OTDR, etc based on OTDR are growing maturely. However, OTDR index such as dynamic range(50dB), sensing distance(10^2km) and spatial solution(10^{-1}m) can not satisfy increasing demand on precision. By using tunable laser source(TLS), the input signal's frequency can be modulated linearly in time, local oscillator(LO) and back-scattering signal thus generate interference beat frequency which can enhance SNR. With overall centimeter to micrometer spatial resolution, OFDR can measure temperature, strain, vibration, etc more precisely. Further, OFDR are also showing tremendous application prospect on 2D shape, 3D shape measuring.

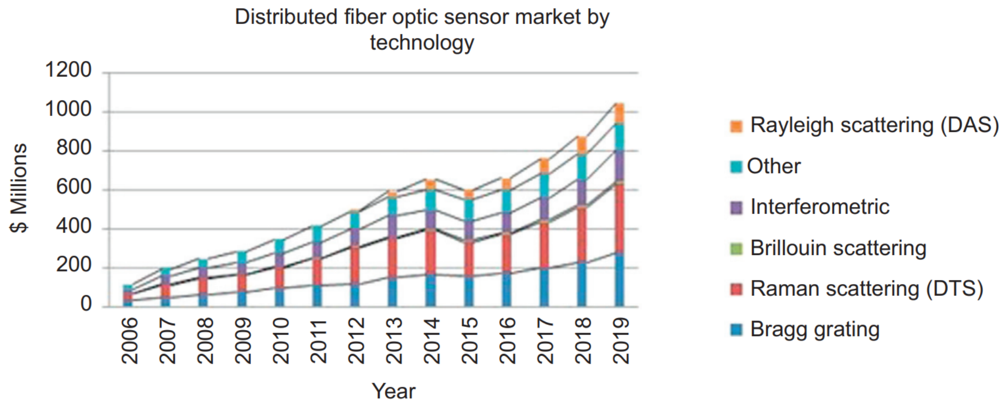

Fig. 1. Photonic Sensor Consortium Market Survey Report (Fig. 5.1, [1])

2. Scattering Theory

2.1. Rayleigh Scattering

Rayleigh scattering theory was first proposed to explain the phenomena when light pass through atmosphere, it is applied when particle size is much shorter than the light's wavelength. The scattering intensity is proportional to the fourth power of the inverse wavelength. Rayleigh scattering is a elastic process, and it is caused by the polarization of the particle. So the scattering light has the same length with input light. Generally, Rayleigh scattering could be proved as a result of the fluctuation of air density. Similarly, in optical fiber, Rayleigh scattering is due to the fluctuation of refractive index profile along the fiber. The fluctuation is caused by random and incoherent thermal fluctuation, the scattering light has no energy lost or gain.

2.2. Brillouin Scattering

Brillouin scattering refers to the interaction of light and the material waves in a medium. There are three mainly material wave: phonons caused by acoustic modes, polaritons caused by charge displacement modes and magnons magnetic spin oscillation modes. The light in the medium may interact with above three quasiparticle, thus loss energy(wavelength shift larger, which is referred to stokes process) or gain energy(wavelength shift shorter, which is referred to Anti-stokes process), thus a inelastic or nonlinear scattering.

2.3. Raman Scattering

Raman scattering is caused by the vibration of molecular bond. Molecular vibration energy is known to be quantized and can be modeled using the quantum harmonic oscillator approximation:

$$E = h(n + \frac{1}{2})\mu = h(n + \frac{1}{2})\frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{1}$$

Where n is the quantum number. The energy range for molecular vibrations is approximately from 5 to 3500 cm^{-1}. A molecule can be excited to a higher vibration mode through the direct absorption of a photon, which falls in the terahertz or infrared range. This inelastic scattering process is called Stokes Raman scattering, an increase in photon energy which leaves the molecule down to a lower vibration energy state is called anti-Stokes scattering. Compared to Brillouin scattering which shows a larger scale of medium properties, Raman scattering can represent information of medium chemical composition and molecular structure.

