Recent advances in long-range high-resolution optical reflectometry (Invited)

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Abstract. In this invited talk, three advanced methods to improve both the spatial resolution and the measurement range are presented which paves the way for new horizons in high-end applications. The first one is to develop an optical source with ultra-highly-linear frequency sweeping rate, and use it for optical frequency domain reflectometry (OFDR). The second one is to use linear optical sampling (LOS) technique to measure ultra-short pulse used for optical time domain reflectometry (OTDR) and adopt dispersion compensation scheme. The third one is to use LOS technique for characterizing the ultra-wide linearly chirped signals for pulse compression.

1. Introduction

Optical reflectometry may either realize an ultrahigh spatial resolution but with a limited measurement range such as optical low coherence reflectometry (OLCR), or realize a long measurement range while having limitations on spatial resolution such as optical time domain reflectometry (OTDR). However, for some high-end applications such as fiber-to-the-home (FTTH) access network diagnosis, the requirements on both spatial resolution and measurement range are very strict. For example, bend-insensitive fiber is widely installed in FTTH networks, but the bending in optical fiber links is very difficult to locate by using reflectometry to detect loss for this kind of fiber, which shortens the service lifetime of the optical fiber if the bending is ignored and just as it is. In order to locate the bending position, a reflectometry capable of measuring the polarization change with a high spatial resolution is required. Usually, a millimeter spatial resolution is necessary to locate the bending, and a measurement range of several kilometers is required for these FTTH-related applications. Moreover, the vision of telecommunication carriers is to establish a remote online optical fiber line detection and monitoring system at the telecom buildings. In order to realize the management, optical identification (OID) devices are usually necessary to be embedded into the fiber connectors or optical network devices. The number of OID coding is set to 8 bits (256 codes), 16 bits (65536 codes), or even more. Spatial multiplexing and wavelength multiplexing technology are two representative technologies of OID manufacturing, but the wavelength multiplexing method is still at the stage of scientific research because of its difficulty in realizing. Due to the limited space in the connector whose length is less than two centimeters, spatial multiplexing technology restricts each bit length, and therefore optical reflectometry equipped at the buildings need to have millimeter or sub-mm spatial resolution with a measurement range of several kilometers or even several tens of kilometers. This is very challenging and researchers have made many attempts to push the reflectometry performance.

There are different limitations for optical reflectometry technique. For optical frequency domain reflectometry (OFDR), it is very vulnerable to the phase noise of both optical source and the fiber for long-distance measurement. For OTDR, to achieve a high spatial resolution, there is a high demand for bandwidth and sensitivity of the detection system to detect the ultrashort pulse, and the dispersion effect should be carefully dealt with for long-distance measurement. Another technique called pulse compression method has better spatial resolution over OTDR, and is immune to phase noise of optical source compared with OFDR but also has very strict requirements on the bandwidth of the receiving system. Therefore, there are three advanced methods to deal with these problems. The first one is to develop an optical source with ultra-highly-linear frequency sweeping rate, and use it for OFDR [1]. The second one is to use linear optical sampling (LOS) technique to measure ultra-short pulse used for OTDR and adopt dispersion compensation scheme [2]. The third one is to use LOS technique for characterizing the ultra-wide linearly chirped signals for pulse compression [3]. In this invited talk, we will introduce these three methods in details.
2. Wide-band ultra-linearly swept optical source for OFDR

In an OFDR system, a narrower spatial resolution requires a larger sweeping span. By utilizing the external modulation method, the sweeping rate is an ultra-linear one same as the swept radio frequency (RF) signals used for the modulation. If we use the high-order sideband, an enlarged span can be obtained. However, it is still limited because of the overlap between two adjacent high-order sidebands. In order to further broaden the frequency sweeping span, injection-locking technique is introduced to extract the frequency-swept lightwave from the overlapped high-order sidebands but is still limited by the electronic bottleneck. An effective solution is to use all-optical processing technique, for example, using optical nonlinear effect to generate new frequency components and further broaden the sweeping span. The principles are shown in Fig. 1 and Fig. 2.

Note that the high-order sideband modulation and the optical nonlinear effect have capabilities of broadening the frequency sweeping span, but it will also magnify the laser phase noise and bring more phase noise if the RF signal sweeps nonlinearly. In order to mitigate the effect of the phase noise and extend the measurement range, a phase noise compensation (PNC) technique may be introduced in the system.

By using the technique described above, in an experiment [1], a wide-band ultra-linearly swept optical source is realized with a sweeping span of 100 GHz. This source is used as the optical source for OFDR systems, and a 2-km SMF is used as the FUT, a spatial resolution of 1.1 mm at the far end of the FUT was realized, as shown in Fig. 3. The measurement range of the proposed system is now limited by the memory of the analog-to-digital converter (ADC), which is very promising to be further expanded. It is believed that this system is suitable for applications where both high spatial resolution and relatively long measurement range are required.

