論 文 内 容 の 要 旨

Optical fiber has been used in numerous applications ranging from transmission systems to medical. Practice of optical fiber in communication systems has been researched for a past few decades. Presently, high speed communication systems are possible because of optical fiber as it has outperformed the conventional form of transmission mediums in terms of speed. Recently, another field where optical fiber is earning lot of popularity is optical fiber sensing networks where optical fiber is used as a sensor for various measurements such as temperature/strain, vibration. There are a few advantages of using optical fiber over conventional sensors such as optical fiber can be used in harsh conditions, immune to external perturbations, offers distributed sensing capability. Optical reflectometry techniques are very useful instrument in optical communication systems and optical sensing networks. The fault location and fiber loss which are important factors for optical link diagnosis are analyzed by the means of optical reflectometry techniques and in optical sensing networks reflectometry is being used as a tool to sense the change in temperature/strain or vibration. Spatial resolution and sensitivity are the two essential factors to evaluate the performance of optical reflectometry techniques. Sensitivity sets a limit up to which measurements can be performed and spatial resolution is a precision parameter which tells how close two events can be detected separately. Despite of poor sensitivity and low spatial resolution the optical time domain reflectometry technique (OTDR) is the mainly used reflectometry technique because of long measurement range. On the other hand optical frequency domain reflectometry (OFDR) has higher spatial resolution and better sensitivity but its practice is limited to short length measurements and diagnosis of optical components. The reason for short length measurement limitation in OFDR is the laser phase noise, as the measurement range exceeds the laser coherence length the phase noise increases significantly and degrades the signal to noise ratio (SNR) to undetectable level. One method to perform measurements beyond the laser coherence length were reported called phase noise compensated OFDR (PNC-OFDR) but proposed method was cumbersome involving lot of computational processing and time. In this research a new type of OFDR called double sideband phase noise cancelled OFDR (DB-PNC OFDR) is proposed in which the laser phase noise in OFDR is cancelled out, the proposed method is simpler in configuration and does not require cumbersome computational processing. The phase noise cancellation by means of the proposed method sets OFDR free from measurement within the coherence length limitation and measurements beyond the laser coherence length have been made possible. The proposed OFDR is using the double sideband suppressed carrier (DSB-SC) modulation to cancel the laser phase noise. DSB-SC modulation creates two sidebands and when the sweep frequency is applied they are swept in opposite directions, the swept DSB-SC signal is used as OFDR signal. Modulated signal is divided into two arms as a reference and a probe arm. The probe arm signal is sent through fiber under test (FUT) and backscattered signal from FUT is coupled with reference arm signal. Then coupled signal is passed through the optical filter where two sidebands are separated and detected as individual channels. Two detected channels had equal phase noise but opposite in the sign, therefore on multiplying two channels cancelled out the laser phase noise and remaining term was only the beat frequency. The proposed method can be deployed in two type of arrangements heterodyne detection and phase diversity detection. The heterodyne detection works well if break point is located over far distance, however, if the break point is located over short distance the phase noise is not cancelled completely because of spectral fold back phenomenon. As a solution of heterodyne detection spectrum fold back problem phase diversity detection technique can be used, since fold back of spectrum phenomenon does not occur in phase diversity detection. The proposed method had been demonstrated by the means of experiments. In one of the demonstrations two break points 10 cm far from each other were detected in a short (120 m) and long fiber (20 km) using phase diversity detection technique. Both lengths of fiber were beyond the laser coherence length (100 m) where phase noise has significant influence. Furthermore, the high spatial resolution achievability of the proposed OFDR was also demonstrated by measuring the fiber temperature dependence with good accuracy in a 1 km long fiber with a laser of 100 m coherence length.

Chromatic dispersion affects in the transmission optical fiber are treated as one of the impairments for the overall performance. In order to design a system which can compensate chromatic dispersion affects in the fiber link, it is required to have a precise knowledge about chromatic dispersion of the optical fiber. Phase shift method and sideband modulation are the two well-known method for accurate chromatic dispersion measurement in the optical fiber. However, both mentioned methods are the two end methods which means both ends of the optical fiber are required to be accessible. In a scenario where optical fiber is already deployed as a part of transmission network it is always not possible to have access to both ends of the fiber. In such a condition measuring chromatic dispersion using OTDR is preferred because it is a one end measurement technique. Nevertheless, poor spatial resolution of OTDR results in inaccurate measurement. Some methods to measure chromatic dispersion in long optical fibers are proposed using OTDR with spatial resolution in meters but the accuracy was not appreciable because of poor spatial resolution. Chromatic dispersion measurement using conventional OFDR with cm level spatial resolution are also demonstrated which resulted in good accuracy but reported method was only good for short length fibers because measurements have to be taken within the laser coherence length. In this research a new method to measure chromatic dispersion with higher accuracy in long optical fiber is proposed. The proposed method uses DB-PNC OFDR which can perform measurements in the long optical fiber. It was demonstrated the proposed method can measure chromatic dispersion in a 50 km long fiber link made up of two 20 km and one 10 km long dispersion shifted fibers. The chromatic dispersion of each fiber segment was measured in connected and detached arrangements. The obtained results from proposed method were compared with phase shift method and a close match was observed. The achieved spatial resolution was 7.9 mm and chromatic dispersion with accuracy as good as ± 0.096 ps/nm/km was measured. Moreover, in order to show proposed method can measure chromatic dispersion in other types of the fiber, chromatic dispersion in a 25 km long standard single mode fiber was also measured with accuracy ± 0.076 ps/nm/km.