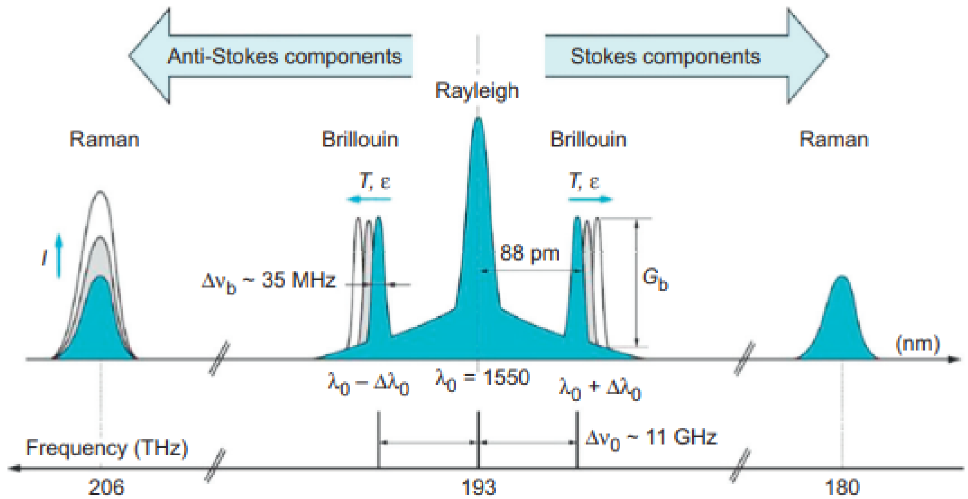

Fig. 2. The optical spectrum of the scattering phenomena in silica (SiO2) optical fibers, used in distributed sensing, for an injected laser wavelength of 1550 nm. (Fig. 5.3, [1])

Figure.2 shows scattering light wavelength shift caused by Rayleigh, Brillouin and Raman scattering.

3. OTDR

3.1. Principle of OTDR

The modulated input impulse light pass through the fiber and continuously back-scatter to the detector, when meet inhomogeneities and impurities caused by the change of thermal, stress, strain and pressure, etc in the environment, the intensity of scattering light increase suddenly and can be detected by Photo detectors. A schematic diagram is shown below as Fig.3. The intensity vary with time domain information can be converted into distance domain. It appears a overall exponential decay along distance:

$$P(z) = P_0 e^{-\alpha z} \tag{2}$$

where α is the average loss coefficient.

For the pulse width W, Rayleigh scattering light power along fiber is:

$$P_R(z) = P(z) s \alpha_s W \frac{v}{2} = P_0 e^{-\alpha v t} s \alpha_s W \frac{v}{2} \tag{3}$$

s is Rayleigh scattering power capture coefficient[2], v is the light travel velocity along fiber, α_s is Rayleigh scattering coefficient.

Some sudden change points during the decay signals indicates localize breaks, connectors, fiber splices or bendings along the fiber. OTDR technique can be utilized for fiber quantity test and analysis, including losses, defect and so on. However, when dealing with long distance, the noise greatly affect the dynamic range($D = L\alpha$, L is the test distance) of OTDR. Besides the direct back-scattering light only captures obvious physical parameter change, for small variation, the resolution is limited to satisfy. Some further developed techniques such as C-OTDR, P-OTDR and ϕ-OTDR can solve the questions.

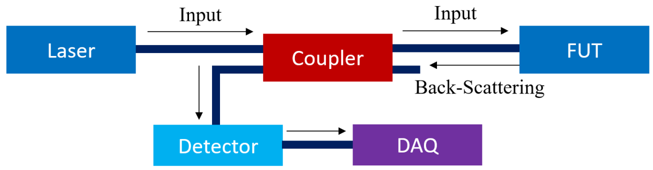

Fig. 3. Schematic diagram of OTDR

3.2. C-OTDR

C-OTDR operates based on heterodyne coherent detection. An AOM is equipped in this system, the input narrow band light is thus applied with a frequency shift, the frequency-shifted back scattering signal interference with local signal and generate a beat frequency signal. With balanced detection, the common mode is cut off, a band pass filter keeps mid-frequency and most of the noise is removed thus increasing dynamic range and SNR. C-OTDR requires good quantity of laser's monochromaticity and frequency stability. A demonstration diagram is shown below Fig.4.