3. LOS technique-assisted OTDR (LOS-OTDR)

To realize an ultra-high spatial resolution by using OTDR, it is necessary to find a technique with a large detection-bandwidth. LOS technique, known for the capability of observing the complex amplitude response of ultra-short optical pulses using slow electronics with a low bandwidth, and its shot-noise limited sensitivity, has been used in many fields for monitoring the waveform in
high speed transmission systems. The signal under detection (SUT) interferes with the sampling signal launched from the mode-locked laser (MLL) and is then detected by the ordinary photodiodes. Because the timing jitter of the MLL is several femtoseconds, the sampling rate can be up to 100 TS/s, and this makes it possible to measure ultra-short pulse launched from pulsed lasers and its reflected lightwave from optical fibers. In addition, MLLs usually have a linewidth better than 1 kHz, which makes it a promising optical source for long-range sensing applications. Therefore, the adoption of LOS technique in reflectometry system has the potential to realize an ultra-high spatial resolution with a long measurement range.

It should also be mentioned that the RBS signal is not measured by this method since it is \(-100\) dB for a spatial resolution of 1 mm, which is below the noise floor. The pulse broadening is mainly caused by chromatic dispersion (CD) effect as it propagates in the fiber under test (FUT). As the spatial resolution increases, it is necessary to deal with the influence of dispersion which depends on the wavelength range of the probe pulses and the measurement distance.

Since LOS technique has the capability to obtain both intensity and phase information of the signal, digital compensation in the frequency domain is a good method to mitigate the degrading effects caused by CD effect. By adopting a digital CD compensation algorithm at long distances, a spatial resolution of 340 \(\mu\)m is achieved at 10 km, as shown in Fig. 4 [2]. This technique shows a new application prospect for OTDR system in ultra-high resolution distributed applications such as OID for PONs or precisely locating the abnormal reflections in aircrafts.

**4. Pulse compression technique with the aid of LOS technique**

Pulse compression techniques based on matched filtering method using linearly chirped pulses (LCPs) or phase coded pulses are widely used in modern radar systems and distributed fiber sensing systems for high spatial resolution and large dynamic range. In some other applications such as biomedical imaging, LCPs are used as optical sources for extracting depth of the organization sample, which show a great prospect in tumor detection. In particular for long distance applications such as coherent radar systems and distributed fiber sensing systems, pulse compression techniques allow to transmit long pulses minimizing the transmitted peak power while maintaining a high spatial resolution.

For pulse compression method, to achieve a large time-bandwidth product (TBWP), using a linearly chirped fiber Bragg grating (LCFBG) with a large dispersion coefficient to linearly sweep the optical frequency with a wide range is a good option. Therefore, to use LCFBG for generating LCP signal, and to detect in combination with LOS technique, make it possible to achieve LCP with a large bandwidth and TBWP. It is easy to generate and detect sub-THz-range linearly chirped signal, and achieve a sub-millimeter spatial resolution with a low-bandwidth photodetector and an ADC, breaking the limitation of the electronic bottleneck. The schematic diagram of this method is shown in Fig. 5. An ultrashort optical pulse train with tens of nanometers wavelength range...
from a femtosecond laser is rectangular shaped through an optical bandpass filter. An LCFBG is utilized as a dispersive element to implement a wavelength-to-time mapping effect.

An experiment shows a sweeping range of 450 GHz when a 10-m long LCFBG with 1981 ps/nm dispersion coefficient is chosen as the dispersion element, and the pulse is then stretched to a temporal duration of 10 ns [3]. The generated LCP is characterized by using LOS technique, and then the data are used to calculate the autocorrelation of the pulse. The main lobe of the autocorrelation has an FWHM of 2.4 ps, corresponding to a pulse compression ratio of 4167. To extend the measurement range, an intensity modulator may be adopted to act as a temporal gate. By increasing the length of the pulse pattern, the time apertures may be increased freely. Taking advantage of the delta function property of its autocorrelation function, pseudo-random binary sequence (PRBS) is used in the experiment to generate similar correlation gate since it is simple.

In another experiment [3], only restricted by the wavelength range of the sampling laser, the maximum frequency-range achieved is 700 GHz, corresponding to 120 μm spatial resolution in optical fiber and 180 μm spatial resolution in free space. In addition, long time apertures chirped pulse train is achieved with PRBS phase modulation, which makes it possible to enable long measurement range as well as ultra-high spatial resolution. This method features the generation and detection of large bandwidth LCPs and paves the way for new horizons in ultra-high spatial resolution and long measurement range LIDAR, distributed fiber sensing and biomedical imaging.

5. Conclusion
In this invited talk, three advanced methods to improve both the spatial resolution and the measurement range are presented. With these methods, a spatial resolution of sub-millimeter and a long measurement range of 10 kilometer-level can be realized which paves the way for new horizons in high-end distributed fiber-optic applications.

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References
[1] B. Wang, X. Fan, S. Wang, J. Du, and Z. He, "Long-range Millimeter-resolution OFDR Based on 100 GHz Linear Frequency-sweep of Optical Source by Injection-locking Technique and Cascaded FWM Process," Optics Express, 2017, 25, 3514-3524.
[2] S. Wang, X. Fan, and Z. He, "Ultra-high resolution Optical Reflectometry based on Linear Optical Sampling Technique with Digital Dispersion Compensation," IEEE Photonics Journal, 2017, 9, 6804710.
[3] S. Wang, X. Fan, B. Wang, G. Yang, and Z. He, "Sub-THz-range linearly chirped signals characterized using linear optical sampling technique to enable sub-millimeter resolution for optical sensing applications," Optics Express, 2017, 25, 10224-10233.

Fig. 5. Experimental configuration to generate and detect LCPs [3].