Laser phase noise is an intrinsic impairment which is linked with the presence of spectral band in the emitted light. The measurement of the laser phase noise can reveal the spectral linewidth of the laser light and laser linewidth information is essential in many situations. In this research a new method to estimate the laser phase noise is also proposed. The proposed method of laser phase noise estimation is the extension of DB-PNC OFDR method. As described above the two detected channels in DB-PNC

OFDR had equal phase noise but opposite in the sign, therefore if phases of both channels are estimated through signal processing and then subtracting estimated phases from each other will cancel beat frequency and the remained term will be purely the phase noise. The estimated phase noise can be used in other application such as the laser linewidth measurement and it can be again used to cancel the laser phase noise in OFDR. If the estimated laser phase noise is multiplied with the one of the channel which has equal but opposite phase noise, it can result in cancellation of the laser phase noise in the OFDR. With the help of experiment it is shown that the proposed method of phase noise estimation can estimate the laser phase noise correctly, it was proved by using the estimated phase noise to cancel the laser phase noise in OFDR and detecting the breakpoint in a 20 km long fiber with 100 m coherence length laser. There are some advantages of canceling the laser phase noise using estimated phase noise instead of multiplying two channels. The multiplication process converts the beat frequency to twice of the original value, because of doubled beat frequency the minimum required sampling rate was also twice and minimum four times of the original beat frequency in order to fulfil Nyqusit rate requirement. Higher sampling rate required high speed ADC and additional noises because of high sampling rate were not favorable for overall results. Moreover higher sampling rate requirement degrades the spatial resolution between two points as is calculated by $\Delta l = \frac{c f_s}{4n\beta N}$, where f_s is the sampling frequency of A/D converter and N is the length of data point.

OFDR is better known for its high spatial resolution capability. The spatial resolution in OFDR is limited by the frequency sweep span through this formula $\Delta l = \frac{c}{2n\Delta f}$ where Δf is the sweep frequency span. In certain situation the available sweep span is limited by the bottle necks in the present electronics. In such a situation the achievable spatial resolution is limited. Recently some methods are proposed to increase frequency sweep span in OFDR, however reported methods were using four wave mixing (FWM) involving two laser sources which increased the phase noise by 3-times, hence reducing the measuring length by 3-times. In this research a novel method to increase the available frequency sweep span up to 3-times is proposed which ultimately resulted in the enhancement in spatial resolution up to 3- times. The proposed method uses degenerated (FWM) with DSB-SC modulation involving only one laser source which resulted in preserved coherence length because there was no additional phase noise involved. Two side bands created by DSB-SC modulation are treated as two separate signals and when they travel through a non-linear medium it results in generation of two new frequencies called idlers. When the sweep frequency is applied two sidebands sweep in opposite direction and as a result if sidebands move one unit in frequency, the idler is moved 3-units because frequency difference between two sidebands increased two times. The proposed frequency span broadening method can be used with ordinary OFDR arrangement and as well as DB-PNC OFDR arrangement. The feasibilities of the proposed method are demonstrated by the means of experiments, around 3.4 cm spatial resolution was achieved in ordinary OFDR with only 1 GHz sweep span which corresponds to 10.2 cm spatial resolution. Moreover, phase noise cancellation with enhanced spatial resolution was also demonstrated by cancelling the laser phase noise in a 10 km long fiber and achieving spatial resolution around 8.4 cm with only 400 MHZ sweep span which corresponds to 25.2 cm spatial resolution.

Thesis Structure

This thesis consists of 7 chapters, description is given below

Chapter 1: This chapter is based on introduction which includes background and some description about statement problem. The second part summarizes contribution of research in this thesis and last part defines the structure of the thesis.

Chapter 2: This chapter starts with types of scattering and general working principle of reflectometry technique. In following part of this chapter two mainly used reflectometry techniques OTDR and OFDR are explained briefly along with problems and limitations faced by both techniques and a comparison between both techniques is also given. This chapter ends with the main problem in OFDR which is mentioned as problem statement of this research.

Chapter 3: The proposed method to solve OFDR problem is described in this chapter. This chapter is further divided into two possible arrangements of the proposed theory. Heterodyne detection method is simple but has got a limitation and as a solution phase diversity detection was proposed. Feasibility of proposed theory is confirmed by the means of experiments and high spatial resolution capability of proposed OFDR is demonstrated by detecting two break points 10 cm apart from each other, moreover fiber temperature dependence was also measured with high spatial resolution.

Chapter 4: A new method to measure chromatic dispersion is presented in this chapter. This new proposed method uses DB-PNC OFDR to measure chromatic dispersion in long optical fibers which can outperform conventional method of measuring chromatic dispersion based on OTDR. The proposed method was demonstrated using experiment where chromatic dispersion in a 50 km dispersion shifted fiber was measured with 7.9 mm spatial resolution. Measured results were compared with phase shift method and a close match was observed which confirms the accuracy of proposed method.

Chapter 5: This chapter is based on proposal of a new scheme to estimate laser phase noise. The proposed method is extension of DB-PNC OFDR, the experimental setup and the theory is similar to that of DB-PNC OFDR with some extra signal processing involved. The proposed scheme can estimate laser phase noise and the estimated laser phase noise can be used to cancel phase noise in OFDR with some additional advantages of reduced sampling speed required and high spatial resolution.

Chapter 6: In this chapter a new method to increase frequency sweep span is presented. The proposed method is capable of increasing the available sweep span by 3-times hence the spatial resolution by 3-times. With the help of experiments it is demonstrated the proposed method can increase sweep span in ordinary and as well as in DB-PNC OFDR.

Chapter 7: This is the last chapter which is based on overall conclusion of the work presented in the thesis. Another part of this chapter talks about the possible future works and three significant future works are discussed.