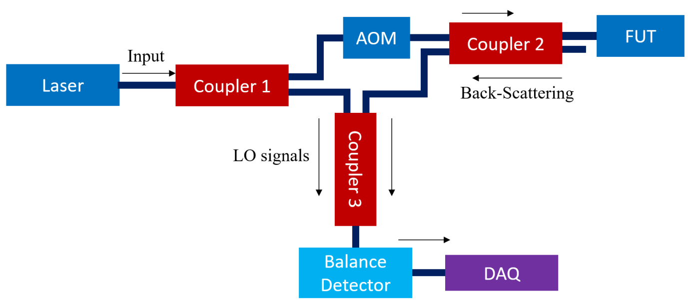

Fig. 4. Schematic diagram of C-OTDR

3.3. P-OTDR

P-OTDR utilize polarization distribution in fiber to obtain high resolution sensing information. The polarization controller set after coupler ensures a fixed input polarization state, and plays as a polarization analyser for back scattering signal. The polarization distribution information along the fiber is converted into intensity variation and captured by the detector. Suppose at distance l from the start point, a thermal change or strain change is induced in the region Δl. The changed birefringence causes a change of phase:

$$\Delta\phi = \Delta\beta\Delta l \tag{4}$$

The thermal $\theta(l)$ and stress distribution $T(l)$ can be calculated from the phase change:

$$\theta(l) - \theta(0) = c_\theta \frac{d\phi}{dt} \tag{5}$$

$$T(l) - T(0) = c_T \frac{d\phi}{dt} \tag{6}$$

Specific expression of c_θ and c_T are derivated in [3].

Although P-OTDR utilizes polarization distribution can measure more precisely, it still has few shortcomings that impede commercialization:

1. The polarization stability of system itself. To capture polarization distribution information in high precision, polarization state stability is a crucial factor, but it is greatly sensitive to environment change thus difficult to maintain pure state in a general application scenario.

2. The temperature and stress or other physical information are coupled together in the back forward signals, decoupling temperature and stress influence from the source is a to-be-solved question.

3. P-OTDR also meets trouble in increasing spatial resolution and SNR.

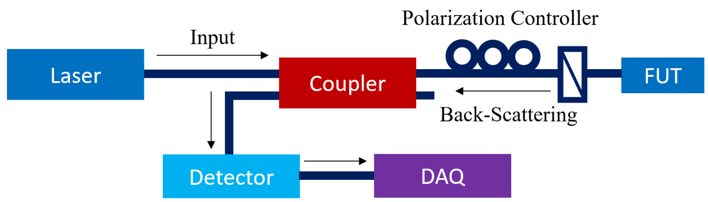

Fig. 5. Schematic diagram of P-OTDR

3.4. ϕ-OTDR

ϕ-OTDR relys on Hooke law and elasto-optical effect, completing sensing by modulating scattering light phase information based on optical path change. Environmental change or disturb induce light path variation:

$$\Delta z_{path} = (n_0 + \Delta n)(l + \Delta l) - n_0 l \tag{7}$$

$$\Delta n = e_z \xi n_0 \tag{8}$$

$$\Delta l = e_z l \tag{9}$$

where e_z is axis strain deformation, ξ is elasto-optical coefficient, is elastic coefficient. Phase change can be represented as:

$$\Delta\phi = 2\pi \frac{\Delta z_{path}}{\lambda} \tag{10}$$

Back scattering light can be written as[2]:

$$P_s(t) = \mid E_0 \mid^2 e^{-2\alpha mn} [\Sigma_{k=1}^{N} p_k \gamma_k + 2\Sigma_{k=1}^{N-1} \Sigma_{l=k+1}^{N} p_k p_l \gamma_k \gamma_l cos[2\phi_{kl}(t)]] \tag{11}$$

E_0 is the input light intensity, n is spatial resolution, p and γ is polarization coefficient and reflection coefficient, ϕ_{kl} is the kth and lth scattering light phase difference.

The spatial resolution of ϕ-OTDR is determined by: $\Delta z = ct_w/2$, t_w is the pulse width, to obtain a better spatial resolution needs smaller t_w, but energy of input light decrease thus limit sensing range. So is is a contradictory to satisfy both spatial resolution and sensing range.

Signal attenuation is a key difficulty in ϕ-OTDR, it can be categorized as interference attenuation and polarization attenuation. The attenuation causes mismatch of LO and signal, and damage the beat signal energy, badly influence system SNR.[4] It is first believed that the attenuation is caused by Rayleigh scattering coefficient random fluctuation, and further explained as refractive index unevenly distribution. Avoiding attenuation will benefit ϕ-OTDR DAS technique further development.

Detecting impulse respond band width and sensing range is also hard to enhance synchronously. To obtain high fidelity signals in some scenario, large impulse respond band width is greatly required, however, neighboring back scattering signals will mix-up in this situation thus reduce sensing range.

3.5. B-OTDR

Brillouin scattering has two typical configuration, one is based on spontaneous Brillouin scattering caused by Brownian motion of molecules in the silica fiber. The onther configuration is based on stimulated Rayleigh scattering due to the electrostriction effect of the silica fiber[1].

As there is frequency shift in back scattering signal, coherent detection method is usually used in B-OTDR. To decouple temperature and strain variation, B-OTDR also includes a reference fiber remaining in unstrained state to eliminate the effect of strain, thus ensure the precise measurement of temperature and strain distribution along fiber.

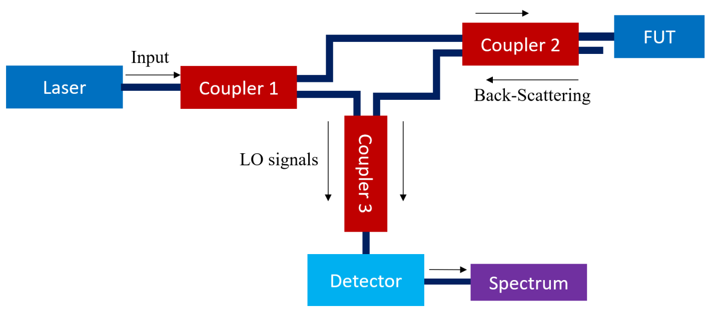

Fig. 6. Schematic diagram of B-OTDR

NTT Communication Lab in Japan reaches 3°C temperature resolution and 100m spatial resolution, over 1.2km sensing range in 1990 based on B-OTDR. And they extended sensing range to 22km with 1°C temperature resolution, 10m resolution three years later[5].

3.6. Raman scattering based OTDR

Raman scattering light intensity is relatively low to be detected, so mutimode fibers with high NA are used to increase the backward signal's intensity. However, mutimode fibers' large attenuation limits its sensing range so restricts many application scenarios.

4. OFDR

4.1. Principle of OFDR

With the tunable laser source(TLS) linearly tuning frequency:

$$\nu = \nu_0 + \gamma t \tag{12}$$

The input optical field in time domain can be written as:

$$E_r(t) = E_0 e^{j[2\pi f_0 t + \pi \gamma t^2 + e(t)]} \tag{13}$$

Where $f_0 = 2\pi\nu_0$, and $e(t)$ is noise in phase. The reflected signal thus represented as:

$$E_s(t) = \sqrt{R(\tau)}E_0 e^{j[2\pi f_0(t-\tau)+\pi\gamma(t-\tau)^2+e(t-\tau)]} \tag{14}$$

And $R(\tau)$ is reflectivity in fibers z=v$\tau/2, thebeatingsignalsfromtheinterferenceof$E$_r(t)$ and $E_s(t)$ are:

$$I(t) = 2\sqrt{R(\tau)}E_0^2 cos[2\pi[f_0\tau + \gamma\tau t + \frac{1}{2}\gamma\tau^2 + e(t) - e(t-\tau)]] \tag{15}$$

With FFT in DAQ, spectrum information are obtained and beat frequency $f_b = \gamma\tau$ is extracted.

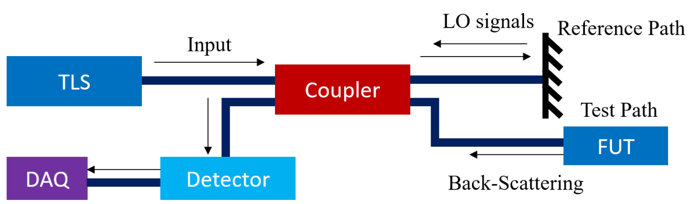

Fig. 7. Schematic diagram of OFDR

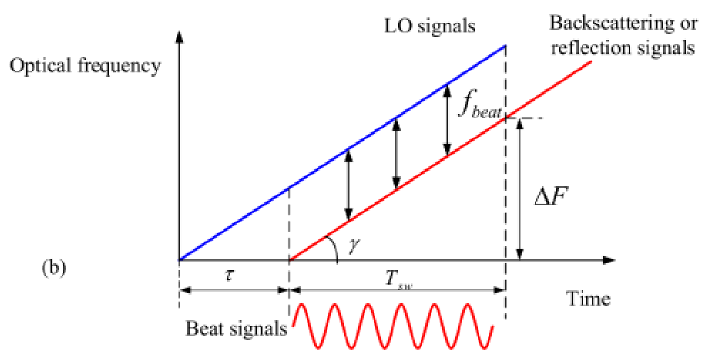

Fig. 8. Linearly tuning optical frequency and beating signals come from the LO light and received light.(Fig.1(b),[6])

4.2. Important parameters in OFDR

4.2.1. Frequency tuning range

The back signal from point z along the fiber can be related with beat frequency f_b:

$$z = \frac{f_b v}{2\gamma} = \frac{f_b c}{2n\gamma} \tag{16}$$

$$\Delta z = \frac{\Delta f_b c}{2n\gamma} = \frac{c}{2n\lambda T} = \frac{c}{2n\Delta F} \tag{17}$$

From the equation above, spatial resolution strongly relate with frequency scan range. However, increasing ΔF raises pressure on hardware and analysis efficiency, so it is theoretically up level limitted.

4.2.2. Frequency tuning speed

γ is another crucial factor of OFDR system. Increasing the tuning speed reduces sensing time and improves measuring precision and stability, but it also rises necessary sampling rate of data acquisition.

4.2.3. TLS band width

The coherent length of laser source is:

$$L = \frac{c}{n}\frac{1}{\pi\Delta\nu} \tag{18}$$

To increase sensing range of the system, a short band width source is needed.

4.3. Nonlinear Phase Noise and solutions

4.3.1. Nonlinear Phase Noise

The tuning coefficient γ is not linearly stable in reality experiment, the nonlinearity makes beat frequency drift and signal's peak is widened, reducing detection precision, so compensation methods are needed to fix the frequency nonliearity. Frequency sampling, software algorithm and short tuning range are three common compensation methods. Frequency sampling method uses DAQ clock which is triggered by optical frequency to sample an auxiliary interferometer signal[7], but limits sensing range as a result of the length of delay line in auxiliary interferometer.

4.3.2. Software Algorithm

Software Algorithm method is actually signal process procedure when hardware fixed, which can extract information that are needed from the whole signal, increase SNR and compensate the influence of nonlinearity. Four methods are briefly reviewed here.

NUFFT uses Gaussian Kernel window to convolute nonlinear beat frequency signal, generating a new frequency distribution and utilizes FFT convert signal to distance domain, deconvoluting lastly to obtain the cared information. Ding et al[8] have reached 51m sensing range and 5cm spatial resolution with NUFFT.

Song et al.[9] have used cubic spline interpolation algorithm to re-sample the interference signal and achieved 300m sensing range and 0.3mm spatial resolution theoretically.

Fumihiko et al.[10] used concatenately generated phase method to compensate the different segments of the main interference line and obtained a 40km sensing range 5cm spatial resolution.

Du et al.[11-13] constructed Deskew Filter method to eliminate nonlinear phase of LO light and nonlinear phase of received light separately, reaching a 80km sensing range and 80cm spatial resolution.

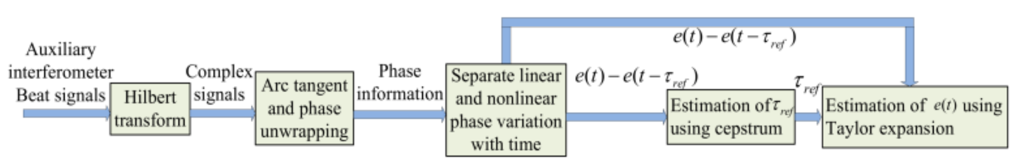

Fig. 9. Signal processing procedure of nonlinear phase restoration from an auxiliary interferometer.(Fig.9,[7])

4.3.3. Short Ranging

Shorting tuning range although restricts spatial resolution, the improved linearity in a short period can increase sensing range, dynamic range and measurement SNR. Many methods in previous work were reviewed in [7], such as Narrow linewidth laser method proposed by Ding et al.[14] accomplished 170km sensing range and 200m spatial resolution, dynamic OFDR proposed by Arbel et al.[15] reached 10km sensing range, Fraction Fourier Transform proposed by Shiloh et al.[16] achieved 20km sensing range and 2.8m spatial resolution and so on. The sensing range reaches from tens kilometers to hundreds kilometers and the spatial resolution reaches from meters to centimeters.

4.4. Rayleigh back scattering spectra (RBS) shifts in OFDR

RBS is a method proposed by Froggatt et al.[17] that can increase spatial resolution to millimeters and temperature measuring precision to 0.08 ℃, strain to $0.8\mu\epsilon$. It is operating on both the reference and the measurement signals on frequency domain, a sliding widow with width Δx slides through distance domain of two signals FFT, and spectrum information in Δx obtained. The strain and temperature variations can be obtained by calculating the cross-correlation of the two spectrum signals. It brings higher pressure on calculating and data processing resource, to obtain a precise resolution, Δx needs to be as small as possible. The responding time of the system therefore is badly influenced. So it is a contradictory on precision and responding sensitivity[18].

4.5. OFDR application

4.5.1. Temperature and strain

As mentioned above, OFDR has great advantage on measuring thermal and strain distribution. While the two physical parameters discrimination is also significant in a measuring system. A general way to achieve that is utilizing two fibers with different response to temperature and strain, such as a SMF and a reduced-cladding SMF, both scattering signals are measured, the temperature and strain variation can be decoupled with coefficient that already known.

4.5.2. Vibration

Cross-correlation is a useful tool for measuring vibration. The back scattering signals is a characteristic feature of a fiber and it's environment, using cross-correlation similarity analysis(CCSA) can analyze the difference between test path and the reference path. Comparing CCSA of each segment of the two path enable one to detect the vibration location and degree.

4.5.3. Pressure

Pressure variation is so small to be directly detected, so the transversal pressure is need to convert to longitudinal strain applied on FUT. So pressure sensitive material such as high Poisson's ratio and low Young modulus material can package fibers to previously enlarge the pressure variation on FUT.

4.5.4. 2D shaping

Optical fibers attached to a 2D surface of some material can capture the deformation variation of it. The strain brings curvature on the material, drifting the wavelength inside the fibers. With the relationship[19] of fiber curvature and wavelength drift, the shape of the 2D surface can be measured.

$$\delta\lambda = \frac{(1 - P_e)\lambda_c}{R} \tag{19}$$

Where P_e is elastic coefficient of the fiber.

4.5.5. 3D shaping

With three fibers or muti-mode fibers group together as a triplet, the 3D shape information can be reconstructed by measuring strain distribution with OFDR, RBS. Under a pre-defined geometry setting, dividing fibers into segments enables a specific spatial resolution on 3D shaping information.

4.5.6. Others

Other parameters such as magnetic field, flow rate, gas density, radiation, etc. can all be measured with Rayleigh Scattering signals along fiber. As temperature and strain variation is easier to reconstruct, it is significant for measuring to use auxiliary device or material to convert the other environmental information to temperature and strain.

5. Conclusion

Distributed optical fiber sensors has drawn great attention recent years, to meet general application scenario and precise measurement on specific usage, dynamic range, sensing range, spatial resolution are crucial factors in DOFS system. As Rayleigh scattering light has larger reflected intensity compared to the Brillouin scattering and Raman scattering, it is still the major measure physics basis. OTDR and OFDR based on Rayleigh scattering are two main designed configurations and were widely extended and developed in the past few years. OTDR was originally used in fiber defect and quantity detection, however,the spatial resolution and sensing range are both limited. with various OTDR-based technique such as C-OTDR, P-OTDR, ϕ-OTDR developed, heterodyne coherent detection, polarization state detection, phase detection are equipped in the system to increase the sensing range and spatial resolution. OTDR system still has unavoidable contradictory in sensing range and spatial resolution because reducing fibers attenuation, ensuring laser's linewidth can not always be satisfied at the same time. OFDR working on TLS provides high SNR beat signal, but the nonlinearty of frequency tuning causes peak widen on frequency domain thus restricts further precision improvement. Frequency-sampling, short tuning range on hardware and series algorithm developed on software side can well fix the problem but raise other negative effect. Complicated algorithm requires more calculation resource in the system so it has bad influence on responding time. Shorting tuning range increases linearity but restricts spatial resolution. Comprising with RBS analysis, cross-correlation analysis and special functional fiber design, OFDR can be equipped in many measuring scenario, such as temperature, strain, vibration, pressure, etc. 2D and 3D shaping are also appearing great attention on DOFS. With respect of different applications, OFDR based system can actually be designed more adaptable to satisfy specific requirement.

6. Reference

[1]. Aghiad Khadour, Julien Waeytens, 5 - Monitoring of concrete structures with optical fiber sensors, Editor(s): F. Pacheco-Torgal, Robert E. Melchers, Xianming Shi, Nele De Belie, Kim Van Tittelboom, Andrés Sáez, In Woodhead Publishing Series in Civil and Structural Engineering, Eco-Efficient Repair and Rehabilitation of Concrete Infrastructures, Woodhead Publishing, 2018, Pages 97-121, ISBN 9780081021811, https://doi.org/10.1016/B978-0-08-102181-1.00005-8.

[2]. Zhang zhijuan, Guo Wenhan, Xu zhiniu, Zhao Lijuan, Principle of Optical Fiber Sensing Technology Based on Φ-OTDR and Its Application Status, School of Electrical and Electron. Engin., North China Electric Power University, Baoding 071003, CHN.

[3]. Liu yanfei, Research on Distributed Optic Fiber Sensor Based on P-OTDR, Beijing Jiaotong University, 2017.

[4]. Cai Haiwen, Ye Qing, Wang Zhaoyong, LuBin, Distributed Optical Fiber Acoustic Sensing Technology Based on Coherent Rayleigh Scattering, Key Laboratory of Space Laser Communication and Detection Technology, Shanghai Institute of Optics and Fine Mechanics Chinese Academy of Sciences Shanghai 201800 China, Centre of Materials Science and Optoelectronics Engineering, University of Chinese Academy of Sciences Beijing 10049 China.

[5]. X. Bao, D. J. Webb, and D. A. Jackson, "22-km distributed temperature sensor using Brillouin gain in an optical fiber," Opt. Lett. 18, 552-554 (1993).

[6]. Ding, Zhenyang, Chenhuan Wang, Kun Liu, Junfeng Jiang, Di Yang, Guanyi Pan, Zelin Pu, and Tiegen Liu. 2018. "Distributed Optical Fiber Sensors Based on Optical Frequency Domain Reflectometry: A review" Sensors 18, no. 4: 1072. https://doi.org/10.3390/s18041072.

[7]. Soller, B.; Gifford, D.; Wolfe, M.; Froggatt, M. High resolution optical frequency domain reflectometry for characterization of components and assemblies. Opt. Express 2005, 13, 666–674.

[8]. Ding, Z.; Liu, T.; Meng, Z.; Liu, K. Note: Improving spatial resolution of optical frequency-domain reflectometry against frequency tuning nonlinearity using non-uniform fast Fourier transform. Rev. Sci. Instrum. 2012, 83, 066110.

[9]. Song, J.; Li, W.; Lu, P.; Xu, Y.; Chen, L.; Bao, X. Long-Range High Spatial Resolution Distributed Temperature and Strain Sensing Based on Optical Frequency-Domain Reflectometry. IEEE Photonics J. 2014, 6, 6801408.

[10]. Koshikiya, Y.; Fan, X.; Ito, F. Long range and cm-level spatial resolution measurement using coherent optical frequency domain reflectometry with SSB-SC Modulator and narrow linewidth fiber laser. J. Lightwave Technol. 2009, 26, 3287–3294.

[11]. Ding, Z.; Yao, X.S.; Liu, T.; Du, Y.; Liu, K.; Jiang, J.; Meng, Z.; Chen, H. Compensation of laser frequency tuning nonlinearity of a long range OFDR using deskew filter. Opt. Express 2013, 21, 3826–3834.

[12]. Du, Y.; Liu, T.; Ding, Z.; Feng, B. Method for improving spatial resolution and amplitude by optimized deskew filter in long-range OFDR. IEEE Photonics J. 2014, 6, 7802811.

[13]. Ding, Z.; Du, Y.; Liu, T.; Yao, X.S.; Feng, B.; Liu, K.; Jiang, J. Long-range high spatial resolution optical frequency-domain reflectometry based on optimized deskew filter method. Proc. SPIE 2014, 9274, 927407.

[14]. Ding, Z.; Yao, X.S.; Liu, T.; Du, Y.; Liu, K.; Han, Q.; Meng, Z.; Jiang, J.; Chen, H. Long Measurement Range OFDR Beyond Laser Coherence Length. IEEE Photonics Technol. Lett. 2013, 25, 202–205.

[15]. Arbel, D.; Eyal, A. Dynamic optical frequency domain reflectometry. Opt. Express 2014, 22, 8823–8830.

[16]. Shiloh, L.; Eyal, A. Distributed acoustic and vibration sensing via optical fractional Fourier transform reflectometry. Opt. Express 2015, 23, 4296–4306.

[17]. Froggatt, M.; Moore, J. High-spatial-resolution distributed strain measurement in optical fiber with Rayleigh scatter. Appl. Opt. 1998, 37, 1735–1740.

[18]. Du, Y.; Liu, T.; Ding, Z.; Han, Q.; Liu, K.; Jiang, J.; Chen, Q.; Feng, B. Cryogenic Temperature Measurement Using Rayleigh Backscattering Spectra Shift by OFDR. IEEE Photonics Technol. Lett. 2014, 26, 1150–1153.

[19]. Rui Gong, Research on Several Key Technologyies of Distributed Optical Fiber Sensing Based on OFDR, School of Electronic Engineering, Beijing University of Posts and Telecommunications, 2021.